Conformal Fractals – Ergodic Theory Methods

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Introduction

Introduction

This book is an introduction to the theory of iteration of expanding and non-uniformly expanding holomorphic maps and topics in geometric measure theory of the underlying invariant fractal sets. Probability measures on these sets yield informations on Hausdorff and other fractal dimensions and properties. The book starts with a comprehensive chapter on abstract ergodic theory followed by chapters on uniform distance expanding maps and *thermodynamical formalism*. This material is applicable in many branches of dynamical systems and related fields, far beyond the applications in this book.

Popular examples of the fractal sets to be investigated are Julia sets for rational functions on the Riemann sphere. The theory which was initiated by Gaston Julia [Julia 1918] and Pierre Fatou [Fatou 1919-1920] has become very popular since appearence of Benoit Mandelbrot's book [Mandelbrot 1982] with beautiful computer made pictures. Then it has become a field of spectacular achievements by top mathematicians during the last 30 years.

Consider for example the map $f(z) = z^2$ for complex numbers z. Then the unit circle $S^1 = \{|z| = 1\}$ is f-invariant, $f(S^1) = S^1 = f^{-1}(S^1)$. For $c \approx 0, c \neq 0$ and $f_c(z) = z^2 + c$, there still exists an f_c-invariant set $J(f_c)$ called the *Julia set* of f_c, close to S^1, homeomorphic to S^1 via a homeomorphism h satisfying equality $f \circ h = h \circ f_c$. However $J(f_c)$ has a fractal shape. For large c the curve $J(f_c)$ pinches at infinitely many points; it may pinch everywhere to become a dendrite, or even crumble to become a Cantor set.

These sets satisfy two main properties, standard attributes of "conformal fractal sets":

1. Their fractal dimensions are strictly larger than the topological dimension.

2. They are conformally "self-similar", namely arbitrarily small pieces have shapes similar to large pieces *via* conformal mappings, here *via* iteration of f.

To measure fractal sets invariant under holomorphic mappings one applies probability measures corresponding to equilibria in the thermodynamical formalism. This is a beautiful example of interlacing of ideas from mathematics and physics.

The following *prototype lemma* [Bowen 1975, Lemma 1.1] stands at the roots of the thermodynamical formalism

Lemma 0.0.1. *(Finite Variational Principle) For given real numbers $\phi_1, \ldots, \phi_n$*

the quantity

$$F(p_1, \ldots p_n) = \sum_{i=1}^{n} -p_i \log p_i + \sum_{i=1}^{n} p_i \phi_i$$

has maximum value $P(\phi_1, \ldots \phi_n) = \log \sum_{i=1}^{n} e^{\phi_i}$ *as* $(p_1, \ldots, p_n)$ *ranges over the simplex* $\{(p_1, \ldots, p_n) : p_i \geq 0, \sum_{i=1}^{n} p_i = 1\}$ *and the maximum is attained only at*

$$\hat{p}_j = e^{\phi_j} \Big(\sum_{i=1}^{n} e^{\phi_i}\Big)^{-1}$$

We can read $\phi_i, p_i, i = 1, \ldots, n$ as a function (*potential*), resp. probability distribution, on the finite space $\{1, \ldots, n\}$. The proof follows from the strict concavity of the logarithm function.

Let us further follow Bowen [Bowen 1975]: The quantity

$$S = \sum_{i=1}^{n} -p_i \log p_i$$

is called *entropy* of the distribution $(p_1, \ldots, p_n)$. The maximizing distribution $(\hat{p}_1, \ldots, \hat{p}_n)$ is called *Gibbs* or *equilibrium state*. In statistical mechanics $\phi_i = -\beta E_i$, where $\beta = 1/kT$, T is a temperature of an external "heat source" and k a physical (Boltzmann) constant. The quantity $E = \sum_{i=1}^{n} p_i E_i$ is the average energy. The Gibbs distribution maximizes thus the expression

$$S - \beta E = S - \frac{1}{kT} E$$

or equivalently minimizes the so-called *free energy* $E - kTS$. The nature prefers states with low energy and high entropy. It minimizes free energy.

The idea of Gibbs distribution as limit of distributions on finite spaces of configurations of states (spins for example) of interacting particles over increasing to infinite, bounded parts of the lattice $\mathbb{Z}^d$, introduced in statistical mechanics first by Bogolubov and Hacet [Bogolyubov & Hacet 1949] and playing there a fundamental role was applied in dynamical systems to study Anosov flows and hyperbolic diffeomorphisms at the end of sixties by Ja. Sinai, D. Ruelle and R. Bowen. For more historical remarks see [Ruelle 1978] or [Sinai 1982]. This theory met the notion of entropy S borrowed from information theory and introduced by Kolmogorov as an invariant of a measure-theoretic dynamical system.

Later the usefulness of these notions to the geometric dimensions has become apparent. It was present already in [Billingsley 1965] but crucial were papers by Bowen [Bowen 1979] and McCluskey & Manning [McCluskey & Manning 1983].

In order to illustrate the idea consider the following example: Let $T_i : I \to I$, $i = 1, \ldots, n > 1$, where $I = [0, 1]$ is the unit interval, $T_i(x) = \lambda_i x + a_i$, where λ_i, a_i are real numbers chosen in such a way that all the sets $T_i(I)$ are pairwise disjoint and contained in I. Define the limit set Λ as follows

$$\Lambda = \bigcap_{k=0}^{\infty} \bigcup_{(i_0, \ldots, i_k)} T_{i_0} \circ \cdots \circ T_{i_k}(I) = \bigcup_{(i_0, i_1 \ldots)} \lim_{k \to \infty} T_{i_0} \circ \cdots \circ T_{i_k}(x),$$

the latter union taken over all infinite sequences $(i_0, i_1, \dots)$, the previous over sequences of length $k + 1$. By our assumptions $|\lambda_j| < 1$ hence the limit exists and does not depend on x.

It occurs that its Hausdorff dimension is equal to the only number α for which

$$|\lambda_1|^\alpha + \cdots + |\lambda_n|^\alpha = 1.$$

Λ is a Cantor set. It is self-similar with small pieces similar to large pieces with the use of linear (more precisely, affine) maps $(T_{i_0} \circ \cdots \circ T_{i_k})^{-1}$. We call such a Cantor set *linear*. We can distribute measure μ by setting $\mu(T_{i_0} \circ \cdots \circ T_{i_k}(I)) = (\lambda_{i_0} \dots \lambda_{i_k})^\alpha$. Then for each interval $J \subset I$ centered at a point of Λ its diameter raised to the power α is comparable to its measure μ (this is immediate for the intervals $T_{i_0} \circ \cdots \circ T_{i_k}(I)$). (A measure with this property for all small balls centered at a compact set, in a euclidean space of any dimension, is called a *geometric measure*.) Hence $\sum(\operatorname{diam} J)^\alpha$ is bounded away from 0 and ∞ for all economical (of multiplicity not exceeding 2) covers of Λ by intervals J.

Note that for each k the measure μ restricted to the space of unions of $T_{i_0} \circ \cdots \circ T_{i_k}(I)$, each such interval viewed as one point, is the Gibbs distribution, where we set $\phi((i_0, \dots, i_k)) = \phi_\alpha((i_0, \dots, i_k)) = \sum_{l=0,\dots,k} \alpha \log \lambda_{i_l}$. The number α is the unique 0 of the *pressure function* $\mathrm{P}(\alpha) = \frac{1}{k+1} \log \sum_{(i_0,\dots,i_k)} e^{\phi_a((i_0,\dots,i_k))}$. In this special affine example this is independent of k. In general non-linear case to define pressure one passes with k to ∞.

The family T_i and compositions is an example of very popular in recent years *Iterated Function Systems* [Barnsley 1988]. Note that on a neighbourhood of each $T_i(I)$ we can consider $\hat{T} := T_i^{-1}$. Then Λ is an invariant repeller for the distance expanding map $\hat{T}$.

The relations between dynamics, dimension and geometric measure theory start in our book with the theorem that the Hausdorff dimension of an expanding repeller is the unique 0 of the adequate pressure function for sets built with the help of $C^{1+\varepsilon}$ usually non-linear maps in $\mathbb{R}$ or conformal maps in the complex plane $\mathbb{C}$ (or in $\mathbb{R}^d, d > 2$; in this case conformal maps must be Möbius, i.e. composition of inversions and symmetries, by Liouville theorem).

This theory was developed for non-uniformly hyperbolic maps or flows in the setting of smooth ergodic theory, see [Katok & Hasselblatt 1995], Mañé [Mañé 1987]. Let us mention also [Ledrappier & Young 1985]. See [Pesin 1997] for recent developments. The advanced chapters of our book are devoted to this theory, but we restrict ourselves to complex dimension 1. So the maps are non-uniformly expanding and the main technical difficulties are caused by critical points, where we have strong contraction since the derivative by definition is equal to 0 at critical points.

A direction not developed in this book are Conformal Iterated Function Systems with infinitely many generators T_i. They occur naturally as return maps in many important constructions, for example for rational maps with parabolic periodic points or in the *Induced Expansion* construction for polynomials [Graczyk & Świątek 1998]. See also the recent [Przytycki & Rivera-Letelier 2007]. Beautiful examples are provided by infinitely generated Kleinian groups. For a

measure theoretic background see [Young 1999].

The systematic treatment of Iterated Function Systems with infinitely many generators can be found in [Mauldin & Urbanski 1996] and [Mauldin & Urbanski 2003], for example. Recently this has been intensively explored in the iteration of entire and meromorphic functions.

Below is a short description of the content of the book.

Chapter 0 contains some introductory definitions and basic examples. It is a continuation of Introduction.

Chapter 1 is an introduction to abstract ergodic theory, here T is a probability measure preserving transformation. The reader will find proofs of the fundamental theorems: Birkhoff Ergodic Theorem and Shannon-McMillan-Breiman Theorem. We introduce entropy, measurable partitions and discuss canonical systems of conditional measures in Lebesgue spaces, the notion of *natural extension* (inverse limit in the appropriate category). We follow here Rohlin's Theory [Rohlin 1949], [Rohlin 1967], see also [Kornfeld , Fomin & Sinai 1982]. Next to prepare to applications for finite-to-one rational maps we sketch Rohlin's theory on countable-to-one endomorphisms and introduce the notion of Jacobian, see also [Parry 1969]. Finally we discuss mixing properties (K-propery, exactness, Bernoulli) and probability laws: Central Limit Theorem (abbr. CLT), Law of Iterated Logarithm (LIL), Almost Sure Invariance Principle (ASIP) for the sequence of functions (random variables on our probability space) $\phi \circ T^n, n = 0, 1, \ldots$.

Chapter 2 is devoted to ergodic theory and termodynamical formalism for general continuous maps on compact metric spaces. The main point here is the so called Variational Principle for pressure, compare the Finite Variational Principle lemma, above. We apply also functional analysis in order to explain Legendre transform duality between entropy and pressure. We follow here [Israel 1979] and [Ruelle 1978]. This material is applicable in *large deviations* and *multifractal analysis*, and is directly related to the uniqueness of Gibbs states question.

In Chapters 1, 2 we often follow the beautiful book by Peter Walters [Walters 1982].

In Chapter 3 *distance expanding maps* are introduced. Analogously to Axiom A diffeomorphisms [Smale 1967], [Bowen 1975] or endomorphisms, [Przytycki 1976] and [Przytycki 1977], we outline a topological theory: spectral decomposition, specification, Markov partition, and start a "bounded distortion" play with Hölder continuous functions.

In Chapter 4 termodynamical formalism and mixing properties of Gibbs measures for open distance expanding maps T and Hölder continuous potentials ϕ are studied. To large extent we follow [Bowen 1975] and [Ruelle 1978]. We prove the existence of Gibbs probability measures (states): m with Jacobian being $\exp -\phi$ up to a constant factor, and T-invariant $\mu = \mu_\phi$ equivalent to m. The idea is to use the *transfer operator* $\mathcal{L}_\phi(u)(x) = \sum_{y \in T^{-1}(x)} u(y) \exp \phi(y)$ on the Banach space of Hölder continuous functions u. We prove the exponential convergence $\xi^{-n} \mathcal{L}_\phi^n(u) \to (\int u \, dm) u_\phi$, where ξ is the eigenvalue of the largest absolute value and u_ϕ the corresponding eigenfunction. One obtains

$u_\phi = dm/d\mu$. We deduce CLT, LIL and ASIP, and the Bernoulli property for the natural extension.

We provide three different proofs of the uniqueness of the invariant Gibbs measure. The first, simplest, follows [Keller 1998], the second relies on the Finite Variational Principle, the third one on the differentiability of the pressure function in adequate function directions.

Finally we prove Ruelle's formula

$$d^2 P(\phi + tu + sv)/dt\, ds|_{t=s=0} = \lim_{n\to\infty} \frac{1}{n} \int \left(\sum_{i=0}^{n-1} (u \circ T^i - \int u\, d\mu_\phi) \cdot \left(\sum_{i=0}^{n-1} (v \circ T^i - \int v\, d\mu_\phi)\right) d\mu_\phi.$$

This expression for $u = v$ is equal to σ^2 in CLT for the sequence $u \circ T^n$ and measure μ_ϕ.

(In the book we use the letter T to denote a measure preserving transformation. Maps preserving an additional structure, continuous, smooth or holomorphic for example, are usually denoted by f or g.)

In Chapter 5 (Section refsec:v5.1) the metric space with the action of a distance expanding map f is embedded in a smooth manifold and it is assumed that the map extends smoothly (or only continuously) to a neighbourhood. Similarly to hyperbolic sets [Katok & Hasselblatt 1995] we discuss basic properties. Te intrinsic property of f being an open map on X occurs equivalent to X being repeller for the extension.

We call the repeller X with the smoothly extended dynamics: *Smooth Expanding Repeller*, abbr. SER.

If an extension is conformal we say (X, f) is a *Conformal Expanding Repeller*, abr CER. In Section 5.2 we discuss some distortion theorems and holomorphic motion to be used later in Section 5.4 and in Chapter 8 to prove analytic dependence of "pressure" and Hausdorff dimension of CER on parameter.

In Section 5.3 we prove that for CER the density $u_\phi = dm/d\mu$ for measures of harmonic potential is real-analytic (extends so on neighbourhood of X). This will be used in 9 for the potential being $-\log|f'|$, in which case μ is equivalent to Hausdorff measure in maximal dimension (geometric measure).

In Chapter 6 we provide in detail D. Sullivan's theory classifying $C^{r+\varepsilon}$ line Cantor sets via *scaling function*, sketched in [Sullivan 1988] and discuss the realization problem [Przytycki & Tangerman 1996]. We also discuss applications for Cantor-like closures of postcritical sets for infinitely renormalizable *Feigenbaum* quadratic-like maps of interval. The infinitesimal geometry of these sets occurs independent of the map, which is one of famous Coullet-Tresser-Feigenbaum universalities.

In Chapter 7 we provide definitions of various "fractal dimensions": Hausdorff, box and packing. We consider also Hausdorff measures with gauge functions different from t^α. We prove "Volume Lemma" linking, roughly speaking, (global) dimension with local dimensions.

In Chapter 8 we develop the theory of Conformal Expanding Repellers and relate pressure with Hausdorff dimension.

Section 8.2 provides a brief exposition of multifractal analysis of Gibbs measure μ of a Hölder potential on CER X. We rely mainly on [Pesin 1997]. In particular we discuss the function $F_\mu(\alpha) := \mathrm{HD}(X_\mu(\alpha))$, where $X_\mu(\alpha) := \{x \in X : d(x) = \alpha\}$ and $d(x) := \lim_{r \to 0} \log \mu(B(x,r))/\log r$. The decomposition $X = \bigcup_\alpha (X_\mu(\alpha)) \cup \hat{X}$, where the limit $d(x)$, called local dimension, does not exist for $x \in \hat{X}$, is called local dimension spectrum decomposition.

Next we follow the easy (uniform) part of [Przytycki, Urbański & Zdunik 1989] and [Przytycki, Urbański & Zdunik 1991]. We prove that for CER (X, f) and Hölder continuous $\phi : X \to R$, for $\kappa = \mathrm{HD}(\mu_\phi)$, Hausdorff dimension of the Gibbs measure μ_ϕ (infimum of Hausdorff dimensions of sets of full measure), either $\mathrm{HD}(X) = \kappa$ the measure μ_ϕ is equivalent to Λ_κ, the Hausdorff measure in dimension κ, and is a *geometric measure*, or μ_ϕ is singular with respect to Λ_κ and the right gauge function for the Hausdorff measure to be compared to μ_ϕ is $\Phi(\kappa) = t^\kappa \exp(c\sqrt{\log 1/t \log \log \log 1/t})$. In the proof we use LIL. This theorem is used to prove a dichotomy for the harmonic measure on a Jordan curve ∂, bounding a domain Ω, which is a repeller for a conformal expanding map. Either ∂ is real analytic or harmonic measure is comparable to the Hausdorff measure with gauge function $\Phi(1)$. This yields an information about the lower and upper growth rates of $|R'(r\zeta)|$, for $r \nearrow 1$, for almost every ζ with $|\zeta| = 1$ and univalent function R from the unit disc $|z| < 1$ to Ω. This is a dynamical counterpart of Makarov's theory of boundary behaviour for general simply connected domains, [Makarov 1985].

We prove in particular that for $f_c(z) = z^2 + c, c \neq 0, c \approx 0$ $1 < \mathrm{HD}(J(f_c)) < 2$.

We show how to express in the language of pressure another interesting function: $\int_{|\zeta|=1} |R'(r\zeta)|^t |d\zeta|$ for $r \nearrow 1$.

Finally we apply our theory to the boundary of von Koch "snowflake" and more general Carleson fractals.

Chapter 9 is devoted to Sullivan's rigidity theorem, saying that two non-linear expanding repellers $(X, f), (Y, g)$ that are Lipschitz conjugate (or more generally there exists a measurable conjugacy that transforms a geometric measure on X to a geometric measure on Y, then the conjugacy extends to a conformal one. This means that measures classify non-linear conformal repellers. This fact, announced in [Sullivan 1986] only with a sketch of the proof, is proved here rigorously for the first time.

(This chapter was one of the eldest chapters in this book; we made it available already in 1991. Many papers have been following it later on.)

In Chapter 10 we start to deal with non-uniform expanding phenomena. A heart of this chapter is the proof of the formula $\mathrm{HD}(\mu) = \mathrm{h}_\mu(f)/\chi_\mu(f)$ for an arbitrary f-invariant ergodic measure μ of positive Laypunov exponent $\chi_\mu := \int \log |f'| \, d\mu$.

(The word non-uniform expanding is used just to say that we consider (typical points of) an ergodic measure with positive Lyapunov exponent. In higher dimension one uses the name non-uniform hyperbolic for measures with all Lyapunov exponents non-zero.)

It is so roughly because a small disc around z, whose n-th image is large, has diameter of order $|(f^n)'(z)|^{-1} \approx \exp -n\chi_\mu$ and measure $\exp -n\, \mathrm{h}_\mu(f)$ (Shannon-McMillan-Breiman theorem is involved here)

Chapter 11 is devoted to conformal measures, namely probability measures with Jacobian $\mathrm{Const}\, \exp -\phi$ or more specifically $|f'|^\alpha$ in a non-uniformly expanding situation, in particular for any rational mapping f on its Julia set J. It is proved that there exists a minimal exponent $\delta(f)$ for which such a measure exists and that $\delta(f)$ is equal to each of the following quantities:

Dynamical Dimension $\mathrm{DD}(J) := \sup\{\mathrm{HD}(\mu)\}$, where μ ranges over all ergodic f-invariant measures on J of positive Lyapunov exponent.

Hyperbolic Dimension $\mathrm{HyD}(J) := \sup\{\mathrm{HD}(Y)\}$, where Y ranges over all Conformal Expanding Repellers in J, or CER's that are Cantor sets.

It is an open problem whether for every rational mapping $\mathrm{HyD}(J) = \mathrm{HD}(J) =$ box dimension of J, but for many nonuniformly expandig mappings these equalities hold. It is often easier to study the continuity of $\delta(f)$ with respect to a parameter, than directly Hausdorff dimension. So one obtains an information about the continuity of dimensions due to the above equalities.

The last Section 11.5 presents a recent approach via pressure for the potential function $-t \log |f'|$, yielding a simple proof of the above equalities of dimensions, see [Przytycki, Rivera-Letelier & Smirnov 2004].

A large part of this book was written in the years 1990-1992 and was lectured to graduate students by each of us in Warsaw, Yale and Denton. We neglected finishing writing, but recently unexpectedly to us the methods in Chapter 11, relating hyperbolic dimension to minimal exponent of conformal measure, were used to study the dependence on ε of the dimension of Julia set for $z^2 + 1/4 + \varepsilon$, for $\varepsilon \to 0$ and other parabolic bifurcations, by A. Douady, P. Sentenac and M. Zinsmeister in [Douady, Sentenac Zinsmeister 1997] and by C. McMullen in [McMullen 1996]. So we decided to make final efforts. Meanwhile nice books appeared on some topics of our book, let us mention [Falconer 1997], [Zinsmeister 1996], [Boyarsky & Góra 1997], [Pesin 1997], [Keller 1998], [Baladi 2000] but a lot of important material in our book is new or was hardly accessible, or is written in an unconventional way.

Warsaw, Denton, 1999-2002, 2006-2009.

Chapter 0

Basic examples and definitions

Let us start with definitions of dimensions. We shall come back to them in a more systematic way in Chapter 7.

Definition 0.2. Let (X, ρ) be a metric space. We call by *upper (lower) box dimension* of X the quantity

$$\overline{\mathrm{BD}}(X) \text{ (or } \underline{\mathrm{BD}}(X)) := \limsup(\liminf)_{r \to 0} \frac{\log N(r)}{-\log r}$$

where $N(r)$ is the minimal number of balls of radius r which cover X.

Sometimes the names *capacity* or *Minkowski dimension* or *box-counting dimension* are used. The name box dimension comes from the situation where X is a subset of a euclidean space $\mathbb{R}^d$. Then one can consider only $r = 2^{-n}$ and $N(2^{-n})$ can be replaced by the number of dyadic boxes $[\frac{k_1}{2^{-n}}, \frac{k_1+1}{2^{-n}}] \times \cdots \times [\frac{k_d}{2^{-n}}, \frac{k_d+1}{2^{-n}}], k_j \in \mathbb{Z}$ intersecting X.

If $\overline{\mathrm{BD}}(X) = \underline{\mathrm{BD}}(X)$ we call the quantity *box dimension* and denote it by $\overline{\mathrm{BD}}(X)$.

Definition 0.3. Let (X, ρ) be a metric space. For every $\kappa > 0$ we define $\Lambda_\kappa(X) = \lim_{\delta \to 0} \inf\{\sum_{i=1}^{\infty} (\mathrm{diam}\, U_i)^\kappa\}$, where the infimum is taken over all countable covers $(U_i, i = 1, 2, \dots)$ of X by sets of diameter not exceeding δ. $\Lambda_\kappa(Y)$ defined as above on all subsets $Y \subset X$ is called κ-th outer *Hausdorff measure*.

It is easy to see that there exists $\kappa_0 : 0 \leq \kappa_0 \leq \infty$ such that for all $\kappa : 0 \leq \kappa < \kappa_0$ $\Lambda_\kappa(X) = \infty$ and for all $\kappa : \kappa_0 < \kappa$ $\Lambda_\kappa(X) = 0$. The number κ_0 is called the *Hausdorff dimension* of X.

Note that if in this definition we replace the assumption: sets of diameter not exceeding δ by equal δ, and $\lim_{\delta \to 0}$ by $\liminf$ or $\limsup$, we obtain box dimension.

A standard example to compare both notions is the set $\{1/n, n = 1, 2, \dots\}$ in $\mathbb{R}$. Its box dimension is equal to $1/2$ and Hausdorff dimension is 0. If one considers $\{2^{-n}\}$ instead one obtains both dimensions 0. Also linear Cantor sets in Introduction have Hausdorff and box dimensions equal. The reason for this is self-similarity.

Example 0.4. Shifts spaces. For every natural number d consider the space Σ^d of all infinite sequences $(i_0, i_1, \dots)$ with $i_n \in \{1, 2, \dots, d\}$. Consider the metric

$$\rho((i_0, i_1, \dots), (i'_0, i'_1, \dots)) = \sum_{n=0}^{\infty} \lambda^n |i_n - i'_n|$$

for an arbitrary $0 < \lambda < 1$. Sometimes it is more comfortable to use the metric

$$\rho((i_0, i_1, \dots), (i'_0, i'_1, \dots)) = \lambda^{-\min\{n : i_n \neq i'_n\}},$$

equivalent to the previous one. Consider $\sigma : \Sigma^d \to \Sigma^d$ defined by $f((i_0, i_1, \dots) = (i_1, \dots)$. The metric space (Σ^d, ρ) is called *one-sided shift space* and the map σ the *left shift*. Often, if we do not specify metric but are interested only in the cartesian product topology in $\Sigma^d = \{1, \dots, d\}^{\mathbb{Z}^+}$, we use the name *topological shift space.*

One can consider the space $\tilde{\Sigma}^d$ of all two sides infinite sequences $(\dots, i_{-1}, i_0, i_1, \dots)$. This is called *two-sided shift space.*

Each point $(i_0, i_1, \dots) \in \Sigma^d$ determines its forward trajectory under σ, but is equipped with a Cantor set of backward trajectories. Together with the topology determined by the metric $\sum_{n=-\infty}^{\infty} \lambda^{|n|} |i_n - i'_n|$ the set $\tilde{\Sigma}^d$ can be identified with the *inverse limit* (in the topological category) of the system $\cdots \to \Sigma^d \to \Sigma^d$ where all the maps $\to$ are σ.

Note that the limit Cantor set Λ in Introduction, with all $\lambda_i = \lambda$ is Lipschitz homeomorphic to Σ^d, with the homeomorphism h mapping $(i_0, i_1, \dots)$ to $\bigcap_k T_{i_0} \circ .. \circ T_{i_k}(I)$. Note that for each $x \in \Lambda$, $h^{-1}(x)$ is the sequence of integers $(i_0, i_1, \dots)$ such that for each k, $\hat{T}^k(x) \in T_{i_k}(I)$. It is called a *coding sequence*. If we allow the end points of $T_i(I)$ to overlap, in particular $\lambda = 1/d$ and $a_i = (i-1)/d$, then $\Lambda = I$ and $h^{-1}(x) = \sum_{k=0}^{\infty} (i_k - 1) d^{-k-1}$.

One generalizes the one (or two) -sided shift space, called sometimes *full shift space* by considering the set Σ_A for an arbitrary $d \times d$ – matrix $A = (a_{ij}$ with $a_{ij} = 0$ or 1 defined by

$$\Sigma_A = \{(i_0, i_1, \dots) \in \Sigma^d : a_{i_t i_{t+1}} = 1 \text{ for every } t = 0, 1, \dots\}.$$

By the definition $\sigma(\Sigma_A) \subset \Sigma_A$. Σ_A with the mapping σ is called a *topological Markov chain*. Here the word *topological* is substantial, otherwise it is customary to think of a finite number of states stochastic process, see Example 0.10.

Example 0.5. adding machine A complementary dynamics on Σ^d above, is given by the map $T((i_0, i_1, \dots)) = (1, 1, \dots, 1, i_k + 1, i_k + 1, \dots)$, where k is the least integer for which $i_k < d$. Finally $(d, d, d, \dots) + 1 = (1, 1, 1, \dots)$. (This is of course compatible with the standard adding, except here the sequences

are infinite to the right and the digits run from 1 to d, rather than from 0 to $d-1$.) Notice that unlike in the previous example with abundance of periodic trajectories, here each T-trajectory is dense in Σ^d (such dynamical system is called *minimal*).

Example 0.6. Iteration of rational maps. Let $f : \overline{\mathbb{C}} \to \overline{\mathbb{C}}$ be a holomorphic mapping of the Riemann sphere $\overline{\mathbb{C}}$. Then it must be rational, i.e. ratio of two polynomials. We assume that the topological degree of f is at least 2. The *Julia set $J(f)$* is defined as follows:

$J(f) = \{z \in \overline{\mathbb{C}} : \forall U \ni z$, U open, the family of iterates $f^n = f \circ \cdots \circ f|_U$, n times, for $n = 1, 2, \ldots$ is not *normal* in the sense of Montel $\}$.

A family of holomorphic functions $f_t : U \to \overline{\mathbb{C}}$ is called *normal* (in the sense of Montel) if it is pre-compact, namely from every sequence of functions belonging to the family one can choose a subsequence uniformly convergent (in the spherical metric on the Riemann sphere $\overline{\mathbb{C}}$) on all compact subsets of U.

$z \in J(f)$ implies for example, that for every $U \ni z$ the family $f^n(U)$ covers all $\overline{\mathbb{C}}$ but at most 2 points. Otherwise by Montel's theorem $\{f^n\}$ would be normal on U.

Another characterization of $J(f)$ is that $J(f)$ is the closure of repelling periodic points, namely those points $z \in \overline{\mathbb{C}}$ for which there exists an integer n such that $f^n(z) = z$ and $|(f^n)'(z)| > 1$.

There is only finite number of attracting periodic points, $|(f^n)'(z)| < 1$; they lie outside $J(f)$, which is an uncountable "chaotic, expansive (repelling)" Julia set. The lack of symmetry between attracting and repelling phenomena is caused by the non-invertibility of f.

It is easy to prove that $J(f)$ is compact, completely invariant: $f(J(f)) = J(f) = f^{-1}(J(f))$, either nowhere dense or equal to the whole sphere (to prove this use Montel's theorem).

For polynomials, the set of points whose images under iterates $f^n, n = 1, 2, \ldots$, tend to ∞, *basin of attraction to ∞*, is connected and completely invariant. Its boundary is the Julia set.

Check that all these general definitions and statements are compatible with the discussion of $f(z) = f_c(z) = z^2 + c$ in Introduction. As an introduction to this theory we recommend for example the books [Beardon 1991], [Carleson & Gamelin 1993], [Milnor 1999] and [Steinmetz 1993].

Below are computer pictures exhibiting some Julia sets: rabbit, basilica[1] and Sierpiński's carpet of their mating, see [Bielefeld ed. 1990].

A Julia set can have Hausdorff dimension arbitrarily close to 0 (but not 0) and arbitrarily close to 2 and even being exactly 2 (but not the whole sphere). More precisely: Julia set is always closed and either the whole sphere or nowhere dense. Recently examples have been found of quadratic polynomials f_c with Julia set of positive Lebesgue measure (with c in the cardioid, Example 5.1.10), see [Buff & Cheritat 2008]. See also

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[1] The name was proposed by Benoit Mandelbrot [Mandelbrot 1982] impressed by the Basilica San Marco in Venice plus its reflection in a flooded Piazza.
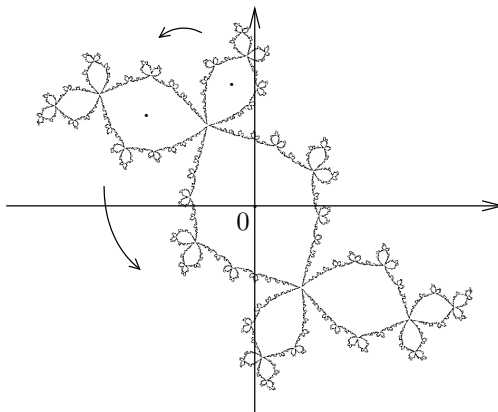
Figure 1: Douady's rabbit. Here $f(z) = z^2 + c$, where $c \approx -0.123 + 0.749i$, is a root of $c^3 + 2c^2 + c + 1 = 0$, see [Carleson & Gamelin 1993]. The three distinguished points constitute a period 3 orbit. The arrows hint the action of f.
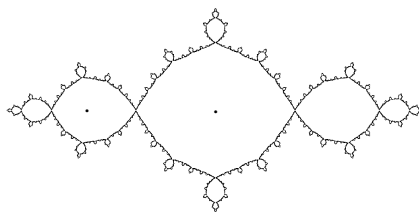
Figure 2: Basilica. For decreasing c this shape appears at $c = -3/4$ with thicker components. $f(z) = z^2 - 1$. The critical point 0 is attracting of period 2
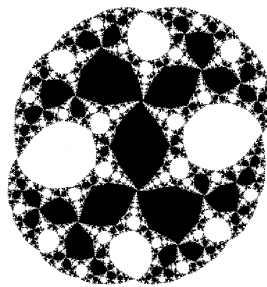
Figure 3: The (outer) basilica mated with the rabbit. Here $f(z) = \frac{z^2+c}{z^2-1}$ where $c = \frac{1+\sqrt{-3}}{2}$. Black is attracted to a period 3 orbit, white to period 2. Julia set is the boundary between black and white.

http://picard.ups-tlse.fr/adrien2008/Slides/Cheritat.pdf

Example 0.7. Complex linear fractals. The linear Cantor set construction in $\mathbb{R}$ described in Introduction can be generalized to conformal linear Cantor and other fractal sets in $\overline{\mathbb{C}}$:

Let $U \subset \mathbb{C}$ be a bounded connected domain and $T_i(z) = \lambda_i z + a_i$, where λ_i, a_i are complex numbers, $i = 1, \ldots, n > 1$. Assume that closures $\operatorname{cl} T_i(U)$ are pairwise disjoint and contained in U. The limit Cantor set Λ is defined in the same way as in Introduction.

In Chapter 9, Example 9.2.8 we shall note that it cannot be the Julia set for a holomorphic extension of $\hat{T} = T_i^{-1}$ on $T_i(U)$ for each i, to the whole sphere $\overline{\mathbb{C}}$.

If we allow that the boundaries of $T_i(U)$ intersect or intersect ∂U we obtain other interesting examples
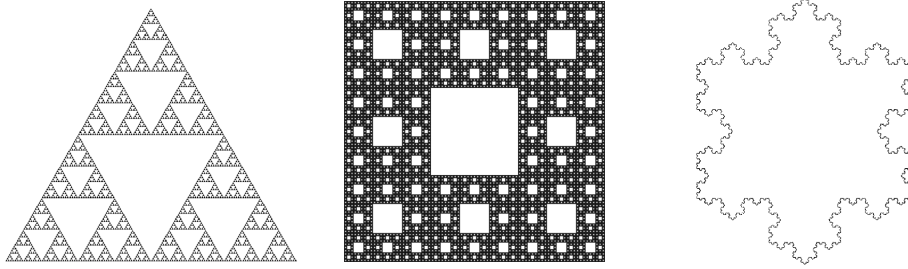
Figure 4: Sierpinski gasket, Sierpinski carpet & the boundary of von Koch snowflake

Example 0.8. Action of Kleinian groups. Beautiful examples of fractal sets arise as limit sets of the action of Kleinian groups on $\overline{\mathbb{C}}$.

Let Ho be the group of all *homographies*, namely the rational mappings of the Riemann sphere of degree 1, i.e. of the form $z \mapsto \frac{az+b}{cz+d}$ where $ad - bc \neq 0$. Every discrete subgroup of Ho is called *Kleinian group*. If all the elements of a Kleinian group preserve the unit disc $\mathbb{D} = \{|z| < 1\}$, the group is called *Fuchsian*.

Consider for example a regular hyperbolic $4n$-gon in $\mathbb{D}$ (equipped with the hyperbolic metric) centered at 0. Denote the consecutive sides by $a_i^j, i = 1, \ldots, n, j = 1, \ldots, 4$ in the lexicographical order: $a_1^1, \ldots a_1^4, a_2^1, \ldots$. Each side is contained in the corresponding circle C_i^j intersecting $\partial \mathbb{D}$ at the right angles. Denote the disc bounded by C_i^j by D_i^j.

It is not hard to see that the closures of D_i^j and D_i^{j+2} are disjoint for each i and $j = 1, 2$.
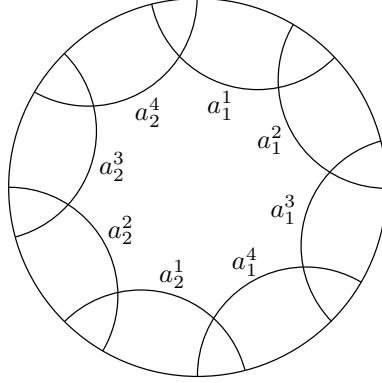
Figure 5: Regular hyperbolic octagon

Let $g_i^j, j = 1, 2$ be the unique homography preserving $\mathbb{D}$ mapping a_i^j to a_i^{j+2} and D_i^j to the complement of $\mathrm{cl}\, D_i^{j+2}$. It is easy to see that the family $\{g_i^j\}$ generates a Fuchsian group G. For an arbitrary Kleinian group G, the *Poincaré limit set* $\Lambda(G) = \bigcup \lim_{k\to\infty} g_k(z)$, the union taken over all sequences of pairwise different $g_k \in G$ such that $g_k(z)$ converges, where z is an arbitrary point in $\overline{\mathbb{C}}$. It is not hard to prove that $\Lambda(G)$ does not depend on z.

For the above example $\Lambda(G) = \partial\mathbb{D}$. If we change slightly g_i^j (the circles C_i^j change slightly), then either $\Lambda(G)$ is a circle S (all new C_i^j intersect S at the right angle), or it is a fractal Jordan curve. The phenomenon is similar to the case of the maps $z \mapsto z^2 + c$ described in Introduction and in more detail in Section 8.5. For details see [Bowen 1979], [Bowen & Series 1979], [Sullivan 1982]. We provide a sketch of the proof in Chapter 8.

If all the closures of the discs $D_i^j, i = 1, \ldots, n, j = 1, \ldots, 4$ become pairwise disjoint, $\Lambda(G)$ becomes a Cantor set (the group is called then a *Schottky group* or a *Kleinian group of Schottky type*).

Example 0.9. Higher dimensions. Though the book is devoted to 1-dimensional real and complex iteration and arising fractals, Chapters 1-3 apply to general situations. A basic example is Smale's horseshoe. Take a square $K = [0, 1] \times [0, 1]$ in the plane $\mathbb{R}^2$ and map it affinely to a strip by squeezing in the horizontal direction and stretching in the vertical, for example $f(x, y) = (\frac{1}{5}x + \frac{1}{4}, 3y - \frac{1}{8})$ and bend the strip by a new affine map g which maps the rectangle $[\frac{1}{5}, \frac{2}{5}] \times [\frac{7}{4}, \frac{23}{8}]$ to $[\frac{3}{5}, \frac{4}{5}] \times [-\frac{1}{8}, 1]$. The resulting composition $T = g \circ f$ maps K to a "horseshoe", see [Smale 1967, p.773]

The map can be easily extended to a C^∞-diffeomorphism of $\overline{\mathbb{C}}$ by mapping a "stadium" extending K, to a bent "stadium", and its complement to the respective complement. The set Λ^K of points not leaving K under action of $T^n, n = \ldots, -1, 0, 1, \ldots$ is the cartesian product of two Cantor sets. This set is T-invariant, "uniformly hyperbolic". In the horizontal direction we have con-
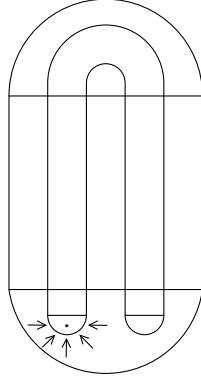
Figure 6: Horseshoe, stadium extension

traction, in the vertical direction uniform expansion. The situation is different from the previous examples of Σ^d or linear Cantor sets, where we had uniform expansion in all directions.

Smale's horseshoe is a universal phenomenon. It is always present for an iterate of a diffeomorphism f having a *transversal homoclinic point* q for a saddle p. The latter says that the stable and unstable manifolds $W^s(p) := \{y : f^n(y) \to p\}, W^u(p) := \{y : f^{-n}(y) \to p\}$ as $n \to \infty$, intersect transversally at q. For more details on hyperbolic sets see [Katok & Hasselblatt 1995]. Compare heteroclinic intersections in Chapter 3, Exercise 3.9.
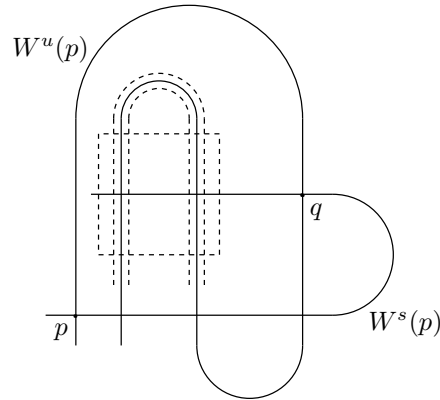
Figure 7: Homoclinic point

Note that $T|_{\Lambda^K}$ is *topologically conjugate* to the left shift σ on the two-sided shift space $\tilde{\Sigma}^2$, namely there exists a homeomorphism $h : \Lambda^K \to \tilde{\Sigma}^2$ such that $h \circ T = \sigma \circ h$. Compare h in Example 0.4. T on Λ^K is the inverse limit of the mapping $\hat{T}$ on the Cantor set described in Introduction, similarly to the

inverse limit $\tilde{\Sigma}^2$ of σ on Σ^2. The philosophy is that hyperbolic systems appear as inverse limits of expanding systems.

A partition of a hyperbolic set Λ into local stable (unstable) manifolds: $W^s(x) = \{y \in \Lambda : (\forall n \geq 0)\rho(f^n(x), f^n(y)) \leq \varepsilon(x)\}$ for a small positive measurable function ε, is an illustration of an abstract ergodic theory measurable partition ξ such that $f(\xi)$ is finer than ξ, $f^n(\xi), n \to \infty$ converges to the partition into points and the conditional entropy $\mathrm{H}_\mu(f(\xi)|\xi)$ is maximal possible, equal to the entropy $\mathrm{h}_\mu(f)$; all this holds for an ergodic invariant measure μ.

The inverse limit of the system $\cdots \to S^1 \to S^1$ where all the maps are $z \mapsto z^2$, is called a solenoid. It has a group structure: $(\ldots, z_{-1}, z_0) \cdot (\ldots, z'_{-1}, z'_0) = (\ldots, z_{-1} \cdot z'_{-1}, z_0 \cdot z'_0)$, which is a trajectory if both factors are, since the map $z \mapsto z^2$ is a homomorphism of the group S^1. Topologically the solenoid can be represented as the attractor A of the mapping of the solid torus $\mathbb{D} \times S^1$ into itself $f(z, w) = (\frac{1}{3}z + \frac{1}{2}w, w^2)$. Its Hausdorff dimension is equal in this special example to $1 + \mathrm{HD}(A \cap \{w = w_0\}) = 1 + \frac{\log 2}{\log 3}$ for an arbitrary w_0, as Cantor sets $A \cap \{w = w_0\}$ have Hausdorff dimensions $\frac{\log 2}{\log 3}$. These are linear Cantor sets discussed in Introduction.

Especially interesting is the question of Hausdorff dimension of A if $z \mapsto \frac{1}{3}z$ is replaced by $z \mapsto \phi(z)$ not conformal. But this higher dimensional problem goes beyond the scope of our book.

If the map $z \mapsto z^2$ in the definition of solenoid is replaced by an arbitrary rational mapping then if f is expanding on the Julia set, the solenoid is locally the cartesian product of an open set in $J(f)$ and the Cantor set of all possible choises of backward trajectories. If however there are critical points in $J(f)$ (or converging under the action of f^n to parabolic points in $J(f)$) the solenoid (inverse limit) is more complicated, see [Lyubich & Minsky 1997] and more recent papers for an attempt to describe it, together with a neighbourhood composed of trajectories outside $J(f)$. We shall not discuss this in our book.

Example 0.10. Bernoulli shifts and Markov chains. For every positive numbers $p_1, \ldots, p_d$ such that $\sum_{i=1}^d p_i = 1$, one introduces on the Borel subsets of Σ^d (or $\tilde{\Sigma}^d$) a probability measure μ by extending to the σ-algebra of all Borel sets the function $\mu(C_{i_0, i_1, \ldots, i_t}) = p_0 p_1 \ldots p_t$, where $C_{i_0, i_1, \ldots, i_t} = \{(i'_0, i'_1, \ldots) : i'_s = i_s$ for every $s = 0, 1, \ldots, t\}$. Each such C is called a *finite cylinder*.

The space Σ^d with the left shift σ and the measure μ is called one-sided *Bernoulli shift*.

On a topological Markov chain $\Sigma_A \subset \Sigma^d$ with $A = (a_{ij})$ and an arbitrary $d \times d$ matrix $M = p_{ij}$ such that $\sum_{j=1}^d p_{ij} = 1$ for every $i = 1, \ldots, d$, $p_{ij} \geq 0$ and $p_{ij} = 0$ if $a_{ij} = 0$, one can introduce a probability measure μ on all Borel subsets of Σ_A by extending $\mu(C_{i_0, i_1, \ldots, i_t}) = p_{i_0} p_{i_0 i_1} \ldots p_{i_{t-1} i_t}$. Here $(p_1, \ldots, p_d)$ is an eigenvector of M^*, namely $\sum_i p_i p_{ij} = p_j$, such that $p_i \geq 0$ for every $i = 1, \ldots, d$ and $\sum_{i=1}^d = 1$.

The space Σ_A with the left shift σ and the measure μ is called one-sided *Markov chain*.

Note that μ is σ-invariant. Indeed,

$$\mu\left(\bigcup_i (C_{i,i_0,\ldots,i_t})\right) = \sum_i p_i p_{ii_0} p_{i_0 i_1} \ldots p_{i_{t-1} i_t} = p_{i_0} p_{i_0 i_1} \ldots p_{i_{t-1} i_t} = \mu(C_{i_0,\ldots,i_t}).$$

As in the topological case if we consider $\tilde{\Sigma}^d$ rather than Σ^d, we obtain two-sided Bernoulli shifts and two-sided Markov chains.

Example 0.11. Tchebyshev polynomial. Let us consider the mapping $T :$ $[-1,1] \to [-1,1]$ of the real interval $[-1,1]$ defined by $T(x) = 2x^2 - 1$. In the co-ordinates $z \mapsto 2z$ it is just a restriction to an invariant interval of the mapping $z \mapsto z^2 - 2$ discussed already in Introduction. The interval $[-1,1]$ is Julia set of T.

Notice that this map is the factor of the mapping $z \mapsto z^2$ on the unit circle $\{|z| = 1\}$ in $\mathbb{C}$ by the orthogonal projection P to the real axis. Since the length measure l is preserved by $z \mapsto z^2$ its projection is preserved by T. Its density with respect to the Lebesgue measure on $[-1,1]$ is proportional to $(dP/dl)^{-1}$, after normalization is equal to $\frac{1}{\pi} \frac{1}{\sqrt{1-x^2}}$. This measure satisfies many properties of Gibbs invariant measures discussed in Chapter 4, though T is not expanding; it has a critical point at 0. This T is the simplest example of a non-uniformly expanding map to which the advanced parts of the book are devoted. See also Figures 1.1 and 1.2 in Section 1.2.

Chapter 1

Measure preserving endomorphisms

1.1 Measure spaces and martingale theorem

We assume that the reader is familiar with the basics elements of measure and integration theory. For a complete treatment see for example [Halmos 1950] or [Billingsley 1979]. We start with some basics to introduce notation and terminology.

A family $\mathcal{F}$ of subsets of a set X is said to be a *σ-algebra* if the following conditions are satisfied:

$$X \in \mathcal{F}, \tag{1.1.1}$$

$$A \in \mathcal{F} \ \Rightarrow \ A^c \in \mathcal{F} \tag{1.1.2}$$

and

$$\{A_i\}_{i=1}^{\infty} \subset \mathcal{F} \ \Rightarrow \ \bigcup_{i=1}^{\infty} A_i \in \mathcal{F}. \tag{1.1.3}$$

It follows from this definition that $\emptyset \in \mathcal{F}$, that the σ-algebra $\mathcal{F}$ is closed under countable intersections and under subtractions of sets. If (1.1.3) is assumed only for finite subfamilies of $\mathcal{F}$ then $\mathcal{F}$ is called an *algebra*. The elements of the σ–algebra $\mathcal{F}$ will be frequently called *measurable* sets.

Notation 1.1.1. *For any family $\mathcal{F}_0$ of subsets of X, we denote by $\sigma(\mathcal{F}_0)$ the least σ–algebra that contains $\mathcal{F}_0$ and we call it the σ–algebra generated by $\mathcal{F}_0$.*

A function on a σ-algebra $\mathcal{F}$, $\mu : \mathcal{F} \to [0, \infty]$, is said to be *σ-additive* if for any countable subfamily $\{A_i\}_{i=1}^{\infty}$ of $\mathcal{F}$ consisting of mutually disjoint sets, we have

$$\mu\Big(\bigcup_{i=1}^{\infty} A_i \Big) = \sum_{i=1}^{\infty} \mu(A_i) \tag{1.1.4}$$

We say then that μ is a *measure*. If we consider in (1.1.4) only finite families of sets, we say μ is *additive*. The two notions: of *additive* and of σ-*additive*, make sense for a σ-algebra as well as for an algebra, provided that in the case of an algebra one extra assumes that if $A_i \in \mathcal{F}$ for all i, then $\bigcup A_i \in \mathcal{F}$. The simplest consequences of the definition of measure are the following:

$$\mu(\emptyset) = 0; \tag{1.1.5}$$

$$\text{if } A, B \in \mathcal{F} \text{ and } A \subset B \text{ then } \mu(A) \leq \mu(B); \tag{1.1.6}$$

if $A_1 \subset A_2 \subset \ldots$ and $\{A_i\}_{i=1}^{\infty} \subset \mathcal{F}$ then

$$\mu\Big(\bigcup_{i=1}^{\infty} A_i \Big) = \sup_i \mu(A_i) = \lim_{i \to \infty} \mu(A_i). \tag{1.1.7}$$

We say that the triple $(X, \mathcal{F}, \mu)$ with a σ-algebra $\mathcal{F}$ and μ a measure on $\mathcal{F}$ is a *measure space*. In this book we will always assume, unless otherwise stated, that μ is a *finite measure* that is $\mu : \mathcal{F} \to [0, \infty)$. By (1.1.6) this equivalently means that $\mu(X) < \infty$. If $\mu(X) = 1$, the triple $(X, \mathcal{F}, \mu)$ is called a *probability space* and μ a *probability measure*.

We say that $\phi : X \to \mathbb{R}$ is a measurable function, if $\phi^{-1}(J) \in \mathcal{F}$ for every interval $J \subset \mathbb{R}$, equivalently for every Borel set $J \subset \mathbb{R}$, (compare Section 1.2). We say that ϕ is μ-integrable if $\int |\phi|\, d\mu < \infty$. We write $\phi \in L^1(\mu)$. More generally, for every $1 \leq p < \infty$ we write $(\int |\phi|^p\, d\mu)^{1/p} = \|\phi\|_p$ and we say that ϕ belongs to $L^p(\mu) = L^p(X, \mathcal{F}, \mu)$. If $\inf_{\mu(E)=0} \sup_{X \setminus E} |\phi| < \infty$, we say $\phi \in L^\infty$ and denote the latter expression by $\|\phi\|_\infty$. The numbers $\|\phi\|_p, 1 \leq p \leq \infty$ are called L^p-norms of ϕ. We usually identify in this chapter functions which differ only on a set of μ-measure 0. After these identifications the linmear spaces $L^p(X, \mathcal{F}, \mu)$ become Banach spaces with the norms $\|\phi\|_\infty$.

We say that a property $q(x)$, $x \in X$, is satisfied for μ almost every $x \in X$ (abbr: a.e.), or μ-a.e., if $\mu(\{x : q(x) \text{ is not satisfied}\}) = 0$. We can consider q as a subset of X with $\mu(X \setminus q) = 0$.

We shall often use in the book the following two facts.

Theorem 1.1.2 (Monotone Convergence Theorem)**.** *Suppose $\phi_1 \leq \phi_2 \leq \ldots$ is an increasing sequence of integrable, real-valued functions on a probability space $(X, \mathcal{F}, \mu)$. Then $\phi = \lim_{n \to \infty} \phi_n$ exists a.e. and $\lim_{n \to \infty} \int \phi_n\, d\mu = \int \phi\, d\mu$. (We allow $+\infty$'s here.)*

and

Theorem 1.1.3 (Dominated Convergence Theorem)**.** *If $(\phi_n)_{n=1}^{\infty}$ is a sequence of measurable real-valued functions on a probability space $(X, \mathcal{F}, \mu)$ and $|\phi_n| \leq g$ for an integrable function g, and $\phi_n \to \phi$ a.e., then ϕ is integrable and $\lim_{n \to \infty} \int \phi_n\, d\mu = \int \phi\, d\mu$.*

Recall now that if $\mathcal{F}'$ is a sub-σ-algebra of $\mathcal{F}$ and $\phi : X \to \mathbb{R}$ is a μ-integrable function, then there exists a unique (mod 0) function, usually denoted by $E(\phi|\mathcal{F}')$, such that $E(\phi|\mathcal{F}')$ is $\mathcal{F}'$-measurable and

$$\int_A E(\phi|\mathcal{F}')\, d\mu = \int_A \phi\, d\mu \tag{1.1.8}$$

for all $A \in \mathcal{F}'$. $E(\phi|\mathcal{F}')$ is called *conditional expectation value* of the function ϕ with respect to the σ-algebra $\mathcal{F}'$. Sometimes we shall use for $E(\phi|\mathcal{F}')$ the simplified notation $\phi_{\mathcal{F}'}$.

For $\mathcal{F}$, generated by a finite partition $\mathcal{A}$ (cf. Section 1.3), one can think of $E(\phi|\sigma(\mathcal{A}))$ as constant on each $A \in \mathcal{A}$ equal to the average $\int_A \phi \, d\mu / \mu(A)$.

The existence of $E(\phi|\mathcal{F}')$ follows from the famous Radon-Nikodym theorem, saying that if $\nu \ll \mu$, both measures defined on the same σ-algebra $\mathcal{F}'$ (where $\nu \ll \mu$ means that ν is *absolutely continuous* with respect to μ, i.e. $\mu(A) = 0 \Rightarrow \nu(A) = 0$ for all $A \in \mathcal{F}'$), then there exists a unique (mod 0) $\mathcal{F}'$-measurable, μ-integrable function $\Phi = d\nu/d\mu : X \to \mathbb{R}^+$ such that for every $A \in \mathcal{F}'$

$$\int_A \Phi \, d\mu = \nu(A).$$

To deduce (1.1.8) we set $\nu(A) = \int_A \phi \, d\mu$ for $A \in \mathcal{F}'$. The trick is that we restrict μ from $\mathcal{F}$ to $\mathcal{F}'$. namely we apply Radon-Nikodym theorem for $\nu \ll \mu|_{\mathcal{F}'}$.

If $\phi \in L^p(X, \mathcal{F}, \mu)$ then $E(\phi|\mathcal{F}') \in L^p(X, \mathcal{F}', \mu)$ for all σ-algebras $\mathcal{F}'$ with L^p norms uniformly bounded. More precisely the operators $\phi \to E(\phi|\mathcal{F}')$ are linear projections from $L^p(X, \mathcal{F}, \mu)$ to $L^p(X, \mathcal{F}', \mu)$, with L^p-norms equal to 1 (see Exercise 1.7).

For a sequence $(\mathcal{F}_n))_{n=1}^\infty$ of σ-algebras contained in $\mathcal{F}$ denote by $\bigvee_{n=1}^\infty \mathcal{F}_n$ the smallest σ-algebra containing $\bigcup_{n=1}^\infty \mathcal{F}_n$ The latter union is usually not a σ-algebra, but only an algebra. According to Notation 1.1.1, $\bigvee_{n=1}^\infty \mathcal{F}_n = \sigma(\bigcup_{n=1}^\infty \mathcal{F}_n)$. Compare Section 1.6 where complete σ-algebras of this form are considered in Lebesgue spaces.

We end this section with the following version of the **Martingale Convergence Theorem**.

Theorem 1.1.4. *If $(\mathcal{F}_n : n \geq 1)$ is either an ascending or descending sequence of σ-algebras contained in $\mathcal{F}$, then for every $\phi \in L^p(\mu)$, $1 \leq p < \infty$, we have*

$$\lim_{n \to \infty} E(\phi|\mathcal{F}_n) = E(\phi|\mathcal{F}'), \quad a.e. \text{ and in } L^p,$$

where $\mathcal{F}'$ is either equal to $\bigvee_{n=1}^\infty \mathcal{F}_n$ or to $\bigcap_{n=1}^\infty \mathcal{F}_n$ respectively.

Recall that a sequence of μ-measurable functions $\psi_n : X \to \mathbb{R}$, $n = 1, 2, \ldots$ is said to *converge in measure* μ to ψ if for every $\varepsilon > 0$, $\lim_{n \to \infty} \mu(\{x \in X : |\psi_n(x) - \psi(x)| \geq \varepsilon\}) \to 0$.)

In this book we denote by $\mathbb{1}_A$ the indicator function of A, namely the function equal to 1 on A and to 0 outside of A.

Remark 1.1.5. For the existence of $\mathcal{F}'$ and the convergence in L^p in Theorem 1.1.4, no monotonicity is needed. It is sufficient to assume that for every $A \in \mathcal{F}$ the limit $\lim E(\mathbb{1}_A|\mathcal{F}_n)$ in measure μ exists.

We shall not provide here any proof of Theorem 1.1.4 in the full generality, (see though Exercise 1.5). Let us provide however at least a proof Theorem 1.1.4

(and Remark 1.1.5 in the case $\lim E(\mathbb{1}_A|\mathcal{F}_n) = \mathbb{1}_A$) for the L^2-convergence for functions $\phi \in L^2(\mu)$. This is sufficient for example to prove the important Theorem 1.8.6 (proof 2) later on in this chapter.

For any ascending sequence $(\mathcal{F}_n)$ we have the equality

$$L^2(X, \mathcal{F}', \mu) = \overline{\bigcup_n L^2(X, \mathcal{F}_n, \mu)} \tag{1.1.9}$$

Indeed, for every $B, C \in \mathcal{F}$ write $B \div C = (B \setminus C) \cup (C \setminus B)$, so-called *symmetric difference* of sets B and C. Notice that for every $B \in \mathcal{F}'$ there exists a sequence $B_n \in \mathcal{F}_n$, $n \geq 1$, such that $\mu(B \div B_n) \to 0$.

This follows for example from Carathéodory's argument, see the comments after the statement of Theorem 1.7.2. We have $\mu(B)$ equal to the outer measure of B constructed from μ restricted to the algebra $\bigcup_{n=1}^{\infty} \mathcal{F}_n$. In the Remark 1.1.5 case where we assumed $\lim E(\mathbb{1}_A|\mathcal{F}_n) = \mathbb{1}_A$, this is immediate.

Hence $L^2(X, \mathcal{F}_n, \mu) \ni \mathbb{1}_{B_n} \to \mathbb{1}_B$ in $L^2(X, \mathcal{F}, \mu)$. Finally, to get (1.7.2), use the fact that every function $f \in L^2(X, \mathcal{F}', \mu)$ can be approximated in the space $L^2(X, \mathcal{F}', \mu)$ by the step functions, i.e. finite linear combinations of indicator functions.

Therefore, since $E(\phi|\mathcal{F}_n)$ and $E(\phi|\mathcal{F}')$ are orthogonal projections of ϕ to $L^2(X, \mathcal{F}_n, \mu)$ and $L^2(X, \mathcal{F}', \mu)$ respectively (exercise) we obtain $E(\phi|\mathcal{F}_n) \to E(\phi|\mathcal{F}')$ in L^2.

For a decreasing sequence $\mathcal{F}_n$ use the equality $L^2(X, \mathcal{F}', \mu) = \bigcap_n L^2(X, \mathcal{F}_n, \mu)$.

1.2   Measure preserving endomorphisms, ergodicity

Let $(X, \mathcal{F}, \mu)$ and $(X', \mathcal{F}', \mu')$ be measure spaces. A transformation $T : X \to X'$ is said to be *measurable* if $T^{-1}(A) \in \mathcal{F}$ for every $A \in \mathcal{F}'$. If moreover $\mu(T^{-1}(A)) = \mu'(A)$ for every $A \in \mathcal{F}'$, then T is called *measure preserving*. We write $\mu' = \mu \circ T^{-1}$ or $\mu' = T_*(\mu)$.

We call $(X', \mathcal{F}', \mu')$ *a factor* (or quotient) of $(X, \mathcal{F}, \mu)$, and $(X, \mathcal{F}, \mu)$ *an extension* of $(X, \mathcal{F}, \mu)$.

If a measure preserving map $T : X \to X'$ is invertible and the inverse T^{-1} is measurable, then clearly T^{-1} is also measure preserving. Therefore T is an *isomorphism* in the category of measure spaces.

If $(X, \mathcal{F}, \mu) = (X', \mathcal{F}', \mu')$ we call T a *measure preserving endomorphisms*; we will say also that measure μ is T–invariant, or that T preserves μ. In the case of $(X, \mathcal{F}, \mu) = (X', \mathcal{F}', \mu')$ an isomorphism T is called *automorphism*.

If T and T' are endomorphisms of $(X, \mathcal{F}, \mu)$ and $(X', \mathcal{F}', \mu')$ respectively and $S : X \to X'$ is a measure preserving transformation from $(X, \mathcal{F}, \mu)$ to $(X', \mathcal{F}', \mu')$ such that $F' \circ S = S \circ F$, then we call $T' : X \to X'$ a factor of $T : X \to X$ and $T : X \to X$ an extension of $T : X' \to X'$.

For every μ-measurable ϕ we define $U_T(\phi) = \phi \circ T$.

U_T is sometimes called Koopman operator. We have following easy

Proposition 1.2.1. *For $\phi \in L^1(X', \mathcal{F}', \mu')$ we have $\int \phi \circ T \, d\mu = \int \phi \, d\mu \circ T^{-1}$. Moreover for each p the adequate restriction of Koopman operator $U_T : L^p(X', \mathcal{F}', \mu') \to L^p(X, \mathcal{F}, \mu)$ is an isometry to the image, surjective iff T is an isomorphism.*

The isometry operator U_T has been widely explored to understand measure preserving endomorphisms T. Especially convenient has been $U_T : L^2(\mu) \to L^2(\mu)$, the isometry of the Hilbert space $L^2(\mu)$. Notice that it is an isomorphism (that is *unitary*) if and only if T is an automorphism. For more properties see Exercise 1.23.

We shall prove now the following very useful fact in which the finiteness of measure is a crucial assumption.

Theorem 1.2.2 (Poincaré Recurrence Theorem)**.** *If $T : X \to X$ is a measure preserving endomorphism, then for every mesurable set A*

$$\mu\big(\{x \in A : T^n(x) \in A \ \text{ for infinitely many } n\text{'s}\}\big) = \mu(A).$$

Proof. Let
$$N = N(T, A) = \{x \in A : T^n(x) \notin A \ \forall n \geq 1\}.$$

We shall first show that $\mu(N) = 0$. Indeed, N is measurable since $N = A \cap \bigcap_{n \geq 1} T^{-n}(X \setminus A)$. If $x \in N$, then $T^n(x) \notin A$ for all $n \geq 1$ and, in particular, $T^n(x) \notin N$ which implies that $x \notin T^{-n}(N)$, and consequently $N \cap T^{-n}(N) = \emptyset$ for all $n \geq 1$. Thus, all the sets $N, T^{-1}(N), T^{-2}(N), \dots$ are mutually disjoint since if $n_1 \leq n_2$, then

$$T^{-n_1}(N) \cap T^{-n_2}(N) = T^{-n_1}(N \cap T^{-(n_2 - n_1)}(N)) = \emptyset.$$

Hence

$$1 \geq \mu\left(\bigcup_{n=0}^{\infty} T^{-n}(N)\right) = \sum_{n=0}^{\infty} \mu(T^{-n}(N)) = \sum_{n=0}^{\infty} \mu(N).$$

Therefore $\mu(N) = 0$. Fix now $k \geq 1$ and put

$$N_k = \{x \in A : T^n(x) \notin A \ \forall n \geq k\}.$$

Then $N_k \subset N(T^k, A)$ and therefore from what have been proved above it follows that $\mu(N_k) \leq \mu(N(T^k, A)) = 0$. Thus

$$\mu\big(\{x \in A : T^n(x) \in A \ \text{ for only finitely many } n\text{'s}\}\big) = 0.$$

The proof is finished. ♣

Definition 1.2.3. A measurable transformation $T : X \to X$ of a measure space $(X, \mathcal{F}, \mu)$ is said to be *ergodic* if for any measurable set A

$$\mu(T^{-1}(A) \div A) = 0 \quad \Rightarrow \quad \mu(A) = 0 \text{ or } \mu(X \setminus A) = 0.$$

Recall the notation $B \div C = (B \setminus C) \cup (C \setminus B)$.

Note that we did not assume in the definition of ergodicity that μ is T-invariant (neither that μ is finite). Suppose that for every E of measure 0 the set $T^{-1}(E)$ is also of measure 0. (In Chapter 4 we call this property of μ with respect to T, *backward quasi-invariance*. In the literature the name *non-singular* is also being used). Then in the definition of ergodicity one can replace $\mu(T^{-1}(A) \div A) = 0$ by $T^{-1}(A) = A$. Indeed having A as in the definition, one can define $A' = \bigcap_{n=0}^{\infty} \bigcup_{m=n}^{\infty} T^{-m}(A)$. Then $\mu(A') = \mu(A)$ and $T^{-1}(A') = A'$. If we assumed that the latter implies $\mu(A') = 0$ or $\mu(X \setminus A') = 0$, then $\mu(A) = 0$ or $\mu(X \setminus A) = 0$.

Remark 1.2.4. If T is an isomorphism then T is ergodic if and only if T^{-1} is ergodic.

Let $\phi : X \to \mathbb{R}$ be a measurable function. For any $n \geq 1$ we define

$$S_n\phi = \phi + \phi \circ T + \ldots + \phi \circ T^{n-1} \tag{1.2.1}$$

Let $\mathcal{I} = \{A \in \mathcal{F} : \mu(T^{-1}(A) \div A) = 0\}$. We call $\mathcal{I}$ the σ-algebra of T-invariant (mod 0) sets. Note that every $\psi : X \to \mathbb{R}$, measurable with respect to $\mathcal{I}$, is T-invariant (mod 0), namely $\psi \circ T = \psi$ on the complement of a set of measure μ equal to 0.

Indeed let $A = \{x \in X : \psi(x) \neq \psi \circ T(x)\}$, and suppose $\mu(A) > 0$. Then there exists $a \in \mathbb{R}$ such that either $A_a^+ = \{x \in A : \psi(x) < a, \psi \circ T(x) > a\}$ or $.\ A_a^- = \{x \in A : \psi(x) > a, \psi \circ T(x) < a\}$ has positive μ-measure. In the case of A^+ we have $\psi \circ T > a$ on $T^{-1}(A_a^+)$. We conclude that $\psi > a$ and $\psi < a$ on $A_a^+ \cap T^{-1}(A_a^+)$ simultaneously, which contradicts $A_a^+ \cap T^{-1}(A_a^+) = \mu(A_a^+) > 0$. The case of A^- can be dealt with similarly.

Theorem 1.2.5 (Birkhoff's Ergodic Theorem). *If $T : X \to X$ is a measure preserving endomorphism of a probability space $(X, \mathcal{F}, \mu)$ and $\phi : X \to \mathbb{R}$ is an integrable function, then*

$$\lim_{n \to \infty} \frac{1}{n} S_n\phi(x) = E(\phi|\mathcal{I}) \ \ for \ \mu\text{-}a.e. \ x \in X \ .$$

If, in addition, T is ergodic, then

$$\lim_{n \to \infty} \frac{1}{n} S_n\phi(x) = \int \phi \, d\mu, \quad for \ \mu\text{-}a.e. \ x \tag{1.2.2}$$

We say that the *time average* exists for μ-almost every $x \in X$. If T is ergodic, we say that the *time average equals the space average*.

If $\phi = \mathbb{1}_A$, the indicator function of a measurable set A, then we deduce that for μ-a.e. $x \in X$ the frequency of hitting A by the forward trajectory of x equals to the measure (probability) of A, namely

$$\lim_{n \to \infty} \#\{0 \leq j < n : T^j(x) \in A\}/n = \mu(A). \tag{1.2.3}$$

This means for example that if we choose a point in X being a bounded invariant part of Euclidean space at random its sufficiently long forward trajectory fills X with the density being approximately the density of μ with respect to the Lebesgue measure, provided μ is equivalent to the Lebesgue measure.

On the figure below, Figure 1.1, for a randomly chosen $x \in [-1, 1]$ the trajectory $T^j(x), j = 0, 1, \ldots, n$, for $T(x) = 2x^2 - 1$ is plotted. See Example 0.9. The interval $[-1, 1]$ is divided into $k = 100$ equal pieces. The computer calculated the number of hits of each piece for $n = 500000$. The resulting graph indeed resembles the graph of $\frac{1}{\pi}\sqrt{1 - x^2}$, Figure 1.2, which is the density of the invariant probability measure equivalent to the length measure. Twice bigger vertical extension of Figure 1.1 than 1.2 results from the vertical scaling giving integral equal to 2.
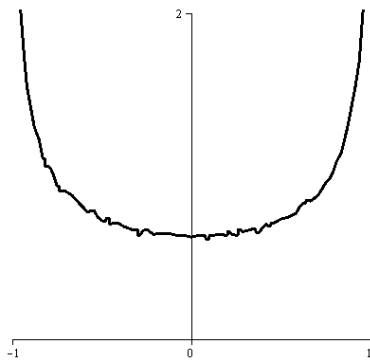
Figure 1.1: The plotted density of an invariant measure for $T(x) = 2x^2 - 1$.
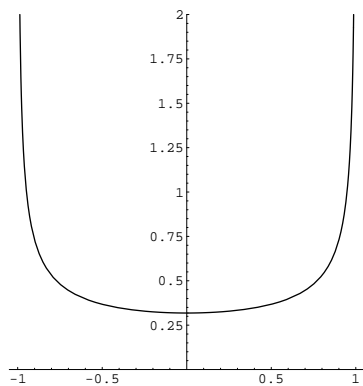
Figure 1.2: The density of an invariant measure for $T(x) = 2x^2 - 1$.

As a corollary of Birkhoff's Ergodic Theorem one can obtain von Neumann's Ergodic Theorem. It says that if $\phi \in L^p(\mu)$ for $1 \le p < \infty$, then the convergence

to $E(\phi|\mathcal{I})$ holds in L^p. It is not difficult, see for example [Walters 1982].

Proof of Birkhoff's Ergodic Theorem. Let $f \in L^1(\mu)$ and $F_n = \max\{\sum_{i=0}^{k-1} f \circ T^i : 1 \le k \le n\}$, for $n = 1, 2, \ldots$. Then for every $x \in X$, $F_{n+1}(x) - F_n(T(x)) = f(x) - \min(0, F_n(T(x))) \ge f(x)$ and is monotone decreasing, since F_n is monotone increasing. The two cases under min are illustrated at Figure 1.3

Case 1   Case 2
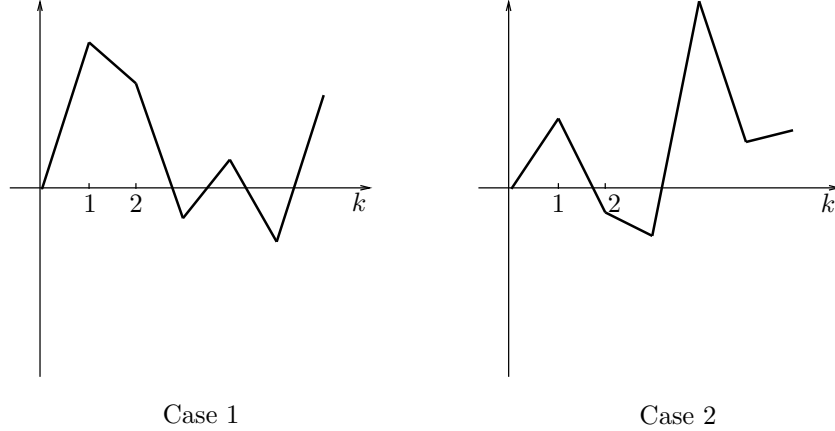
Figure 1.3: Graph of $k \mapsto \sum_{i=0}^{k-1} f \circ T^i(x), k = 1, 2, \ldots$. Case 1. $F_{n+1}(x) = f(x)$ (i.e. $F_n(T(x)) \le 0$). Case 2. $F_{n+1}(x) = f(x) + F_n(T(x))$.   (i.e. $F_n(T(x)) \ge 0$).

Define

$$A = \Big\{x : \sup_n \sum_{i=0}^{n} f(T^i(x)) = \infty\Big\}.$$

Note that $A \in \mathcal{I}$. If $x \in A$, then $F_{n+1}(x) - F_n(T(x))$ monotonously decreases to $f(x)$ as $n \to \infty$. The Dominated Convergence Theorem implies then, that

$$0 \le \int_A (F_{n+1} - F_n)\, d\mu = \int_A (F_{n+1} - F_n \circ T)\, d\mu \to \int_A f\, d\mu. \qquad (1.2.4)$$

(We thus get that $\int_A f\, d\mu \ge 0$, which is a variant of so-called Maximal Ergodic Theorem, see Exercise 1.3.)

Notice that $\frac{1}{n} \sum_{k=0}^{n-1} f \circ T^k \le F_n/n$; so outside A, we have

$$\limsup_{n \to \infty} \frac{1}{n} \sum_{k=0}^{n-1} f \circ T^k \le 0. \qquad (1.2.5)$$

Therefore, if the conditional expectation value $f_\mathcal{I}$ of f is negative a.e., that is if $\int_C f\, d\mu = \int_C f_\mathcal{I}\, d\mu < 0$ for all $C \in \mathcal{I}$ with $\mu(C) > 0$, then, as $A \in \mathcal{I}$, (1.2.4) implies that $\mu(A) = 0$. Hence (1.2.5) holds a.e. Now if we let $f = \phi - \phi_\mathcal{I} - \varepsilon$, then $f_\mathcal{I} = -\varepsilon < 0$. Note that $\phi_\mathcal{I} \circ T = \phi_\mathcal{I}$ implies that

$$\frac{1}{n} \sum_{k=0}^{n-1} f \circ T^k = \Big(\frac{1}{n} \sum_{k=0}^{n-1} \phi \circ T^k\Big) - \phi_\mathcal{I} - \varepsilon.$$

So (1.2.5) yields

$$\limsup_{n\to\infty} \frac{1}{n}\sum_{k=0}^{n-1}\phi\circ T^k \le \phi_{\mathcal{I}} + \varepsilon \quad \text{a.e.}$$

Replacing ϕ by $-\phi$ gives

$$\liminf_{n\to\infty} \frac{1}{n}\sum_{k=0}^{n-1}\phi\circ T^k \ge \phi_{\mathcal{I}} - \varepsilon \quad \text{a.e.}$$

Thus $\lim_{n\to\infty}\frac{1}{n}\sum_{k=0}^{n-1}\phi\circ T^k = \phi_{\mathcal{I}}$ a.e.   ♣

Recall that at the end opposite to the absolute continuity (see Section 1.1) there is the notion of singularity. Two probability measures μ_1 and μ_2 on a σ-algebra $\mathcal{F}$ are called mutually *singular*, $\mu_1 \perp \mu_2$ if there exist disjoint sets $X_1, X_2 \in \mathcal{F}$ with $\mu_i(X_i) = 1$ for $i = 1, 2$.

Theorem 1.2.6. *If $T : X \to X$ is a map measurable with respect to a σ-algebra $\mathcal{F}$ and if μ_1 and μ_2 are two different T-invariant probability ergodic measures on $\mathcal{F}$, then μ_1 and μ_2 are singular.*

Proof. Since μ_1 and μ_2 are different, there exists a measurable set A such that

$$\mu_1(A) \ne \mu_2(A) \tag{1.2.6}$$

By Theorem 1.2.5 (Birkhoff's Ergodic Theorem) applied to μ_1 and μ_2 there exist sets $X_1, X_2 \in \mathcal{F}$ satisfying $\mu_i(X_i) = 1$ for $i = 1, 2$ such that for every $x \in X_i$

$$\lim_{n\to\infty}\frac{1}{n}S_n \mathbb{1}_A(x) = \mu_i(A).$$

Thus in view of (1.2.6) the sets X_1 and X_2 are disjoint. The proof is finished.   ♣

Proposition 1.2.7. *If $T : X \to X$ is a measure preserving endomorphism of a probability space $(X, \mathcal{F}, \nu)$, then ν is ergodic if and only if there is no T-invariant probability measure on $\mathcal{F}$ absolutely continuous with respect to ν and different from ν.*

Proof. Suppose that ν is ergodic and μ is a T-invariant probability measure on $\mathcal{F}$ with $\mu \ll \nu$. Then μ is also ergodic. Otherwise there would exist $A \in \mathcal{F}$ such that $T^{-1}(A) = A$ and $\mu(A), \mu(X \setminus A) > 0$ so $\nu(A), \nu(X \setminus A) > 0$; thus ν would not be ergodic. Hence, by Theorem 1.2.6, $\mu = \nu$.

Suppose in turn that ν is not ergodic and let $A \in \mathcal{F}$ be a T-invariant set such that $0 < \nu(A) < 1$. Then the conditional measure on A is also T-invariant but simultaneously it is distinct from ν and absolutely continuous with respect to ν. The proof is finished.   ♣

Observe now that the space $M(\mathcal{F})$ of probability measures on $\mathcal{F}$ is a convex set i.e. the convex combination $\alpha\mu + (1-\alpha)\nu$, $0 \le \alpha \le 1$, of two such measures

is again in $M(\mathcal{F})$. The subspace $M(\mathcal{F}, T)$ of $M(\mathcal{F})$ consisting of T-invariant measures is also convex.

Recall that a point in a convex set is said to be *extreme* if and only if it cannot be represented as a convex combination of two distinct points with corresponding coefficient $0 < \alpha < 1$. We shall prove the following.

Theorem 1.2.8. *The ergodic measures in $M(\mathcal{F}, T)$ are exactly the extreme points of $M(\mathcal{F}, T)$.*

Proof. Suppose that $\mu, \mu_1, \mu_2 \in M(\mathcal{F}, T)$, $\mu_1 \neq \mu_2$ and $\mu = \alpha \mu_1 + (1 - \alpha)\mu_2$ with $0 < \alpha < 1$. Then $\mu_1 \neq \mu$ and $\mu_1 \ll \mu$. Thus, in view of Proposition 1.2.7, the mesure μ is not ergodic.

Suppose in turn that μ is not ergodic and let $A \in \mathcal{F}$ be a T-invariant set such that $0 < \mu(A) < 1$. Recall that given $B \in \mathcal{F}$ with $\mu(B) > 0$, the *conditional measure* $A \mapsto \mu(A|B)$ is defined by $\mu(A \cap B)/\mu(B)$. Thus the conditional measures $\mu(\cdot|A)$ and $\mu(\cdot|A^c)$ are distinct, T-invariant and $\mu = \mu(A)\mu(\cdot|A) + (1 - \mu(A)\mu(\cdot|A^c)$. Consequently μ is not en extreme point in $M(\mathcal{F}, T)$. The proof is finished. ♣

In Section 1.8 we shall formulate a theorem on decomposition into ergodic components, that will better clarify the situation. This will correspond to the Choquet Theorem in functional analysis, see Section 2.1.

1.3   Entropy of partition

Let $(X, \mathcal{F}, \mu)$ be a probability space. A *partition* of $(X, \mathcal{F}, \mu)$ is a subfamily (*a priori* may be uncountable) of $\mathcal{F}$ consisting of mutually disjoint elements whose union is X.

If $\mathcal{A}$ is a partition and $x \in X$ then the only element of $\mathcal{A}$ containing x is denoted by $\mathcal{A}(x)$ or, if $x \in A \in \mathcal{A}$, by $A(x)$.

If $\mathcal{A}$ and $\mathcal{B}$ are two partitions of X we define their *join* or *joining*

$$\mathcal{A} \vee \mathcal{B} = \{A \cap B : A \in \mathcal{A}, B \in \mathcal{B}\}$$

We write $\mathcal{A} \leq \mathcal{B}$ if and only if $\mathcal{B}(x) \subset \mathcal{A}(x)$ for every $x \in X$, which in other words means that each element of the partition $\mathcal{B}$ is contained in an element of the partition $\mathcal{A}$ or equivalently $\mathcal{A} \vee \mathcal{B} = \mathcal{B}$. We sometimes say in this case, that $\mathcal{B}$ is *finer* than $\mathcal{A}$ or that $\mathcal{B}$ is a *refinement* of $\mathcal{A}$.

Now we introduce the notion of entropy of a countable (finite or infinite) partition and we collect its basic elementary properties. Define the function $k : [0, 1] \rightarrow [0, \infty]$ putting

$$k(t) = \begin{cases} -t \log t & \text{for } t \in (0, 1] \\ 0 & \text{for } t = 0 \end{cases} \tag{1.3.1}$$

Check that the function k is continuous. Let $\mathcal{A} = \{A_i : 1 \leq i \leq n\}$ be a countable partition of X, where $n \geq 1$ is a finite integer or ∞. In the sequel we shall usually write ∞.

The *entropy* of $\mathcal{A}$ is the number

$$\mathrm{H}(\mathcal{A}) = \sum_{i=1}^{\infty} -\mu(A_i) \log \mu(A_i) = \sum_{i=1}^{\infty} k(\mu(A_i)) \qquad (1.3.2)$$

If $\mathcal{A}$ is infinite, $\mathrm{H}(\mathcal{A})$ may happen to be infinite as well as finite.

Define

$$I(x) = I(\mathcal{A})(x) := -\log \mu(\mathcal{A}(x)). \qquad (1.3.3)$$

This is called an information function. Intuitively $I(x)$ is an information on an object x given by the experiment $\mathcal{A}$ in the logarithmic scale. Therefore the entropy in (1.3.2) is the integral (the average) of the information function.

Note that $\mathrm{H}(\mathcal{A}) = 0$ for $\mathcal{A} = \{X\}$ and that if $\mathcal{A}$ is finite, say consists of n elements, then $0 \leq \mathrm{H}(\mathcal{A}) \leq \log n$ and $\mathrm{H}(\mathcal{A}) = \log n$ if and only if $\mu(A_1) = \mu(A_2) = \ldots = \mu(A_n) = 1/n$. This follows from the fact that the logarithmic function is strictly concave.

In this Section we deal only with one fixed measure μ. If however we need to consider more measures simultaneously (see for example Chapter 2) we will rather use the notation $\mathrm{H}_\mu(A)$ for $\mathrm{H}(A)$. We will use also the notation $I_\mu(x)$ for $I(x)$.

Let $\mathcal{A} = \{A_i : i \geq 1\}$ and $\mathcal{B} = \{B_j : j \geq 1\}$ be two countable partitions of X. The *conditional entropy* $\mathrm{H}(\mathcal{A}|\mathcal{B})$ of $\mathcal{A}$ given $\mathcal{B}$ is defined as

$$\begin{aligned}
\mathrm{H}(\mathcal{A}|\mathcal{B}) &= \sum_{j=1}^{\infty} \mu(B_j) \sum_{i=1}^{\infty} -\frac{\mu(A_i \cap B_j)}{\mu(B_j)} \log \frac{\mu(A_i \cap B_j)}{\mu(B_j)} \\
&= \sum_{i,j} -\mu(A_i \cap B_j) \log \frac{\mu(A_i \cap B_j)}{\mu(B_j)} \qquad (1.3.4)
\end{aligned}$$

The first equality, defining $\mathrm{H}(\mathcal{A}|\mathcal{B})$, can be viewed as follows: one considers each element B_j as a probability space with conditional measure $\mu(A|B_j) = \mu(A)/\mu(B_j)$ for $A \subset B_j$ and calculates the entropy of the partition of the set B_j into $A_i \cap B_j$. Then one averages the result over the space of B_j's. (This will be generalized in Definition 1.8.3)

For each x denote $-\log \mu(A(x)|B(x)) = -\log \frac{\mu(A(x) \cap B(x))}{\mu(B(x))})$ by $I(x)$ or $I(\mathcal{A}|\mathcal{B})(x)$. The second equality in (1.3.4) can be rewritten as

$$\mathrm{H}(\mathcal{A}|\mathcal{B}) = \int_X I(\mathcal{A}|\mathcal{B}) \, d\mu. \qquad (1.3.5)$$

Note by the way that if $\tilde{\mathcal{B}}$ is the σ-algebra consisting of all unions of elements of $\mathcal{B}$ (i.e. generated by $\mathcal{B}$, then $I(x) = -\log \mu((\mathcal{A}(x) \cap \mathcal{B}(x))|\mathcal{B}(x)) = -\log E(\mathbb{1}_{\mathcal{A}(x)}|\tilde{\mathcal{B}})(x)$, cf. (1.1.8).

Note finally that for any countable partition $\mathcal{A}$ we have

$$\mathrm{H}(\mathcal{A}|\{X\}) = \mathrm{H}(\mathcal{A}). \qquad (1.3.6)$$

Some further basic properties of entropy of partitions are collected in the following.

Theorem 1.3.1. *Let $(X, \mathcal{F}, \mu)$ be a probability space. If $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ are countable partitions of X then:*

$$\mathrm{H}(\mathcal{A} \vee \mathcal{B}|\mathcal{C}) = \mathrm{H}(\mathcal{A}|\mathcal{C}) + \mathrm{H}(\mathcal{B}|\mathcal{A} \vee \mathcal{C}) \tag{a}$$

$$\mathrm{H}(\mathcal{A} \vee \mathcal{B}) = \mathrm{H}(\mathcal{A}) + \mathrm{H}(\mathcal{B}|\mathcal{A}) \tag{b}$$

$$\mathcal{A} \leq \mathcal{B} \ \Rightarrow \ \mathrm{H}(\mathcal{A}|\mathcal{C}) \leq \mathrm{H}(\mathcal{B}|\mathcal{C}) \tag{c}$$

$$\mathcal{B} \leq \mathcal{C} \ \Rightarrow \ \mathrm{H}(\mathcal{A}|\mathcal{B}) \geq \mathrm{H}(\mathcal{A}|\mathcal{C}) \tag{d}$$

$$\mathrm{H}(\mathcal{A} \vee \mathcal{B}|\mathcal{C}) \leq \mathrm{H}(\mathcal{A}|\mathcal{C}) + \mathrm{H}(\mathcal{B}|\mathcal{C}) \tag{e}$$

$$\mathrm{H}(\mathcal{A}|\mathcal{C}) \leq \mathrm{H}(\mathcal{A}|\mathcal{B}) + \mathrm{H}(\mathcal{B}|\mathcal{C}) \tag{f}$$

Proof. Let $\mathcal{A} = \{A_n : n \geq 1\}$, $\mathcal{B} = \{B_m : m \geq 1\}$, and $\mathcal{C} = \{C_l : l \geq 1\}$. Without loss of generality we can assume that all these sets are of positive measure.

(a) By (1.3.4) we have

$$\mathrm{H}(\mathcal{A} \vee \mathcal{B}|\mathcal{C}) = -\sum_{i,j,k} \mu(A_i \cap B_j \cap C_k) \log \frac{\mu(A_i \cap B_j \cap C_k)}{\mu(C_k)}$$

But

$$\frac{\mu(A_i \cap B_j \cap C_k)}{\mu(C_k)} = \frac{\mu(A_i \cap B_j \cap C_k)}{\mu(A_i \cap C_k)} \frac{\mu(A_i \cap C_k)}{\mu(C_k)}$$

unless $\mu(A_i \cap C_k) = 0$. But then the left hand side vanishes and we need not consider it. Therefore

$$\begin{aligned}
\mathrm{H}(\mathcal{A} \vee \mathcal{B}|\mathcal{C}) &= -\sum_{i,j,k} \mu(A_i \cap B_j \cap C_k) \log \frac{\mu(A_i \cap C_k)}{\mu(C_k)} \\
&\quad -\sum_{i,j,k} \mu(A_i \cap B_j \cap C_k) \log \frac{\mu(A_i \cap B_j \cap C_k)}{\mu(A_i \cap C_k)} \\
&= -\sum_{i,k} \mu(A_i \cap C_k) \log \frac{\mu(A_i \cap C_k)}{\mu(C_k)} + \mathrm{H}(\mathcal{B}|\mathcal{A} \vee \mathcal{C}) \\
&= \mathrm{H}(\mathcal{A}|\mathcal{C}) + \mathrm{H}(\mathcal{B}|\mathcal{A} \vee \mathcal{C})
\end{aligned}$$

(b) Put $\mathcal{C} = \{X\}$ and apply (1.3.6) in (a).

(c) By (a)

$$\mathrm{H}(\mathcal{B}|\mathcal{C}) = \mathrm{H}(\mathcal{A} \vee \mathcal{B}|\mathcal{C}) = \mathrm{H}(\mathcal{A}|\mathcal{C}) + \mathrm{H}(\mathcal{B}|\mathcal{A} \vee \mathcal{C}) \geq \mathrm{H}(\mathcal{A}|\mathcal{C})$$

(d) Since the function k defined by (1.3.1) is strictly concave, we have for every pair i, j that

$$k\left(\sum_l \frac{\mu(C_l \cap B_j)}{\mu(B_j)} \frac{\mu(A_i \cap C_l)}{\mu(C_l)}\right) \geq \sum_l \frac{\mu(C_l \cap B_j)}{\mu(B_j)} k\left(\frac{\mu(A_i \cap C_l)}{\mu(C_l)}\right) \tag{1.3.7}$$

But since $\mathcal{B} \leq \mathcal{C}$, we can write above $C_l \cap B_j = C_l$, hence the left hand side equals to $k\left(\frac{\mu(A_i \cap B_j)}{\mu(B_j)}\right)$ and we conclude with

$$k\left(\frac{\mu(A_i \cap B_j)}{\mu(B_j)}\right) \geq \sum_l \frac{\mu(C_l \cap B_j)}{\mu(B_j)} k\left(\frac{\mu(A_i \cap C_l)}{\mu(C_l)}\right).$$

(Note that till now we have not used the specific form of the function k).

Finally, multiplying both sides of (1.3.7) by $\mu(B_j)$ using the definition of k and summing over i and j we get

$$-\sum_{i,j} \mu(A_i \cap B_j) \log \frac{\mu(A_i \cap B_j)}{\mu(B_j)} \geq -\sum_{i,j,l} \mu(C_l \cap B_j) \frac{\mu(A_i \cap C_l)}{\mu(C_l)} \log \frac{\mu(A_i \cap C_l)}{\mu(C_l)}$$

$$= -\sum_{i,l} \mu(C_l) \frac{\mu(A_i \cap C_l)}{\mu(C_l)} \log \frac{\mu(A_i \cap C_l)}{\mu(C_l)}$$

or equivalently $\mathrm{H}(\mathcal{A}|\mathcal{B}) \geq \mathrm{H}(\mathcal{A}|\mathcal{C})$.

Formula (e) follows immediately from (a) and (d) and formula (f) can proved by a straightforward calculation (its consequences are discussed in Exercise 1.17). ♣

1.4 Entropy of endomorphism

Let $(X, \mathcal{F}, \mu)$ be a probability space and let $T : X \to X$ be a measure preserving endomorphism of X. If $\mathcal{A} = \{A_i\}_{i \in I}$ is a partition of X then by $T^{-1}\mathcal{A}$ we denote the partition $\{T^{-1}(A_i)\}_{i \in I}$. Note that for any countable $\mathcal{A}$

$$\mathrm{H}(T^{-1}\mathcal{A}) = \mathrm{H}(\mathcal{A}) \tag{1.4.1}$$

For all $n \geq m \geq 0$ denote the partition $\bigvee_{i=0}^{n} T^{-i}\mathcal{A} = \mathcal{A} \vee T^{-1}(\mathcal{A}) \vee \cdots \vee T^{-n}(\mathcal{A}) = \bigvee_{i=m}^{n} T^{-i}(\mathcal{A})$ by A_m^n. For $m = 0$ we shall sometimes use the notation $\mathcal{A}^n$.

Lemma 1.4.1. *For any countable partition $\mathcal{A}$,*

$$\mathrm{H}(\mathcal{A}^n) = \mathrm{H}(\mathcal{A}) + \sum_{j=1}^{n} \mathrm{H}(\mathcal{A}|\mathcal{A}_1^j) \tag{1.4.2}$$

Proof. We prove this formula by induction. If $n = 0$, it is tautology. Suppose it is true for $n - 1 \geq 0$. Then with the use of Theorem 1.3.1(b) and (1.4.1) we obtain

$$\mathrm{H}(\mathcal{A}^n) = \mathrm{H}(\mathcal{A}_1^n \vee \mathcal{A}) = \mathrm{H}(\mathcal{A}_1^n) + \mathrm{H}(\mathcal{A}|\mathcal{A}_1^n)$$

$$= \mathrm{H}(\mathcal{A}^{n-1}) + \mathrm{H}(\mathcal{A}|\mathcal{A}_1^n) = \mathrm{H}(\mathcal{A}) + \sum_{j=1}^{n} \mathrm{H}(\mathcal{A}|\mathcal{A}_1^j)$$

Hence (1.4.2) holds for all n. ♣

Lemma 1.4.2. *The sequences $\frac{1}{n+1}\mathrm{H}(\mathcal{A}^n)$ and $\mathrm{H}(\mathcal{A}|\mathcal{A}_1^n)$ are monotone decreasing to a limit $\mathrm{h}(T,\mathcal{A})$.*

Proof. The sequence $\mathrm{H}(\mathcal{A}|\mathcal{A}_1^n)$, $n = 0, 1, \ldots$ is monotone decreasing, by Theorem 1.3.1 (d). Therefore the sequence of averages is also monotone decreasing to the same limit, furthermore it coincides with the limit of the sequence $\frac{1}{n+1}\mathrm{H}(\mathcal{A}^n)$ by (1.4.2). ♣

The limit $\frac{1}{n+1}\mathrm{H}(\mathcal{A}^n)$ whose existence has been shown in Lemma 1.4.2. is known as the *(measure–theoretic) entropy of T with respect to the partition $\mathcal{A}$* and is denoted by $\mathrm{h}(T,\mathcal{A})$ or by $\mathrm{h}_\mu(T,\mathcal{A})$ if one wants to indicate the measure under consideration. Intuitively this means the limit rate of the growth of average (integral) information (in logarithmic scale), under consecutive experiments, for the number of those experiments tending to infinity.

Remark. Write $a_k := \mathrm{H}(\mathcal{A}^{k-1})$. In order to prove the existence of the limit $\frac{1}{n+1}\mathrm{H}(\mathcal{A}^n)$, instead of relying on (1.4.2) and the monotonicity, we could use the estmate

$$a_{n+m} = \mathrm{H}(\mathcal{A}^{n+m-1}) \le \mathrm{H}(\mathcal{A}^{n-1}) + \mathrm{H}(\mathcal{A}_n^{n+m-1}) = a_n + \mathrm{H}(\mathcal{A}^{m-1}) = a_n + a_m.$$

following from Theorem 1.3.1 (e) and from (1.4.1), and apply the following

Lemma 1.4.3. *If $\{a_n\}_{n=1}^\infty$ is a sequence of real numbers such that $a_{n+m} \le a_n + a_m$ for all $n, m \ge 1$ (any such a sequence is called subadditive) then $\lim_{n\to\infty} a_n$ exists and equals $\inf_n a_n/n$. The limit could be $-\infty$, but if the a_n's are bounded below, then the limit will be nonnegative.*

Proof. Fix $m \ge 1$. Each $n \ge 1$ can be expressed as $n = km + i$ with $0 \le i < m$. Then

$$\frac{a_n}{n} = \frac{a_{i+km}}{i+km} \le \frac{a_i}{km} + \frac{a_{km}}{km} \le \frac{a_i}{km} + \frac{ka_m}{km} = \frac{a_i}{km} + \frac{a_m}{m}$$

If $n \to \infty$ then also $k \to \infty$ and therefore $\limsup_{n\to\infty} \frac{a_n}{n} \le \frac{a_m}{m}$. Thus $\limsup_{n\to\infty} \frac{a_n}{n} \le \inf \frac{a_m}{m}$. Now the inequality $\inf \frac{a_m}{m} \le \liminf_{n\to\infty} \frac{a_n}{n}$ finishes the proof. ♣

Notice that there exists a subadditive sequence $(a_n)_{n=1}^\infty$ such that the corresponding sequence a_n/n is not eventually decreasing. Indeed, it suffices to observe that each sequence consisting of 1's and 2's is subadditive and to consider such a sequence having infinitely many 1's and 2's. If for an $n > 1$ we have $a_n = 1$ and $a_{n+1} = 2$ we have $\frac{a_n}{n} < \frac{a_{n+1}}{n+1}$.

One can consider $a_n + Cn$ for any constant $C > 1$ making the example strictly increasing.

Exercise. Prove that Lemma 1.4.1 remains true under the weaker assumptions that there exists $c \in R$ such that $a_{n+m} \le a_n + a_m + c$ for all n and m.

The basic elementary properties of the entropy $\mathrm{h}(T,\mathcal{A})$ are collected in the next theorem below.

Theorem 1.4.4. *If $\mathcal{A}$ and $\mathcal{B}$ are countable partitions of finite entropy then*

$$\text{h}(T, \mathcal{A}) \leq \text{H}(\mathcal{A}) \tag{a}$$

$$\text{h}(T, \mathcal{A} \vee \mathcal{B}) \leq \text{h}(T, \mathcal{A}) + \text{h}(T, \mathcal{B}) \tag{b}$$

$$\mathcal{A} \leq \mathcal{B} \;\Rightarrow\; \text{h}(T, \mathcal{A}) \leq \text{h}(T, \mathcal{B}) \tag{c}$$

$$\text{h}(T, \mathcal{A}) \leq \text{h}(T, \mathcal{B}) + \text{H}(\mathcal{A}|\mathcal{B}) \tag{d}$$

$$\text{h}(T, T^{-1}(\mathcal{A})) = \text{h}(T, \mathcal{A}) \tag{e}$$

$$\textit{If } k \geq 1 \textit{ then } \text{h}(T, \mathcal{A}) = \text{h}\big(T, \mathcal{A}^{k}\big) \tag{f}$$

$$\textit{If } T \textit{ is invertible and } k \geq 1, \textit{ then } \text{h}(T, \mathcal{A}) = \text{h}\Big(T, \bigvee_{i=-k}^{k} T^{i}(\mathcal{A})\Big) \tag{g}$$

The standard proof (see for example [Walters 1982]) based on Theorem 1.3.1 and formula (1.3.2) is left for the reader as an exercise. Let us prove only item (d).

$$\text{h}(T, \mathcal{A}) = \lim_{n \to \infty} \frac{1}{n} \text{H}(\mathcal{A}^{n-1}) = \lim_{n \to \infty} \frac{1}{n} \Big(\text{H}(\mathcal{A}^{n-1}|\mathcal{B}^{n-1}) + \text{H}(\mathcal{B}^{n-1})\Big)$$

$$\leq \lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} H(T^{-j}(\mathcal{A})|\mathcal{B}^{n-1}) + \lim_{n \to \infty} \frac{1}{n} \text{H}(\mathcal{B}^{n-1})$$

$$\leq \lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} H(T^{-j}(\mathcal{A})|T^{-j}(\mathcal{B})) + \text{h}(T, \mathcal{B}) \leq \text{H}(\mathcal{A}|\mathcal{B}) + \text{h}(T, \mathcal{B}).$$

Here is one more useful fact, stronger than Theorem 1.4.4(c):

Theorem 1.4.5. *If $T : X \to X$ is a measure preserving endomorphism of a probability space $(X, \mathcal{F}, \mu)$, $\mathcal{A}$ and $\mathcal{B}_m, m = 1, 2, \ldots$ are countable partitions with finite entropy, and $\text{H}(\mathcal{A}|\mathcal{B}_m) \to 0$ as $m \to \infty$, then*

$$\text{h}(T, \mathcal{A}) \leq \liminf_{m \to \infty} \text{h}(T, \mathcal{B}_m).$$

In particular, for $\mathcal{B}_m := \mathcal{B}^m = \bigvee_{j=0}^{m} T^{-j}(\mathcal{B})$, one obtains $\text{h}(T, \mathcal{A}) \leq \text{h}(T, \mathcal{B})$.

Proof. By Theorem 1.4.4(d), we get for every positive integer m, that

$$\text{h}(T, \mathcal{A}) \leq \text{H}(\mathcal{A}|\mathcal{B}_m) + \text{h}(T, \mathcal{B}_m).$$

Letting $m \to \infty$ this yields the first part of the assertion. If $\mathcal{B}_m = \mathcal{B}^m$, then $\text{h}(T, \mathcal{B}^m) = \text{h}(T, \mathcal{B})$, by Theorem 1.4.4(f), and the second part of the theorem follows as well. ♣

The *(measure-theoretic) entropy of an endomorphism* $T : X \to X$ is defined as

$$\text{h}_\mu(T) = \text{h}(T) = \sup_{\mathcal{A}}\{\text{h}(T, \mathcal{A})\} \tag{1.4.8}$$

where the supremum is taken over all finite (or countable of finite entropy) partitions of X. See Exercise 1.21.

It is clear from the definition that the entropy of T is an isomorphism invariant.

Later on (see Th. 1.8.7, Remark 1.8.9, Corollary 1.8.10 and Exercise 1.18) we shall discuss the cases where $H(\mathcal{A}|\mathcal{B}_n) \to 0$ for every $\mathcal{A}$ (finite or of finite entropy). This will allow us to write $h_\mu(T) = \lim_{m\to\infty} h(T, \mathcal{B}_m)$ or $h(T) = h(T, \mathcal{B})$.

The following theorem is very useful.

Theorem 1.4.6. *If $T : X \to X$ is a measure preserving endomorphism of a probability space $(X, \mathcal{F}, \mu)$ then*

$$h(T^k) = k\, h(T) \text{ for all } k \geq 1, \tag{a}$$

$$\text{If } T \text{ is invertible then } h(T^{-1}) = h(T). \tag{b}$$

Proof. (a) Fix $k \geq 1$. Since

$$\lim_{n\to\infty} \frac{1}{n} H\Big(\bigvee_{j=0}^{n-1} T^{-kj}\Big(\bigvee_{i=0}^{k-1} T^{-i}\mathcal{A}\Big)\Big) = \lim_{n\to\infty} \frac{k}{nk} H\Big(\bigvee_{i=0}^{nk-1} T^{-i}\mathcal{A}\Big) = k\, h(T, \mathcal{A})$$

we have $h\big(T^k, \bigvee_{i=0}^{k-1} T^{-i}\mathcal{A}\big) = k\, h(T, \mathcal{A})$. Therefore

$$k\, h(T) = k \sup_{\mathcal{A} \text{ finite}} h(T, \mathcal{A}) = \sup_{\mathcal{A}} h\big(T^k, \bigvee_{i=0}^{k-1} T^{-i}\mathcal{A}\big) \leq \sup_{\mathcal{B}} h(T^k, \mathcal{B}) = h(T^k)$$

$$(1.4.3)$$

On the other hand, by Theorem 1.4.4(c), we get $h(T^k, \mathcal{A}) \leq h\big(T^k, \bigvee_{i=0}^{k-1} T^{-i}\mathcal{A}\big) = k\, h(T, \mathcal{A})$, and therefore, $h(T^k) \leq k\, h(T)$. The result follows from this and (1.4.3).

(b) In view of (1.4.1) for all finite partitions $\mathcal{A}$ we have

$$H\Big(\bigvee_{i=0}^{n-1} T^i \mathcal{A}\Big) = H\Big(T^{-(n-1)} \bigvee_{i=0}^{n-1} T^i \mathcal{A}\Big) = H\Big(\bigvee_{i=0}^{n-1} T^{-i} \mathcal{A}\Big)$$

This finishes the proof.   ♣

Let us end this Section with the following theorem to be used for example in Section 2.6.

Theorem 1.4.7. *If μ and ν are two probability measures on $(X, \mathcal{F})$ both preserved by an endomorphism $T : X \to X$. Then for every $a : 0 < a < 1$ and the measure $\rho = a\mu + (1-a)\nu$ we have*

$$h_\rho(T) = a\, h_\mu(T) + (1-a)\nu(T).$$

In other words the mapping $\mu \mapsto h_\mu$ is affine.

The proof can be found in [Denker, Grillenberger & Sigmund 1976, Prop.10.13] or [Walters 1982, Th.8.1]. We leave it to the reader as an exercise.

Hint: Prove first that for every $A \in \mathcal{F}$ we have

$$0 \le k(\rho(A)) - ak(\mu(A)) - (1-a)k(\nu(A)) \le -(a \log a)\mu(A) - ((1-a)\log(1-a))\nu(A),$$

using the concavity of the function $k(t) = -t \log t$, see (1.3.1). Summing it up over $A \in \mathcal{A}$ for a finite partition $\mathcal{A}$, obtain

$$0 \le \mathrm{H}_\rho(\mathcal{A}) - a\,\mathrm{H}_\mu(\mathcal{A}) - (1-a)\,\mathrm{H}_\nu(\mathcal{A}) \le \log 2.$$

Apply this to partitions $\mathcal{A}^n$ and use Theorem 1.4.6(a).

using the concavity of the function $k(t) = -t \log t$, see (1.3.1).

Remark. This theorem can be easily deduced from the ergodic decomposition theorem (Theorem 1.8.11) for Lebesgue spaces, see Exercise1.16. In the setting of Chapter 2, for Borel measures on a compact metric space X, one can refer also to Choquet's Theorem 2.1.11.

1.5   Shannon-Mcmillan-Breiman theorem

Let $(X, \mathcal{F}, \mu)$ be a probability space, let $T : X \to X$ be a measure preserving endomorphism of X and let $\mathcal{A}$ be a countable finite entropy partition of X.

Lemma 1.5.1 (maximal inequality).   *For each $n = 1, 2, \ldots$ let $f_n = I(\mathcal{A}|\mathcal{A}_1^n)$ and $f^* = \sup_{n \ge 1} f_n$. Then for each $\lambda \in \mathbb{R}$ and each $A \in \mathcal{A}$*

$$\mu(\{x \in A : f^*(x) > \lambda\}) \le e^{-\lambda}. \tag{1.5.1}$$

Proof. For each $A \in \mathcal{A}$ and $n = 1, 2, \ldots$ let $f_n^A = -\log E(\mathbb{1}_A|\mathcal{A}_1^n)$. Of course $f_n = \sum_{A \in \mathcal{A}} \mathbb{1}_A f_n^A$. Denote

$$B_n^A = \{x \in X : f_1^A(x), \ldots, f_{n-1}^A(x) \le \lambda, f_n^A(x) > \lambda\}.$$

Since $B_n^A \in \mathcal{F}(\mathcal{A}_1^n)$, the σ-algebra generated by $\mathcal{A}_1^n$,

$$\mu(B_n^A \cap A) = \int_{B_n^A} \mathbb{1}_A \, d\mu = \int_{B_n^A} E(\mathbb{1}_A|\mathcal{A}_1^n) \, d\mu = \int_{B_n^A} e^{-f_n^A} \, d\mu \le e^{-\lambda}\mu(B_n^A).$$

Therefore

$$\mu(\{x \in A : f^*(x) > \lambda\}) = \sum_{n=1}^{\infty} \mu(B_n^A \cap A) \le e^{-\lambda} \sum_{n=1}^{\infty} \mu(B_n^A) \le e^{-\lambda}.$$

$\clubsuit$

Corollary 1.5.2. *The function f^* is integrable and $\int f^* \, d\mu \le \mathrm{H}(\mathcal{A}) + 1$.*

Proof. Of course $\mu(\{x \in A : f^* > \lambda\}) \leq \mu(A)$, so $\mu(\{x \in A : f^*(x) > \lambda\}) \leq \min\{\mu(A), e^{-\lambda}\}$. So, by Lemma 1.5.1,

$$
\begin{aligned}
\int_X f^* \, d\mu &= \sum_{A \in \mathcal{A}} \int_A f^* \, d\mu = \sum_{A \in \mathcal{A}} \int_0^\infty \mu\{x \in A : f^*(x) > \lambda\} \, d\lambda \\
&\leq \sum_{A \in \mathcal{A}} \int_0^\infty \min\{\mu(A), e^{-\lambda}\} \, d\lambda \\
&= \sum_{A \in \mathcal{A}} \left(\int_0^{-\log \mu(A)} \mu(A) \, d\lambda + \int_{-\log \mu(A)}^\infty e^{-\lambda} \, d\lambda \right) \\
&= \sum_{A \in \mathcal{A}} \left(-\mu(A)(\log \mu(A)) + \mu(A) \right) = \mathrm{H}(\mathcal{A}) + 1.
\end{aligned}
$$

♣

Note that if $\mathcal{A}$ is finite, then the integrability of f^* follows from the integrability of $f^*|_A$ for each A, following immediately from Lemma 1.5.1. The difficulty with infinite $\mathcal{A}$ is that there is no $\mu(A)$ factor on the right hand side of (1.5.1).

Corollary 1.5.3. *The sequence* $(f_n)_{n=1}^\infty$ *converges a.e. and in* L^1.

Proof. $E(\mathbb{1}_A | \mathcal{A}_1^n)$ is a martingale to which we can apply Theorem 1.1.4. This gives convergence a.e., hence convergence a.e. of each f_n^A, hence of f_n. Now convergence in L^1 follows from Corollary 1.5.2. and Dominated Convergence Theorem. ♣

Theorem 1.5.4 (Shannon-McMillan-Breiman)**.** *Suppose that* $\mathcal{A}$ *is a countable partition of finite entropy. Then there exist limits*

$$
f = \lim_{n \to \infty} I(\mathcal{A} | \mathcal{A}_1^n) \quad \text{and} \quad f_\mathcal{I}(x) = \lim_{n \to \infty} \frac{1}{n} \sum_{i=0}^{n-1} f(T^i(x)) \text{ for a.e. } x
$$

and

$$
\lim_{n \to \infty} \frac{1}{n+1} I(\mathcal{A}^n) = f_\mathcal{I} \quad \text{a.e. and in } L^1. \tag{1.5.2}
$$

Furthermore

$$
\mathrm{h}(T, \mathcal{A}) = \lim_{n \to \infty} \frac{1}{n+1} \mathrm{H}(\mathcal{A}^n) = \int f_\mathcal{I} \, d\mu = \int f \, d\mu. \tag{1.5.3}
$$

The limit f will gain a new interpretation in (1.8.6), in the context of Lebesgue spaces, where the notion of information function I will be generalized.

Proof. First note that the sequence $f_n = I(\mathcal{A} | \mathcal{A}_1^n), n = 1, 2, \ldots$ converges to an integrable function f by Corollary 1.5.3. (Caution: though the integrals of f_n decrease to the entropy, Lemma 1.4.2, it is usually not true that f_n decrease.)

Hence the a.e. convergence of time averages to $f_{\mathcal{I}}$ holds by Birkhoff's Ergodic Theorem. It will suffice to prove (1.5.2) since then (1.5.3), the second equality, holds by integration and the last equality by Birkhoff's Ergodic Theorem, the convergence in L^1.

(In fact (1.5.3) follows already from Corollary 1.5.3. Indeed $\lim_{n\to\infty} \frac{1}{n+1} \mathrm{H}(\mathcal{A}^n) = \lim_{n\to\infty} \mathrm{H}(\mathcal{A}|\mathcal{A}_1^n) = \lim_{n\to\infty} \int I(\mathcal{A}|\mathcal{A}_1^n)\,d\mu = \int \lim_{n\to\infty} I(\mathcal{A}|\mathcal{A}_1^n)\,d\mu = \int f\,d\mu.$)

Let us establish now some identities (compare Lemma 1.4.1). Let $\{\mathcal{A}_n : n \geq 0\}$ be a sequence of countable partitions. Then we have

$$I\Big(\bigvee_{i=0}^n \mathcal{A}_i\Big) = I\Big(\mathcal{A}_0|\bigvee_{i=1}^n \mathcal{A}_i\Big) + I\Big(\bigvee_{i=1}^n \mathcal{A}_i\Big)$$

$$= I\Big(\mathcal{A}_0|\bigvee_{i=1}^n \mathcal{A}_i\Big) + I\Big(\mathcal{A}_1|\bigvee_{i=2}^n \mathcal{A}_i\Big) + \cdots + I(\mathcal{A}_n).$$

In particular, it follows from the above formula that for $\mathcal{A}_i = T^{-i}\mathcal{A}$, we have

$$I(\mathcal{A}^n) = I(\mathcal{A}|\mathcal{A}_1^n) + I(T^{-1}\mathcal{A}|\mathcal{A}_2^n) + \ldots + I(T^{-n}\mathcal{A})$$
$$= I(\mathcal{A}|\mathcal{A}_1^n) + I(\mathcal{A}|\mathcal{A}_1^{n-1}) \circ T + \ldots I(\mathcal{A}) \circ T^n$$
$$= f_n + f_{n-1} \circ T + f_{n-2} \circ T^2 + \ldots + f_0 \circ T^n,$$

where $f_k = I(\mathcal{A}|\mathcal{A}_1^k)$, $f_0 = I(\mathcal{A})$. Now

$$\Big|\frac{1}{n+1}I(\mathcal{A}^n) - f_{\mathcal{I}}\Big| \leq \Big|\frac{1}{n+1}\sum_{j=0}^n (f_{n-i} \circ T^i - f \circ T^i)\Big| + \Big|\frac{1}{n+1}\sum_{j=0}^n f \circ T^i - f_{\mathcal{I}}\Big|.$$

Since by Birkhoff's Ergodic Theorem the latter term converges to zero both almost everywhere and in L^1, it suffices to prove that for $n \to \infty$

$$\frac{1}{n+1}\sum_{i=0}^n g_{n-i} \circ T^i \to 0 \quad \text{a.e. and in } L^1. \tag{1.5.4}$$

where $g_k = |f - f_k|$.

Now, since T is measure preserving, for every $i \geq 0$

$$\int g_{n-i} \circ T^i d\mu = \int g_{n-i} d\mu.$$

Thus $\frac{1}{n}\sum_{i=0}^n \int g_{n-i} \circ T^i\,d\mu = \frac{1}{n}\sum_{i=0}^n \int g_{n-i}\,d\mu \to 0$, since $f_k \to f$ in L^1 by Corollary 1.5.3. Thus we established the L^1 convergence in (1.5.4).

Now, let $G_N = \sup_{n>N} g_n$. Of course G_N is monotone decreasing and since $g_n \to 0$ a.e. (Corollary 1.5.3) we get $G_N \searrow 0$ a.e.. Moreover, by Corollary 1.5.2, $G_0 \leq \sup_n f_n + f \in L_1$.

For arbitrary $N < n$ we have

$$\frac{1}{n+1}\sum_{i=0}^n g_{n-i} \circ T^i = \frac{1}{n+1}\sum_{i=0}^{n-N-1} g_{n-i} \circ T^i + \frac{1}{n+1}\sum_{i=n-N}^n g_{n-i} \circ T^i$$

$$\leq \frac{1}{n+1}\sum_{i=0}^{n-N-1} G_N \circ T^i + \frac{1}{n+1}\sum_{i=n-N}^n G_0 \circ T^i.$$

Hence, for $K_N = G_0 + G_0 \circ T + \ldots + G_0 \circ T^N$

$$\limsup_{n\to\infty} \frac{1}{n+1}\sum_{i=0}^{n} g_{n-i} \circ T^i \leq (G_N)_{\mathcal{I}} + \limsup_{n\to\infty} \frac{1}{n+1} K_N \circ T^{n-N} = (G_N)_{\mathcal{I}} \quad \text{a.e.,}$$

where $(G_N)_{\mathcal{I}} = \lim_{n\to\infty} \frac{1}{n+1}\sum_{i=0}^{n} G_N \circ T^i$ by Birkhoff's Ergodic Theorem.

Now $(G_N)_{\mathcal{I}}$ decreases with N because G_N decreases, and

$$\int (G_N)_{\mathcal{I}}\, d\mu = \int G_N d\mu \to 0$$

because G_N are non-negative uniformly bounded by $G_0 \in L^1$ and tend to 0 a.e.

Hence $(G_N)_{\mathcal{I}} \to 0$ a.e. Therefore

$$\limsup_{n\to\infty} \frac{1}{n+1}\sum_{i=0}^{n} g_{n-i} \circ T^i \to 0 \quad \text{a.e.}$$

establishing the missing a.e. convergence in (1.5.4).   ♣

As an immediate consequence of (1.5.2) and (1.5.3) for T ergodic, along with $f_{\mathcal{I}} = \int f_{\mathcal{I}}\, d\mu$, we get the following:

Theorem 1.5.5 (Shannon-McMillan-Breiman, ergodic case)**.** *If $T : X \to X$ is ergodic and $\mathcal{A}$ is a countable partition of finite entropy, then*

$$\lim_{n\to\infty} \frac{1}{n} I(\mathcal{A}^{n-1})(x) = \mathrm{h}_\mu(T, \mathcal{A}). \quad \text{for a.e. } x \in X$$

The left hand side expression in the above equality can be viewed as a *local entropy* at x. The Theorem says that at a.e. x the local entropy exists and is equal to the entropy (compare comments after (1.3.2) and Lemma 1.4.2).

1.6   Lebesgue spaces, measurable partitions and canonical systems of conditional measures

Let $(X, \mathcal{F}, \mu)$ be a probability space. We consider only *complete* measures (probabilities), namely such that every subset of a measurable set of measure 0 is measurable. If a measure is not complete we can always consider its completion, namely to add to $\mathcal{F}$ all sets A for which there exists $B \in \mathcal{F}$ with $A \div B$ contained in a set in $\mathcal{F}$ of measure 0.

Notation 1.6.1. *Consider $\mathcal{A}$, an arbitrary partition of X, not necessarily countable nor consisting of measurable sets. We denote by $\tilde{\mathcal{A}}$ the sub σ-algebra of $\mathcal{F}$ consisting of those sets in $\mathcal{F}$ that are unions of whole elements (fibres) of $\mathcal{A}$.*

Note that in the case where $\mathcal{A} \subset \mathcal{F}$, we have $\tilde{\mathcal{A}} \supset \sigma(\mathcal{A})$, the latter defined in Notation 1.1.1, but the inclusion can be strict. For example, if $\mathcal{A} \subset \mathcal{F}$ is the partition of X into points, then $\sigma(\mathcal{A})$ consists of all countable sets and their complements in X, and $\tilde{\mathcal{A}} = \mathcal{F}$. Obviously $\tilde{\mathcal{A}} \supset \{\emptyset, X\}$.

Definition 1.6.2. The partition $\mathcal{A}$ is called *measurable* if it satisfies the following separation property.

There exists a sequence $\mathbf{B} = (B_n)_{n=1}^{\infty}$ of subsets of $\tilde{\mathcal{A}}$ such that for any two distinct $A_1, A_2 \in \mathcal{A}$ there is an integer $n \geq 1$ such that either

$$A_1 \subset B_n \quad \text{and} \quad A_2 \subset X \setminus B_n$$

or

$$A_2 \subset B_n \quad \text{and} \quad A_1 \subset X \setminus B_n.$$

Since each element of the measurable partition $\mathcal{A}$ can be represented as an intersection of countably many elements B_n or their complements, each element of $\mathcal{A}$ is measurable. Let us stress however that the measurability of all elements of $\mathcal{A}$ is not sufficient for $\mathcal{A}$ to be a measurable partition (see Exercise 1.7). The sequence $\mathbf{B}$ is called a *basis* for $\mathcal{A}$.

Remark 1.6.3. A popular definition of an uncountable measurable partition $\mathcal{A}$ is that there exists a sequence of finite partitions (recall that this means: finite partitions into measurable sets) $\mathcal{A}_n, n = 0, 1, \ldots$, such that $\mathcal{A} = \bigvee_{n=0}^{\infty} \mathcal{A}_n$. Here (unlike later on) the join $\bigvee$ is in the set-theoretic sense, i.e. as $\{A_{n_1} \cap A_{n_2} \cap \cdots : A_{n_i} \in \mathcal{A}_{n_i}, i = 1, \ldots\}$. Clearly it is equivalent to the separation property in Definition 1.6.2.

Notice that for any measurable map $T : X \to X'$ between probability measure spaces, if $\mathcal{A}$ is a measurable partition of X', then $T^{-1}(\mathcal{A})$ is a measurable partition of X.

Now we pass to the very useful class of probability spaces: *Lebesgue spaces*.

Definition 1.6.4. We call a sequence $\mathbf{B} = (B_n)_{n=1}^{\infty}$ of subsets of $\mathcal{F}$, *basis* of $(X, \mathcal{F}, \mu)$ if the two following conditions are satisfied:

(i) $\mathbf{B}$ assures the separation property in Definition 1.6.2 for $\mathcal{A} = \varepsilon$, the partition into points, (i.e. $\mathbf{B}$ is a basis for ε);

(ii) for any $A \in \mathcal{F}$ there exists a set $C \in \sigma(\mathbf{B})$ such that $C \supset A$ and $\mu(C \setminus A) = 0$.

(Recall again, Notation 1.1.1, that $\sigma(\mathbf{B})$ denotes the smallest σ-algebra containing all the sets $B_n \in \mathbf{B}$. Rohlin used the name Borel σ-algebra.)

A probability space $(X, \mathcal{F}, \mu)$ having a basis is called *separable*.

Now let $\varepsilon = \pm 1$ and $B_n^{(\varepsilon)} = B_n$ if $\varepsilon = 1$ and $B_n^{(\varepsilon)} = X \setminus B_n$ if $\varepsilon = -1$. To any sequence of numbers $\varepsilon_n, n = 1, 2, \ldots$ there corresponds the intersection $\bigcap_{n=1}^{\infty} B_n^{(\varepsilon_n)}$. By (i) every such intersection contains no more than one point.

A probability space $(X, \mathcal{F}, \mu)$ is said to be *complete* with respect to a basis $\mathbf{B}$ if all the intersections $\bigcap_{n=1}^{\infty} B_n^{(\varepsilon_n)}$ are non-empty. The space $(X, \mathcal{F}, \mu)$ is said

to be *complete* (mod 0) with respect to a basis $\mathbf{B}$ if X can be included as a subset of full measure into a certain measure space $(\overline{X}, \overline{\mathcal{F}}, \overline{\mu})$ which is complete with respect to its own basis $\overline{\mathbf{B}} = (\overline{B}_n)$ satisfying $\overline{\mathbf{B}}_n \cap X = B_n$ for all n.

It turns out that a space which is complete (mod 0) with respect to one basis is also complete (mod 0) with respect to its every other basis.

Definition 1.6.5. A probability space $(X, \mathcal{F}, \mu)$ complete (mod 0) with respect to one of its bases is called a *Lebesgue space*.

Exercise. If $(X_1, \mathcal{F}_1, \mu_1)$ and $(X_2, \mathcal{F}_2, \mu_2)$ are two probability spaces with complete measures, such that $X_1 \subset X_2$, $\mu_2(X_2 \setminus X_1) = 0$ and $\mathcal{F}_1 = \mathcal{F}_2|_{X_1}, \mu_1 = \mu_2|_{\mathcal{F}_1}$ (where $\mathcal{F}_2|_{X_1} := \{A \cap X_1 : A \in \mathcal{F}_2\}$), then the first space is Lebesgue if and only if the second is.

It is not difficult to check that (see Exercise 1.9) that $(X, \mathcal{F}, \mu)$ is a Lebesgue space if and only if $(X, \mathcal{F}, \mu)$ is isomorphic to the unit interval (equipped with classical Lebesgue measure) together with countably many atoms.

Theorem 1.6.6. *Assume that $T : X \to X'$ is a measurable injective map from a Lebesgue space $(X, \mathcal{F}, \mu)$ onto a separable space $(X', \mathcal{F}', \mu')$ and pre-images of the sets of mesure 0 (or positive) are of measure 0 (resp. positive). Then the space $(X', \mathcal{F}', \mu')$ is Lebesgue and T^{-1} is a measurable map.*

Remark that in particular a measurable, measure preserving, injective map between Lebesgue spaces is an isomorphism. If $X = X', \mathcal{F} \supset \mathcal{F}', \mathcal{F} \neq \mathcal{F}'$ and $X', \mathcal{F}', \mu'$ is separable, then the above implies that $(X, \mathcal{F}, \mu)$ is not Lebesgue.

Let now $(X, \mathcal{F}, \mu)$ be a Lebesgue space and $\mathcal{A}$ be a measurable partition of X. We say that a property holds for all almost all atoms of $\mathcal{A}$ if and only if the union of atoms for which it is satisfied is measurable, and of full measure. The following fundamental theorem holds:

Theorem 1.6.7. *For almost all $A \in \mathcal{A}$ there exists a Lebesgue space $(A, \mathcal{F}_A, \mu_A)$ such that the following conditions are satisfied:*

(1) *If $B \in \mathcal{F}$, then $B \cap A \in \mathcal{F}_A$ for almost all $A \in \mathcal{A}$.*

(2) *$\mathcal{F}$-measurable for all $B \in \mathcal{F}$, where $A(x)$ is the element of $\mathcal{A}$ containing x.*

(3)
$$\mu(B) = \int_X \mu_{A(x)}(B \cap A(x)) \, d\mu(x) \tag{1.6.1}$$

Remark 1.6.8. One can consider the quotient (factor) space $(X/\mathcal{A}, \mathcal{F}_\mathcal{A}, \mu_\mathcal{A})$ with $X/\mathcal{A}$ being defined just as $\mathcal{A}$ and with $\mathcal{F}_\mathcal{A} = p(\tilde{\mathcal{A}})$, see Notation 1.6.1 for tilde, and $\mu_\mathcal{A}(B) = \mu(p^{-1}(B))$, for the projection map $p(x) = A(x)$. It can be proved that the factor space is again a Lebesgue space. Then $x \mapsto \mu_A(x)(B \cap A(x))$ is $\mathcal{F}_\mathcal{A}$-measurable and the property (1.6.1) can be rewritten in the form

$$\mu(B) = \int_{X/\mathcal{A}} \mu_A(B \cap A) \, d\mu_\mathcal{A}(A). \tag{1.6.2}$$

Remark 1.6.9. If a partition $\mathcal{A}$ is finite or countable, then the measures μ_A are just the conditional measures given by the formulas $\mu_A(B) = \mu(A \cap B)/\mu(A)$.

Remark 1.6.10. (1.6.1) can be rewritten for every μ-integrable function ϕ, or non-negative μ-measurable ϕ if we allow $+\infty$-ies, as

$$\int \phi \, d\mu = \int_X \left(\int_{A(x)} \phi|_{A(x)} \, d\mu_{A(x)} \right) d\mu(x). \tag{1.6.3}$$

This is a version of Fubini's Theorem.

The family of measures $\{\mu_A : A \in \mathcal{A}\}$ is called the *canonical system of conditional measures* with respect to the partition $\mathcal{A}$. It is unique (mod 0) in the sense that any other system μ_A' coincides with it for almost all atoms of $\mathcal{A}$.

The method of construction of the system μ_A is *via* conditional expectations values with respect to the σ-algebra $\tilde{\mathcal{A}}$. Having chosen a basis (B_n) of the Lebesgue space $(X, \mathcal{F}, \mu)$, for every finite intersection

$$B = \bigcap_i B_{n_i}^{(\varepsilon_{n_i})} \tag{1.6.4}$$

one considers $\phi_B := E(\mathbb{1}_B | \tilde{\mathcal{A}})$, that can be treated as a function on the factor space $X/\mathcal{A}$, unique on a.e. $A \in \mathcal{A}$, and such that for all $Z \in \tilde{\mathcal{A}}$

$$\mu(B \cap Z) = \int_{p(Z)} \phi_B(A) \, d\mu_{\mathcal{A}}(A).$$

Clearly $(B_n \cap A)_{n=1}^{\infty}$ is a basis for all A. It is not hard to prove that for a.e. A, for each B from our countable family (1.6.4), $\phi_B(A)$ as a function of B generates Lebesgue space on A, with $\mu_A(B) := \phi_B(A)$. Uniqueness of ϕ_B yields additivity.

Theorem 1.6.11. *If $T : X \to X'$ is a measurable map of a Lebesgue space $(X, \mathcal{F}, \mu)$ onto a Lebesgue space $(X', \mathcal{F}', \mu')$, then the induced map from $(X/\zeta, \mathcal{F}_\zeta, \mu_\zeta)$ for $\zeta = T^{-1}(\varepsilon)$, to $(X', \mathcal{F}', \mu')$ is an isomorphism.*

Proof. This immediately follows from the fact that the factor space is a Lebesgue space and from Theorem 1.6.6. ♣

In what follows we consider partitions (mod 0), i.e. we identify two partitions if they coincide, restricted to a measurable subset of full measure. For these classes of equivalence we use the same notation $\leq, \geq$ as in Section 1.3. They define a partial order. If $\mathcal{A}_\tau$ is a family of measurable partitions of a measure space (unlike in previous Sections the family may be uncountable), then by its product $\mathcal{A} = \bigvee_\tau \mathcal{A}_\tau$ we mean the measurable partition $\mathcal{A}$ determined by the following two conditions.

(i) $\mathcal{A} \geq \mathcal{A}_\tau$ for every τ;
(ii) if $\mathcal{A}' \geq \mathcal{A}_\tau$ for every τ and $\mathcal{A}'$ is measurable, then $\mathcal{A}' \geq \mathcal{A}$.
Similarly, replacing $\geq$ by $\leq$, we define the intersection $\bigwedge_\tau \mathcal{A}_\tau$.

The product and intersection exist in a Lebesgue space (i.e. the partially ordered structure is complete). They of course generalize the notions dealt with in Section 1.4. Clearly for a countable family of measurable partitions $\mathcal{A}_\tau$ the above $\bigvee$ and the set-theoretic one coincide (the assumption that the space is Lebesgue and the reasoning (mod 0) is not needed). In Exercise 1.13 we give some examples.

There is a natural one-to-one correspondence between the measurable partitions (mod 0) of a Lebesgue space $(X, \mathcal{F}, \mu)$ and the complete σ-subalgebras of $\mathcal{F}$, i.e. such σ-algebras $\mathcal{F}' \subset \mathcal{F}$ that the measure μ restricted to $\mathcal{F}'$ is complete. This correspondence is defined by assigning to each $\mathcal{A}$ the σ-algebra $\mathcal{F}(\mathcal{A})$ of all sets which coincide (mod 0) with the sets of $\tilde{\mathcal{A}}$ (defined at the beginning of this Section). To operations on the measurable partitions (mod 0) there correspond operations on the corresponding σ-algebras. Namely, if $\mathcal{A}_\tau$ is a family of measurable partitions (mod 0), then

$$\mathcal{F}(\bigvee_\tau \mathcal{A}_\tau) = \bigvee_\tau \mathcal{F}(\mathcal{A}_\tau), \qquad \mathcal{F}(\bigwedge_\tau \mathcal{A}_\tau) = \bigwedge_\tau \mathcal{F}(\mathcal{A}_\tau).$$

Here $\bigwedge_\tau \mathcal{F}(\mathcal{A}_\tau) = \bigcap_\tau \mathcal{F}(\mathcal{A}_\tau)$ is the set-theoretic intersection of the σ-algebras, while $\bigvee_\tau \mathcal{F}(\mathcal{A}_\tau)$ is the set-theoretic intersection of all the σ-algebras which contain all $\mathcal{F}(\mathcal{A}_\tau)$.

For any measurable partition $\mathcal{A}$ and any μ-integrable function $\phi : X \to \mathbb{R}$ write

$$E(f|\mathcal{A})(x) := \int f|_{\mathcal{A}(x)} \, d\mu_{\mathcal{A}(x)} \text{ a.e.} \tag{1.6.5}$$

Notice that by the definition of canonical system of conditional measures and by the definition of conditional expectation value, for any measurable partition $\mathcal{A}$ we get the identity

$$E(f|\mathcal{A}) = E(f|\mathcal{F}(\mathcal{A})). \tag{1.6.6}$$

A sequence of measurable partitions $\mathcal{A}_n$ is called *(monotone) increasing* or *ascending* if for all $n_1 \leq n_2$ we have $\mathcal{A}_{n_1} \leq \mathcal{A}_{n_2}$. It is called *(monotone) decreasing* or *descending* if for all $n_1 \leq n_2$ we have $\mathcal{A}_{n_1} \geq \mathcal{A}_{n_2}$.

For a monotone increasing (decreasing) sequence of measurable partitions $\mathcal{A}_n$ and $\mathcal{A} = \bigvee_n \mathcal{A}_n$ ($\mathcal{A} = \bigwedge_n \mathcal{A}_n$ respect.) we write $\mathcal{A}_n \nearrow \mathcal{A}$ (or $\mathcal{A}_n \searrow \mathcal{A}$). In the language of measurable partitions of a Lebesgue space, due to req(identity), the Martingale Theorem 1.1.4 can be expressed as follows:

Theorem 1.6.12. *If $\mathcal{A}_n \nearrow \mathcal{A}$ or $\mathcal{A}_n \searrow \mathcal{A}$, then for every integrable function f, $E(f|\mathcal{A}_n) \to E(f|\mathcal{A})$ μ a.s.*

1.7   Rohlin natural extension

We shall prove here following very useful

Theorem 1.7.1. *For every measure preserving endomorphism T of a Lebesgue space $(X, \mathcal{F}, \mu)$ there exists a Lebesgue space $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ with measure preserving transformations $\pi_n : \tilde{X} \to X, n \leq 0$ satisfying $T \circ \pi_{n-1} = \pi_n$, which is an inverse limit of the system $\cdots \xrightarrow{T} X \xrightarrow{T} X$.*

Moreover there exists an automorphisms $\tilde{T}$ of $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ satisfying

$$\pi_n \circ \tilde{T} = T \circ \pi_n \tag{1.7.1}$$

for every $n \leq 0$

Recall that in *category theory* [Lang 1970, Ch. I], for a sequence (system) of objects and morphisms $\cdots \xrightarrow{M_{n-1}} O_{n-1} \xrightarrow{M_n} \cdots \xrightarrow{M_0} O_0$ an object O equipped with morphisms $\pi_n : O \to O_n$ is called an *inverse limit* if $M_n \circ \pi_{n-1} = \pi_n$ and for every other O' equipped with morphisms $\pi'_n : O' \to O_n$ satisfying $M_n \circ \pi'_{n-1} = \pi'_n$ there exists a unique morphism $M : O' \to O$ such that $\pi_n \circ M = \pi'_n$ for every $n \leq 0$.

In particular, if all O_n are the same $(= O_0)$ and additionally $M_1 : O_0 \to O_0$ is chosen, then for $\pi'_n := M_{n+1} \circ \pi_n : O \to O_0$, $n \leq 0$ there exists $M : O \to O$ such that $\pi_n \circ M = \pi'_n = M_{n+1} \circ \pi_n$ for every n. It is easy to see that M is an automorphism.

In Theorem 1.7.1, the objects are probability spaces or probability spaces with complete probabilities, and morphisms are measure preserving transformations or measure preserving transformations up to sets of measure 0. (We have thus multiple meaning of Theorem 1.7.1.)

Thus the first part of Theorem 1.7.1 produces $\tilde{T}$ satisfying (1.7.1) automatically, via the category theory definition. The automorphism $\tilde{T}$ is called Rohlin's *natural extension* of T, compare the terminology at the beginning of Section 1.2. This is a "minimal" extension of T to an automorphism.

One can consider $\cdots \xrightarrow{T_{n-1}} X_n \xrightarrow{T_n} X_n \xrightarrow{T_{n+1}} \ldots$ in place of $\cdots \xrightarrow{T} X \xrightarrow{T} X$ for all $n \in \mathbb{Z}$ in the statement of Theorem 1.7.1. We have chosen a simplified version with all T_n equal to T to simplify notation and since only such a version will be used in this book.

In the proof of Theorem 1.7.1 we shall use the following.

Theorem 1.7.2 (Extension of Measure)**.** *Every probability measure ν (σ-additive) on an algebra $\mathcal{G}_0$ of subsets of a set X can be uniquely extended to a measure on the σ-algebra $\mathcal{G}$ generated by $\mathcal{G}_0$*

This Theorem can be proved with the use of the famous Carathéodory's, [Carathéodory 1927, Ch. V] construction. We define the outer measure:

$$\nu_e(A) = \inf \nu(B) : B \in \mathcal{G}_0, A \subset B$$

for every $A \subset X$.

We say that A is *Carathéodory measurable* if for every $E \subset X$ the outer measure ν_e satisfies

$$\nu_e(E) = \nu_e(E \cap A) + \nu_e(E \setminus A).$$

The family of these sets turns out to be a σ-algebra containing $\mathcal{G}_0$, hence containing $\mathcal{G}$.

For a general definition of outer measures and a sketch of the theory see Chapter 7.

Proof of Theorem 1.7.1. Denote $\Pi = X^{\mathbb{Z}_-}$, the set theory cartesian product of a countable number of X's, more precisely the space of sequences (x_n) of points in X indexed by non-positive integers. For each $i \leq 0$ denote by $\pi_i : \Pi \to X$ the projection to the i-th coordinate, $\pi_i((x_n)_{n \in \mathbb{Z}_-}) = x_i$.

We start with producing the inverse limit in the set-theoretic category. Set

$$\tilde{X} = \{(x_n)_{n \in \mathbb{Z}_-} : T(x_n) = x_{n+1} \ \forall n < 0\}. \tag{1.7.2}$$

The mappings π_n in the statement of Theorem 1.7.1 will be the restrictions of the π_n's defined above, to $\tilde{X}$.

We shall endow Π with a σ-algebra $\mathcal{F}_\Pi$ and probability measure μ_Π, whose restrictions to $\tilde{X}$ will yield the inverse limit $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$. The measure μ_Π will occur to be "supported" on $\tilde{X}$.

For each $n \leq 0$ consider the σ-algebra $\mathcal{G}_n = \pi_n^{-1}(\mathcal{F})$. Let $\mathcal{F}_{\Pi,0}$ be the smallest algebra of subsets of Π containing all σ-algebras $\mathcal{G}_n$. It is easy to see that $\mathcal{F}_{\Pi,0}$ consists of finite unions of pairwise disjoint "cylinders" $\bigcap_{i=n}^{0} \pi_i^{-1}(C_i))$, considered for arbitrary finite sequences of sets $C_i \in \mathcal{F}, i = n, ..., 0$ for an arbitrary $n \in \mathbb{Z}_-$. Define

$$\mu_\Pi\left(\bigcap_{i=n}^{0} \pi_i^{-1}(C_i)\right) := \mu\left(\bigcap_{i=n}^{0} T^{-(i-n)}(C_i)\right). \tag{1.7.3}$$

We extend the definition to finite unions of disjoint cylinders A_k by $\mu_\Pi(\bigcup_k A_k) := \sum_k \mu_\Pi(A_k)$.

To assure that μ_Π is well defined it is sufficient to prove the compatibility condition:

$$\mu_\Pi\left(\bigcap_{i=n}^{0} \pi_i^{-1}(C_i)\right) + \mu_\Pi\left(\left(\bigcap_{i:n \leq i \leq 0, i \neq j} \pi_i^{-1}(C_i)\right) \cap \pi_j^{-1}(C_j')\right)$$

$$= \mu_\Pi\left(\left(\bigcap_{i:n \leq i \leq 0, i \neq j} \pi_i^{-1}(C_i)\right) \cap \pi_j^{-1}(C_j \cup C_j')\right), \tag{1.7.4}$$

for all sequences $C_i \in \mathcal{F}, i = n, ..., 0$ and $C_j' \in \mathcal{F}$ disjoint from C_j. Fortunately (1.7.4) follows immediately from (1.7.3) and from the additivity of the measure μ_Π.

The next step is to observe that μ_Π is σ-additive on the algebra $\mathcal{F}_{\Pi,0}$. For this end we use the assumption that $(X, \mathcal{F}, \mu)$ is a Lebesgue space[1]. We just assume that X is a full Lebesgue measure subset of the unit interval $[0,1]$, with classical Lebesgue measure and atoms, and the σ-algebra of Lebesgue measurable sets $\mathcal{F}$, see Exercise 1.9. Now it is sufficient to apply the textbook fact that for every Lebesgue measurable set $C \subset [0,1]$ and $\varepsilon > 0$ there exists a compact set $P \subset C$ with $\mu(C \setminus P) < \varepsilon$. (This is also often being proved by the Lebesgue measure construction via Carathéodory's outer measure). Compare the notion of regularity of measure in Section 2.1.

Consider Π endowed with the product topology, compact by Tichonov's Theorem. Then all π_i are continuous and for every $\varepsilon > 0$ and for every cylinder $A = \bigcap_{i=n}^{0} \pi_i^{-1}(C_i))$ we can find a compact cylinder $K = \bigcap_{i=n}^{0} \pi_i^{-1}(P_i))$, with compact $P_i \subset C_i$, such that $\mu_\Pi(A \setminus K) < \varepsilon$. This follows from the definition (1.7.3) and the T-invariance of μ. The same immediately follows for finite unions of cylinders.

To prove the σ-additivity of μ_Π on $\mathcal{F}_{\Pi,0}$ it is sufficient to prove that for every descending sequence of sets $A_k \in \mathcal{F}_{\Pi,0}, i = 1, 2, \ldots$ if

$$\bigcap_k A_k = \emptyset \text{ then } \mu_\Pi(A_k) \to 0. \tag{1.7.5}$$

Suppose to the contrary that there exists $\varepsilon > 0$ such that $\mu_\Pi(A_k) \geq \varepsilon$ for every k. For each k, consider a compact set $K_k \subset A_k$ such that $\mu(A_k \setminus K_k) \leq \varepsilon 2^{-k-1}$. Then all $L_m := \bigcap_{k=1}^{m} K_k$ are non-empty, since $\mu_\Pi(L_m) \geq \varepsilon/2$. Hence, $\bigcap_{k=1}^{\infty} A_k \supset \bigcap_{k=1}^{\infty} L_k \neq \emptyset$ as $(L_k)_{k=1}^{\infty}$ is a descending family of non-empty compact sets. Thus, we have proved that μ_Π is σ-additive on $\mathcal{F}_{\Pi,0}$.

The measure μ_Π extends to σ-additive measure on a σ-algebra generated by $\mathcal{F}_{\Pi,0}$ by Theorem 1.7.2. Set this extension to be our $(\Pi, \mathcal{F}_\Pi, \mu_\Pi)$.

Now we shall prove that the set $\Pi \setminus \tilde{X}$ is μ_Π-measurable and that $\mu_\Pi(\Pi \setminus \tilde{X}) = 0$. To this end we will take care that the compact sets $K = K_k$ lie in $\tilde{X}$. Denote

$$\tilde{X}^n := \{(x_i)_{i \in \mathbb{Z}_-} : T(x_i) = x_{i+1} \ \forall n \leq i < 0\}. \tag{1.7.6}$$

Let us recall that $A = \bigcap_{i=n}^{0} \pi_i^{-1}(C_i))$. Notice that $\pi_n^{-1}(T^{-(i-n)}(C_i)) \cap \tilde{X}^n \subset \pi^{-1}(C_i)$ but they have the same measure μ_Π, by the formula (1.7.3). Let P_n be a compact subset of $C_n' := \bigcap_{i=n}^{0} T^{-(i-n)}(C_i)$ such that $\mu_\Pi(C_n' \setminus P_n) < \varepsilon$ and T^j restricted to P_n is continuous for all $j = 1, ..., n$. This is possible by Luzin's Theorem.

Then all $T^j(P_n)$ are compact sets, in particular μ-measurable. Hence, each $Q_n := \bigcap_{i=n}^{0} \pi_i^{-1}(T^{i-n}(P_n))$ belongs to $\mathcal{F}_{\Pi,0}$, in particular it is μ_Π-measurable. It is contained in $\tilde{X}^n$ but need not be contained in $\tilde{X}$. To cope with this trouble, express A as $A_N = \bigcap_{i=N}^{0} \pi_i^{-1}(C_i))$ for N arbitrarily large, setting $C_i = X$ for $i : N \leq i < n$. Then find Q_N for A_N and $\varepsilon_n = \varepsilon 2^{-N-1}$ and finally set

---

[1] This is a substantial assumption, being overlooked by some authors, see Notes at the end of this chapter.

$Q = \bigcap Q_N$. The set Q is μ_Π-measurable (even compact), contained in $\tilde{X}$ and $\mu_\Pi(A \setminus Q) \leq \varepsilon$.

For $A = \Pi$ we conclude with μ_Π-measurable $Q \subset \tilde{X}$ with $\mu_\Pi(\Pi \setminus Q) \leq \varepsilon$, for an arbitrary $\varepsilon > 0$. Hence $\mu_\Pi(\Pi \setminus \tilde{X} = 0$.

Notice that the measure μ_Π is complete (i.e. all subsets of measurable sets of measure 0 are measurable) by Carathéodory's construction. Now we prove that it is a Lebesgue space. Let $\mathbf{B} = (B_l)_{l=1}^\infty$ be a basis of $(X, \mathcal{F}, \mu)$. Then clearly the family $\mathbf{B}_\Pi := \{\pi_n^{-1}(B_l) : l \geq 1, n \leq 0\}$ is a basis of the partition ε in Π. The family $\mathbf{B}_\Pi$ generates the σ-algebra $\mathcal{F}_\Pi$ in the sense of Definition 1.6.4 (ii)), because $\mathbf{B}$ generates $\mathcal{F}$ in this sense, and by Carathéodory's outer measure construction. The probability space $(\Pi, \mathcal{F}_\Pi, \mu_\Pi)$ is complete with respect to $\mathbf{B}_\Pi$ since $(X, \mathcal{F}, \mu)$ is complete with respect to $\mathbf{B}$ and by the cartesian product definition.

Finally, let us restrict all the objects to $\tilde{X}$. In particular $\tilde{F} := \{A \cap \tilde{X} : A \in \mathcal{F}_\Pi\}$, $\tilde{\mu}$ is the restriction of μ_Π to $\tilde{F}$, and $\tilde{\mathbf{B}} := \{B \cap \tilde{X} : B \in \mathbf{B}_\Pi\}$. The resulting probability space $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ is complete (mod 0) with respect to $\tilde{\mathbf{B}}$. Therefore it is a Lebesgue space, see Definition 1.6.5; the extension required by the definition is just $(\Pi, \mathcal{F}_\Pi, \mu_\Pi)$ with the basis $\mathbf{B}_\Pi$.

Suppose $(X', \mathcal{F}', \mu')$ is any Lebesgue measure space, with measure preserving transformations $\pi_n' : X' \to X, n \leq 0$ satisfying $T \circ \pi_{n-1}' = \pi_n'$. Then define $M : X' \to \tilde{X}$ by

$$M(x') = (\ldots \pi_{n-1}'(x'), \pi_n'(x'), ..., \pi_0'(x')). \tag{1.7.7}$$

We get $\pi_n \circ M = \pi_n'$ by definition. We leave the proof of the measurability of M to the reader.

Uniqueness of M follows from the fact that if $M(x') = (\ldots y_n, \ldots, y_0)$ for $y_j \in X$, then from $\pi_n \circ M = \pi_n'$ μ'-a.e., we get $y_n = \pi_n'(x')$ a.e.   ♣

Remark 1.7.3. $\tilde{X}$ can be interpreted as the space of all backward trajectories for T. The map $\tilde{T} : \tilde{X} \to \tilde{X}$ can be defined by the formula

$$\tilde{T}((x_n)_{n \in \mathbb{Z}_-}) = (\ldots, x_{-2}, x_{-1}, x_0, T(x_0)). \tag{1.7.8}$$

$\tilde{X}$ could be defined in (1.7.2) as the space of full trajectories $\{(x_n)_{n \in \mathbb{Z}}; T(x_n) = x_{n+1}\}$. Then (1.7.8) is the *shift to the left*.

The formula (1.7.8) holds because $\tilde{T}$ defined by it, satisfies (1.7.1), and because of uniqueness of maps $\tilde{T}$ satisfying (1.7.1)

Remark 1.7.4. Alternatively to compact sets in $\tilde{X}^n$, we could find for all $n \leq 0$, sets $E_{n,i} \supset \tilde{X}^n$, with $\tilde{\mu}_\Pi(E_{n,i} \setminus \tilde{X}^n) \to 0$ as $i \to \infty$, which are unions of cylinders $\bigcap_{i=-n}^0 \pi_i^{-1}(C_i)$. This agrees with the following general fact:

If a sequence of sets Σ generates a σ-algebra $\mathcal{G}$ with a mesure ν on it (see Definition 1.6.4 (ii)) then for every $A \in \mathcal{G}$ there exists $C \supset A$ with $\nu(C \setminus A) = 0$ such that $C \in \Sigma'_{d\sigma\delta}$, i.e. C is a countable intersection of countable unions of finite intersections of sets belonging to Σ or their complements. Exercise: Prove

this general fact, using Carathéodory's outer measure constructed on measurable sets.

Remark 1.7.5. Another way to prove Theorem 1.7.1 is to construct $\tilde{\mathcal{F}}$ and $\tilde{\mu}$ on $\tilde{X}$ already at the beginning. One defines $\tilde{\mu}$ also by the formula (1.7.3).

More specifically, for the maps π_n restricted now to $\tilde{X}$, consider $\mathcal{G}_n = \pi_n^{-1}(\mathcal{F})$. Note that this is an ascending sequence of σ-algebras with growing $|n|$ because $\pi_n^{-1}(A) = \pi_{n-1}^{-1}(T^{-1}(A))$ for every $A \in \mathcal{F}$. Write $\tilde{\mathcal{F}}_0 = \bigcup_{n \le 0} \mathcal{G}_n$. This is an algebra. For every $A \in \mathcal{F}$ and $n \le 0$ define $\tilde{\mu}(\pi_n^{-1}(A)) := \mu(A)$. This is well-defined because if $C = \pi_n^{-1}(A_1) = \pi_m^{-1}(A_2)$ for $A_1, A_2 \in \mathcal{F}$ and $n < m$ then $A_1 = T^{-(m-n)}(A_2)$. Since T preserves μ, we have $\mu(A_1) = \mu(A_2)$. This measure is σ-additive on the algebra $\tilde{\mathcal{F}}_0$ since we managed to approximate "from below" each its element by a compact set, see the proof of Theorem 1.7.1. Hence, we find $\tilde{\mathcal{F}}$ and $\tilde{\mu}$ on $\tilde{X}$ by Carathéodory's theory.

Unfortunately the measure space $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ is usually not complete with respect to the basis $\hat{\mathbf{B}}$, constructed in the proof of Theorem 1.7.1. To make it complete (mod 0) we need to extend it, and the only way we know how to acomplish this, is to construct the space $(\Pi, \mathcal{F}_\Pi, \mu_\Pi)$.

We end this section with another version of Theorem 1.7.1. First the following definition:

Definition 1.7.6. Suppose that T is an automorphism of a Lebesgue space $(X, \mathcal{F}, \mu)$. Let ζ be a measurable partition. Assume it is forward invariant, namely $T(\zeta) \ge \zeta$, equivalently $T^{-1}(\zeta) \le \zeta$. Then ζ is said to be *exhausting* if $\bigvee_{n \ge 0} T^n(\zeta) = \varepsilon$.

Theorem 1.7.7. *For every measure preserving endomorphism T of a Lebesgue space $(X, \mathcal{F}, \mu)$ there exist a Lebesgue space $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$, its automorphism $\tilde{T}$, and a forward invariant for $\tilde{T}$ exhausting measurable partition ζ, such that $(X, \mathcal{F}, \mu) = (\tilde{X}/\zeta, \tilde{\mathcal{F}}_\zeta, \tilde{\mu}/\zeta)$ the factor space, cf. Remark 1.6.8, and T is factor of $\tilde{T}$, namely $T \circ p = p \circ \tilde{T}$ for the projection $p : \tilde{X} \to X$.*

Proof. Take $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ and $\tilde{T}$ from Theorem 1.7.1. Set $\zeta := \pi_0^{-1}(\varepsilon)$. By (1.7.1) and $T^{-1}(\varepsilon) \le \varepsilon$ we get $\tilde{T}^{-1}(\zeta) \le \zeta$.

If $\varepsilon' = \bigvee_{n \ge 0} T^n(\zeta)$ is not the partition of $\tilde{X}$ into points, then $\tilde{T}/\varepsilon'$ is an automorphism of $(\tilde{X}/\varepsilon', \tilde{\mathcal{F}}_{\varepsilon'}, \tilde{\mu}_{\varepsilon'})$. Moreover if we denote by p' the projection from $\tilde{X}$ to $\tilde{X}/\varepsilon'$ then we can write $\pi_n = \pi'_n \circ p'$ for some maps π'_n for every $n \le 0$. By the definition of inverse limit, p' has an inverse which is impossible.

The last part, that $\bigvee_{n \ge 0} T^n(\zeta)$ is the partition of $\tilde{X}$ into points, has also an immediate proof following directly from the form of $\tilde{X}$ in (1.7.2). Indeed for $n \ge 0$ the element of $T^n(\zeta)$ containing $\tilde{x} = (\ldots, x_{-2}, x_{-1}, x_0$ is the n-th image of the element of ζ containing $\tilde{T}^{-n}(\tilde{x})$ i.e. containing $(\ldots, x_{-n-1}, x_{-n})$. So it is equal to $\{(\ldots, x'_{-n-1}, x'_{-n}, \ldots, x'_0) \in \tilde{X} : x'_{-n} = x_{-n})\}$. Intersecting over $n \to \infty$, we obtain $\{\tilde{x}\}$.   ♣

1.8   Generalized entropy, convergence theorems

This section contains generalizations of entropy notions, introduced in Section 1.3, to the case of all measurable partitions. The triple $(X, \mathcal{F}, \mu)$ is assumed to be a Lebesgue space.

Definition 1.8.1. If $\mathcal{A}$ is a measurable partition of X then its (generalized) entropy is defined as follows:

$$H(\mathcal{A}) = \infty \text{ if } \mathcal{A} \text{ is not a countable partition (mod 0);}$$

$$H(\mathcal{A}) = \sum_{A \in \mathcal{A}} -\mu(A) \log \mu(A) \text{ if } \mathcal{A} \text{ is a countable partition (mod 0).}$$

Lemma 1.8.2. *If $\mathcal{A}_n$ and $\mathcal{A}$ are measurable partitions of X and $\mathcal{A}_n \nearrow \mathcal{A}$, then $H(\mathcal{A}_n) \nearrow H(\mathcal{A})$.*

Proof. Write $H(\mathcal{A}) = \int I(\mathcal{A}) \, d\mu$ where $I(\mathcal{A})(x) = -\log \mu(\mathcal{A}(x))$ is the information function (compare Section 1.4). We set $\log 0 = -\infty$, hence $I(\mathcal{A})(x) = \infty$ if $\mu(\mathcal{A}(x)) = 0$. Write the same for $\mathcal{A}_n$. As $\mu(\mathcal{A}_n(x)) \searrow \mu(\mathcal{A}(x))$ for a.e. x, the convergence in our Lemma follows from the Monotone Convergence Theorem. ♣

Definition 1.8.3. If $\mathcal{A}$ and $\mathcal{B}$ are two measurable partitions of X, then the (generalized) *conditional entropy* $H(\mathcal{A}|\mathcal{B}) = H_\mu(\mathcal{A}|\mathcal{B})$ of partition $\mathcal{A}$ subject to $\mathcal{B}$ is defined by the following integral

$$H_\mu(\mathcal{A}|\mathcal{B}) = \int_{X/\mathcal{B}} H_{\mu_B}(\mathcal{A}|B) \, d\mu_{\mathcal{B}}(B) \tag{1.8.1}$$

where $\mathcal{A} \cap B$ is the partition $\{A \cap B : A \in \mathcal{A}\}$ of B and $\{\mu_B, B \in \mathcal{B}\}$ forms a canonical system of conditional measures, see Section 1.7. For the integral in (1.8.1) to be well-defined, we have to know that the function $B \mapsto H_{\mu_B}(\mathcal{A}|B)$, $B \in \mathcal{B}$ is measurable. In order to see this choose a sequence of finite partitions $\mathcal{A}_n \nearrow \mathcal{A}$ (see Remark 1.6.3). Each conditional entropy function $H_{\mu_B}(\mathcal{A}_n|B)$ is measurable as a function of B in the factor space $(X/\mathcal{B}, \mathcal{F}_{\mathcal{B}}, \mu_{\mathcal{B}})$, hence of course as a function on $(X, \mathcal{F}, \mu)$, since it is a finite sum of measurable functions

$$B \mapsto -\mu_B(A \cap B) \log \mu_B(A \cap B) \text{ for } A \in \mathcal{A}.$$

Since $\mathcal{A}_n|B \nearrow \mathcal{A}|B$ for a.e. B, we obtain, by using Lemma 1.8.2, that $H_{\mu_B}(\mathcal{A}_n|B) \to H_{\mu_B}(\mathcal{A}|B)$. Hence $H_{\mu_B}(\mathcal{A}|B)$ is measurable, so our definition of $H_\mu(\mathcal{A}|\mathcal{B})$ makes sense (we allow ∞'s here).

Of course (1.8.1) can be rewritten in the form

$$\int_X H_{\mu_{\mathcal{B}(x)}}(\mathcal{A}|\mathcal{B}(x)) \, d\mu(x), \tag{1.8.2}$$

with $H_{\mu_B}(\mathcal{A}|B)$ understood as constant function on each $B \in \mathcal{B}$ (compare (1.6.1) versus (1.6.2)). As in Section 1.3 we can write

$$H_\mu(\mathcal{A}|\mathcal{B}) = \int_X I(\mathcal{A}|\mathcal{B}) \, d\mu, \tag{1.8.3}$$

where $I(\mathcal{A}|\mathcal{B})$ is the *conditional information function*:

$$I(\mathcal{A}|\mathcal{B})(x) := -\log \mu_{\mathcal{B}(x)}(\mathcal{A}(x) \cap \mathcal{B}(x)).$$

Indeed $I(\mathcal{A}|\mathcal{B})$ is non-negative and μ-measurable as being equal to $\lim_{n \to \infty} I(\mathcal{A}_n|\mathcal{B})$ (a.e.), so (1.8.3) follows from (1.6.3).

Lemma 1.8.4. *If $\{\mathcal{A}_n : n \geq 1\}$ and $\mathcal{A}$ are measurable partitions, $\mathcal{A}_n \searrow \mathcal{A}$ and $\mathrm{H}(\mathcal{A}_1) < \infty$ then $\mathrm{H}(\mathcal{A}_n) \searrow \mathrm{H}(\mathcal{A})$.*

Proof. The proof is similar to Proof of Lemma 1.8.2. ♣

Theorem 1.8.5. *If $\mathcal{A}, \mathcal{B}$ are measurable partitions and $\{\mathcal{A}_n : n \geq 1\}$ is an ascending (descending and $\mathrm{H}(\mathcal{A}_1|\mathcal{B}) < \infty$) sequence of measurable partitions converging to $\mathcal{A}$, then*

$$\lim_{n \to \infty} \mathrm{H}(\mathcal{A}_n|\mathcal{B}) = \mathrm{H}(\mathcal{A}|\mathcal{B}) \tag{1.8.4}$$

and the convergence is respectively monotone.

Proof. Applying Lemmas 1.8.2 and 1.8.4 we get the monotone convergence $\mathrm{H}_{\mu_B}(\mathcal{A}_n|B) \to \mathrm{H}_{\mu_B}(\mathcal{A}|B)$ for almost all $B \in X/\mathcal{B}$. Thus the integrals in the Definition 1.8.3 converge by the Monotone Convergence Theorem. ♣

Theorem 1.8.6. *If $\mathcal{A}, \mathcal{B}$ are measurable partitions and $\{\mathcal{B}_n : n \geq 1\}$ is a descending (ascending and $\mathrm{H}(\mathcal{A}|\mathcal{B}_1) < \infty$) sequence of measurable partitions converging to $\mathcal{B}$, then*

$$\lim_{n \to \infty} \mathrm{H}(\mathcal{A}|\mathcal{B}_n) = \mathrm{H}(\mathcal{A}|\mathcal{B}) \tag{1.8.5}$$

and the convergence is respectively monotone.

Proof 1. Assume first that $\mathcal{A}$ is finite (or countable with finite entropy). Then the a.e. convergence $I(\mathcal{A}|\mathcal{B}_n) \to I(\mathcal{A}|\mathcal{B})$ follows from the Martingale Convergence Theorem (more precisely from Theorem 1.6.12), applied to $f = \mathbb{1}_A$, the indicator functions of $A \in \mathcal{A}$.

   Now it is sufficient to prove that $\sup_n I(\mathcal{A}|\mathcal{B}_n) \in L^1$ in order to use the Dominated Convergence Theorem (compare Corollary 1.5.3) and (1.8.3). One can repeat the proofs of Lemma 1.5.1 (for ascending $\mathcal{B}_n$) and Corollary 1.5.2.

   The monotonicity of the sequence $\mathrm{H}(\mathcal{A}|\mathcal{B}_n)$ relies on Theorem 1.3.1(d). However for infinite $\mathcal{B}_n$ one needs to approximate $\mathcal{B}_n$ by finite (or finite entropy) partitions. For details see [Rohlin 1967, Sec. 5.12].

   For $\mathcal{A}$ measurable, represent $\mathcal{A}$ as $\lim_{j \to \infty} \mathcal{A}_j$ for an ascending sequence of finite partitions $\mathcal{A}_j, j = 1, 2, \ldots$; then refer to Theorem 1.8.5. In the case of descending sequence $\mathcal{B}_n$ the proof is straightforward. In the case of ascending $\mathcal{B}_n$ use

$$\mathrm{H}(\mathcal{A}|\mathcal{B}_n) - \mathrm{H}(\mathcal{A}_j|\mathcal{B}_n) = H(\mathcal{A}|(\mathcal{A}_j \vee \mathcal{B}_n)) \leq H(\mathcal{A}|(\mathcal{A}_j \vee \mathcal{B}_1)) = \mathrm{H}(\mathcal{A}|\mathcal{B}_1) - \mathrm{H}(\mathcal{A}_j|\mathcal{B}_1).$$

This implies that the convergence as $j \to \infty$ is uniform with respect to n, hence in the limit $\mathrm{H}(\mathcal{A}|\mathcal{B}_n) \to H(\mathcal{A}|\mathcal{B})$. ♣

Proof 2. For $\mathcal{A}$ finite (or countable with finite entropy) there is a simpler way to prove (1.8.5). By Theorem 1.1.4, for every $A \in \mathcal{A}$, the sequence $E(\mathbb{1}_A | \mathcal{F}(\mathcal{B}_n))$ converges to $E(\mathbb{1}_A | \mathcal{F}(\mathcal{B}))$ in L^2. Hence, for every $A \in \mathcal{A}$, the sequence $\mu_{\mathcal{B}_n(x)}(A \cap \mathcal{B}_n(x))$ converges to $\mu_{\mathcal{B}(x)}(A \cap \mathcal{B}(x))$ in measure μ. By continuity of the function $k(t) = -t \log t$, compare Section 1.3, this implies the convergence

$$k(\mu_{\mathcal{B}_n(x)}(A \cap \mathcal{B}_n(x))) \to k(\mu_{\mathcal{B}(x)}(A \cap \mathcal{B}(x)))$$

in measure μ (we do not assume $x \in A$ here). Summing over all $A \in \mathcal{A}$ we obtain the convergence $\mathrm{H}_{\mu_{\mathcal{B}_n(x)}}(\mathcal{A}|\mathcal{B}_n(x)) \to \mathrm{H}_{\mu_{\mathcal{B}}(x)}(\mathcal{A}|\mathcal{B}(x))$ in measure μ. These functions are uniformly bounded by $\log \#\mathcal{A}$ (or by $\mathrm{H}(\mathcal{A})$) and non-negative, hence we get the convergence in L^1 and in consequence, due to (1.8.2), we obtain (1.8.5). (Note that we have not used the a.e. convergence coming from Theorem 1.1.4, but only the convergence in L^2 which has been proved there.)   ♣

Observe that we can rewrite now the definition of the entropy $\mathrm{h}_\mu(T, \mathcal{A})$ from Section 1.5 as follows

$$\mathrm{h}_\mu(T, \mathcal{A}) = \mathrm{H}(\mathcal{A}|\mathcal{A}^-), \quad \text{where} \quad \mathcal{A}^- := \bigvee_{n=1}^{\infty} T^{-n}(\mathcal{A}). \qquad (1.8.6)$$

A countable partition $\mathcal{B}$ is called *a countable (one-sided) generator* for an endomorphism of a Lebesgue space if $\mathcal{B}^m \nearrow \varepsilon$. Due to Theorem 1.8.6 we obtain the following facts useful for computing the entropy for concrete examples.

Theorem 1.8.7. *(a) If $\mathcal{B}_m$ is a sequence of finite partitions of a Lebesgue space, such that $\mathcal{B}_m \nearrow \varepsilon$, then, for any endomorphism $T : X \to X$, $\mathrm{h}(T) = \lim_{m\to\infty} \mathrm{h}(T, \mathcal{B}_m)$.*
(b) If $\mathcal{B}$ is a countable one-sided generator with finite entropy for an endomorphism T of a Lebesgue space, then $\mathrm{h}(T) = \mathrm{h}(T, \mathcal{B})$.

Proof. By Theorem 1.8.6 for every finite partition $\mathcal{A}$ we have $\lim_{m\to\infty} \mathrm{H}(\mathcal{A}|\mathcal{B}_m) = \mathrm{H}(\mathcal{A}|\varepsilon) = 0$. Hence in view of Theorem 1.4.5, $\mathrm{h}(T) = \lim_{m\to\infty} \mathrm{h}(T, \mathcal{B}_m)$. This proves (a). Theorem 1.4.5 together with the definition of generator prove also (b).   ♣

Remark 1.8.8. For T being an automorphism, one considers two-sided countable (in particular finite) generators, i.e. partitions of $\mathcal{B}$ for which $\bigvee_{n=-\infty}^{\infty} T^n(\mathcal{B}) = \varepsilon$. Then, as in the one-sided case, finiteness of $\mathrm{H}(\mathcal{B})$ implies that $\mathrm{h}(T) = \mathrm{h}(T, \mathcal{B})$.

Remark 1.8.9. In both Theorem 1.8.6 and Theorem 1.8.7(a), the assumption of monotonicity of $\mathcal{B}_m$ can be weakened. Assume for example that $\mathcal{A}$ is finite and $\mathcal{B}_m \to \varepsilon$ in the sense that for every measurable set Y, $E(\mathbb{1}_Y | \mathcal{B}_m) \to \mathbb{1}_Y$ in measure, as in Remark 1.1.5. Then $\mathrm{H}(\mathcal{A}|\mathcal{B}_m) \to 0$, hence $\mathrm{h}(T) = \lim_{m\to\infty} \mathrm{H}(T, \mathcal{B}_m)$.

Indeed for $\mathrm{H}(\mathcal{A}|\mathcal{B}_m) \to 0$ just repeat Proof 2 of Theorem 1.8.6. The convergence in measure μ of $\mu_{\mathcal{B}_n(x)}(A \cap \mathcal{B}_n(x)))$ to $\mu_{\varepsilon(x)}(A \cap \varepsilon(x)))$ means that $E(\mathbb{1}_A | \mathcal{B}_n) \to \mathbb{1}_A$, which has just been assumed.

Corollary 1.8.10. *Assume that X is a compact metric space and that $\mathcal{F}$ is the σ-algebra of Borel sets (generated by open sets). Then if $\sup_{B \in \mathcal{B}_m}\big(\mathrm{diam}(B)\big) \to 0$ as $m \to \infty$, then $\mathrm{h}(T) = \lim_{m \to \infty} \mathrm{H}(T, \mathcal{B}_m)$.*

Proof. It is sufficient to check $E(\mathbb{1}_A|\mathcal{B}_m) \to \mathbb{1}_A$ in measure. First note that for every $\delta > 0$ there exist an open set U and closed set K such that $K \subset A \subset U$ and $\mu(U \setminus K) \leq \delta$. This property is called *regularity* of our measure μ and is true for every finite measure on the σ-algebra of Borel sets of a metric space (compactness is not needed here). It can be proved by Carathéodory's argument, compare the proof of Theorem 1.1.4. Namely, we construct the outer measure with the help of open sets, as in the sketch of the proof of theorem 1.7.2 (where we used $\mathcal{G}_0$) and we notice that since each closed set is an intersection of a descending sequence of open sets, we will have the same outer measure if in the construction of outer measure we use the algebra generated by open sets. Now we can refer to Theorem 1.7.2.

Now, due to compactness of X, hence K, for m large enough the set $A' := \bigcup\{B \in \mathcal{B}_m : B \cap K \neq \emptyset\}$ contains K and is contained in U, hence $\mu(A \div A') \leq \delta$. This implies that

$$\int_X |E(\mathbb{1}_A|\mathcal{B}_m) - \mathbb{1}_A|\, d\mu =$$

$$\int_{X \setminus (A \cup A')} E(\mathbb{1}_A|\mathcal{B}_m)\, d\mu + \int_{A \div A'} |E(\mathbb{1}_A|\mathcal{B}_m) - \mathbb{1}_A|\, d\mu + \int_{A \cap A'} \mathbb{1}_A - E(\mathbb{1}_A|\mathcal{B}_m)\, d\mu$$

$$\leq \frac{\delta}{\mu(X \setminus A')} \mu(X \setminus (A \cup A')) + \delta + \Big(1 - \frac{\mu(A \cap A')}{\mu(A')}\Big)\mu(A \cap A') \leq 3\delta.$$

Hence $\mu\{x : |E(\mathbb{1}_A|\mathcal{B}_m) - \mathbb{1}_A| \geq \sqrt{3\delta}\} \leq \sqrt{3\delta}$. ♣

For a simpler proof, omitting Theorem 1.8.6, see Exercise 1.18.

We end this Section with the *ergodic decomposition theorem* and the adequate entropy formula. Compare this with Choquet Representation Theorem: Theorem 2.1.11 and Theorem 2.1.13.

Let T be a measure preserving endomorphism of a Lebesgue space. A measurable partition $\mathcal{A}$ is said to be T-invariant if $T(A) \subset A$ for almost every $A \in \mathcal{A}$. The induced map $T_A = T|_A : A \to A$ is a measurable endomorphism of the Lebesgue space $(A, \mathcal{F}_A, \mu_A)$. One calls T_A a *component* of T.

Theorem 1.8.11. *(a) There exists a finest measurable partition $\mathcal{A}$ (mod 0) into T-invariant sets (called the ergodic decomposition). Almost all of its components are ergodic.*
(b) $h(T) = \int_{X/\mathcal{A}} h(T_A)\, d\mu_{\mathcal{A}}(A)$.

Proof. The part (a) will not be proved. Let us mention only that the ergodic decomposition partition corresponds (see Section 1.6) to the completion of $\mathcal{I}$, the σ-subalgebra of $\mathcal{F}$ consisting of T invariant sets in $\mathcal{F}$ (compare Theorem 1.2.5).

To prove the part (b) notice that for every T-invariant measurable partition $\mathcal{A}$, for every finite partition ξ and almost every $A \in \mathcal{A}$, writing ξ_A for the partition $\{s \cap A : s \in \xi\}$, we obtain

$$\mathrm{h}(T_A, \xi_A) = H(\xi_A|\xi_A^-) = \int_A I_{\mu_A}(\xi_A|\xi_A^-)\, d\mu_A.$$

Notice next that the latter information function is equal a.e. to $I_\mu(\xi|\xi^- \vee \mathcal{A})$ restricted to A. Hence

$$\int_{X/\mathcal{A}} h(T_A)\, d\mu_{\mathcal{A}}(A) = \int_{X/\mathcal{A}} d\mu_{\mathcal{A}} \int_A I_{\mu_A}(\xi_A|\xi_A^-)\, d\mu_A =$$

$$\int_X I_\mu(\xi|\xi^- \vee \mathcal{A})\, d\mu = \mathrm{H}(\xi|\xi^- \vee \mathcal{A}) = \mathrm{h}(T, \xi)$$

The latter equality follows from an approximation of $\mathcal{A}$ by finite T-invariant partitions $\eta \nearrow \mathcal{A}$ and from

$$\mathrm{H}(\xi|\xi^- \vee \eta) = \mathrm{H}(\xi \vee \eta|\xi^- \vee \eta^-) = \lim_{n \to \infty} \frac{1}{n} \mathrm{H}((\xi \vee \eta)^n) =$$

$$\lim_{n \to \infty} \frac{1}{n} \mathrm{H}(\xi^n \vee \eta) = \lim_{n \to \infty} \frac{1}{n} \mathrm{H}(\xi^n) = H(T, \xi).$$

Let now ξ_n be a sequence of finite partitions such that $\xi_n \nearrow \varepsilon$. Then $\mathrm{h}(T, \xi_n) \nearrow \mathrm{h}(T)$ and $\mathrm{h}(T_A, (\xi_n)_A) \nearrow \mathrm{h}(T_A)$. So $\mathrm{h}(T, \xi_n) = \int_{X/\mathcal{A}} h(T_A, \xi_n)\, d\mu_{\mathcal{A}}(A)$ and Lebesgue monotone convergence theorem prove (b)   ♣

1.9 Countable to one maps, Jacobian and entropy of endomorphisms

We start with a formulation of

Theorem 1.9.1 (Rohlin's fundamental theorem of cross-sections)**.** *. Suppose that $\mathcal{A}$ and $\mathcal{B}$ are two measurable partitions of a Lebesgue space $(X, \mathcal{F}, \mu)$ such that $\mathcal{A} \cap B$ (see Definition 1.8.3) is countable (mod 0 with respect to μ_B) for almost every $B \in \mathcal{B}$. Then there exists a countable partition $\gamma = \{\gamma_1, \gamma_2, \dots\}$ of X (mod 0) such that each $\gamma_j \in \gamma$ intersects almost every B at not more than one point, which is then an atom of μ_B, in particular*

$$\mathcal{A} \vee \mathcal{B} = \gamma \vee \mathcal{B} \quad (mod\ 0).$$

Furthermore, if $\mathrm{H}(\mathcal{A}|\mathcal{B}) < \infty$, then γ can be chosen so that

$$\mathrm{H}(\gamma) < H(\mathcal{A}|\mathcal{B}) + 3\sqrt{H(\mathcal{A}|\mathcal{B})} < \infty.$$

Definition 1.9.2. Let $(X, \mathcal{F}, \mu)$ be a Lebesgue space. Let $T : X \to X$ be a measurable endomorphism. We say that T is *essentially countable to one* if the measures μ_A of a canonical system of conditional measures for the partition $\mathcal{A} := T^{-1}(\varepsilon)$ are purely atomic (mod 0 with respect to μ_A), for almost all $A \in \mathcal{A}$.

Lemma 1.9.3. *If T is essentially countable to one and preserves μ then there exists a measurable set $Y \subset X$ of full measure such that $T(Y) \subset Y$ and*

1. $T^{-1}(x) \cap Y$ is countable for every $x \in Y$, i.e. $T|_Y$ is countable to one. Moreover for almost every $x \in Y$ $T^{-1}(x) \cap Y$ consists only of atoms of the conditional measure $\mu_{T^{-1}(x)}$;

2. $T(B)$ is measurable if $B \subset Y$ is measurable;

3. $T|_Y$ is forward quasi-invariant, namely $\mu(B) = 0$ for $B \subset Y$ implies $\mu(T(B)) = 0$.

Proof. Let Y' be the union of atoms mentioned in Definition 1.9.2.. We can write, due to Theorem 1.9.1, $Y' = \bigcup_j \gamma_j$, so Y' is measurable. Set $Y = \bigcap_{n=0}^{\infty} T^{-n}(Y')$. Denote the partition $T^{-1}(\varepsilon)$ in Y by ζ. Property 1. follows from the construction. To prove 2. we use the fact that $(Y/\zeta, \mathcal{F}_\zeta, \mu_\zeta)$ is a Lebesgue space and the factor map $T_\zeta : Y_\zeta \to X$ is an automorphism (Th. 1.6.11). So, for measurable $B \subset Y$, the set

$$\{A \in \zeta : \mu_A(B \cap A) \neq 0\} = \{A \in \zeta : A \cap B \neq \emptyset\} \qquad (1.9.1)$$

is measurable by Theorem 1.6.7(2) and therefore its image under T_ζ, equal to $T(B)$, is measurable. If $\mu(B) = 0$, then the set in (1.9.1) has measure μ_ζ equal to 0, hence, as T_ζ is isomorphism, we obtain that $T(B)$ is measurable and of measure 0. ♣

The key property in the above proof is the equality (1.9.1). Without assuming that μ_A are purely atomic there could exist B of measure 0 with $C := \{A \in \zeta : \mu_A(B \cap A) \neq 0\}$ not measurable in $\mathcal{F}_\zeta$.

To have such a situation just consider a non-measurable $C \subset Y/\zeta$. Consider the disjoint union $D := C \cup Y$ and denote the embedded C by C'. Finally, defining measure on D, put $\mu(C') = 0$ and μ on the embedded Y. Define $T(c') = T(c)$ for $C \ni c$ and c' being the image of c under the abovementioned embedding. Thus C' is measurable, of measure 0, whereas $T(C')$ is not measurable because C is not measurable and T_ζ is isomorphism.

Definition 1.9.4. Let $(X, \mathcal{F}, \mu)$ and $(X', \mathcal{F}', \mu')$ be probability measure spaces. Let $T : X \to X'$ be a measurable homomorphism. We say that a real, nonnegative, measurable function J is a *weak Jacobian* if there exists E of measure 0 such that for every measurable $A \subset X \setminus E$ on which T is injective, the set $T(A)$ is measurable and $\mu(T(A)) = \int_A J \, d\mu$. We say J is *strong Jacobian*, or just *Jacobian*, if the above holds without assuming $A \subset X \setminus E$.

We say that T is *forward quasi-invariant* if $(\mu(A) = 0) \Rightarrow (\mu'(T(A)) = 0)$. Notice that if T is forward quasi-invariant then automatically a weak Jacobian is a strong Jacobian.

Proposition 1.9.5. *Let $(X, \mathcal{F}, \mu)$ be Lebesgue space and $T : X \to X$ be a measurable, essentially countable to one, endomorphism. Then there exists a weak Jacobian $J = J_\mu$. It is unique (mod 0). For T restricted to Y (Lemma 1.9.3) J is a strong Jacobian.*

Proof. Consider the partition $\gamma = \{\gamma_1, \gamma_2, \dots\}$ given by Theorem 1.9.1 with $\mathcal{A} = \varepsilon$ and $\mathcal{B} = T^{-1}(\varepsilon)$. Then for each j the map $T|_{\gamma_j \cap Y}$ is injective. Moreover by Lemma 1.9.3, $T|_{\gamma_j \cap Y}$ maps measurable sets onto measurable sets and is forward quasi-invariant. Therefore J exists on each $\gamma_j \cap Y$ by Radon-Nikodym theorem.

By the presentation of each $A \subset Y$ as $\bigcup_{j=1}^{\infty} A \cap \gamma_j$ the function J satisfies the assertion of the Proposition. The uniqueness follows from the uniqueness of Jacobian in Radon-Nikodym theorem on each $\gamma_j \cap Y$.   ♣

Theorem 1.9.6. *Let $(X, \mathcal{F}, \nu)$ be a Lebesgue space. Let $T : X \to X$ be a ν preserving endomorphism, essentially countable to one. Then its Jacobian J_ν, strong on Y defined in Lemma 1.9.3, weak on X, has logarithm equal to $I_\nu(\varepsilon | T^{-1}(\varepsilon))$. (We do not need to assume here $T(Y) \subset Y$. I stands for the information function, see Sections 1.4 and 1.8).*

Proof. Consider already T restricted to Y. Let $Z \subset Y$ be an arbitrary measurable set such that T is 1–to–1 on it. For each $y \in Y$ denote by $A(y)$ the element of $\zeta = T^{-1}(\varepsilon)$ containing y. We obtain

$$
\nu\big(T(Z)\big) = \nu\Big(T^{-1}\big(T(Z)\big)\Big) = \int_{T^{-1}\big(T(Z)\big)} 1 \, d\nu(y)
$$

$$
= \int_{T^{-1}\big(T(Z)\big)} \left(\int_{A(y)} \mathbb{1}_Z(x)/\nu_{A(y)}\{x\}) \, d\nu_{A(y)}(x) \right) d\nu(y)
$$

$$
= \int_{T^{-1}\big(T(Z)\big)} (\mathbb{1}_Z(y)/\nu_{A(y)}\{y\}) \, d\nu(y) = \int_Z (1/\nu_{A(y)}\{y\}) \, d\nu(y).
$$

Therefore $J_\nu(y) = 1/\nu_{A(y)}\{y\})$ and its logarithm equal to $I_\nu(\varepsilon | T^{-1}(\varepsilon))(y)$.

♣

Theorem 1.9.6 gives rise to the so called Rohlin formula:

Theorem 1.9.7. *Let $(X, \mathcal{F}, \mu)$ be a Lebesgue space. Let $T : X \to X$ be a measure μ-preserving endomorphism, essentially countable to one. Suppose that on each component A of the ergodic decomposition (cf. Theorem 1.8.11) the restriction T_A has a countable one-sided generator of finite entropy. Then*

$$
h_\mu(T) = \mathrm{H}_\mu(\varepsilon | T^{-1}(\varepsilon)) = \int I_\mu(\varepsilon | T^{-1}(\varepsilon)) \, d\mu = \int \log J_\mu \, d\mu.
$$

Proof. The third equality follows from Theorem 1.9.6, the second one is the definition of the conditional entropy, see Sec. 8. To prove the first equality we can assume, due to Theorem 1.8.11, that T is ergodic. Then, for ζ, a countable one-sided generator of finite entropy, with the use of Theorems 1.8.5 and 1.8.7(b), we obtain

$$
\mathrm{H}(\varepsilon | T^{-1}(\varepsilon)) = \mathrm{H}(\varepsilon | \zeta^-) = \lim_{n \to \infty} \mathrm{H}(\zeta^n | \zeta^-) = \mathrm{H}(\zeta | \zeta^-) = \mathrm{h}(T, \zeta) = \mathrm{h}(T).
$$

♣

Remark. The existence of a countable one-sided generator, without demanding finite entropy, is a general, not very difficult, fact, namely the following holds:

Theorem 1.9.8. *Let $(X, \mathcal{F}, \mu)$ be Lebesgue space. Let $T : X \to X$ be a μ-preserving aperiodic endomorphism, essentially countable to one. Then there exists a countable one-sided generator, namely a countable partition ζ such that $\zeta \vee \zeta^- = \varepsilon$ (mod 0).*

Aperiodic means there exists no B of positive measure and a positive integer n so that $T^n|_B =$ id. For the proof see [Rohlin 1967, Sec. 10.12-13] or [Parry 1969]. To construct ζ one uses the partition γ ascribed to ε and $T^{-1}(\varepsilon)$ according to Theorem 1.9.1 and so-called *Rohlin towers*.

The existence of a one-sided generator with finite entropy is in fact equivalent to $H(\varepsilon|\varepsilon^-) = \mathrm{h}(T) < \infty$. The proof of the implication to the right is contained in Proof of Th. 1.9.7. The reverse implication, the construction of the partition, is not easy, it uses in particular the estimate in Th. 1.9.1.

The existence of a one-sided generator with finite entropy is a strong property. It may fail even for *exact* endomorphisms, see Sec. 10 and Exercise 1.22. Neither its existence implies exactness, Exercise 1.22. To the contrary, for automorphisms, two-sided generators, even finite, always exist, provided the map is aperiodic.

1.10 Mixing properties

In this section we examine briefly some mixing properties of a measure preserving endomorphism that are stronger than ergodicity. A measure preserving endomorphism is said to be *weakly mixing* if and only if for every two measurable sets A and B

$$\lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} |\mu(T^{-j}(B) \cap A) - \mu(A)\mu(B)| = 0$$

To see that a weakly mixing transformation is ergodic, suppose that $T^{-1}(B) = B$. Then $T^{-k}(B) = B$ for all $k \geq 0$ and consequently for every n,

$$\frac{1}{n} \sum_{j=0}^{n-1} |\mu(T^{-j}(B) \cap B) - \mu(B)\mu(B)| = |\mu(B) - \mu(B)^2| \to 0.$$

Thus $\mu(B) - \mu(B)^2 = 0$ and therefore $\mu(B) = 0$ or 1.

A measure preserving endomorphism is said to be *mixing* if and only if for every two measurable sets A and B

$$\lim_{n \to \infty} \mu(T^{-n}(B) \cap A) - \mu(A)\mu(B) = 0$$

Clearly, every mixing transformation is weakly mixing. The property equivalent to the mixing property is the following: for all square integrable functions f and

g

$$\lim_{n\to\infty} \int f(g \circ T^n)\, d\mu = \int f\, d\mu \int g\, d\mu.$$

Indeed, the former property follows from the latter if we substitute the indicator functions $\mathbb{1}_A$, $\mathbb{1}_B$ in place of f, g respectively. To prove the opposite implication notice that with the help of Hölder inequality it is sufficient to restrict our considerations to simple functions $f = \sum_i a_i \mathbb{1}_{A_i}$ and $g = \sum_j a_j \mathbb{1}_{A_j}$, where (A_i) and (B_j) are arbitrary finite partitions. Then

$$\left| \int f(g \circ T^n)\, d\mu - \int f\, d\mu \int g\, d\mu \right|$$

$$= \left| \sum_{i,j} a_i b_j (\mu(A_i \cap T^{-n}(B_j)) - \mu(A_i)\mu(B_j)) \right| \to 0$$

because every summand converges to 0 as $n \to \infty$.

In the sequel we will deal also with stronger mixing properties. An endomorphism is called K-*mixing* if for every measurable set A and every finite partition $\mathcal{A}$

$$\lim_{n\to\infty} \sup_{B \in \mathcal{F}(\mathcal{A}_n^\infty)} |\mu(A \cap B) - \mu(A)\mu(B)| = 0,$$

Recall that $\mathcal{F}(\mathcal{A}_n^\infty)$ for $n \geq 0$ means the complete σ-algebra assigned to the partition $\mathcal{A}_n^\infty = \bigvee_{j=n}^\infty T^{-j}(\mathcal{A})$. The following theorem provides us with alternative definitions of the K-mixing property in the case when T is an automorphism.

Theorem 1.10.1. *Let $(X, \mathcal{F}, \mu)$ be a Lebesgue space and $T : X \to X$ be its measure-preserving automorphism. Then the following conditions are equivalent:*

(a) T is K-mixing.

(b) For every finite partition $\mathcal{A}$ $\mathrm{Tail}(\mathcal{A}) := \bigwedge_{n=0}^\infty \bigvee_{k=n}^\infty T^{-k}(\mathcal{A})$ is equal to the trivial partition $\nu = \{X\}$

(c) For every finite partition $\mathcal{A} \neq \nu$, $\mathrm{h}_\mu(T, \mathcal{A}) > 0$ (T has completely positive entropy)

(d) There exists a forward invariant exhausting measurable partition α (i.e. satisfying $T^{-1}(\alpha) \leq \alpha$, $T^n(\alpha) \nearrow \varepsilon$, see Definition 1.6.4) such that $T^{-n}(\alpha) \searrow \nu$.

The property $\mathrm{Tail}(\mathcal{A}) = \nu$ is a version of the 0-1 Law. An automorphism satisfying (d) is usually called: K-*automorphism*. The symbol K comes from the name: Kolmogorov. Each partition satisfying the properties of α in (d) is called K-partition.

Remark. the properties (a)-(c) make sense for endomorphisms and they are equivalent (proofs are the same as for automorphisms). Moreover they hold for an endomorphis iff they hold for its natural extension.

Proof. (a part of) To show the reader what Theorem 1.10.1 is about let us prove at least some implications:

(a)$\Rightarrow$(b) Let $A \in \mathcal{F}(\text{Tail}(\mathcal{A}))$ for a finite partition $\mathcal{A}$. Then for every $n \geq 0$, $A \in \mathcal{F}(\bigvee_{k=n}^{\infty} T^{-k}(\mathcal{A}))$. Hence, by K-mixing, $\mu(A \cap A) - \mu(A)\mu(A) = 0$ and therefore $\mu(A) = 0$ or 1.

(b)$\Rightarrow$(c) Suppose (b) and assume $\text{h}(T, \mathcal{A}) = 0$ for a finite partition $\mathcal{A}$. Then $\text{H}(\mathcal{A}|\mathcal{A}^-) = 0$, hence $I(\mathcal{A}|\mathcal{A}^-) = 0$ a.s. (see Section 1.8), hence $\mathcal{A} \leq \mathcal{A}^-$. Thus,

$$\bigvee_{k=0}^{\infty} T^{-k}(\mathcal{A}) = \bigvee_{k=1}^{\infty} T^{-k}(\mathcal{A}) \text{ and } \bigvee_{k=m}^{\infty} T^{-k}(\mathcal{A}) = \bigvee_{k=n}^{\infty} T^{-k}(\mathcal{A})$$

for every $m, n \geq 0$. So $\nu = \bigwedge_{n=0}^{\infty} \bigvee_{k=n}^{\infty} T^{-k}(\mathcal{A}) = \bigvee_{k=0}^{\infty} T^{-k}(\mathcal{A}) \geq \mathcal{A}$. So $\mathcal{A} = \nu$ the trivial partition. Thus, for every non-trivial partition $\mathcal{A}$ we have $\text{h}(T, \mathcal{A}) > 0$.

(b)$\Rightarrow$(d) (in case there exists a finite two-sided generator $\mathcal{B}$, meaning that $\bigvee_{n=-\infty}^{\infty} T^n(\mathcal{B}) = \varepsilon$). Notice that $\alpha = \bigvee T_{n=0}^{\infty} T^{-n}(\mathcal{B})$ is exhausting. ♣

Let us finish the Section with the following useful:

Definition 1.10.2. A measure preserving endomorphism is said to be *exact* if

$$\bigwedge_{n=0}^{\infty} T^{-n}(\varepsilon) = \nu,$$

(Remind that ε is the partition into points and ν is the trivial partition $\{X\}$.)

Exercise. Prove that exactness is equivalent to the property that $\mu_e(T^n(A)) \to 1$ for every A of positive measure (μ_e is the outer measure generated by μ), or to the property that $\mu(T^n(A)) \to 1$ provided $\mu(A) > 0$ and the sets $T^n(A)$ are measurable.

The property of being *exact* implies the natural extension to be a K-automorphism (in Theorem 1.10.1(d) set for α the lift of ε). The converse is of course false. The automorphisms of spaces not being one atom spaces, are not exact. Observe however that if T is an automorphism and α is a measurable partition satisfying (d), then the factor map T/α on X/α is exact.

Exercise. Prove that T is the natural extension of T/α.

Recall finally (Section 1.9) that even for exact endomorphisms, $\text{h}(\varepsilon|T^{-1}(\varepsilon))$ can be strictly less than $\text{h}(T)$.

1.11 Probability laws and Bernoulli property

Let $(X, \mathcal{F}, \mu)$ be a probability space and, whenever it is needed, a Lebesgue space, and let $T : X \to X$ be an endomorphism preserving μ. Let f and g be

real-valued square-integrable functions on X. For every positive integer n, the n-th *correlation* of the pair f, g, is the number

$$C_n(f, g) := \int f \cdot (g \circ T^n) \, d\mu - \int f \, d\mu \int g \, d\mu.$$

provided the above integrals exist. Notice that due to T-invariance of μ we can also write

$$C_n(f, g) = \int (f - Ef)\big((g - Eg) \circ T^n\big) \, d\mu,$$

where $Ef = \int f \, d\mu$ and $Eg = \int g \, d\mu$.

Keep $g : X \to \mathbb{R}$ a square-integrable function. The limit

$$\sigma^2 = \sigma^2(g) = \lim_{n \to \infty} \frac{1}{n} \int \Big(\sum_{j=0}^{n-1} g \circ T^j - nEg\Big)^2 d\mu \qquad (1.11.1)$$

is called *asymptotic variance* or *dispersion* of g, provided it exists. Write $g_0 = g - Eg$. Then we can rewrite the above formula as

$$\sigma^2 = \lim_{n \to \infty} \frac{1}{n} \int \Big(\sum_{j=0}^{n-1} g_0 \circ T^j\Big)^2 d\mu. \qquad (1.11.2)$$

Another useful expression for the asymptotic variance is the following.

$$\sigma^2(g) = \int g_0^2 \, d\mu + 2 \sum_{j=1}^{\infty} \int g_0 \cdot (g_0 \circ T^j) \, d\mu. \qquad (1.11.3)$$

The convergence of the series of correlations $C_n(g, g)$ in (1.11.3) easily implies that $\sigma^2(g)$ from this formula is equal to σ^2 defined in (1.11.1), compare the computation in the proof of Theorem 1.11.3 later on.

We say that the *Law of Iterated Logarithm*, LIL, holds for g if $\sigma^2(g)$ exists (i.e. the above series converges) and

$$\limsup_{n \to \infty} \frac{\sum_{j=0}^{n-1} g \circ T^j - nEg}{\sqrt{n \log \log n}} = \sqrt{2\sigma^2} \quad \mu - \text{ almost surely .} \qquad (1.11.4)$$

μ almost surely, (a.s.), means μ almost everywhere, (a.e.). This is the language of probability theory.)

We say that the *Central Limit Theorem*, CLT, holds, if for all $r \in \mathbb{R}$, in the case $\sigma^2 \neq 0$,

$$\mu\left(\left\{x \in X : \frac{\sum_{j=0}^{n-1} g \circ T^j - nEg}{\sqrt{n}} < r\right\}\right) \to \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{r} e^{-t^2/2\sigma^2} \, dt, \quad (1.11.5)$$

and in the case $\sigma^2 = 0$ the convergence holds for $r \neq 0$ with 0 on the right hand side for $r < 0$ and 1 for $r > 0$.

The LIL and CLT for $\sigma^2 \neq 0$ are often, and this is the case in Theorem 1.11.1 below, a consequence of the *Almost Sure Invariance Principle*, ASIP, which says that the sequence of random variables g, $g \circ T$, $g \circ T^2$, *centered at the expectation value* i.e. if $Eg = 0$, is "approximated with the rate $n^{1/2-\varepsilon}$" with some $\varepsilon > 0$, depending on δ in Theorem 1.11.1 below, by a martingale difference sequence and a respective Brownian motion.

Theorem 1.11.1. *Let $(X, \mathcal{F}, \mu)$ be a probability space and T an endomorphism preserving μ. Let $\mathcal{G} \subset \mathcal{F}$ be a σ-algebra. Write $\mathcal{G}_m^n := \bigvee_{j=m}^{n} T^{-j}(\mathcal{G})$ (notation from Section1.6) for all $m \leq n \leq \infty$, and suppose that the following property, called ϕ-mixing, holds:*
There exists a sequence $\phi(n), n = 0, 1, ..$ of positive numbers satisfying

$$\sum_{n=1}^{\infty} \phi^{1/2}(n) < \infty, \qquad (1.11.6)$$

such that for every $A \in \mathcal{G}_0^m$ and $B \in \mathcal{G}_n^{\infty}$, $0 \leq m \leq n$ we have

$$|\mu(A \cap B) - \mu(A)\mu(B)| \leq \phi(n-m)\mu(A). \qquad (1.11.7)$$

Now consider a $\mathcal{G}_0^{\infty}$ measurable function $g : X \to \mathbb{R}$ such that

$$\int |g|^{2+\delta}\, d\mu < \infty \ \ \text{for some } \delta > 0,$$

and that for all $n \geq 1$

$$\int |h - E(h|\mathcal{G}_0^n)|^{2+\delta})\, d\mu \leq Kn^{-s}, \quad for K > 0, s > 0 \ large \ enough. \quad (1.11.8)$$

(A concrete formula for s, depending on δ, can be given.)
Then g satisfies CLT and LIL.

LIL for $\sigma^2 \neq 0$ is a special case, for $\psi(n) = \sqrt{2 \log \log n}$, of the following property for a square integrable function $g : X \to \mathbb{R}$ for which σ^2 exists, provided $\int g\, d\mu = 0$: for every real positive non-decreasing function ψ and one has,

$$\mu\left(\left\{x \in X : \sum_{j=0}^{n} g(T^j(x)) > \psi(n)\sqrt{\sigma^2 n} \text{ for infinitely many } n\right\}\right) = 0 \text{ or } 1$$

according as the integral $\int_1^{\infty} \frac{\psi(t)}{t} \exp(-\frac{1}{2}\psi^2(t))\, dt$ converges or diverges.

As we already remarked, this Theorem, for $\sigma^2 \neq 0$, is a consequence of ASIP and similar conclusions for the standard Brownian motion. We do not give the proofs here. For ASIP and further references see [Philipp, Stout 1975, Ch. 4 and 7]. Let us discuss only the existence of σ^2. It follows from the following consequence of (1.11.7): For α, β square integrable real-valued functions on X,

α measurable with respect to $\mathcal{G}_0^m$ and β measurable with respect to $\mathcal{G}_n^\infty$, we have

$$\left| \int (\alpha\beta \, d\mu - E\alpha \, E\beta) \, d\mu \right| \le 2(\phi(n-m))^{1/2} \|\alpha\|_2 \|\beta\|_2. \qquad (1.11.9)$$

The proof of this inequality is not difficult, but tricky, with the use of Hölder inequality, see [Ibragimov 1962] or [Billingsley 1968]. It is sufficient to work with simple functions $\alpha = \sum_i a_i \mathbb{1}_{A_i}, \beta = \sum_j a_j \mathbb{1}_{A_j}$ for finite partitions (A_i) and (B_j), as in dealing with mixing properties in Section 1.10. Note that if instead of (1.11.7) we have stronger:

$$|\mu(A \cap B) - \mu(A)\mu(B)| \le \phi(n-m)\mu(A)\mu(B), \qquad (1.11.10)$$

as will be the case in Chapter 3, then we very easily obtain in (1.11.9) the estimate by $\phi(n-m)\|\alpha\|_1\|\beta\|_1$, by the computation the same as for mixing in Section 1.10.

We may assume that g is centered at the expectation value. Write $g = k_n + r_n = E(g|\mathcal{G}_0^{[n/2]}) + (g - E(g|\mathcal{G}_0^{[n/2]}))$. We have

$$\left| \int g(g \circ T^n) \, d\mu \right| \le$$

$$\left| \int k_n(k_n \circ T^n) \, d\mu \right| + \left| \int k_n(r_n \circ T^n) \, d\mu \right| + \left| \int r_n(k_n \circ T^n) \, d\mu \right| + \left| \int r_n(r_n \circ T^n) \, d\mu \right| \le$$

$$2(\phi(n - [n/2]))^{1/2}\|k_n\|_2^2 + 2\|k_n\|_2\|r_n\|_2 + \|r_n\|_2^2 \le$$
$$2(\phi(n - [n/2]))^{1/2}\|k_n\|_2^2 + 2K[n/2]^{-s}\|k_n\|_2 + K[n/2]^{-2s},$$

the first summand estimated according to (1.11.9). For $s > 1$ we thus obtain convergence of the series of correlations.

Let us go back to the discussion of the ϕ-mixing property. If $\mathcal{G}$ is associated to a finite partition that is a one-sided generator, ϕ-mixing with $\phi(n) \to 0$ as $n \to \infty$ (that is weaker than (1.11.6)), implies K-mixing (see Section 1.10). Indeed B is the same in both definitions, whereas A in K-mixing can be approximated by sets belonging to $\mathcal{G}_0^m$. We leave details to the reader.

Intuitively both notions mean that any event B in remote future weakly depends on the present state A, i.e. $|\mu(B) - \mu(B|A)|$ is small.

In applications $\mathcal{G}$ will be usually associated to a finite or countable partition.

In Theorems 1.11.1, the case $\sigma^2 = 0$ is easy. It relies on Theorem 1.11.3 below. Let us first introduce the following fundamental

Definition 1.11.2. Two functions $f, g : X \to \mathbb{R}$ (or $\mathbb{C}$) are said to be *cohomologous* in a space $\mathcal{K}$ of real (or complex) -valued functions on X (or f is called cohomologous to g), if there exists $h \in \mathcal{K}$ such that

$$f - g = h \circ T - h. \qquad (1.11.11)$$

If f, g are defined mod 0, then (1.11.11) is understood a.s. This formula is called a *cohomology equation*.

Theorem 1.11.3. *Let f be a square integrable function on a probability space $(X, \mathcal{F}, \mu)$, centered at the expectation value. Assume that*

$$\sum_{n=0}^{\infty} n |\int f \cdot (f \circ T^n) \, d\mu| < \infty. \qquad (1.11.12)$$

Then the following three conditions are equivalent:

(a) $\sigma^2(f) = 0$;

(b) *All the sums $S_n = S_n f = \sum_{j=0}^{n-1} f \circ T^j$ have the norm in L^2 (the space square integrable functions) bounded by the same constant;*

(c) *f is cohomologous to 0 in the space $\mathcal{H} = L^2$.*

Proof. The implication (c)$\Rightarrow$(a) follows immediately from (1.11.1) after substituting $f = h \circ T - h$. Let us prove (a)$\Rightarrow$(b). Write C_j for the correlations $\int f \cdot (f \circ T^j) \, d\mu, j = 0, 1, \ldots$. Then

$$\int |S_n|^2 \, d\mu = nC_0^2 + 2 \sum_{j=1}^{n} (n-j) C_j$$

$$= n \Big(C_0^2 + 2 \sum_{j=1}^{\infty} C_j \Big) - 2n \sum_{j=n+1}^{\infty} C_j - 2 \sum_{j=1}^{n} j \cdot C_j = n\sigma^2 - I_n - II_n.$$

Since $I_n \to 0$ and II_n stays bounded as $n \to \infty$ and $\sigma^2 = 0$, we deduce that all the sums S_n are uniformly bounded in L^2.

(b)$\Rightarrow$(c): $f = h \circ T - h$ for any h, a limit in the weak topology, of the sequence $\frac{1}{n} S_n$ bounded in $L^2(\mu)$. We leave the easy computation to the reader. (This computation will be given in detail in the similar situation of Bogolyubov-Krylov Theorem, in Remark 2.1.14.). ♣

Now Theorem 1.11.1 for $\sigma^2 = 0$ follow from (c), which gives $\sum_{j=0}^{n-1} f \circ T^j = h \circ T^n - h$, with the use of Borel-Cantelli lemma.

Remark. Theorem 1.11.1 in the two-sided case: where g depens on $\mathcal{G}_j = T^j(\mathcal{G})$ for $j = \ldots, -1, 0, 1, \ldots$ for an automorphism T, also holds. In (1.11.8) one should replace $\mathcal{G}_0^n$ by $\mathcal{G}_{-n}^n$.

Given two finite partitions $\mathcal{A}$ and $\mathcal{B}$ of a probability space and $\varepsilon \geq 0$ we say that $\mathcal{B}$ is ε-*independent* of $\mathcal{A}$ if there is a subfamily $\mathcal{A}' \subset \mathcal{A}$ such that $\mu(\bigcup \mathcal{A}') > 1 - \varepsilon$ and for every $A \in \mathcal{A}'$

$$\sum_{B \in \mathcal{B}} \left| \frac{\mu(A \cap B)}{\mu(A)} - \mu(B) \right| \leq \varepsilon. \qquad (1.11.13)$$

Given an ergodic measure preserving endomorphism $T : X \to X$ of a Lebesgue space, a finite partition $\mathcal{A}$ is called *weakly Bernoulli* (abbr. WB) if for every $\varepsilon > 0$ there is an $N = N(\varepsilon)$ such that the partition $\bigvee_{j=n}^{s} T^{-j}(\mathcal{A})$ is

ε-independent of the partition $\bigvee_{j=0}^{m} T^{-j}(\mathcal{A})$ for every $0 \leq m \leq n \leq s$ such that $n - m \geq N$.

Of course in the definition of ε-independence we can consider any measurable (maybe uncountable) partition $\mathcal{A}$ and write conditional measures $\mu_A(B)$ in (1.11.13). Then for T an automorphism we can replace in the definition of WB $\bigvee_{j=n}^{s} T^{-j}(\mathcal{A})$ by $\bigvee_{j=0}^{s-n} T^{-j}(\mathcal{A})$ and $\bigvee_{j=0}^{m} T^{-j}(\mathcal{A})$ by $\bigvee_{j=-n}^{m-n} T^{-j}(\mathcal{A})$ and set $n = \infty, n - m \geq N$. WB in this formulation becomes one more version of weak dependence of present (and future) from remote past.

If $\varepsilon = 0$ and $N = 1$ then all partitions $T^{-j}(\mathcal{A})$ are mutually independent (recall that $\mathcal{A}, \mathcal{B}$ are called independent if $\mu(A \cap B) = \mu(A)\mu(B)$ for every $A \in \mathcal{A}, B \in \mathcal{B}$.). We say then that $\mathcal{A}$ is Bernoulli. If $\mathcal{A}$ is a one-sided generator (two-sided generator), then clearly T on $(X, \mathcal{F}, \mu)$ is isomorphic to one-sided (two-sided) Bernoulli shift of $\sharp \mathcal{A}$ symbols, see Chapter 0, Examples 0.10. The following famous theorem of Friedman and Ornstein holds.

Theorem 1.11.4. *If $\mathcal{A}$ is a finite weakly Bernoulli two-sided generating partition of X for an automorphism T, then T is isomorphic to a two-sided Bernoulli shift.*

Of course the standard Bernoulli partition (in particular the number of its states) in the above Bernoulli shift can be different from the image under the isomorphism of the WB partition.

Bernoulli shift above is unique in the sense that all two-sided Bernoulli shifts of the same entropy are isomorphic [Ornstein 1970].

Note that ϕ-mixing in the sense of (1.11.10), with $\phi(n) \to 0$, for $\mathcal{G}$ associated to a finite partition $\mathcal{A}$, implies weak Bernoulli property.

Central Limit Theorem is a much weaker property than LIL. We want to end this Section with a useful abstract theorem that allows us to deduce CLT for g without specifying $\mathcal{G}$. This Theorem similarly as Theorem 1.11.1 can be proved with the use of an approximation by a martingale difference sequence.

Theorem 1.11.5. *Let $(X, \mathcal{F}, \mu)$ be a probability space and $T : X \to X$ an automorphism preserving μ. Let $\mathcal{F}_0 \subset \mathcal{F}$ be a σ-algebra such that $T^{-1}(\mathcal{F}_0) \subset F_0$. Denote $\mathcal{F}_n = T^{-n}(\mathcal{F}_0)$ for all integer $n = \ldots, -1, 0, 1, \ldots$ Let g be a real-valued square integrable function. If*

$$\sum_{n \geq 0} \|E(g|\mathcal{F}_n) - Eg\|_2 + \|g - E(g|\mathcal{F}_{-n})\|_2 < \infty, \qquad (1.11.14)$$

then g satisfies CLT.

Exercises

Ergodic theorems, ergodicity

1.1. Prove that for any two σ-algebras $\mathcal{F} \supset \mathcal{F}'$ and ϕ an $\mathcal{F}$-measurable function, the conditional expectation value operator $L^p(X, \mathcal{F}, \mu) \ni \phi \rightarrow E(\phi|\mathcal{F}')$ has norm 1 in L^p, for every $1 \le p \le \infty$.

Hint: Prove that $E((\vartheta \circ |\phi|)|\mathcal{F}') \ge \vartheta \circ E((|\phi|)|\mathcal{F}')$ for convex ϑ, in particular for $t \mapsto t^p$.

1.2. Prove that if $S : X \rightarrow X'$ is a measure preserving surjective map for measure spaces $(X, \mathcal{F}, \mu)$ and $(X', \mathcal{F}', \mu')$ and there are measure preserving endomorphisms $T : X \rightarrow X$ and $T' : X' \rightarrow X'$ satisfying $S \circ T = T' \circ S$, then T ergodic implies T' ergodic, but not *vice versa*. Prove that if $(X, \mathcal{F}, \mu)$ is Rohlin's natural extension of $(X', \mathcal{F}', \mu')$, then $(X', \mathcal{F}', \mu')$ implies $(X, \mathcal{F}, \mu)$ ergodic.

1.3. (a) Prove Maximal Ergodic Theorem: Let $f \in L^1(\mu)$ for T a measure preserving endomorphism of a probability space $(X, \mathcal{F}, \mu)$. Then for $A := \{x : \sup_{n \ge 0} \sum_{i=0}^{n} f(T^i(x)) > 0\}$ it holds $\int_A f \ge 0$.
(b) Note that this implies the Maximal Inequality for the so-called maximal function $f^* := \sup_{n \ge 1} \frac{1}{n} \sum_{i=0}^{n-1} f(T^i(x))$:

$$\mu(\{f^* > \alpha\}) \le \frac{1}{\alpha} \int_{\{f^* > \alpha\}} f \, d\mu, \quad \text{for every real } \alpha.$$

(c) Deduce Birkhoff's Ergodic Theorem.

Hint: One can proceed directly. Another way is to prove first the a.e. convergence on a set D of functions dense in L^1. Decomposed functions in L^2 in sums $g = h_1 + h_2$, where h_1 is T invariant in the case T is an automorphism (i.e. $h_1 = h_1 \circ T$) and $h_2 = -g \circ T + g$. Consider only $g \in L^\infty$. If T is not an automorphism, $h_1 = U^*(h_1)$ for U^* being conjugate to the Koopman operator $U(f) = f \circ T$, compare Sections 4.2 and 4.7. To pass to the closure of D use the Maximal Inequality. One can also just refer to the Banach Principle below. Its assumption $\sup_n |T_n f| < \infty$ a.e. for $T_n f = \frac{0}{n-1} \sum_{k=0}^{n-1} f \circ T^k$, follows from the Maximal Inequality. See [Petersen 1983].

1.4. Prove the Banach Principle: Let $1 \le p < \infty$ and let $\{T_n\}$ be a sequence of bounded linear operators on L^p. If $\sup_n |T_n f| < \infty$ a.e. for each $f \in L^p$ then the set of f for which $T_n f$ converges a.e. is closed in L^p.

1.5. Let $(X, \mathcal{F}, \mu)$ be a probability space, let $\mathcal{F}_1 \subset \mathcal{F}_2 \subset \cdots \subset \mathcal{F}$ be an increasing to $\mathcal{F}$ sequence of σ-algebras and $\phi \in L^p$, $1 \le p \le \infty$. Prove Martingale Convergence Theorem in the version of Theorem 1.1.4, saying that $\phi_n := E(\phi|\mathcal{F}_n) \rightarrow E(\phi|\mathcal{F})$ a.e. and in L^p.

Steps:

1) Prove: $\mu\{\max_{i \le n} \phi_i > \alpha\} \le \frac{1}{\alpha} \int_{\{\max_{i \le n} \phi_i > \alpha\}} \phi_n \, d\mu$. (Hint: decompose $X = \bigcup_{k=1}^{n} A_k$ where $A_k := \{\max_{i < k} \phi_i \le \alpha < \phi_k\}$ and use Tchebyshev inequality on each A_k. Compare Lemma 1.5.1).

2) Use Banach Principle checking first the convergence a.e. on the set of indicator functions on each $\mathcal{F}_n$.

1.6. For a Lebesgue integrable function $f : \mathbb{R} \rightarrow \mathbb{R}$ the Hardy-Littlewod maximal function is

$$Mf(t) = \sup_{\varepsilon > 0} \frac{1}{2\varepsilon} \int_{-\varepsilon}^{\varepsilon} |f(t+s)| \, ds.$$

(a) Prove the Maximal Inequality of F. Riesz $m(\{x \in \mathbb{R} : Mf(x) > \alpha\}) \leq \frac{2}{\alpha}\|f\|_1$, for every $\alpha > 0$, where m is the Lebesgue measure.

(b) Prove the Lebesgue Differentiation Theorem: For a.e. t

$$\lim_{\varepsilon \to 0} \frac{1}{2\varepsilon} \int_{-\varepsilon}^{\varepsilon} |f(t+s)|\, ds = f(t).$$

Hint: Use Banach Principle (Exercise 1.4) using the fact that the above equality holds on the set of differentiable functions, which is dense in L^1.

(c) Generalize this theory to $f : \mathbb{R}^d \to R$, $d > 1$; the constant 2 is then replaced by another constant resulting from Besicovitch Covering Theorem, see Chapter 7.

Lebesgue spaces, measurable partitions

1.7. Let T be an ergodic automorphism of a probability non-atomic measure space and $\mathcal{A}$ its partition into orbits $\{T^n(x), n = \ldots, -1, 0, 1 \ldots\}$. Prove that $\mathcal{A}$ is not measurable.

Suppose we do not assume ergodicity of T. What is the largest measurable partition, smaller than the partition into orbits? (Hint: Theorem 1.8.11.)

1.8. Prove that the following partitions of measure spaces are not measurable:

(a) Let $T : S^1 \to S^1$ be a mapping of the unit circle with Haar (length) measure defined by $T(z) = e^{2\pi i \alpha} z$ for an irrational α. $\mathcal{P}$ is the partition into orbits;

(b) T is the automorphism of the 2-dimensional torus $\mathbb{R}^2/\mathbb{Z}^2$, given by a hyperbolic integer matrix of determinant 1. Let $\mathcal{P}$ be the partition into stable, or unstable, lines (i.e. straight lines parallel to an eigenvector of the matrix);

(c) Let $T : S^1 \to S^1$ be defined by $T(z) = z^2$. Let $\mathcal{P}$ be the partition into *grand orbits*, i.e. equivalence classes of the relation $x \sim y$ iff $\exists m, n \geq 0$ such that $T^m(x) = T^n(y)$.

1.9. Prove that every Lebesgue space is isomorphic to the unit interval equipped with the Lebesgue measure together with countably many atoms.

1.10. Prove that every separable complete metrisable (Polish) space with a measure on the σ-algebra containing all open sets, minimal among complete measures, is Lebesgue space.

Hint: [Rohlin 1949, 2.7].

1.11. Let $(X, \mathcal{F}, \mu)$ be a Lebesgue space. Then $Y \subset X, \mu_e(Y) > 0$ is measurable iff $(Y, \mathcal{F}_Y, \mu_Y)$ is a Lebesgue space, where μ_e is the outer measure, $\mathcal{F}_Y = \{A \cap Y : A \in \mathcal{F}\}$ and $\mu_Y(A) = \frac{\mu_e(A \cap Y)}{\mu_e(Y)}$.

Hint: If $\mathbf{B} = (B_n)$ is a basis for $(X, \mathcal{F}, \mu)$, then $(B'_n) = (B_n \cap Y)$ is a basis for $(Y, \mathcal{F}_Y, \mu_Y)$. Add to Y one point for each sequence $(B'_n{}^{\varepsilon_n})$ whose intersection is missing in Y and in the space $\tilde{Y}$ obtained in such a way generate complete measure space $(\tilde{Y}, \tilde{\mathcal{F}}, \tilde{\mu})$ from the extension $\tilde{\mathbf{B}}$ of the basis (B'_n). Borel sets with respect to $\mathbf{B}$ in X correspond to Borel sets with respect to $\tilde{\mathbf{B}}$ and sets of μ

measure 0 correspond to sets of $\tilde{\mu}$ measure 0. So measurability of Y implies $\tilde{\mu}(\tilde{Y} \setminus Y) = 0$.

1.12. Prove Theorem1.6.6.

Hint: In the case when both spaces are unit intervals with standard Lebesgue measure, consider all intervals J' with rational endpoints. Each $J = T^{-1}(J')$ is contained in a Borel set B_J with $\mu(B_J \setminus J) = 0$. Remove from X a Borel set of measure 0 containing $\bigcup_J (B_J \setminus J)$. Then T becomes a Borel map, hence it is a Baire function, hence due to the injectivity it maps Borel sets to Borel sets.

1.13. (a) Consider the unit square $[0,1] \times [0,1]$ equipped with Lebesgue measure. For each $x \in [0,1]$ let $\mathcal{A}_x$ be the partition into points (x', y) for $x' \neq x$ and the interval $\{x\} \times [0,1]$. What is $\bigwedge_x \mathcal{A}_x$? Let $\mathcal{B}_x$ be the partition into the intervals $\{x'\} \times [0,1]$ for $x' \neq x$ and the points $\{(x,y) : y \in [0,1]\}$. What is $\bigvee_x \mathcal{B}_x$?

(b) Find two measurable partitions $\mathcal{A}, \mathcal{A}'$ of a Lebesgue space such that their set-theoretic intersection (i.e. the largest partition such that $\mathcal{A}, \mathcal{A}'$ are finer than this partition) is not measurable.

1.14. Prove that if $F : X \to X$ is an ergodic endomorphism of a Lebesgue space then its natural extension is also ergodic.

Hint: See [Kornfeld , Fomin & Sinai 1982, Sec.10.4].

1.15. Find an example of $T : X \to X$ an endomorphism of a probability space $(X, \mathcal{F}, \mu)$, injective and onto, such that for the system $\cdots \xrightarrow{T} X \xrightarrow{T} X$, natural extension does not exist.

Hint: Set X to be the unit circle and T irrational rotation. Let A be a set consisting of exactly one point in each T-orbit. Set $B = \bigcup_{j \geq 0} T^j(A)$. Notice that B is not Lebesgue measurable and that the outer measure of B is 1 (use *unique ergodicity* of T, i.e. that (1.2.2) holds for every x)

Let $\mathcal{F}$ be the σ-algebra consisting of all the sets $C = B \cap D$ for D Lebesgue measurable, set $\mu(C) = \mathrm{Leb}(D)$, and for $C \subset X \setminus B$, set $\mu(C) = 0$. Note that $\bigcap_{n \geq 0} T^n(B) = \emptyset$ and in the set-theoretic inverse limit the set $\pi_{-n}^{-1}(B) = \pi_0^{-1}(T^n(B))$ would be of measure 1 for every $n \geq 0$.

Entropy, generators, mixing

1.16. Prove Theorem 1.4.7 provided $(X, \mathcal{F}, \rho)$ is a Lebesgue space, using Theorem 1.8.11 (ergodic decomposition theorem) for ρ.

1.17. (a) Prove that in a Lebesgue space $d(\mathcal{A}, \mathcal{B}) := H(\mathcal{A}|\mathcal{B}) + H(\mathcal{B}|\mathcal{A})$ is a metric in the space Z of countable partitions (mod 0) of finite entropy. Prove that the metric space (Z, d) is separable and complete.

(b) Prove that if T is an endomorphism of the Lebesgue space, then the function $\mathcal{A} \to \mathrm{h}(T, \mathcal{A})$ is continuous for $\mathcal{A} \in Z$ with respect to the above metric d.

Hint: $|\mathrm{h}(T, \mathcal{A}) - \mathrm{h}(T, \mathcal{B})| \leq \max\{\mathrm{H}(\mathcal{A}|\mathcal{B}), \mathrm{H}(\mathcal{B}|\mathcal{A})\}$. Compare the proof of Th. 1.4.5.

1.18. (a) Let $d_0(\mathcal{A}, \mathcal{B}) := \sum_i \mu(A_i \div B_i)$ for partitions of a probability space into r measurable sets $\mathcal{A} = \{A_i, i = 1, \ldots, r\}$ and $\mathcal{B} = \{B_i, i = 1, \ldots, r\}$. Prove

that for every r and every $d > 0$ there exists $d_0 > 0$ such that if $\mathcal{A}, \mathcal{B}$ are partitions into r sets and $d_0(\mathcal{A}, \mathcal{B}) < d_0$, then $d(\mathcal{A}, \mathcal{B}) < d$

(b)   Using (a) give a simple proof of Corollary 1.8.10. (Hint: Given an arbitrary finite $\mathcal{A}$ construct $\mathcal{B} \leq \mathcal{B}_m$ so that $d_0(\mathcal{A}, \mathcal{B})$ be small for m large. Next use (a) and Theorem 1.4.4(d)).

1.19.   Prove that there exists a finite one-sided generator for every T, a continuous positively expansive map of a compact metric space (see the definition of *positively expansive* in Ch.2, Sec.5).

1.20.   Compute the entropy h(T) for Markov chains, see Chapter 0.

1.21.   Prove that the entropy h(T) defined either as supremum of h$(T, \mathcal{A})$ over finite partitions, or over countable partitions of finite entropy, or as $\sup H(\xi|\xi^-)$ over all measurable partitions ξ that are forward invariant (i.e. $T^{-1}(\xi) \leq \xi$), is the same.

1.22.   Let T be an endomorphism of the 2-dimensional torus $\mathbb{R}^2/\mathbb{Z}^2$, given by an integer matrix of determinant larger than 1 and with eigenvalues λ_1, λ_2 such that $|\lambda_1| < 1$ and $|\lambda_2| > 1$. Let S be the endomorphism of $\mathbb{R}^2/\mathbb{Z}^2$ being the Cartesian product of $S_1(x) = 2x \pmod 1$ on the circle $\mathbb{R}/\mathbb{Z}$ and of $S_2(y) = y + \alpha$ $\pmod 1$, the rotation by an irrational angle α. Which of the maps T, S is exact? Which has a countable one-sided generator of finite entropy?

Answer: T does not have the generator, but it is exact. The latter holds because for each small parallelepiped P spanned by the eigendirections there exists n such that $T^n(P)$ covers the torus with multiplicity bounded by a constant not depending on P. This follows from the fact that λ_j are algebraic numbers and from Roth's theorem about Diophantine approximation. S is not exact, but it is ergodic and has a generator.

1.23.   (a) Prove that ergodicity of an endomorphism $T : X \to X$ for a probability space $(X, \mathcal{F}, \mu)$ is equivalent to the non-existence of a non-constant measurable function ϕ such that $U_T(\phi) = \phi$, where U_T is Koopman operator, see 1.2.1 and notes following it.

(b) Prove that for an automorphism T, weak mixing is equivalent to the non-existence of a non-constant eigenfunction for U_T acting on $L^2(X, \mathcal{F}, \mu)$.

(c) Prove that if T is a K-mixing automorphism then $L^2 \ominus$constant functions decomposes in a countable product of pairwise orthogonal U_T-invariant subspaces H_i each of which contains h_i such that for each i all $U_T^j(h_i), j \in \mathbb{Z}$ are pairwise orthogonal and span H_i. (This property is called: countable Lebesgue spectrum.)

Hint: use condition (d) in 1.10.1

1.24.   Prove that if the definition of partition $\mathcal{A}$ ε-independent of partition $\mathcal{B}$ is replaced by $\sum_{A \in \mathcal{A}, B \in \mathcal{B}} |\mu(A \cap B) - \mu(A)\mu(B)|$, then the definition of weakly Bernoulli is equivalent to the old one. (Note that now the expression is symmetric with respect to $\mathcal{A}, \mathcal{B}$.)

Bibliographical notes

For the Martingale Convergence Theorem see for example [Doob 1953], [Billingsley 1979], [Petersen 1983] or [Stroock 1993]. Its standard proofs go via a *maximal function*, see Exercise 1.5. We borrowed the idea to rely on Banach Principle in Exercise 1.4, from [Petersen 1983]. We followed the way to use a maximal inequality in Proof of Shannon, McMillan, Breiman Theorem in Section 1.5, Lemma 1.5.1, where we relied on [Petersen 1983] and [Parry 1969]. Remark 1.1.5 is taken from [Neveu 1964, Ch. 4.3], see for example [Hoover 1991] for a more advanced theory. In Exercises 1.3-1.6 we again took the idea to rely on Banach Principle from [Petersen 1983].

   Standard proofs of Birkhoff's Ergodic Theorem also use the idea of maximal function. This concerns in particular the extremaly simple proof in Section 1.2, which has been taken from [Katok & Hasselblatt 1995]. It uses famous Garsia's proof of the Maximal Ergodic Theorem.

   Koopman's operator was introduced by Koopman in the L^2 setting in [Koopman 1931].

   For the material of Section 1.6 and related exercises see [Rohlin 1949]. It is also written in an elegant and a very concise way in [Cornfeld, Fomin & Sinai 1982].

   The consideration in Section 1.7 leading to the extension of the compatible family $\tilde{\mu}_{\Pi,n}$ to $\tilde{\mu}_\Pi$ is known as Kolmogorov Extension Theorem (or Kolmogorov Theorem on the existence of stochastic process). First, one verifies the σ-additivity of a measure on an algebra, next uses the Extension Theorem 1.7.2. Our proof of σ-additivity of $\tilde{\mu}$ on $\tilde{X}$ via Lusin theorem is also a variant of Kolmogorov's proof. The proofs of σ-additivity on algebras depend unfortunately on topological concepts. Halmos wrote [Halmos 1950, p. 212]: "this peculiar and somewhat undesirable circumstance appears to be unavoidable" Indeed the σ-additivity may be not true, see [Halmos 1950, p. 214]. Our example of non-existence of natural extension, Exercise 1.15, is in the spirit of Halmos' example. There might be troubles even with extending a measure from cylinders in product of two measure spaces, see [Marczewski & Ryll-Nardzewski 1953] for a counterexample. On the other hand product measures extend to generated σ-algebras without any additional assumptions [Halmos 1950], [Billingsley 1979].

   For Th. 1.9.1: the existence of a countable partition into cross-sections, see [Rohlin 1949]; for bounds of its entropy, see for example [Rohlin 1967, Th. 10.2], or [Parry 1969]. The simple proof of Th. 1.8.6 via convergence in measure has been taken from [Rohlin 1967] and [Walters 1982]. Proof of Th. 1.8.11(b) is taken from [Rohlin 1967, sec. 8.10-11 and 9.8].

   For Th. 1.9.6 see [Parry 1969, L. 10.5]; our proof is different. For the construction of a one-sided generator and a 2-sided generator see again [Rohlin 1967], [Parry 1969] or [Cornfeld, Fomin & Sinai 1982]. The same are references to the theory of measurable invariant partitions: exhausting and extremal, and to Pinsker partition, which we omitted because we do not need these notions further in the book, but which are fundamental to understand deeper the measure-theoretic entropy theory. Finally we encourage the reader to become acquainted with spectral theory of dynamical systems, in particular in relation to mixing properties; for an introduction see for example [Cornfeld, Fomin & Sinai 1982],

[Parry 1981] (in particular Appendix), [Walters 1982].

Th. 1.11.1 can be found in [Philipp, Stout 1975]. See also [Przytycki, Urbański & Zdunik 1989]. For (1.11.9) see [Ibragimov 1962, 1.1.2] or [Billingsley 1968]. For Th. 1.11.3 see [Leonov 1961], [Ibragimov 1962, 1.5.2] or [Przytycki, Urbański & Zdunik 1989, Lemma 1]. Theorem 1.11.5 can be found in [Gordin 1969]. We owe the idea of the proof of the exactness via Roth's theorem in 1.22 to Wieslaw Szlenk. Generalizations to higher dimensions lead to Wolfgang Schmidt's Diophantine Approximation Theorem.

Chapter 2

Ergodic theory on compact metric spaces

In the previous chapter a measure preserved by a measurable map T was given *a priori*. Here a continuous mapping T of a topological compact space is given and we look for various measures preserved by T. Given a real continuous function ϕ on X we try to maximize the functional *measure theoretical entropy* *+integral*, i.e. $h_\mu(T) + \int \phi \, d\mu$. Supremum over all probability measures on the Borel σ-algebra turns out to be *topological pressure*, similar to P in the prototype lemma on the finite space or $P(\alpha)$ for ϕ_α on the Cantor set discussed in the Introduction. We discuss equilibria, namely measures on which supremum is attained. This chapter provides an introduction to the theory called *thermodynamical formalism*, which will be the main technical tool in this book. We will continue to develop the thermodynamical formalism in more specific situations in Chapter 4.

2.1 Invariant measures for continuous mappings

We recall in this section some basic facts from functional analysis needed to study the space of measures and invariant measures. We recall Riesz Representation Theorem, weak* topology, Schauder Fixed Point Theorem. We recall also Krein-Milman theorem on extremal points and its stronger form: Choquet representation theorem. This gives a variant of Ergodic Decomposition Theorem from Chapter 1.

Let X be a topological space. The *Borel σ-algebra* $\mathcal{B}$ of subsets of X is defined to be generated by open subsets of X. We call every probability measure on the Borel σ-algebra of subsets of X, a *Borel probability measure* on X. We denote the set of all such measures by $M(X)$.

Denote by $C(X)$ the Banach space of real-valued continuous functions on X with the supremum norm: $\sup |\phi| := \sup_{x \in X} |\phi(x)|$. Sometimes we shall use the notation $||\phi||_\infty$, introduced in Section 1.1 in $L^\infty(\mu)$, though it is compatible

only if μ is positive on open sets, even in absence of μ.

Note that each Borel probability measure μ on X induces a bounded linear functional F_μ on $C(X)$ defined by the formula

$$F_\mu(\phi) = \int \phi \, d\mu. \qquad (2.1.1)$$

One can extend the notion of measure and consider σ-additive set functions, known as *signed measures*. Just in the definition of measure from Section 1.1 consider $\mu : \mathcal{F} \to [-\infty, \infty)$ or $\mu : \mathcal{F} \to (-\infty, \infty]$ and keep the notation $(X, \mathcal{F}, \mu)$ from Ch.1. The set of signed measures is a linear space. On the set of finite signed measures, namely with the range $\mathbb{R}$, one can introduce the following total variation norm:

$$v(\mu) := \sup\left\{ \sum_{i=1}^{n} |\mu(A_i)| \right\},$$

where the supremum is taken over all finite sequences (A_i) of disjoint sets in $\mathcal{F}$.

It is easy to prove that every finite signed measure is bounded and that it has finite total variation. It is also not difficult to prove the following

Theorem 2.1.1 (Hahn-Jordan decomposition). *For every signed measure μ on a σ-algebra $\mathcal{F}$ there exists $A_\mu \in \mathcal{F}$ and two measures μ^+ and μ^- such that $\mu = \mu^+ - \mu^-, \mu^-$ is zero on all measurable subsets of A_μ and μ^- is zero on all measurable subsets of $X \setminus A_\mu$.*

Notice that $v(\mu) = \mu^+(X) + \mu^-(X)$.

A measure (or signed measure) is called *regular*, if for every $A \in \mathcal{F}$ and $\varepsilon > 0$ there exist $E_1, E_2 \in \mathcal{F}$ such that $\overline{E}_1 \subset A \subset \mathrm{Int} E_2$ and for every $C \in \mathcal{F} with C \subset E_2 \setminus E_1$, we have $|\mu(C)| < \varepsilon$.

If X is a topological space, denote the space of all regular finite signed measures with the total variation norm, by $\mathrm{rca}(X)$. The abbreviation rca replaces *regular countably additive*.

If $\mathcal{F} = \mathcal{B}$, the Borel σ-algebra, and X is metrizable, regularity holds for every finite signed measure. It can be proved by Carathéodory's outer measure argument, compare the proof of Corollary 1.8.10.

Denote by $C(X)^*$ the space of all bounded linear functionals on $C(X)$. This is called the *dual space* (or *conjugate space*). *Bounded* means here bounded on the unit ball in $C(X)$, which is equivalent to *continuous*. The space $C(X)^*$ is equipped with the norm $||F|| = \sup\{F(\phi) : \phi \in C(X), |\phi| \leq 1\}$, which makes it a Banach space.

There is a natural order in $\mathrm{rca}(X)$: $\nu_1 \leq \nu_2$ iff $\nu_2 - \nu_1$ is a measure.

Also in the space $C(X)^*$ one can distinguish positive functionals, similarly to measures amongst signed measures, as those which are non-negative on the set of functions $C^+(X) := \{\phi \in C(X) : \phi(x) \geq 0 \text{ for every } x \in X\}$. This gives the order: $F \leq G$ for $F, G \in C(X)^*$ iff $G - F$ is positive.

Remark that $F \in C(X)^*$ is positive iff $||F|| = F(\mathbb{1})$, where $\mathbb{1}$ is the function on X identically equal to 1. Also for every bounded linear operator $F : C(X) \to C(X)$ which is positive, namely $F(C^+(X)) \subset C^+(X)$, we have $||F|| = |F(\mathbb{1})|$.

Remark that (2.1.1) transforms measures to positive linear functionals.

The following fundamental theorem of F. Riesz says more about the transformation $\mu \mapsto F_\mu$ in (2.1.1) (see [Dunford & Schwartz 1958, pp. 373,380] for the history of this theorem):

Theorem 2.1.2 (Riesz representation theorem). *If X is a compact Hausdorff space, the transformation $\mu \mapsto F_\mu$ defined by (2.1.1) is an isometric isomorphism between the Banach space $C(X)^*$ and $rca(X)$. Furthermore this isomorphism preserves order.*

In the sequel we shall often write μ instead of F_μ and *vice versa* and $\mu(\phi)$ or $\mu\phi$ instead of $F_\mu(\phi)$ or $\int \phi \, d\mu$.

Notice that in Theorem 2.1.2 the hard part is the existence, i.e. that for every $F \in C(X)^*$ there exists $\mu \in \mathrm{rca}(X)$ such that $F = F_\mu$. The uniqueness is just the following:

Lemma 2.1.3. *If μ and ν are finite regular Borel signed measures on a compact Hausdorff space X, such that $\int \phi \, d\mu = \int \phi \, d\nu$ for each $\phi \in C(X)$, then $\mu = \nu$.*

Proof. This is an exercise on the use the regularity of μ and ν. Let $\eta := \mu - \nu = \eta^+ - \eta^-$ in the Hahn-Jordan decomposition. Suppose that that $\mu \neq \nu$. Then η^+ (or η^-) is non-zero, say $\eta^+(X) = \eta^+(A_\eta) = \varepsilon > 0$, where A_η is the set defined in Theorem 2.1.1. Let E_1 be a closed set and E_2 be an open set, such that $E_1 \subset A_\eta \subset E_2$, $\eta^-(E_2 \setminus A_\eta) < \varepsilon/2 \, and \, \eta^+(A_\eta \setminus E_1) < \varepsilon/2$. There exists $\phi \in C(X)$ with values in $[0,1]$ identically equal 1 on E_1 and 0 on $X \setminus E_2$. Then

$$
\begin{aligned}
\int \phi \, d\eta &= \int_{E_1} \phi \, d\eta + \int_{A_\eta \setminus E_1} \phi \, d\eta + \int_{E_2 \setminus A_\eta} \phi \, d\eta + \int_{X \setminus E_2} \phi \, d\eta \\
&= \int_{E_1} \phi \, d\eta^+ + \int_{A_\eta \setminus E_1} \phi \, d\eta^+ - \int_{E_2 \setminus A_\eta} \phi \, d\eta^- \\
&\geq \eta^+(E_1) - \int_{E_2 \setminus A_\eta} \phi \, d\eta^- \\
&\geq \varepsilon - \varepsilon/2 > 0. \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (2.1.2)
\end{aligned}
$$

♣

The space $C(X)^*$ can be also equipped with the weak* topology. In the case where X is *metrizable*, i.e. if there exists a metric on X such that the topology induced by this metric is the original topology on X, weak* topology is characterized by the property that a sequence $\{F_n : n = 1, 2, \ldots\}$ of functionals in $C(X)^*$ converges to a functional $F \in C(X)^*$ if and only if

$$
\lim_{n \to \infty} F_n(\phi) = F(\phi) \quad\quad\quad\quad\quad\quad\quad\quad (2.1.3)
$$

for every function $\phi \in C(X)$.

If we do not assume X to be metrizable, weak* topology is defined as the smallest one in which all elements of $C(X)$ are continuous on $C(X)^*$ (recall that

$\phi \in C(X)$ acts on $F \in C(X)^*$ by $F(\phi)$). One says *weak** to distinguish this topology from the *weak topology* where one considers all continuous functionals on $C(X)^*$ and not only those represented by $f \in C(X)$. This discussion of topologies concerns of course every Banach space B and its dual B^*.

Using the bijection established by Riesz representation theorem we can move the weak* topology from $C(X)^*$ to rca(X) and restrict it to $M(X)$. The topology on $M(X)$ obtained in this way is usually called the *weak* topology* on the space of probability measures (sometimes one omits * to simplify the language and notation but one still has in mind weak*, unless stated otherwise). In view of (2.1.3), if X is metrizable, this topology is characterized by the property that a sequence $\{\mu_n : n = 1, 2, \ldots\}$ of measures in $M(X)$ converges to a measure $\mu \in M(X)$ if and only if

$$\lim_{n \to \infty} \mu_n(\phi) = \mu(\phi) \tag{2.1.4}$$

for every function $\phi \in C(X)$. Such convergence of measures will be called *weak* convergence* or *weak convergence* and can be also characterized as follows.

Theorem 2.1.4. *Suppose that X is metrizable (we do not assume compactness here). A sequence $\{\mu_n : n = 1, 2, \ldots\}$, of Borel probability measures on X converges weakly to a measure μ if and only if $\lim_{n \to \infty} \mu_n(A) = \mu(A)$ for every Borel set A such that $\mu(\partial A) = 0$.*

Proof. Suppose that $\mu_n \to \mu$ and $\mu(\partial A) = 0$. Then there exist sets $E_1 \subset \operatorname{Int} A$ and $E_2 \supset \overline{A}$ such that $\mu(E_2 \setminus E_1) = \varepsilon$ is arbitrarily small. Indeed metrizability of X implies that every open set, in particular int$A$, is the union of a sequence of closed sets and every closed set is the intersection of a sequence of open sets. For example $\operatorname{Int} A = \bigcup_{n=1}^{\infty} \{x \in X : \inf_{z \notin \operatorname{int} A} \rho(x, z) \geq 1/n\}$ for a metric ρ.

Next, there exist $f, g \in C(X)$ with range in the unit interval $[0, 1]$ such that f is identically 1 on E_1, 0 on $X \setminus \operatorname{int} A$, g identically 1 on cl A and 0 on $X \setminus E_2$. Then $\mu_n(f) \to \mu(f)$ and $\mu_n(g) \to \mu(g)$. As $\mu(E_1) \leq \mu(f) \leq \mu(g) \leq \mu(E_2)$ and $\mu_n(f) \leq \mu_n(A) \leq \mu_n(g)$ we obtain

$$\mu(E_1) \leq \mu(f) = \lim_{n \to \infty} \mu_n(f) \leq \liminf_{n \to \infty} \mu_n(A)$$
$$\leq \limsup_{n \to \infty} \mu_n(A) \leq \lim_{n \to \infty} \mu_n(g) = \mu(g) \leq \mu(E_2).$$

As also $\mu(E_1) \leq \mu(A) \leq \mu(E_2)$, letting $\varepsilon \to 0$ we obtain $\lim_{n \to \infty} \mu_n(A) = \mu(A)$.

Proof in the opposite direction follows from the definition of integral: approximate uniformly an arbitrary continuous function f by simple functions $\sum_{i=1}^{k} \varepsilon_i \mathbb{1}_{E_i}$ where $E_i = \{x \in X : \varepsilon_i \leq f(x) < \varepsilon_{i+1}\}$, for an increasing sequence $\varepsilon_i, i = 1, \ldots, k$ such that $\varepsilon_i - \varepsilon_{i-1} < \varepsilon$ and $\mu(f^{-1}(\{\varepsilon_i\})) = 0$, with $\varepsilon \to 0$. It is possible to find such numbers ε_i because only countably many sets $f^{-1}(a)$ for $a \in \mathbb{R}$ can have non-zero measure. ♣

Example 2.1.5. The assumption $\mu(\partial A) = 0$ is substantial. Let X be the interval $[0, 1]$. Denote by δ_x the delta Dirac measure concentrated at the point

x, which is defined by the following formula:

$$\delta_x(A) = \begin{cases} 1, & \text{if } x \in A \\ 0, & \text{if } x \notin A \end{cases}$$

for all sets $A \in \mathcal{B}$.

Consider non-atomic probability measures μ_n supported respectively on the ball $B(x, \frac{1}{n})$. The sequence μ_n converges weakly to δ_x but does not converge on $\{x\}$.

Of particular importance is the following

Theorem 2.1.6. *The space $M(X)$ is compact in the weak* topology.*

This theorem follows immediately from compactness in weak* topology of any subset of $C(X)^*$ closed in weak* topology, which is bounded in the standard norm of the dual space $C(X)^*$ (compare for example [Dunford & Schwartz 1958, V.4.3], where this result is proved for all spaces dual to Banach spaces). $M(X)$ is weak*-closed since it is closed in the dual space norm and convex, by Hahn-Banach theorem. (Caution: convexity is a substantial assumption. Indeed, the unit sphere in an infinite dimensional Banach space for example, is never weak*-closed, as 0 is in its closure.

It turns out (see [Dunford & Schwartz 1958, V.5.1]) that if X is compact metrizable, then every weak*-compact subset of the space $C(X)^*$ with weak* topology is metrizable, hence in particular $M(X)$ is metrizable. (Caution: $C(X)^*$ itself is not metrizable for infinite X. The reason is for example that it does not have a countable basis of topology at 0.)

Let now $T : X \to X$ be a continuous transformation of X. The mapping T is measurable with respect to the Borel σ-algebra. At the very begining of Section 1.2 we have defined T-invariant meaures μ to satisfy the condition $\mu = \mu \circ T^{-1}$. It means that Borel probability T-invariant meaures are exactly the fixed points of the transformation $T_* : M(X) \to M(X)$ defined by the formula $T_*(\mu) = \mu \circ T^{-1}$.

We denote the set of all T-invariant measures in $M(X)$ by $M(X, T)$. This notation is consistent with the notation from Section 1.2. We omit here the σ-algebra $\mathcal{F}$ because it is always the Borel σ-algebra $\mathcal{B}$.

Noting that $\int \phi \, d(\mu \circ T^{-1}) = \int \phi \circ T \, d\mu$ for any $\mu \in M(X)$ and any integrable function ϕ (Proposition 1.2.1), it follows from Lemma 2.1.3 that a Borel probability measure μ is T-invariant if and only if for every continuous function $\phi : X \to \mathbb{R}$

$$\int \phi \, d\mu = \int \phi \circ T \, d\mu. \tag{2.1.5}$$

In order to look for fixed points of T_* one can apply the following very general result whose proof (and the definition of locally convex topological vector spaces, abbreviation: LCTVS) can be found for example in [Dunford & Schwartz 1958] or [Edwards 1995].

Theorem 2.1.7 (Schauder-Tychonoff Theorem [Dunford & Schwartz 1958, V.10.5])**.**
. If K is a non-empty compact convex subset of an LCTVS then any continuous transformation $H : K \to K$ has a fixed point.

Assume from now on that X is compact and metrizable. In order to apply the Schauder-Tychonoff theorem consider the LCTVS $C(X)^*$ with weak* topology and $K \subset C(X)^*$, being the image of $M(X)$ under the identification between measures and functionals, given by the Riesz representation theorem. With this identification we can consider T_* acting on K. Notice that T_* is continuous on $M(X)$ (or K) in the weak* topology. Indeed, if $\mu_n \to \mu$ weakly*, then for every continuous function $\phi : X \to \mathbb{R}$, since $\phi \circ T$ is continuous, we get $\mu_n(\phi \circ T) \to \mu(\phi \circ T)$, i.e. $T_*(\mu_n)(\phi) \to T_*(\mu)(\phi)$, hence $T_*(\mu_n) \to T_*(\mu)$ weakly*.

We obtain

Theorem 2.1.8 (Bogolyubov–Krylov theorem [Walters 1982, 6.9.1])**.** *. If $T : X \to X$ is a continuous mapping of a compact metric space X, then there exists on X a Borel probability measure μ invariant under T.*

Thus, our space $M(X, T)$ is non-empty. It is also weak* compact, since it is closed as the set of fixed points for a continuous transformation.

As an immediate consequence of this theorem and Theorem 1.8.11 (Ergodic Decomposition Theorem), we get the following:

Corollary 2.1.9. *If $T : X \to X$ is a continuous mapping of a compact metric space X, then there exists a Borel ergodic probability measure μ invariant under T.*

We shall use the notation $M_e(X, T)$ for the set of all ergodic measures in $M(X, T)$. Write also $\mathcal{E}(M(X, T))$ for the set of extreme points in $M(X, T)$.

Thus, because of Theorem 1.2.8 and Corollary 2.1.9, we know that $M_e(X, T) = \mathcal{E}(M(X, T)) \neq \emptyset$.

In fact Corollary 2.1.9 can be obtained in a more elementery way without using Theorem 1.8.11. Namely it now immediately follows from Theorem 1.2.8 and the following

Theorem 2.1.10 (Krein–Milman theorem on extremal points [Dunford & Schwartz 1958, V.8.4])**.** *. If K is a non-empty compact convex subset of an LCTVS then the set $\mathcal{E}(K)$ of extreme points of K is nonempty and moreover K is the closure of the convex hull of $\mathcal{E}(K)$.*

Below we state Choquet's representation theorem which is stronger than Krein-Milman theorem. It corresponds to the Ergodic Decomposition Theorem (Theorem 1.8.11). We formulate it in $C(X)^*$ with weak* topology as in [Walters 1982, p. 153]. The reader can find a general LCTVS version in [Phelps 1966]. For example it is sufficient to add to the assumptions of the Krein-Milman theorem, the metrizability of K.

We rely here also on [Ruelle 1978, Appendix A.5], where the reader can find further references.

Theorem 2.1.11 (Choquet representation theorem)**.** *Let K be a nonempty compact convex set in $M(X)$ with weak* topology, for X a compact metric space. Then for every $\mu \in K$ there exists a "mass distribution" i.e. measure $\alpha_\mu \in M(\mathcal{E}(K))$ such that*

$$\mu = \int m\, d\alpha_\mu(m).$$

This integral converges in weak* topology which means that for every $f \in C(X)$

$$\mu(f) = \int m(f)\, d\alpha_\mu(m). \tag{2.1.6}$$

If $T : X \to X$ is a continuous mapping of a compact metric space X, then there

Notice that we have had already the formula analogous to (2.1.6) in Remark 1.6.10.

Notice that Krein-Milman theorem follows from Choquet representation theorem because one can weakly approximate α_μ by measures on $\mathcal{E}(K)$ with finite support (finite linear combinations of Dirac measures).

Exercise. Prove that if we allow α_μ to be supported on the closure of $\mathcal{E}(K)$, then the existence of such α_μ follows from the Krein-Milman theorem.

Example 2.1.12. For $K = M(X)$ we have $\mathcal{E}(K) = \{$Dirac measures on $X\}$. Then $\alpha_\mu\{\delta_x : x \in A\} = \mu(A)$ for every $A \in \mathcal{B}$ defines a Choquet representation for every $\mu \in M(X)$. (Exercise)

Choquet's theorem asserts the existence of α_μ satisfying (2.1.6) but does not claim uniqueness, which is usually not true. A compact closed set K with the uniqueness of α_μ satisfying (2.1.6), for every $\mu \in M(K)$ is called *simplex* (or *Choquet simplex*).

Theorem 2.1.13. *the set $K = M(X)$ or $K = M(X,T)$ for every continuous $T : X \to X$ is a simplex.*

A proof in the case of $K = M(X)$ is very easy, see Example 2.1.12. A proof for $K = M(X,T)$ is not hard either. The reader can look in [Ruelle 1978, A.5.5]. The proof there relies on the fact that two different measures $\mu_1, \mu_2 \in \mathcal{E}(M(X,T))$ are singular (see Theorem 1.2.6). Observe that $||\mu_1 - \mu_2|| = 2$. One proves in fact that for every $\mu_1, \mu_2 \in M(X,T)$, $||\alpha_{\mu_1} - \alpha_{\mu_2}|| = ||\mu_1 - \mu_2||$.

Let us go back to Schauder-Tychonoff theorem (Th 2.1.7). We shall use it in this book later, in Section 4.2, for maps different from T_*. Just Bogolyubov-Krylov theorem proved above with the help of Theorem 2.1.7, has a different more elementary proof due to the fact that T_* is affine. A general theorem on the existence of a fixed point for a family of commuting continuous affine maps on K is called Markov-Kakutani theorem , [Dunford & Schwartz 1958, V.10.6], [Walters 1982, 6.9]).

Remark 2.1.14. An alternative proof of Theorem 2.1.8. Take an arbitrary $\nu \in M(X)$ and consider the sequence

$$\mu_n = \mu_n(\nu) = \frac{1}{n} \sum_{j=0}^{n-1} T_*^j(\mu)$$

In view of Theorem 2.1.4, it has a weakly convergent subsequence, say $\{\mu_{n_k} : k = 1, 2, \ldots\}$. Denote its limit by μ. We shall show that μ is T-invariant.

We have

$$T_*(\mu_{n_k}) = T_* \left(\frac{1}{n_k} \sum_{j=0}^{n_k-1} T_*^j(\nu) \right) = \left(\frac{1}{n_k} \sum_{j=0}^{n_k-1} T_*^{j+1}(\nu) \right)$$

So for every $\phi \in C(X)$ we have

$$\left| \mu(\phi) - T_*(\mu(\phi)) \right| = \left| \lim_{k \to \infty} \left(\mu_{n_k}(\phi) - T_*(\mu_{n_k})(\phi)| \right) \right| \leq$$

$$\lim_{k \to \infty} \frac{1}{n_k} |\nu(\phi) - T_*^{n_k}(\nu)(\phi)| \leq \lim_{k \to \infty} \frac{2}{n_k} ||\phi||_\infty = 0.$$

This in view of Lemma 2.1.3 finishes the proof.

Remark 2.1.15. If in the above proof we consider $\nu = \delta_x$, a Dirac measure, then $T_*^j(\delta_x) = \delta_{T^j(x)}$ and $\mu_n(\phi) = \frac{1}{n} \sum_{j=0}^{n-1} \phi(T^j(x))$. If we have *a priori* $\mu \in M(X, T)$ then

$$\mu_n(\delta_x) = \frac{1}{n} \sum_{j=0}^{n-1} \delta_{T^j(x)}$$

is weakly convergent for μ-a.e.$x \in X$ by Birkhoff's Ergodic Theorem.

Remark 2.1.16. Recall that in Birkhoff's Ergodic Theorem (Chapter 1), for $\mu \in M(X, T)$ for every integrable function $\phi : X \to \mathbb{R}$ one considers $\lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} \phi(T^j(x))$ for a.e. x. This "almost every" depends on ϕ. If X is compact, as it is the case in this chapter, one can reverse the order of quantifiers for continuous functions.

Namely there exists $\Lambda \in \mathcal{B}$ such that $\mu(\Lambda) = 1$ and for every $\phi \in C(X)$ and $x \in \Lambda$ the limit $\lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} \phi(T^j(x))$ exists.

Remark 2.1.17. We could take in Remark 2.1.14 an arbitrary sequence $\nu_n \in M(X)$ and take $\mu_n := \mu_n(\nu_n)$. This gives a general method of constructing measures in the space $M(X, T)$, see for example the proof of Variational Principle in Section 2.5. This point of view is taken from [Walters 1982].

We end this Section with the following lemma useful in the sequel.

Lemma 2.1.18. *For every finite partition* P *of the space* $(X, \mathcal{B}, \mu)$, *with* X *a compact metric space,* $\mathcal{B}$ *the Borel* σ-*algebra and* $\mu \in M(X, T)$, *if* $\sum_{A \in \mathrm{P}} \mu(\partial A) = 0$, *then the entropy* $\mathrm{H}_\nu(\mathrm{P})$ *is a continuous function of* $\nu \in M(X, T)$ *at* μ. *The entropy* $\mathrm{h}_\nu(T, \mathrm{P})$ *is upper semicontinuous at* μ.

Proof. The continuity of $\mathrm{H}_\nu(\mathrm{P})$ follows immediately from Theorem 2.1.4. This fact applied to the partitions $\bigvee_{i=1}^{n-1} T^{-i}\mathrm{P}$ gives the upper semicontinuity of $\mathrm{h}_\nu(T, \mathrm{P})$ being the limit of the decreasing sequence of continuous functions $\frac{1}{n}\mathrm{H}_\nu(\bigvee_{i=1}^{n-1} T^{-i}\mathrm{P})$. See Lemma 1.4.3. ♣

2.2 Topological pressure and topological entropy

This section is of topological character and no measure is involved. We introduce and examine here some basic topological invariants coming from thermodynamic formalism of statistical physics.

Let $\mathcal{U} = \{A_i\}_{i \in I}$ and $\mathcal{V} = \{B_j\}_{j \in J}$ be two covers of a compact metric space X. We define the new cover $\mathcal{U} \vee \mathcal{V}$ putting

$$\mathcal{U} \vee \mathcal{V} = \{A_i \cap B_j : i \in I, j \in J\} \tag{2.2.1}$$

and we write

$$\mathcal{U} \prec \mathcal{V} \Longleftrightarrow \forall_{j \in J} \exists_{i \in I} B_j \subset A_i \tag{2.2.2}$$

Let, as in the previous section, $T : X \to X$ be a continuous transformation of X. Let $\phi : X \to \mathbb{R}$ be a continuous function, frequently called *potential*, and let $\mathcal{U}$ be a finite, open cover of X. For every integer $n \geq 1$, we set

$$\mathcal{U}^n = \mathcal{U} \vee T^{-1}(\mathcal{U}) \vee \ldots \vee T^{-(n-1)}(\mathcal{U}),$$

for every set $Y \subset X$,

$$S_n \phi(Y) = \sup\Big\{ \sum_{k=0}^{n-1} \phi \circ T^k(x) : x \in Y \Big\},$$

and for every $n \geq 1$,

$$Z_n(\phi, \mathcal{U}) = \inf_{\mathcal{V}} \Big\{ \sum_{U \in \mathcal{V}} \exp S_n \phi(U) \Big\} \tag{2.2.3}$$

where $\mathcal{V}$ ranges over all covers of X contained (in the sense of inclusion) in $\mathcal{U}^n$. The quantity $Z_n(\phi, \mathcal{U})$ is sometimes called the partition function.

Lemma 2.2.1. *The limit* $\mathrm{P}(\phi, \mathcal{U}) = \lim_{n \to \infty} \frac{1}{n} \log Z_n(\phi, \mathcal{U})$ *exists and moreover it is finite. In addition* $\mathrm{P}(\phi, \mathcal{U}) \geq -||\phi||_\infty$.

Proof. Fix $m, n \geq 1$ and consider arbitrary covers $\mathcal{V} \subset \mathcal{U}^m$, $\mathcal{G} \subset \mathcal{U}^n$ of X. If $U \in \mathcal{V}$ and $V \in \mathcal{G}$ then

$$S_{m+n}\phi(U \cap T^{-m}(V)) \leq S_m\phi(U) + S_n\phi(V)$$

and thus

$$\exp\big(S_{m+n}\phi(U \cap T^{-m}(V))\big) \leq \exp S_m\phi(U) \exp S_n\phi(V)$$

Since $U \cap T^{-m}(V) \in \mathcal{V} \vee T^{-m}(\mathcal{G}) \subset \mathcal{U}^m \vee T^{-m}(\mathcal{U}^n) = \mathcal{U}^{m+n}$, we therefore obtain,

$$
\begin{aligned}
Z_{m+n}(\phi,\mathcal{U}) &\leq \sum_{U\in\mathcal{V}}\sum_{V\in\mathcal{G}} \exp\big(S_{m+n}f(U \cap T^{-m}(V))\big) \\
&\leq \sum_{U\in\mathcal{V}}\sum_{V\in\mathcal{G}} \exp S_m\phi(U)\exp S_n\phi(V) \\
&= \sum_{U\in\mathcal{V}} \exp S_m\phi(U) \times \sum_{V\in\mathcal{G}} \exp S_n\phi(V). \qquad (2.2.4)
\end{aligned}
$$

Ranging now over all $\mathcal{V}$ and $\mathcal{G}$ as specified in definition (2.2.3), we get $Z_{m+n}(\phi,\mathcal{U}) \leq Z_m(\phi,\mathcal{U}) \cdot Z_n(\phi,\mathcal{U})$. This implies that

$$\log Z_{m+n}(\phi,\mathcal{U}) \leq \log Z_m(\phi,\mathcal{U}) + \log Z_n(\phi,\mathcal{U}).$$

Moreover, $Z_n(\phi,\mathcal{U}) \geq \exp(-n||\phi||_\infty)$. So, $\log Z_n(\phi,\mathcal{U}) \geq -n||\phi||_\infty$, and applying Lemma 1.4.3 now, finishes the proof.   ♣

Notice that, although in the notation $P(\phi,\mathcal{U})$, the transformation T does not directly appear, however this quantity depends obviously also on T. If we want to indicate this dependence we write $P(T,\phi,\mathcal{U})$ and similarly $Z_n(T,\phi,\mathcal{U})$ for $Z_n(\phi,\mathcal{U})$. Given an open cover $\mathcal{V}$ of X let

$$\mathrm{osc}(\phi,\mathcal{V}) = \sup_{V\in\mathcal{V}}\big(\sup\{|\phi(x) - \phi(y)| : x,y \in V\}\big).$$

Lemma 2.2.2. *If $\mathcal{U}$ and $\mathcal{V}$ are finite open covers of X such that $\mathcal{U} \succ \mathcal{V}$, then $P(\phi,\mathcal{U}) \geq P(\phi,\mathcal{V}) - \mathrm{osc}(\phi,\mathcal{V})$.*

Proof. Take $U \in \mathcal{U}^n$. Then there exists $V = i(U) \in \mathcal{V}^n$ such that $U \subset V$. For every $x,y \in V$ we have $|S_n\phi(x) - S_n\phi(y)| \leq \mathrm{osc}(\phi,\mathcal{V})n$ and therefore

$$S_n\phi(U) \geq S_n\phi(V) - \mathrm{osc}(\phi,\mathcal{V})n \qquad (2.2.5)$$

Let now $\mathcal{G} \subset \mathcal{U}^n$ be a cover of X and let $\tilde{\mathcal{G}} = \{i(U) : U \in \mathcal{U}^n\}$. The family $\tilde{\mathcal{G}}$ is also an open finite cover of X and $\tilde{\mathcal{G}} \subset \mathcal{V}^n$. In view of (2.2.5) and (2.2.3) we get

$$\sum_{U\in\mathcal{G}} \exp S_n\phi(U) \geq \sum_{V\in\tilde{\mathcal{G}}} \exp S_n\phi(V)e^{-\mathrm{osc}(\phi,\mathcal{V})n} \geq e^{-\mathrm{osc}(\phi,\mathcal{V})n}Z_n(\phi,\mathcal{V}).$$

Therefore, applying (2.2.3) again, we get $Z_n(\phi,\mathcal{U}) \geq \exp(-\mathrm{osc}(\phi,\mathcal{V})n)Z_n(\phi,\mathcal{V})$. Hence $P(\phi,\mathcal{U}) \geq P(\phi,\mathcal{V}) - \mathrm{osc}(\phi,\mathcal{V})$.   ♣

Definition 2.2.3 (topological pressure)**.** Consider now the family of all sequences $(\mathcal{V}_n)_{n=1}^\infty$ of open finite covers of X such that

$$\lim_{n\to\infty} \mathrm{diam}(\mathcal{V}_n) = 0, \qquad (2.2.6)$$

and define the topological pressure $P(T,\phi)$ as the supremum of upper limits

$$\limsup_{n\to\infty} P(\phi,\mathcal{V}_n),$$

taken over all such sequences. Notice that by Lemma 2.2.1, $P(T,\phi) \geq -||\phi||_\infty$.

The following lemma gives us a simpler way to calculate topological pressure, showing that in fact in its definition we do not have to take the supremum.

Lemma 2.2.4. *If $(\mathcal{U}_n)_{n=1}^{\infty}$ is a sequence of open finite covers of X such that $\lim_{n\to\infty}\operatorname{diam}(\mathcal{U}_n) = 0$, then the limit $\lim_{n\to\infty}\operatorname{P}(\phi,\mathcal{U}_n)$ exists and is equal to $\operatorname{P}(T,\phi)$.*

Proof. Assume first that $\operatorname{P}(T,\phi)$ is finite and fix $\varepsilon > 0$. By the definition of pressure and uniform continuity of ϕ there exists $\mathcal{W}$, an open cover of X, such that

$$\operatorname{osc}(\phi,\mathcal{W}) \leq \frac{\varepsilon}{2} \text{ and } \operatorname{P}(\phi,\mathcal{W}) \geq \operatorname{P}(T,\phi) - \frac{\varepsilon}{2}. \tag{2.2.7}$$

Fix now $q \geq 1$ so large that for all $n \geq q$, $\operatorname{diam}(\mathcal{U}_n)$ does not exceed a Lebesgue number of the cover $\mathcal{W}$. Take $n \geq q$. Then $\mathcal{U}_n \succ \mathcal{W}$ and applying (2.2.7) and Lemma 2.2.2 we get

$$\operatorname{P}(\phi,\mathcal{U}_n) \geq \operatorname{P}(\phi,\mathcal{W}) - \frac{\varepsilon}{2} \geq \operatorname{P}(T,\phi) - \frac{\varepsilon}{2} - \frac{\varepsilon}{2} = \operatorname{P}(T,\phi) - \varepsilon. \tag{2.2.8}$$

Hence, letting $\varepsilon \to 0$, $\liminf_{n\to\infty}\operatorname{P}(\phi,\mathcal{U}_n) \geq \operatorname{P}(T,\phi)$. This finishes the proof in the case of finite pressure $\operatorname{P}(T,\phi)$. Notice also that actually the same proof goes through in the infinite case. ♣

Since in the definition of numbers $\operatorname{P}(\phi,\mathcal{U})$ no metric was involved, they do not depend on a compatible metric under consideration. And since also the convergence to zero of diameters of a sequence of subsets of X does not depend on a compatible metric, we come to the conclusion that the topological pressure $\operatorname{P}(T,\phi)$ is independent of any compatible metric (depends of course on topology).

The reader familiar with directed sets will notice easily that the family of all finite open covers $\mathcal{U}$ of X equipped with the relation "$\prec$" is a directed set and topological pressure $\operatorname{P}(T,\phi)$ is the limit of the generalized sequence $\operatorname{P}(\phi,\mathcal{U})$. However we can assure him/her that this remark will not be used anywhere in this book.

Definition 2.2.5 (topological entropy)**.** If the function ϕ is identically zero, the pressure $\operatorname{P}(T,\phi)$ is usually called *topological entropy* of the map T and is denoted by $\operatorname{h_{top}}(T)$. Thus, we can define

$$\operatorname{h_{top}}(T) := \sup_{\mathcal{U}} \limsup_{n\to\infty} \frac{1}{n} \log\big(\inf_{\mathcal{U}^n \prec \mathcal{V}} \#\mathcal{V}\big).$$

Notice that, due to $\phi \equiv 0$, we could replace $\lim_{\operatorname{diam}(\mathcal{U})\to 0}\operatorname{P}(\phi,\mathcal{U})$ in the definition of topological pressure, by $\sup_{\mathcal{U}}$ here, and $\mathcal{V}$ being a subset of $\mathcal{U}^n$ by $\mathcal{U}^n \prec \mathcal{V}$.

In the rest of this section we establish some basic elementary properties of pressure and provide its more effective characterizations. Applying Lemma 2.2.2, we obtain

Corollary 2.2.6. *If $\mathcal{U}$ is a finite, open cover of X, then $\operatorname{P}(T,\phi) \geq \operatorname{P}(\phi,\mathcal{U}) - \operatorname{osc}(\phi,\mathcal{U})$.*

Lemma 2.2.7. $P(T^n, S_n\phi) = n\,P(T, \phi)$ *for every* $n \geq 1$. *In particular* $h_{\text{top}}(T^n) = nh_{\text{top}}(T)$.

Proof. Put $g = S_n\phi$. Take $\mathcal{U}$, a finite open cover of X. Let $\overline{\mathcal{U}} = \mathcal{U} \vee T^{-1}(\mathcal{U}) \vee \dots \vee T^{-(n-1)}(\mathcal{U})$. Since now we actually deal with two transformations T and T^n, we do not use the symbol $\mathcal{U}^n$ in order to avoid possible misunderstandings. For any $m \geq 1$ consider an open set $U \in \mathcal{U} \vee T^{-1}(\mathcal{U}) \vee \dots \vee T^{-(nm-1)}(\mathcal{U}) = \overline{\mathcal{U}} \vee T^{-n}(\overline{\mathcal{U}}) \vee \dots \vee T^{-n(m-1)}(\overline{\mathcal{U}})$. Then for every $x \in U$ we have

$$\sum_{k=0}^{mn-1} \phi \circ T^k(x) = \sum_{k=0}^{m-1} g \circ T^{nk}(x),$$

and therefore, $S_{mn}\phi(U) = S_m g(U)$, where the symbol S_m is considered here with respect to the map T^n. Hence $Z_{mn}(T, \phi, \mathcal{U}) = Z_m(T^n, g, \overline{\mathcal{U}})$, and this implies that $P(T^n, g, \overline{\mathcal{U}}) = n\,P(T, \phi, \mathcal{U})$. Since given a sequence $(\mathcal{U}_k)_{k=1}^{\infty}$ of open covers of X whose diameters converge to zero, the diameters of the sequence of its refinements $\overline{\mathcal{U}_k}$ also converge to zero, applying now Lemma 2.2.4 finishes the proof. ♣

Lemma 2.2.8. *If* $T : X \to X$ *and* $S : Y \to Y$ *are continuous mappings of compact metric spaces and* $\pi : X \to Y$ *is a continuous surjection such that* $S \circ \pi = \pi \circ T$, *then for every continuous function* $\phi : Y \to \mathbb{R}$ *we have* $P(S, \phi) \leq P(T, \phi \circ \pi)$.

Proof. For every finite, open cover $\mathcal{U}$ of Y we get

$$P(S, \phi, \mathcal{U}) = P(T, \phi \circ \pi, \pi^{-1}(\mathcal{U})). \tag{2.2.9}$$

In view of Corollary 2.2.6 we have

$$\begin{aligned} P(T, \phi \circ \pi) &\geq P(T, \phi \circ \pi, \pi^{-1}(\mathcal{U})) - \text{osc}(\phi \circ \pi, \pi^{-1}(\mathcal{U})) \\ &= P(T, \phi \circ \pi, \pi^{-1}(\mathcal{U})) - \text{osc}(\phi, \mathcal{U}). \end{aligned} \tag{2.2.10}$$

Let $(\mathcal{U}_n)_{n=1}^{\infty}$, be a sequence of open finite covers of Y whose diameters converge to 0. Then also $\lim_{n\to\infty} \text{osc}(\phi, \mathcal{U}_n)) = 0$ and therefore, using Lemma 2.2.4, (2.2.9) and (2.2.10) we obtain

$$P(S, \phi) = \lim_{n\to\infty} P(S, \phi, \mathcal{U}_n) = \lim_{n\to\infty} P(T, \phi \circ \pi, \pi^{-1}(\mathcal{U}_n)) \leq P(T, \phi \circ \pi)$$

The proof is finished. ♣

In the sequel we will need the following technical result.

Lemma 2.2.9. *If* $\mathcal{U}$ *is a finite open cover of* X *then* $P(\phi, \mathcal{U}^k) = P(\phi, \mathcal{U})$ *for every* $k \geq 1$.

Proof. Fix $k \geq 1$ and let $\gamma = \sup\{|S_{k-1}\phi(x)| : x \in X\}$. Since $S_{k+n-1}\phi(x) = S_n\phi(x) + S_{k-1}\phi(T^n(x))$, for every $n \geq 1$ and $x \in X$, we get

$$S_n\phi(x) - \gamma \leq S_{k+n-1}\phi(x) \leq S_n\phi(x) + \gamma.$$

Therefore, for every $n \geq 1$ and every $U \in \mathcal{U}^{k+n-1}$,

$$S_n\phi(U) - \gamma \leq S_{k+n-1}\phi(U) \leq S_n\phi(U) + \gamma.$$

Since $(\mathcal{U}^k)^n = \mathcal{U}^{k+n-1}$, these inequalities imply that

$$e^{-\gamma}Z_n(\phi, \mathcal{U}^k) \leq Z_{n+k-1}(\phi, \mathcal{U}) \leq e^{\gamma}Z_n(\phi, \mathcal{U}^k).$$

Letting now $n \to \infty$, the required result follows.   ♣

2.3   Pressure on compact metric spaces

Let ρ be a metric on X. For every $n \geq 1$ we define the new metric ρ_n on X by putting

$$\rho_n(x, y) = \max\{\rho(T^j(x), T^j(y)) : j = 0, 1, \ldots, n - 1\}.$$

Given $r > 0$ and $x \in X$ by $B_n(x, r)$ we denote the open ball in the metric ρ_n centered at x and of radius r. Let $\varepsilon > 0$ and let $n \geq 1$ be an integer. A set $F \subset X$ is said to be (n, ε)-*spanning* if and only if the family of balls $\{B_n(x, \varepsilon) : x \in F\}$ covers the space X. A set $S \subset X$ is said to be (n, ε)-*separated* if and only if $\rho_n(x, y) \geq \varepsilon$ for any pair x, y of different points in S. The following fact is obvious.

Lemma 2.3.1. *Every maximal, in the sense of inclusion, (n, ε)-separated set forms an (n, ε)-spanning set.*

We would like to emphasize here that the word maximal refering to separated sets will be in this book always understood in the sense of inclusion and not in the sense of cardinality. We finish this section with the following characterization of pressure.

Theorem 2.3.2. *For every $\varepsilon > 0$ and every $n \geq 1$ let $F_n(\varepsilon)$ be a maximal (n, ε)-separated set in X. Then*

$$P(T, \phi) = \lim_{\varepsilon \to 0} \limsup_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n\phi(x)$$

$$= \lim_{\varepsilon \to 0} \liminf_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n\phi(x).$$

Proof. Fix $\varepsilon > 0$ and let $\mathcal{U}(\varepsilon)$ be a finite cover of X by open balls of radii $\varepsilon/2$. For any $n \geq 1$ consider $\underline{\mathcal{U}}$, a subcover of $\mathcal{U}(\varepsilon)^n$ such that

$$Z_n(\phi, \mathcal{U}(\varepsilon)) = \sum_{U \in \underline{\mathcal{U}}} \exp S_n\phi(U),$$

where $Z_n(\phi, \mathcal{U}(\varepsilon))$ was defined by formula (2.2.3). For every $x \in F_n(\varepsilon)$ let $U(x)$ be an element of $\underline{\mathcal{U}}$ containing x. Since $F_n(\varepsilon)$ is an (n, ε)-separated set, we deduce that the function $x \mapsto U(x)$ is injective. Therefore

$$Z_n(\phi, \mathcal{U}(\varepsilon)) = \sum_{U \in \underline{\mathcal{U}}} \exp S_n \phi(U) \geq \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(U(x)) \geq \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x).$$

Thus by Lemma 2.2.1,

$$P(\phi, \mathcal{U}(\varepsilon)) \geq \limsup_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x).$$

Hence, letting $\varepsilon \to 0$ and applying Lemma 2.2.4 we get

$$P(T, \phi) \geq \limsup_{\varepsilon \to 0} \limsup_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x). \qquad (2.3.1)$$

Let now $\mathcal{V}$ be an arbitrary finite open cover of X and let $\delta > 0$ be a Lebesgue number of $\mathcal{V}$. Take $\varepsilon < \delta/2$. Since for any $k = 0, 1, \ldots, n-1$ and for every $x \in F_n(\varepsilon)$,

$$\mathrm{diam}\big(T^k(B_n(x, \varepsilon))\big) \leq 2\varepsilon < \delta,$$

we conclude that for some $U_k(x) \in \mathcal{V}$,

$$T^k(B_n(x, \varepsilon)) \subset U_k(x).$$

Since the family $\{B_n(x, \varepsilon) : x \in F_n(\varepsilon)\}$ covers X (by Lemma 2.3.1), it implies that the family $\{U(x) : x \in F_n(\varepsilon)\} \subset \mathcal{V}^n$ also covers X, where $U(x) = U_0(x) \cap T^{-1}(U_1(x)) \cap \ldots \cap T^{-(n-1)}(U_{n-1}(x))$. Therefore,

$$Z_n(\phi, \mathcal{V}) \leq \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(U(x)) \leq \exp\big(\mathrm{osc}(\phi, \mathcal{V})n\big) \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x).$$

Hence

$$P(\phi, \mathcal{V}) \leq \mathrm{osc}(\phi, \mathcal{V}) + \liminf_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x),$$

and consequently

$$P(\phi, \mathcal{V}) - \mathrm{osc}(\phi, \mathcal{V}) \leq \liminf_{\varepsilon \to 0} \liminf_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x).$$

Letting $\mathrm{diam}(\mathcal{V}) \to 0$ we get

$$P(T, \phi) \leq \liminf_{\varepsilon \to 0} \liminf_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x).$$

Combining this and (2.3.1) finishes the proof.   ♣

Frequently we shall use the notation

$$\overline{P}(T, \phi, \varepsilon) := \limsup_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x)$$

and

$$\underline{P}(T, \phi, \varepsilon) := \liminf_{n \to \infty} \frac{1}{n} \log \sum_{x \in F_n(\varepsilon)} \exp S_n \phi(x)$$

Actually these limits depend also on the sequence $(F_n(\varepsilon))_{n=1}^{\infty}$ of maximal (n, ε)-separated sets under consideration. However it will be always clear from the context which sequence is being considered.

2.4 Variational Principle

In this section we shall prove the theorem called *Variational Principle*. It has a long history and establishes a useful relationship between measure-theoretic dynamics and topological dynamics.

Theorem 2.4.1 (Variational Principle). *If $T : X \to X$ is a continuous transformation of a compact metric space X and $\phi : X \to \mathbb{R}$ is a continuous function, then*

$$P(T, \phi) = \sup \left\{ h_\mu(T) + \int \phi \, d\mu : \mu \in M(T) \right\},$$

where $M(T)$ denotes the set of all Borel probability T-invariant measures on X. In particular, for $\phi \equiv 0$,

$$h_{\text{top}}(T) = \sup\{h_\mu(T) : \mu \in M(T)\}.$$

The proof of this theorem consists of two parts. In the Part I we show that $h_\mu(T) + \int \phi \, d\mu \le P(T, \phi)$ for every measure $\mu \in M(T)$ and the Part II is devoted to proving inequality $\sup\{h_\mu(T) + \int \phi \, d\mu : \mu \in M(T)\} \ge P(T, \phi)$.

Proof of Part I. Let $\mu \in M(T)$. Fix $\varepsilon > 0$ and consider a finite partition $\mathcal{U} = \{A_1, \ldots, A_s\}$ of X into Borel sets. One can find compact sets $B_i \subset A_i$, $i = 1, 2, \ldots, s$, such that for the partition $\mathcal{V} = \{B_1, \ldots, B_s, X \setminus (B_1 \cup \ldots \cup B_s)\}$ we have

$$H_\mu(\mathcal{U}|\mathcal{V}) \le \varepsilon,$$

where the conditional entropy $H_\mu(\mathcal{U}|\mathcal{V})$ has been defined in (1.3.3). Therefore, as in the proof of Theorem 1.4.4(d), we get for every $n \ge 1$ that

$$H_\mu(\mathcal{U}^n) \le H_\mu(\mathcal{V}^n) + n\varepsilon. \tag{2.4.1}$$

Our first aim is to estimate from above the number $H_\mu(\mathcal{V}^n) + \int S_n \phi \, d\mu$. Putting $b_n = \sum_{B \in \mathcal{V}^n} \exp S_n \phi(B)$, keeping notation $k(x) = -x \log x$, and using

concavity of the logarithmic function we obtain by Jensen inequality,

$$
\begin{aligned}
\mathrm{H}_\mu(\mathcal{V}^n) + \int S_n \phi \, d\mu &\le \sum_{B \in \mathcal{V}^n} \mu(B)\big(S_n\phi(B) - \log \mu(B)\big) \\
&= \sum_{B \in \mathcal{V}^n} \mu(B) \log\big(e^{S_n\phi(B)}/\mu(B)\big) \\
&\le \log\Big(\sum_{B \in \mathcal{V}^n} e^{S_n\phi(B)}\Big).
\end{aligned}
\tag{2.4.2}
$$

(compare the Lemma in Introduction).

Take now $0 < \delta < \frac{1}{2}\inf\{\rho(B_i, B_j) : 1 \le i \ne j \le s\} > 0$ so small that

$$
|\phi(x) - \phi(y)| < \varepsilon
\tag{2.4.3}
$$

whenever $\rho(x,y) < \delta$. Consider an arbitrary maximal (n,δ)-separated set $E_n(\delta)$. Fix $B \in \mathcal{V}^n$. Then, by Lemma 2.3.1, for every $x \in B$ there exists $y \in E_n(\delta)$ such that $x \in B_n(y, \delta)$, whence $|S_n\phi(x) - S_n\phi(y)| \le \varepsilon n$ by (2.4.3). Therefore, using finiteness of the set $E_n(\delta)$, we see that there exists $y(B) \in E_n(\delta)$ such that

$$
S_n\phi(B) \le S_n\phi(y(B)) + \varepsilon n
\tag{2.4.4}
$$

and

$$
B \cap B_n(y(B), \delta) \ne \emptyset.
$$

The definitions of δ and of the partition $\mathcal{V}$ imply that for every $z \in X$,

$$
\#\{B \in \mathcal{V} : B \cap B(z, \delta) \ne \emptyset\} \le 2.
$$

Thus

$$
\#\{B \in \mathcal{V}^n : B \cap B_n(z, \delta) \ne \emptyset\} \le 2^n.
$$

Therefore the function $\mathcal{V}^n \ni B \mapsto y(B) \in E_n(\delta)$ is at most 2^n to 1. Hence, using (2.4.4),

$$
2^n \sum_{y \in E_n(\delta)} \exp S_n\phi(y) \ge \sum_{B \in \mathcal{V}^n} \exp\big(S_n\phi(B) - \varepsilon n\big) = e^{-\varepsilon n} \sum_{B \in \mathcal{V}^n} \exp S_n\phi(B).
$$

Taking now the logarithms of both sides of this inequality, dividing them by n and applying (2.4.2), we get

$$
\begin{aligned}
\log 2 + \frac{1}{n}\log\Big(\sum_{y \in E_n(\delta)} \exp S_n\phi(y)\Big) &\ge -\varepsilon + \frac{1}{n}\log\Big(\sum_{B \in \mathcal{V}^n} \exp S_n\phi(B)\Big) \\
&\ge \frac{1}{n}\mathrm{H}_\mu(\mathcal{V}^n) + \frac{1}{n}\int S_n\phi \, d\mu - \varepsilon.
\end{aligned}
$$

So, by (2.4.1),

$$
\frac{1}{n}\log\Big(\sum_{y \in E_n(\delta)} \exp S_n\phi(y)\Big) \ge \frac{1}{n}\mathrm{H}_\mu(\mathcal{U}^n) + \int \phi \, d\mu - (2\varepsilon + \log 2).
$$

In view of the definition of entropy $h_\mu(T, \mathcal{U})$, presented just after Lemma 1.4.2, by letting $n \to \infty$, we get

$$\underline{P}(T, \phi, \delta) \geq h_\mu(T, \mathcal{U}) + \int \phi \, d\mu - (2\varepsilon + \log 2).$$

Applying now Theorem 2.3.2 with $\delta \to 0$ and next letting $\varepsilon \to 0$, and finally taking supremum over all Borel partitions $\mathcal{U}$ lead us to the following

$$P(T, \phi) \geq h_\mu(T) + \int \phi \, d\mu - \log 2.$$

And applying with every $n \geq 1$ this estimate to the transformation T^n and to the function $S_n\phi$, we obtain

$$P(T^n, S_n\phi) \geq h_\mu(T^n) + \int S_n\phi \, d\mu - \log 2$$

or equivalently, by Lemma 2.2.7 and Theorem 1.4.6(a)

$$n \, P(T, \phi) \geq n \, h_\mu(T) + n \int \phi \, d\mu - \log 2$$

Dividing both sides of this inequality by n and letting then $n \to \infty$, the proof of Part I follows. ♣

In the proof of part II we will need the following two lemmas.

Lemma 2.4.2. *If μ is a Borel probability measure on X, then for every $\varepsilon > 0$ there exists a finite partition $\mathcal{A}$ such that $\mathrm{diam}(\mathcal{A}) \leq \varepsilon$ and $\mu(\partial A) = 0$ for every $A \in \mathcal{A}$.*

Proof. Let $E = \{x_1, \ldots, x_s\}$ be an $\varepsilon/4$-spanning set (that is with respect to the metric $\rho = \rho_0$) of X. Since for every $i \in \{1, \ldots, s\}$ the sets $\{x : \rho(x, x_i) = r\}$, $\varepsilon/4 < r < \varepsilon/2$, are closed and mutually disjoint, only countably many of them can have positive measure μ. Hence, there exists $\varepsilon/4 < t < \varepsilon/2$ such that for every $i \in \{1, \ldots, s\}$

$$\mu(\{x : \rho(x, x_i) = t\}) = 0. \tag{2.4.5}$$

Define inductively the sets $A_1, A_2, \ldots, A_s$ putting $A_1 = \{x : \rho(x, x_1) \leq t\}$ and for every $i = 2, 3, \ldots, s$

$$A_i = \{x : \rho(x, x_i) \leq t\} \setminus (A_1 \cup A_2 \cup \ldots \cup A_{i-1}).$$

The family $\mathcal{U} = \{A_1, \ldots, A_s\}$ is a partition of X with diameter not exceeding ε. Using (2.4.5) and noting that generally $\partial(A \setminus B) \subset \partial A \cup \partial B$, we conclude by induction that $\mu(\partial A_i) = 0$ for every $i = 1, 2, \ldots, s$. ♣

Proof of Part II. Fix $\varepsilon > 0$ and let $E_n(\varepsilon)$, $n = 1, 2, \ldots$, be a sequence of maximal (n, ε)-separated set in X. For every $n \geq 1$ define measures

$$\mu_n = \frac{\sum_{x \in E_n(\varepsilon)} \delta_x \exp S_n \phi(x)}{\sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x)} \text{ and } m_n = \frac{1}{n} \sum_{k=0}^{n-1} \mu_n \circ T^{-k},$$

where δ_x denotes the Dirac measure concentrated at the point x (see (2.1.2)). Let $(n_i)_{i=1}^{\infty}$ be an increasing sequence such that m_{n_i} converges weakly, say to m and

$$\lim_{i \to \infty} \frac{1}{n_i} \log \sum_{x \in E_{n_i}(\varepsilon)} \exp S_n \phi(x) = \limsup_{n \to \infty} \frac{1}{n} \log \sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x). \qquad (2.4.6)$$

Clearly $m \in M(T)$. In view of Lemma 2.4.2 there exists a finite partition γ such that $\operatorname{diam}(\gamma) \leq \varepsilon$ and $\mu(\partial G) = 0$ for every $G \in \gamma$. For any $n \geq 1$ put $g_n = \sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x)$. Since $\#(G \cap E_n(\varepsilon)) \leq 1$ for every $G \in \gamma^n$, we obtain

$$\begin{aligned}
\mathrm{H}_{\mu_n}(\gamma^n) + \int S_n \phi \, d\mu_n &= \sum_{x \in E_n(\varepsilon)} \left(-\log \mu_n(x) + S_n \phi(x) \right) \mu_n(x) \\
&= \sum_{x \in E_n(\varepsilon)} \frac{\exp S_n \phi(x)}{g_n} \left(S_n \phi(x) - \log\left(\frac{\exp S_n \phi(x)}{g_n} \right) \right) \\
&= g_n^{-1} \sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x) \left(S_n \phi(x) - S_n \phi(x) + \log g_n \right) \\
&= \log g_n \qquad\qquad (2.4.7)
\end{aligned}$$

Fix now $M \in \mathbb{N}$ and $n \geq 2M$. For $j = 0, 1, \ldots, M - 1$, let $s(j) = \mathrm{E}(\frac{n-j}{M}) - 1$, where $\mathrm{E}(x)$ denotes the integer part of x. Note that

$$\begin{aligned}
\bigvee_{k=0}^{s(j)} T^{-(kM+j)} \gamma^M &= T^{-j}\gamma \vee \ldots \vee T^{-(s(j)M+j)-(M-1)}\gamma \\
&= T^{-j}\gamma \vee \ldots \vee T^{-((s(j)+1)M+j-1)}\gamma
\end{aligned}$$

and

$$(s(j)+1)M + j - 1 \leq n - j + j - 1 = n - 1.$$

Therefore, setting $R_j = \{0, 1, \ldots, j-1, (s(j)+1)M+j, \ldots, n-1\}$, we can write

$$\gamma^n = \bigvee_{k=0}^{s(j)} T^{-(kM+j)} \gamma^M \vee \bigvee_{i \in R_j} T^{-i}\gamma.$$

Hence

$$\begin{aligned}
\mathrm{H}_{\mu_n}(\gamma^n) &\leq \sum_{k=0}^{s(j)} \mathrm{H}_{\mu_n}\left(T^{-(kM+j)}\gamma^M \right) + \mathrm{H}_{\mu_n}\left(\bigvee_{i \in R_j} T^{-i}\gamma \right) \\
&\leq \sum_{k=0}^{s(j)} \mathrm{H}_{\mu_n \circ T^{-(kM+j)}}(\gamma^M) + \log\left(\#\left(\bigvee_{i \in R_j} T^{-i}\gamma \right) \right).
\end{aligned}$$

Summing now over all $j = 0, 1, \ldots, M - 1$, we then get

$$M \, \mathrm{H}_{\mu_n}(\gamma^n) \leq \sum_{j=0}^{M-1} \sum_{k=0}^{s(j)} \mathrm{H}_{\mu_n \circ T^{-(kM+j)}}(\gamma^M) + \sum_{j=0}^{M-1} \log(\#\gamma^{\#R_j})$$

$$\leq \sum_{l=0}^{n-1} \mathrm{H}_{\mu_n \circ T^{-l}}(\gamma^M) + 2M^2 \log \#\gamma$$

$$\leq n \, \mathrm{H}_{\frac{1}{n} \sum_{l=0}^{n-1} \mu_n \circ T^{-l}}(\gamma^M) + 2M^2 \log \#\gamma.$$

And applying (2.4.7) we obtain,

$$M \log\Big(\sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x) \Big) \leq n \, \mathrm{H}_{m_n}(\gamma^M) + M \int S_n \phi \, d\mu_n + 2M^2 \log \#\gamma.$$

Dividing both sides of this inequality by Mn, we get,

$$\frac{1}{n} \log\Big(\sum_{x \in E_n(\varepsilon)} \exp S_n \phi(x) \Big) \leq \frac{1}{M} \mathrm{H}_{m_n}(\gamma^M) + \int \phi \, dm_n + 2\frac{M}{n} \log \#\gamma.$$

Since $\partial T^{-1}(A) \subset T^{-1}(\partial A)$ for every set $A \subset X$, the measure m of the boundaries of the partition γ^M is equal to 0. Letting therefore $n \to \infty$ along the subsequence $\{n_i\}$ we conclude from this inequality, Lemma 2.1.18 and Theorem 2.1.4 that

$$\overline{\mathrm{P}}(T, \phi, \varepsilon) \leq \frac{1}{M} \mathrm{H}_m(\gamma^M) + \int \phi \, dm.$$

Now letting $M \to \infty$ we get,

$$\overline{\mathrm{P}}(T, \phi, \varepsilon) \leq \mathrm{h}_m(T, \gamma) + \int \phi \, dm \leq \sup \Big\{ h_\mu(T) + \int \phi \, d\mu : \mu \in M(T) \Big\}.$$

Applying finally Theorem 2.3.2 and letting $\varepsilon \searrow 0$, we get the desired inequality.

♣

Corollary 2.4.3. *Under assumptions of Theorem 2.4.1*

$$\mathrm{P}(T, \phi) = \sup\{\mathrm{h}_\mu(T) + \int \phi \, d\mu : \mu \in M_e(T)\},$$

where $M_e(T)$ denotes the set of all Borel ergodic probability T-invariant measures on X.

Proof. Let $\mu \in M(T)$ and let $\{\mu_x : x \in X\}$ be the ergodic decomposition of μ. Then $\mathrm{h}_\mu = \int \mathrm{h}_{\mu_x} \, d\mu(x)$ and $\int \phi \, d\mu = \int (\int \phi \, d\mu_x) \, d\mu(x)$. Therefore

$$\mathrm{h}_\mu + \int \phi \, d\mu = \int \Big(\mathrm{h}_{\mu_x} + \int \phi \, d\mu_x \Big) \, d\mu(x)$$

and consequently, there exists $x \in X$ such that $\mathrm{h}_{\mu_x} + \int \phi \, d\mu_x \geq \mathrm{h}_\mu + \int \phi \, d\mu$ which finishes the proof.

♣

Corollary 2.4.4. *If $T : X \to X$ is a continuous transformation of a compact metric space X, $\phi : X \to \mathbb{R}$ is a continuous function and Y is a forward invariant subset of X (i.e. $T(Y) \subset Y$), then $\mathrm{P}(T|_Y, \phi|_Y) \leq \mathrm{P}(T, \phi)$.*

Proof. The proof follows immediatly from Theorem 2.4.1 by the remark that each $T|_Y$-invariant measure on Y can be treated as a measure on X and it is then T-invariant. ♣

2.5   Equilibrium states and expansive maps

We keep in this section the notation from the previous one. A measure $\mu \in M(T)$ is called an *equilibrium state* for the transformation T and function ϕ if

$$\mathrm{P}(T, \phi) = \mathrm{h}_\mu(T) + \int \phi \, d\mu.$$

The set of all those measures will be denoted by $E(\phi)$. In the case $\phi = 0$ the equilibrium states are also called *maximal measures*. Similarly (in fact even easier) as Corollary 2.4.4 one can prove the following.

Proposition 2.5.1. *If $E(\phi) \neq \emptyset$ then $E(\phi)$ contains ergodic measures.*

As the following example shows there exist transformations and functions which admit no equilibrium states.

Example 2.5.2. Let $\{T_n : X_n \to X_n\}_{n \geq 1}$ be a sequence of continuous mappings of compact metric spaces X_n such that for every $n \geq 1$

$$\mathrm{h}_{\mathrm{top}}(T_n) < \mathrm{h}_{\mathrm{top}}(T_{n+1}) \text{ and } \sup_n \mathrm{h}_{\mathrm{top}}(T_n) < \infty \qquad (2.5.1)$$

The disjoint union $\oplus_{n=1}^\infty X_n$ of the spaces X_n is a locally compact space, and let $X = \{\omega\} \cup \oplus_{n=1}^\infty X_n$ be its Alexandrov one-point compactification. Define the map $T : X \to X$ by $T|_{X_n} = T_n$ and $T(\omega) = \omega$. The reader will check easily that T is continuous. By Corollary 2.4.4 $\mathrm{h}_{\mathrm{top}}(T_n) \leq \mathrm{h}_{\mathrm{top}}(T)$ for all $n \geq 1$. Suppose that μ is an ergodic maximal measure for T. Then $\mu(X_n) = 1$ for some $n \geq 1$ and therefore

$$\mathrm{h}_{\mathrm{top}}(T) = \mathrm{h}_\mu(T_n) \leq \mathrm{h}_{\mathrm{top}}(T_n) < \mathrm{h}_{\mathrm{top}}(T_{n+1}) \leq \mathrm{h}_{\mathrm{top}}(T)$$

which is a contradiction. In view of Proposition 2.5.1 this shows that T has no maximal measure.

A more difficult problem is to find a transitive and smooth example without maximal measure (see for instance [Misiurewicz 1973]).

The remaining part of this section is devoted to provide sufficient conditions for the existence of equilibrium states and we start with the following simple general criterion which will be the base to obtain all others.

Proposition 2.5.3. *If the function $M(T) \ni \mu \to h_\mu(T)$ is upper semi-continuous then each continuous function $\phi : X \to \mathbb{R}$ has an equilibrium state.*

Proof. By the definition of weak* topology the function $M(T) \ni \mu \to \int \phi \, d\mu$ is continuous. Therefore the lemma follows from the assumption, the weak*-compactness of the set $M(T)$ and Theorem 2.4.1 (Variational Principle). ♣

As an immediate consequence of Theorem 2.4.1 we obtain the following.

Corollary 2.5.4. *If $h_{\text{top}}(T) = 0$ then each continuous function on X has an equilibrium state.*

A continuous transformation $T : X \to X$ of a compact metric space X equipped with a metric ρ is said to be *(positively) expansive* if and only if

$$\exists \delta > 0 \text{ such that } (\rho(T^n(x), T^n(y)) \leq \delta \; \forall n \geq 0 \;) \Longrightarrow x = y.$$

The number δ which appeared in this definition is called an *expansive constant* for $T : X \to X$.

Although at the end of this section we will introduce a related but different notion of expansiveness of homeomorphisms, we will frequently omit the word "positively". Note that the property of being expansive does not depend on the choice of a metric compatible with the topology. From now on in this chapter the transformation T will be assumed to be positively expansive, unless stated otherwise. The following lemma is an immediate consequence of expansiveness.

Lemma 2.5.5. *If $\mathcal{A}$ is a finite Borel partition of X with diameter not exceeding an expansive constant then $\mathcal{A}$ is a generator for every Borel probability T-invariant measure μ on X.*

The main result concerning expansive maps is the following.

Theorem 2.5.6. *If $T : X \to X$ is positively expansive then the function $M(T) \ni \mu \to h_\mu(T)$ is upper semi-continuous and consequently (by Proposition 2.5.3) each continuous function on X has an equilibrium state.*

Proof. Let $\delta > 0$ be an expansive constant of T and let $\mu \in M(T)$. By Lemma 2.4.2 there exists a finite partition $\mathcal{A}$ of X such that $\text{diam}(\mathcal{A}) \leq \delta$ and $\mu(\partial A) = 0$ for every $A \in \mathcal{A}$.

Consider now a sequence $(\mu_n)_{n=1}^\infty$ of invariant measures converging weakly to μ. In view of Lemma 2.5.5 and Theorem 1.8.7(b), we have

$$h_\nu(T) = h_\nu(T, \mathcal{A})$$

for every $\nu \in M(T)$, in particular for $\nu = \mu$ and $\nu = \mu_n$ with $n = 1, 2, \dots$. Hence, due to Lemma 2.1.18

$$h_\mu(T) = h_\mu(T, \mathcal{A}) \geq \limsup_{n \to \infty} h_{\mu_n}(T, \mathcal{A}) = \limsup_{n \to \infty} h_{\mu_n}(T).$$

The proof is finished. ♣

Below we prove three additional interesting results about expansive maps.

Lemma 2.5.7. *If $\mathcal{U}$ is a finite open cover of X with diameter not exceeding an expansive constant of an expansive map $T : X \to X$, then $\lim_{n\to\infty} \operatorname{diam}(\mathcal{U}^n) = 0$.*

Proof. Let $\mathcal{U} = \{U_1, U_2, \ldots, U_s\}$. By expansiveness for every sequence $(a_n)_{n=0}^{\infty}$ of elements of the set $\{1, 2, \ldots, s\}$

$$\#\left(\bigcap_{n=0}^{\infty} T^{-n}(\overline{U_{a_n}}) \right) \leq 1$$

and hence

$$\lim_{k\to\infty} \operatorname{diam}\left(\bigcap_{n=0}^{k} T^{-n}(\overline{U_{a_n}}) \right) = 0.$$

Therefore, given a fixed $\varepsilon > 0$ there exists a minimal finite $k = k(\{a_n\})$ such that

$$\operatorname{diam}\left(\bigcap_{n=0}^{k} T^{-n}(\overline{U_{a_n}}) \right) < \varepsilon.$$

Note now that the function $\{1, 2, \ldots, s\}^{\mathbb{N}} \ni \{a_n\} \mapsto k(\{a_n\})$ is continuous, even more, it is locally constant. Thus, by compactness of the space $\{1, 2, \ldots, s\}^{\mathbb{N}}$, this function is bounded, say by t, and therefore

$$\operatorname{diam}(\mathcal{U}^n) < \varepsilon$$

for every $n \geq t$. The proof is finished.   ♣

Combining now Lemma 2.2.4, Lemma 2.5.7 and Lemma 2.2.9, we get the following fact corresponding to Theorem 1.8.7 b).

Proposition 2.5.8. *If $\mathcal{U}$ is a finite open cover of X with diameter not exceeding an expansive constant then $\mathrm{P}(T, \phi) = \mathrm{P}(T, \phi, \mathcal{U})$.*

As the last result of this section we shall prove the following.

Proposition 2.5.9. *There exists a constant $\eta > 0$ such that $\forall \varepsilon > 0 \exists n(\varepsilon) \geq 1$, such that*

$$\rho(x, y) \geq \varepsilon \implies \rho_{n(\varepsilon)}(x, y) > \eta.$$

Proof. Let $\mathcal{U} = \{U_1, U_2, \ldots, U_s\}$ be a finite open cover of X with diameter not exceeding an expansive constant δ and let η be a Lebesgue number of $\mathcal{U}$. Fix $\varepsilon > 0$. In view of Lemma 2.5.7 there exists an $n(\varepsilon) \geq 1$ such that

$$\operatorname{diam}(\mathcal{U}^{n(\varepsilon)}) < \varepsilon. \tag{2.5.2}$$

Let $\rho(x, y) \geq \varepsilon$ and suppose that $\rho_{n(\varepsilon)}(x, y) \leq \eta$. Then,

$$\forall (0 \leq j \leq n(\varepsilon) - 1) \ \exists (U_{i_j} \in \mathcal{U}) \ \text{such that } T^j(x), T^j(y) \in U_{i_j}$$

and therefore

$$x, y \in \bigcap_{j=0}^{n(\varepsilon)-1} T^{-j}(U_{i_j}) \in \mathcal{U}^{n(\varepsilon)}$$

Hence $\operatorname{diam}(\mathcal{U}^{n(\varepsilon)}) \geq \rho(x,y) \geq \varepsilon$ which contradicts (2.5.2). The proof is finished. ♣

As we have mentioned at the begining of this section there is a notion related to positive expansiveness which makes sense only for homeomorphisms. Namely we say that a homeomorphism $T : X \to X$ is *expansive* if and only if

$$\exists \delta > 0 \text{ such that } (\rho(T^n(x), T^n(y)) \leq \delta \ \forall n \in \mathbb{Z}) \Longrightarrow x = y$$

We will not explore this notion in our book – we only want to emphasize that for expansive homeomorphisms analogous results (with obvious modifications) can be proved (in the same way) as for positively expansive mappings. Of course each positively expansive homeomorphism is expansive.

2.6 Topological pressure as a function on the Banach space of continuous functions. The issue of uniqueness of equilibrium states

Let $T : X \to X$ be a continuous mapping of a compact topological space X. We shall discuss here the topological pressure function $\mathrm{P} : C(X) \to \mathbb{R}$, $\mathrm{P}(\phi) = \mathrm{P}(T, \phi)$. Assume that the topological entropy is finite, $\mathrm{h}_{\mathrm{top}}(T) < \infty$. Hence, the pressure P is also finite, because for example

$$\mathrm{P}(\phi) \leq \mathrm{h}_{\mathrm{top}}(T) + \sup \phi. \tag{2.6.1}$$

This estimate follows directly from the definitions, see Section 1.2. It is also an immediate consequence of Theorem 2.4.1 (Variational Principle) in case X is metrizable.

Let us start with the following easy

Theorem 2.6.1. *The pressure function P is Lipschitz continuous with the Lipschitz constant 1.*

Proof. Let $\phi \in C(X)$. Recall from Section 2.2 that in the definition of pressure we have considered the following partition function

$$Z_n(\phi, \mathcal{U}) = \inf_{\mathcal{V}} \left\{ \sum_{U \in \mathcal{V}} \exp S_n \phi(U) \right\},$$

where $\mathcal{V}$ ranges over all covers of X contained in $\mathcal{U}^n$. Now if also $\psi \in C(X)$, then we obtain for every open cover $\mathcal{U}$ and positive integer n that

$$Z_n(\psi, \mathcal{U}) e^{-||\phi-\psi||_\infty n} \leq Z_n(\phi, \mathcal{U}) \leq Z_n(\psi, \mathcal{U}) e^{||\phi-\psi||_\infty n}$$

Taking limits if $n \nearrow \infty$ we get $\mathrm{P}(\psi) - ||\phi - \psi||_\infty \leq \mathrm{P}(\phi) \leq \mathrm{P}(\psi) + ||\phi - \psi||_\infty$, hence $|P(\psi) - P(\phi)| \leq ||\psi - \phi||_\infty$. ♣

Theorem 2.6.2. *If X is a compact metric space then the topological pressure function* $\mathrm{P} : C(X) \to \mathbb{R}$ *is convex.*

We provide two different proofs of this important theorem. One elementary, the other relying on the Variational Principle (Theorem 2.4.1).

Proof 1. By Hölder inequality applied with the exponents $a = 1/\alpha, b = 1/(1 - \alpha)$, so that $1/a + 1/b = \alpha + 1 - \alpha = 1$ we obtain for an arbitrary finite set $E \subset X$

$$\frac{1}{n} \log \sum_E e^{S_n(\alpha\phi) + S_n(1-\alpha)\psi} = \frac{1}{n} \log \sum_E e^{\alpha S_n(\phi)} e^{(1-\alpha)S_n(\psi)}$$

$$\leq \frac{1}{n} \log \left(\sum_E e^{S_n(\phi)} \right)^\alpha \left(\sum_E e^{S_n(\psi)} \right)^{1-\alpha}$$

$$\leq \alpha \frac{1}{n} \log \left(\sum_E e^{S_n(\phi)} \right) + (1-\alpha) \frac{1}{n} \log \left(\sum_E e^{S_n(\psi)} \right).$$

To conclude the proof apply now the definition of pressure with $E = F_n(\varepsilon)$ that are (n, ε)-separated sets, see Theorem 2.3.2.   ♣

Proof 2. It is sufficient to prove that the function

$$\hat{P} := \sup_{\mu \in M(X,T)} L_\mu \phi \;\; \text{where} L_\mu \phi := \mathrm{h}_\mu(T) + \mu\phi$$

(where $\mu\phi$ abbreviates $\int \phi \, d\mu$, see Section 2.1) is convex, because by the Variational Principle $\hat{P}(\phi) = P(\phi)$.

That is we need to prove that the set

$$A := \{(\phi, y) \in C(X) \times \mathbb{R} : y \geq \hat{P}(\phi)\}$$

is convex. Observe however that by its definition $A = \bigcap_{\mu \in M(X,T)} L_\mu^+$, where by L_μ^+ we denote the upper half space $\{(\phi, y) : y \geq L_\mu \phi\}$. Since all the halfspaces L_μ^+ are convex, the set A is convex as their intersection.   ♣

Remark 2.6.3. We can write $L_\mu \phi = \mu\phi - (-h_\mu(T))$. The function $\hat{\mathrm{P}}(\phi) = \sup_{\mu \in M(T)} L_\mu \phi$ defined on the space $C(X)$ is called the Legendre-Fenchel transform of the convex function $\mu \mapsto -h_\mu(T)$ on the weakly*-compact convex set $M(T)$. We shall abbreviate the name Legendre-Fenchel transform to LF-transform. Observe that this transform generalizes the standard Legendre transform of a strictly convex function h on a finite dimensional linear space, say $\mathbb{R}^n$,

$$y \mapsto \sup_{x \in \mathbb{R}^n} \{\langle x, y \rangle - h(x)\},$$

where $\langle x, y \rangle$ is the scalar (inner) product of x and y.

Note that $-h_\mu(T)$ is not strictly convex (unless $M(X, T)$ is a one element space) because it is affine, see Theorem 1.4.7.

Proof 2 just repeats the standard proof that the Legendre transform is convex.

In the sequel we will need so called geometric form of the Hahn-Banach theorem (see [Bourbaki 1981, Th.1, Ch.2.5], or Ch. 1.7 of [Edwards 1995].

Theorem 2.6.4 (Hahn-Banach). *Let A be an open convex non-empty subset of a real topological vector space V and let M be a non-empty affine subset of V (linear subspace moved by a vector) which does not meet A. Then there exists a codimension 1 closed affine subset H which contains M and does not meet A.*

Suppose now that $P : V \to \mathbb{R}$ is an arbitrary convex continuous function on a real topological vector space V. We call a continuous linear functional $F : V \to \mathbb{R}$ *tangent* to P at $x \in V$ if

$$F(y) \leq P(x + y) - P(x) \tag{2.6.2}$$

for every $y \in V$. We denote the set of all such functionals by $V^*_{x,P}$. Sometimes the term *supporting functional* is being used in the literature.

Applying Theorem 2.6.4 we easily prove that for every x the set $V^*_{x,P}$ is non-empty. Indeed, we can consider the open convex set $A = \{(x, y) \in V \times \mathbb{R}\} : y > P(x)\}$ in the vector space $V \times \mathbb{R}$ with the product topology and the one-point set $M = \{x, P(x)\}$, and define a supporting functional we look for, as having the graph $H - \{x, P(x)\}$ in $V \times \mathbb{R}$.

We would also like to bring reader's attention to the following another general fact from functional analysis.

Theorem 2.6.5. *Let V be a separable Banach space and $P : V \to \mathbb{R}$ be a convex continuous function. Then for every $x \in V$ the function P is differentiable at x in every direction (Gateaux differentiable), or in a dense in the weak topology set of directions, if and only if $V^*_{x,P}$ is a singleton.*

Proof. Suppose first that P is not differentiable at some point x and direction y. Choose an arbitrary $F \in V^*_{x,P}$. Non-differentiability in the direction $y \in V$ implies that there exist $\varepsilon > 0$ and a sequence $\{t_n\}_{n \geq 1}$ converging to 0 such that

$$P(x + t_n y) - P(x) \geq t_n F(y) + \varepsilon |t_n|. \tag{2.6.3}$$

In fact we can assume that all t_n, $n \geq 1$, are positive by passing to a subsequence and replacing y by $-y$ if necessary. We shall prove that (2.6.3) implies the existence of $\hat{F} \in V^*_{x,P} \setminus \{F\}$. Indeed, take $F_n \in V^*_{x+t_n y,P}$. Then, by (2.6.2) applied for F_n at $x + t_n y$ and $-t_n y$ in place of x and y, we have

$$P(x) - P(x + t_n y) \geq F_n(-t_n y) \tag{2.6.4}$$

The inequalities (2.6.3) and (2.6.4) give

$$t_n F(y) + \varepsilon t_n \leq t_n F_n(y).$$

Hence

$$(F_n - F)(y) \geq \varepsilon. \tag{2.6.5}$$

In the case when P is Lipschitz continuous, and this is the case for topological pressure see (Theorem 2.6.1), which we are mostly interested in, all F_n's, $n \geq 1$, are uniformly bounded. Indeed, let L be a Lipschitz constant of P. Then for every $z \in V$ and every $n \geq 1$,

$$F_n(z) \leq P(x + t_n y + z) - P(x + t_n y) \leq L||z||$$

So, $||F_n|| \leq L$ for every $n \geq 1$. Thus, there exists $\hat{F} = \lim_{n \to \infty} F_n$, a weak*-limit of a sequence $\{F_n\}_{n \geq 1}$ (subsequence of the previous sequence). We used here the fact that a bounded set is metrizable in weak*-topology, (compare Section 2.1).

By (2.6.5) $(\hat{F} - F)(y) \geq \varepsilon$. Hence $\hat{F} \neq F$. Since

$$P(x + t_n y + v) - P(x + t_n y) \geq F_n(v) \quad \text{for all} n \text{and} v \in V$$

passing with n to ∞ and using continuity of P, we conclude that $\hat{F} \in V_{x,P}^*$.

If we do not assume that P is Lipschitz continuous, we restrict F_n to the 1-dimensional space spanned by y i.e. we consider $F_n|_{\mathbb{R}y}$. In view of (2.6.5) for every $n \geq 1$ there exists $0 \leq s_n \leq 1$ such that $F_n(s_n y) - F(s_n y) = \varepsilon$. Passing to a subsequence, we may assume that $\lim_{n \to \infty} s_n = s$ for some $s \in [0, 1]$. Define

$$f_n = s_n F_n|_{\mathbb{R}y} + (1 - s_n)F|_{\mathbb{R}y}.$$

Then $f_n(y) - F(y) = \varepsilon$ hence $||f_n - F|_{\mathbb{R}y}|| = \frac{\varepsilon}{||y||}$ for every $n \geq 1$. Thus the sequence $\{f_n\}_{n \geq 1}$ is uniformly bounded and, consequently, it has a weak-* limit $\hat{f} : \mathbb{R}y \to \mathbb{R}$. Now we use Theorem 2.6.4 (Hahn-Banach) for the affine set M being the graph of $\hat{f}$ translated by $(x, P(x))$ in $V \times \mathbb{R}$. We extend M to H and find the linear functional $\hat{F} \in V_{x,P}^*$ whose graph is $H - (x, P(x))$, continuous since H is closed. Since $\hat{F}(y) - F(y) = \hat{f}(y) - F(y) = \varepsilon$, $\hat{F} \neq F$.

Suppose now that $V_{x,P}^*$ contains at least two distinct linear functionals, say F and $\hat{F}$. So, $F(y) - \hat{F}(y) > 0$ for some $y \in V$. Suppose on the contrary that P is differentiable in every direction at the point x. In particular P is differentiable in the direction y. Hence

$$\lim_{t \to 0} \frac{P(x + ty) - P(x)}{t} = \lim_{t \to 0} \frac{P(x - ty) - P(x)}{-t}$$

and consequently

$$\lim_{t \to 0} \frac{P(x + ty) + P(x - ty) - 2P(x)}{t} = 0.$$

On the other hand, for every $t > 0$, we have $P(x + ty) - P(x) \geq F(t) = tF(y)$ and $P(x - ty) - P(x) \geq \hat{F}(-ty) = -t\hat{F}(y)$, hence

$$\liminf_{t \to 0} \frac{P(x + ty) + P(x - ty) - 2P(x)}{t} \geq F(y) - \hat{F}(y) > 0.$$

, a contradiction.

In fact $F(y) - \hat{F}(y) = \varepsilon > 0$ implies $F(y') - \hat{F}(y') \geq \varepsilon/2 > 0$ for all y' in the neighbourhood of y in the weak topology defined just by $\{y' : (F - \hat{F})(y - y') < \varepsilon/2\}$. Hence P is not differentiable in a weak*-open set of directions. ♣

Let us go back now to our special situation:

Proposition 2.6.6. *If $\mu \in M(T)$ is an equilibrium state for $\phi \in C(X)$, then the linear functional represented by μ is tangent to P at ϕ.*

Proof. We have

$$\mu(\phi) + h_\mu = P(\phi)$$

and for every $\psi \in C(X)$

$$\mu(\phi + \psi) + h_\mu \leq P(\phi + \psi).$$

Subtracting the sides of the equality from the respective sides of the latter inequality we obtain $\mu(\psi) \leq P(\phi + \psi) - P(\phi)$ which is just the inequality defining tangent functionals. ♣

As an immediate consequence of Proposition 2.6.6 and Theorem 2.6.5 we get the following.

Corollary 2.6.7. *If the pressure function P is differentiable at ϕ in every direction, or at least in a dense, in the weak topology set of directions, then there is at most one equilibrium state for ϕ.*

Due to this Corollary, in future (see Chapter 4), in order to prove uniqueness it will be sufficient to prove differentiability of the pressure function in a weak*-dense set of directions.

The next part of this section will be devoted to kind of reversing Proposition 2.6.6 and Corollary 2.6.7. and to better understanding of the mutual Legendre-Fenchel transforms $-h$ and P. This is a beautiful topic but will not have applications in the rest of this book. Let us start with a characterization of T-invariant measures in the space of all signed measures $C(X)^*$ formulated by means of the pressure function P.

Theorem 2.6.8. *For every $F \in C(X)^*$ the following three conditions are equivalent:*

(i) *For every $\phi \in C(X)$ it holds $F(\phi) \leq \mathrm{P}(\phi)$.*

(ii) *There exists $C \in \mathbb{R}$ such that for every $\phi \in C(X)$ it holds $F(\phi) \leq \mathrm{P}(\phi) + C$.*

(iii) *F is represented by a probability invariant measure $\mu \in M(X, T)$.*

Proof. (iii) $\Rightarrow$ (i) follows immediately from the Variational Principle:

$$F(\phi) \leq F(\phi) + h_\mu(T) \leq \mathrm{P}(\phi) \text{ for every } \phi \in C(X).$$

(i) $\Rightarrow$ (ii) is obvious. Let us prove that (ii) $\Rightarrow$ (iii). Take an arbitrary non-negative $\phi \in C(X)$, i.e. such that for every $x \in X, \phi(x) \geq 0$. For every real $t < 0$ we have

$$F(t\phi) \leq \mathrm{P}(t\phi) + C$$

Since $t\phi \leq 0$ it immediately follows from (2.6.1) that $\mathrm{P}(t\phi) \leq \mathrm{P}(0)$. Hence $F(t\phi) \leq P(0) + C$. So,

$$|t|F(\phi) \geq -(C + \mathrm{P}(0)), \text{ hence } F(\phi) \geq \frac{-(C + \mathrm{P}(0))}{|t|}.$$

Letting $t \to -\infty$ we obtain $F(\phi) \geq 0$. We estimate the value of F on constant functions t. For every $t > 0$ we have $F(t) \leq \mathrm{P}(t) + C \leq \mathrm{P}(0) + t + C$. Hence $F(1) \leq 1 + \frac{\mathrm{P}(0)+C}{t}$. Similarly $F(-t) \leq \mathrm{P}(-t) + C = \mathrm{P}(0) - t + C$ and therefore $F(1) \geq 1 - \frac{\mathrm{P}(0)+C}{t}$. Letting $t \to \infty$ we thus obtain $F(1) = 1$. Therefore by Theorem 2.1.1 (Riesz Representation Theorem), the functional F is represented by a probability measure $\mu \in M(X)$. Let us finally prove that μ is T-invariant. For every $\phi \in C(X)$ and every $t \in \mathbb{R}$ we have by (i) that

$$F(t(\phi \circ T - \phi)) \leq \mathrm{P}(t(\phi \circ T - \phi)) + C.$$

It immediately follows from Theorem 2.4.1 (Variational Principle) that $\mathrm{P}(t(\phi \circ T - \phi)) = \mathrm{P}(0)$. Hence

$$|F(\phi \circ T) - F(\phi)| \leq \left| \frac{\mathrm{P}(0) + C}{t} \right|.$$

Thus, letting $|t| \to \infty$, we obtain $F(\phi \circ T) = F(\phi)$, i.e T-invariance of μ.   ♣

We shall prove the following.

Corollary 2.6.9. *Every functional F tangent to P at $\phi \in C(X)$, i.e. $F \in C(X)^*_{\phi,P}$, is represented by a probability T-invariant measure $\mu \in M(X,T)$.*

Proof. Using Theorem 2.6.1, we get for every $\psi \in C(X)$ that

$$F(\psi) \leq P(\phi+\psi) - P(\phi) \leq P(\psi) + |P(\phi+\psi) - P(\psi)| - P(\phi) \leq P(\psi) + ||\phi||_\infty - P(\phi).$$

So condition (ii) of Theorem 2.6.8 holds, hence (iii) holds meaning that F is represented by $\mu \in M(X,T)$.   ♣

We can now almost reverse Proposition 2.6.6. Namely being a functional tangent to P at ϕ implies being an "almost" equilibrium state for ϕ.

Theorem 2.6.10. *It holds that $F \in C(X)^*_{\phi,P}$ if and only if F, actually the measure $\mu = \mu_F \in M(X,T)$ representing F, is a weak*-limit of measures $\mu_n \in M(X,T)$ such that*

$$\mu_n \phi + \mathrm{h}_{\mu_n}(T) \to \mathrm{P}(\phi).$$

Proof. In one way the proof is simple. Assume that $\mu = \lim_{n\to\infty} \mu_n$ in the weak* topology and $\mu_n \phi + h_{\mu_n}(T) \to P(\phi)$. We proceed as in Proof of Proposition 2.6.6. In view of Theorem 2.4.1 (Variational Principle) $\mu_n(\phi+\psi) + h_{\mu_n}(T) \leq P(\phi+\psi)$ which means that $\mu_n(\psi) \leq P(\phi + \psi) - (\mu_n\phi + h_{\mu_n}(T))$. Thus, letting $n \to \infty$, we get $\mu(\psi) \leq P(\phi + \psi) - P(\phi)$. This means that $\mu \in C(X)^*_{\phi,P}$.

Now, let us prove our theorem in the other direction. Recall again that the function $\mu \mapsto h_\mu(T)$ on $M(X,T)$ is affine (Theorem 1.4.7), hence concave. Set $\overline{h}_\mu(T) = \limsup_{\nu \to \mu} h_\nu(T)$, with $\nu \to \mu$ in weak*-topology. The function $\mu \mapsto \overline{h}_\mu(T)$ is also concave and upper semicontinuous on $M(T) = M(X,T)$. In the sequel we shall prefer to consider the function $\mu \mapsto -\overline{h}_\mu(T)$ which is lower semicontinuous and convex.

We need the following.

Lemma 2.6.11 (On composing two LF-transformations.)**.** *For every $\mu \in M(T)$*

$$\sup_{\vartheta \in C(X)} \left(\mu\vartheta - \sup_{\nu \in M(T)} (\nu\vartheta - (-h_\nu(T))) \right) = -\overline{h}_\mu(T)), \qquad (2.6.6)$$

which, due to the Variational Principle, takes the form

$$\sup_{\vartheta \in C(X)} \left(\mu\vartheta - P(\vartheta) \right) = -\overline{h}_\mu(T)) \qquad (2.6.7)$$

Proof. To prove (2.6.6), observe first that for every $\vartheta \in C(X)$,

$$\mu\vartheta - \sup_{\nu \in M(T)} (\nu\vartheta - (-h_\nu(T))) \leq \mu\vartheta - (\mu\vartheta - (-\overline{h}_\mu(T))) = -\overline{h}_\mu(T)).$$

Notice that we obtained above $-\overline{h}_\nu(T))$ rather than merely $-h_\nu(T))$, by taking all sequences $\mu_n \to \mu$, writing on the right hand side of the above inequality the expression $\mu\vartheta - (\mu_n\vartheta - (-h_{\mu_n}\vartheta(T)))$, and letting $n \to \infty$. So

$$\sup_{\vartheta \in C(X)} \left(\mu\vartheta - \sup_{\nu \in M(T)} (\nu\vartheta - (-h_\nu(T))) \right) \leq -\overline{h}_\mu(T). \qquad (2.6.8)$$

This says that the LF-transform of the LF-transform of $-h_\mu(T)$ is less than or equal to $-\overline{h}_\mu(T)$. The preceding LF-transform was discussed in Remark 2.6.3. The following LF-transformation, leading from $\vartheta \to P(\vartheta)$ to $\nu \to -(-h_\nu(T))$ is defined by $\sup_{\vartheta \in C(X)} \left(\mu\vartheta - P(\vartheta) \right)$.

Let us prove now the opposite inequality. We refer to the following consequence of the geometric form of Hahn-Banach Theorem [Bourbaki 1981, Ch. II.§5. Prop. 5]:

Let M be a closed convex set in a locally convex vector space V. Then every lower semi-continuous convex function f defined on M is the supremum of a family of functions bounded above by f, which are restrictions to M of continuous affine functions on V.

We shall apply this theorem to $V = C^*(X)$ endowed with the weak*-topology, to $f(\nu) = \mathrm{h}_\nu(T)$. We use the fact that every linear functional continuous with respect to this topology is represented by an element belonging to $C(X)$. (This is a general fact concerning dual pairs of vector spaces, [Bourbaki 1981, Ch. II.§6. Prop. 3]). Thus, for every $\varepsilon > 0$ there exists $\psi \in C(X)$ such that for every $\nu \in M(T)$,

$$(\nu - \mu)(\psi) \leq -\mathrm{h}_\nu(T) - (-\overline{\mathrm{h}}_\mu(T)) + \varepsilon. \tag{2.6.9}$$

So

$$\mu\psi - \sup_{\nu \in M(T)} (\nu\psi - (-\mathrm{h}_\nu(T))) \geq -\overline{\mathrm{h}}_\mu(T) - \varepsilon.$$

Letting $\varepsilon \to 0$ we obtain

$$\sup_{\vartheta \in C(X)} \left(\mu\vartheta - \sup_{\nu \in M(T)} (\nu\vartheta - (-\mathrm{h}_\nu(T))) \right) \geq -\overline{\mathrm{h}}_\mu(T).$$

♣

Continuation of Proof of Theorem 2.6.10. Fix $\mu = \mu_F \in C(X)^*_{\phi,\mathrm{P}}$. From $\mu\psi \leq P(\phi + \psi) - P(\phi)$ we obtain

$$P(\phi + \psi) - \mu(\phi + \psi) \geq \mathrm{P}(\phi) - \mu\phi \text{ for all } \psi \in C(X).$$

So,

$$\inf_{\psi \in C(X)} \{\mathrm{P}(\psi) - \mu\psi\} \geq \mathrm{P}(\phi) - \mu\phi. \tag{2.6.10}$$

This expresses the fact that the supremum (– infimum above) in the definition of the LF-transform of P at F is attained at ϕ at which F is tangent to P.

By Lemma 2.6.11 and (2.6.10) we obtain

$$\overline{\mathrm{h}}_\mu \geq \mathrm{P}(\phi) - \mu\phi. \tag{2.6.11}$$

So, by the definition of $\overline{\mathrm{h}}_\mu$ there exists a sequence of measures $\mu_n \in M(T)$ such that $\lim_{n \to \infty} \mu_n = \mu$ and $\lim_{n \to \infty} h_{\mu_n} \geq P(\phi) - \mu\phi$. The proof is finished.   ♣

Remark 2.6.12. In Lemma 2.6.11 we considered as $\mu = \mu_F$ an arbitrary $\mu \in M(T)$; we did not assume that μ_F is tangent to P, i.e. that $F \in C(X)^*_{\phi,P}$. Then considering $\varepsilon > 0$ in (2.6.9) was necessary; without $\varepsilon > 0$ this formula might happen to be false, see Example 2.6.15.

In the proof of Theorem 2.6.10, for $\mu \in C(X)^*_{\phi,\mathrm{P}}$, we obtain from (2.6.11) and the inequality $\mathrm{h}_\nu(T) \leq \mathrm{P}(\phi) - \nu\phi$ for every $\nu \in M(T)$ that

$$h_\nu(T) - \overline{\mathrm{h}}_\mu(T) \leq (\mu - \nu)\phi, \tag{2.6.12}$$

which is just (2.6.9) with $\varepsilon = 0$.

The meaning of this, is that if $\mu = \mu_F$ is tangent to P at ϕ then ϕ is tangent to $-\overline{\mathrm{h}}$, the LF-transform of P, at μ.

Conversely, if ψ satisfies (2.6.12) i.e. ψ is tangent to $-\overline{\mathrm{h}}$ at $\mu \in M(T)$ then, as in the second part of the proof of Theorem 2.6.10 we can prove the inequality analogous to (2.6.10), namely that

$$\sup_{\nu \in M(T)} \nu\psi - (-\overline{\mathrm{h}}_\mu(T)) = \mathrm{P}(\psi) \le \mu\psi - (-\overline{\mathrm{h}}_\mu(T)).$$

Hence μ is tangent to P at ψ

Assume now the upper semicontinuity of the entropy $\mathrm{h}_\mu(T)$ as a function of μ. Then, as an immediate consequence of Theorem 2.6.10, we obtain.

Corollary 2.6.13. *If the entropy is upper semicontinuous, then a functional $F \in C(X)^*$ is tangent to P at $\phi \in C(X)$ if and only if it is represented by a measure which is an equilibrium state for ϕ.*

Recall that the upper semicontinuity of entropy implies the existence of at least one equilibrium state for every continuous $\phi : X\mathbb{R}$, already by Proposition 2.5.3)

Now we can complete Corollary 2.6.7.

Corollary 2.6.14. *If the entropy is upper semicontinuous then the pressure function P is differentiable at $\phi \in C(X)$ in every direction, or in a set of directions dense in the weak topology, if and only if there is at most one equilibrium state for ϕ.*

Proof. This Corollary follows directly from Corollary 2.6.13 and Theorem 2.6.5.
♣

After discussing functionals tangent to P and proving that they coincide with the set of equilibrium states for maps for which the entropy is upper semicontinuous as the function on $M(T)$ the question arises of whether all measures in $M(T)$ are equilibrium states of some continuous functions. The answer given below is no.

Example 2.6.15. We shall construct a measure $m \in M(T)$ which is not an equilibrium state for any $\phi \in C(X)$. Here X is the one sided shift space Σ^2 with the left side shift map σ. Since this map is obviously expansive, it follows from Theorem 2.5.6 that the entropy function is upper semicontinues. Let $m_n \in M(\sigma)$ be the measure equidistributed on the set Per_n of points of period n, i.e.

$$m_n = \sum_{x \in \mathrm{Per}_n} \frac{1}{\mathrm{Card}\,\mathrm{Per}_n} \delta_x$$

where δ_x is the Dirac measure supported by x. m_n converge weak* to $\mu_{\max}$, the measure of maximal entropy: $\log 2$. (Check that this follows for example from

the part II of the proof of the Variational Principle.) Let $t_n, n = 0, 1, 2, \ldots$ be a sequence of positive real numbers such that $\sum_{n=0}^{\infty} t_n = 1$. Finally define

$$m = \sum_{n=0}^{\infty} t_n m_n$$

Let us prove that there is no $\phi \in C(X)$ tangent to h at m. Let $\mu_n = R_n \mu_{\max} + \sum_{j=0}^{n-1} t_j m_j$, where $R_n = \sum_{j=n}^{\infty} t_j$. We have of course $h_{m_n}(\sigma) = 0$, $n = 1, 2, \ldots$. Therefore, $h_m(\sigma) = 0$. This follows for example from Theorem 1.8.11 (ergodic decomposition theorem) or just from the fact that h is affine on $M(\sigma)$, Theorem 1.4.7.

Thus, since h is affine,

$$h_{\mu_n}(\sigma) - h_m(\sigma) = R_n \, h_{\mu_{\max}}(\sigma) = R_n \log 2 \qquad (2.6.13)$$

and for an arbitrary $\phi \in C(\Sigma^2)$

$$(\mu_n - m)\phi = (R_n \mu_{\max} - \sum_{j=n}^{\infty} t_j m_j)\phi \leq R_n \varepsilon_n \qquad (2.6.14)$$

where $\varepsilon_n \to 0$ as $n \to \infty$ because $m_j \to \mu_{\max}$. The inequalities (2.6.13) and (2.6.14) prove that ϕ is not "tangent" to h at m. More precisely, we obtain $h_{\mu_n}(\sigma) - h_m(\sigma) > (\mu_n - m)\phi$ for n large, i.e.

$$-h_{\mu_n}(\sigma) - (-h_m(\sigma)) > (\mu_n - m)\psi$$

for $\psi = -\phi$, opposite to the tangency inequality (2.6.12). So, by Remark 2.6.12, m is not tangent to any ϕ for the pressure function P.

In fact it is easy to see that m is not an equilibrium state for any $\phi \in C(\Sigma^2)$ directly: For an arbitrary $\phi \in C(\Sigma^2)$ we have $\mu_{\max}\phi < P(\phi)$ because $h_{\mu_{\max}}(\sigma) > 0$. So $m_n \phi < P(\phi)$ for all n large enough as $m_n \to \mu_{\max}$. Also $m_n \phi \leq P(\phi)$ for all n's. So for m being the average of m_n's we have $m\phi = m\phi + h_m(\sigma) < P(\phi)$. So ϕ is not an equilibrium state.

The measure m in this example is very non-ergodic, this is necessary as will follow from Exercise 2.15.

Exercises

Topological entropy

2.1. Let $T : X \to X$ and $S : Y \to Y$ be two continuous maps of compact metric spaces X and Y respectively. Show that $h_{\text{top}}(T \times S) = h_{\text{top}}(T) + h_{\text{top}}(S)$.

2.2. Prove that $T : X \to X$ is an isometry of a compact metric space X, then $h_{\text{top}}(T) = 0$

2.3. Show that if $T : X \to X$ is a local homeomorphism of a compact connected metric space and $d = \#T^{-1}(x)$ (note that it is independent of $x \in X$), then $\mathrm{h_{top}}(T) \geq \log d$.

2.4. Prove that if $f : M \to M$ is a C^1 endomorphism of a compact differentiable manifold M, then $\mathrm{h_{top}}(f) \geq \log \deg(f)$, where $\deg(f)$ means degree of f.

   Hint: Look for (n, ϵ)-separated points in $f^{-n}(x)$ for "good" x.
See [Misiurewicz & Przytycki 1977] or [Katok & Hasselblatt 1995]).

2.5. Let $S^1 = \{z \in \mathbb{C} : |z| = 1\}$ be the unit circle and let $f_d : S^1 \to S^1$ be the map defined by the formula $f_d(z) = z^d$. Show that $\mathrm{h_{top}}(f_d) = \log d$.

2.6. Let $\sigma_A : \Sigma_A \to \Sigma_A$ be the shift map generated by the incidence matrix A. Prove that $\mathrm{h_{top}}(\sigma_A)$ is equal to the logarithm of the spectral radius of A.

2.7. Show that for every continuous potential ϕ, $\mathrm{P}(\phi) \leq \mathrm{h_{top}}(T) + \sup(\phi)$ (see (2.6.1)).

2.8. Provide an example of a transitive diffeomorphism without measures of maximal entropy.

2.9. Provide an example of a transitive diffeomorphism with at least two measures of maximal entropy.

2.10. Find a sequence of continuous maps $T_n : X_n \to X_n$ such that $\mathrm{h_{top}}(T_{n+1}) > \mathrm{h_{top}}(T_n)$ and $\lim_{n\to\infty} \mathrm{h_{top}}(T_n) < \infty$.

Topological pressure: functional analysis approach

2.11. Prove that for an arbitrary convex continuous function $P : V \to \mathbb{R}$ on a real Banach space V the set of tangent functionals: $\bigcup_{x\in V} V_{x,P}^*$ is dense in the norm topology in the set of so-called P-bounded functionals:

$$\{F \in V^* : (\exists C \in \mathbb{R}) \text{ such that } (\forall\, x \in V),\ \ F(x) \leq P(x) + C\}.$$

Remark. The conclusion is that for P being the pressure function on $C(X)$, tangent measures are dense in $M(X, T)$, see Theorem 2.5.6. Hint: This follows from Bishop – Phelps Theorem, see [Bishop & Phelps 1963] or Israel's book [Israel 1979, pp. 112-115], which can be stated as follows:

   For every P-bounded functional F_0, for every $x_0 \in V$ and for every $\varepsilon > 0$ there exists $x \in V$ and $F \in V^*$ tangent to P at x such that

$$\|F - F_0\| \leq \varepsilon \text{ and } \|x - x_0\| \leq \frac{1}{\varepsilon}\Big(P(x_0) - F_0(x_0) + s(F_0),$$

where $s(F_0) := \sup_{x'\in V}\{F_0 x' - P(x')\}$ (this is $-\overline{\mathrm{h}}$, the LF-transform of P).

   The reader can imagine F_0 as asymptotic to P and estimate how far is the tangency point x of a functional F close to F_0.

2.12. Prove that in the situation from Exercise 2.11, for every $x \in V$, the set $V_{x,P}^*$ is convex and weak*-compact.

2.13. Let E_ϕ denote the set of all equilibrium states for $\phi \in C(X)$.

(i) Prove that E_ϕ is convex.

(ii) Find an example that E_ϕ is not weak*-compact.

(iii) Prove that extremal points of E_ϕ are extremal points of $M(X,T)$.

(iv) Prove that almost all measures in the ergodic decomposition of an arbitrary $\mu \in E_\phi$ belong also to E_ϕ. (One says that every equilibrium state has a unique decomposition into pure, i.e. ergodic, equilibrium states .)

Hints: In (ii) consider a sequence of Smale horseshoes of topological entropies $\log 2$ converging to a point fixed for T. To prove (iii) and (iv) use the fact that entropy is an affine function of measure.

2.14. Find an example showing that the point (iii) of Exercise 2.13 is false if we consider $C(X)^*_{\phi,P}$ rather than E_ϕ.

Hint: An idea is to have two fixed points p, q and two trajectories $(x_n), (y_n)$ such that $x_n \to p, y_n \to q$ for $n \to \infty$ and $x_n \to q, y_n \to p$ for $n \to -\infty$. Now take a sequence of periodic orbits γ_k approaching $\{p, q\} \cup \{x_n\} \cup \{y_n\}$ with periods tending to ∞. Take their Cartesian products with corresponding invariant subsets A_k's of small horseshoes of topological entropies less than $\log 2$ but tending to $\log 2$, diameters of the horseshoes shrinking to 0 as $k \to \infty$. Then for $\phi \equiv 0$ $C(X)^*_{\phi,P}$ consists only of measure $\frac{1}{2}(\delta_p + \delta_q)$. One cannot repeat the proof in Exercise 2.13(iii) with the function $\overline{h}_\mu$ instead of the entropy function h_μ, because $\overline{h}_\mu$ is no more affine !

This is Peter Walters' example, for details see the preprint [Walters-preprint].

2.15. Suppose that the entropy function h_μ is upper semicontinuous (then for each $\phi \in C(x)$ $C(X)^*_{\phi,P} = E_\phi$, see Corollary 2.6.13). Prove that

(i) every $\mu \in M(T)$ which is a finite combination of ergodic masures $\mu = \sum t_j m_j$, $m_j \in M(T)$, is tangent to P more precisely there exists $\phi \in C(X)$ such that $\mu, m_j \in C(X)^*_{\phi,P}$ and moreover they are equilibrium states for ϕ.

(ii) if $\mu = \int_{M_e(T)} m d\alpha(m)$ where $M_e(X,T)$ consists of ergodic measures in $M(X,T)$ and α is a probability non-atomic measure on $M_e(X,T)$, then there exists $\phi \in C(X)$ which has uncountably many ergodic equilibria in the support of α.

(iii) the set of elements of $C(X)$ with uncountably many ergodic equilibria is dense in $C(X)$.

Hint: By Bishop – Phelps Theorem (Remark in Exercise 2.11) there exists $\nu \in E_\phi$ arbitrarily close to μ. Then in its ergodic decomposition there are all the measures μ_j because all ergodic measures are far apart from each other (in the norm in $C(X)^*$). These measures by Exercise 2.13 belong to the same E_ϕ what proves (i). For more details and proofs of (ii) and (iii) see [Israel 1979, Theorem V.2.2] or [Ruelle 1978, 3.17, 6.15].

Remark. In statistical physics the occurence of more then one equilibrium for $\phi \in C(X)$ is called "phase transition". (iii) says that the set of functions with "very rich" phase transition is dense. For the further discussion see also [Israel 1979, V.2].

2.16. Prove the following. Let $P : V \to \mathbb{R}$ be a continuous convex function on a real Banach space V with norm $\|\cdot\|_V$. Suppose P is differentiable at $x \in V$ in

every direction. Let $W \subset V$ be an arbitrary linear subspace with norm $\| \cdot \|_W$ such that the embedding $W \subset V$ is continuous and the unit ball in $(W, \| \cdot \|_W)$ is compact in $(V, \| \cdot \|_V)$. Then $P|_W$ is differentiable in the sense that there exists a functional $F \in V^*$ such that for $y \in W$ it holds

$$|P(x + y) - P(x) - F(y)| = o(\|y\|_W).$$

Remark. In Chapter 3 we shall discuss W being the space of Hölder continuous functions with an arbitrary exponent $\alpha < 1$ and the entropy function will be upper semicontinuous. So the conclusion will be that uniqueness of the equilibrium state at an arbitrary $\phi \in C(X)$ is equivalent to the differentiability in the direction of this space of Hölder functions.

2.17. (Walters) Prove that the pressure function P is Frechet differentiable at $\phi \in C(X)$ if and only if P affine in a neighbourhood of ϕ. Prove also the conclusion: P is Frechet differentiable at every $\phi \in C(X)$ if and only if T is uniquely ergodic, namely if $M(X, T)$ consists of one element.

2.18. Prove S. Mazur's Theorem: If $P : V \to \mathbb{R}$ is a continuous convex function on a real separable Banach space V then the set of points at which there exists a unique functional tangent to P is dense G_δ.

Remark. In the case of the pressure function on $C(X)$ this says that for a dense G_δ set of functions there exists at most one equilibrium state. Mazur's Theorem contrasts with the theorem from Exercise 16 (iii).

Bibliographical notes

The concept of topological pressure in dynamical context was introduced by D. Ruelle in [Ruelle 1973] and since then have been studied in many papers and books. Let us mention only [Bowen 1975], [Walters 1976], [Walters 1982] and [Ruelle 1978]. The topological entropy was introduced earlier in [Adler, Konheim & McAndrew 1965]. The Variational Principle (Theorem 2.4.1) has been proved for some maps in [Ruelle 1973]. The first proofs of this principle in its full generality can be found in [Walters 1976] and [Bowen 1975]. The simplest proof presented in this chapter is taken from [Misiurewicz 1976]. In the case of topological entropy (potential $\phi = 0$) the corresponding results have been obtained earlier: Goodwyn in [Goodwyn 1969] proved the first part of the Variational Principle, Dinaburg in [Dinaburg 1971] proved its full version assuming that the space X has finite covering topological dimension and finally Goodman proved in [Goodman 1971] the Variational Principle for topological entropy without any additional assumptions. The concept of equilibrium states and expansive maps in mathematical setting was introduced in [Ruelle 1973] where the first existence and uniqueness type results have appeared. Since then these concepts have been explored by many authors, in particular in [Bowen 1975] and [Ruelle 1978]. The material of Section 2.6 is mostly taken from [Ruelle 1978], [Israel 1979] and [Ellis 1985].

Chapter 3

Distance expanding maps

We devote this Chapter to a study in detail of topological properties of distance expanding maps. Often however weaker assumptions will be sufficient. We always assume the maps are continuous on a compact metric space X, and we usually assume that the maps are open, which means that open sets have open images. This is equivalent to saying that if $f(x) = y$ and $y_n \to y$ then there exist $x_n \to x$ such that $f(x_n) = y_n$ for n large enough.

In view of Section 3.6, in theorems with assertions of topological character, only the assumption that a map is expansive leads to the same conclusions as if we assumed that the map is expanding. We shall prove in Section 3.6 that for every expansive map there exists a metric compatible with the topology on X given by an original metric, such that the map is distance expanding with respect to this new metric.

Recall that for (X, ρ), a compact metric space, a continuous mapping $T : X \to X$ is said to be *distance expanding* (with respect to the metric ρ) if there exist constants $\lambda > 1$, $\eta > 0$ and $n \geq 0$, such that for all $x, y \in X$

$$\rho(x, y) \leq 2\eta \implies \rho(T^n(x), T^n(y)) \geq \lambda \rho(x, y) \qquad (3.0.1)$$

We say that T is *distance expanding at a set* $Y \subset X$ if the above holds for all $z \in Y$ and for every $x, y \in B(z, \eta)$.

In the sequel we will always assume that $n = 1$ i.e. that

$$\rho(x, y) \leq 2\eta \implies \rho(T(x), T(y)) \geq \lambda \rho(x, y), \qquad (3.0.2)$$

unless otherwise stated. One can achieve this in two ways:

(1) If T is Lipschitz continuous (say with constant $L > 1$), replace the metric $\rho(x, y)$ by $\sum_{j=0}^{n-1} \rho(T^j(x), T^j(y))$. Of course then λ and η change. As an exercise you can check that the number $1 + (\lambda - 1)\left(\frac{L-1}{L^n - 1}\right)$ can play the role of λ in (3.0.2).

Notice that the ratio of both metrics is bounded; in particular they yield the same topologies.

For another improvement of ρ, working without assuming Lipschitz continuity of T, see 3.6.3.

(2) Work with T^n instead of T.

Sometimes, in order to simplify notation, we shall write *expanding*, instead of *distance expanding*.

3.1 Distance expanding open maps, basic properties

Let us first make a simple observation relating the propery of being *expanding* and being *expansive*.

Theorem 3.1.1. *Distance expanding property implies forward expansive property.*

Proof. By the definition of "expanding" above, if $0 < \rho(x,y) \leq 2\eta$, then $\rho(T(x), T(y)) \geq \lambda\rho(x,y)$ ... $\rho(T^n(x), T^n(y)) \geq \lambda^n\rho(x,y)$, until for the first time n it happens $\rho(T^n(x), T^n(y)) > 2\eta$. Such n exists since $\lambda > 1$. Therefore T is forward expansive with the expansivness constant $\delta = 2\eta$.   ♣

Let us prove now a lemma where we assume only $T : X \to X$ to be a continuous open map of a compact metric space X. We do not need to assume in this lemma that T is distance expanding.

Lemma 3.1.2. *If $T : X \to X$ is a continuous open map, then for every $\eta > 0$ there exists $\xi > 0$ such that $T(B(x,\eta)) \supset B(T(x),\xi)$ for every $x \in X$.*

Proof. For every $x \in X$ let

$$\xi(x) = \sup\{r > 0 : T(B(x,\eta)) \supset B(T(x),r)\}.$$

Since T is open, $\xi(x) > 0$. Since $T(B(x,\eta)) \supset B(T(x),\xi(x))$, it suffices to show that $\xi = \inf\{\xi(x) : x \in X\} > 0$. Suppose conversely that $\xi = 0$. Then there exists a sequence of points $x_n \in X$ such that

$$\xi(x_n) \to 0 \quad \text{as} \quad n \to \infty \tag{3.1.1}$$

and, as X is compact, we can assume that $x_n \to y$ for some $y \in X$. Hence $B(x_n,\eta) \supset B(y,\frac{1}{2}\eta)$ for all n large enough. Therefore

$$T(B(x_n,\eta)) \supset T\left(B\left(y,\frac{1}{2}\eta\right)\right) \supset B(T(y),\varepsilon) \supset B\left(T(x_n),\frac{1}{2}\varepsilon\right)$$

for some $\varepsilon > 0$ and again for every n large enough. The existence of ε such that the second inclusion holds follows from the openness of T. Consequently $\xi(x_n) \geq \frac{1}{2}\varepsilon$ for these n, which contradicts (3.1.1).   ♣

Definition 3.1.3. If $T : X \to X$ is an expanding map, then by (3.0.1), for all $x \in X$, the restriction $T|_{B(x,\eta)}$ is injective and therefore it has the inverse map on $T(B(x,\eta))$. (The same holds for expanding at a set Y for all $x \in Y$.)

If additionally $T : X \to X$ is an open map, then, in view of Lemma 3.1.2, the domain of the inverse map contains the ball $B(T(x), \xi)$. So it makes sense to define the restriction of the inverse map,

$$T_x^{-1} : B(T(x), \xi) \to B(x, \eta) \tag{3.1.2}$$

Observe that for every $y \in X$ and every $A \subset B(y, \xi)$

$$T^{-1}(A) = \bigcup_{x \in T^{-1}(y)} T_x^{-1}(A) \tag{3.1.3}$$

Indeed, the inclusion $\supset$ is obvious. So suppose that $x' \in T^{-1}(A)$. Then $y' = T(x') \in B(y, \xi)$. Hence $y \in B(y', \xi)$. Let $x = T_{x'}^{-1}(y)$. As T_x^{-1} and $T_{x'}^{-1}$ coincide on y, they coincide on y' because they map y' into $B(x, \eta)$ and T is injective on $B(x, \eta)$. Thus $x' = T_x^{-1}(y')$.

Formula (3.1.3) for all $A = B(y, \xi)$ implies that T is so-called *covering map*.

(This property is in fact a standard definition of a covering map, except that for general covering maps, on non-compact spaces ξ may depend on y. We proved in fact that a local homeomorphism of a compact space is a covering map)

From now on throughout this Section, wherever the notation T^{-1} appears, we assume also the expanding property, i.e. (3.0.2). We then get the following.

Lemma 3.1.4. *If $x \in X$ and $y, z \in B(T(x), \xi)$ then*

$$\rho(T_x^{-1}(y), T_x^{-1}(z)) \leq \lambda^{-1} \rho(y, z)$$

In particular $T_x^{-1}(B(T(x), \xi)) \subset B(x, \lambda^{-1}\xi) \subset B(x, \xi)$ and

$$T(B(x, \lambda^{-1}\xi)) \supset B(T(x), \xi) \tag{3.1.4}$$

for all $\xi > 0$ small enough (what specifies the inclusion in Lemma 3.1.2).

Definition 3.1.5. For every $x \in X$, every $n \geq 1$ and every $j = 0, 1, \ldots, n-1$ write $x_j = T^j(x)$. In view of Lemma 3.1.4 the composition

$$T_{x_0}^{-1} \circ T_{x_1}^{-1} \circ \ldots \circ T_{x_{n-1}}^{-1} : B(T^n(x), \xi) \to X$$

is well-defined and will be denoted by T_x^{-n}.

Below we collect the basic elementary properties of maps T_x^{-n}. They follow immediately from (3.1.3) and Lemma 3.1.4. For every $y \in X$

$$T^{-n}(A) = \bigcup_{x \in T^{-n}(y)} T_x^{-n}(A) \tag{3.1.5}$$

for all sets $A \subset B(y, \xi)$;

$$\rho(T_x^{-n}(y), T_x^{-n}(z)) \leq \lambda^{-n} \rho(y, z) \text{ for all } y, z \in B(T^n(x), \xi); \tag{3.1.6}$$

$$T_x^{-n}(B(T^n(x), r)) \subset B(x, \min\{\eta, \lambda^{-n}r\}) \text{ for every } r \leq \xi. \tag{3.1.7}$$

Remark. All these properties hold, and notation makes sense, also for open maps $T : X \to X$ expanding at $Y \subset X$, provided $x, T(x), \ldots, T^n(x) \in Y$.

3.2   Shadowing of pseudoorbits

We keep the notation of Section 3.1. We consider an open distance expanding map $T : X \to X$ with the constants η, λ, ξ.

Let n be a non-negative integer or $+\infty$. Given $\alpha \geq 0$ a sequence $(x_i)_0^n$ is said to be an α-*pseudo-orbit* (alternatively called: α-*orbit, α-trajectory, α-T-trajectory*) for $T : X \to X$ of length $n + 1$ if for every $i = 0, \ldots, n - 1$

$$\rho(T(x_i), x_{i+1}) \leq \alpha. \tag{3.2.1}$$

Of course every (genuine) orbit $(x, T(x), \ldots, T^n(x))$, $x \in X$, is an α-pseudo-orbit for every $\alpha \geq 0$. We shall prove a kind of a converse fact, that in the case of open, distance expanding maps, each "sufficiently good" pseudo-orbit can be approximated (shadowed) by an orbit. To make this precise we proceed as follows. Let $\beta > 0$. We say that an orbit of $x \in X$, β-*shadows* the pseudo-orbit $(x_i)_0^n$ if and only if for every $i = 0, \ldots, n$

$$\rho(T^i(x), x_i) \leq \beta. \tag{3.2.2}$$

Definition 3.2.1. We say that a continuous map $T : X \to X$ has *shadowing property* if for every $\beta > 0$ there exists $\alpha > 0$ such that every α-pseudo-orbit of finite or infinite length can be β-shadowed by an orbit.

Note that due to the compactness of X shadowing property for all finite n implies shadowing with $n = \infty$.

Here comes a simple observation yielding the uniqueness of the shadowing. Assume only that T is expansive (cf. Section 2.2).

Proposition 3.2.2. *If 2β is less than an expansiveness constant of T (we do not need to assume here that T is expanding with respect to the metric ρ) and $(x_i)_0^\infty$ is an arbitrary sequence of points in X, then there exists at most one point x whose orbit β-shadows the sequence $(x_i)_{i=0}^\infty$.*

Proof. Suppose the forward orbits of x and y β-shadow (x_i). Then for every $n \geq 0$ we have $\rho(T^n(x), T^n(y)) \leq 2\beta$. Then since 2β is the expansiveness constant for T we get $x = y$.   ♣

We shall now prove some less trivial results, concerning the existence of β-shadowing orbits.

Lemma 3.2.3. *Let $T : X \to X$ be an open distance expanding map. Let $0 < \beta < \xi$, $0 < \alpha \leq \min\{(\lambda - 1)\beta, \xi\}$. If $(x_i)_0^\infty$ is an α-pseudo-orbit, then the points $x_i' = T_{x_i}^{-1}(x_{i+1})$ are well-defined and*

(a) For all $i = 0, 1, 2, \ldots, n - 1$,

$$T_{x_i'}^{-1}(\overline{B(x_{i+1}, \beta)}) \subset \overline{B(x_i, \beta)}$$

and consequently, for all $i = 0, 1, \ldots, n$, the compositions

$$S_i := T_{x_0'}^{-1} \circ T_{x_1'}^{-1} \circ \ldots \circ T_{x_{i-1}'}^{-1} : \overline{B(x_i, \beta)} \to X$$

are well-defined.

(b) The sequence of closed sets $S_i(\overline{B(x_i, \beta)})$, $i = 0, 1, \ldots, n$, is descending.

(c) The intersection

$$\bigcap_{i=0}^{n} S_i(\overline{B(x_i, \beta)})$$

is non-empty and the forward orbits (for times $0, 1, \ldots, n$) of all the points of this intersection β-shadow the pseudo-orbit $(x_i)_0^n$.

Proof. x_i' are well-defined by $\alpha \leq \xi$. In order to prove (a) observe that by (3.1.7) and we have

$$T_{x_i'}^{-1}(\overline{B(x_{i+1}, \beta)}) \subset \overline{B(x_i', \lambda^{-1}\beta)} \subset \overline{B(x_i, \lambda^{-1}\beta + \lambda^{-1}\alpha)}$$

and $\lambda^{-1}\beta + \lambda^{-1}\alpha \leq \beta$ as $\alpha \leq (\lambda - 1)\beta$. The statement (b) follows immediately from (a). The first part of (c) follows immediately from (b) and the compactness of the space X. To prove the second part denote the intersection which appears in (c) by A. Then $T^i(A) \subset \overline{B(x_i, \beta)}$ for all $i = 0, 1, \ldots, n$. Thus the forward orbit of every point in A, β shadows $(x_i)_0^n$. The proof is finished. ♣

As an immediate consequence of Lemma 3.2.3 we get the following.

Corollary 3.2.4 (Shadowing lemma). *Every open, distance expanding map satisfies the shadowing property. More precisely, for all $\beta > 0$ and $\alpha > 0$ as in Lemma 3.2.3 every α-pseudo-orbit $(x_i)_0^n$ can be β-shadowed by an orbit in X.*

As a consequence of Corollary 3.2.4 we shall prove the following.

Corollary 3.2.5 (Closing lemma). *Let $T : X \to X$ be an expansive map, satisfying the shadowing property. Then for every $\beta > 0$ there exists $\alpha > 0$ such that if $x \in X$ and $\rho(x, T^l(x)) \leq \alpha$ for some $l \geq 1$, then there exists a periodic point of period l whose orbit β-shadows the pseudo-orbit $(x, T(x), \ldots, T^{l-1}(x))$. The choice of α to β is the same as in the definition of shadowing.*

In particular the above holds for every $T : X \to X$ an open, distance expanding map.

Proof. We can assume without loss of generality that 2β is less than the expansiveness constant for T.Since $\rho(x, T^l(x)) \leq \alpha$, the sequence made up as the infinite concatenation of the sequence $(x, T(x), \ldots, T^{l-1}(x))$ is an α-pseudo-orbit. Hence, by shadowing with $n = \infty$, there is a point $y \in X$ whose orbit β-shadows this pseudo-orbit. But note that then the orbit of the point $T^l(y)$ also does it and therefore, by Proposition 3.2.2, $T^l(y) = y$. The proof is finished. ♣

Note that the assumption T is expansive is substantial. The adding machine map, see Example 0.5, satisfies the shadowing property, whereas it has no periodic orbits at all. In fact the same proof yields the following *periodic shadowing.*

Definition 3.2.6. We say that a continuous map $T : X \to X$ satisfies *periodic shadowing* property if for every $\beta > 0$ there exists $\alpha > 0$ such that for every finite n and every *periodic α-pseudo-orbit* $x_0, \ldots, x_{n-1}$, that is a sequence of points $x_0, \ldots, x_{n-1}$ such that $\rho(T(x_i), x_{(i+1)(\mathrm{mod}n)}) \leq \alpha$, there exists a point $y \in X$ of period n such that for all $0 \leq i < n$, $\rho(T^i(y), x_i) \leq \beta$.

Note that shadowing and periodic shadowing can hold for the maps that are not expansive. One can just add artificially the missing periodic orbits, of periods 2^n to the adding machine space. This example appears in fact as the nonwandering set for any Feigenbaum-like map of the interval, see Section 6.6.

3.3   Spectral decomposition. Mixing properties

Let us start with general observations concerning iterations of continuous mappings

Definition 3.3.1. Let X be a compact metric space. We call a continuous mapping $T : X \to X$ for a *topologically transitive* if for all non-empty open sets $U, V \subset X$ there exists $n \geq 0$ such that $T^n(U) \cap V \neq \emptyset$. By compactness of X topological transitivity implies that T maps X onto X.

Example 3.3.2. Consider a topological Markov chain Σ_A, or $\tilde{\Sigma}_A$ in a one-sided or two-sided shift space of d states, see Example 0.4. Observe that the left shift map s on the topological Markov chain is topologically transitive iff the matrix A is *irreducible* that is for each i, j there exists an $n > 0$ such that the i, j-th entry $A_{i,j}^n$ of the n-th composition matrix A^n is non-zero.

One can consider a directed graph consisting of d vertices such that there is an edge from a vertex v_i to v_j iff $A_{i,j} \neq 0$; then one can identify elements of the topological Markov chain with infinite paths in the graph (that is sequences of edges indexed by all integers or nonnegative integers depending on whether we consider the two-sided or one-sided case, such that each edge begins at the vertex, where the preceding edge ends). Then it is easy to see that A is irreducible iff for every two vertices v_1, v_2 there exists a finite path from v_i to v_j.

A notion stronger than the topological transitivity, which makes a non-trivial sense only for non-invertible maps T, is the following

Definition 3.3.3. A continuous mapping $T : X \to X$ for a compact metric space X is called *topologically exact* (or *locally eventually onto*) if for every open set $U \subset X$ there exists $n > 0$ such that $T^n(U) = X$.

In Example 3.3.2 in the one-sided shift space case topological exactness is equivalent to the property that there exists $n > 0$ such that the matrix A^n has all entries positive. Such a matrix is called *aperiodic*.

In the two-sided case aperiodicity of the matrix is equivalent to *topological mixing* of the shift map. We say a continuous map is *topologically mixing* if for every non-empty open sets $U, V \subset X$ there exists $N > 0$ such that for every $n \geq N$ we have $T^n(U) \cap V \neq \emptyset$.

Proposition 3.3.4. *The following 3 conditions are equivalent:*

(1) $T : X \to X$ is topologically transitive.

(2) For all non-empty open sets $U, V \subset X$ and every $N \geq 0$ there exists $n \geq N$ such that $T^n(U) \cap V \neq \emptyset$.

(3) There exists $x \in X$ such that every $y \in X$ is its ω-limit point, that is for every $N \geq 0$ the set $\{T^n(x)\}_{n=N}^{\infty}$ is dense in X.

Proof. Let us prove first the implication (1)$\Rightarrow$(3). So, suppose $T : X \to X$ is topologically transitive. Then for every open non-empty set $V \subset X$, the set

$$K(V) := \{x \in X : \text{there exists } n \geq 0 \text{ such that } T^n(x) \in V\} = \bigcup_{n \geq 0} T^{-n}(V)$$

is open and dense in X. Let $\{V_k\}_{k \geq 1}$ be a countable basis of topology of X. By Baire's category theorem, the intersection

$$K := \bigcap_{k \geq 1} \bigcap_{N \geq 0} K(T^{-N}(V_k))$$

is a dense G_δ subset of X. In particular K is non-empty and by its definition the trajectory $(T^n(x))_{n=N}^{\infty}$ is dense in X for every $x \in K$. Thus (1) implies (3).

Let us now prove that (3)$\Rightarrow$(2). Indeed, if $(T^n(x))_0^{\infty}$ is a trajectory satisfying the condition (3), then for all non-empty open sets $U, V \subset X$ and $N \geq 0$, there exist $n \geq m > 0, n - m \geq N$ such that $T^m(x) \in U$ and $T^n(x) \in V$. Hence $T^{n-m}(U) \cap V \neq \emptyset$. Thus (3) implies (2). Since (2) implies (1) trivially, the proof is complete. ♣

Definition 3.3.5. A point $x \in X$ is called wandering if there exists an open neighhbourhood V of x such that $V \cap T^n(V) = \emptyset$ for all $n \geq 1$. Otherwise x is called non-wandering. We denote the set of all non-wandering points for T by Ω or $\Omega(T)$.

Proposition 3.3.6. *For $T : X \to X$ satisfying the periodic shadowing property, the set of periodic points is dense in the set Ω of non-wandering points.*

Proof. Given $\beta > 0$ let $\alpha > 0$ come from the definition of shadowing. Take any $x \in \Omega(T)$ Then by the definition of $\Omega(T)$ there exists $y \in B(x, \alpha/2)$ and $n > 0$ such that $T^n(y) \in B(x, \alpha/2)$. So $\rho(y, T^n(y)) \leq \alpha$. Therefore $(y, T(y), \dots, T^n(y))$ can be β-shadowed by a periodic orbit. Since we can take β arbitrarily small, we obtain the density of periodic points in $\Omega(T)$. ♣

Remark 3.3.7. It is not true that for every open, distance expanding map $T : X \to X$ we have $\overline{\mathrm{Per}} = X$. Here is an example: Let $X = \{(1/2)^n : n = 0, 1, 2, \dots\} \cup \{0\}$. Let $T((1/2)^n) = (1/2)^{n-1}$ for $n > 0$, $T(0) = 0, T(1) = 1$. Let the metric be the restriction to X of the standard metric on the real line. Then $T : X \to X$ is distance expanding but $\Omega(T) = \mathrm{Per}(T) = \{0\} \cup \{1\}$. See also Exercise 3.4.

Here is the main theorem of this section. Its assertion holds under the assumption that $T : X \to X$ is open, distance expanding and even under weaker assumptions below.

Theorem 3.3.8 (on the existence of Spectral Decomposition). *Suppose that $T : X \to X$ is an open map which satisfies also the periodic shadowing property and is expanding at the set of nonwandering points $\Omega(T)$ (equal here to $\overline{\mathrm{Per}(T)}$, the closure of the set of periodic points, by Proposition 3.3.6). Then $\Omega(T)$ is the union of finitely many disjoint compact sets $\Omega_j, j = 1, \ldots, J$, with*

$$(T|_{\Omega(T)})^{-1}(\Omega_j) = \Omega_j$$

and each $T|_{\Omega_j}$ is topologically transitive.

Each Ω_j is the union of $k(j)$ disjoint compact sets Ω_j^k which are cyclically permuted by T and such that $T^{k(j)}|_{\Omega_j^k}$ is topologically exact.

Proof of Theorem 3.3.8. Let us start with defining an equivalence relation $\sim$ on $\mathrm{Per}(T)$. For $x, y \in \mathrm{Per}(T)$ we write $x \sim_\to y$ if for every $\varepsilon > 0$ there exist $x' \in X$ and positive integer m such that $\rho(x, x') < \varepsilon$ and $T^m(x') = T^m(y)$. We write $x \sim y$ if $x \sim_\to y$ and $y \sim_\to x$. Of course for every $x \in \mathrm{Per}(T)$, $x \sim x$, so the relation is symmetric.

Now we shall prove it is transitive. Suppose that $x \sim y$ and $y \sim z$. Let k_y, k_z denote periods of y, z respectively. Let x' be close to x and $T^n(x') = T^n(y) = y$; an integer n satisfiying the latter equality exists since we can take an integer so that the first equality holds and then take any larger integer divisible by k_y. Choose n divisible by $k_y k_z$. Next, since T is open, for y' close enough to y, with $T^m(y') = T^m(z) = z$ for m divisible by k_z, there exists x'' close to x' such that $T^n(x'') = y'$. Hence $T^{n+m}(x'') = T^m(y') = z = T^{n+m}(z)$, since both m and n are divisible by k_z. Thus $x \sim z$. We have thus shown that $\sim$ is an equivalence relation. This proof is illustrated at Figure 3.1.
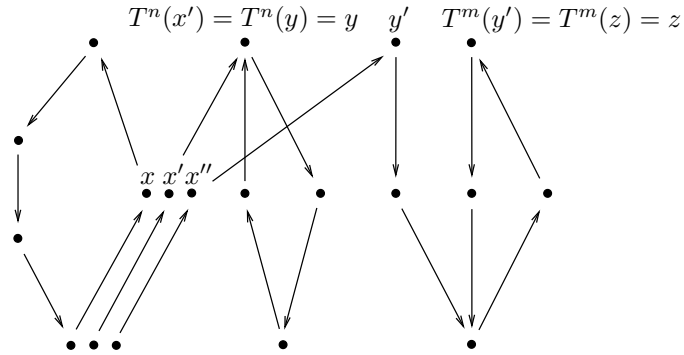

Figure 3.1: Transitivity, the expanding case.

(Figure 3.2 illustrates the transitivity for hyperbolic sets $\overline{\text{Per}(T)}$, see Exercises or [Katok & Hasselblatt 1995], where $x \sim y$ if the unstable manifold of x intersects transversally the stable manifold of y. In our expanding case the role of transversality is played by the openness of T.)

So far we have not used the expanding assumption.

Observe now that for all $x, y \in \text{Per}(T)$, $\rho(x, y) \leq \xi$ implies $x \sim y$. Indeed, we can take $x' = T_x^{-nk_x k_y}(y)$ for n arbitrarily large. Then x' is arbitrarily close to x and $T^{nk_x k_y}(x') = y = T^{nk_x k_y}(y)$. Hence the number of equivalence classes of $\sim$ is finite. Denote them $P_1, \ldots, P_N$. Moreover the sets $\overline{P_1}, \ldots, \overline{P_N}$ are pairwise disjoint and the distances between them are at least ξ. We have $T(\text{Per}(T)) = \text{Per}(T)$, and if $x \sim y$ then $T(x) \sim T(y)$. The latter follows straight from the definition of $\sim$. So T permutes the sets P_i. This permutation decomposes into cyclic permutations we were looking for. More precisely: consider the partition of $\overline{\text{Per}(T)}$ into the sets of the form

$$\bigcup_{n=0}^{\infty} T^n(\overline{P_i}), \ i = 1, \ldots, N.$$

The unions are in fact formed over finite families. It does not matter in which place the closure is placed in these unions, because X is compact so for every $A \subset X$ we have $T(\overline{A}) = \overline{T(A)}$. We consider this partition as a partition into Ω_j's we were looking for. Ω_j^k's are the summands $T^n(\overline{P_i})$ in the unions.

Observe now that T is topologically transitive on each Ω_j.

Indeed, if periodic x, y belong to the same Ω_j there exist $x' \in B(x, \xi)$ and $y' \in B(y, \xi)$ such that $T^n(x') = T^{n_0}(y)$ and $T^m(y') = T^{m_0}(x)$ for some natural numbers n, m and $n_0 \leq k_y, m_0 \leq k_x$. For an arbitrary $\beta > 0$ choose $\alpha > 0$ from the definition of periodic shadowing and consider x'', y'' such that $\rho(x'', x) \leq \alpha$, $\rho(y'', y) \leq \alpha$ and $T^{n_1}(x'') = x'$, $T^{m_1}(y'') = y'$ for some natural numbers n_1, m_1, existing by the expanding property at $\overline{\text{Per}(T)}$. Then the sequence of points $T(x''), \ldots, T^{n_1+n+k_y-n_0}(x''), T(y''), \ldots, T^{m_1+m+k_x-m_0}(y'')$ is a periodic α-pseudo-orbit, of period $n_1 + n + k_y - n_0 + m_1 + m + k_x - m_0$, so it can be β-shadowed by a periodic orbit. Thus, there exists $z \in \text{Per}(T)$ such that $\rho(z, x) \leq \beta$ and $\rho(T^N(z), y) \leq \beta$ for an integer $N > 0$. Now take arbitrary open sets U and V in X intersecting Ω_j and consider periodic points $x \in \Omega_j \cap U$ and $y \in \Omega_j \cap V$ Take β such that $B(x, \beta) \subset U$ and $B(y, \beta) \subset V$. We find a periodic point z as above. Note that, provided $\beta \leq \xi$, $z \sim x$ and $T^N(z) \sim y$. We obtain $T^N(z) \in T^N(U \cap \Omega_j) \cap (V \cap \Omega_j)$ so this set is nonempty. This proves the topological transitivity of $T|_{\Omega_j}$.

Note that by the way we proved that the orbits (their finite parts) $x'', \ldots, T^{n_1}(x'') = x', \ldots, T^n(x')$ and $y'', \ldots, T^{m_1}(y'') = y', \ldots, T^m(y')$ with n_1, n and m_1, m arbitrarily large, can be arbitrarily well shadowed by parts of periodic orbits. This corresponds to the approximation of a transversal homoclinic orbit or of cycles of transversal heteroclinic orbits by periodic ones, in the hyperbolic theory for diffeomorphisms (see also Exercise 3.7).

This analogy justifies the name *heteroclinic cycle points* for the points x' and y', or *heteroclinic cycle orbits* for their orbits discussed above. Thus we proved

Lemma 3.3.9. *Under the assumptions of Theorem 3.3.8 every heteroclinic cycle point is a limit of periodic points.*

The following is interesting in itself:

Lemma 3.3.10. $T|_{\overline{\mathrm{Per}(T)}}$ *is an open map.*

Proof. Fix $x, y \in \overline{\mathrm{Per}(T)}$ and $\rho(T(x), y) \le \varepsilon \le \xi/3$. Since T is open, by Lemma 3.1.2, and due to the expanding property at $\overline{\mathrm{Per}(T)}$ there exists $\hat{y} = T_x^{-1}(y) \in B(x, \lambda^{-1}\xi/3)$ We want to prove that $\hat{y} \in \overline{\mathrm{Per}(T)}$.

There exist $z_1, z_2 \in \mathrm{Per}(T)$ such that $\rho(z_1, x) \le \lambda^{-1}\xi/3$ and $\rho(z_2, y) \le \xi/3$. Hence $\rho(T(z_1), z_2) \le \xi$, hence $T(z_1) \sim z_2$, hence z_1 and z_2 belong to the same Ω_j. Then $T_x^{-1}(z_2)$ is a heteroclinic cycle point, so by Lemma 3.3.9 $T_x^{-1}(z_2)$, hence $\hat{y}$, are limits of periodic points.   ♣

Continuation of the proof of Theorem 3.3.8. We can prove now the topological exactness of $T^{k(j)}|_{\Omega_j^k}$. So fix $\Omega_j^k = P_i$ with $T^{k(j)}(P_i) = P_i$. Let $\{x_s\}, s = 1, \ldots S$ be a $\xi'/2$-spanning set in P_i, where ξ' is a constant having the properties of ξ for the map $T|_{\overline{\mathrm{Per}}}$, existing by the openness of $T|_{\overline{\mathrm{Per}(T)}}$ (Lemma 3.1.2). Write $k(P_i) = \prod_{s=1}^{S} k_{x_s}$. Take an arbitrary open set $U \subset \overline{P_i}$. It contains a periodic point x.

Note that for every ball $B = B(y, r)$ in $\overline{\mathrm{Per}(T)}$ with the origin at $y \in \mathrm{Per}(T)$ and radius r less than η and $\lambda^{-k_y}\xi'$, we have $T^{k_y}(B) \supset B(y, \lambda^{k_y}r)$. Repeating this step by step we obtain $T^{nk(y)}(B) \supset B(y, \xi')$, (see (3.1.7).

Let us go back to U and consider $B_x = B(x, r) \subset U$ with $r \le \lambda^{-k(P_i)}\xi'$. Then $T^{nk(P_i)}(B_x)$ is an increasing family of sets for $n = 0, 1, 2, \ldots$.

By the definition of $\sim$, the set $\bigcup_{n \ge 0} T^{nk(P_i)}(B_x)$ contains $\{x_s :, s = 1, \ldots S\}$, because the points x_s are in the relation $\sim$ with x. This uses the fact proved above, see Lemma 3.3.9, that x' in the definition of $\sim$, such that $T^m(x') = T^m(x_s)$, belongs to $\overline{\mathrm{Per}(T)}$. It belongs even to P_i, since for $z \in \mathrm{Per}(T)$ close to x' we have $z \sim x_s$, with the use of the same x' as one of a heteroclinic cycle points. Hence, the observation above $\bigcup_{n \ge 0} T^{nk(P_i)}(B_x)$ contains the ball $B(x_s, \xi')$ for each s. So it contains $\overline{P_i}$. Since $T^{nk(P_i)}(B_x)$ is an increasing family of open sets in $\overline{\mathrm{Per}(T)}$ that is compact, just one of these sets covers $\overline{\mathrm{Per}(T)}$. The topological exactness and therefore Theorem 3.3.8 is proved.   ♣

Remark 3.3.11. In Theorem 3.3.8 one can replace the assumption the assumption of periodic shadowing by just $\overline{\mathrm{Per}\,T} = \Omega(T)$. (By analogy to Axiom A diffeomorphisms we can call an open map $T : X \to X$ expanding on $\Omega(T)$ and such that $\overline{\mathrm{Per}(T)} = \Omega(T)$, an *Axiom A Ω distance expanding map*.)

Indeed, in Proof of Theorem 3.3.8 we used shadowing only to approximate heteroclinic cycle points by periodic ones. It is sufficient however to notice that heteroclinic cycle points are non-wandering, by the openness of T. (In

particular periodic shadowing is not needed in Lemma 3.3.9 to conclude the non-wandering).

This yields topological transitivity of each $T|_{\Omega_j}$ with the proof similar as before. We find the periodic point z by $\overline{\mathrm{Per}(T)} = \Omega(T)$.

We do not know whether expanding on $\Omega(T)$ implies $\Omega(T) = \overline{\mathrm{Per}(T)}$, For diffeomorphisms hyperbolic on Ω it does not.

As a corollary we obtain the following two theorems.

Theorem 3.3.12. *Let $T : X \to X$ be a continuous mappping for X a compact metric space. Assume that T is open distance expanding, or at least expanding at the set $\overline{\mathrm{Per}(T)}$ satisfying the periodic shadowing property. Then, if T is topologically transitive, or is surjective and its spectral decomposition consists of just one set $\Omega_1 = \bigcup_{k=1}^{k(1)} \Omega_1^k$, the following properties hold:*

(1) The set of periodic points is dense in X, which is thus equal to Ω_1.

(2) For every open $U \subset X$ there exists $N = N(U)$ such that $\bigcup_{j=0}^{N} T^j(U) = X$.

(3) $(\forall r > 0)(\exists N)(\forall x \in X) \bigcup_{j=0}^{N} T^j(B(x,r)) = X$.

(4) The following specification property holds: For every $\beta > 0$ there exists a positive integer N such that for every $n \geq 0$ and every T-orbit $(x_0, \ldots x_n)$ there exists a periodic point y of period not larger than $n + N$ whose orbit for the times $0, \ldots, n$ β-shadows $(x_0, \ldots x_n)$.

Proof. By the topological transitivity, for every open set U there exists $n \geq 1$ such that $T^n(U) \cap U \neq \emptyset$, (use the condition (2) in Proposition 3.3.4 for $N = 1$). Hence for the set Ω of the non-wandering points, we have $\Omega = X$. This gives the density of $\mathrm{Per}(T)$ by Proposition 3.3.6.

If we assume only that there is one $\Omega_1(= \Omega = \overline{\mathrm{Per}(T)})$ in the Spectral Decomposition, then for an arbitrary $z \in X$ we find by the surjectivity of Ta an infinite backward orbit z_{-n} of z. Notice then, that $z_{-n} \to \Omega$ and $T^n(z) \to \Omega$, which follows easily from the definition of Ω. So for every $\alpha > 0$ there exist $w_1, w_2 \in \mathrm{Per}(T)$ and natural numbers k, n such that $T^k(w_2) \sim w_1$, $\rho(w_1, z_{-n}) \leq \alpha$ and $\rho(w_2, T^n(z)) \leq \alpha$. This allows us to find a periodic point in $B(z, \beta)$, where $\beta > 0$ is arbitrarily small and α chosen for β from the periodic shadowing property.

We conclude that $X = \bigcup_{j=1}^{J} \Omega_j$, each Ω_j is T-invariant, closed, and also open since Ω_j's are at least ξ-distant from each other. So $J = 1$. Otherwise, by the topological transitivity, for $j \neq i$ there existed n such that $T^n(\Omega_j) \cap \Omega_i \neq \emptyset$, what would contradict the T-invariance of Ω_j.

Thus $X = \bigcup_{k=1}^{k(1)}(\Omega_1^k)$, and the assertion (2) follows immediately from the topological exactness of $T^{k(1)}$ on each set Ω_1^k, $k = 1, \ldots, k(1)$.

The property (3) follows from (2), where given r we choose $N = \max\{N(U)\}$ associated to a finite cover of X by sets U of diameter not exceeding $r/2$. Indeed, then for every $B(x, r)$ the set U containing x is a subset of $B(x, r)$.

Now let us prove the specification property. By the property (3) for every $\alpha > 0$ there exists $N = N(\alpha)$ such that for every $v, w \in X$ there exists $m \leq N$ and $z \in B(v, \alpha)$ such that $T^m(z) \in B(w, \alpha)$. Consider any T-orbit $x_0, \ldots x_n$. Then consider an α-pseudo-orbit $x_0, \ldots x_{n-1}, z, \ldots, T^{m-1}(z)$ with $m \leq N$ and $z \in B(x_n, \alpha), T^m(z) \in B(x_0, \alpha)$. By Corollary 3.2.5 we can β-shadow it by a periodic orbit of period $n + m \leq n + N$.   ♣

The same proof yields this.

Theorem 3.3.13. *Let T satisfy the assumptions of Theorem 3.3.12, and let it be also topologically mixing, i.e. $k(1) = 1$. Then*

(1) T is topologically exact, i.e. for every open $U \subset X$ there exists $N = N(U)$ such that $T^N(U) = X$.

(2) $(\forall r > 0)(\exists N)(\forall x \in X)$ $T^N(B(x, r)) = X$.

3.4   Hölder continuous functions

For distance expanding maps, Hölder continuous functions play a special role. Recall that a function $\phi : X \to \mathbb{C}$ (or $\mathbb{R}$) is said to be *Hölder continuous* with an exponent $0 < \alpha \leq 1$ if and only if there exists $C > 0$ such that

$$|\phi(y) - \phi(x)| \leq C\rho(y, x)^\alpha$$

for all $x, y \in X$. All Hölder continuous functions are continuous, if $\alpha = 1$ they are usually called Lipschitz continuous.

Let $C(X)$ denote, as in the previous chapters, the space of all continuous, real or complex-valued functions defined on a compact metric space X and for $\psi : X \to \mathbb{C}$ we write $\|\psi\|_\infty := \sup\{|\psi(x)| : x \in X\}$ for its supremum norm. For any $\alpha > 0$ let $\mathcal{H}_\alpha(X)$ denote the space of all Hölder continuous functions with exponent $\alpha > 0$. If $\psi \in \mathcal{H}_\alpha(X)$ let

$$\vartheta_{\alpha,\xi}(\psi) = \sup\left\{\frac{|\psi(y) - \psi(x)|}{\rho(y, x)^\alpha} : x, y \in X, \ x \neq y, \ \rho(x, y) \leq \xi\right\}$$

and

$$\vartheta_\alpha(\psi) = \sup\left\{\frac{|\psi(y) - \psi(x)|}{\rho(y, x)^\alpha} : x, y \in X, x \neq y\right\}.$$

Note that

$$\vartheta_\alpha(\psi) \leq \max\left\{\frac{2\|\psi\|_\infty}{\xi^\alpha}, \vartheta_{\alpha,\xi}(\psi)\right\}.$$

The reader will check easily that $\mathcal{H}_\alpha(X)$ becomes a Banach space when equipped with the norm

$$\|\psi\|_{\mathcal{H}_\alpha} = \vartheta_\alpha(\psi) + \|\psi\|_\infty.$$

Thus, to estimate in future $\|\psi\|_{\mathcal{H}_\alpha}$ it is enough to estimate $\vartheta_{\alpha,\xi}(\psi)$ and $\|\psi\|_\infty$.

The following result is a straightforward consequence of Arzela-Ascoli theorem.

Theorem 3.4.1. *Any bounded subset of the Banach space $\mathcal{H}_\alpha(X)$ with the norm $\|\cdot\|_{\mathcal{H}_\alpha}$ is relatively compact as a subset of the Banach space $C(X)$ with the supremum norm $\|\cdot\|_\infty$. Moreover if $\{\psi_n : n = 1, 2, \ldots\}$ is a sequence of continuous functions in $\mathcal{H}_\alpha(X)$ such that $\|x_n\|_{\mathcal{H}_\alpha} \leq C$ for all $n \geq 1$ and some constant C and if $\lim_{n\to\infty} \|\psi_n - \psi\|_\infty = 0$ for some $\psi \in C(X)$, then $\psi \in \mathcal{H}_\alpha(X)$ and $\|\psi\|_{\mathcal{H}_\alpha} \leq C$.*

Now let us formulate a simple but very basic lemma in which you will see a coherence of the expanding property of T and the Hölder continuity property of a function.

Lemma 3.4.2 (pre-Bounded Distortion Lemma for Iteration). *Let $T : X \to X$ be a distance expanding map and $\phi : X \to \mathbb{C}$ be a Hölder continuous function with the exponent α. Then for every positive integer n and all $x, y \in X$ such that*

$$\rho(T^j(x), T^j(y)) < 2\eta \quad \text{for all} \;\; j = 0, 1, \ldots, n-1, \tag{3.4.1}$$

we have, with $C(T, \phi) := \left(\frac{\vartheta_\alpha(\phi)}{1 - \lambda^{-\alpha}} \right)$

$$|S_n\phi(x) - S_n\phi(y)| \leq C(T, \phi)\rho(T^n(x), T^n(y))^\alpha, \tag{3.4.2}$$

where $S_n\phi(z) := \sum_{j=0}^{n-1} \phi \circ T^j(x)$.

If T is open we can assume $x, y \in T_z^{-n}(B(T^n(z), \xi)$ for a point $z \in X$, instead of (3.4.1). Then in (3.4.2) we can replace ϑ_α by $\vartheta_{\alpha,\xi}$.

The point of (3.4.2) is that the coefficient $C(T, \phi) = \frac{\vartheta_\alpha(\phi)}{1 - \lambda^{-\alpha}}$ does not depend on x, y nor on n.

Proof. By (3.0.2) we have $\rho(T^j(x), T^j(y)) \leq \lambda^{-(n-j)}\rho(T^n(y), T^n(z))$ for every $0 \leq j \leq n$. Hence

$$|\phi(T^j(y)) - \phi(T^j(z))| \leq \vartheta_\alpha(\phi)\lambda^{-(n-j)\alpha}\rho(T^n(y), T^n(z))^\alpha$$

Thus

$$|S_n\phi(y) - S_n\phi(z)| \leq \vartheta_\alpha(\phi)\rho(T^n(y), T^n(z))^\alpha \sum_{j=0}^{n-1} \lambda^{-(n-j)\alpha}$$

$$\leq \vartheta_\alpha(\phi)\rho(T^n(y), T^n(z))^\alpha \sum_{j=0}^{\infty} \lambda^{-j\alpha}$$

$$= \frac{\vartheta_\alpha(\phi)}{1 - \lambda^{-\alpha}}\rho(T^n(y), T^n(z))^\alpha$$

The proof is finished. ♣

For an open distance expanding topologically transitive map we can replace topological pressure defined in Chapter 2 by a corresponding notion related with a "tree" of pre-images of an arbitrary point (compare this with Exercise 4 ??? in Chapter 2).

Proposition 3.4.3. *If $T : X \to X$ is a topologically transitive distance expanding map, then for every Hölder continuous potential $\phi : X \to \mathbb{R}$ and for every $x \in X$ there exists the limit*

$$\mathrm{P}_x(T, \phi) := \lim_{n \to \infty} \frac{1}{n} \log \sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x})$$

and it is equal to the topological pressure $\mathrm{P}(T, \phi)$. In addition, there exists a constant C such that for all $x, y \in X$ and every positive integer n

$$\frac{\sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x})}{\sum_{\overline{y} \in T^{-n}(y)} \exp S_n \phi(\overline{y})} < C \tag{3.4.3}$$

Proof. If $\rho(x, y) < \xi$ then (3.4.3) follows immediately from Lemma 3.4.2 with the constant, $C = C_1 := \exp(C(T, \phi)\xi^\alpha)$, since this is the bound for the ratio of corresponding summands for each backward trajectory, by Lemma 3.4.2. Now observe that by the topological transitivity of T there exists N (depending on ξ) such that for all $x, y \in X$ there exists $0 \le m < N$ such that $T^m(B(x, \xi)) \cap B(y, \xi) \ne \emptyset$. Indeed, by condition (3) in Proposition 3.3.4 we can find two blocks of a trajectory of z with dense ω-limit set, say $T^k(z), \ldots, T^{k'}(z)$ and $T^l(z), \ldots, T^{l'}(z)$ with $l > k'$, each ξ-dense in X. Then we set $N = l' - k$. We can find t between k and k' and s between l and l' so that $T^t(z) \in B(x, \xi)$ and $T^s(z) \in B(y, \xi)$. We have $m := s - t \le N$.

Now fix arbitrary $x, y \in X$. So, there exists a point $y' \in T^{-m}(B(y, \xi)) \cap B(x, \xi)$. We then have

$$\sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x}) \le C_1 \sum_{\overline{y'} \in T^{-n}(y')} \exp S_n \phi(\overline{y'})$$

$$= C_1 \exp(-S_m \phi(T^n(y'))) \sum_{\overline{y'} \in T^{-n}(y')} \exp S_{n+m} \phi(\overline{y'})$$

$$\le C_1 \exp(-m \inf \phi) \sum_{\overline{y'} \in T^{-(n+m)}(T^m(y'))} \exp S_{n+m} \phi(\overline{y'})$$

$$\le C_1 \exp(-m \inf \phi) \sum_{\overline{y'} \in T^{-(n+m)}(T^m(y'))} \exp S_n \phi(T^m(\overline{y'})) \exp S_m \phi(\overline{y'})$$

$$\le C_1 \exp(m \sup \phi - m \inf \phi) \sum_{\overline{y'} \in T^{-(n+m)}(T^m(y'))} \exp S_n \phi(T^m(\overline{y'}))$$

$$\le C_1 \exp(2N||\phi||_\infty) D^N \sum_{\overline{y'} \in T^{-n}(T^m(y'))} \exp S_n \phi(\overline{y'})$$

$$\le C_1^2 \exp(2N||\phi||) D^N \sum_{\overline{y} \in T^{-n}(y)} \exp S_n \phi(\overline{y}),$$

where $D = \sup\{\#(T^{-1}(z)) : z \in X\} < \infty$. This proves (3.4.3).

Observe that each set $T^{-n}(x)$ is $(n, 2\eta)$-separated, whence

$$\limsup_{n\to\infty} \frac{1}{n} \log \sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x}) \leq \mathrm{P}(T, \phi),$$

by the characterization of pressure given in Theorem 2.3.2.

In order to prove the opposite inequality fix $\varepsilon < 2\xi$ and for every $n \geq 1$, an (n, ε)-separated set F_n. Cover X by finitely many balls

$$B(z_1, \varepsilon/2), B(z_2, \varepsilon/2), \ldots, B(z_k, \varepsilon/2).$$

Then $F_n = F_n \cap \left(\bigcup_{j=1}^k T^{-n}\big(B(z_j, \varepsilon/2)\big) \right)$ and therefore

$$\sum_{z \in F_n} \exp(S_n \phi(z)) \leq \sum_{j=1}^k \sum_{F_n \cap T^{-n}(B(z_j, \varepsilon/2))} \exp(S_n \phi(z)).$$

Consider an arbitrary j and $y \in\in F_n \cap T^{-n}(B(z_j, \varepsilon/2))$. Let $\overline{z_{j,y}} \in T^{-n}(z_j)$ be defined by $y \in T^{-n}_{\overline{z_{j,y}}}(B(z_j, \varepsilon/2))$. We shall show that the function $y \mapsto \overline{z_{j,y}}$ is injective. Indeed, suppose that $\overline{z_j} = \overline{z_{j,a}} = \overline{z_{j,b}}$ for some $a, b \in F_n \cap T^{-n}(B(z_j, \varepsilon/2))$. Then

$$\rho(T^l(a), T^l(b)) \leq \rho(T^l(a), T^l(\overline{z_j})) + \rho(T^l(\overline{z_j}), T^l(b)) \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$$

for every $0 \leq l \leq n$. So, $a = b$ since F_n is (n, ε)-separated.

Hence, using Lemma 3.4.2 (compare (3.4.3)), we obtain

$$\sum_{z \in F_n} \exp(S_n \phi(z)) \leq \sum_{j=1}^k C \sum_{\overline{z_j}} \exp(S_n \phi(\overline{z_j})) \leq kC^2 \sum_{\overline{x} \in T^{-n}(x)} \exp(S_n \phi(\overline{x}))$$

Letting $n \nearrow \infty$, next $\varepsilon \to 0$, and then applying Theorem 2.3.2, we therefore get

$$\mathrm{P}(T, \phi) \leq \liminf_{n\to\infty} \frac{1}{n} \log \sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x}).$$

Thus

$$\liminf_{n\to\infty} \frac{1}{n} \log \sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x}) \geq \mathrm{P}(T, \phi) \geq \limsup_{n\to\infty} \frac{1}{n} \log \sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x}).$$

So liminf=limsup above, the limit exists and is equal to $\mathrm{P}(T, \phi)$. ♣

Remark 3.4.4. It follows from Proposition 3.4.3, the proof of the Variational Principle Part II (see Section 2.4), and the expansiveness of T that for every $x \in X$ every weak limit of the measures $\frac{1}{n} \sum_{k=0}^{n-1} \mu_n \circ T^{-k}$, for

$$\mu_n = \frac{\sum_{\overline{x} \in T^{-n}(x)} \delta_x \exp S_n \phi(\overline{x})}{\sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x})}$$

and δ_x denoting the Dirac measure concentrated at the point x, is an equilibrium state for ϕ. In fact our very special situation we can say a lot more about the measures involved. Chapter 4 will be devoted to this end.

Let us finish this section with one more very useful fact (compare Theorem 1.11.3.)

Proposition 3.4.5. *Let $T : X \rightarrow X$ be an open, distance expanding, topologically transitive map. If $\phi, \psi \in \mathcal{H}_\alpha(X)$, then the following conditions are equivalent.*

(1) If $x \in X$ is a periodic point of T and if n denotes its period, then $S_n\phi(x) - S_n\psi(x) = 0$.

(2) There exists a constant $C > 0$ such that for every $x \in X$ and integer $n \geq 0$, we have $|S_n\phi(x) - S_n\psi(x)| \leq C$.

(3) There exists a function $u \in \mathcal{H}_a$ such that $\phi - \psi = u \circ T - u$.

Proof. The implications $(3) \Longrightarrow (2) \Longrightarrow (1)$ are very easy. The first one is obtained by summing up the equation in (3) along the orbit $x, T(x), \ldots, T^{n-1}(x)$ which gives $C = 2 \sup |u|$. The second one holds because otherwise, if $S_n\phi(x) - S_n\psi(x) = K \neq 0$ for x of period n, then we have $S_{jn}\phi(x) - S_{jn}\psi(x) = jK$ which contradicts (2) for j large enough. Now let us prove $(1) \Longrightarrow (3)$. Let $x \in X$ be a point such that for every $N \geq 0$ the orbit $(x_n)_N^\infty$ is dense in X. Such x exists by topological transitivity of T, see Proposition 3.3.4. Write $\eta = \phi - \psi$. Define u on the forward orbit of x, the set $A = \{T^n(x)\}_0^\infty$ by $u(x_n) = S_n\eta(x)$. If x is periodic then X is just the orbit of x and the function u is well defined due to the equality in (1). So, suppose that x is not periodic. Set $x_n = T^n(x)$. Then $x_n \neq x_m$ for $m \neq n$ hence u is well defined on A. We will show that it extends in a Hölder continuous manner to $\overline{A} = X$. Indeed, if we take points $x_m, x_n \in A$ such that $m < n$ and $\rho(x_m, x_n) < \varepsilon$ for ε small enough, then $x_m, \ldots, x_{n-1}$ can be β-shadowed by a periodic orbit $y, \ldots, T^{n-m-1}(y)$ of period $n - m$ by Corollary 3.2.5, where ε is related to β in the same way as α related to β in that Corollary. Then by the Lemma 3.4.2

$$|u(x_n) - u(x_m)| = |S_n\eta(x) - S_m\eta(x)| = |S_{n-m}\eta(x_m)|$$
$$= |S_{n-m}\eta(x_m) - S_{n-m}\eta(y)| \leq \vartheta(\phi)_\alpha \varepsilon^\alpha.$$

In particular we proved that u is uniformly continuous on A which allows us to extend u continuously to $\overline{A}$. By taking limits we see that this extension satisfies the same Hölder estimate on $\overline{A}$ as on A. Also the equality in (3) true on A, extends to $\overline{A}$ by the definition of u and by the continuity of η and u . The proof is finished.   ♣

Remark 3.4.6. The equality in (3) is called *cohomology equation* and u is a solution of this equation, compare Section 1.11. Here the cohomology equation is solvable in the space $\mathcal{K} = \mathcal{H}_\alpha$. Note that proving $3) \Longrightarrow 2)$ we used only the assumption that u is bounded. So, going through $2) \Longrightarrow 1) \Longrightarrow 3)$ we prove

that if the cohomology equation is solvable with u bounded, then automatically $u \in \mathcal{H}_\alpha$. The reader will see later that frequently, even under assumptions on T weaker than expanding, to prove that u is a "good" function it suffices to assume u to be measurable and finite almost everywhere, for some probability T-invariant measure with support X. Often u is forced to be as regular as ϕ and ψ are. This type of theorems are called *Livśic type theorems*.

3.5 Markov partitions and symbolic representation

We shall prove in this section that the topological Markov chains (Chapter 0, Example0.6) describe quite precisely the dynamics of general open expanding maps.

This can be done through so called Markov partitions of X. The sets of a partition will play the role of "cylinders" $\{i_0 = \text{Const}\}$ in the symbolic space Σ_A.

Definition 3.5.1. A finite cover $\Re = \{R_1, \ldots, R_n\}$ of X is said to be a *Markov partition* of the space X for the mapping T if $\text{diam}(\Re) < \min\{\eta, \xi\}$ and the following conditions are satisfied.

(a) $R_i = \overline{\text{Int } R_i}$ for all $i = 1, 2, \ldots, d$

(b) $\text{Int } R_i \cap \text{Int } R_j = \emptyset$ for all $i \neq j$

(c) $\text{Int } R_j \cap T(\text{Int } R_i) \neq \emptyset \implies R_j \subset T(R_i)$ for all $i, j = 1, 2, \ldots, d$

Theorem 3.5.2. *For an open, distance expanding map $T : X \to X$ there exist Markov partitions of arbitrarily small diameters.*

Proof. Fix $\beta < \min\{\eta/4, \xi\}$ and let α be the number associated to β as in Lemma 3.2.3. Choose $0 < \gamma \leq \min\{\beta/2, \alpha/2\}$ so small that

$$\rho(x, y) \leq \gamma \implies \rho(T(x), T(y)) \leq \alpha/2. \tag{3.5.1}$$

Let $E = \{z_1, \ldots, z_r\}$ be a γ-spanning set of X. Define the space Ω by putting

$$\Omega = \{q = (q_i) \in E^{\mathbb{Z}^+} : \rho(T(q_i), q_{i+1}) \leq \alpha \text{ for all } i \geq 0\}$$

By definition, all elements of the space Ω are α-pseudo-orbits and therefore, in view of Corollary 3.2.4 and Lemma 3.2.3, for every sequence $q \in \Omega$ there exists a unique point whose orbit β-shadows q. Denote this point by $\Theta(q)$. In this way we have defined a map $\Theta : \Omega \to X$. We will need some of its properties.

Let us show first that Θ is surjective. Indeed, since E is a γ spanning set, for every $x \in X$ and every $i \geq 0$ there exists $q_i \in E$ such that

$$\rho(T^i(x), q_i) < \gamma.$$

Therefore, using also (3.5.1),

$$\rho(T(q_i), q_{i+1}) \leq \rho(T(q_i), T(T^i(x))) + \rho(T^{i+1}(x), q_{i+1}) < \alpha/2 + \gamma \leq \alpha/2 + \alpha/2 = \alpha$$

for all $i \geq 0$. Thus $q = (q_i)_{i=0}^{\infty} \in \Omega$ and (as $\gamma < \beta$) $x = \Theta(q)$. The surjectivity of Θ is proved.

Now we shall show that Θ is continuous. For this aim we will need the following notation. If $q \in \Omega$ then we put

$$q(n) = \{p \in \Omega : p_i = q_i \text{ for every } i = 0, 1, \ldots, n\} \qquad (3.5.2)$$

To prove continuity suppose that $p, q \in \Omega$, $p(n) = q(n)$ with some $n \geq 0$ and put $x = \Theta(q)$, $y = \Theta(p)$. Then for all $i = 0, 1, \ldots, n$,

$$\rho(T^i(x), T^i(y)) \leq \rho(T^i(x), q_i) + \rho(p_i, T^i(y)) \leq \beta + \beta = 2\beta$$

As $\beta < \eta$, we therefore obtain by (3.0.2) that

$$\rho(T^{i+1}(x), T^{i+1}(y)) \geq \lambda\rho(T^i(x), T^i(y))$$

for $i = 0, 1, \ldots, n - 1$, (see (3.1.6)), and consequently $\rho(x, y) \leq \lambda^{-n}2\beta$. The continuity of Θ is proved.

Now for every $k = 1, \ldots, r$ define the sets

$$P_k = \Theta(\{q \in \Omega : q_0 = z_k\}).$$

Since Θ is continuous, Ω is a compact space, and the sets $\{q \in \Omega : q_0 = z_k\}$ are closed in Ω, all sets P_k are closed in X.

Denote

$$W(k) = \{l : \rho(T(z_k), z_l) \leq \alpha\}.$$

The following basic property is satisfied:

$$T(P_k) = \bigcup_{l \in W(k)} P_l. \qquad (3.5.3)$$

Indeed, if $x \in P_k$ then $x = \Theta(q)$ for $q \in \Omega$ with $q_0 = z_k$. By the definition of Ω we have $q_1 = z_l$ for some $l \in W(k)$. We obtain $T(x) \in P_l$.

Conversely, let $x \in P_l$ for $l \in W(k)$. It means that $x = \Theta(q)$ for some $q \in \Omega$ with $q_0 = z_l$. By the definition of $W(k)$ the concatenation $z_k q$ belongs to Ω and therefore the point $T(\Theta(z_k q))$ β-shadows q. Thus $T(\Theta(z_k q)) = \Theta(q) = x$, hence $x \in T(P_k)$.

Let now

$$Z = X \setminus \bigcup_{n=0}^{\infty} T^{-n}\left(\bigcup_{k=1}^{r} \partial P_k\right).$$

Note that the boundary set $\partial P_k := \overline{P_k} \setminus \text{Int } P_k$ is closed, by definition. It is also nowhere dense, since P_k itself is closed. Indeed, by the definition of interior each point in ∂P_k is a limit of a sequence of points belonging to $X \setminus P_k$, hence belonging to $X \setminus \overline{P_k}$, hence not belonging to ∂P_k. Since T is open, also all the sets $T^{-n}(\partial P_k)$ are nowhere dense. They are closed by the continuity of T. We

conclude, referring to Baire Theorem, that Z is dense in X; its complement is of the first Baire category.

For any $x \in Z$ denote

$$P(x) = \{k \in \{1, \ldots, r\} : x \in P_k\},$$

$$Q(x) = \Big\{l \notin P(x) : P_l \cap \big(\bigcup_{k \in P(x)} P_k \big) \neq \emptyset \Big\},$$

and

$$S(x) = \bigcap_{k \in P(x)} \text{Int } P_k \setminus \big(\bigcup_{k \in Q(x)} P_k \big) = \bigcap_{k \in P(x)} \text{Int } P_k \setminus \big(\bigcup_{k \notin P(x)} P_k \big).$$

We shall show that the family $\{S(x) : x \in Z\}$ is in fact finite and moreover, that the family $\{\overline{S(x)} : x \in Z\}$ is a Markov partition of diameter not exceeding 2β.

Indeed, since $\text{diam}(P_k) \leq 2\beta$ for every $k = 1, \ldots, r$ we have

$$\text{diam}(S(x)) \leq 2\beta \tag{3.5.4}$$

As the sets $S(x)$ are open, we have

$$\overline{\text{Int } \overline{S(x)}} = \overline{S(x)} \tag{3.5.5}$$

for all $x \in Z$. This proves the property (a) in Definition 3.5.1.

We shall now show that for every $x \in Z$

$$T(S(x)) \supset S(Tx). \tag{3.5.6}$$

Note first that for $K(x) := \bigcup_{k \in P(x)} P_k \cup \bigcup_{l \in Q(x)} P_l$ we have $\text{diam}(K(x)) \leq 8\beta$ and therefore, by the assumption $\beta < \eta/4$, the map T restricted to $K(x)$ (and even to its neighbourhood U) is injective.

Consider $k \in P(x)$. Then there exists $l \in W(k)$ such that $T(x) \in P_l$, see (3.5.3), and using the definition of Z we get $T(x) \in \text{Int}(P_l)$. Using the injectivity of $T|_U$ and the continuity of T, and then (3.5.3), we obtain $\text{Int } P_k \supset T|_U^{-1}(\text{Int}(T(P_k)))$, hence

$$T(\text{Int } P_k) \supset \text{Int}(T(P_k)) \supset \text{Int } P_l \supset S(T(x)),$$

and therefore

$$T\Big(\bigcap_{k \in P(x)} \text{Int } P_k \Big) \supset S(T(x)). \tag{3.5.7}$$

Now consider $k \in Q(x)$. Observe that by the injectivity of $T|_{K(x)}$ the assumption $x \notin P_k$ implies $T(x) \notin P_l$, $l \in W(k)$.

Thus, using (3.5.3), we obtain

$$T(P_k) \subset \bigcup_{l \notin P(T(x))} P_l.$$

Hence

$$T\Big(\bigcup_{l \in Q(x)} P_l \Big) \cap S(T(x)) = \emptyset.$$

Combining this and (3.5.7) gives

$$T\Big(\bigcap_{k \in P(x)} \operatorname{Int} P_k \setminus \Big(\bigcup_{k \in Q(x)} P_k \Big) \Big) \supset S(T(x)),$$

which exactly means that formula (3.5.6) is satisfied and therefore

$$T(\overline{S(x)}) \supset \overline{S(Tx)}. \qquad\qquad (3.5.8)$$

We shall now prove the following claim.

Claim. If $x, y \in Z$ then either $S(x) = S(y)$ or $S(x) \cap S(y) = \emptyset$.

Indeed, if $P(x) = P(y)$ then also $Q(x) = Q(y)$ and consequently $S(x) = S(y)$. If $P(x) \neq P(y)$ then there exists $k \in P(x) \div P(y)$, say $k \in P(x) \setminus P(y)$. Hence $S(x) \subset \operatorname{Int} P_k$ and $S(y) \subset X \setminus P_k$. Therefore $S(x) \cap S(y) = \emptyset$ and the Claim is proved.

(One can write the family $S(x)$ as $\bigvee_{k=1,\dots,r} \{\operatorname{Int} P_k, X \setminus P_k\}$, compare notation in Ch.1. Then the assertion of the Claim is immediate.)

Since the family $\{P(x) : x \in Z\}$ is finite so is the family $\{S(x) : x \in Z\}$. Note that $S(x) \cap S(y) = \emptyset$ implies $\operatorname{Int} \overline{S(x)} \cap \operatorname{Int} \overline{S(y)} = \emptyset$. This is a general property of pairs of open sets, $U \cap V = \emptyset$ implies $\overline{U} \cap V = \emptyset$ implies $\operatorname{Int} \overline{U} \cap V = \emptyset$ implies $\operatorname{Int} \overline{U} \cap \overline{V} = \emptyset$ implies $\operatorname{Int} \overline{U} \cap \operatorname{Int} \overline{V} = \emptyset$.

Since $\bigcup_{x \in Z} S(x) \supset Z$ and Z is dense in X, we thus have $\bigcup_{x \in Z} \overline{S(x)} = X$. That the family $\{\overline{S(x)} : x \in Z\}$ is a Markov partition for T of diameter not exceeding 2β follows now from (3.5.5), (3.5.6), (3.5.4) and from the claim. The proof is finished.   ♣

Remark 3.5.3. If in Theorem 3.5.2 we omit the assumption that T is an open map, but assume that $X \subset W$ and T extends to an open map in W, then the assertion about the existence of the Markov partition holds for $\tilde{X}$, an arbitrarily small T invariant extension of X.

The proof is the same. One finds $\tilde{X} := \Theta(\Omega) \supset X$; it need not be equal to X. The only difficulty is to verify that the sets $T^{-j}(\partial P_k)$ for all $j \geq 1$ are nowhere dense. We can prove it assumed $\lambda > 2$, where it follows immediately from

Lemma 3.5.4. *For each cylinder $[q_0, ..., q_n]$ its Θ-image contains an open set in $\tilde{X}$.*

Proof. Let $L := \sup |T'|$. Assume $\gamma << \alpha$. Choose an arbitrary $q_{n+1}, ...$ such that for all $j \geq n$ we have $\rho(T(q_j), q_{j+1}) \leq \gamma$. Let $x = \Theta((q_0, ...))$. We prove that every $y \in \tilde{X}$ close enough to x, $\rho(x, y) \leq \epsilon$, belongs to $\Theta([q_1, ..., q_n])$.

Since $y \in \tilde{X}$, by forward invariance of $\tilde{X}$ we get $T^{n+1}(y) \in \tilde{X}$. Hence there exists a sequence of points $z_0, ... \in E$ such that $T^{n+1}(y) = \Theta((z_0, ...))$. In

consequence the sequence $s = (q_0, ..., q_n, z_0, z_1, ...)$ of points in E satisfies the following

$$\rho\big(T(q_j), q_{j+1}\big) \le \alpha \ \text{ for } j = 0, 1, ..., n-1.$$

$$\rho\big(T(q_n), z_0\big) \le \rho\big(T(q_n), q_{n+1}\big) + \rho\big(q_{n+1}, T^{n+1}(x)\big) + \rho\big(T^{n+1}(x), T^{n+1}(y)\big) +$$

$$\rho\big(T^{n+1}(y), z_0\big) \le \gamma + \frac{1/\lambda}{1 - 1/\lambda}\gamma + L^{n+1}\epsilon + \frac{1/\lambda}{1 - 1/\lambda}\alpha \le \alpha$$

as we can assume $\lambda > 2$ and

$$\rho(T(z_j), z_{j+1}) \le \alpha \ \text{ for } j = 0, 1, ...$$

Therefore $\Theta(s) = y$ and $s \in [q_0, ..., q_n]$. ♣

Therefore there is an arbitrary small extension of X to a compact set $\tilde{X}$ which is $F = T^n$ invariant for an integer $n > 0$ and has Markov partition $\{R_i\}$ for F. Then take $\hat{X} = \bigcup_{j \ge 0} T^j(\tilde{X})$. It is easy to check that the family of the closures of the intersections of the sets $T^{-j}_{T^{n-j}(x)}(\text{Int } R_i)$, for $x \in \text{Int } R_k$ and interiors in $\tilde{X}$ constitutes a Markov partition of $\hat{X}$ for T.

Example 3.5.5. It is not true that in the situation of Remark 3.5.3 one can always extend X to a T-invariant set $\tilde{X}$, in an arbitrarily small neighbourhood of X, on which T is open (i.e. $(\tilde{X}, T)$ is a repeller, see Section 5.1). Indeed, consider in the plane the set X being the union of a circle together with its diameter interval. It is easy to find a mapping T defined on a neighbourhood of X, preserving X, smooth and expanding. Then at least one of preimages of one of to triple points (end points of the diameter) is not a triple point. Denote it by A. T restricted to X is not open at A. Adding a short arc γ starting at A, disjoint from X (except A), a preimage of an arc in X does not make T open. Indeed, it is not open at the second end of γ. (It is not open also at T-preimages of A but we can cope with this trouble by adding preimages of γ under iteration of T)

On the other hand, (X, T) can be extended to a repeller if X is a Cantor set. This fact will be applied in Section 10.6.

Proposition 3.5.6. *Let $T : W \to W$ be an open continuous map of a compact metric space (W, ρ). Let $X \subset W$ be a T-invariant set, such that T is expanding in a neighbourhood U of X, i.e. (3.0.1) holds for $x, y \in U$. Then, in an arbitrarily small neighbourhood of X in W there exists $\tilde{X}$ containing X such that T is open on it.*

Proof. One can change the metric ρ on W to a metric ρ' giving the same topology, such that (X, T) is distance expanding on U in ρ' in the sense of (3.0.2),

see Section 3.1 for T Lipschitz or the formula defining ρ' in Lemma 3.6.3 in the general case.

First we prove that there exist arbitrarily small $r > 0$ such that $B(X, r) := \{z \in W : \rho'(z, X) < r\} \subset U$, consists of a finite number of open domains $U_k(r) \subset W$, with pairwise disjoint closures in W.

For any $z, z' \in B(X, r)$ define $z \sim_r z'$ if there exists a sequence $x_1, ..., x_n \in X$ such that $z \in B(x_1, r), z' \in B(x_n, r)$ and for all $k = 1, ..., n - 1$, $B(x_k, r) \cap B(x_{k+1}, r) \neq \emptyset$, the balls in (W, ρ'). This is an equivalence relation, each equivalence class contains a point in X, and for $x \in V_r \cap X, x' \in V_r' \cap X'$ for two different equivalence classes V_r, V_r', we have $\rho(x, x') \geq r$. So by compactness of X there is at most a finite number of the equivalence classes. Denote their number by $N(r)$. Clearly, for every $r < r'$ for every V_r there exists $V_{r'}$ such that $V_r \subset V_{r'}$ and every $V_{r'}$ contains some V_r. Hence the function $r \mapsto N(r)$ is monotone decreasing. Let $r_1 > r_2 > ... > r_n > ... \searrow 0$ be the sequence of consecutive points of its discontinuity. Take any $r > 0$ not belonging to this sequence. Let $r_j < r < r_{j-1}$. Denote $\varepsilon = (r_{j-1} - r)/2$. Consider two different sets V_r and V_r'. Suppose there is $z_0 \in \overline{V}_r \cap \overline{V}_r'$. Then there are points $z \in V_r$ and $z' \in V_r'$ such that $\rho'(z, z') < \varepsilon$. Then $z \sim_{r+\varepsilon} z'$. So both V_r and V_r' are contained in the same equivalence class of $\sim_{r+\varepsilon}$. So $N(r) > N(r + \varepsilon)$ what contradicts the definition of ε.

Observe that $\sup_k \operatorname{diam} U_k(r) \to 0$ as $r \to 0$ since X is a Cantor set. Indeed, for every $\delta > 0$ there is a covering of X by pairwise disjoint closed sets A_j of diameter $< \delta$. Then for $r < \inf_{j \neq j'} \operatorname{dist}(A_j, A_{j'})/2$ each two distinct $A_j, A_{j'}$ belong to different $\sim_r$ equivalence classes.

Thus, we can assume for $U_k = U_k(r)$, that $\operatorname{diam} U_k < \xi$. So we can consider the branches of $g = T_x^{-1}$ on U_k's for all $x \in X$, see Lemma 3.1.2. Then each g maps $\bar{U}_k$ into some $U_{k'}$ because it is a contraction (by the factor λ^{-1}). Then denote g by $g_{k',k}$. Finally define

$$\tilde{X} = \bigcap_{n=0}^{\infty} \bigcup_{k_1,...,k_n} g_{k_1,k_2} \circ g_{k_2,k_3} \circ ... \circ g_{k_{n-1},k_n}(U_{k_n}), \qquad (3.5.9)$$

the union over all $k_1, ..., k_n$ such that $g_{k_j,k_{j+1}}$ exist for all $j = 1, ..., n - 1$. It follows that for r small enough the family of sets $\{U_k(r) \cap \tilde{X}\}$ is a Markov partition of $\tilde{X}$ with pairwise disjoint "cylinders", and $(\tilde{X}, T)$ is topologically conjugate to a topological Markov chain, see Example 0.4. Hence T is open on $\tilde{X}$ (see more details below).   ♣

Each Markov partition gives rise to a coding (symbolic representation) of $T : X \to X$ as follows (an example was provided in Proposition 3.5.6 above).

Theorem 3.5.7. *Let $T : X \to X$ be an open, distance expanding map. Let $\{R_1, ..., R_d\}$ be a Markov partition. Let $A = (a_{i,j})$ be a $d \times d$ matrix with $a_{i,j} = 0$ or 1 depending as the intersection $T(\operatorname{Int} R_i) \cap \operatorname{Int} R_j$ is empty or not.*

Then consider the corresponding one-sided topological Markov chain Σ_A with the left shift map $\sigma : \Sigma_A \to \Sigma_A$, see Ch.0.3. Define the map $\pi : \Sigma_A \to X$ by

$$\pi((i_0, i_1, \dots)) = \bigcap_{n=0}^{\infty} T^{-n}(R_{i_n}).$$

Then π is a well defined Hölder continuous mapping onto X and $T \circ \pi = \pi \circ \sigma$. Moreover $\pi|_{\pi^{-1}(X \setminus \bigcup_{n=0}^{\infty} T^{-n}(\bigcup_i \partial R_i))}$ is injective.

Proof. For an arbitrary sequence $(i_0, i_1, \dots) \in \Sigma_A$, $a_{i,j} = 1$ implies $T(R_{i_n}) \supset R_{i_{n+1}}$. Since $\operatorname{diam} R_{i_n} < 2\eta$, T is injective on R_{i_n}, hence there exists an inverse branch $T^{-1}_{R_{i_n}}$ on $R_{i_{n+1}}$ The subscript R_{i_n} indicates that we take the branch leading to R_{i_n}, compare notation from Section 3.1. Thus, $T^{-1}_{R_{i_n}}(R_{i_{n+1}}) \subset R_{i_n}$. Hence

$$T^{-1}_{R_{i_0}} T^{-1}_{R_{i_1}} \dots T^{-1}_{R_{i_n}}(R_{i_{n+1}}) \subset T^{-1}_{R_{i_0}} T^{-1}_{R_{i_1}} \dots T^{-1}_{R_{i_{n-1}}}(R_{i_n}).$$

So $\bigcap_{n \geq 0} T^{-n}(R_{i_n}) \neq \emptyset$, as the intersection of a descending family of compact sets. We have used here that

$$
\begin{aligned}
T^{-1}_{R_{i_0}} \dots T^{-1}_{R_{i_{n-1}}}(R_{i_n}) &= T^{-1}_{R_{i_0}} \dots T^{-1}_{R_{i_{n-2}}}(T^{-1}(R_{i_n}) \cap R_{i_{n-1}}) \\
&= T^{-1}_{R_{i_0}} \dots T^{-1}_{R_{i_{n-3}}}(T^{-2}(R_{i_n}) \cap T^{-1} R_{i_{n-1}} \cap R_{i_{n-2}}) \\
&= \dots \\
&= \bigcap_{k=0}^{n} T^{-k}(R_{i_k})
\end{aligned}
$$

following from $T^{-1}_{R_{i_k}}(A) = T^{-1}(A) \cap R_{i_k}$ for every $A \subset R_{i_{k+1}}$, $k = 0, \dots, n-1$.

Our infinite intersection consists of only one point, since $\operatorname{diam}(R_i)$ are all less than an expansivness constant.

Let us prove now that π is Hölder continuous. Indeed, $\rho'((i_n), (i'_n)) \leq \lambda_1^{-N}$ implies $i_n = i'_n$ for all $n = 0, \dots, N-1$, where the metric ρ' comes from Example 0.4, with the factor $\lambda = \lambda(\rho') > 1$. Then, for $x = \pi((i_n))$, $y = \pi((i'_n))$ and every $n : 0 \leq n < N$ we have $T^n(x), T^n(y) \in R_{i_n}$, hence $\rho(T^n(x), T^n(y)) \leq \operatorname{diam} R_{i_n} \leq \xi$, hence $\rho(x, y) \leq \lambda^{-(N-1)}\xi$. Therefore π is Hölder continuous, with exponent $\min\{1, \log \lambda / \log \lambda(\rho')\}$.

Let us deal now with the injectivity. If $x = \pi((i_n))$ and $T^n(x) \in \operatorname{Int} R_{i_n}$ for all $n = 0, 1, \dots$, then $T^n(x) \notin R_j$ for all $j \neq i_n$. So, if $x \in \bigcap_n T^{-n}(R_{i'_n})$, then all $i'_n = i_n$.

Finally π maps Σ_A onto X. Indeed, by definition $\pi(\Sigma_A)$ contains $X \setminus \bigcup_{n=0}^{\infty} T^{-n}(\bigcup_i \partial R_i)$ which is dense in X. Since $\pi(\Sigma_A)$ is compact, it is therefore equal to X. ♣

Remark. One should not think that π is always injective on the whole Σ_A. Consider for example the mapping of the unit interval $T(x) = 2x \,(\operatorname{mod} 1)$, compare Example 0.4. Then dyadic expansion of x is not unique for $x \in \bigcup_{n=0}^{\infty} T^{-n}(\{\frac{1}{2}\})$.

Dyadic expansion is the inverse, π^{-1}, of the coding obtained from the Markov partition $[0,1] = \{[0,\frac{1}{2}],[\frac{1}{2},1]\}$.

Recall finally that $\sigma : \Sigma_A \to \Sigma_A$ is an open, distance expanding map. The partition into the cylinders $C_i := \{(i_n) : i_0 = i\}$ for $i = 1,\ldots,d$, is a Markov partition into closed-open sets. The corresponding coding π is just the identity.

Another fact concerning a similarity between (Σ_A,σ) and (X,T) is the following

Theorem 3.5.8. *For every Hölder continuous function $\phi : X \to \mathbb{R}$ the function $\phi \circ \pi$ is Hölder continuous on Σ_A and the pressures coincide, $\mathrm{P}(T,\phi) = \mathrm{P}(\sigma,\phi \circ \pi)$.*

Proof. The function $\pi \circ \Phi$ is Hölder continuous as a composition of Hölder continuous functions. Consider next an arbitrary point $x \in X \setminus \bigcup_{n=0}^\infty T^{-n}(\bigcup_i \partial R_i)$. Then, using Proposition 3.4.3 for T and σ we obtain

$$\mathrm{P}(T,\phi) = \mathrm{P}_x(T,\phi) = \mathrm{P}_{\pi^{-1}(x)}(\sigma,\phi \circ \pi) = \mathrm{P}(\sigma,\phi \circ \pi).$$

The middle equality follows directly from the definitions.   ♣

Finally we shall prove that π is injective in the measure-theoretic sense.

Theorem 3.5.9. *For every ergodic Borel probability measure μ on Σ_A, invariant under the left shift map σ, positive on open sets, the mapping π yields an isomorphism between the probability spaces $(\Sigma_A,\mathcal{F}_{\Sigma_A},\mu)$ and the $(X,\mathcal{F}_X,\mu \circ \pi^{-1})$, for $\mathcal{F}$ respective (completed) Borel σ-algebras, conjugating the shift map σ to the transformation $T : X \to X$ (i.e. $\pi \circ \sigma = T \circ \pi$).*

Proof. The set $\partial = \bigcup_{i=1}^d \partial(R_i)$, and hence $\pi^{-1}(\partial)$, have non-empty open complements in Σ_A. Since $T(\partial) \subset \partial$, we have $\sigma(\pi^{-1}(\partial)) \subset \pi^{-1}(\partial)$, hence $\pi^{-1}(\partial) \subset \sigma^{-1}(\pi^{-1}(\partial))$. Since μ is σ-invariant, we conclude by ergodicity of μ that $\mu(\pi^{-1}(\partial))$ is either equal to 0 or to 1. But the complement of $\pi^{-1}(\partial)$, as a non-empty open set, has positive measure μ. Hence $\mu(\pi^{-1}(\partial)) = 0$. Hence $\mu(E) = 0$ for $E := \bigcup_{n=0}^\infty \sigma^{-n}(\pi^{-1}(\partial))$ and by Theorem 3.5.7 π is injective on $\Sigma_A \setminus E$. This proves that π is the required isomorphism.   ♣

3.6   Expansive maps are expanding in some metric

Theorem 3.1.1 says that distance expanding maps are expansive. In this section we prove the following much more difficult result which can be considered as a sort of the converse statement and which provides an additional strong justification to explore expanding maps.

Theorem 3.6.1. *If a continuous map $T : X \to X$ of a compact metric space X is (positively) expansive then there exists a metric on X, compatible with the topology, such that the mapping T is distance expanding with respect to this metric.*

The proof of Theorem 3.6.1 given here relies heavily on the old topological result of Frink (see [Frink 1937], comp. [Kelley 1955, p. 185]) which we state below without proof.

Lemma 3.6.2 (The Metrization Lemma of Frink). *Let $\{U_n\}_{n=0}^{\infty}0\}$ be a sequence of open neighborhoods of the diagonal $\Delta \subset X \times X$ such that $U_0 = X \times X$,*

$$\bigcap_{n=1}^{\infty} U_n = \Delta, \tag{3.6.1}$$

and for every $n \geq 1$

$$U_n \circ U_n \circ U_n \subset U_{n-1}. \tag{3.6.2}$$

Then there exists a metric ρ, compatible with the topology on X, such that for every $n \geq 1$,

$$U_n \subset \{(x,y) : \rho(x,y) < 2^{-n}\} \subset U_{n-1}. \tag{3.6.3}$$

We will also need the following almost obvious result.

Lemma 3.6.3. *If $T : X \to X$ is a continuous map of a compact metric space X and T^n is distance expanding for some $n \geq 1$, then T is distance expanding with respect to some metric compatible with the topology on X.*

Proof. Let ρ be a compatible metric with respect to which T^n is distance expanding and let $\lambda > 1$ and $\eta > 0$ be constants such that

$$\rho(T^n(x), T^n(y)) \geq \lambda \rho(x,y)$$

whenever $\rho(x,y) < 2\eta$. Put $\xi = \lambda^{\frac{1}{n}}$ and define the new metric ρ' by setting

$$\rho'(x,y) = \rho(x,y) + \frac{1}{\xi}\rho(T(x),T(y)) + \ldots + \frac{1}{\xi^{n-1}}\rho(T^{n-1}(x), T^{n-1}(y))$$

Then ρ' is a metric on X compatible with the topology and $\rho'(T(x), T(y)) \geq \xi\rho'(x,y)$ whenever $\rho'(x,y) < 2\eta$. ♣

Now we can pass to the proof of Theorem 3.6.1.

Proof of Theorem 3.6.1. Let d be a metric on X compatible with the topology, and let $3\theta > 0$ be an expansive constant associated to T which does not exceed the constant η claimed in Proposition 2.5.9. For any $n \geq 1$ and $\gamma > 0$ let

$$V_n(\gamma) = \{(x,y) \in (X \times X) : d(T^j(x), T^j(y)) < \gamma \quad \text{for every } j = 0, \ldots, n\}.$$

Then in view of Proposition 2.5.9 there exists $M \geq 1$ such that

$$V_M(3\theta) \subset \{(x,y) : d(x,y) < \theta\}. \tag{3.6.4}$$

Define $U_0 = X \times X$ and $U_n = V_{Mn}(\theta)$ for every $n \geq 1$. We will check that the sequence $\{U_n\}_{n=0}^{\infty}$ satisfies the assumptions of Lemma 3.6.2. Indeed, (3.6.1)

follows immediately from expansiveness of T. Now we shall prove condition (3.6.2). We shall proceed by induction. For $n = 1$ nothing has to be proved. Suppose that (3.6.2) holds for some $n \geq 1$. Let (x, u), (u, v), $(v, y) \in U_{n+1}$. Then by the triangle inequality

$$d(T^j(y), T^j(x)) < 3\theta \qquad \text{for every } j = 0, \ldots, (n+1)M.$$

Therefore, using (3.6.4), we conclude that

$$d(T^j(y), T^j(x)) < \theta \qquad \text{for every } j = 0, \ldots, Mn.$$

Equivalently $(x, y) \in V_{Mn}(\theta) = U_n$ which finishes the proof of (3.6.2).

So, we have shown that the assumptions of Lemma 3.6.2 are satisfied, and therefore we obtain a compatible metric ρ on X satisfying (3.6.3). In view of Lemma 3.6.3 it suffices to show that T^{3M} is expanding with respect to the metric ρ. So suppose that $0 < \rho(x, y) < \frac{1}{16}$. Then by (3.6.1) there exists an $n \geq 0$ such that

$$(x, y) \in U_n \setminus U_{n+1}. \tag{3.6.5}$$

As $0 < \rho(x, y) < \frac{1}{16}$, this and (3.6.3) imply that $n \geq 3$. It follows from (3.6.5) and the definitions of U_n and $V_{Mn}(\theta)$, that there exists $Mn < j \leq (n+1)M$ such that $d(T^j(y), T^j(x)) \geq \theta$. Since $3 \leq n$ we conclude that $d(T^i(T^{3M}(x)), T^i(T^{3M}(y))) \geq \theta$ for some $0 \leq i \leq (n-2)M$ and therefore $(T^{3M}(x), T^{3M}(y)) \notin U_{n-2}$. Consequently, by (3.6.3) and (3.6.5) we obtain that

$$\rho(T^{3M}(x), T^{3M}(y)) \geq 2^{-(n-1)} = 2 \cdot 2^{-n} > 2\rho(x, y).$$

The proof is finished.   ♣

Exercises

3.1. Prove the following *Shadowing Theorem* generalizing Corollary 3.2.4 (Shadowing lemma) and Corollary 3.2.5 (Closing lemma):

Let $T : X \to X$ be an open map, expanding at a compact set $Y \subset X$. Then, for every $\beta > 0$ there exists $\alpha > 0$ such that for every map $\Gamma : Z \to Z$ for a set Z and a map $\Phi : Z \to B(Y, \alpha)$ satisfying $\rho(T\Phi(z), \Phi\Gamma(z)) \leq \alpha$ for every $z \in Z$, there exists a map $\Psi : Z \to X$ satisfying $T\Phi = \Phi\Gamma$ (hence $T(Y') \subset Y'$ for $Y' = \Psi(Z)$) and such that for every $z \in Z$, $\rho(\Psi(z), \Phi(z)) \leq \beta$. If Z is a metric space and Γ, Φ are continuous, then Ψ is continuous. If $T(Y) \subset Y$ and the map $T|_Y : Y \to Y$ be open, then $Y' \subset Y$.

(Hint: see 5.1)

3.2.

3.3. Prove the following *structural stability theorem.*

Let $T : X \to X$ be an open map with a compact set $Y \subset X$ such that $T(Y) \subset Y$. Then for every $\lambda > 1$ and $\beta > 0$ there exists $\alpha > 0$ such that if $S : X \to X$ is distance expanding at Y with the expansion factor λ and for all

$y \in Y$ $\rho(S(y), T(y)) \leq \alpha$ then there exists a continuous mapping $h : Y \to X$ such that $Sh|_Y = hT|_Y$, in particular $S(Y') \subset Y'$ for $Y' = h(Y)$, and $\rho(h(z), z) \leq \beta$.

Hint: apply the previous exercise for $Z = Y, \Gamma = T|_Y, \Phi = \text{id}, T = S$ and $Y = Y$. Compare also 5.1

3.4. Prove that if $T : X \to X$ is an open, distance expanding map and X is compact connected, then $T : X \to X$ is topologically exact.

3.5. Prove that for $T : X \to X$ a continuous map on a compact metric space X the topological entropy is attained on the set of non-wandering points, namely $h_{\text{top}}(T) = h_{\text{top}}(T|_{\Omega}(T))$.

Hint: Use the Variational Principle (Theorem 2.4.1).

3.6. Prove Lemma 3.3.9 and hence Theorem 3.3.8 (Spectral Decomposition) without the assumption of periodic shadowing, assuming that T is a branched covering of the Riemann sphere.

3.7. Prove the existence of stable and unstable manifolds for hyperbolic sets and *Smale's Spectral Decomposition Theorem for Axiom A diffeomorphisms.*

An invariant set Λ for a diffeomorphism T is called *hyperbolic* if there exist constants $\lambda > 1$ and $C > 0$ such that the tangent bundle on X restricted to tangent spaces over points in Λ, $T_\Lambda X$ decomposes into DT-invariant subbundles $T_\Lambda X = T_\Lambda^u X \oplus T_\Lambda^s X$ such that $||DT^n(v)|| \geq C\lambda^n$ for all $v \in T_\Lambda^u X$ and $n \geq 0$ and $||DT^n(v)|| \geq C\lambda^n$ for all $v \in T_\Lambda^s X$ and $n \leq 0$.

Prove that for every $x \in \Lambda$ the sets $W^u(x) = \{y \in X : \rho(T^n(x), T^n(y)) \to 0 \text{ as} n \to -\infty\}$, and $W^s(x) = \{y \in X : \rho(T^n(x), T^n(y)) \to 0 \text{ as} n \to \infty\}$ are immersed manifolds. (They are called *unstable* and *stable manifolds.*)

Assume next that a diffeomorphism $T : X \to X$ satisfies *Smale's Axiom A condition*, that is the set of non-wandering points Ω is hyperbolic and $\Omega = \overline{\text{Per}}$.

Then the relation between periodic points is as follows. $x \sim y$ if there are points $z \in W^u(x) \cap W^s(y)$ and $z' \in W^u(y) \cap W^s(x)$ where $W^u(x)$a and $W^s(y)$, and $W^u(y)$a and $W^s(x)$ respectively, intersect transversally, that is the tangent spaces to these manifolds at z and z' span the whole tangent spaces.

Prove that this relation yields Spectral Decomposition, as in Theorem 3.3.8, with topological transitivity assertion rather than topological exactness of course.

As one of the steps prove a lemma corresponding to Lemma 3.3.9 about approximation of a transversal heteroclinic cycle points by periodic ones. That is assume that $x_1, x_2, \ldots, x_n$ are hyperbolic periodic points (i.e. their orbits are hyperbolic sets) for a diffeomorphism, and $W^u_{x_i}$ has a point p_i of transversal intersection with $W^s_{x_{(i+1) \bmod n}}$ for each $i = 1, \ldots, n$. Then $p_i \in \overline{\text{Per}}$.

(For the theory of hyperbolic sets for diffeomorphisms see for example [Katok & Hasselblatt 1995].)

3.8. Prove directly that 1) $\implies$ 2) in Proposition 3.4.5, using the specification property, Theorem 3.3.12.

3.9. Suppose $T : X \to X$ is a distance expanding map on a closed surface. Prove that there exist a Markov partition for an iterate T^N compatible with a cell complex structure. That is elements R_i of the partitions are topological
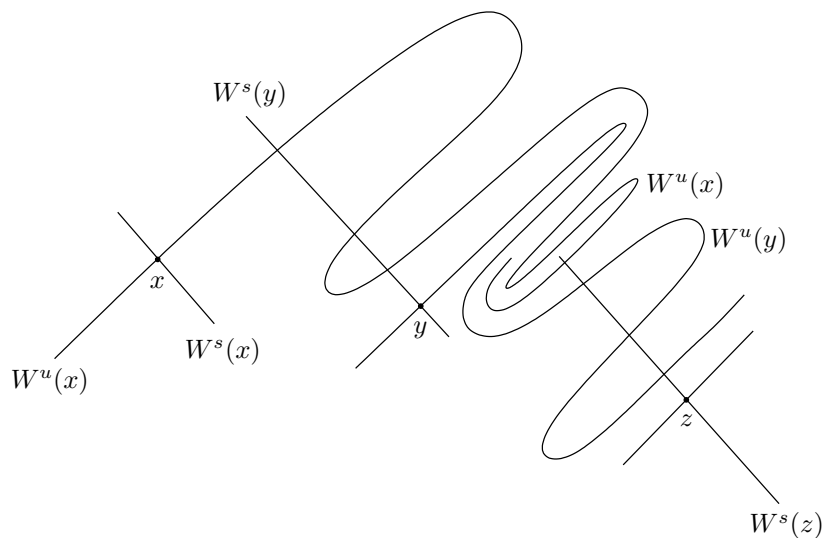
Figure 3.2: Transitivity for diffeomorphisms.

discs, the 1-dimensional "skeleton" $\bigcup_i \partial R_i$ is a graph consisting of a finite number of continuous curves "edges" intersecting one another only at end points, called "vertices". Intersection of each two R_i is empty or one vertex or one edge, each vertex is contained in 2 or 3 edges.

(Hint: Start with any cellular partition, with R_i being nice topological discs and correct it by adding or subtracting components of $T^{-N}(R_i), T^{-2N}(R_i)$, etc. See [Farrell & Jones 1979] for details.)

3.10. Prove that if T is an expanding map of the 2-dimensional torus $\mathbb{R}^2/\mathbb{Z}^2$, a factor map of a linear map of $\mathbb{R}^2$ given by an integer matrix with two irrational eigenvalues of different moduli (for example $\left(\begin{smallmatrix} 0 & 11 \\ -1 & 7 \end{smallmatrix} \right)$ but not $\left(\begin{smallmatrix} 2 & 0 \\ 0 & 3 \end{smallmatrix} \right)$), then ∂R_i cannot be differentiable.

(Hint: Smooth curves $T^n(\partial R_i)$ become more and more dense in $\mathbb{R}^2/\mathbb{Z}^2$ as $n \to \infty$, stretching in the direction of the eigenspace corresponding to the eigenvalue with a larger modulus. So they cannot omit Int R_i.

The same argument, looking backward, says that the components of $T^{-n}(\text{Int } R_i)$ are dense and very distorted, since the eigenvalues have different moduli. The curve ∂R_i must manouver between them, so it is "fractal". See [Przytycki & Urbański 1989] for more details.)

Bibliographical Notes

The Shadowing Lemma in the hyperbolic setting has appeared in [Anosov 1970], [Bowen 1979] and [Kushnirenko 1972]. See [Katok & Hasselblatt 1995] for the variant as in Exercise 3.1. In the context of C^1-differentiable (distance) expand-

ing maps on smooth compact manifolds the shadowing property was proved in [Shub 1969], where structural stability was also extablished. D. Sullivan introduced in [Sullivan 1982] the notion of *telescope* for the sequence $T_{x'_i}^{-1}(\overline{B(x_{i+1}, \beta)}) \subset \overline{B(x_i, \beta)}$ to capture a shadowing orbit, hence to prove stability of expanding repellers, compare Section 5.1 in the context of hyperbolic rational functions. This stability was also proved in [Przytycki 1977]. Later a comprehensive monography on shadowing by S. Yu. Pilyugin [Pilyugin 1999] appeared.

The existence of Spectral Decomposition in the sense of Theorem 3.3.8 (see Exercise 3.7) was first proved by S. Smale [Smale 1967] for diffeomorphisms, called by him *Axiom A*, defined by the property that the set of non-wandering points Ω is hyperbolic and $\Omega = \overline{\text{Per}}$, see also [Katok & Hasselblatt 1995] and further historical informations therein. In a topological setting an analogous theory was founded by Bowen [Bowen 1970], for introduced by him *Axiom A** homeomorphisms. *Axiom A endomorphisms* were studied in [Przytycki 1977], comprising the diffeomorphisms and expanding (smooth) cases. For open, distance expanding maps $\Omega = \overline{\text{Per}}$ (Proposition 3.3.6) corresponds to the analogous fact for Anosov diffeomorphisms. It is not known whether $\Omega = X$ for all Anosov diffeomorphisms . It is not true for some distance expanding endomorphisms (Remark 3.3.7), but it is true for T smooth and X a connected smooth manifold (Exercise 3.4), see [Shub 1969].

The construction of Markov partition in Sec. 5 is similar to the construction for basic sets of Axiom A diffeomorphisms in [Bowen 1975]. The case of X not locally maximal for T has been studied recently in the case of diffeomorphisms [Crovisier 2002], [Fisher 2006]. The noninvertible case is considered here for the first time to our knowledge.

For a general theory of cellular Markov partitions, including Exercise 3.9, see [Farrell & Jones 1993]. The fact that Hausdorff dimension of the boundaries of 2-dimensional cells is greater than 1, in particular their non-differentiability, Exercise 3.10, follows from [Przytycki & Urbański 1989].

Chapter 4

Thermodynamical formalism

In Chapter 2 (Th. 2.5.6) we proved that for every positively expansive map $T : X \to X$ of a compact metric space and an arbitrary continuous function $\phi : X \to \mathbb{R}$ there exists an equilibrium state. In Remark 3.4.4 we provided a specific construction for T an open distance expanding topologically transitive map and a Hölder continuous function ϕ. Here we shall construct this equilibrium measure with a greater care and study its miraculous regularity with respect to the "potential" function ϕ, its "mixing" properties and uniqueness. So, for the entire chapter we fix an open, distance expanding, topologically transitive map $T : X \to X$ of a compact metric space (X, ρ), with constants η, λ, ξ introduced in Chapter 3.

4.1 Gibbs measures: introductory remarks

A probability measure μ on X and the Borel σ-algebra of sets is said to be a *Gibbs state (measure)* for the potential $\phi : X \to \mathbb{R}$ if there exist $P \in \mathbb{R}$ and $C \geq 1$ such that for all $x \in X$ and all $n \geq 1$,

$$C^{-1} \leq \frac{\mu\big(T_x^{-n}(B(T^n(x), \xi))\big)}{\exp(S_n \phi(x) - Pn)} \leq C \tag{4.1.1}$$

If in addition μ is T-invariant, we call μ an *invariant Gibbs state* (or *measure*).

We denote the set of all Gibbs states of ϕ by G_ϕ. It is obvious that if μ is a Gibbs state of ϕ and ν is equivalent to μ with Radon-Nikodym derivatives uniformly bounded from above and below, then ν is also a Gibbs state. The following proposition shows that the converse is also true and it identifies the constant P appearing in the definition of Gibbs states as the topological pressure of ϕ.

Proposition 4.1.1. *If μ and ν are Gibbs states associated to the map T and a Hölder continuous function ϕ and the corresponding constants are denoted respectively by P, C and Q, D then $P = Q = \mathrm{P}(T, \phi)$ and the measures μ and ν are equivalent with mutual Radon-Nikodym derivatives uniformly bounded.*

Proof. Since X is a compact space, there exist finitely many points $x_1, \ldots, x_l \in X$ such that $B(x_1, \xi) \cup \ldots \cup B(x_l, \xi) = X$. We claim that for every compact set $A \subset X$, every $\delta > 0$, and for all $n \geq 1$ large enough,

$$\mu(A) \leq CDl \exp((Q - P)n)(\nu(A) + \delta). \tag{4.1.2}$$

By the compactness of A and by the regularity of the measure ν there exists $\varepsilon > 0$ such that $\nu(B(A, \varepsilon)) \leq \nu(A) + \delta$. Fix an integer $n \geq 1$ so large that $\xi \lambda^{-n} < \frac{\varepsilon}{2}$ and for every $1 \leq i \leq l$ let

$$X(i) = \{x \in T^{-n}(x_i) : A \cap T_x^{-n}(B(x_i, \xi)) \neq \emptyset\}.$$

Then

$$A \subset \bigcup_{i=1}^{l} \bigcup_{x \in X(i)} T_x^{-n}(B(x_i, \xi)) \subset B(A, \varepsilon)$$

and, since for any fixed $1 \leq i \leq l$ the sets $T_x^{-n}(B(x_i, \xi))$ for $x \in T^{-n}(x_i)$ are mutually disjoint, it follows from (4.1.1) that

$$\mu(A) \leq \mu\left(\bigcup_{i=1}^{l} \bigcup_{x \in X(i)} T_x^{-n}(B(x_i, \xi))\right) \leq \sum_{i=1}^{l} \sum_{x \in X(i)} \mu\left(T_x^{-n}(B(x_i, \xi))\right)$$

$$\leq C \sum_{i=1}^{l} \sum_{x \in X(i)} \exp(S_n\phi(x) - Pn)$$

$$= C \exp((Q - P)n) \sum_{i=1}^{l} \sum_{x \in X(i)} \exp(S_n\phi(x) - Qn)$$

$$\leq CD \exp((Q - P)n) \sum_{i=1}^{l} \sum_{x \in X(i)} \nu\left(T_x^{-n}(B(x_i, \xi))\right)$$

$$\leq CD \exp((Q - P)n)l\nu(B(A, \varepsilon))$$

$$\leq CDl \exp((Q - P)n)(\nu(A) + \delta)$$

Exchanging the roles of μ and ν we also obtain

$$\nu(A) \leq CDl \exp((P - Q)n)(\mu(A) + \delta) \tag{4.1.3}$$

for all $n \geq 1$ large enough. So, if $P \neq Q$, say $P < Q$, then it follows from (4.1.3) applied to the compact set X that $\nu(X) = 0$. Hence $P = Q$, and, as by regularity of μ and ν, (4.1.2) and (4.1.3) continue to be true for all Borel subsets of X, we conclude that μ and ν are equivalent with the Radon-Nikodym

derivative $d\mu/d\nu$ bounded from above by CDl and from below by $(CDl)^{-1}$
(letting $\delta \to 0$).

It is left to show that $P = \mathrm{P}(T, \phi)$. Looking at the expression after the third
inequality sign in our estimates of $\mu(A)$ with $A = X$ we get

$$0 = \log \mu(X) \leq \log C + \log\Big(\sum_{i=1}^{l} \sum_{x \in X(i)} \exp(S_n\phi(x))\Big) - Pn.$$

Since for every i, $X(i)$ is an (η, n)-separated set, taking into account division by
n in the definition of pressure, we can replace here $\sum_i$ by a largest summand
for each n. We get $P \leq P(T, \phi)$.

On the other hand for an arbitrary $x \in X$,

$$\sum_{y \in T^{-n}(x)} \exp(S_n\phi(y) - Pn) \leq C \sum_{y \in T^{-n}(x)} \mu\big(T_y^{-n}(B(x, \xi))\big) \leq C\mu(X) = C$$

gives $\mathrm{P}(T, \phi) = \mathrm{P}_x(T, \phi) \leq P$, for P_x defined in 3.4.3 applicable due to topolog-
ical transitivity of T. The proof is finished.   ♣

Remark 4.1.2. In order to prove Proposition 4.1.1 except the part identifying
P as $\mathrm{P}(T, \phi)$ we used only the inequalities

$$C^{-1} \leq \frac{\mu\big(T_x^{-n}(B(T^n(x), \xi))\big) \exp Pn}{\nu\big(T_x^{-n}(B(T^n(x), \xi))\big) \exp Qn} \leq C.$$

We needed the function ϕ in (4.1.1) and its Hölder continuity only to prove that
$P = Q = P(T, \phi)$. Hölder continuity allows us also to replace x in $S_n\phi(x)$ by
an arbitrary point contained in $T_x^{-n}(B(T^n(x), \xi))$.

Remark 4.1.3. For $\mathcal{R} = \{R_1, \ldots, R_d\}$, a Markov partition of diameter smaller
than ξ, (4.1.1) produces a constant C depending on $\mathcal{R}$ (see Exercise 4.1) such
that

$$C^{-1} \leq \frac{\mu\big(R_{j_0,\ldots,j_{n-1}}\big)}{\exp(S_n\phi(x) - Pn)} \leq C \tag{4.1.4}$$

for every admissible sequence $j_0, j_1, \ldots j_{n-1}$ and every $x \in R_{j_0,\ldots,j_{n-1}}$. In par-
ticular (4.1.4) holds for the shift map of a one-sided topological Markov chain.

The following completes Proposition 4.1.1.

Proposition 4.1.4. *If ϕ and ψ are two arbitrary Hölder continuous functions
on X, then the following conditions are equivalent:*

(1) *$\phi - \psi$ is cohomologous to a constant in the space of bounded functions (see
Def. 1.11.2).*

(2) *$G_\phi = G_\psi$.*

(3) *$G_\phi \cap G_\psi \neq \emptyset$.*

Proof. Of course (2) implies (3). That (1) implies (2) is also obvious. If (3) is satisfied, that is if there exists $\mu \in G_\phi \cap G_\psi$, then it follows from (4.1.1) that

$$D^{-1} \leq \exp(S_n(\phi)(x) - S_n(\psi)(x) - n\,\mathrm{P}(\phi) + n\,\mathrm{P}(\psi)) \leq D$$

for some constant D, all $x \in X$ and $n \in \mathbb{N}$. Applying logarithms we see that the condition (2) in Proposition 3.4.5 is satisfied with ϕ and ψ replaced by $\phi - \mathrm{P}(\phi)$ and $\psi - \mathrm{P}(\psi)$ respectively. Hence, by this Proposition, $\phi - P(\phi)$ and $\psi - \mathrm{P}(\psi)$ are cohomologous, which finishes the proof.   ♣

We shall prove later that the class of Gibbs states associated to T and ϕ is not empty (Section4.3 and contains exactly one Gibbs state which is T-invariant (Corollary 4.2.14). Actually we shall prove a stronger uniqueness theorem. We shall prove that any invariant Gibbs state is an equilibrium state for T and ϕ and prove (Section4.6) uniqueness of the equilibrium states for open expanding topologically transitive maps T and Hölder continuous functions $\phi : X \to \mathbb{R}$.

Proposition 4.1.5. *A probability T-invariant Gibbs state μ is an equilibrium state for T and ϕ.*

Proof. Consider an arbitrary finite partition $\mathcal{P}$ into Borel sets of diameter less than $\min(\eta, \xi)$. Then for every $x \in X$ we have $T_x^{-n}(B(T^n(x), \xi)) \supset \mathcal{P}^n(x)$, where $\mathcal{P}^n(x)$ is the element of the partition $\mathcal{P}^n = \bigvee_{j=0}^{n} \mathcal{P}$ that contains x. Hence $\mu\big(T_x^{-n}(B(T^n(x), \xi))\big) \geq \mu(\mathcal{P}^n(x))$. Therefore by the Shannon-McMillan-Breiman Theorem and (4.1.1) one obtains

$$\mathrm{h}_\mu(T) \geq \mathrm{h}_\mu(T, \mathcal{P}) \geq \int \Big(\limsup_{n \to \infty} \frac{1}{n}(n\,\mathrm{P}(T, \phi)) - S_n\phi(x)\Big)d\mu = \mathrm{P}(T, \phi) - \int \phi\,d\mu.$$

or in other words, $\mathrm{h}_\mu(T) + \int \phi\,d\mu \geq \mathrm{P}(T, \phi)$ which just means that μ is an equilibrium state.   ♣

4.2 Transfer operator and its conjugate. Measures with prescribed Jacobians

Suppose first that we are in the situation of Chapter 1, i.e. T is a measurable map. Suppose that m is *backward quasi-invariant* with respect to T, i.e.

$$T_*(m) = m \circ T^{-1} \prec m. \tag{4.2.1}$$

(Sometimes this property is called *non-singular*.) Then by the Radon-Nikodym Theorem there exists an m-integrable function $\Phi : X \to [0, \infty)$ such that for every measurable set $A \subset X$ we have

$$m(T^{-1}(A)) = \int_A \Phi\,dm.$$

One writes $d(m \circ T^{-1})/dm = \Phi$. In the situation of this Chapter, where T is a local homeomorphism (one does not need expanding yet) if T^{-1} has d branches on a ball $B(x, \xi)$ mapping the ball onto $U_1, \ldots, U_d$ respectively, then

$$\Phi = \sum_{j=1}^{d} \Phi_j \quad \text{where} \quad \Phi_j := d(m \circ (T|_{U_j})^{-1})/dm.$$

If we consider measures absolutely continuous with respect to a backward quasi-invariant "reference measure" m then the transformation $\mu \mapsto T_*(\mu)$ can be rewritten in the language of densities with respect to m as follows,

$$d\mu/dm \mapsto d(T_*\mu)/dm = \sum_{j=1}^{d} \big((d\mu/dm) \circ (T|_{U_j})^{-1}\big)\Phi_j. \qquad (4.2.2)$$

It is comfortable to define

$$\Psi(z) = \frac{d(m \circ (T|_{U_j})^{-1})}{dm}(T(z)), \qquad (4.2.3)$$

i.e. $\Psi = \Phi_j \circ T$ for $z \in U_j$. Notice that Ψ is defined on a set whose T-image has full measure (which is maybe larger than just a set of full measure, in the case a set of measure zero is mapped by T to a set of positive measure), see Section 4.6 for further discussion.

The transformation in (4.2.2) can be considered as a linear operator $\mathcal{L}_m :$ $L^1(m) \to L^1(m)$, called *transfer operator*,

$$\mathcal{L}_m(u)(x) = \sum_{\overline{x} \in T^{-1}(x)} u(\overline{x})\Psi(\overline{x}).$$

This definition makes sense, because if we change u on a set A of measure 0, then even if $m(T(A)) > 0$, we have $\Phi_j|_{T(A) \cap B(x,\xi)} = 0$ m-a.e., hence $\mathcal{L}_m(u)$ does not depend on the values of u on $T(A)$. We have the convention that if u is not defined (on a set of measure 0) and $\Psi = 0$, then $u\Psi = 0$.

The transformation $\mathcal{L}_m$ makes in fact sense in a more general situation, where $T : X \to X$ is measurable map of a probability space $(X, \mathcal{F}, m)$, backward quasi-invariant (non-singular), finite (or countable) -to-one. Instead of U_j we write $X = \bigcup X_j$, where X_j are measurable, pairwise disjoint, and for each j the map $T|_{X_j} \to T(X_j)$ is a measurable isomorphism.

Proposition 4.2.1.

$$\int \mathcal{L}_m(u)\, dm = \int u\, dm \quad \text{for all} \quad u \in L^1(m). \qquad (4.2.4)$$

Conversely, if (4.2.4) holds where in the definition of $\mathcal{L}_m$ we put an arbitrary m integrable function Ψ, then Ψ satisfies (4.2.3).

Proof. It is sufficient to consider $u = \mathbb{1}_A$ the indicator function for an arbitrary measurable $A \subset X_j$. We have

$$\int \mathcal{L}_m(\mathbb{1}_A)\, dm = \int_{T(A)} \Psi \circ (T|_{X_j})^{-1}\, dm = \int_{T(A)} \Phi_j\, dm = m(A),$$

the latter true by change of coordinates if and only if Φ_j is Jacobian as above. Compare Lemma 4.2.5.   ♣

It follows from (4.2.4) that $\mathcal{L}_m$ restricted to non-negative functions is an isometry in the $L^1(m)$ norm. The transfer operator $\mathcal{L}_m : L^1(m) \to L^1(m)$ is an example of Markov operator, see Exercise 4.4

By (4.2.2) we obtain the following characterization of probability T-invariant measures absolutely continuous with respect to m.

Proposition 4.2.2. *The probability measure $\mu = hm$ for $h \in L^1(m)$, $h \geq 0$, is T-invariant if and only if*

$$\mathcal{L}_m(h) = h.$$

Remark 4.2.3. For the operator $\mathcal{L}_m$ we have the identity

$$\mathcal{L}_m\big(f \cdot (g \circ T)\big) = \mathcal{L}_m(f) \cdot g. \tag{4.2.5}$$

making sense for any measurable functions $f, g : X \to \mathbb{R}$. Hence, using (4.2.4), for all $f \in L^\infty((\mu)$ and $g \in L^1(\mu)$, we get

$$\int f \cdot (g \circ T)\, dm = \int \mathcal{L}_m(f \cdot (g \circ T))\, dm = \int \mathcal{L}_m(f) \cdot g\, dm \tag{4.2.6}$$

and iterating this equality, we get

$$\int f \cdot (g \circ T^n)\, dm = \int \mathcal{L}_m^n(f) \cdot g\, dm. \tag{4.2.7}$$

for all $n = 1, 2, \dots$.

Remark 4.2.4. Since $\mathcal{L}_m$ acts on $L^1(m)$ we can consider the *conjugate* (another name: *adjoint*) operator $\mathcal{L}_m^* : L^\infty(m) \to L^\infty(m)$. Notice that

$$\int \mathcal{L}_m^*(f) \cdot g\, dm = \int f \cdot \mathcal{L}_m(g)\, dm = \int \mathcal{L}_m((f \circ T) \cdot g)\, dm = \int (f \circ T) \cdot g\, dm,$$

by definition and (4.2.4). Hence $\mathcal{L}_m^*(f) = f \circ T$.

Recall from Section 1.2 that $h \to h \circ T$ is called Koopman operator, here acting on $L^\infty(m)$. So the operator conjugate to $\mathcal{L}_m$ is this Koopman operator. If one considers both operators acting on $L^2(m)$, which is the case for m being T invariant (see Exercise 4.3), then these operators are mutually conjugate.

Continuous case

After this introduction, the appearance of the following linear operator, called Perron-Frobenius-Ruelle or Ruelle or Araki or also *transfer operator*, is not surprising:

$$\mathcal{L}_\phi(u)(x) = \sum_{\overline{x} \in T^{-1}(x)} u(\overline{x}) \exp(\phi(\overline{x})). \tag{4.2.8}$$

If the function ϕ is fixed we omit sometimes the subscript ϕ at $\mathcal{L}$. The function ϕ is often called a *potential* function. This term is compatible with the term used for ϕ in Section 4.1 for $P = 0$. It will become clear later on. The transfer's conjugate operator will be our tool to find a backward quasi-invariant measure m such that Ψ will be a scalar multiple of $\exp\phi$, hence $\mathcal{L}_m$ will be a scalar multiple of $\mathcal{L}_\phi$. Then in turn we will look for fixed points of $\mathcal{L}_m$ to find invariant measures. Restricting our attention to $\exp\phi$, we restrict considerations to Ψ strictly positive defined everywhere. One sometimes allows ϕ to have the value $-\infty$, but we do not consider this case in our book. See e.g. [Keller 1998]

Let us be now more specific. Let $\phi : X \to \mathbb{R}$ be a continuous function. Consider $\mathcal{L}_\phi$ acting on the Banach space of continuous functions $\mathcal{L}_\phi : C(X) \to C(X)$. It is a continuous linear operator and its norm is equal to $\sup_x \sum_{\overline{x} \in T^{-1}(x)} \exp(\phi(\overline{x})) = \sup \mathcal{L}_\phi(\mathbb{1})$ as this is a positive operator i.e. it maps real non-negative functions to real non-negative functions (see Section 2.1). Consider the conjugate operator $\mathcal{L}_\phi^* : C^*(X) \to C^*(X)$. Note that as conjugate to a positive operator it is also positive, i.e. transforms measures into measures.

Lemma 4.2.5. *For every $\mu \in C^*(X)$ and every Borel set $A \subset X$ on which T is injective*

$$\mathcal{L}_\phi^*(\mu)(A) = \int_{T(A)} \exp(\phi \circ (T|_A)^{-1})d\mu \tag{4.2.9}$$

Proof. It is sufficient to prove (4.2.9) for $A \subset B(x,r)$ with any $x \in X$ and $r > 0$ such that T is injective on $B(x,2r)$ (say $r = \eta$). Now approximate in pointwise convergence the indicator function χ_A by uniformly bounded continuous functions with support in $B = B(x,2r)$. We have for any such function f,

$$\mathcal{L}_\phi^*(\mu)(f) = \mu(\mathcal{L}_\phi(f)) = \int_{T(B)} (f \exp(\phi)) \circ (T|_B)^{-1}d\mu.$$

We used here the fact that the only branch of T^{-1} mapping $T(B)$ to the support of f is that one leading $T(B)$ to B. Passing with f to the limit χ_A on both sides (Dominated Convergence Theorem, Section 1.1) gives (4.2.9). ♣

Observe that whereas $\mathcal{L}_\phi$ transports a measure from the past (more precisely: transports a density, see (4.2.2)), $\mathcal{L}_\phi^*$ pulls a measure back from the future with Jacobian $\exp\phi \circ T^{-1}$. This is the right operator to use, to look for the missing "reference measure" m.

Definition 4.2.6. J is called the *weak Jacobian* if $J : X \to [0, \infty)$ and there exists a Borel set $E \subset X$ such that $\mu(E) = 0$ and for every Borel set $A \subset X$ on which T is injective, $\mu(T(A \setminus E)) = \int_A J d\mu$.

Recall from Chapter 1 (Def. 1.9.4) that a measurable function $J : X \to [0, \infty)$ is called the *Jacobian* or the *strong Jacobian* of a map $T : X \to X$ with respect to a measure μ if for every Borel set $A \subset X$ on which T is injective $\mu(T(A)) = \int_A J d\mu$. In particular μ is forward quasi-invariant (cf. Lemma 1.9.3 and Definition 1.9.4).

Notice that if μ is backward quasi-invariant then the condition that J is the weak Jacobian translates to $\mu(A) = \int_{T(A)} \frac{1}{J \circ (T|_A)^{-1}} d\mu$.

Corollary 4.2.7. *If a probability measure μ satisfies $\mathcal{L}_\phi^*(\mu) = c\mu$ (i.e. μ is an eigen-measure of $\mathcal{L}_\phi^*$ corresponding to a positive eigenvalue c), then $c \exp(-\phi)$ is the Jacobian of T with respect to μ.*

Proof. Substitute $c\mu$ in place of $\mathcal{L}^*(\mu)$ in (4.2.9). It then follows that μ is backward quasi-invariant and $c \exp(-\phi)$ is the weak Jacobian of T with respect to μ. Since $\frac{1}{\exp(-\phi)} = \exp \phi$ is positive everywhere, $c \exp(-\phi)$ is the strong Jacobian of T. ♣

Theorem 4.2.8. *Let $T : X \to X$ be a local homeomorphism of a compact metric space X and let $\phi : X \to \mathbb{R}$ be a continuous function. Then there exists a Borel probability measure $m = m_\phi$ and a constant $c > 0$, such that $\mathcal{L}_\phi^*(m) = cm$. The function $c \exp(-\phi)$ is the strong Jacobian for T with respect to the measure m.*

Proof. Consider the map $l(\mu) := \frac{\mathcal{L}^*(\mu)}{\mathcal{L}^*(\mu)(\mathbb{1})}$ on the convex set of probability measures on X, i.e. on $M(X)$, endowed with the weak* topology (Sec. 2.1). The transformation l is continuous in this topology since $\mu_n \to \mu$ weak* implies for every $u \in C(X)$ that $\mathcal{L}^*(\mu_n)(u) = \mu_n(\mathcal{L}(u)) \to \mu(\mathcal{L}(u)) = \mathcal{L}^*(\mu)(u)$. As $M(X)$ is weak* compact (see Th. 2.1.6) we can use Theorem 2.1.7 (Schauder-Tychonoff fixed point theorem) to find $m \in M(X)$ such that $l(m) = m$. Hence $\mathcal{L}^*(m) = cm$ for $c = \mathcal{L}^*(m)(\mathbb{1})$. Thus T has the Jacobian equal to $c \exp(-\phi)$, by Corollary 4.2.7. ♣

Note again that we write $\exp \phi$ in order to guarantee it never vanishes, so that there exists the Jacobian for T with respect to m. To find an eigen-measure m for $\mathcal{L}^*$ (i.e. with a weak Jacobian being a multiple of $\exp(-\phi)$) we could perfectly well allow $\exp \phi = 0$.

We have the following complementary fact in the case when Jacobian J exists.

Proposition 4.2.9. *If $T : X \to X$ is a local homeomorphism of a compact metric space X and a Jacobian J with respect to a probability measure m exists, then for every Borel set A*

$$\frac{1}{d} \int_A J \, dm \le m(T(A)) \le \int_A J \, dm.$$

where d is the degree of T ($d := \sup_{x \in X} \sharp T^{-1}(\{x\})$). In particular if $m(A) = 0$, then $m(T(A)) = 0$.

Proof. Let us partition A into finitely many Borel sets, say $A_1, A_2, \ldots, A_n$, of diameters so small that T restricted to each of them is injective. Then, on the one hand,

$$m(T(A)) = m\Big(\bigcup_{i=1}^{n} T(A_i) \Big) \leq \sum_{i=1}^{n} m(T(A_i)) = \sum_{i=1}^{n} \int_{A_i} J \, dm = \int_A J \, dm.$$

and on the other hand, since the multiplicity of the family $\{T(A_i) : 1 \leq i \leq n\}$ does not exceed d,

$$m(T(A)) = m\Big(\bigcup_{i=1}^{n} T(A_i) \Big) \geq \frac{1}{d} \sum_{i=1}^{n} m(T(A_i)) = \frac{1}{d} \sum_{i=1}^{n} \int_{A_i} J \, dm = \frac{1}{d} \int_A J \, dm.$$

The proof is finished. ♣

Let us go back to T, a distance expanding topologically transitive open map.

Proposition 4.2.10. *The measure m produced in Theorem 4.2.8 is positive on non-empty open sets. Moreover for every $r > 0$ there exists $\alpha = \alpha(r) > 0$ such that for every $x \in X$, $m(B(x,r)) \geq \alpha$.*

Proof. For every open $U \subset X$ there exists $n \geq 0$ such that $\bigcup_{j=0}^{n} T^j(U) = X$ (Theorem 3.3.12). So, by Proposition 4.2.9, $m(U) = 0$ would imply that $1 = m(X) \leq \sum_{j=0}^{n} m(T^j(U)) = 0$, a contradiction.

Passing to the second part of the proof, let $x_1, \ldots, x_m$ be an $r/2$-net in X and $\alpha := \min_{1 \leq j \leq m} \{m(B(x_j, r/2))\}$. Since for every $x \in X$ there exists j such that $\rho(x, x_j) \leq r/2$, we have $B(x, r) \supset B(x_j, r/2)$, and so $m(B(x,r)) \geq m(B(x_j, r/2))$. Thus it is enough to set $\alpha(r) := \alpha$. ♣

Proposition 4.2.11. *The measure m is a Gibbs state of ϕ and $\log c = \mathrm{P}(T, \phi)$.*

Proof. We have for every $x \in X$ and every integer $n \geq 0$,

$$m(B(T^n(x), \xi)) = \int_{T_x^{-n}(B(T^n(x),\xi))} c^n \exp(-S_n \phi) \, dm.$$

Since, by Lemma 3.4.2, the ratio of the supremum and infimum of the integrand of the above integral is bounded from above by a constant $C > 0$ and is bounded from below by C^{-1}, we obtain

$$1 \geq m(B(T^n(x), \xi)) \geq C^{-1} c^n \exp(-S_n \phi(x)) m\big(T_x^{-n}(B(T^n(x), \xi))\big)$$

and

$$\alpha(\xi) \leq m(B(T^n(x), \xi)) \leq C c^n \exp(-S_n \phi(x)) m(T_x^{-n}(B(T^n(x), \xi))).$$

Hence

$$\alpha(\xi)C^{-1} \le \frac{m(T_x^{-n}(B(T^n(x),\xi)))}{\exp(S_n\phi(x) - n\log c)} \le C,$$

and therefore m is a Gibbs state. That $\log c = \mathrm{P}(T,\phi)$ follows now from Proposition 4.1.1. ♣

We give now a simple direct proof of equality $\log c = \mathrm{P}(T,\phi)$. First note that by the definition of $\mathcal{L}_\phi$ and a simple inductive argument, for every integer $n \ge 0$,

$$\mathcal{L}_\phi^n(u)(x) = \sum_{\overline{x}\in T^{-n}(x)} u(\overline{x})\exp(S_n\phi(\overline{x})). \qquad (4.2.10)$$

The estimate (3.4.3) can be rewritten as

$$C^{-1} \le \mathcal{L}^n(\mathbb{1})(x)/\mathcal{L}^n(\mathbb{1})(y) \le C \quad \text{for every } x, y \in X. \qquad (4.2.11)$$

Now $c^n = c^n m(\mathbb{1}) = (\mathcal{L}^*)^n(m)(\mathbb{1}) = m(\mathcal{L}^n(\mathbb{1}))$ and hence

$$\log c = \lim_{n\to\infty} \frac{1}{n}\log m(\mathcal{L}^n(\mathbb{1})) = P(T,\phi),$$

where the last equality follows from (4.2.11) and Proposition 3.4.3.

Note that in the last equality above we used the property that m is a measure, more precisely that the linear functional corresponding to m is positive. For m a signed eigen-measure and c a complex eigenvalue for $\mathcal{L}^*$ we would obtain only $\log|c| \le P(T,\phi)$ (one should consider a function u such that $\sup|u| = 1$ and $m(u) = 1$ rather than the function $\mathbb{1}$) and indeed usually the point spectrum of $\mathcal{L}^*$ is big(ref ??????).

We are already in the position to prove some ergodic properties of Gibbs states.

Theorem 4.2.12. *If $T : X \to X$ is an open, topologically exact, distance expanding map, then the system (T, m) is exact in the measure theoretic sense, namely for every A of positive measure $m(T^n(A)) \to 1$ as $n \to \infty$, see Definition 1.10.2 and the exercise following it.*

Proof. Let E be an arbitrary Borel subset of X with $m(E) > 0$. By regularity of the measure m we can find a compact set $A \subset E$ such that $m(A) > 0$. Fix an arbitrary $\varepsilon > 0$. As in the proof of Proposition 4.1.1, we find for every n large enough, a cover of A by sets D_ν of the form $T_x^{-n}(B(x_i,\xi)), x \in X(i), i = 1,\ldots,l$ such that $m(\bigcup_\nu D_\nu) \le m(A) + \varepsilon$. Hence $m(\bigcup_\nu(D_\nu \setminus A)) \le \varepsilon$. Since the multiplicity of this cover is at most l, we have

$$\sum_\nu m(D_\nu \setminus A) \le l\varepsilon.$$

Hence,

$$\frac{\sum_\nu m(D_\nu \setminus A)}{\sum_\nu m(D_\nu)} \le \frac{l\varepsilon}{m(A)}.$$

Therefore for all n large enough there exists $D = D_\nu = T_x^{-n}(B)$, with some $B = B(x_i, \xi))$, $1 \le i \le l$, such that

$$\frac{m(D \setminus A)}{m(D)} \le \frac{l\varepsilon}{m(A)}.$$

Hence, as $B \setminus T^n(A) \subset T^n(D \setminus A)$,

$$\begin{aligned}
\frac{m(B \setminus T^n(A))}{m(B)} &\le \frac{\int_{D \setminus A} c^n \exp(-S_n\phi)dm}{\int_D c^n \exp(-S_n\phi)dm} \\
&\le C^2 \frac{m(D \setminus A)}{m(D)} \le C^2 \frac{l\varepsilon}{m(A)}.
\end{aligned}$$

By the topological exactness of T, there exists $N \ge 0$ such that for every i we have $T^N(B(x_i, \xi)) = X$. In particular $T^N(B) = X$. So, using Proposition 4.2.9, we get

$$m(X \setminus T^N(T^n(A))) \le m(T^N(B \setminus T^n(A))) \le c^N (\inf \exp \phi)^{-N} \frac{Cl\varepsilon}{m(A)}.$$

Letting $\varepsilon \to 0$, we obtain $m(X \setminus T^N(T^n(A))) \to 0$ as $n \to \infty$. Hence $m(T^{N+n}(A)) \to 1$. ♣

We have considered here a special Gibbs measure $m = m_\phi$. Notice however that by Proposition 4.1.1 the assertion of Theorem 4.2.12 holds for every Gibbs measure associated to T and ϕ.

Corollary 4.2.13. *If $T : X \to X$ is an open, topologically transitive, distance expanding map, then for every Hölder potential $\phi : X \to \mathbb{R}$, every Gibbs measure for ϕ is ergodic.*

Proof. By Th. 3.3.8 and Th. 3.3.12 there exists a positive integer N such that T^N is topologically mixing on a T^N-invariant closed-open set $Y \subset X$, where all $T^j(Y)$ are pairwise disjoint and $\bigcup_{j=0,\ldots,N-1} T^j(Y) = X$. So our $T^N|_Y$, being also an open expanding map, is topologically exact by Theorem 3.3.8, hence exact in the measure-theoretic sense by Theorem 4.2.12. Let $m(E) > 0$. Then there is $k \ge 0$ such that $m(E \cap T^k(Y)) > 0$. Then for every $j = 0, \ldots, N-1$ we have $m(T^{Nn}T^j(E \cap T^k(Y))) \to m(T^j(T^k(Y)))$, hence $m(\bigcup_{n \ge 0} T^n(E)) \to 1$. For E being T-invariant this yields $m(E) = 1$. This implies ergodicity. ♣

With the use of Proposition 1.2.7 we get the following fact promised in Section 4.1.

Corollary 4.2.14. *If $T : X \to X$ is an open, topologically transitive, distance expanding map, then for every Hölder continuous potential $\phi : X \to \mathbb{R}$, there is at most one invariant Gibbs measure for ϕ.*

4.3   Iteration of the transfer operator. Existence of invariant Gibbs measures

It is comfortable to consider the normalized operator $\mathcal{L}_{\overline{\phi}}$ with $\overline{\phi} = \phi - \mathrm{P}(T, \phi)$. We have $\mathcal{L}_{\overline{\phi}} = \mathrm{e}^{-\mathrm{P}(T, \phi)} \mathcal{L}_{\phi}$ (recall that $\mathrm{P}(T, \phi) = \log c$). Then for the reference measure $m = m_{\phi}$ satisfying $\mathcal{L}_{\phi}^{*}(m) = \mathrm{e}^{\mathrm{P}(\phi)} m$ we have $\mathcal{L}_{\overline{\phi}}^{*}(m) = m$, i.e.

$$\int u \, dm = \int \mathcal{L}_{\overline{\phi}}(u) \, dm \quad \text{for every} \ \ u \in C(X). \tag{4.3.1}$$

For a fixed potential ϕ we often denote $\mathcal{L}_{\overline{\phi}}$ by $\mathcal{L}_0$. By (4.2.11), for all $x, y \in X$, and all non-negative integers n,

$$\mathcal{L}_0^n(\mathbb{1})(x) / \mathcal{L}_0^n(\mathbb{1})(y) \le C. \tag{4.3.2}$$

Multiplying this inequality by $\mathcal{L}_0^n(\mathbb{1})(y)$ and then integrating with respect to the variable x and y we get respectively the first and the third of the following inequalities below

$$C^{-1} \le \inf \mathcal{L}_0^n(\mathbb{1}) \le \sup \mathcal{L}_0^n(\mathbb{1}) \le C. \tag{4.3.3}$$

By (3.4.2) for every $x, y \in X$ such that $x \in B(y, \xi)$ we have an inequality which is more refined than (3.4.3). Namely,

$$\frac{\mathcal{L}_{\phi}^n(\mathbb{1})(x)}{\mathcal{L}_{\phi}^n(\mathbb{1})(y)} = \frac{\sum_{\overline{x} \in T^{-n}(x)} \exp S_n \phi(\overline{x})}{\sum_{\overline{y} \in T^{-n}(y)} \exp S_n \phi(\overline{y})}$$

$$\le \sup_{\overline{x} \in T^{-n}(x)} \frac{\exp S_n \phi(\overline{x})}{\exp S_n \phi(y_n(\overline{x}))} \le \exp(C_1 \rho(x, y)^{\alpha}), \tag{4.3.4}$$

where $C_1 = \frac{\vartheta_{\alpha}(\phi)}{1 - \lambda^{-\alpha}}$ and $y_n(\overline{x}) := T_{\overline{x}}^{-n}(y)$. By this estimate and by (4.3.3) we get for all $n \ge 1$ and all $x, y \in X$ such that $x \in B(y, \xi)$, the following

$$\mathcal{L}_0^n(\mathbb{1})(x) - \mathcal{L}_0^n(\mathbb{1})(y) = \Big(\frac{\mathcal{L}_0^n(\mathbb{1})(x)}{\mathcal{L}_0^n(\mathbb{1})(y)} - 1\Big)\mathcal{L}_0^n(\mathbb{1})(y)$$

$$\le C|\exp(C_1 \rho(x, y)^{\alpha}) - 1| \le C_2 \rho(x, y)^{\alpha} \tag{4.3.5}$$

with C_2 depending on C, C_1 and ξ.

Proposition 4.3.1. *There exists a positive function $u_{\phi} \in \mathcal{H}_{\alpha}(X)$ such that $\mathcal{L}_0(u_{\phi}) = u_{\phi}$ and $\int u_{\phi} \, dm = 1$.*

Proof. By (4.3.5) and (4.3.3) the functions $\mathcal{L}_0^n(\mathbb{1})$ have uniformly bounded norms in the space $\mathcal{H}_{\alpha}(X)$ of all Hölder continuous functions, see Sec. 3.4. Hence by Arzela-Ascoli theorem there exists a limit $u_{\phi} \in C(X)$ for a subsequence of $u_n = \frac{1}{n} \sum_{j=0}^{n-1} \mathcal{L}_0^j(\mathbb{1})$, $n = 1, \dots$. Of course $u_{\phi} \in \mathcal{H}_{\alpha}(X)$, $C^{-1} \le u_{\phi} \le C$, and using (4.3.3), a straightforward computation shows that $\mathcal{L}_0(u_{\phi}) = u_{\phi}$ (compare 2.1.14). Also $\int u_{\phi} \, dm = \lim_{n \to \infty} \int u_n \, dm = \int \mathbb{1} \, dm = 1$. The proof is finished.   ♣

Combining this proposition, Proposition 4.2.2, Proposition 4.2.11 and Corollary 4.2.14, we get the following.

Theorem 4.3.2. *For every Hölder continuous function $\phi : X \to \mathbb{R}$ there exists a unique invariant Gibbs state associated to T and ϕ, namely $\mu_\phi = u_\phi m_\phi$.*

In the rest of this Section we study in detail the iteration of $\mathcal{L}_0$ on the real or complex Banach spaces $C(X)$ and an $\mathcal{H}_\alpha$.

Definition 4.3.3. We call a bounded linear operator $Q : B \to B$ on a Banach space B *almost periodic* if for every $b \in B$ the family $\{Q^n(b)\}_{n=0}^{\infty}$ is relatively compact, i.e. its closure in B is compact in the norm topology.

Proposition 4.3.4. *The operators $\mathcal{L}_0^n$ acting on $C(X)$ have the norms uniformly bounded for all $n = 1, 2, \ldots$.*

Proof. By the definition of $\mathcal{L}$, by (4.3.3) and by $\int \mathcal{L}_0^n(\mathbb{1}) = 0$, for every $u \in C(X)$ we get

$$\sup |\mathcal{L}_0^n(u)| \leq \sup |u| \sup \mathcal{L}_0^n(\mathbb{1}) \leq C \sup |u|. \tag{4.3.6}$$

♣

Remark that in the Proof above, instead of referring to the form of $\mathcal{L}$ one can only refer to the fact that $\mathcal{L}$ is a positive operator, hence its norm is attained at $\mathbb{1}$.

Consider an arbitrary function $h : [0, \infty) \to [0, \infty)$ such that $h(0) = 0$, continuous at 0 and monotone increasing. We call such a function an abstract modulus of continuity. If $u : X \to \mathbb{C}$ is a function such that there is $\xi > 0$ such that for all $x, y \in X$ with $\rho(x, y) \leq \xi$

$$|u(x) - u(y)| \leq h(\rho(x, y)) \tag{4.3.7}$$

we say that h is a modulus of continuity of u. Given also $b \geq 0$ we denote by $C_h^b(X)$ the set of all functions $u \in C(X)$ such that $||u||_\infty \leq b$ and h is a modulus of continuity of u with fixed $\xi > 0$. By Arzela-Ascoli theorem each $C_h^b(X)$ is a compact subset of $C(X)$.

Theorem 4.3.5. *The operator $\mathcal{L}_0 : C(X) \to C(X)$ is almost periodic. Moreover, if $b \geq 0$, h is an abstract modulus of continuity, $\theta \geq 0$, and ξ as in Lemma 3.1.2 then for all $\phi \in \mathcal{H}_\alpha$ with $\vartheta_\alpha(\phi) \leq \theta$ there exists $\hat{b}$ and $\hat{C}$ depending only on b and θ such that for the abstract modulus of continuity $\hat{h}(t) = \hat{C}(t^\alpha + h(t))$*

$$\{\mathcal{L}_0^n(u) : u \in C_h^b(X), n \geq 0\} \subset C_{\hat{h}}^{\hat{b}}(X). \tag{4.3.8}$$

Proof. It follows from (4.3.6) that we can set $\hat{b} = Cb$. For every $x \in X$ and $n \geq 0$ denote $\exp(S_n \overline{\phi}(x))$ by $E_n(x)$. Consider arbitrary points $x \in X$ and

$y \in B(x, \xi)$. Use the notation $y_n(\overline{x}) := T_{\overline{x}}^{-n}(y)$, the same as in (4.3.4). Fix $u \in C_h^b$ By (4.3.5) and (4.3.3) we have for every $u \in C(X)$

$$|\mathcal{L}_0^n(u)(x)\mathcal{L}_0^n(u)(y)| = \Big| \sum_{\overline{x} \in T^{-n}(x)} u(\overline{x})E_n(\overline{x}) - u(y_n(\overline{x}))E_n(y_n(\overline{x})) \Big|$$

$$\leq \Big| \sum_{\overline{x} \in T^{-n}(x)} u(\overline{x})(E_n(\overline{x}) - E_n(y_n(\overline{x}))) \Big| + \Big| \sum_{\overline{x} \in T^{-n}(x)} E_n(y_n(\overline{x}))(u(\overline{x}) - u(y_n(\overline{x}))) \Big|$$

$$\leq \|u\|_\infty C_2\rho(x,y)^\alpha + Ch\Big(\sup_{\overline{x} \in T^{-n}(x)} |u(\overline{x}) - u(y_n(\overline{x}))| \Big)$$

$$\leq bC_2\rho(x,y)^\alpha + Ch(\lambda^{-n}\rho(x,y)) \leq bC_2\rho(x,y)^\alpha + Ch(\rho(x,y)) \qquad (4.3.9)$$

Therefore we are done by setting $\hat{C} := \max(bC_2, C)$. ♣

For $u \in \mathcal{H}_\alpha$ we obtain the fundamental estimate (4.3.10).

Theorem 4.3.6. *There exist constants $C_3, C_4 > 0$ such that for every $u \in \mathcal{H}_\alpha$, all $n = 1, 2, \ldots$ and $\lambda > 1$ from the expanding property of T,*

$$\vartheta_\alpha(\mathcal{L}_0^n(u)) \leq C_3\lambda^{-n\alpha}\vartheta_\alpha(u) + C_4\|u\|_\infty, \qquad (4.3.10)$$

Proof. Continuing the last line of (4.3.9) and using $\rho(\overline{x}, y_n(\overline{x})) \leq \lambda^{-n}\rho(\overline{x}, \overline{y})$ we obtain

$$|\mathcal{L}_0^n(u)(x) - \mathcal{L}_0^n(u)(y)| \leq \|u\|_\infty C_2\rho(x,y)^\alpha + C\vartheta_{\alpha,\xi}(u)\lambda^{-n\alpha}\rho(x,y)^\alpha.$$

This proves (4.3.10), provisionally with $\vartheta_{\alpha,\xi}$ rather than ϑ_α, with $C_3 = C$ from (3.4.3) and (4.3.3) and with $C_4 = C_2$ (recall that the latter constant is of order CC_1 where C_1 appeared in (4.3.4)). To get a bound on ϑ_α replace C_4 by $\max\{C_4, 2C/\xi^\alpha\}$, see (4.3.6) and Section 3.4. ♣

Corollary 4.3.7. *There exist an integer $N > 0$ and real numbers $0 < \tau < 1, C_5 > 0$ such that for every $u \in \mathcal{H}_\alpha$,*

$$\|\mathcal{L}_0^N(u)\|_{\mathcal{H}_\alpha} \leq \tau\|u\|_{\mathcal{H}_\alpha} + C_5\|u\|_\infty \qquad (4.3.11)$$

Proof. This Corollary immediately follows from (4.3.10) and Proposition 4.3.4. ♣

In fact a reverse implication, yielding (4.3.10) for iterates of $\mathcal{L}^N$, holds

Proposition 4.3.8. *(4.3.11) together with (4.3.6) imply*

$$\exists C_6 > 0 \; \forall n = 1, 2, \ldots \quad \|\mathcal{L}_0^{nN}(u)\|_{\mathcal{H}_\alpha} \leq \tau^n\|(u)\|_{\mathcal{H}_\alpha} + C_6\|u\|_\infty \qquad (4.3.12)$$

Proof. Substitute in (4.3.11) $\mathcal{L}_0^N(u)$ in place of u etc. n times using $\|\mathcal{L}_0^j(u)\|_\infty \leq C\|u\|_\infty$. We obtain (4.3.12) with $C_6 = CC_5/(1 - \tau)$. ♣

4.4 Convergence of $\mathcal{L}^n$. Mixing properties of Gibbs measures

Recall that by Proposition 4.3.1 there exists a positive function $u_\phi \in \mathcal{H}_\alpha(X)$ such that $\mathcal{L}_0(u_\phi) = u_\phi$ and $\int u_\phi dm_\phi = 1$.

It is convenient to replace the operator $\mathcal{L}_0 = \mathcal{L}_{\overline{\phi}}$ by the operator $\hat{\mathcal{L}} = \hat{\mathcal{L}}_\phi$ defined by

$$\hat{\mathcal{L}}(u) = \frac{1}{u_\phi} \mathcal{L}_0(uu_\phi).$$

If we denote the operator of multiplication by a function w by the same symbol w then we can write

$$\hat{\mathcal{L}}(u) = u_\phi^{-1} \circ \mathcal{L}_0 \circ u_\phi.$$

Since $\hat{\mathcal{L}}$ and $\mathcal{L}_0$ are conjugate by the operator u_ϕ, their spectra are the same. In addition, as this operator u_ϕ is positive, non-negative functions go to non-negative functions. Hence measures are mapped to measures by the conjugate operator.

Proposition 4.4.1. $\hat{\mathcal{L}} = \mathcal{L}_\psi$ where $\psi = \overline{\phi} + \log u_\phi - \log u_\phi \circ T = \phi - \mathrm{P}(T, \phi) + \log u_\phi - \log u_\phi \circ T$.

Proof.

$$\hat{\mathcal{L}}(u)(x) = \frac{1}{u_\phi(x)} \sum_{T(\overline{x})=x} u(\overline{x}) u_\phi(\overline{x}) \exp \phi(\overline{x}) =$$

$$\sum_{T(\overline{x})=x} u(\overline{x}) \exp(\phi(\overline{x}) + \log u_\phi(\overline{x}) - \log u_\phi(x)).$$

♣

Note that the eigenfunction u_ϕ for $\mathcal{L}_0$ has changed to the eigenfunction $\mathbb{1}$ for $\hat{\mathcal{L}}$. In other words we have the following

Proposition 4.4.2. $\hat{\mathcal{L}}(\mathbb{1}) = \mathbb{1}$, *i.e. for every $x \in X$*

$$\sum_{\overline{x} \in T^{-1}(x)} \exp \psi(\overline{x}) = 1. \tag{4.4.1}$$

♣

Note that Jacobian of T with respect to the Gibbs measure $\mu = u_\phi m$ (see Th. 4.3.2) is $(u_\phi \circ T)(\exp(-\overline{\phi}))u_\phi^{-1} = \exp(-\psi)$. So for ψ the reference measure (with Jacobian $\exp(-\psi)$) and the invariant Gibbs measure coincide.

Note that passing from $\mathcal{L}_\phi$, through $\mathcal{L}_{\overline{\phi}}$, to $\mathcal{L}_\psi$ we have been replacing ϕ by cohomological (up to a constant) functions. By Proposition 4.1.4. this does not change the set of Gibbs states.

One can think of the transformation $u \mapsto u/u_\phi$ as new coordinates on $C(X)$ or $\mathcal{H}_\alpha(X)$ (real or complex-valued functions). $\mathcal{L}_0$ changes in these coordinates to $\mathcal{L}_\psi$ and the functional $m(u)$ to $m(u_\phi u)$. The latter, denote it by m_ψ, is the eigen-measure for $\mathcal{L}_\psi^*$ with the eigenvalue 1. It is positive because the operator u_ϕ is positive (see the comment above). So $\exp(-\psi)$ is the Jacobian for m_ψ by Corollary 4.2.7. Hence by (4.4.1), m_ψ is T-invariant. This is our invariant Gibbs measure μ.

Proposition 4.3.4 applied to $\hat{\mathcal{L}}$ takes the form:

Proposition 4.4.3. $\|\hat{\mathcal{L}}\|_\infty = 1$.

Proof. $\sup |\hat{\mathcal{L}}(u)| \le \sup |u|$ because $\hat{\mathcal{L}}$ is an operator of "taking an average" of u from the past (by Proposition 4.4.2). The equality follows from $\hat{\mathcal{L}}(\mathbb{1}) = \mathbb{1}$.   ♣

The topological exactness of T gives a stronger result:

Lemma 4.4.4. *Let* $T : X \to X$ *be a topologically exact, distance expanding open map. Suppose that* $g : [0, \infty) \to [0, \infty)$ *is an abstract modulus of continuity. Then for every* $K > 0$ *and* $\delta_1 > 0$ *there exist* $\delta_2 > 0$ *and* $n > 0$ *such that*

- *for all* $\phi \in \mathcal{H}_\alpha$ *with* $\|\phi\|_{\mathcal{H}_\alpha} \le K$ *and*

- *for all* $u \in C(X, \mathbb{R})$ *with* g *being its modulus of continuity and such that* $\int u d\mu = 0$ *and* $\|u\|_\infty \ge \delta_1$,

we have for $\hat{\mathcal{L}} = \hat{\mathcal{L}}_\phi$

$$\|\hat{\mathcal{L}}^n(u)\|_\infty \le \|u\|_\infty - \delta_2.$$

Proof. Fix $\varepsilon > 0$ so small that $g(\varepsilon) < \delta_1/2$. Let n be ascribed to ε according to Theorem 3.3.13(2), namely $\forall x \; T^n(B(x, \varepsilon)) = X$. Since $\int u d\mu = 0$, there exist $y_1, y_2 \in X$ such that $u(y_1) \le 0$ and $u(y_2) \ge 0$. For an arbitrary $x \in X$ choose $x' \in B(y_1, \varepsilon) \cap T^{-n}(x)$ (it exists by the definition of n). We have $u(x') \le u(y_1) + g(\varepsilon) \le \delta_1/2 \le \|u\|_\infty - \delta_1/2$. So,

$$\hat{\mathcal{L}}^n(u)(x) = u(x') \exp S_n \psi(x') + \sum_{\overline{x} \in T^{-n}(x) \setminus \{x'\}} u(\overline{x}) \exp S_n \psi(\overline{x})$$

$$\le (\|u\|_\infty - \delta_1/2) \exp S_n \psi(x') + \|u\|_\infty \sum_{\overline{x} \in T^{-n}(x) \setminus \{x'\}} \exp S_n \psi(\overline{x})$$

$$\le \|u\|_\infty \Big(\sum_{\overline{x} \in T^{-n}(x)} \exp S_n \psi(\overline{x}) \Big) - (\delta_1/2) \exp S_n \psi(x')$$

$$= \|u\|_\infty - (\delta_1/2) \exp S_n \psi(x').$$

Similarly for $x'' \in B(y_2, \varepsilon) \cap T^{-n}(x)$

$$\hat{\mathcal{L}}^n(u)(x) \ge -\|u\|_\infty + (\delta_1/2) \exp S_n \psi(x'').$$

Thus we have proved our lemma with $\delta_2 := (\delta_1/2) \inf_{x \in X} \exp S_n \psi(x)$. To finish the proof we need to relate δ_2 to ϕ rather than to ψ. To this end notice that for

every $x \in X$ we have $\psi(x) \geq \phi(x) - 2\log ||(u_\phi)||_\infty - P(T, \phi) \geq -3\log ||(u_\phi)||_\infty - \mathrm{h}_{\mathrm{top}}(T)$, and $||u_\phi||_\infty \leq C$, where C depends on K, see (4.3.3), (3.4.2), (3.4.3).

♣

We shall prove now a theorem which completes Proposition 4.3.4 and Theorem 4.3.5.

Theorem 4.4.5. *For every* $u \in C(X, \mathbb{C})$ *and* T, *topologically exact distance expanding open map, we have for* $c = e^{P(T,\phi)}$

$$\lim_{n \to \infty} ||c^{-n}\mathcal{L}_\phi^n(u) - m_\phi(u)u_\phi||_\infty = 0 \tag{4.4.2}$$

In particular if $\int u \, d\mu = 0$, *then*

$$\lim_{n \to \infty} ||\hat{\mathcal{L}}^n(u)||_\infty = 0 \tag{4.4.3}$$

Moreover the convergences in (4.4.2) and (4.4.3) are uniform for $u \in C_h^b$ *and* ϕ *in an arbitrary bounded subset* H *of in* $\mathcal{H}_\alpha(X)$.

Proof. For real-valued u, with $\int u d\mu = 0$, the sequence $a_n(u) := ||\hat{\mathcal{L}}^n(u)||_\infty$ is monotone decreasing by Proposition 4.4.3. Suppose that $\lim_{n \to \infty} a_n = a > 0$. By Theorem 4.3.5 all the iterates $\hat{\mathcal{L}}^n(u)$ have a common modulus of continuity g. So applying Lemma 4.4.4 with this g and $\delta_1 = a$ we find n_0 and $\delta_2 > 0$ such that $||\hat{\mathcal{L}}^{n_0}(\hat{\mathcal{L}}^n(u))||_\infty \leq ||\hat{\mathcal{L}}^n(u)||_\infty - \delta_2$ for every $n \geq 0$. So, for n such that $||\hat{\mathcal{L}}^n(u)||_\infty < a + \delta_2$ we obtain $||\hat{\mathcal{L}}^{n+n_0}(u)||_\infty < a$, a contradiction with the definition of a. This proves (4.4.3) for u real-valued. For u complex-valued with $\int u d\mu = 0$, decompose u in the real and complex parts.

To prove (4.4.2) notice first that for an arbitrary $u \in C(X, \mathbb{C})$ the convergence in (4.4.3) yields, due to $\hat{\mathcal{L}}(\mathbb{1}) = \mathbb{1}$,

$$||\hat{\mathcal{L}}^n(u) - \mu(u)\mathbb{1}||_\infty = ||\hat{\mathcal{L}}^n(u - \mu(u)\mathbb{1})||_\infty \to 0.$$

Change now coordinates on $C(X)$ to go back to $\mathcal{L}_0$ and next replace it by $c^{-1}\mathcal{L}_\phi$. One obtains (4.4.2).

For the last part of the theorem, set

$$a_n := \sup\{||\hat{\mathcal{L}}_\phi^n(u) : \phi \in H, u \in C_h^b; u \geq 0\}$$

and proceed in the same way as above with the help of the full power of Lemma 4.4.4

♣

Note that (4.4.2) means weak*-convergence of measures

$$\lim_{n \to \infty} \sum_{\overline{x} \in T^{-n}(x)} c^{-n} \exp(S_n\phi(\overline{x}))\delta_{\overline{x}} \to u_\phi(x)m_\phi$$

for every $x \in X$. Using (4.4.2) also for $u = \mathbb{1}$, we obtain

$$\lim_{n \to \infty} \mathcal{L}_\phi^n(\mathbb{1})(x))^{-1} \sum_{\overline{x} \in T^{-n}(x)} (\exp(S_n\phi(\overline{x}))\delta_{\overline{x}} \to m_\phi. \qquad (4.4.4)$$

In the sequel one can consider either $C(X, \mathbb{R})$ or $C(X, \mathbb{C})$. Let us decide for $C(X, \mathbb{C})$.

Note that by $\mathcal{L}_\phi^*(m_\phi) = cm_\phi$, we have the $\mathcal{L}$-invariant decomposition

$$C(X) = \operatorname{span}(u_\phi) \oplus \ker(m_\phi). \qquad (4.4.5)$$

For $u \in \operatorname{span}(u_\phi)$ we have $\mathcal{L}_\phi(u) = cu$. On $\ker(m_\phi)$, by Theorem 4.4.5, $c^{-n}\mathcal{L}_\phi^n \to 0$ in strong topology. Denote $(\mathcal{L}_\phi)|_{\ker(m_\phi)}$ by $\mathcal{L}_{\ker,\phi}$. For $\mathcal{L}_{\ker,\phi}$ restricted to $\mathcal{H}_\alpha$ we can say more about the above convergence:

Theorem 4.4.6. *There exists an integer $n > 0$ such that for $c = e^{P(T,\phi)}$*

$$\|c^{-n}\mathcal{L}_{\ker,\phi}^n\|_{\mathcal{H}_\alpha} < 1.$$

Proof. Again it is sufficient to consider a real-valued function u with $\mu(u) = 0$ and the operator $\hat{\mathcal{L}}$. Set $\delta = \min\{1/8C_4, 1/4\}$, with C_4 taken from (4.3.10). By Theorem 4.3.6 for u such that $\|u\|_{\mathcal{H}_\alpha} \leq 1$ all functions $\hat{\mathcal{L}}^n(u)$ have the same modulus of continuity $g(\varepsilon) = C_7\varepsilon^\alpha$ with $C_7 = C_3 + C_4 > 0$. Hence, from Theorem 4.4.5 we conclude that $(\exists n_1)(\forall n \geq n_1)(\forall u : \|u\|_{\mathcal{H}_\alpha} \leq 1)$

$$\|\hat{\mathcal{L}}^n(u)\|_\infty \leq \delta. \qquad (4.4.6)$$

Next, for n_2 satisfying $C_3\lambda^{-n_2\alpha}C_7 + C_4\delta \leq 1/4$, again by Theorem 4.3.6, we obtain

$$\vartheta_\alpha(\hat{\mathcal{L}}^{n_2}(\hat{\mathcal{L}}^{n_1}(u)) \leq 1/4.$$

Hence $\|\hat{\mathcal{L}}^{n_1+n_2}(u)\|_{\mathcal{H}_\alpha} \leq 1/2$. The theorem has thus been proved with $n = n_1 + n_2$. ♣

Note that Theorem 4.4.5 could be deduced from Theorem 4.4.6 by approximation of continuous functions uniformly by Hölder ones, and using Proposition 4.3.4.

Corollary 4.4.7. *The convergences in Theorem 4.4.5 for $u \in \mathcal{H}_\alpha$ are exponential. Namely there exist $0 < \tau < 1$ and $C \geq 0$ such that for every function $u \in \mathcal{H}_\alpha$*

$$\|c^{-n}\mathcal{L}_\phi^n(u) - m_\phi(u)u_\phi\|_\infty \leq \|c^{-n}\mathcal{L}_\phi^n(u) - m_\phi(u)u_\phi\|_{\mathcal{H}_\alpha} \leq C\|u - m_\phi(u)u_\phi\|_{\mathcal{H}_\alpha}\tau^n. \qquad (4.4.7)$$

In particular if $\int u d\mu = 0$ then

$$\|\hat{\mathcal{L}}^n(u)\|_\infty \leq \|\hat{\mathcal{L}}^n(u)\|_{\mathcal{H}_\alpha} \leq C\|u\|_{\mathcal{H}_\alpha}\tau^n. \qquad (4.4.8)$$

Remark 4.4.8. Theorem 4.4.6 along with (4.4.5) and the fact that $c^{-1}\mathcal{L}\phi(u_\phi) = u_\phi$ implies that the spectrum of the operator $\mathcal{L}_\phi : \mathcal{H}_\alpha \to \mathcal{H}_\alpha$ consists of two parts, the number $c = e^{P(T,\phi)}$ which is its simple and isolated eigenvalue, and the rest, contained in a disc centered at 0 with radius $< c$. There thus exists a "spectral gap". An isolated eigenvalue moves analytically for analytic family of transfer operators induced by analytic families of maps T and potential functions ϕ, yielding the analyticity of $P(T, f)$. See Notes at the end of this chapter.

Now we can study "mixing" properties of the dynamical system (T, μ) for our invariant Gibbs measure μ. Roughly speaking the speed of mixing is related to the speed of convergence of $\mathcal{L}^n_{\mathrm{ker},\phi}$ to 0.

The first dynamical (mixing) consequence of Theorem 4.4.6 is the following result known in the literature as the exponential decay of correlations, see the definition in Section 1.11.

Theorem 4.4.9. *There exist $C \geq 1$ and $\rho < 1$ such that for all $f \in \mathcal{H}_\alpha$ and all $g \in L^1(\mu)$,*

$$C_n(f,g) \leq C\rho^n \|f - Ef\|_{\mathcal{H}_\alpha} \|g - Eg\|_1.$$

Proof. Set $F = f - Ef$, $G = g - Eg$ and consider $\hat{\mathcal{L}}$ acting on $C(X)$, as a restriction of $\mathcal{L}_\mu$ acting on $L^1(\mu)$. By (4.2.7) and by (4.4.8) we obtain

$$|C_n(f,g)| = \left| \int F \cdot (G \circ T^n) \, d\mu \right| = \left| \int \hat{\mathcal{L}}^n(F) \cdot G \, d\mu \right| \leq C\tau^n \|F\|_{\mathcal{H}_\alpha} \|G\|_1.$$

♣

Exercise. Prove that for all μ square-integrable functions f, g one has $\int f \cdot (g \circ T^n) \, d\mu \to Ef \cdot Eg$. (Hint: approximate f and g by Hölder functions. Of course the information on the speed of convergence would become lost.)

The convergence in the exercise is one of several equivalent definitions of the *mixing* property, see Section 1.10. We proved however earlier the stronger property: measure-theoretical exactness, Theorem 4.2.12.

We can make a better use of the exponential convergence in Theorem 4.4.9 for T being the shift on the one-sided shift space:

Theorem 4.4.10. *Let $\sigma : \Sigma_A \to \Sigma_A$ be a topologically mixing topological one-sided Markov chain with the alphabet $\{1, ..., d\}$ and σ the left shift, see Chapter 0. Let $\mathcal{F}$ be the σ-algebra generated by the partition $\mathcal{A}$ into 0-cylinders, i.e sets with fixed 0-th symbol. For every $0 \leq k \leq l$ denote by $\mathcal{F}^l_k$ the σ-algebra generated by $\mathcal{A}^l_k = \bigvee_{j=k}^l T^{-j}(\mathcal{A})$, i.e. by the sets (cylinders) with fixed $k, k+1, \ldots, l$'th symbols. Let $\phi : \Sigma_A \to \mathbb{R}$ be a Hölder continuous function.*

Then there exist $0 < \rho < 1$ and $C > 0$ such that for every $n \geq k \geq 0$, every function $f : \Sigma_A \to \mathbb{R}$ measurable with respect to $\mathcal{F}^k_0$ and every μ_ϕ-integrable

function $g : \Sigma_A \to \mathbb{R}$

$$\left| \int f \cdot (g \circ T^n) \, d\mu_\phi - Ef \cdot Eg \right| \leq C\rho^{n-k} \|f - Ef\|_1 \|g - Eg\|_1. \qquad (4.4.9)$$

Proof. Assume $Ef = Eg = 0$. By Theorem 4.4.9,

$$\left| \int f \cdot (g \circ T^n) \, d\mu \right| = \left| \int g \cdot \mathcal{L}^{n-k}(\hat{\mathcal{L}}^k(f)) \, d\mu \right| \leq \|g\|_1 C\rho^{n-k} \|\hat{\mathcal{L}}^k(f)\|_{\mathcal{H}_\alpha}. \quad (4.4.10)$$

Decompose f into real and imaginary parts and represent each one by the difference of nowhere negative functions. This allows, in the estimates to follow, to assume that $f \geq 0$.

Notice that for every cylinder $A \in \mathcal{A}$ and $x \in A$, in the expression

$$\hat{\mathcal{L}}^k(f)(x) = \sum_{T^k(y)=x} f(y) \exp S_k \psi(y)$$

there is no dependence of $f(y)$ on $x \in A$ because f is constant on cylinders of $\mathcal{A}_0^k$. So

$$\frac{\sup_A \hat{\mathcal{L}}^k(f)}{\inf_A \hat{\mathcal{L}}^k(f} \leq \sup_{B \in \mathcal{A}_0^k} \sup_{y,y' \in B} \exp\big(S_k\psi(y) - S_k\psi(y')\big) \leq C,$$

with the constant C resulting from Section 3.4. So,

$$\sup_A \hat{\mathcal{L}}^k(f) \leq \frac{C}{\mu(A)} \int \hat{\mathcal{L}}^k(f) \, d\mu = \frac{C}{\mu(A)} \|f\|_1 \leq \left(\frac{C}{\inf_{A \in \mathcal{A}} \mu(A)}\right) \|f\|_1 = C' \|f\|_1,$$

where the last equality defines C'.

It is left still to estimate the pseudonorms $\vartheta_{\alpha,\xi}$ and ϑ_α of $\hat{\mathcal{L}}^k(f)$, cf. Sectio 3.4. We assume that ξ is less than the minimal distance between the cylinders in $\mathcal{A}$. We have, similarly to (4.3.5), for x, y belonging to the same cylinder $A \in \mathcal{A}$,

$$|\hat{\mathcal{L}}^k(f)(x) - \hat{\mathcal{L}}^k(f)(y)| = \left| \left(\frac{\hat{\mathcal{L}}^k(f)(x)}{\hat{\mathcal{L}}^k(f)(y)} - 1 \right) \right| |\hat{\mathcal{L}}^k(f)(y)|$$

$$\leq (\exp C_1 \rho(x,y)^\alpha - 1)\|C'\|f\|_1 \leq C'' \rho(x,y)^\alpha \|f\|_1.$$

for a constant C''.

Hence, $\vartheta_{\alpha,\xi}(\hat{\mathcal{L}}^k(f)) \leq \|f\|_1 C''$ and, passing to ϑ_α as in Section 3.4, we get

$$\vartheta_\alpha(\hat{\mathcal{L}}^k(f)) \leq \|f\|_1 \max\{C'', 2C'\xi^{-\alpha}\}.$$

Thus, continuing (4.4.10), we obtain for a constant C that

$$C_n(f,g) \leq \|f\|_1 \|g\|_1 C\rho^{n-k}.$$

♣

An immediate corollary from Theorem 4.4.10 is that for every $B_1 \in \mathcal{F}_0^k$ and a Borel B_2 (i.e. $B_2 \in \mathcal{F}_0^\infty$),

$$|\mu(B_1 \cap T^{-n}(B_2)) - \mu(B_1)\mu(B_2)| \leq C\rho^{n-k}\mu(B_1)\mu(B_2). \qquad (4.4.11)$$

Compare it with (1.11.10). Therefore, for any non-negative integer t and every $A \in \mathcal{F}_0^k$

$$\sum_{B \in \mathcal{A}_0^t} |\mu(T^{-n}(B)|A) - \mu(B)| \leq C\rho^{n-k},$$

for the conditional measures $\mu(\cdot|A)$, with respect to A.

This means that $\mathcal{A}$ satisfies the weak Bernoulli property, hence the natural extension $(\tilde{X}, \tilde{T}, \tilde{\mu})$ is measure-theoretically isomorphic to a two-sided Bernoulli shift, see Section 1.11.

Corollary 4.4.11. *Every topologically exact, distance expanding open map T : $X \to X$, with invariant Gibbs measure $\mu = \mu_\phi$ for a Hölder continuous function $\phi : X \to \mathbb{R}$, has the natural extension $(\tilde{X}, \tilde{T}, \tilde{\mu})$ measure-theoretically isomorphic to a two-sided Bernoulli shift.*

Proof. Let $\pi : \Sigma_A \to X$ be the coding map from a one-sided topological Markov chain, due to a Markov partition, see Theorem 3.5.7. Since the map π is Hölder continuous, the function $\phi \circ \pi : \Sigma_A \to \mathbb{R}$ is also Hölder continuous, hence we have the invariant Gibbs measure $\mu_{\phi\circ\pi}$. For this measure we can apply Theorem 4.4.10 and its corollaries. Recall also that by Theorem 3.5.9 π yields a measure-theoretical isomorphism between $\mu_{\phi\circ\pi}$ and $\mu_{\phi\circ\pi} \circ \pi^{-1}$, Therefore to end the proof it is enough to prove the following.

Lemma 4.4.12. *The measures μ_ϕ and $\mu_{\phi\circ\pi} \circ \pi^{-1}$ coincide.*

Proof. The function $\exp(-\phi \circ \pi + P - h)$ for $h := \log u_{\phi\circ\pi} + \log u_{\phi\circ\pi} \circ \sigma)$, is the strong Jacobian for the shift map σ and the measure $\mu_{\phi\circ\pi}$, where P is the topological pressure for both $(\sigma, \phi \circ \pi)$ and (T, ϕ), see Theorem 3.5.8. Since π yields a measure-theoretical isomorphism between $\mu_{\phi\circ\pi}$ and $\mu_{\phi\circ\pi} \circ \pi^{-1}$, the measure $\mu_{\phi\circ\pi} \circ \pi^{-1}$ is forward quasi-invariant under T with the strong Jacobian $\exp(-\phi + P - h \circ \pi^{-1})$. T with respect to μ_ϕ has strong Jacobian of the same form, maybe with a priori different h cohomologous to 0 in bounded functions. Therefore both measures are equivalent, hence as ergodic they coincide.   ♣

4.5   More on almost periodic operators

In this Section we show how to deduce Theorem 4.4.5 (on convergence) and Theorem 4.4.6 and Corollary 4.4.7 (exponential convergence) from general functional analysis theorems. We do not need this later on in our book, but the theorems are useful in other important situations . . . . .

Recall (Definition 4.3.3) that $Q : F \to F$ a bounded linear operator of a Banach space is called almost periodic if for every $b \in F$ the sequence $Q^n(b)$ is relatively compact. By the Banach-Steinhaus Theorem there is a constant $C \geq 0$ such that $\|Q^n\| \leq C$ for every $n \geq 0$.

Theorem 4.5.1. *If $Q : F \to F$ is an almost periodic operator on a complex Banach space F, then*

$$F = F_0 \oplus F_{\mathrm{u}}, \tag{4.5.1}$$

where $F_0 = \{x \in F : \lim_{n \to \infty} A^n(x) = 0\}$ and F_{u} is the closure of the linear subspace of F generated by all eigenfunctions of eigenvalues of modulus 1.

Adding additional assumptions one gains additional information on the above decomposition.

Definition 4.5.2. Let $F = C(X)$ and suppose $Q : F \to F$ is *positive*, namely $f \geq 0$ implies $Q(f) \geq 0$. Then Q is called *primitive* if for every $f \in C(X), f \geq 0, f \not\equiv 0$ there exists $n \geq 0$ such that for every $x \in X$ it holds $Q^n(f)(x) > 0$. If we change the order of the quantificators to: ... for every x there exists n ..., then we call Q *non-decomposable*.

Theorem 4.5.3. *For $Q : C(X) \to C(X)$, a (real or complex) linear almost periodic positive primitive operator of spectral radius equal to 1, we have*

(1) *$dim(C(X)_{\mathrm{u}}) = 1$ in the decomposition (4.5.1),*

(2) *the eigenvalue corresponding to $C(X)_{\mathrm{u}}$ is equal to 1 and the respective eigenfunction u_Q is positive (everywhere > 0).*

(3) *In addition there exists a probability measure m_Q on X invariant under the conjugate operator Q^*, such that for every $u \in C(X)$ we have the strong convergence,*

$$Q^n(u) \to u_Q \int u \, dm_Q.$$

Proof. This is just a repetition of considerations of Sections 2-4. First find a probability measure m such that $Q^*(m) = m$ as in Theorem 4.2.8 (we leave a proof that the eigenvalue is equal to 1, to the reader). Next observe that by the almost periodicity of Q the sequence of averages $a_n := \frac{1}{n} \sum_{j=0}^{n-1} Q^j(\mathbb{1})$ is relatively compact (an exercise). Let u_Q be any function in the limit. Then $u_Q \geq 0$ is an eigenfunction for the eigenvalue 1. It is not identically 0 since $\int a_n dm = 1$ for all $n \geq 0$. We have $u_Q = Q(u_Q) > 0$ because Q is nondecomposable. Finally for $\hat{Q}(u) := Q(uu_Q)u_Q^{-1}$ we have $\hat{Q}(\mathbb{1}) = \mathbb{1}$ and we repeat Proof of Theorem 4.4.5, replacing the property of topological exactness by primitivity. ♣

Notice that this yields Theorem 4.4.5 because of

Proposition 4.5.4. *If an open expanding map T is topologically exact then for every continuous function ϕ the transfer operator $Q = \mathcal{L}_{\overline{\phi}}$ is primitive.*

The proof is easy, it is in fact contained in the proof of Lemma 4.4.4.

Assume now only that T is topologically transitive. Let Ω^k denote the sets from spectral decomposition $X = \Omega = \bigcup_{k=1}^{n} \Omega^k$ as in Theorem 3.3.8. Write

$u_Q \in C(X)$ for an eigenfunction of the operator Q as before. Notice now (exercise!) that the space F_u for the operator $Q = \mathcal{L}_{\overline{\phi}}$ is spanned by n eigenfunctions $v_t = \sum_{k=1}^{n} \chi_{\Omega^k} \lambda^{-tk} u_Q$, $t = 1, \ldots, n$, where χ means indicator functions, with $\lambda = \varepsilon^{2\pi i/n}$. Each v_t corresponds to the eigenvalue λ^t. Thus the set of these eigenvalues is a cyclic group.

It is also an easy exercise to describe F_u if $X = \Omega = \bigcup_{j=1}^{J} \bigcup_{k=1}^{k(j)} \Omega_j^k$. The set of eigenvalues is the union of J cyclic groups. It is harder to understand F_u and the corresponding set of eigenvalues for T open expanding, without assuming $\Omega = X$.

A general theorem related to Theorem 4.4.6 and Corollary 4.4.7 is the following.

Theorem 4.5.5 (Ionescu Tulcea and Marinescu). *Let $(F, | \cdot |)$ be a Banach space equipped with a norm $| \cdot |$ and let $E \subset F$ be its dense linear subspace. E is assumed to be a Banach space with respect a norm $\| \cdot \|$ defined on it. Let $Q : F \to F$ be a bounded linear operator which preserves E, whose restriction to E is also bounded with respect to the norm $\| \cdot \|$.*
Suppose the following conditions are satisfied.

(1) *If $(x_n : n = 1, 2, \ldots)$ is a sequence of points in E such that $\|x_n\| \leq K_1$ for all $n \geq 1$ and some constant K_1, and if $\lim_{n \to \infty} |x_n - x| = 0$ for some $x \in F$, then $x \in E$ and $\|x\| \leq K_1$.*

(2) *There exists a constant K such that $|Q^n| \leq K$ for all $n = 1, 2, \ldots$.*

(3) *$\exists N \geq 1 \quad \exists \tau < 1 \quad \exists K_2 > 0 \quad \|Q^N(x)\| \leq \tau \|x\| + K_2 |x|$ for all $x \in E$.*

(4) *For any bounded subset A of the Banach space E with the norm $\| \cdot \|$, the set $Q^N(A)$ is relatively compact as a subset of the Banach space F with the norm $| \cdot |$.*

Then

(5) *There exist at most finitely many eigenvalues of $Q : F \to F$ of modulus 1, say $\gamma_1, \ldots, \gamma_p$.*

(6) *Let $F_i = \{x \in F : Q(x) = \gamma_i x\}$, $i = 1, \ldots, p$. Then $F_i \subset E$ and $\dim(F_i) < \infty$.*

(7) *The operator $Q : F \to F$ can be represented as*

$$Q = \sum_{i=1}^{p} \gamma_i Q_i + S$$

where Q_i and S are bounded, $Q_i(F) = F_i$, $\sup_{n \geq 1} |S^n| < \infty$ and

$$Q_i^2 = Q_i, \quad Q_i Q_j = 0 \ (i \neq j), \quad Q_i S = S Q_i = 0$$

Moreover,

(8) $S(E) \subset E$ and $S|_E$ considered as a linear operator on $(E, \|\cdot\|)$, is bounded and there exist constants $K_3 > 0$ and $0 < \tilde{\tau} < 1$ such that

$$\|S^n|_E\| \leq K_3 \tilde{\tau}^n$$

for all $n \geq 1$.

The proof of this theorem can be found in [Ionescu Tulcea & Marinescu 1950].

Now, in view of Theorem 3.4.1 and Corollary 4.3.7, Theorem 4.5.5 applies to the operator $Q = \mathcal{L}_{\bar{\phi}} : C(X) \to C(X)$ if one substitutes $F = C(X)$, $E = \mathcal{H}_\alpha(X)$. If T is topologically exact and in consequence Q is primitive on $C(X)$, then $\dim(\oplus F_i) = 1$ and the corresponding eigenvalue is equal to 1, as in Theorem 4.5.3.

4.6   Uniqueness of equilibrium states

We have proved already the existence (Theorem 4.3.2) and uniqueness (Corollary 4.2.14) of invariant Gibbs states and proved that invariant Gibbs states are equilibrium states (Proposition 4.1.5). Here we shall give three different proofs of uniqueness of equilibrium states.

Let ν be a T-invariant measure and let a finite real function J_ν be the corresponding Jacobian in the weak sense, J_ν is defined ν-a.e. . By the invariance of ν we have $\nu(E) = 0 \Rightarrow \nu(T^{-1}(E)) = \nu(E) = 0$, i.e. ν is backward quasi-invariant. At the beginning of Sec.2 we defined in this situation $\Psi = \Phi_x \circ T$ with $\Phi_x = \frac{d\nu \circ T_x^{-1}}{d\nu}$ defined for ν-a.e. point in the domain of a branch T_x^{-1}. (In Sec.2 we used notation Φ_j for Φ_x.) By definition Φ_x is strong Jacobian for T_x^{-1}.

Notice that for ν-a.e. z

$$(J_\nu \circ T_x^{-1}) \cdot \Phi_x(z) = \begin{cases} 1, & \text{if } \Phi_x(z) \neq 0; \\ 0, & \text{if } \Phi_x(z) = 0. \end{cases} \qquad (4.6.1)$$

Indeed, after removal of $\{z : \Phi_x(z) = 0\}$ the measures ν and $\nu \circ T^{-1}$ are equivalent, hence Jacobians of T and T_x^{-1} are mutual reciprocals. We can fix J_ν on the set $T^{-1}(\{z : \Phi_x(z) = 0\})$ arbitrarily, since this set has measure ν equal to 0.

Recall that we have defined $\mathcal{L}_\nu : L^1(\nu) \to L^1(\nu)$, the transfer operator associated with the measure ν as follows

$$\mathcal{L}_\nu(g)(x) = \sum_{y \in T^{-1}(x)} g(y) \Psi(y).$$

Recall that if T maps a set A of measure 0 to a set of positive measure, then Ψ is specified, equal to 0, on a subset of A that is mapped by T to a set of full measure ν in $T(A)$.

Then since ν is T-invariant, $\mathcal{L}_\nu(\mathbb{1}) = \mathbb{1}$ and for every ν-integrable function g we have $\int \mathcal{L}_\nu(g) \, d\nu = \int g \, d\nu$, compare (4.2.4).

Lemma 4.6.1. *Let $\psi : X \to \mathbb{R}$ be a continuous function such that $\mathcal{L}_\psi(\mathbb{1}) = \mathbb{1}$, i.e. for every x, $\sum_{y \in T^{-1}(x)} \exp(\psi(y)) = 1$, and let ν be an ergodic equilibrium state for ψ. Then J_ν is strong Jacobian and $J_\nu = \exp(-\psi)$ ν-almost everywhere.*

Proof. The proof is based on the following computation using the inequality $1 + \log(x) \le x$, with the equality only for $x = 1$.

$$1 = \int \mathbb{1}\, d\nu \ge \int \mathcal{L}_\nu(J_\nu \exp \psi)\, d\nu = \int J_\nu \exp \psi\, d\nu$$

$$\ge \int \big(1 + \log(J_\nu \exp \psi)\big)\, d\nu = 1 + \int \psi d\nu + \int \log J_\nu\, d\nu$$

$$= 1 + \int \psi d\nu + h_\nu(T) \ge 1.$$

To obtain the first inequality, write

$$\mathcal{L}_\nu(J_\nu \exp \psi)(x) = \sum_{y \in T^{-1}(x)} J_\nu(y)(\exp \psi(y))\Psi(y)$$

which is equal to 1 if $\Psi(y) > 0$ for all $y \in T^{-1}(x))$, or < 1 otherwise. This follows from (4.6.1) and from $\sum_{y \in T^{-1}(x)} \exp \psi(y) = 1$.
    The last inequality follows from

$$\int \psi d\nu + h_\nu(T) = P(\psi) \ge \limsup_{n \to \infty} \frac{1}{n} \log \sum_{y \in T^{-n}(x)} \exp S_n \psi(y) = 0,$$

see Theorem 2.3.2, since all points in $T^{-n}(x)$ are (n, η)-separated, for $\eta > 0$ defined in Chapter 3.
    Therefore, all the inequalities in this proof must become equalities. Thus, the Jacobian $\Phi_x \ne 0$ for each branch T_x^{-1} and $J_\nu = \exp(-\psi)$, ν- a.e.   ♣

    Notice that we have not assumed above that ψ is Hölder. Now, we shall assume it.

Theorem 4.6.2. *There exists exactly one equilibrium state for each Hölder continuous potential ϕ.*

Proof. Let ν be an equilibrium state for ϕ. As in Sec.4 set $\psi = \phi - P(T, \phi) + \log u_\phi \circ T - \log u_\phi$ and ν is also equilibrium state for ψ. Then by Lemma 4.6.1 its Jacobian is strong Jacobian, equal to $\exp(-\psi)$. Hence,

$$\nu\big(T_z^{-n}(B(T^n(z), \xi))\big) = \int_{B(T^n(z), \xi)} \exp\big(S_n \psi(T_z^{-n}(x))\big)\, d\nu(x)$$

$$= \int_{B(T^n(z), \xi)} \frac{u_\phi(x)}{u_\phi(T^n(x))} \exp(S_n \phi - n P(T, \phi))(T_z^{-n}(x))\, d\nu(x).$$

So, by *pre-bounded distortion lemma* (Lemma 3.4.2),

$$\frac{\inf |u_\phi|}{\sup |u_\phi|} BC^{-1} \le \frac{\nu\big(T_z^{-n}(B(T^n(z), \xi))\big)}{\exp(S_n\phi - nP(T, \phi))(z)} \le \frac{\sup |u_\phi|}{\inf |u_\phi|} C,$$

where $B = \inf\{\nu(B(y, \xi))\}$. It is positive by Proposition 4.2.10.

Therefore ν is an invariant Gibbs state for ϕ; unique by Corollary 4.2.14.   ♣

Remark 4.6.3. In fact already the knowledge that $\exp(-\psi)$ is weak Jacobian implies automatically that it is a strong Jacobian. Indeed by the invariance of ν we have

$$\sum_{y\in T^{-1}(x)} \Phi_y(y) = 1 = \sum_{y\in T^{-1}(x)} \exp \psi(y)$$

and each non-zero summand on the left is equal to a corresponding summand on the right. So there are no summands equal to 0.

Uniqueness. Proof II. We shall provide the second proof of Lemma 4.6.1. It is not so elementary as the previous one, but it exhibits a relation with the finite space *prototype lemma* in Introduction.

For every $y \in X$ put $A(y) := T^{-1}\big(T(\{y\})\big)$. Let $\{\nu_A\}$ denote the canonical system of conditional measures for the partition of X into the sets $A = A(y)$, see Section 1.6. Since there exists a finite one-sided generator, see Lemma 2.5.5, with the use of Theorem 1.9.7 we obtain

$$0 = P(T,\, \psi) = h_\nu(T) + \int \psi\, d\nu = H_\nu\left(\varepsilon \mid T^{-1}(\varepsilon)\right) + \int \psi\, d\nu =$$

$$= \int \Big(\sum_{z\in A(y)} \nu_{A(y)}(\{z\})\big(- \log \big(\nu_{A(y)}(\{z\})\big) + \psi(z)\big)\Big)\, d\nu(y).$$

The latter expression is always negative except for the case $\nu_{A(y)}(z) = \exp\psi(z)$ ν-a.e. by the prototype lemma. So for a set $Y = T^{-1}\big(T(Y)\big)$ of full measure ν, for every $y \in Y$ we have

$$\nu_{A(y)}(\{y\}) = \exp \psi(y), \quad \text{in particular } \nu_{A(y)}(\{y\}) \ne 0. \tag{4.6.2}$$

Hence, for every Borel set $Z \subset Y$ such that T is 1–to–1 on it, we can repeat the calculation in the proof of Theorem 1.9.6 and get

$$\nu\big(T(Z)\big) = \int_Z 1/\nu_{A(y)}(\{y\})\, d\nu(y)$$

So our Jacobian for $T|_Y$ is equal to $1/\nu_{A(y)}$ hence to $\exp(-\psi)$ by (4.6.2) and it is strong on Y. Observe finally that $\nu\big(T(X \setminus Y)\big) = 0$ because $X \setminus Y = T^{-1}\big(T(X \setminus Y)\big)$ and ν is T-invariant. So $\exp(-\psi)$ is a strong Jacobian on X.

Uniqueness. Proof III. Due to Corollary 2.6.7 it is sufficient to prove the differentiability of the pressure function $\phi \mapsto P(T, \phi)$ at Hölder continuous ϕ, in a set of directions dense in the weak topology on $C(X)$.

Lemma 4.6.4. *Let $\phi : X \to \mathbb{R}$ be a Hölder continuous function with exponent α and let μ_ϕ denote the invariant Gibbs measure for ϕ. Let $F : X \to \mathbb{R}$ be an arbitrary continuous function. Then, for every $x \in X$,*

$$\lim_{n \to \infty} \frac{\sum_{y \in T^{-n}(x)} \frac{1}{n} S_n F \exp(S_n \phi)(y)}{\sum_{y \in T^{-n}(x)} \exp(S_n \phi)(y)} = \int F \, d\mu_\phi. \tag{4.6.3}$$

In addition the convergence is uniform for an equicontinuous family of F's and for ϕ's in a bounded subset of the Banach space of Hölder functions $\mathcal{H}_\alpha(X)$.

Proof. The left hand side of (4.6.3) can be written in the form

$$\lim_{n \to \infty} \frac{\frac{1}{n} \sum_{j=0}^{n-1} \mathcal{L}_\phi^n (F \circ T^j)(x)}{\mathcal{L}_\phi^n(\mathbb{1})(x)} = \lim_{n \to \infty} \frac{\frac{1}{n} \sum_{j=0}^{n-1} \mathcal{L}^{n-j}(F \cdot \mathcal{L}^j(\mathbb{1}))(x)}{\mathcal{L}^n(\mathbb{1})(x)}. \tag{4.6.4}$$

where $\mathcal{L} = \mathcal{L}_0 = e^{-P(T,\phi)} \mathcal{L}_\phi$.

Since by Theorem 4.3.5 $F \cdot \mathcal{L}^j(\mathbb{1})$ is an equicontinuous family of functions, we obtain the uniform convergence

$$\mathcal{L}^{n-j}(F \cdot \mathcal{L}^j(\mathbb{1}))(x) \to u_\phi(x) \int F \cdot \mathcal{L}^j(\mathbb{1}) \, dm_\phi$$

as $n - j \to \infty$, see Theorem 4.4.5.

Therefore we can continue (4.6.4) to get

$$\lim_{n \to \infty} \frac{\frac{1}{n} \sum_{j=0}^{n-1} u_\phi(x) \int F \cdot \mathcal{L}^j(\mathbb{1}) \, dm_\phi}{u_\phi(x)} = \lim_{n \to \infty} \frac{1}{n} \sum_{j=0}^{n-1} \int F \cdot \mathcal{L}^j(\mathbb{1}) \, dm_\phi = \int F \, d\mu_\phi$$

since $\mathcal{L}^j(\mathbb{1})$ uniformly converges to u_ϕ and $\mu_\phi = u_\phi m_\phi$. ♣

Now we shall calculate the derivative $d\,\mathrm{P}(T, \phi + t\gamma)/dt$ for all Hölder continuous functions $\phi, \gamma : X \to \mathbb{R}$ at every $t \in \mathbb{R}$. In particular, this will give differentiability at $t = 0$. Thus our dense set of directions is spanned by the Hölder continuous functions γ.

Theorem 4.6.5. *We have*

$$\frac{d}{dt} \mathrm{P}(T, \phi + t\gamma) = \int \gamma \, d\mu_{\phi + t\gamma} \tag{4.6.5}$$

for all $t \in \mathbb{R}$.

Proof. Write

$$P_n(t) := \frac{1}{n} \log \sum_{y \in T^{-n}(x)} \exp(S_n(\phi + t\gamma))(y) \tag{4.6.6}$$

and

$$Q_n(t) := \frac{dP_n}{dt}(t) = \frac{\frac{1}{n} \sum_{y \in T^{-n}(x)} S_n \gamma(y) \exp(S_n(\phi + t\gamma))(y)}{\sum_{y \in T^{-n}(x)} \exp(S_n(\phi + t\gamma)(y)}. \tag{4.6.7}$$

By Lemma 4.6.4, $\lim_{n\to\infty} Q_n(t) = \int \gamma \, d\mu_{\phi+t\gamma}$ and the convergence is locally uniform with respect to t. Since, in addition, $\lim_{n\to\infty} P_n(t) = \P(t)$, we conclude that $P(T, \phi + t\gamma) = \lim_{n\to\infty} P_n(t)$ is differentiable and the derivative is equal to the limit of derivatives: $\lim_{n\to\infty} Q_n(t) = \int \gamma \, d\mu_{\phi+t\gamma}$,   ♣

Notice that the differential (Gateaux) operator $\gamma \mapsto \int \gamma \, d\mu_\phi$ is indeed the one from Proposition 2.6.6. Notice also that *a posteriori*, by Corollary 2.6.7, we proved that for ϕ Hölder continuous, $P(T, \phi)$ is differentiable in the direction of every continuous function. This is by the way obvious in general: two different supporting functionals are different restricted to any dense subspace.

4.7 Probability laws and $\sigma^2(u, v)$

Exponential convergences in Section 4.4 allow to prove the probability laws.

Theorem 4.7.1. *Let $T : X \to X$ be an open distance expanding topologically exact map and μ the invariant Gibbs measure for a Hölder continuous function $\phi : X \to \mathbb{R}$. Then if $g : X \to \mathbb{R}$ satisfies*

$$\sum_{n=0}^{\infty} \|\hat{\mathcal{L}}^n(g - \mu(g))\|_2 < \infty, \tag{4.7.1}$$

in particular if g is Hölder continuous, Central Limit Theorem (CLT) holds for g. If g is Hölder continuous then Law of Iterated Logarithm (LIL) holds.

Proof. We first show how CLT can be deduced from Theorem 1.11.5. We can assume $\mu(g) = 0$. Let $(\tilde{X}, \tilde{\mathcal{F}}, \tilde{\mu})$ be the natural extension (see Section 1.7). Recall that $\tilde{X}$ can be viewed as the set of all T-trajectories $(x_n)_{n\in\mathbb{Z}}$ (or backward trajectories), $\tilde{T}((x_n)) = (x_{n+1})$ and $\pi_n((x_n)) = x_n$. It is sufficient now to check (1.11.14) for the automorphism $\tilde{T}$ the function $\tilde{g} = g \circ \pi_0$ and $\tilde{\mathcal{F}}_0 = \pi_0^{-1}(\mathcal{F})$ for the completed Borel σ-algebra $\mathcal{F}$. Since $\tilde{g}$ is measurable with respect to $\tilde{\mathcal{F}}_0$ it is also measurable with respect to all $\tilde{\mathcal{F}}_n = \tilde{T}^{-n}(\tilde{\mathcal{F}}_0)$ for $n \leq 0$ hence $\tilde{g} = E(\tilde{g}|\tilde{\mathcal{F}}_n)$. So we need only to prove $\sum_{n\geq 0}^{\infty} \|E(\tilde{g}|\tilde{\mathcal{F}}_n)\|_2 < \infty$.

Since for $n \geq 0$ we have $\pi_0 \circ \tilde{T}^n = \tilde{T}^n \circ \pi_0$ we have $E(\tilde{g}|\tilde{\mathcal{F}}_n) = E(g|\mathcal{F}_n) \circ \pi_0$. So, we need to prove that $\sum_{n\geq 0}^{\infty} \|E(g|\mathcal{F}_n)\|_2 < \infty$.

Let us start with a general fact concerning an arbitrary probability space $(X, \mathcal{F}, \mu)$ and an endomorphism T preserving μ.

Lemma 4.7.2. *Let U denote the unitary operator on $L^2(X, \mathcal{F}, \mu)$ associated to T, namely $U(f) = f \circ T$ (called Koopman operator, see the beginning of Section 4.2 and Section 1.2. Let U^* be the operator conjugate to U acting also on $L^2(X, \mathcal{F}, \mu)$. Then for every $k \geq 0$ the operator $U^k U^{*k}$ is the orthogonal projection of $H_0 = L^2(X, \mathcal{F}, \mu)$ onto $H_k = L^2(X, T^{-k}(\mathcal{F}), \mu)$.*

Proof. For each $k \geq 0$ the function $U^k(u) = u \circ T^k$ is measurable with respect to $T^{-k}(\mathcal{F})$, so the range of $U^k U^{*k}$ is indeed in $H_k = L^2(X, T^{-k}(\mathcal{F}), \mu)$.

For any $u, v \in H_0$ write $\int u \cdot v \, d\mu = \langle u, v \rangle$, the scalar product of u and v. For arbitrary $f, g \in H_0$ we calculate

$$\langle U^k U^{*k}(f), g \circ T^k \rangle = \langle U^k U^{*k}(f), U^k(g) \rangle$$

$$= \langle U^{*k}(f), g \rangle = \langle f, U^k(g) \rangle = \langle f, g \circ T^k \rangle.$$

It is clear that all functions in $H_k = L^2(X, T^{-k}(\mathcal{F}), \mu)$ are represented by $g \circ T^k$ with $g \in L^2(X, \mathcal{F}, \mu)$. Therefore by the above equality for all $h \in H_k$, we obtain

$$\langle f - U^k U^{*k}(f), h \rangle = \langle f, h \rangle - \langle f, h \rangle = 0. \tag{4.7.2}$$

In particular for $f \in H_k$ we conclude from (4.7.2) for $h = f - U^k U^{*k}(f)$, that $\langle f - U^k U^{*k}(f), f - U^k U^{*k}(f) \rangle = 0$ hence $U^k U^{*k}(f) = f$. Therefore $U^k U^{*k}$ is a projection onto H_k, which is orthogonal by (4.7.2). ♣

Since the conditional expectation value $f \mapsto E(f | T^{-k}(\mathcal{F}))$ is also the orthogonal projection onto H_k we conclude that $E(f | T^{-k}(\mathcal{F})) = U^k U^{*k}(f)$.

Now, let us pass to our special situation of Theorem 4.7.1.

Lemma 4.7.3. *For every $f \in L^2(X, \mathcal{F}, \mu)$ we have $U^*(f) = \hat{\mathcal{L}}(f)$.*

Proof. $\langle U^* f, g \rangle = \langle f, U g \rangle = \int f \cdot (g \circ T) \, d\mu = \int \hat{\mathcal{L}}(f \cdot (g \circ T)) \, d\mu =$, $\int (\hat{\mathcal{L}}(f)) \cdot g \, d\mu = \langle \hat{\mathcal{L}}(f), g \rangle$, compare (4.2.7). ♣

Proof of Theorem 4.7.1. Conclusion. We can assume that $\mu(g) = 0$. We have

$$\sum_{n \geq 0}^{\infty} \|E(g | \mathcal{F}_n)\|_2 = \sum_{n \geq 0}^{\infty} \|U^n U^{*n}(g)\|_2 = \sum_{n \geq 0}^{\infty} \|\hat{\mathcal{L}}^n(g)\|_2 < \infty,$$

where the inequality been assumed in (4.7.1). Thus CLT has been proved by applying Theorem 1.11.5. If g is Hölder continuous it satisfies (4.7.1). Indeed $\hat{\mathcal{L}}^k(g)$ converges to 0 in the sup norm exponentially fast as $k \to \infty$ by Corollary 4.4.7 (see (4.4.8)). This implies the same convergence in L^2 hence the convergence of the above series. ♣

We have proved CLT and LIL using Theorem 1.11.5. Now let us show how to prove CLT and LIL with the use of Theorem 1.11.1, for Hölder continuous g. As in Proof of Corollary 4.4.11, let $\pi : \Sigma_A \to X$ be coding map from a 1-sided topological Markov chain with d symbols generated by a Markov partition, see Section 3.5. Since π is Hölder continuous, if g and ϕ are Hölder continuous, then the compositions $g \circ \pi, \phi \circ \pi$ are Hölder continuous too. π is an isomorphism between the measures $\mu_{\phi \circ \pi}$ on Σ_A and μ_ϕ on X, see Section 3.5 and Lemma 4.4.12. The function $g \circ \pi$ satisfies the assumptions of Theorem 1.11.1 with respect to the σ-algebra $\mathcal{F}$ associated to the partition of Σ_A into 0-th cylinders, see Theorem 4.4.10. ϕ-mixing follows from (4.4.10) and the estimate in (1.11.8)

is exponential with an arbitrary δ due to the Hölder continuity of $g \circ \pi$. Hence, by Theorem 1.11.1, $g \circ \pi$ and therefore g satisfy CLT and LIL.

In Section 4.6 we calculated the first derivative of the pressure function. Here using the same method we calculate the second derivative and we see that it is a respective dispersion (asymptotic variance) σ^2, see Section 1.11.

Theorem 4.7.4. *For all $\phi, u, v : X \to \mathbb{R}$ Hölder continuous functions there exists the second derivative*

$$\frac{\partial^2}{\partial s \partial t} P(T, \phi + su + tv)|_{s=t=0} = \lim_{n \to \infty} \frac{1}{n} \int S_n(u - \mu_\phi u) S_n(v - \mu_\phi v) \, d\mu_\phi, \quad (4.7.3)$$

where μ_ϕ is the invariant Gibbs measure for ϕ. In particular

$$\frac{\partial^2}{\partial t^2} P(T, \phi + tv)|_{t=0} = \sigma^2_{\mu_\phi}(v)$$

(where $\sigma^2_{\mu_\phi}(v)$ is the asymptotic variance discussed in CLT, Ch1.11). In addition, the function $(s, t) \mapsto P(T, \phi + su + tv)$ is C^2-smooth.

Proof. By Sec. 4.6, see (4.6.3), (4.6.7),

$$\frac{\partial^2}{\partial s \partial t} P(T, \phi + su + tv)|_{t=0}$$

$$= \frac{\partial}{\partial s} \lim_{n \to \infty} \frac{\frac{1}{n} \sum_{y \in T^{-n}(x)} S_n v(y) \exp S_n(\phi + su)(y)}{\sum_{y \in T^{-n}(x)} \exp S_n(\phi + su)(y)}. \quad (4.7.4)$$

Now we change the order of $\partial/\partial s$ and lim. This will be justified if we prove the uniform convergence of the resulting derivative functions.

Fixed $x \in X$ and n we abbreviate in the further notation $\sum_{y \in T^{-n}(x)}$ to $\sum_y$ and compute

$$F_n(s) := \frac{\partial}{\partial s} \left(\frac{\sum_y S_n v(y) \exp S_n(\phi + su)(y)}{\sum_y \exp S_n(\phi + su)(y)} \right)$$

$$= \frac{\sum_y S_n u(y) S_n v(y) \exp S_n(\phi + su)(y)}{\sum_y \exp S_n(\phi + su)(y)}$$

$$- \left(\sum_y S_n u(y) \exp S_n(\phi + su)(y) \right) \left(\sum_y S_n v(y) \exp S_n(\phi + su)(y) \right)$$

$$\times \left(\sum_y \exp S_n(\phi + su)(y) \right)^2$$

$$= \frac{\mathcal{L}^n \big((S_n u)(S_n v) \big)(x)}{\mathcal{L}^n(\mathbb{1})(x)} - \frac{\mathcal{L}^n(S_n u)(x)}{\mathcal{L}^n(\mathbb{1})(x)} \frac{\mathcal{L}^n(S_n v)(x)}{\mathcal{L}^n(\mathbb{1})(x)}.$$

As in Section 4.6 we write here $\mathcal{L} = \mathcal{L}_0 = e^{-P(T, \phi+su)}\mathcal{L}_{\phi+su}$. It is useful to write the later expression for $F_n(s)$ in the form

$$F_n(s) = \int (S_n u)(S_n v) \, d\mu_{s,n} - \int (S_n u) \, d\mu_{s,n} \int (S_n v) \, d\mu_{s,n} \qquad (4.7.5)$$

or

$$F_n(s) = \sum_{i,j=0}^{n-1} \int (u \circ T^i - \mu_{s,n}(u \circ T^i))(v \circ T^j - \mu_{s,n}(v \circ T^j)) \, d\mu_{s,n}, \qquad (4.7.6)$$

where $\mu_{s,n}$ is the probability measure distributed on $T^{-n}(x)$ according to the weights $\exp(S_n(\phi + su))(y) / \sum_y \exp S_n(\phi + su)(y)$.

Note that $\frac{1}{n}F_n(s)$ with $F_n(s)$ as in the formula (4.7.6) resembles already (4.7.3) because $\mu_{s,n} \to m_{\phi+su}$ in the weak*-topology, see (4.4.4). However we still need to work a little bit.

For each i, j denote the respective summand in (4.7.6) by $K_{i,j}$. To simplify notation denote $u \circ T^i$ by u_i and $v \circ T^j$ by v_j. We have

$$K_{i,j} = \frac{\mathcal{L}^n \big((u_i - \mu_{s,n}u_i)(v_j - \mu_{s,n}v_j) \big)(x)}{\mathcal{L}^n(\mathbb{1})(x)}$$

and for $0 \le i \le j < n$, using (4.2.7) twice,

$$K_{i,j} = \frac{\mathcal{L}^{n-j}\Big(\big(\mathcal{L}^{j-i}((u - \mu_{s,n}u_i)\mathcal{L}^i(\mathbb{1})) \big)\big(v - \mu_{s,n}v_j \big) \Big)(x)}{\mathcal{L}^n(\mathbb{1})(x)}. \qquad (4.7.7)$$

By Corollary 4.4.7 for $\tau < 1$ and Hölder norm $|| \cdot ||_{\mathcal{H}_\alpha}$ for an exponent $\alpha > 0$, transforming the integral as in Proof of Theorem 4.4.9, we get

$$||\mathcal{L}^{j-i}((u - \mu_{s,n}u_i)\mathcal{L}^i(\mathbb{1})) - u_{\phi+su}\left(\int u_i \, dm_{\phi+su} - \mu_{s,n}u_i \right)||_{\mathcal{H}_\alpha} \le C\tau^{j-i}$$

where C depends only on Hölder norms of u and $\phi + su$. The difference in the large parentheses, denote it by $D_{i,n}$, is bounded by $C\tau^{n-i}$ in the Hölder norm, again by Corollary 4.4.7.

We conclude that for all j the functions

$$L_j := \sum_{i \le j} \mathcal{L}^{j-i}((u - \mu_{s,n}u_i)\mathcal{L}^i(\mathbb{1}))$$

are uniformly bounded in the Hölder norm $|| \cdot ||_{\mathcal{H}_\alpha}$ by a constant C depending again only on $||u||_{\mathcal{H}_\alpha}$ and $||\phi + su||_{\mathcal{H}_\alpha}$. Hence summing over $i \le j$ in (4.7.7) and applying $\mathcal{L}^{n-j}$ we obtain

$$\Big\| \sum_{i=0}^j K_{i,j} - \sum_{i=0}^j \int (u_i - \mu_{s,n}u_i)(v_j - \mu_{s,n}v_j) \, dm_{\phi+su} \Big\|_\infty \le C\tau^{n-j}.$$

Here C depends also on $||v||_{\mathcal{H}_\alpha}$. We can replace the first sum by the second sum without changing the limit in (4.7.4) since after summing over $j = 0, 1, \ldots, n-1$, dividing by n and passing with n to ∞, they lead to the same result. Let us show now that $\mu_{s,n}$ can be replaced by $m_{\phi+su}$ in the above estimate without changing the limit in (4.7.4). Indeed, using the formula $ab - a'b' = (a - a')b' + a(b - b')$, we obtain

$$\left| \int (u_i - m_{\phi+su} u_i)(v_j - m_{\phi+su} v_j) \, dm_{\phi+su} - \int (u_i - \mu_{s,n} u_i)(v_j - \mu_{s,n} v_j) \, dm_{\phi+su} \right|$$
$$\leq |(\mu_{s,n} u_i - m_{\phi+su} u_i) \cdot (m_{\phi+su} v_j - \mu_{s,n} v_j)$$
$$+ \left| \int (u_i - m_{\phi+su} u_i) \cdot (\mu_{s,n} v_j - m_{\phi+su} v_j) \, dm_{\phi+su} \right|.$$

Since $D_{i,n} \leq C\tau^{n-i}$ and $D_{j,n} \leq C\tau^{n-j}$, the first summand is bounded above by $\tau^{n-i}\tau^{n-j}$. Note that the second summand is equal to 0. Thus, our replace-memnt is justified.

The last step is to replace $m = m_{\phi+su}$ by the invariant Gibbs measure $\mu = \mu_{\phi+su}$.

Similarly as above we can replace m by μ in mu_i, mv_i. Indeed,

$$|mu_i - \mu u_i| = \left| \int u \cdot \mathcal{L}^i(\mathbb{1}) \, dm - \int uu_{\phi+su} \, dm \right|$$
$$= \left| \int u \cdot (\mathcal{L}^i(\mathbb{1}) - u_{\phi+su}) \, dm \right| \leq Cm(u)\tau^i. \qquad (4.7.8)$$

Thus the resulting difference is bounded by $Cm(u)m(v)\tau^i\tau^j$. Finally we justify the replacement of m by μ at the second integral in the previous formula. To simplify notation write $F = u - \mu u, G = v - \mu v$. Since $j \geq i$, using (4.7.8), we can write

$$\left| \int (F \circ T^i)(G \circ T^j) \, dm - \int (F \circ T^i)(G \circ T^j) \, d\mu \right| =$$
$$= \left| \int (F \cdot (G \circ T^{j-i})) \circ T^i \, dm - \int (F \cdot (G \circ T^{j-i})) \circ T^i \, d\mu \right|$$
$$\leq C\tau^i \int |F \cdot (G \circ T^{j-i})| \, dm \leq Cm(F)m(G)\tau^i\tau^{j-i} = Cm(F)m(G)\tau^j$$

by Theorem 4.4.9 (exponential decay of correlations), the latter C depending again on the Hölder norms of $u, v, \phi + su$. Summing over all $0 \leq i \leq j < n$ gives the bound $Cm(F)m(G)\sum_{j=0}^{n-1} j\tau^j$ and our replacement is justified. For $i > j$ we do the same replacements changing the roles of u and v. The C^2-smoothness follows from the uniformity of the convergence of the sequence of the functions $F_n(s)$, for $\phi + tv$ in place of ϕ, with respect to the variables (s, t), resulting from the proof.   ♣

Exercises

4.1. Prove that (4.1.1) with an arbitrary $0 < \xi' \leq \xi$ in place of ξ implies (4.1.1) for every $0 < \xi' \leq \xi$ (with C depending on ξ').

4.2. Let $A = (a_{ij})$ be a non-zero $k \times k$ matrix with all entries non-negative. Assume that A is *irreducible*, namely that for any pair (i,j) there is some $n > 0$ such that the i,j-th entry a_{ij}^n of A^n is positive. Prove that there is a unique positive eigenvalue λ with left (row) and right (column) eigenvectors $v = (v_1, ..., .v_k)$ and $u = (u_1, ..., u_k)$ with all coordinates positive. The eigenvalue λ is simple. All other eigenvalues have absolute values smaller than λ.

   Check that the matrix $P = (p_{ij})$ with $p_{ij} := v_i a_{ij}/\lambda v_j$ is stochastic, that is $0 \leq p_{ij} \leq 1$ and $\sum_i p_{ij} = 1$ for all $j = 1, ..., k$. (One interprets p_{ij} as the probability of i under the condition j. Caution: often the roles of i and j are opposite.) Notice that $q = (u_1 v_1, ..., u_k v_k)$ satisfies $Pq = q$ (it is the stationary probability distribution).

   Prove that for each pair (i,j) $\lim_{n\to\infty} \lambda^{-n} a_{ij}^n \to u_i v_j$.

   Identify the vectors u and v for a piecewise affine (piecewise increasing) mapping of the interval $T : [0,1] \to [0,1]$. More precisely, let $0 = x_1 < x_2 < ... < x_k < x_{k+1} = 1$ and for each $i = 1, ..., k$ let $x_i = y_{i,1} < y_{i,2} < ... < y_{i,k+1} = x_{i+1}$. Consider T affine on each interval $[y_{i,j}, y_{i,j+1})$ mapping it onto $[x_j, x_{j+1})$, such that $T' = \text{Const } a_{ij}$. Consider the potential function $\phi = -\log F'$. What is the eigen-measure of the related transfer operator? What is the invariant Gibbs measure? Compare Exercise 4.7.

4.3. Prove that if a probability measure m is T-invariant then $\mathcal{L}_m(L^2(m)) \subset L^2(m)$ and the norm of $\mathcal{L}$ in $L^2(m)$ is equal to 1.

4.4. A linear operator $Q : L^1(\mu) \to L^1(\mu)$ for a measure space $(X, \mathcal{F}, \mu)$ (we allow μ to be infinite, say σ-finite) is called *Markov operator* if for all $u \geq 0$, $u \in L^1(\mu)$ the following two conditions hold.

(a) $Q(u) \geq 0$ (compare the notion of *positive operator*),

(b) $||Q(u)||_1 = ||u||_1$ (compare (4.2.4).
   (This notion generalizes the notion of transfer operator $\mathcal{L}_m$, see Section 4.2.)

   Prove that

(1) $||Q(u)||_1 \leq ||u||_1$ for all $u \in L^1(\mu)$,

(2) If $|Q^n(u)| \leq g$ for some positive $u, g \in L^1(\mu)$ and all $n = 1, 2, ...$, then there exists nonzero $u_* \in L^1(\mu)$ such that $Q(u_*) = u_*$.

(3) Suppose additionally that there is a compact set $A \subset L^1$ such that for d the distance in L^1, for every $u \in L^1(\mu)$ it holds $d(Q^n(u), A) \to 0$ as $n \to \infty$. (This property is called *strongly constrictive*).

   Then there exist two finite sequences of non-negative functions $g_i \in L^1(\mu), k_i \in L^\infty(\mu), i = 1, ..., p$, and a linear bounded operator $S : L^1(\mu) \to L^1(\mu)$ such that

for every $u \in L^1(\mu)$

$$Q(u) = \sum_{i=1}^{r} \lambda_i(u)g_i + S,$$

where $\lambda_i(u) = \int uk_i \, d\mu$, the functions g_i have disjoint supports and are permuted by Q, and $||Q^n S(u)||_1 \to 0$ as $n \to \infty$.

Hint: see Spectral Decomposition Theorem in [Lasota & Mackey 1985] and [Lasota, Li & Yorke 1984].

(4) Suppose additionally that there is $A \subset X$ with $\mu(A) > 0$ such that for every $u \in L^1(\mu)$ we have $Q^n(u) > 0$ on A for all n large enough. Then $\lim ||Q^n(u) - (\int u \, d\mu)u_*||_1 = 0$. (This property i called *asymptotically stable.*)

Hint: Deduce it from (3), see the Asymptotic Stability Section in [Lasota & Mackey 1985] .

(5) Prove that if a Markov operator Q satisfies the following *lower bound function* property:

There exists a nonnegative integrable function $h : X \to \mathbb{R}$ such that $||h||_1 > 0$ and such that for every non-negative $u \in L^1(\mu)$ with $||u||_1 = 1$,

$$\lim_{n \to \infty} || \min(Q^n(u) - h, 0)||_1 = 0,$$

then Q is asymptotically stable.

Hint: Consider $u \in L^1(\mu)$ with $\int u \, d\mu = 0$ and decompose it in positive and negative parts $u = u^+ + u^-$. Using h observe that iterating Q on u^+ and u^- we achieve the cancelling $h - h$. For details see [Lasota & Mackey 1985].

(Notice that the existence of the lower bound function u replaces the assumption on the existence of the set A in (4) and allows to get rid of the constrictivness assumption).

4.5. Consider a measure space $(X, \mathcal{F}, \mu)$ and a measurable function $K : X \times X \to \mathbb{R}$, non-negative and such that $\int_X K(x, y) \, d\mu(x) = 1$ for all $y \in X$ (such a function is called a *stochastic kernel*. Define the associated *integral operator* by

$$P(u)(x) = \int_X K(x, y)u(y) \, d\mu(y), \quad \text{for } u \in L^1(\mu).$$

Consider the convolutions

$$K_n(x, y) := \int K(x, z_{n-1})K(z_{n-1}, z_{n-2})...K(z_1, y) \, d\mu(z_{n-1})...d\mu(z_1).$$

Prove that if there exists $n \geq 0$ such that $\int_X \inf_y K_n(x, y) \, d\mu(x) > 0$, then Q is asymptotically stable.

4.6. Let $T : X \to X$ be a measurable backward quasi-invariant endomorphism of a measure space $(X, \mathcal{F}, m)$. Suppose there exist disjoint sets $A, B \subset X$, both of positive measure m, with $T(A) = X$.

Prove that for $\mathcal{L}_m : L^1(m) \to L^1(m)$ being the transfer operator as in Section 4.2 all λ with $|\lambda| < 1$ belong to its spectrum. In particular 1 is not an

isolated eigenvalue (there is no spectral gap, compare Remark 4.4.8). Is there a spectral gap for $\mathcal{L}_\phi$ for $T : X \to X$ an open expanding topologically transitive map, acting on $C(X)$ for Hölder continuous ϕ? (In Corollary 4.4.7 we restrict the domain of $\mathcal{L}_\phi$ to Hölder continuous functions).

Hint: Prove that all $\lambda, |lambda| < 1$ belong to the spectrum of the conjugate Koopman operator on $L^\infty(m)$. Indeed $\mathcal{L}^* - \lambda \mathrm{Id}$ is not onto, hence not invertible. No function which is identically 0 on A and non-zero on B is in the image.

4.7. Let $I_1, I_2, ..., I_N$ be a partition of the unit interval $[0,1]$ into closed subintervals ((up to end points, i.e. every two neighbours have a common end point). Let $T : [0,1] \to [0,1]$ be a piecewise $C^{1+\epsilon}$ expanding mapping. This means that the restriction of T to each I_j has an extension to a neighbourhood of the closure of I_j which is differentiable with the first derivative Hölder continuous of the modulus larger than 1. Suppose that each $T(I_j)$ is union of some I_i's (Markov property) and for each I_j there is n such that $T^n(I_j) = [0,1]$.

Prove the following so-called *Folklore Theorem*: There is an exact in the measure-theoretic sense T-invariant probability measure μ on $[0,1]$ equivalent to the length measure l, with $\frac{d\mu}{dl}$ bounded and bounded away from 0, Hölder continuous on each I_j.

Hint: consider the potential function $\phi = -\log|T'|$.

4.8. For T as in Exercise 4.7 assume that T is C^2 on I_j's, but do not assume Markov property. Prove that there exists a finite number of T-invariant probability measure absolutely continuous with respect to the length measure l.

Hint: This is famous Lasota-Yorke theorem [Lasota & Yorke 1973]. Instead of Hölder continuous functions consider the transfer operator $\mathcal{L}$ on the functions of bounded variation of derivative.

In fact by Ionescu Tulcea, Marinescu Theorem 4.5.5 item (8), there exists a spectral gap, see Remark 4.4.8, so we can prove probability laws as in Theorem 4.7.1.

4.9. Prove the existence of invariant Gibbs measure, Theorem 4.3.2, for ϕ satisfying the following *Bowen's condition*: there exists $\delta > 0$ and $C > 0$ with the property that whenever $\rho(T^i(x), T^i(z)) \le \delta$ for $0 \le i \le n-1$, then

$$\left| \sum_{i=0}^{n-1} \phi(T^i(x)) - \phi(T^i(z)) \right| \le C,$$

and for $T : X \to X$ open topologically transitive map of a compact metric space which is *non-contracting*, namely there exists $\eta > 0$ such that for all $x, y \in X$ $\rho(x,y) \le \eta$ implies $\rho(T(x), T(y)) \ge \rho(x,y)$.

For m satisfying $\mathcal{L}_\phi^*(m) = cm$ (see Theorem 4.2.8) prove the convergences (4.4.2). and (4.4.3).

Hint: see [Walters 1978].

Bibliographical notes

Writing Sections 4.1 – 4.4 we relied mainly on the books [Bowen 1975] and [Ruelle 1978]. See also [Zinsmeister 1996] and [Baladi 2000].

References to the facts in Section sec:4.5 concerning almost periodic operators can be found in [Lyubich & Lyubich 1986] and [Lyubich 1983]. For the proof of Ionescu Tulcea & Marinescu Theorem see [Ionescu Tulcea & Marinescu 1950]. For Markov operators see [Lasota & Mackey 1985].

As we mentioned already in Introduction, the first, simplest, proof of uniqueness of equilibrium follows [Keller 1998]. The second is similar to one in [Przytycki 1990]; the idea taken from Ledrappier's papers, see e.g.[Ledrappier 1984].

For the Perron-Frobenius theory for finite matrices, Exercise 4.2, see for example [Walters 1982] and the references therein.

Folklore theorem in Exercise 4.7 can be found for example in [Boyarsky & Góra 1997].

The consequences of holomorphic dependence of the operator on parameters (in particular the holomorphic dependence of an isolated eigenvalue of multiplicity one, see Remark 4.4.8) is comprehensively written in [Kato 1966].

We owe Exercise 4.6 to R. Rudnicki.

Chapter 5

Expanding repellers in manifolds and Riemann sphere, preliminaries

In this chapter we shall consider a compact metric space X with an open, distance expanding map T on it, embedded isometrically into a smooth Riemannian manifold M. We shall assume that T extends to a neighbourhood U of X to a mapping f of class $C^{1+\varepsilon}$ for some $0 < \varepsilon \leq 1$ or smoother, including real-analytic. $C^{1+\varepsilon}$ and more general $C^{r+\varepsilon}$ for $r = 1, 2, \ldots$ means the r-th derivative is Hölder continuous with the exponent ε for $\varepsilon < 1$ and Lipschitz continuous for $\varepsilon = 1$. We shall assume also that there exists a constant $\lambda > 1$ such that for every $x \in U$ and for every non-zero vector v tangent to M at x, it holds $||Df(v)|| > \lambda||v||$, where $|| \cdot ||$ is the norm induced by the Riemannian metric. The pair (X, f) will be called an *expanding repeller* and f an *expanding map*. If f is of some class A, e.g. C^α or analytic, we will say the expanding repeller is of that class or that this is an A-expanding repeller. In particular, if f is conformal we call (X, f) a **conformal expanding repeller**, abbr. **CER**. Finally if we skip the assumption $T = f|_X$ is open on X, we will call (X, f) an *expanding set*. Sometimes to distinguish the domain of f we shall write (X, f, U).

In Sections 5.2 and 5.3 we provide some introduction to conformal expanding repellers, studying transfer operator, postponing the main study to Chapters 8 and 9, where we shall use tools of geometric measure theory.

In Section 5.4 we discuss analytic dependence of transfer operator on parameters.

5.1   Basic properties

For any expanding set there exist constants playing the analogous role as constants for (open) distance expanding maps:

Lemma 5.1.1. *For any expanding set (X, f) with λ, U as in the definition and f differentiable, for every $\eta > 0$ small enough, there exist $U' \subset U$ a neighbourhood of X such that $B(X, \eta) \subset U'$, $B(U', \eta) \subset U$ and for every $x \in U'$ the map f is injective on $B(x, \eta)$. Moreover $f(B(x, \eta)) \supset B(f(x), \eta)$ and f increases distances on $B(x, \eta)$ at least by the factor λ.*

Proof. We leave the proof to the reader as an easy exercise; compare Proof of Lemma 5.1.2.   ♣

In the sequel we shall consider expanding sets together with the constants η, λ from Lemma 5.1.1. Write also $\xi := \lambda \eta$. For the expanding repeller (X, f) these constants satisfy the properties of the constants η, ξ, λ for the distance expanding map $T = f|_X$ on X, provided η is small enough, compare Lemmas 3.1.2 and 3.1.4. For every $x \in X$ we can consider the branch f_x^{-1} on $B(f(x), \xi)$, mapping $f(x)$ to x, extending the branch T_x^{-1} defined on $B(f(x), \xi) \cap X$. Similarly we can consider such branches of f^{-1} for $x \in U'$

Let now X be a compact subset of M forward invariant, namely $f(X) \subset X$, for a continuous mapping f defined on a neighbourhood U of X. We say X is a *repeller* if there exists a neighbourhood U' of X in U such that for every $y \in U' \setminus X$ there exists $n > 0$ such that $f^n(y) \notin U'$. In other words

$$X = \bigcap_{n > 0} f^{-n}(U'). \tag{5.1.1}$$

In the lemma below we shall see that the extrinsic property of being repeller is equivalent to the intrinsic property of being open for f on X. It is a topological lemma, no differentiability is invoked.

Lemma 5.1.2. *Let X be a compact subset of M forward invariant for a continuous mapping f defined on its neighbourhood U. Suppose that f is an open map on U. Then if X is a repeller then $f|_X$ is an open map in X. Conversely, if f is distance expanding on a neighbourhood of X and $f|_X$ is an open map, then X is a repeller, i.e. satisfies (5.1.1).*

Proof. If $f|_X$ were not open there would exist a sequence of points $x_n \in X$ converging to $x \in X$ a point $y \in X$ such that $f(y) = x$ and an open set V in M containing y so that no x_n is in $f(V \cap X)$. But as f is open there exists a sequence $y_n \in V$, $y_n \to y$ and $f(y_n) = x_n$ for all n large enough. Thus the forward trajectory of each y_n stays in every U' even in X except y_n itself which is arbitrarily close to X with n respectively large. This contradicts the repelling property.

Conversely, suppose that X is not a repeller. Then for $U'' = B(X, r) \subset U'$ (U' from Lemma 5.1.1) with an arbitrary $r < \xi$ there exists $x \in U'' \setminus X$ such that its forward trajectory is also in U''. Then there exists $n > 0$ such that $\text{dist}(f^n(x), X) < \lambda \text{dist}(f^{n-1}(x), X)$. Let y be a point in X closest to $f^n(x)$. Then by Lemma 5.1.1 there exists $y' \in B(f^{n-1}(x), \eta)$ such that $f(y') = y$ and by the construction $y' \notin X$. Thus, letting $r \to 0$, we obtain a sequence of points x_n not in X but converging to $x_0 \in X$ with images in X. So $f(x_n) \notin$

$f|_X(B(x_0, \eta) \cap X)$ because they are f-images of $x_n \in B(x_0, \eta) \setminus X$ for n large enough and f is injective on $B(x_0, \eta)$. But $f(x_n) \to f(x_0)$. So $f(x_0)$ does not belong to the interior of $f|_X(B(x_0, \eta) \cap X)$, so $f|_X$ is not open. ♣

To complete the description we provide one more fact:

Proposition 5.1.3. *If (X, f) is an expanding set in a manifold M, then it is a repeller iff there exists U'' a neighbourhood of X in M such that for every sequence of points $x_n \in U''$, $n = 0, -1, -2, \ldots, -N$, where N is any positive number or ∞, such that $f(x_n) = x_{n+1}$ for $n < 0$, i.e. for every backward trajectory in U'', there exists a backward trajectory $y_n \in X$ such that $x_n \in B(y_n, \eta)$.*
Additionally, if (X, f) is an expanding repeller and f maps X onto X, then for every $x_0 \in U''$ there exist x_n and y_n as above.

Proof. If U'' is small enough then by the openess of $f|_X$ if $f(y) = z \in X$ and $y \in U''$ then $y \in X$, compare Proof of Lemma 5.1.2. So, given x_n, defining $y_n = f_{x_n}^{-1}(y_{n+1})$, starting with $y_0 \in X$ such that $\rho(x_0, y_0) < \xi$ we prove that $y_n \in X$.

Conversely, if $f^n(x) \in U''$ for all $n = 0, 1, \ldots$, then for each n we consider $f^n(x), f^{n-1}(x), \ldots, x$ as a backward trajectory and find a backward trajectory $y(n)_0, y(n)_{-1}, \ldots, y(n)_{-n}$ in X such that $f^{n-i}(x) \in B(y(n)_{-i}, \eta)$ for all $i = 0, \ldots, n$. In particular we deduce that $\rho(x, y(n)_{-n}) \le \eta \lambda^{-n}$. We conclude that the distance of x from X is arbitrarily small, i.e. $x \in X$.

To prove the last assertion, given only x_0 we find $y_0 \in X$ close to x_0, next take any backward trajectory $y_n \in X$ existing by the "onto" assumption and find $x_n = f_{x_n}^{-1}(y_{n+1})$ by induction, analogously to finding y_n for x_n above. ♣

Remark 5.1.4. The condition after "iff" in this proposition (for $N = \infty$) can be considered in the "inverse limit", saying that every backward trajectory in U'' is in the "unstable manifold" of a backward trajectory in X.

Now we shall prove a lemma corresponding to the Shadowing lemma 3.2.4. For any two mappings F, G on the common domain A, to a metric space with a metric ρ, we write $\mathrm{dist}(F, G) := \sup_{x \in A} \rho(f(x), g(x))$. Recall that we say that a sequence of points (y_i) β-shadows (x_i) if $\rho(x_i, y_i) \le \beta$.

Lemma 5.1.5. *Let (X, f, U) be an expanding set in a manifold M. Then for every $\beta : 0 < \beta < \eta$ there exist $\varepsilon, \alpha > 0$ (it is sufficient that $\alpha + \varepsilon < (\lambda - 1)\beta$) such that if a continuous mapping $g : U \to M$ is α-C^0-close to f, i.e. $\mathrm{dist}(f, g) \le \alpha$, then every $\varepsilon - f$-trajectory $x = x_0, x_1, \ldots, x_n$ in U' can be β-shadowed by at least one g-trajectory. In particular there exists X_g a compact forward g-invariant set, i.e. such that $g(X_g) \subset X_g$, and a continuous mapping $h_{gf} : X_g \to M$ such that $\mathrm{dist}(h_{gf}, \mathrm{id}|_{X_g}) \le \beta$ and $h_{gf}(X_g) = X$.*
If g is Lipschitz continuous, then h_{gf} is Hölder continuous.

Proof. It is similar to that of Shadowing Lemma but needs some more care. If we treat $x_i, i = 0, \dots, n$ as an $\alpha + \varepsilon$-trajectory for g we cannot refer to Proof of Shadowing Lemma because we have not assumed g is expanding.

Let us make however similar choices as there, for $\beta < \eta$ let $\alpha + \varepsilon = \beta(\lambda - 1)$. Then by Lemma 5.1.1

$$f(\operatorname{cl} B(x_i, \beta)) \supset \operatorname{cl} B(f(x_i), \lambda\beta), \quad i = 0, 1, \dots, n. \tag{5.1.2}$$

We left it in Proof of Lemma 5.1.1 as an exercise. One proof could use an integration.

We shall give however a standard topological argument, proving (5.1.2) with $\lambda' \leq \lambda$ arbitrarily close to λ for β small enough, using the local aproximation of f by Df, which will be of use later on also for g. This argument corresponds to Rouché's theorem in 1 complex variable (preservance of index of a curve under small perturbation).

In the closed ball $B_1 = \operatorname{cl} B(x_i, \beta)$ for β small enough, f is $\beta(\lambda - \lambda')$-$C^0$-close to Df, (locally it makes sense to compare f with Df using local charts on the manifold M). To get β independent of i we use f being C^1.

Hence f and Df are homotopic as maps of the sphere $S_1 = \partial B_1$ to $M \setminus z$ for any $z \in B(f(x_i), \lambda'\beta)$, just along the intervals joining the corresponding image points. If z were missing in $f(B_1)$ then we could project $f(B_1)$ to $S_2 = \partial B(f(x_i), \lambda'\beta)$ along the radii from z. Denote such a projection from any w by P_w.

$P_z \circ f|_{S_1} : S_1 \to S_2$ is not homotopic to a constant map, because it is homotopic to $P_z \circ Df|_{S_1}$ which is homotopic to $P_{f(x_i)} \circ DF|_{S_1}$ by using P_t, $t \in [z, f(x_i)]$, and finally $P_{f(x_i)} \circ Df|_{S_1}$ is not homotopic to a constant because Df is an isomorphism (otherwise, composing with Df^{-1} we would get the identity on S_1 homotopic to a constant map).

On the other hand $P_z \circ f|_{S_1}$ is homotopic to a constant since it extends to the continuous map $P_z \circ f|_{B_1}$.

Precisely the same topological argument shows that, setting $x_{n+1} = f(x_n)$,

$$g(\operatorname{cl} B(x_i, \beta)) \supset \operatorname{cl} B(f(x_i), \lambda'\beta - \alpha) \supset$$

$$\operatorname{cl} B(x_{i+1}, \lambda'\beta - \alpha - \varepsilon) \supset \operatorname{cl} B(x_{i+1}, \beta) \quad i = 0, 1, \dots, n. \tag{5.1.3}$$

So the intersection $A(x) := \bigcap_{j=0}^{n} g^{-j}(\operatorname{cl} B(x_j, \beta))$ is non-empty and the forward g-trajectory of any point in $A(x)$ β-shadows $x_i, i = 0, \dots, n-1$.

The sequence $B(x_0, \beta) \to f(B(x_0, \beta)) \supset B(x_1, \beta) \to f(B(x_1, \beta)) \supset B(x_2, \beta) \to \dots$ is called a "telescope". The essence of the proof was the existence and the stability of telescopes.

To prove the last assertion, let $\varepsilon = 0$, $x_i \in X$ and $n = \infty$. For the above sets $A(x) = A(x, g, \beta)$ set

$$X(g, \beta) = \bigcup_{x \in X} A(x, g, \beta) \qquad X_g = \operatorname{cl} X(g, \beta).$$

Suppose $\beta < \eta$. Then for $x, y \in X$ $x \neq y$ we have $A(x) \cap A(y) = \emptyset$ because the constant of expansiveness of f on X is 2η. This allows to define $h_{gf}(y) = x$ for every $y \in A(x)$.

If $y \in \operatorname{cl} A(x)$ then by the definition for every $n \geq 0$ $f^n(y) \in \operatorname{cl} A(f^n(x))$. This proves the g-invariance of X_g and $h_{gf} \circ g = f \circ h_{gf}$. The continuity of h_{gf} holds because for an arbitrary n if $y, y' \in X(g, \beta)$ and $\operatorname{dist}(y, y')$ is small enough, say less than $\varepsilon(n)$, then $\operatorname{dist}(g^j(y), g^j(y')) < \eta - \beta$ for every $j = 0, 1, \ldots, n$. $\varepsilon(n)$ does not depend on y, y' since g is uniformly continuous on a compact neighbourhood of X in M. Then $\operatorname{dist}(f^j(x), f^j(x')) < 2\eta$, where $x = h_{gf}(y), x' = h_{gf}(y')$. Hence $\operatorname{dist}(x, x') < \lambda^{-n} 2\eta$. We obtain h_{gf} uniformly continuous on $X(g, \beta)$, hence it extends continuously to the closure X_g. ♣

If g is Lipschitz continuous with $\operatorname{dist}(\gamma(y) - g(y')) \leq L \operatorname{dist}(y, y')$, then we set $\varepsilon(n) := (\eta - \beta) L^{-n}$. Then, for $\operatorname{dist}(y, y') \leq \varepsilon(n)$, we get $\operatorname{dist}(x, x') \leq \lambda^{-n} 2\eta = M\varepsilon(n)^{\log \lambda / \log L}$ for $M = (\frac{1}{\eta - \beta})^{\log \lambda / \log L} 2\eta$. In consequence h_{gf} is Hölder with exponent $\log \lambda / \log L$.

The existence of h_{gf} does not depend on the construction of X_g. Namely the following holds.

Proposition 5.1.6. *Let Y be a forward g-invariant subset of $U' \supset X$ defined in Lemma 5.1.1, for continuous $g : U \to M$ α-close to f. Then, for every $\beta : 0 < \beta < \eta$ and for every $\alpha : 0 < \alpha < \beta(\lambda - 1)$ there exists a unique transformation $h_{gf} : Y \to U$ such that $h_{gf} \circ g = f \circ h_{gf}$ and $\rho(h_{gf}, \operatorname{id}|_Y) < \beta$. (We call such a transformation h_{gf} a semiconjugacy to the image.) This transformation is continuous, and $\rho(h_{gf}, \operatorname{id}|_Y) \leq \frac{\alpha}{\lambda - 1}$. If $g|_Y$ is positively expansive and 2β is less than the constant of expansiveness then h_{gf} is injective (called then a conjugacy to the image X_f). If X is a repeller then $X_f \subset X$. If g is Lipschitz, then h_{gf} is Hölder continuous.*

Proof. Each g-trajectory y_n in Y is an α-f-trajectory and we can refer to Lemma 5.1.5 for α playing the role of ε and $g = f$. We find an f-trajectory x_n such that $\rho(x_n, y_n) \leq \alpha / (\lambda - 1)$ and define $h_{gf}(y_n) = x_n$. The uniqueness follows from the positive expansivness of f with constant $2\eta > 2\beta$. The continuity can be proved as in Lemma 5.1.5. ♣

Proposition 5.1.7. *Let (X, f, U) be an expanding set. Then there exists $\mathcal{U}$ a neighbourhood of f in C^1 topology, i.e. $\mathcal{U} = \{g : U \to M : g \in C^1, \rho(f, g) < \alpha, \|Df(x) - Dg(x)\| < \alpha \ \forall x \in U\}$, for a number $\alpha > 0$, such that for every $g \in \mathcal{U}$ there exists an expanding repeller X_g for g and a homeomorphism $h_{gf} : X_g \to X$ such that $h_{gf} \circ g = f \circ h_{gf}$ on X_g. Moreover for each $x \in X$ the function $\mathcal{U} \to M$ defined by $g \mapsto x_g := h_{gf}^{-1}(x)$ is Lipschitz continuous, where $\mathcal{U}$ is considered with the metric $\rho(g_1, g_2)$ (in C^0 topology). All h_{gf} and their inverses are Hölder continuous with the same exponent and common upper bound of their Hölder norms.*

Proof. For $\mathcal{U}$ small enough all $g \in \mathcal{U}$ are also expanding, with the constant λ maybe replaced by a smaller constant but also bigger then 1 and η, U' the same.

Then X_g and h_{gf} exist by Lemma 5.1.5. Since g is expanding, hence expansive on X_g, h_{gf} is injective by Proposition 5.1.6.

To prove Lipschitz continuity of x_g, consider $g_1, g_2 \in \mathcal{U}$. Then

$$h = h_{g_2 f}^{-1} \circ h_{g_1 f} : X_{g_1} \to X_{g_2}$$

is a homeomorphism, such that $\rho(g_1, g_2) < 2\alpha/(\lambda - 1) < \beta$ for appropriate α, where λ is taken to be common for all $g \in \mathcal{U}$.

On the other hand by Proposition 5.1.6 aplied to g_2 in place of f and g_1 in place of g, for the forward invariat set $Y = X_{g_1}$ there exists a homeomorphism $h_{g_1 g_2} : Y \to X_{g_2}$ conjugating g_1 to g_2. We have $\rho(h_{g_1 g_2}, \mathrm{id}|_{X_{g_1}}) < \rho(g_1, g_2)/(\lambda - 1)$. By the uniqueness in Lemma 5.1.5, we have $h = h_{g_1 g_2}$ hence $\rho(h, \mathrm{id}|_{X_{g_1}}) < \rho(g_1, g_2)/(\lambda - 1)$, which yields the desired Lipschitz continuity of x_g.   ♣

Hölder continuity of h_{gf} and h_{gf}^{-1} follows from Lemma 5.1.5. Uniform Hölder exponent results from the existence of a common Lipschitz constant and expanding exponent for g C^1-close to f. The uniformity of the Hölder norm follow sfrom the formula ending Proof of Lemma 5.1.5.

Examples

Example 5.1.8. Let $f : M \to M$ be an expanding mapping on a compact manifold M, that is the repeller X is the whole manifold. Then f is C^1-structurally stable. This means that there exists $\mathcal{U}$, a neighbourhood of f in C^1 topology, such that for every $g : M \to M$ in $\mathcal{U}$ there exists a homeomorphism $h_{gf} : M \to M$ conjugating g and f.

This follows from Proposition 5.1.7. Note that $X_g = M$, since being homeomorphic to M it is a boundaryless manifold of the same dimension as M and it is compact, hence if $\mathcal{U}$ is small enough, it is equal to M (note that we have not assumed connectedness of M).

A standard example of an expanding mapping on a compact manifold is an expanding endomorphism of a torus $f : \mathbb{T}^d = \mathbb{R}^d / \mathbb{Z}^d \to \mathbb{T}^d$, that is a liner mapping of $\mathbb{R}^d$ given by an integer matrix A, mod $\mathbb{Z}^d$.

Example 5.1.9. Let $f : \mathbb{C}^d \to \mathbb{C}^d$ be the cartesian product of z^2's, that is $f(z_1, \ldots, z_d) = (z_1^2, \ldots, z_d^2)$. Then the torus $\mathbb{T}^d = \{|z_i| = 1, i = 1, \ldots, d\}$ is an expanding repeller. By Proposition 5.1.7 it is stable under small C^1, in particular complex analytic, perturbations g. This means in particular that there exists a topological d-dimensional torus invariant under g close to $\mathbb{T}^d$.

Example 5.1.10. Let $f_c : \bar{\mathbb{C}} \to \bar{\mathbb{C}}$ be defined by $f_c(z) = z^2 + c, c \approx 0$, compare Introduction and Chapter 0. As in Example 5.1.9, there exists a Jordan curve X_{f_c} close to the unit circle which is an f_c-invariant repeller and a homeomorphic conjugacy $h_{f_c f_0}$. It is not hard to see that $X_{f_c} = J(f_c)$ the Julia set, see Example 0.6.

The equation of a fixed point for f_c is $z_c^2 + c = z_c$ and if we want a fixed point z_c to be attracting (note that there are 2 fixed points, except $c = 1/4$) we

want $|f_c'(z_c)| = |2z_c| < 1$. This means c is in the domain $\mathcal{M}_0$ bounded by the cardioid $c = -(\lambda/2)^2 + \lambda/2$ for λ in the unit circle.
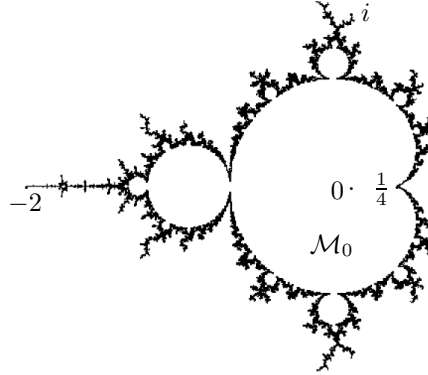
Figure 5.1: Mandelbrot set

It is not hard to prove that $\mathcal{M}_0$ is precisely the domain of c where the homeomorphisms $h_{f_c f_0}$ and in particular their domains X_{f_c} exist. Each X_{f_c} is a Jordan curve (X_{f_c}, f_c) is an expanding repeller and the "motion" $c \mapsto z_c := h_{f_c f_0}^{-1}(z)$ is continuous for each z in the unit circle X_{f_0}. In fact X_{f_c} is equal to Julia set $J(f_c)$ for f_c. At c in the cardioid, a self-pinching of X_{f_c} at infinitely many points happens. In fact the motion is holomorphic, see Section 5.2.

$\mathcal{M}_0$ is a part of Mandelbrot set $\mathcal{M}$ where $J(f_c)$ is connected. When c leaves $\mathcal{M}$, Julia set crumbles into a Cantor set.

5.2 Complex dimension one. Bounded distortion and other techniques

The basic property is so called *Bounded Distortion for Iteration*. We have had already that kind of lemma, Lemma 3.4.2 (Pre- Bounded Distortion Lemma for Iteration), used extensively in Chapter 4. Here it will get finally its geometric sense.

Definition 5.2.1. We say that V an open subset of $\mathbb{C}$ or $\mathbb{R}$ has distortion with respect to $z \in V$ bounded by C if there exist $R > r > 0$ such that $R/r \leq C$ and $B(z, r) \subset V \subset B(z, R)$.

Lemma 5.2.2 (Distortion Lemma for Iteration). *Let (X, f) be a $C^{1+\varepsilon}$-expanding set in $\mathbb{R}$ or a conformal expanding set in $\mathbb{C}$. Then there exists a constant $C > 0$ such that*

1. For every $x \in X$ and $n \geq 0$, for every $r \leq \xi$ the distortion of the set $f_x^{-n}(B(f^n(x), r))$ with respect to x is less than $\exp Cr$ in the conformal case and less than $\exp Cr^\varepsilon$ in the real case.

2. *The same bound holds for the distortion of $f^n(B(x, r'))$ for any $r' > 0$ under the assumption $f^j(B(x, r')) \subset B(f^j(x), r)$ for every $j = 1, \ldots, n$. Moreover*

3. *If $y_1, y_2 \in B(x, r')$ then $\frac{\rho(f^n(y_1), f^n(x))}{\rho(f^n(y_2), f^n(x))} : \frac{\rho(y_1, x)}{\rho(y_2, x)} < \exp Cr$ or $\exp Cr^\varepsilon$.*
Finally, in terms of derivatives,

4. $\exp Cr$ *and* $\exp Cr^\varepsilon$ *bound the fractions*

$$\frac{|(f^n)'(x)|}{r/\operatorname{diam} f_x^{-n}(B(f^n(x), r))} \quad and \quad \frac{|(f^n)'(x)|}{\operatorname{diam} f^n(B(x, r'))/r'}$$

from above and the inverses bound these fractions from below.

5. *For $y_1, y_2 \in f_x^{-n}(B(f^n(x), r))$*

$$\left| \frac{(f^n)'(y_1)}{(f^n)'(y_2)} - 1 \right| < Cr \quad or \quad Cr^\varepsilon.$$

Proof. Cr and Cr^ε bound the additive distortions of the functions $\log |(f^n)'|$ and $\operatorname{Arg}(f^n)'$ (in the complex holomorphic case) on the sets $f_x^{-n}(B(f^n(x), r))$ and $B(x, r')$. Indeed, these functions are of the form $S_n \psi$ for Hölder $\psi = \log |f'|$ or $\operatorname{Arg} f'$, see Chapter 3. We use Pre-Bounded Distortion Lemma 3.4.2. To conclude the assertions involving diameters integrate $|(f^n)'|$ or the inverse along curves.   ♣

In the conformal situation, in $\overline{\mathbb{C}}$, instead of refering to Lemma 5.2.2, one can often refer to Koebe Distortion Lemma, putting $g = f^n$ or inverse.

Lemma 5.2.3 (Koebe Distortion Lemma in the Riemann sphere). *Given $\varepsilon > 0$ there exists a constant $C = C(\varepsilon)$ such that for every $\lambda : 0 < \lambda < 1$ for every conformal (holomorphic univalent) map on the unit disc in $\mathbb{C}$ to the Riemann sphere $\overline{\mathbb{C}}$, $g : \mathbb{D} \to \overline{\mathbb{C}}$, such that $\operatorname{diam}(\overline{\mathbb{C}} \setminus g(\mathbb{D})) \geq \varepsilon$, for all $y_1, y_2 \in \lambda \mathbb{D}$,*

$$|g'(y_1)/g'(y_2)| \leq C(1-\lambda)^{-4}.$$

diameter and derivatives in the Riemann sphere metric.

One can replace $\mathbb{D}$ by any disc $B(x, r) \subset \overline{\mathbb{C}}$ with $\operatorname{diam} \overline{\mathbb{C}} \setminus B(x, r) ge \varepsilon$ and $y_1, y_2 \in B(x, \lambda r)$.

This Lemma follows easily from the classical lemma in the complex plane, see for example [Carleson & Gamelin 1993, Section I.1].

Lemma 5.2.4 (Koebe Distortion Lemma). *For every holomorphic univalent function $g : \mathbb{D} \to \mathbb{C}$ for every $z \in \mathbb{D}$*

$$\frac{1-|z|}{1+|z|^3} \leq \frac{|g'(z)|}{g'(0)} \leq \frac{1+|z|}{1-|z|)^3}.$$

Remark 5.2.5. In the situation of Lemma 5.2.3 fixed an arbitrary $g : \mathbb{D} \to oc$ there exists $C = C(g)$ such that for all $y, y_1, y_2 \in \lambda \mathbb{D}$

$$|g'(y)/g'(0)| \leq C(1-\lambda)^2 \quad |g'(0)/g'(y)| \leq C(1-\lambda)^2$$

and in particular

$$|g'(y_1)/g'(y_2)| \leq C(1-\lambda)^{-2}.$$

Of fundamental importance is the so-called holomorphic motion approach:

Definition 5.2.6. Let (X, ρ_X) and (Y, ρ_Y) be metric spaces. We call a mapping $f : X \to Y$ *quasisymmetric*, if there exists a constant $M > 0$ such that for all $x, y, z \in X$ if $\rho_X(x, y) = \rho_X(x, z)$, then $\rho_Y(f(x), f(y)) \leq M \rho_Y(f(x), f(z))$.

In case X is an open subset of a Euclidean space of dimension at least 2, the name *quasiconformal* is usually used. In this case several equivalent definitions are being used.

Definition 5.2.7. Let A be a subset of $\overline{\mathbb{C}}$. A mapping $i_\lambda(z)$ for $\lambda \in \mathbb{D}$ the unit disc, and $z \in A$ is called *holomorphic motion* of A if

(i) for every $\lambda \in \mathbb{D}$ the mapping i_λ is an injection;
(ii) for every $z \in A$ the mapping $\lambda \mapsto i_\lambda(z)$ is holomorphic;
(iii) i_0 is identity (i.e. inclusion of A in $\overline{\mathbb{C}}$).

Lemma 5.2.8 (Maǹè, Sad, Sullivan's $\lambda-$lemma, see [Mañé, Sad & Sullivan 1983]). *Let $i_\lambda(z)$ be a holomorphic motion of $A \subset \overline{\mathbb{C}}$. Then every i_λ has a quasisymmetric extension $i_\lambda : \overline{A} \to \overline{\mathbb{C}}$ which is an injection, for every $z \in \overline{A}$ the mapping $\lambda \to i_\lambda(z)$ is holomorphic, and the map $\mathbb{D} \times \overline{A} \ni (\lambda, z) \mapsto i_\lambda(z)$ is continuous.*

Note that the assumption that the domain of lambdas is complex is substantial. If for example the motion is only for $\lambda \in \mathbb{R}$, then the lemma is false. Consider for example the motion of $\mathbb{C}$ such that the lower halfplane moves in one direction, $i_\lambda(z) = z + \lambda$, and the upper (closed) halfplane moves in the opposite direction, $i_\lambda(z) = z - \lambda$. Then i_λ is even not continuous. However this motion cannot be extended to complex lambdas, to injections.

Proof. The proof is based in the following: any holomorphic map of $\mathbb{D}$ to the triply punctured sphere $\overline{\mathbb{C}} \backslash \{0, 1, \infty\}$ is distance non-increasing for the hyperbolic metrics on $\mathbb{D}$ and $\overline{\mathbb{C}} \setminus \{0, 1, \infty\}$ (Schwarz lemma). Choose three points of A and renormalize i (i.e. for each i_λ compose it with a respective homography) so that the images by i_λ of these three points are constantly $0, 1$ and ∞. (We can assume A is infinite, otherwise the Lemma is trivial.)

For any three other point $x, y, z \in A$, consider the functions $x(\lambda) = i_\lambda(x)$, $y(\lambda) = i_\lambda(y)$, $z(\lambda) = i_\lambda(z), w(\lambda) = (y(\lambda) - x(\lambda))/y(\lambda)$. These functions avoid $0,1,\infty$. Fix any $0 < m < M < \infty$. Let $y(0) \in A$ and $y(0)$ be in the ring $P(m, M) = \{m \leq |y| \leq M\}$. Then $|x(0) - y(0)|$ small implies $w(0)$ small, hence for any $\lambda \leq R$ for an arbitrary constant $R : 0 < R < 1$, the hyperbolic distance between $w(0)$ and $w(\lambda)$ in $\overline{\mathbb{C}} \setminus \{0, 1, \infty\}$ is less than R, hence $w(\lambda)$ is small. Therefore $x(\lambda) - y(\lambda)$ is small.

Thus each i_λ is uniformly continuous on $A \cap P(m, M)$. Moreover the family i_λ is equicontinuous for $|\lambda| \leq R$

The annulus $P(m, M)$ for $m < 1 < M$ contains 1, so permuting the roles of $0,1,\infty$ we see that the annuli cover the sphere. So i_λ has a continuous extension to $\overline{A}$. The extensions for $|\lambda| \leq R$ are equicontinuous.

Similarly we prove that if $|x(0) - y(0)|$ is large, then $x(\lambda) - y(\lambda)$ is large. Therefore these extensions are injections.

To prove i_λ is quasi-symmetric consider $g(\lambda) = \frac{x(\lambda) - y(\lambda)}{x(\lambda) - z(\lambda)}$. This function also omits $0, 1, \infty$. Assume $|g(0)| = 1$. Then for $|\lambda| \le R < 1$ the hyperbolic distance of $g(\lambda)$ from the unit circle is not larger than R. Therefore $|g(\lambda)|$ is uniformly bounded for $|\lambda| \le R$.

Note finally that for each $x \in \overline{A}$ the map $\lambda \mapsto i_\lambda(x)$ is holomorphic as the limit of holomorphic functions $i_\lambda(z)$, $z \to x, z \in A$. In particular it is continuous. So, due to the equicontinuity of the family i_λ, i is continuous on $\mathbb{D} \times \overline{A}$. ♣

Remark 5.2.9. For $X \subset \mathbb{C}$ a topologically mixing expanding repeller for f holomorphic λ-lemma gives a new proof of stability under holomorphic perturbations of f to g, see Lemma 5.1.5 and Proposition 5.1.6. One can choose a periodic orbit $P \subset X$ and consider $A = \bigcup_{n=0}^{\infty} (f|_X)^{-n}(P)$. Since (X, f) is topologically exact, see ....., A is dense in X. By Implicit Function Theorem P moves holomorphically under small holomorphic perturbations $g = g_\lambda$ of f. So A moves holomorphically, staying close to X (by the repelling property of (X, f)). So h_{fg}'s can be defined as $i_\lambda : X \to X_g$. Due to λ-lemma we conclude they are quasi-symmetric.

Remark 5.2.10. The maps i_λ of the holomorphic motion in Lemma 5.2.8 are Hölder continuous. Moreover, for $\lambda \in A$ any compact subset of D, they have a common Hölder exponent $\beta = \beta_A$ and a common norm in $\mathcal{H}_\beta$.

This follows from Slodkowski's theorem [Slodkowski 1991] saying that the motion $i_\lambda(z)$ extends to whole Riemann sphere. Then we refer to the fact that each quasisymmetric (K-quasiconformal) homeomorphism is Hölder, with exponent $1/K$ and uniformly bounded Hölder norm, see [Ahlfors 1966].

5.3 Transfer operator for conformal expanding repeller with harmonic potential

We consider a conformal expanding repeller, that is an expanding repeller (X, f) for $X \subset \overline{\mathbb{C}}$ and f conformal on a neighbourhood of X. This is a preparation to a study in Chapters 8 and 9.

We consider potentials of the form $\phi = -t \log |f'|$ for all t real and related transfer operators $\mathcal{L}_\phi$ on (continuous) real functions on X, see Section 4.2. We proved in Chapter 4 that $\mathcal{L}$ has unique positive eigenfunction u_ϕ and there exist m_ϕ on X the eigenmeasure of $\mathcal{L}^*$, and μ_ϕ the invariant Gibbs measure equivalent to it and u_ϕ is the Radon-Nikodym derivative $\frac{d\mu_\phi}{dm_\phi}$. Our aim is to prove that u_ϕ has a real-analytic extension to a neighbourhood of X.

We begin with the following.

Definition 5.3.1. A conformal expanding repeller $f : X \to X$ is said to be real-analytic if X is contained in a finite union of pairwise disjoint real-analytic curves.

These curves will be denoted by $\Gamma = \Gamma_f$. Frequently in such a context we will alternatively speak about real analyticity of the set X.

Theorem 5.3.2. *If $f : X \to X$ is an orientation preserving conformal expanding repeller, $X \subset C$, then the Radon-Nikodym derivative $u = u_\phi = d\mu_\phi/dm_\phi$ has a real-analytic real-valued extension on a neighbourhood of X in $\mathbb{C}$. If f is real-analytic, then u has a real-analytic extension on a neighbourhood of X in Γ and complex-valued complex analytic extension on a neighbourhood in $\overline{\mathbb{C}}$.*

Proof. Since f is conformal and orientation preserving, f is holomorphic on a neighbourhood of X in $\mathbb{C}$. Take $r > 0$ so small that for every $x \in X$, every $n \geq 1$ and every $y \in f^{-n}(x)$ the holomorphic inverse branch $f_y^{-n} : B(x, 2r) \to \mathbb{C}$ sending x to y is well-defined.

Suppose first that (X, f) is real-analytic. (We could deduce this case from the general case but we separate it as simpler.) Take an atlas of real analytic maps (charts) $\phi_j : \Gamma_j \to \mathbb{R}$ for Γ_j the components of Γ; they extend complex-analytically to a neighbourhood of Γ in $\overline{\mathbb{C}}$. (if Γ_j is a closed curve we can use Arg)

For $x \in \Gamma_j \cap J(f)$ we write $\Gamma_{j(x)}$ and $\phi_{j(x)}$. For all $k \geq 1$ and all $y \in f^{-k}(x)$ consider for all $z \in \Gamma_j(x) \cap B(x, r)$ for r small enough, the positive real-analytic function on $\phi_{j(x)}(B(x, r))$, for

$$|(f_y^{-k})'(\phi_{j(x)}^{-1}(z))|$$

Consider the following sequence of complex analytic functions on $z \in \phi_{j(x)}(B(x, r))$

$$g_n(z) = \sum_{y \in f^{-n}(x)} \left((f_y^{-n})'(\phi_{j(x)}^{-1}(z)) \right)^t \exp(-nP(t)),$$

where $P(t) = P(f|_X, -t \log|f'|)$ denotes the pressure.

There is no problem here with raising to the t-th power since $B(x, r)$, the domain of all $|(f_y^{-n})'|$ is simply connected. Since the latter functions are positive in $\mathbb{R}$, we can choose the branches of the t-th powers to be also positive in $\mathbb{R}$. By Koebe Distortion Lemma (or Bounded Distortion for Iteration Lemma 5.2.2) for r small enough and every $w = B' := \phi_{j(x)}^{-1}(z) \in B(x, r)$, every $n \geq 1$ and every $y \in f^{-n}(x)$ we have $|(f_y^{-n})'(w)| \leq K|(f_y^{-n})'(x)|$. Hence $|g_n(z)| \leq Kg_n(x)$. Since, by (4.4.2) with $u \equiv 1$ and $c = P(t)$, the sequence $g_n(x)$ converges, we see that the functions $\{g_n|_{B'}\}_{n \geq 1}$ are uniformly bounded. So they form a normal family in the sense of Montel, hence we can choose a convergent subsequence g_{n_j}. Since $g_n(z)$ converges to the $u \circ \phi_{j(x)}^{-1}(z)$ for all $z \in X \cap B'$, it follows that the $g_{n_j} \circ \phi_{j(x)}$ converges to a complex-analytic function on $B(x, r)$ extending u.

Let us pass now to the proof of the first part of this proposition. That is, we relax the X-th real analyticity assumption and we want to construct a real-analytic real-valued extension of u to a neighbourhood of X in $\mathbb{C}$. Our strategy

is to work in $\mathbb{C}^2$, to use an appropriate version of Montel's theorem and, in general, to proceed similarly as in the first part of the proof. So, fix $v \in X$. Identify now $\mathbb{C}$, where our f acts, to $\mathbb{R}^2$ with coordinates x, y, the real and complex part of z. Embed this into $\mathbb{C}^2$ with x, y complex. Denote the above $\mathbb{C} = \mathbb{R}^2$ by $\mathbb{C}_0$. We may assume that $v = 0$ in $\mathbb{C}_0$. Given $k \geq 0$ and $v_k \in f^{-k}(v)$ define the function $\rho_{v_k} : B_{\mathbb{C}_0}(0, 2r) \to \mathbb{C}$ (the ball in $\mathbb{C}_0$) by setting

$$\rho_{v_k}(z) = \frac{(f_{v_k}^{-k})'(z)}{(f_{v_k}^{-k})'(0)},$$

Since $B_{\mathbb{C}_0}(0, 2r) \subset \mathbb{C}_0$ is simply connected and ρ_{v_n} nowhere vanishes, all the branches of logarithm $\log \rho_{v_n}$ are well defined on $B_{\mathbb{C}_0}(0, 2r)$. Choose this branch that maps 0 to 0 and denote it also by $\log \rho_{v_n}$. By Koebe's Distortion Theorem $|\rho_{v_k}|$ and $|\operatorname{Arg} \rho_{v_k}|$ are bounded on $B(0, r)$ by universal constants K_1, K_2 respectively. Hence $|\log \rho_{v_k}| \leq K = (\log K_1) + K_2$. We write

$$\log \rho_{v_k} = \sum_{m=0}^{\infty} a_m z^m$$

and note that by Cauchy's inequalities

$$|a_m| \leq K/r^m. \tag{5.3.1}$$

We can write for $z = x + iy$ in $\mathbb{C}_0$

$$\operatorname{Re} \log \rho_{v_k} = \operatorname{Re} \sum_{m=0}^{\infty} a_m (x+iy)^m = \sum_{p,q=0}^{\infty} \operatorname{Re}\left(a_{p+q}\binom{p+q}{q}i^q\right)x^p y^q := \sum c_{p,q} x^p y^q.$$

In view of (5.3.1), we can estimate $|c_{p,q}| \leq |a_{p+q}|2^{p+q} \leq Kr^{-(p+q)}2^{p+q}$. Hence $\operatorname{Re} \log \rho_{v_k}$ extends, by the same power series expansion $\sum c_{p,q} x^p y^q$, to the polydisc $D_{\mathbb{C}^2}(0, r/2)$ and its absolute value is bounded there from above by K. Now for every $k \geq 0$ consider a real-analytic function b_k on $B_{\mathbb{C}_0}(0, 2r)$ by setting

$$b_k(z) = \sum_{v_k \in f^{-k}(0)} |(f_{v_k}^{-k})'(z)|^t \exp(-kP(t)).$$

By (4.4.2) the sequence $b_k(0)$ is bounded from above by a constant L. Each function b_k extends to the function

$$B_k(z) = \sum_{v_k \in f^{-k}(0)} |(f_{v_k}^{-k})'(0)|^t \, e^{t \operatorname{Re} \log \rho_{v_k}(z)} \exp(-kP(t)).$$

whose domain, similarly as the domains of the functions $\operatorname{Re} \log \rho_{v_k}$, contains the polydisc $D_{\mathbb{C}^2}(0, r/2)$. Finally we get for all $k \geq 0$ and all $z \in D_{\mathbb{C}^2}(0, r/2)$

$$|B_k(z)| = \sum_{v_k \in f^{-k}(0)} |(f_{v_k}^{-k})'(0)|^t \, e^{\operatorname{Re}(t \operatorname{Re} \log \rho_{v_k}(z))} \exp(-kP(t))$$

$$\leq \sum_{v_k \in f^{-k}(0)} |(f_{v_k}^{-k})'(0)|^t \, e^{t|\operatorname{Re} \log \rho_{v_k}(z)|} \exp(-kP(t))$$

$$\leq e^{Kt} \sum_{v_k \in f^{-k}(0)} |(f_{v_k}^{-k})'(0)|^t \exp(-kP(t)) \leq e^{Kt} L.$$

Now by Cauchy's integral formula (in $D_{\mathbb{C}^2}(0, r/2)$) for the second derivatives we prove that the family B_n is equicontinuous on, say, $D_{\mathbb{C}^2}(0, r/3)$. Hence we can choose a uniformly convergent subsequence and the limit function G is complex analytic and extends u on $X \cap B(0, r/3)$, by (4.4.2). Thus we have proved that u extends to a complex analytic function in a neighbourhood of every $v \in X$ in $\mathbb{C}^2$, i.e. real analytic in $\mathbb{C}_0$. These extensions coincide on the intersections of the neighbourhoods, otherwise X is real analytic and we are in the case considered at the beginning of the proof. see Chapter 9, Lemma 9.1.4 for more details ♣

In Theorem 5.3.2 we wanted to be concrete and considered the potential function $-t \log |f'|$ (normalized). In fact we proved the following more general theorem

Theorem 5.3.3. *If $f : X \to X$ is an orientation preserving conformal expanding repeller, $X \subset C$ and ϕ is a real-valued function on X which extends to a harmonic function on a neighbourhood of X in $\overline{\mathbb{C}}$, then $u_\phi = d\mu_\phi/dm_\phi$ has a real-analytic real-valued extension on a neighbourhood of X in $\mathbb{C}$.*

Proof. We can assume that pressure $P(f, \phi) = 0$. As in the previous proof choose $0 \in X$ Assume that r is small enough that all $v_k \in f^{-k}(0)$ and all $k = 1, 2, \ldots$ all the branches f^{-k} on $B(0, r)$ and the compositions $\phi \circ f^{-k}$ exist and are bounded by a constant $K > 0$. They are harmonic as the compositions of holomorphic functions with harmonic ϕ. We have

$$b_k(z) = \sum_{v_k \in f^{-k}(0)} e^{S_k(\phi)(z)} \leq e^{2K} \sum_{v_k \in f^{-k}(0)} e^{S_k(\phi(0))} \leq e^{2K} L,$$

where $L = \sup_k \mathcal{L}_\phi{}^k(\mathbb{1})(0)$. We have used the estimate (5.3.1) for harmonic functions $u_{v_k} = S_k(\phi)(z) - S_k(\phi)(0) = \sum_{m=0}^{\infty} a_m z^m$, where for each v_k we define $S_k(\phi)(z) = \sum_{i=0}^{k-1} \phi(f^i(f_{v_k}^{-k}(z))$.

This version of (5.3.1) follows from Poisson formula for harmonic functions u_{v_k}, which are uniformly bounded on $B(0, r)$ due to the uniform exponential convergence to 0 of $|f^{-i}(0) - f^{-k}(z)|$ as $i \to \infty$. See for example Harnack inequalities in [Hayman & Kennedy 1976, Section 1.5.6 Example 2].   ♣

Remark 5.3.4. Proofs of Theorem 5.3.2 and Theorem 5.3.3 are the same. In Theorem 5.3.2 we explicitly write complex analytic power series extension in $\mathbb{C}^2$ of $\log |(f^{-k})'|$, whereas in Theorem 5.3.3 we observe that a general harmonic function is real-analytic and discuss in particular its domain in complex extension. For a more precise description of domains of complex extensions of harmonic functions (in any dimension) see [Hayman & Kennedy 1976, Section 1.5.3]; more references are provided there.

Remark 5.3.5. A version of Theorem 5.3.3 holds in the real case (say if X is in a finite union of pairwise disjoint circles and straight lines), with finite smoothness.

Namely, if we assume the potential ϕ is $C^{r+\varepsilon}$ for $r \geq 1, 0 \leq \varepsilon \leq 1$ and $r + \varepsilon > 1$, then for m the density u_ϕ of the invariant Gibbs measure μ_ϕ with respect to the eigenmeasure m_ϕ of $\mathcal{L}$, see the beginning of this Section, is $C^{r+\varepsilon}$.

For a sketch of the proof see Chapter 6, Section 6.4 and Exercise 6.5. See also [Boyarsky & Góra 1997].

5.4   Analytic dependence of transfer operator on potential function

In this section we prove a fundamental theorem about analytic dependence of transfer operators on real Hölder potentials and then we derive some consequences concerning analytic dependence of pressure with respect to potential and conformal expanding map (repeller) depending analytically on a parameter. We will apply Mañé, Sad, Sullivan's $\lambda-$lemma, see Section 5.2. In Chapter 8 we will deduce analytic dependence of Hausdorff dimension of a conformal expanding repeller, on parameter.

Let T be a continuous open topologically mixing distance expanding map on a compact metric space (X, ρ), cf. Chapters 3 and 4. For every point $x \in X$ define $\mathcal{H}_{\beta;x}$ to be the Banach space of complex valued Hölder continuous functions with exponent β, whose domain is the ball $B(x, \delta)$ with $\delta > 0$ so small that all the inverse branches of T are well defined on $B(x, \delta)$, for example $\delta \leq \xi$ in Section 3.1. The Hölder variation ϑ_β and the Hölder norm $|| \cdot ||_\beta = || \cdot ||_{\mathcal{H}_\beta}$ are defined in the standard way, see Chapter 3.

Let $L(F)$ and $L(F_1, F_2)$ denote the spaces of continuous linear operators from F to itself or from F_1 to F_2 respectively, for F, F_1, F_2 Banach spaces.

For every function $\Phi : G \to L(\mathcal{H}_\beta)$ and every $x \in X$ define the function $F_x : G \to L(\mathcal{H}_\beta, \mathcal{H}_{\beta;x})$ by the formula

$$\Phi_x(\lambda)(\psi) = \Phi(\lambda)(\psi)|_{B(x,\delta)}.$$

Sometimes we write $\Phi(\lambda)_x$.

We start with the following.

Lemma 5.4.1. *Let G be an open subset of a complex plane $\mathbb{C}$ and fix a function $\Phi : G \to L(\mathcal{H}_\beta)$. If for every $x \in X$ the function $\Phi_x : G \to L(\mathcal{H}_\beta, \mathcal{H}_{\beta;x})$ is complex analytic and $\sup\{||\Phi_x(\lambda)||_\beta : x \in X : \lambda \in G\} < +\infty$, then the function $\Phi : G \to L(\mathcal{H}_\beta)$ is complex analytic.*

Proof. Fix $\lambda^0 \in G$ and take $r > 0$ so small that the disc centered at λ^0 of radius r, $D(\lambda^0, r)$, is contained in G. Then for each $x \in X$

$$\Phi_x(\lambda) = \sum_{n=0}^{\infty} a_{x,n}(\lambda - \lambda^0)^n \quad \lambda \in D(\lambda^0, r).$$

with some $a_{x,n} \in L(\mathcal{H}_\beta, \mathcal{H}_{\beta;x})$, convergence in the operators norm.

Put $M = \sup\{||\Phi_x(\lambda)||_\beta : x \in X : \lambda \in G\} < +\infty$. It follows from Cauchy's inequalities that

$$||a_{x,n}||_\beta \le Mr^{-n}. \tag{5.4.1}$$

Now for every $n \ge 0$ define the operator a_n by

$$a_n(\phi)(z) = a_{z,n}(\phi)(z), \quad \phi \in \mathcal{H}_\beta, \ z \in X.$$

Then

$$||a_n(\phi)||_\infty \le ||a_{z,n}||_\infty ||\phi||_\infty \le ||a_{z,n}||_\beta ||\phi||_\beta. \tag{5.4.2}$$

Now, if $|z - x| < \delta$, then for every $\phi \in \mathcal{H}_\beta$ and every $w \in D(x,\delta) \cap D(z,\delta)$,

$$\sum_{n=0}^{\infty} a_{x,n}(\phi)(w)(\lambda - \lambda^0)^n = (\Phi_x(\lambda)(\phi))(w) = (\Phi(\lambda)(\phi))(w) = (\Phi_z(\lambda)(\phi))(w)$$

$$= \sum_{n=0}^{\infty} a_{z,n}(\phi)(w)(\lambda - \lambda^0)^n$$

for all $\lambda \in D(\lambda^0, r)$. The uniqueness of coefficients of Taylor series expansion implies that for all $n \ge 0$,

$$a_{x,n}(\phi)(w) = a_{z,n}(\phi)(w).$$

Since $x, z \in D(x,\delta) \cap D(z,\delta)$, we thus get, using (5.4.1),

$$|a_n(\phi)(z) - a_n(\phi)(x)| = |a_{z,n}(\phi)(z) - a_{x,n}(\phi)(x)| = |a_{x,n}(\phi)(z) - a_{x,n}(\phi)(x)|$$

$$\le ||a_{x,n}(\phi)||_\beta |x - z|^\beta \le ||a_{x,n}||_\beta ||\phi||_\beta |x - z|^\beta$$

$$\le Mr^{-n} ||\phi||_\beta |x - z|^\beta.$$

Consequently, $\vartheta_\beta(a_n(\phi)) \le Mr^{-n} ||\phi||_\beta$. Combining this with (v5.4a.2), we obtain $||a_n(\phi)||_\beta \le 2Mr^{-n} ||\phi||_\beta$. Thus $a_n \in L(\mathcal{H}_\beta)$ and $||a_n||_\beta \le 2Mr^{-n}$. Thus the series

$$\sum_{n=0}^{\infty} a_n(\lambda - \lambda^0)^n$$

converges absolutely uniformly on $D(\lambda^0, r/2)$ and $|| \sum_{n=0}^{\infty} a_n(\lambda - \lambda^0)^n ||_\beta \le 2M$ for all $\lambda \in D(\lambda^0, r/2)$. Finally, for every $\phi \in \mathcal{H}_\beta$ and every $z \in X$,

$$\Big(\sum_{n=0}^{\infty} a_n(\lambda - \lambda^0)^n \Big)(\phi)(z) = \sum_{n=0}^{\infty} a_n(\phi)(z)(\lambda - \lambda^0)^n = \sum_{n=0}^{\infty} a_{z,n}(\phi)(z)(\lambda - \lambda^0)^n$$

$$= \Big(\sum_{n=0}^{\infty} a_{z,n}(\lambda - \lambda^0)^n \Big)(\phi)(z) = \Phi_z(\lambda)(\phi)(z)$$

$$= (\Phi(\lambda)\phi)(z).$$

So, $\Phi(\lambda)(\phi) = \Big(\sum_{n=0}^{\infty} a_n(\lambda - \lambda^0)^n \Big)(\phi)$ for all $\phi \in \mathcal{H}_\beta$, and consequently, $\Phi(\lambda) = \sum_{n=0}^{\infty} a_n(\lambda - \lambda^0)^n$, $\lambda \in D(\lambda^0, r/2)$. We are done. ♣

The main technical result of this section concerns the analytic dependence of transfer operator $\mathcal{L}_{\phi_\lambda}$, on parameter λ, is the following

Theorem 5.4.2. *Suppose that G is an open subset of the complex space $\mathbb{C}^d$ with some $d \geq 1$. If for every $\lambda \in G$, $\phi_\lambda : X \to \mathbb{C}$ is a β-Hölder complex valued potential, $H = \sup\{||\phi_\lambda||_\beta : \lambda \in G\} < \infty$, and for every $z \in X$ the function $\lambda \mapsto \phi_\lambda(z)$, $\lambda \in G$, is holomorphic, then the map $\lambda \mapsto \mathcal{L}_{\phi_\lambda} \in L(\mathcal{H}_\beta)$, $\lambda \in G$, is holomorphic.*

Proof. We have for all $\lambda \in G$ and all $v \in X$ that

$$|| \exp(\phi_\lambda \circ T_v^{-1})||_\infty \leq e^H, \tag{5.4.3}$$

where T_v^{-1} is the branch of T^{-1} on $B(T(v), \delta)$ mapping $T(v)$ to v, compare notation in Section 3.1. In virtue of Hartogs Theorem in order to prove our theorem, we may assume without loss of generality that $d = 1$, i.e. $G \subset \mathbb{C}$. Now fix $\lambda^0 \in G$ and take a radius $r > 0$ so small that $\overline{B}(\lambda^0, r) \subset G$. By our assumptions the function $\lambda \mapsto \exp(\phi_\lambda \circ T_v^{-1}(z))$ is holomorphic for every $z \in B(T(v), \delta)$. Consider its Taylor series expansion

$$\exp(\phi_\lambda \circ T_v^{-1}(z)) = \sum_{n=0}^{\infty} a_{v,n}(z)(\lambda - \lambda^0)^n, \quad \lambda \in B(\lambda^0, r).$$

In view of Cauchy's inequalities and (5.4.3) we get

$$|a_{v,n}(z)| \leq e^H r^{-n}, \tag{5.4.4}$$

and, for $w, z \in B(T(v), \delta)$, using also Cauchy's inequalities,

$$|a_{v,n}(w) - a_{v,n}(z)| \leq r^{-n} \sup_{\lambda \in G} | \exp(\phi_\lambda \circ T_v^{-1}(w)) - \exp(\phi_\lambda \circ T_v^{-1}(z))|$$

$$\leq \hat{c} r^{-n}|w - z|^\beta, \tag{5.4.5}$$

where $\hat{c}$ is a constant depending only on T and H. Take an arbitrary $\phi \in \mathcal{H}_\beta$ and consider the product $a_{v,n}(z) \cdot \phi(T_v^{-1}(z))$. In view of (5.4.4) and (5.4.5), we obtain

$$|a_{v,n}(w)\phi(T_v^{-1}(w)) - a_{v,n}(z)\phi(T_v^{-1}(z))| \leq$$

$$\leq |a_{v,n}(w) - a_{v,n}(z)| \cdot ||\phi||_\infty + |a_{v,n}(z)| \cdot ||\phi||_\beta L^\beta |w - z|^\beta$$

$$\leq r^{-n}(\hat{c} + e^H L^\beta)||\phi||_\beta |w - z|^\beta$$

$$= \hat{c}_1 r^{-n}||\phi||_\beta |w - z|^\beta,$$

where $\hat{c}_1 = \hat{c}(1 + L^\beta)$ and L is a common Lipschitz constant for all branches T_v^{-1} coming from the expanding property. Combining this and (5.4.4) we conclude that the formula $N_{v,n}\phi(z) = a_{v,n}(z)\phi(T_v^{-1}(z))$ defines a bounded linear operator $N_{v,n} : \mathcal{H}_\beta \to \mathcal{H}_{\beta;x}$, where $x = T(v)$, and

$$||N_{v,n}||_\beta \leq (e^H + \hat{c}_1)r^{-n}.$$

Consequently the function $\lambda \mapsto N_{v,n}(\lambda - \lambda^0)^n$, $\lambda \in B(\lambda^0, r/2)$, is analytic and $||N_{v,n}(\lambda - \lambda^0)^n||_\beta \leq 2^{-n}(e^H + \hat{c}_1)$. Thus the series

$$A_{\lambda,v} = \sum_{n=0}^{\infty} N_{v,n}(\lambda - \lambda^0)^n, \ \lambda \in D(\lambda^0, r/2),$$

converges absolutely uniformly in the Banach space $L(\mathcal{H}_\beta, \mathcal{H}_{\beta,x})$, $||A_{\lambda,v}||_\beta \leq 2(e^H + \hat{c}_1)$ and the function $\lambda \mapsto A_{\lambda,v} \in L(\mathcal{H}_\beta, \mathcal{H}_{\beta;x})$, $\lambda \in B(\lambda^0, r/2)$, is analytic. Hence, $\mathcal{L}_{\lambda,x} = \sum_{v \in f^{-1}(x)} A_{\lambda,v} \in L(\mathcal{H}_\beta, \mathcal{H}_{\beta;x})$,

$$||\mathcal{L}_{\lambda,x}||_\beta \leq 2N(T)(e^H + \hat{c}_1),$$

where $N(T)$ is the number of preimages of a point in X, and the function $\lambda \mapsto \mathcal{L}_{\lambda,x}$, $\lambda \in D(\lambda^0, r/2)$, is analytic. Since $\mathcal{L}_{\lambda,x} = (\mathcal{L}_{\phi_\lambda})_x$, invoking Lemma 5.4.1 concludes the proof.   ♣

Now consider an expanding conformal repeller (X, f, U), in $\overline{\mathbb{C}}$, $f : U \to \overline{\mathbb{C}}$ conformal, preserving X, $T = f|_X$, and holomorphic perturbations $f_\lambda : U \to \overline{\mathbb{C}}$, $\lambda \in \Lambda$, where Λ is an open subset of $\mathbb{C}^d$, $f_{\lambda_0} = f$ for some $\lambda_0 \in \Lambda$. Let $i_\lambda : X \to X_\lambda$ be the corresponding holomorphic motion coming from Lemma 5.2.8 and Remark 5.2.9 ($d > 1$ does not cause problems).

Our goal is to prove that the pressure function $(\lambda, t) \mapsto \mathrm{P}(\lambda, t) = \mathrm{P}(f_\lambda, -t \log |f'_\lambda|) \in \mathbb{R}$ for $t \in \mathbb{R}$, is real-analytic. The idea is to consider potentials $\phi_{\lambda,t} = -t \log |f'_\lambda| \circ i_\lambda : X \to \mathbb{R}$, $(\lambda, t) \in \Lambda \times \mathbb{R}$, to embed them into a holomorphic family to satisfy the assumptions of Theorem 5.4.2 and then to use Kato's theorem for perturbations of linear operators. Indeed, by Lemma 5.2.8, for every $z \in X$, the function $\lambda \mapsto \Psi_z(\lambda) = \log |f'_\lambda(i_\lambda(z))| - \log |f'(z)|$ is harmonic on Λ and $\Psi_z(\lambda_0) = 0$. Fix $r > 0$ so small that $B(\lambda_0, 2r) \subset \Lambda$. Then

$$M = \sup\{|\Psi_z| : (z, \lambda) \in X \times B(\lambda_0, r)\} < +\infty.$$

So, each function Ψ_z extends holomorphically to $\lambda \in B_{\mathbb{C}^{2d}}(\lambda_0, r/2)$, we will use the same symbol Ψ_z for this extension, and

$$M_1 = \sup\{|\Psi_z(\lambda)| : (z, \lambda) \in X \times B_{\mathbb{C}^{2d}}(\lambda_0, r/2)\} < +\infty.$$

Since all the functions i_λ, $\lambda \in B(\lambda_0, r)$, are Hölder continuous with a common Hölder exponent, say β, and common Hölder norm for the exponent β, see Proposition 5.1.7 or Remark 5.2.10, an easy application of Cauchy inequalities gives that for all $\lambda \in B_{\mathbb{C}^{2d}}(\lambda_0, r/2)$ the function $z \mapsto \Psi_z(\lambda)$ is Hölder continuous with the exponent β and the corresponding Hölder norms are uniformly bounded, say by M_2. Thus the potentials

$$\phi_{\lambda,t}(z) = -t\Psi_z(\lambda) + t \log |f'(z)|, \ (\lambda, t) \in B_{\mathbb{C}^{2d}}(\lambda_0, r/2) \times U,$$

for any bounded $U \subset \mathbb{C}$, satisfy the assumptions of Theorem 5.4.2 and for all $(\lambda, t) \in B(\lambda_0, r/2) \times \mathbb{R}$, we have $\phi_{\lambda,t} = -t \log |f'_\lambda \circ i_\lambda|$. As an immediate application of this theorem, we get the following.

Lemma 5.4.3. *The function*

$$(\lambda, t) \mapsto \mathcal{L}_{\phi_{\lambda,t}} \in L(\mathcal{H}_\beta), \ (\lambda, t) \in B_{\mathbb{C}^{2d}}(\lambda_0, r/2) \times \mathbb{C},$$

is holomorphic.

Since for all $(\lambda, t) \in B(\lambda_0, r/2) \times \mathbb{R}$, $\exp(\mathrm{P}(\lambda, t)$ is a simple isolated eigenvalue of $\mathcal{L}_{\phi_{\lambda,t}} \in L(\mathcal{H}_\beta)$ depending continuously on (λ, t), it follows from Lemma 5.4.3 and Kato's perturbation theorem for linear operators that there exists a holomorphic function $\gamma : B_{\mathbb{C}^{2d}}(\lambda_0, R) \times \mathbb{C} \to \mathbb{C}$ ($R \in (0, r/2]$ sufficiently small) such that $\gamma(\lambda, t)$ is an eigenvalue of the operator $\mathcal{L}_{\phi_{\lambda,t}}$ for all $(\lambda, t) \in B_{\mathbb{C}^{2d}}(\lambda_0, R) \times \mathbb{C}$ and $\gamma(\lambda, t) = \exp(\mathrm{P}(\lambda, t))$ for all $(\lambda, t) \in B(\lambda_0, R) \times \mathbb{R}$. Consequently, the function $(\lambda, t) \mapsto \mathrm{P}(\lambda, t)$, $(\lambda, t) \in B(\lambda_0, R) \times \mathbb{R}$, is real-analytic, and as real analyticity is a local property, we finally get the following.

Theorem 5.4.4. *The pressure function* $(\lambda, t) \mapsto \mathrm{P}(f_\lambda, -t \log |f'_\lambda|)$, $t \in \mathbb{R}$, *is real-analytic.*

Bibliographical notes

Lemma 5.1.2 and Proposition 5.1.3 establishing the equivalence of various properties of being a repeller for an expanding set, correspond to the equivalence for hyperbolic subsets of properties "local product structure", being "isolated" and "unstable set" being union of unstable manifolds of "individual trajectories", see [Katok & Hasselblatt 1995, Section 18.4]. For the theory of hyperbolic endomorphisms, in particular in the inverse limit (backward trajectories) language, as in Remark 5.1.4, see [Przytycki 1976] and [Przytycki 1977]. In [Przytycki 1977] some examples of Axiom A endomorphisms, whose basic sets are expanding repellers, are discussed. The example 5.1.9 was studied by M. Denker and S.-M. Heinemann in [Denker & Heinemann 1998]. For Section 5.4 compare [Mauldin & Urbanski 2003, Section 2.6.]. Theorem 5.4.4 holds in a setting more general than expanding, see Section 11.5, [Stratmann & Urbanski 2003] and [Przytycki & Rivera-Letelier 2008].

Chapter 6

Cantor repellers in the line, Sullivan's scaling function, application in Feigenbaum universality

The aim of this Chapter is to study thoroughly Cantor sets in the line with expanding maps on them. After very general previous chapters we want for a while to concentrate on the real one-dimensional situation, i.e. fractals in the line. Starting from Chapter 8 we shall mainly work with the one-dimensional complex case (conformal fractals) the main aim of this book. Some consideration from this Section will be continued, including the complex case, in Chapter 9.

In Section 6.1 we supply a 1-sided shift space Σ^d (see Chapter 0 with ambient real one-dimensional differentiable structures, basically $C^{1+\varepsilon}$, (Hölder continuous differentials). In Section 6.2 we ask when the shift map extends $C^{1+\varepsilon}$ to a neighbourhood of the Cantor set being an embedding of Σ^d into a real line. In case it does, we have a $C^{1+\varepsilon}$ expanding repeller, see the definition at the beginning of Chapter 5. There a scaling function appears, which is a complete geometric invariant for the $C^{1+\varepsilon}$-equivalence (conjugacy). It happens that scaling functions classify also $C^{r+\varepsilon}$ equivalence classes for $C^{r+\varepsilon}$ Cantor expanding repellers, for all $r = 1, 2, \ldots, \infty$, $0 \le \varepsilon \le 1, r + \varepsilon > 1$ and for the real-analytic case. Section 6.3 is devoted to that (for $\varepsilon > 0$, for $\varepsilon = 0$ see Section 6.4). However scaling functions "see" the smoothness of the Cantor repeller, namely the smoother the differentiable structure the less scaling functions can occur, see examples at the end of Section 6.2 and Section 6.4.

In Section 6.5 we define so-called generating families of expanding maps. It is a bridge towards Section 6.6, where Feigenbaum's universality, concerning the geometry of the Cantor set being the closure of the forward trajectory of the critical point of the quadratic-like map of the interval will be discussed.

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While the proofs in Sections 6.1–6.5 are written very detaily, Section 6.6 has a sketchy character. We do not involve much in the theory of iterations of maps of the interval. We refer the reader to [Collet & Eckmann 1980] and [de Melo & van Strien 1993].

For the universality see [Sullivan 1991] and [McMullen 1996], where the key theorem towards this, namely the exponential convergence of renormalizations has been proved, with the use of complex methods. (For more references see Notes at the end of this Chapter.)

In section 6.6 we just show how the exponential convergence yields the $C^{1+\varepsilon}$ equivalence of Cantor sets being closures of postcritical sets.

Most of this Chapter is written on the basis of Dennis Sullivan's paper [Sullivan 1988], completed by the paper by F. Przytycki and V. Tangerman [Przytycki & Tangerman 1996] .

6.1 $C^{1+\varepsilon}$-equivalence

For simplicity we shall consider here only the class $\mathcal{H}$ of homeomorphic embeddings of Σ^d into unit interval $[0,1] \subset \mathbb{R}$ such that the order is preserved, i.e. for $h : \Sigma^d \to \mathbb{R}$ if $\alpha = (\alpha_0, \alpha_1, \dots), \beta = (\beta_0, \beta_1, \dots) \in \Sigma^d$, $\alpha_j = \beta_j$ for all $j < n$ and $\alpha_n < \beta_n$ then $h(\alpha) < h(\beta)$. In Section 6.5 we need to consider more general situations but the basic facts stay precisely the same.

Consider an arbitrary $h \in \mathcal{H}$. For every $j_0, j_1, \dots, j_n \in \{1, \dots, d\}, n > 0$ denote by $I_{j_0,\dots,j_n}$ the closed interval with ends $h((j_0, j_1, \dots, j_n, 1, 1, 1, \dots))$ and $h((j_0, j_1, \dots, j_n, d, d, d, \dots))$. The interval $[h((1, 1, \dots)), h((d, d, \dots))]$ will be denoted by I. For $j_n < d$ denote by $G_{j_0,\dots,j_n}$ the open interval with the ends $h((j_0, j_1, \dots, j_n, d, d, d, \dots))$ and $h((j_0, j_1, \dots, j_n+1, 1, 1, 1, \dots))$, the letters G stand for gaps here because of the disjointness with $h(\Sigma^d)$. Denote $E_n = \bigcup_{(j_0,\dots,j_n)} I_{j_0,\dots,j_n}$. We see that $h(\Sigma^d)$ is a Cantor set $\bigcap_{n=0}^{\infty} E_n$.

Definition 6.1.1. Given $h \in \mathcal{H}$ and $w = (j_0, j_1, \dots, j_n)$ where each $j_t \in \{1, \dots, d\}$ we call the sequence of numbers $A_j(h, w) := \frac{|I_{w, \frac{j+1}{2}}|}{|I_w|}$ for j odd, $A_j(h, w) := \frac{|G_{w, \frac{j}{2}}|}{|I_w|}$ for j even, $j = 1, \dots, 2d-1$, the *ratio geometry* of w, ($|\cdot|$ denote lengths here). The ratio geometry is the function $w \mapsto (A_j(h, w), j = 1, \dots 2d-1)$.

Definition 6.1.2. We say $h \in \mathcal{H}$ has *bounded geometry* if the ratios $A_j(h, w)$ are uniformly, for all w, j, bounded away from zero. We denote the space of h's from $\mathcal{H}$ with the bounded geometry by $\mathcal{H}$b. We say $h \in \mathcal{H}$ has *exponential geometry* if $|I_{j_0,\dots,j_n}|$ converge to 0 uniformly exponentially fast in n and not faster. We denote the space of h's from $\mathcal{H}$ with the exponential geometry by $\mathcal{H}$e. Observe that $\mathcal{H}$e $\supset \mathcal{H}$b.

Definition 6.1.3. Given $h_1, h_2 \in \mathcal{H}$ we say they have *equivalent geometries* if $\frac{A_j(h_1, w)}{A_j(h_2, w)}$ converge to 1 uniformly in length of w. We say h_1, h_2 have *exponentially*

equivalent geometries if the convergence is exponentially fast with the length of w.

One can easily check that the exponential geometry is the property of the geometric equivalence classes and that the bounded geometry property is the property of the exponentially equivalent geometry classes.

Definition 6.1.4. We say that $h_1, h_2 \in \mathcal{H}$ are $C^{1+\varepsilon}$-equivalent if there exists an increasing $C^{1+\varepsilon}$-diffeomorphism ϕ of a neighbourhood of $h_1(\Sigma^d)$ to a neighbourhood of $h_2(\Sigma^d)$ such that $\phi|_{h_1(\Sigma^d)} \circ h_1 = h_2$. We call $\phi|_{h_1(\Sigma^d)}$ the *canonical conjugacy*, as it is uniquely determined by h_1 and h_2. So $C^{r+\varepsilon}$ means that the canonical conjugacy extends $C^{r+\varepsilon}$.

Each class of equivalence will be called a $C^{1+\varepsilon}$-structure for Σ^d. These definitions are valid also for $C^{1+\varepsilon}$ replaced by $C^{r+\varepsilon}$ for every $r = 0, 1, \ldots, \infty, \omega, 0 \leq \varepsilon \leq 1$. For $\varepsilon = 0$ this means the continuity of the r-th derivative (however, we shall usually assume $\varepsilon > 0$), for $0 < \varepsilon < 1$ its Hölder continuity, for $\varepsilon = 1$ Lipschitz continuity. ω means real-analytic.

Proposition 6.1.5. *Let $h_1, h_2 \in \mathcal{H}$. Then if they are C^1-equivalent, they have equivalent geometries.*

We leave a simple proof to the reader. Also the following holds

Theorem 6.1.6. *Let $h_1, h_2 \in \mathcal{H}e$. Then h_1, h_2 are $C^{1+\varepsilon}$-equivalent for some $\varepsilon > 0$ if and only if h_1 and h_2 have exponentially equivalent geometries.*

Proof. We shall use the fact that a real function ϕ is $C^{1+\varepsilon}$-smooth if and only if there exists a constant $C > 0$ such that for every $x < y < z$

$$\frac{\phi(y) - \phi(x)}{y - x} - \frac{\phi(z) - \phi(y)}{z - y} < C(z - x)^\varepsilon \tag{6.1.1}$$

(this is an easy calculus exercise).

Suppose there exists a diffeomorphism ϕ as in the definition of the equivalence. As ϕ is a diffeomorphism we can write (6.1.1) for it in a multiplicative form and obtain for each $w = (j_1, j_2, \ldots, j_n)$ and $j = 1, \ldots, d$ and intervals for h_1

$$\left| \frac{|\phi(I_{wj})|}{|I_{wj}|} \Big/ \frac{|\phi(I_w)|}{|I_w|} - 1 \right| < \text{Const} \, |I_w|^\varepsilon \tag{6.1.2}$$

and the analogous inequalities for the gaps. Changing order in this bifraction we obtain $\frac{A_j(h_1, w)}{A_j(h_2, w)}$ converging to 1 exponentially fast with n, the length of w. We have used here the assumption $h_1 \in \mathcal{H}e$ to get $|I_w| \leq \exp{-\delta n}$ for some $\delta > 0$. Thus we proved the Theorem to one side. Using Sullivan's words we proved that the ratio geometry is determined exponentially fast in length of w by the $C^{1+\varepsilon}$-structure.

Now we shall prove Theorem to the other side. Let us fix first some notation. For every $m \geq 0$ denote by $\mathcal{G}^m$ the set of all intervals $I_{j_0, j_1, \ldots, j_m}$ and $G_{j_0, j_1, \ldots, j_m}$.

We must extend the mapping $h_2 \circ h_1^{-1} : h_1(\Sigma^d) \to h_2(\Sigma^d$ to a mapping ϕ on all the gaps G_w for h_1. (We could use Whitney Extension Theorem, see Remark 6.1.7, but we will give a direct proof)). The extension will be denoted by ϕ. For each two points $u < v$ on which ϕ is already defined we denote $\frac{\phi(v)-\phi(u)}{v-u}$ by $R(u,v)$. We shall use also the notation $R(J)$ if u, v are ends of an interval J.

Given $G_{j_0,j_1,\ldots,j_n}$ with the ends $a < b$ we want to have the derivatives

$$\phi'(a) = \lim_{m\to\infty} R(J_m(a)), \qquad \phi'(b) = \lim_{m\to\infty} R(J_m(b)) \qquad (6.1.3)$$

where $J_m(a), J_m(b) \in \mathcal{G}^m, m \geq n$, all $J_m(a)$ have the right end a and all $J_m(b)$ have the left end b.

It is easy to see that the limits exist are uniformly bounded and uniformly bounded away from 0 for all G's. This follows from the following distortion estimate (compare Section 5.2):

For every $j_0, \ldots, j_m$ if $J \subset I_{j_0,\ldots,j_m} = I$ and $J \in \mathcal{G}^k, k > m$ then

$$\left| \frac{R(J)}{R(I)} - 1 \right| \leq \mathrm{Const}\, \exp{-m\delta} \qquad (6.1.4)$$

Here δ is the exponent of the assumed convergence in the notion of the exponential equivalence of geometries. This property can be called bounded distortion property, compare Section 5.2.

To prove (6.1.4) observe that there is a sequence $I_{j_0,\ldots,j_m} = J_m \supset J_{m+1} \supset \cdots \supset J_k = J$ of intervals such that $J_j \in \mathcal{G}^j$ and by the assumptions of Theorem

$$1 - \mathrm{Const}\, \exp{-(j-1)\delta} \leq \left| \frac{R(I_j)}{R(I_{j-1})} \right| \leq 1 + \mathrm{Const}\, \exp{-(j-1)\delta}$$

We obtain (6.1.4) by multiplying these inequalities over $j = m+1, \ldots, k$.

If $x \in I_{j_0,\ldots,j_m} = I$ is the end point of any gap, then

$$\left| \frac{\phi'(x)}{R(I)} - 1 \right| \leq \mathrm{Const}\, \exp{-m\delta} \qquad (6.1.5)$$

(In fact x can be any point of $h_1(\Sigma^d)$ in I but there is no need to define here ϕ' at these points except the ends of gaps. Compare Remark 5.3.4.)

To get (6.1.5) one should consider an infinite sequence of intervals containing x and consider the infinite product over $j = m+1, \ldots$.

Later on we shall use also a constant $\varepsilon > 0$ such that for every $s \geq 0$

$$\exp{-s\delta} \leq \mathrm{Const}\, \inf_{J \in \mathcal{G}^s} |J|^\varepsilon. \qquad (6.1.6)$$

Such an ε exists because by the exponential geometry assumption $\inf_{J \in \mathcal{G}^s} |J|$ cannot converge to 0 faster than exponentially.

We can go back to our interval (a, b). We extend ϕ' linearly to the interval $[a, \frac{a+b}{2}]$ and linearly to $[\frac{a+b}{2}, b]$, continuously to $[a, b]$. Moreover we care about

choosing $\phi'(\frac{a+b}{2}) = t$ such that $\int_{[a,b]} \phi'(x)dx = \phi(b) - \phi(a)$. But our gap $G_{j_0,\ldots,j_n}$ is in the interval $I_{j_0,\ldots,j_{n-1}}$ so by (6.1.5)

$$\left| \frac{R(a,b)}{\phi'(a)} - 1 \right| < \text{Const} \exp -(n-1)\delta$$

and the same for $\phi'(b)$. This and the computation

$$R(a,b) = \frac{\int_{[a,b]} \phi'(x)dx}{b-a} = \frac{1}{2}(b-a)(\frac{\phi'(a)+t}{2} + \frac{\phi'(b)+t}{2})/(b-a) = \frac{1}{4}(\phi'(a)+\phi'(b)+2t)$$

show that

$$\left| \frac{t}{\phi'(a)} - 1 \right|, \left| \frac{t}{\phi'(b)} - 1 \right| < \text{Const} \exp -n\delta. \qquad (6.1.7)$$

In particular $t > 0$, hence ϕ is increasing.

Now we need to prove the property (6.1.1). It is sufficient to consider points x, y, z in gaps because $h_1(\Sigma^d)$ is nowhere dense.

We shall construct a finite family $\mathcal{A}(x,y)$ of intervals in $\bigcup_{m=0}^{\infty} \mathcal{G}^m$ "joining" the gaps in which x and y lie. Suppose $x < y$ and let n be the largest integer such that x, y belong to the same element of $\mathcal{G}^n$. If x, y belong to different elements of $\mathcal{G}^0$ we take $n = -1$.

If x, y belong to a gap $G_{j_0,\ldots,j_n}$ then $\mathcal{A}(x,y)$ is empty. If they belong to $I_{j_0,\ldots,j_n}$ then they belong to different intervals $J(x,n+1), J(y,n+1)$ of $\mathcal{G}^{n+1}$. We account to $\mathcal{A}(x,y)$ all the intervals in $\mathcal{G}^{n+1}$ lying between $J(x,n+1)$ and $J(y,n+1)$ excluding $J(x,n+1)$ and $J(y,n+1)$ themselves. We shall continue with $J(x,n+1)$, the procedure for $J(y,n+1)$ is analogous.

If $J(x,n+1)$ is a gap we end the process, nothing new will be accounted to $\mathcal{A}(x,y)$ from this side. In the opposite case we account to $\mathcal{A}(x,y)$ all the intervals of $\mathcal{G}^{n+2}$ in $J(x,n+1)$ to the right of x not containing x and denote this one which contains x by $J(x,n+2)$. We continue this procedure by induction until $J(x,m)$ is for the first time a gap.

Thus the "joining" set $\mathcal{A}(x,y)$ has been constructed.

Consider first the case $\mathcal{A}(x,y) = \emptyset$. It is easy to see that then both x, y belong to $G_{j_0,\ldots,j_n}$. Suppose $x, y \in (a, \frac{a+b}{2}]$ where a, b are ends of the gap and t will be the value of ϕ' in the middle, as in the notation before. For $u \in [x,y]$ by the linearity of ϕ' and using (6.1.7) we obtain

$$|\phi'(u) - \phi'(x)| \leq \frac{2(u-x)}{b-a}|t - \phi'(a)| \leq \text{Const} \frac{(u-x)}{b-a}\phi'(a)\exp -n\delta.$$

Next using the fact that $\phi'(a)$ is uniformly bounded and by (6.1.6) we get

$$R(x,y) = \int_{[x,y]} \phi'(u)du/(y-x) \leq \phi'(x)(1 + \text{Const}\frac{y-x}{b-a}(b-a)^\varepsilon)$$

$$\leq \phi'(x)\left(1 + \text{Const}(y-x)^\varepsilon\right) \qquad (6.1.8)$$

and the analogous bound from below. The case x, y are to the right of $\frac{a+b}{2}$ can be dealt with similarly. We can also write in (6.1.8) $\phi'(y)$ instead of $\phi'(x)$. Finally if $x < \frac{a+b}{2} < y$ we obtain (6.1.8) by summing up the estimates for $(x, \frac{a+b}{2}]$ and $[\frac{a+b}{2}, y)$.

Consider the case $\mathcal{A}(x, y) \neq \emptyset$. Let $m \geq n$ be the smallest integer such that there exists $J_{j_0,\dots,j_m} \in \mathcal{A}(x, y) \cap \mathcal{G}^m$, ($J$ can be I or G what means it can be a gap or non-gap).

Denote the right end of the gap containing x by x' and the left end of the gap containing y by y'.

We obtain with the use of (6.1.4)

$$R(x', y') = \frac{\sum_{J \in \mathcal{A}(x,y)} |\phi(J)|}{\sum_{J \in \mathcal{A}(x,y)} |J|} \leq R(I_{j_0,\dots,j_{m-1}})(1 + \text{Const} \exp -(m-1)\delta). \quad (6.1.9)$$

We used the fact that all $J \in \mathcal{A}(x, y)$ are in $I_{j_0,\dots,j_{m-1}}$. By (6.1.7) we obtain

$$\phi'(x') \leq R(I_{j_0,\dots,j_{m-1}})(1 + \text{Const} \exp -m\delta).$$

From these and the analogous inequalities to the other side we obtain finally

$$\left| \frac{R(x', y')}{\phi'(x)} - 1 \right| \leq \text{Const} \exp -m\delta \leq \text{Const}(y' - x')^{\varepsilon}. \quad (6.1.10)$$

The similar inequality holds for $\phi'(y)$.

We will conclude now. By (6.1.8) and (6.1.10) each two consecutive terms in the sequence

$$\phi'(x), R(x, x'), \phi'(x'), R(x', y'), \phi'(y'), R(y', y), \phi'(y)$$

have the ratio within the distance from 1 bounded by $\text{Const}(y - x)^{\varepsilon}$. So

$$\left| \frac{R(x, y)}{\phi'(y)} - 1 \right| < \text{Const}(y - x)^{\varepsilon} \quad (6.1.11)$$

Recall now that to prove (6.1.1) we picked also a third point: $z > y$. If y, z play the role of previous x, y we obtain

$$\left| \frac{R(y, z)}{\phi'(y)} - 1 \right| < \text{Const}(z - y)^{\varepsilon}.$$

So

$$\left| \frac{R(x, y)}{R(y, z)} - 1 \right| < \text{Const}(z - x)^{\varepsilon}.$$

Using the uniform boundness of R's we obtain this in the additive form i.e. (6.1.1). Theorem is proved.

Remark 6.1.7. One can shorten the above proof by referring to Whitney Extension Theorem (see for example Section 7.2).

Indeed, one can define $\phi'(x)$ for every $x \in h_(\Sigma^d)$, $x = \bigcap_{m=0}^{\infty} I_{j_0,\dots,j_m}$, by the formula (as (6.1.3)) $\phi'(x) = \lim R(I_{j_0,\dots,j_m})$.

Then the estimate (6.1.8) for all $x, y \in h_1(\Sigma^d)$, rewritten as

$$\phi(y) = \phi(x) + \phi'(x)(y - x) + O(|y - x|^{1+\varepsilon})$$

which, together with Hölder continuity of ϕ' with exponent ε (see (6.1.5) and (6.1.6)) are precisely the assumptions for the Whitney Theorem, that asserts that ϕ has a $C^{1+\varepsilon}$ extension.

Remark 6.1.8. It is substantial to assume in Theorem 6.1.6 that the convergence $\frac{A_j(h_1,w)}{A_j(h_2,w)} \to 1$ is exponential i.e. the geometries are exponentially equivalent. Otherwise $\phi'(a)$ in (6.1.3) may not exist.

To prove the existence of ϕ' on $h_1(\Sigma^d)$, the uniform convergence of the finite (in case they end with expressions involving gaps) or infinite products $\prod_n \frac{A_{j_{n+1}}(h_1,(j_0,\dots,j_n))}{A_{j_{n+1}}(h_2,(j_0,\dots,j_n))}$ is sufficient.

Remark 6.1.9. For each $h_1, h_2 \in \mathcal{H}$ the order preserving mapping $\phi : h_1(\Sigma^d) \to h_2(\Sigma^d)$ is quasisymmetric (see Definition 5.2.6). The equivalence of the geometries is equivalent to the 1-quasisymmetric equivalence, cf. Exercise 6.2.

Example 6.1.10. It can happen that above $\phi : h_1(\Sigma^d) \to h_2(\Sigma^d)$ is Lipschitz continuous but all extensions are non-differentiable at every point in $h_1(\Sigma^d)$.

Let $h_i : \Sigma^3 \to \mathbb{R}$ be defined by $h_1((j_0,\dots)) = a =: .a_1 a_2 \dots$ in the development of a in base 6, where

$a_s = 0$ if $j_s = 1$, $a_s = 2$ if $j_s = 2$ and $a_s = 5$ if $j_s = 3$ for h_1

and

$a_s = 0$ if $j_s = 1$, $a_s = 3$ if $j_s = 2$ and $a_s = 5$ if $j_s = 3$ for h_2
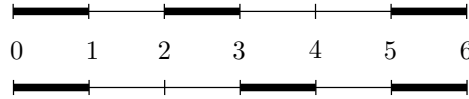
Figure 6.1: "Generators" of two differentiably different Cantor sets

In the case ϕ conjugates expanding maps on the circle this cannot happen. For example Lipschitz conjugacy has points of differentiability hence by expanding property of, say analytic, maps involved, it is analytic (see Chapter 8). For Cantor sets, as above, if they are non-linear (see Chapter 9 for definition), then ϕ Lipschitz implies ϕ analytic. However for linear sets, as in this example, an additional invariant is needed to describe classes of $C^{1+\varepsilon}$-equivalence, so-called scaling function, see the next Section 6.2.

6.2 Scaling function. $C^{1+\varepsilon}$-extension of the shift map

Until now we have not discussed dynamics . Recall however that we have on Σ^d the left side shift map $s(j_0, j_1, \dots) = (j_1, \dots)$. We ask for a condition about the ratio geometry for $h \in \mathcal{H}$ under which s, more precisely $h \circ s \circ h^{-1}$, extends $C^{1+\varepsilon}$ to a neighbourhood of $h(\Sigma^d)$.

Definition 6.2.1. For the ratio geometry of $h \in \mathcal{H}$ we consider the sequence of functions to $\mathbb{R}^{2d-1}$

$$S_n(j_{-n}, \dots, j_{-1}) = (S_n(j_{-n}, \dots, j_{-1})_j, j = 1, \dots, 2d-1) :=$$
$$(A_j(h, (j_{-n}, \dots, j_{-1})), j = 1, \dots, 2d-1).$$

We call this a *scaling sequence* of functions. The limit

$$S(\dots, j_{-2}, j_{-1}) = \lim_{n \to \infty} S_n(j_{-n}, \dots, j_{-1})$$

if it exists, is called *scaling function.* By the definition

$$\sum_{j=1}^{2d-1} S_n(\cdot)_j \equiv \sum_{j=1}^{2d-1} S(\cdot)_j \equiv 1.$$

Let us discuss now the domain of S_n, S. These functions are defined on one-sided sequences of symbols from $\{1, \dots, d\}$ so formally on Σ^d. We want to be more precise however.

Consider the natural extension of Σ^d i.e. 2-sided shift space $\tilde{\Sigma}^d = \{(\dots, j_{-1}, j_0, j_1, \dots)\}$. Then S can be considered as a function on $\tilde{\Sigma}^d$ but for each $(\dots, j_{-1}, j_0, j_1, \dots)$ depending only on the past $(\dots, j_{-2}, j_{-1})$. The functions S_n depend only on finite past.

Definition 6.2.2. The domain of S and S_n is the factor of $\tilde{\Sigma}^d$ where we forget about the present and future, i.e. we forget about the coordinates $j_0, j_1, \dots$. We call this factor *dual Cantor set* and denote by Σ^{d*}. The range of S and S_n is the $2d-2$-dimensional simplex Simp_{2d-2} being the convex hull of the $2d-1$ points $(0, \dots, 1, \dots, 0)$, with 1 at the position $j = 1, 2, \dots, 2d-1$.

Thus S is not a function on $h(\Sigma^d)$ but if we consider $h(\Sigma^d)$ with the shift map $h \circ s \circ h^{-1}$ then we can see the dual Cantor set, i.e. the domain of S and S_n, as the set of all infinite choices of consecutive branches of $(h \circ s \circ h^{-1})^{-1}$ on $h(\Sigma^d)$.

Remark that if instead of $(h(\Sigma^d), h \circ s \circ h^{-1})$ we considered an arbitrary, say distance expanding, repeller we could define backward branches only locally, i.e. there would be no natural identification of fibres of the past over two different distant points of the repeller.

Proposition 6.1.5 yields

Proposition 6.2.3. *If $h_1, h_2 \in \mathcal{H}$ are C^1-equivalent and there exists a scaling function S for h_1, then h_2 has also a scaling function, equal to the same S.*

In particular this says that C^1-equivalence preserves scaling function. Note that this is not the case for Lipschitz equivalence, see Example 6.1.10.

From Theorem 6.1.6 we easily deduce the following

Theorem 6.2.4. *If $h \in \mathcal{H}e$ and $h \circ s \circ h^{-1}$ extends to a $C^{1+\varepsilon}$-mapping s_h on a neighbourhood of $h(\Sigma^d)$ then*

$$\frac{S_n}{S_{n+1}} \to 1, \quad \text{the convergence is uniformly exponentially fast.} \qquad (6.2.1)$$

Conversely, if $h \in \mathcal{H}$ and (6.2.1) is satisfied then $h \in \mathcal{H}e$ and $h \circ s \circ h^{-1}$ extends to a $C^{1+\varepsilon}$-mapping.

Proof. Consider the sets $\Sigma_i^d = \{\alpha \in \Sigma^d : \alpha_0 = i\}$ for $i = 1, \ldots, d$. Each Σ_i^d can be identified with Σ^d by $L_i((\alpha_0, \alpha_1, \ldots)) = (i, \alpha_0, \alpha_1, \ldots)$. Of course $h_i := h \circ L_i \in \mathcal{H}$. Denote $h \circ s \circ h^{-1} : h(\Sigma_i^d) \to h(\Sigma^d)$ by s_i. We have $s_i \circ h_i = h$. So by Theorem 6.1.6 all s_i extend $C^{1+\varepsilon}$ iff $\frac{A_j(h,w)}{A_j(h_i,w)}$ converge to 1 uniformly exponentially fast in length of w These ratios are equal to $\frac{A_j(h,w)}{A_j(h,iw)}$ i.e. $\frac{S_n}{S_{n+1}}$, n being the length of w. So we obtain precisely the assertion of our Theorem.

To apply Theorem 6.1.6 we used the observation that (6.2.1) easily implies $h \in \mathcal{H}b$ (by a sort of bounded distortion for iterates of $h \circ s \circ h^{-1}$ property), in particular $h \in \mathcal{H}e$, see Proposition 6.2.9. ♣

Example 6.2.5. Note that s_h of class $C^{1+\varepsilon}$ (even C^ω) does not imply $h \in \mathcal{H}e$. Indeed, consider h such that s_h has a parabolic point, for example $s_h(x) = x + 6x^2$ for $0 \le x \le 1/3$ and $s_h(x) = 1 - 3(1-x)$ for $2/3 \le x \le 1$.

Remark 6.2.6. The assertions of Theorems 6.1.6 and 6.2.4 stay true if each Cantor set is constructed with the help of the intervals $I_{j_0,\ldots,j_n}$ as before but we do not assume that the left end of $I_{j_0,\ldots,j_n,1}$ coincides with the left end of $I_{j_0,\ldots,j_n}$ and that the right end of $I_{j_0,\ldots,j_n,d}$ coincides with the right end of $I_{j_0,\ldots,j_n}$.

So there might be some "false" gaps in $I_{j_0,\ldots,j_n}$ to the left of $I_{j_0,\ldots,j_n,1}$ and to the right of $I_{j_0,\ldots,j_n,d}$. In the definitions of bounded and exponential geometry we do not assume anything about these gaps, they may shrink faster than exponentially as $n \to \infty$. But whereever ratios are involved, i.e. in $A_j(h_1, w), A_j(h_2, w)$ in Theorem 6.1.6 or S, S_n in Theorem 6.2.4 we take these gaps into account, so $j = 0, 1, \ldots, 2d$.

The condition sufficient in Theorem 6.1.6 to $C^{1+\varepsilon}$-equivalence is that $A_j(h_1, w) - A_j(h_2, w) \to 0$ exponentially fast.

The condition sufficient in Theorem 6.2.4 to the $C^{1+\varepsilon}$-extentiability of $h \circ s \circ h^{-1}$ is that $S_n \to S$ exponentially fast.

To prove these assertions observe that if we extend gaps of the $n + 1$-th generation (between $I_{j_0,\ldots,j_n,j}$ and $I_{j_0,\ldots,j_n,j+1}$, $j = 1, \ldots, d-1$) by false gaps of

higher generations to get real gaps of the resulting Cantor set, then they and the remaining intervals satisfy the assumptions of Theorems 6.1.6 and 6.2.4.

This remark will be used in the Section 6.4.

Definition 6.2.7. We say that $h \in \mathcal{H}$ satisfying (6.2.1) has an *exponentially determined geometry*. The set of such h's will be denoted by $\mathcal{H}ed$.

Definition 6.2.8. Let $j = (j_n)_{n=\ldots,-2,-1}, j' = (j'_n)_{n=\cdots-2,-1} \in \Sigma^{d*}$. Denote by $j \cap j'$ the sequence $(j_{-N}, \ldots, j_{-1})$ with $N = N(j, j')$ the largest integer (or ∞) such that $j_{-n} = j'_{-n}$ for all $n \leq N$. For an arbitrary $\delta > 0$ define the metric ρ_δ on Σ^{d*} by

$$\rho_\delta(j, j') = \exp -\delta N(j, j').$$

Let us make the following simple observation

Proposition 6.2.9. a) $\mathcal{H}e \supset \mathcal{H}b \supset \mathcal{H}ed$.

b) *If $h \in \mathcal{H}ed$ then the scaling function S exists is Hölder continuous with respect to any metric ρ_δ, see Definition 6.2.8, and $S(\cdot)_i$ are bounded away from 0 and 1.*

(Observe however that the converse is false. One can take each S_n constant hence S constant, but $\frac{S_n}{S}$ converging to 1 slower than exponentially so $h \notin \mathcal{H}ed$.)

c) *If $h \in \mathcal{H}ed$ then $(h(\Sigma^d), s_h)$ is a $C^{(1+\varepsilon)}$ expanding repeller. (We shall use also the words $C^{(1+\varepsilon)}$-Cantor repeller in the line.)*

Proof. We leave a) and b) to the reader (the second inclusion in a) was already commented in Proof of Theorem 6.2.4) and prove c). Similarly as in Proof of Theorem 6.1.6. the property (6.1.5), we obtain the existence of a constant $C > 0$ such that for $x = h((j_0, j_1, \ldots)) \in \Sigma^d$ and $n \geq 0$

$$C^{-1} < |(s_h^n)'(x)| / \frac{|I|}{|I_{j_0,\ldots,j_n}|} < C.$$

As $h \in \mathcal{H}e$, in particular $|I_{j_0,\ldots,j_n}| \to 0$ uniformly we obtain $|(s_h^n)'(x)| > 1$ for all n large enough and all x.

It follows from Theorem 6.1.6 that classes of $C^{1+\varepsilon}$-equivalence in $\mathcal{H}ed$ are parametrized by Hölder continuous functions on Σ^{d*} (as scaling functions). To have the one-to-one correspondence we need only to prove the existence theorem:

Theorem 6.2.10. *For every Hölder continuous function $S : \Sigma^{d*} \to \mathbb{R}_+^{2d-1}$ such that*

$$\sum_{j=1}^{2d-1} S(\cdot)_j \equiv 1 \tag{6.2.2}$$

there exists $h \in \mathcal{H}ed$ such that S is the scaling function of h.

First let us state the existence lemma:

Lemma 6.2.11. *Given numbers $A_{w,j} > 0$ for every $w = (j_0, \ldots, j_n), n = 0, 1, \ldots$, $j = 1, \ldots 2d - 1$, such that $\sum_{j=1}^{2d-1} A_{w,j} = 1$, there exists $h \in \mathcal{H}$ such that $A_{w,j} = A_j(h, w)$ i.e. h has the prescribed ratio geometry.*

Proof of Lemma 6.2.11. One builds a Cantor set by removing gaps of consecutive generations , from each I_w gaps of lengths $A_{w,j}|I_w|$, j even, so that the intervals not removed have lengths $A_{w,j}$, j odd, $j = 1, \ldots, 2d - 1$.

Proof of Theorem 6.2.10. Let $A_{w,j} := S((\ldots, 1, 1, w))_j$. By (6.2.2) $\sum_{j=1}^{2d-1} A_{w,j} = 1$ so we can apply Lemma 6.2.11. The property (5.4.11), the exponential convergence, follows immediately from the Hölder continuity of S and the fact that S is bounded away from 0 as positive continuous on the compact space Σ^{d*}.

Summary: $C^{1+\varepsilon}$-structures in $\mathcal{H}$ed are in a one-to-one correspondence with the Hölder continuous scaling functions on the dual Cantor set.

Until now we were not interested in ε in $C^{1+\varepsilon}$. It occurs however that scaling functions "see" ε. First we introduce a metric ρ_S on Σ^{d*} depending only on a scaling function S, so that for a constant $K > 0$, for every j, j':

$$\frac{1}{K} \leq \frac{|I_{j \cap j'}|}{\rho_S(j,\, j')} \leq K. \tag{6.2.3}$$

Definition 6.2.12.

$$\rho_S(j,\, j') = \sup_w \prod_{t=1}^{n=N(j \cap j')} S(wj_{-n}j_{-n+1}..j_{-t-1})_{j_t}$$

supremum over all w left infinite sequences of symbols in $\{1, \ldots, d\}$.

The estimate (6.2.3) follows easily from the exponential determination of geometry, we leave details to the reader.

Theorem 6.2.13. *Fix $0 < \epsilon \leq 1$. The following are equivalent:*
1. There exists $h \in \mathcal{H}$ed, a $C^{1+\epsilon}$ embedding , i.e. $h \circ s \circ h^{-1}$ extends to s_h being $C^{1+\epsilon}$, with scaling function S.
2. The scaling S is C^ϵ on (Σ^{d*}, ρ_S). (Here C^1 means Lipschitz).

Proof. Substituting $\phi = s_h$, we can write (6.1.2), for all $n > N$ and all $i = 1, 2, \ldots, 2d - 1$, in the form

$$|S_n(j_{-n}, \ldots, j_{-1})_i - S_{n-1}(j_{-n}, \ldots, j_{-1})_i| \leq \text{Const}\, |I_{j_{-n}, \ldots, j_{-1}}|^\varepsilon.$$

Summing up this geometric series for an arbitrary $j \in \Sigma^{d*}$ over $n = N, N + 1, \ldots$ for $N = N(j, j')$, doing the same for another $j' \in \Sigma^{d*}$, and noting that $|S_N(j_{-N}, \ldots, j_{-1}) = |S_N(j'_{-N}, \ldots, j_{-1})$, yields

$$|S(j)_i - S(j')_i| \leq \text{Const}\, |I_{j \cap j'}|^\varepsilon.$$

Applying (6.2.3) to the right hand side we see that S is Hölder continuous with respect to ρ_S.

For the proof to the other side see Proof of Theorem 6.2.10. The construction gives the property (5.4.1a) for $\phi = s_h$, the extension as in Proof of Theorem 6.1.6. ♣

Example 6.2.14. For every $0 < \varepsilon_1 < \varepsilon_2 \leq 1$ there exists S admitting a $C^{1+\varepsilon_1}$ embedding $h \in \mathcal{H}$ed, but not $C^{1+\varepsilon_2}$. We find S as follows. For an arbitrary (small) $\nu : 0 < \nu < (\varepsilon_1 - \varepsilon_2)/2$ we can easily find a function $S : \Sigma^{d*} \to \mathrm{Simp}_{2d-2}$ which is $C^{\varepsilon_1 + \nu}$ but is not $C^{\varepsilon_2 - \nu}$, in the metric ρ_δ, $\delta > \log d$ (Definition 6.2.8).

We can find in fact S so that for every $j \in \Sigma^{d*}$ and $i = 1, 3, \ldots, 2d - 1$ we have $|-\log S(j)_i/\delta - 1| < \nu/3$. (If $d \geq 3$ we can even have $S(j)_i = \log \delta$ constant for $i = 1, 3, \ldots, 2d - 1$, changing only gaps, i even.) Then, for all j, j' and $N = N(j, j')$, and a constant $K > 0$

$$K^{-1}(\exp -N\delta)^{1-\nu/2} \leq |I_{j \cap j'}| \leq K(\exp -N\delta)^{1+\nu/3}.$$

Since $\rho_\delta(j, j') = \exp -N\delta$ we conclude that S is at best $(1 + \varepsilon_2 - \nu)/(1 - \nu/3) < \varepsilon_2$-Hölder with respect to ρ_S. Hence s_h cannot be $C^{1+\varepsilon_2}$, by Theorem 6.2.13. Meanwhile a construction as in Proof of Theorem 6.2.10 gives S being ε_1-Hölder, hence s_h is $C^{1+\varepsilon_1}$

6.3   Higher smoothness

Definition 6.3.1. For every $r = 1, 2, \ldots, \infty, \omega$ and $0 \leq \varepsilon \leq 1$ we can consider in $\mathcal{H}$e the subset $C^{r+\varepsilon}\mathcal{H}$ of such h's that $h \circ s \circ h^{-1}$ extends to a neighbourhood of $h(\Sigma^d)$ to a function of class $C^{r+\varepsilon}$.

By Theorem 6.2.4, for $r + \varepsilon > 1$,
$$C^{r+\varepsilon}\mathcal{H} \subset \mathcal{H}\text{ed}.$$

Theorem 6.3.2. *If $h_1, h_2 \in C^{r+\varepsilon}\mathcal{H}$, $0 \leq \varepsilon \leq 1, r + \varepsilon > 1$, have equivalent geometries then h_1, h_2 are $C^{r+\varepsilon}$-equivalent i.e. there exists a $C^{r+\varepsilon}$-diffeomorphism ϕ of a neighbourhood of $h_1(\Sigma^d)$ to a neighbourhood of $h_2(\Sigma^d)$ such that*

$$\phi|_{h_1(\Sigma^d)} \circ h_1 = h_2, \tag{6.3.1}$$

i.e. the canonical conjugacy extends $C^{r+\varepsilon}$

We will prove here this Theorem for $\varepsilon > 0$. A different proof in Section 6.4 will contain also the case of $\varepsilon = 0$.

Remark 6.3.3. For h_1, h_2 in the class in $\mathcal{H}$ of functions having a scaling function, the condition h_1, h_2 have equivalent geometries means the scaling functions are the same. In the more narrow class $\mathcal{H}$ed it means the canonical conjugacy ϕ extends $C^{1+\delta}$ for some $\delta > 0$, see Theorem 6.1.6. The virtue of Theorem 6.3.2 is that the more narrow the class the better ϕ is forced to be. This is again a Livshic type theorem.

Before proving Theorem 6.3.2 let us make a general calculation.

For any sequence of C^r real maps $F_j, j = 1, \ldots, m$ consider the r-th derivative of the composition $(F_m \circ \cdots \circ F_1)^{(r)}$, supposed that the maps can be composed, i.e. that the range of each F_j is in the domain of F_{j+1}. We start with

$$(F_m \circ \cdots \circ F_1)'(z) = \prod_{j=1}^{m} F_j'(z_{j-1})$$

where $z_0 = z$ and $z_j = F_j(z_{j-1})$.

Differentiating again we see that

$$(F_m \circ \cdots \circ F_1)''(z) = \sum_{j=1}^{m} \Big(\prod_{i=1}^{j-1}(F_i'(z_{i-1}))^2 \Big(\prod_{i=j+1}^{m} F_i'(z_{i-1})\Big)\big(F_j''(z_{j-1})\big).$$

By induction we obtain

$$(F_m \circ \cdots \circ F_1)^{(r)}(z) = \sum_{1 \le j_1, \ldots, j_{r-1} \le m} W_{j_1, \ldots, j_{r-1}}^r(z),$$

where

$$W_{j_1, \ldots, j_{r-1}}^r(z) = \Phi_{j_1, \ldots, j_{r-1}}(z) P_{j_1, \ldots, j_{r-1}}(z),$$

where for $j_1', \ldots, j_{r-1}'$ denoting a permutation of $j_1, \ldots, j_{r-1}$ so that $j_1' \le \cdots \le j_{r-1}'$ we denote

$$\Phi_{j_1, \ldots, j_{r-1}}(z) := \Big(\prod_{i=1}^{j_1'-1} (F_i'(z_{i-1})) \Big)^r \Big(\prod_{i=j_1'+1}^{j_2'-1} (F_i'(z_{i-1})) \Big)^{r-1} \cdots \Big(\prod_{i=j_{r-1}'+1}^{m} (F_i'(z_{i-1})) \Big)$$

$$(6.3.2)$$

and

$$P_{j_1, \ldots, j_{r-1}}(z) = \prod_{i=1}^{r'-1} P_{j_i}(z),$$

where each P_{j_i} is the sum of at most $(r-1)!$ terms of the form $\prod_{\sum t_s = r, \max t_s \ge 2} F_{j_i}^{(t_s)}(z_{j_i-1})$. We replaced above r by $r' \le r$, since if some j_s repeats, we consider it in the product above only ones.

This can be seen by considering for each $j_1, \ldots, j_{r-1}$ tree graphs with vertices at m levels, $0, \ldots, m-1$, i.e. derivatives at $z_0, \ldots, z_{m-1}$, each vertex (except for level 0) joined to the previous level vertices by the number of edges equal to the order of derivative. Φ gathers levels with only first derivatives, P the remaining ones.

By induction, when we consider first derivative of the product related to the tree $\mathcal{T}$ corresponding to r-th derivative, we obtain a sum of expressions corresponding to trees, each received from the $\mathcal{T}$ by adding a branch from a vertex in $\mathcal{T}$ of a level $j_r - 1$, composed of new vertices v_i at levels $0 \le i < j_r - 1$ and edges e_i joining v_i to v_{i+1}. Since the number of the vertices in T at each level, in particular level $j_r - 1$ is at most r, we have at most r graphs which arise from T by differentiating at the level $j_r - 1$.

Proof of Theorem 6.3.2. The method, passing to small and next to large scale, is similar to the method of the second proof of Theorem 8.5.5.

Choose an arbitrary sequence of branches of $s_{h_1}^{-n}$ on a neighbourhood of $h_1(\Sigma^d)$ and denote them by g_n, $n = 1, 2, \dots$.

We have ψ a diffeomorphism assuring the $C^{1+\delta}$-equivalence, see the Remark 6.3.3 above. (In fact we shall use only C^1.) We define on a neighbourhod of $h_1(\Sigma^d)$

$$\phi_n = s_{h_2}^n \circ \psi \circ g_n$$

Of course $\phi_n = \psi$ on $h_1(\Sigma^d)$. However s_{h_1}, s_{h_2} are defined only on neighbourhoods $U_\nu = B(h_\nu(\Sigma^d), \varepsilon)$ of $h_\nu(\Sigma^d)$, for some $\varepsilon > 0$, $\nu = 1, 2$. As s_{h_ν} are expanding we can assume $s_{h_\nu}^{-1}(U_\nu) \subset U_\nu$ so all the maps g_n are well defined. We shall explain now why all the ϕ_n above are well defined.

Observe first that due to the assumption that ψ is a C^1 diffeomorphism, (6.3.1) and that $h_1(\Sigma^d)$ has no isolated points, there exists a constant $C > 0$ such that for every $x \in h_1(\Sigma^d)$, $j \geq 0$:

$$C^{-1} < |(s_{h_1}^j)'(x)/|(s_{h_2}^j)'(\psi(x))| < C \qquad (6.3.3)$$

So by the bounded distortion property for iterates of s_{h_ν} (following from the expanding property and the $C^{1+\varepsilon}$-smoothness, see Ch.5.2), for every $j = 0, 1, \dots, n$, if we know already that $s_{h_2}^j \circ \psi \circ g_n$ is defined on $B := B(h_1(\Sigma^d), \eta/(2C^2 \sup \psi'))$, we obtain

$$s_{h_2}^j \psi g_n(B) \subset B(h_2(\Sigma^d), \eta). \qquad (6.3.4)$$

So $s_{h_2}^{j+1} \circ \psi \circ g_n$ is defined on B , and so on, up to $j = n$. (2 in the denominator of the radius of B is a bound taking care about the distortions, sufficient for η small enough. Pay attention to the possibility that U_i is not connected, but this has no influence to the proof.)

We shall find a conjugacy ϕ from the assertion of Theorem being the limit of a uniformly convergent subsequence of ϕ_n so it will also be ψ on $h_1(\Sigma^d)$ hence (6.2.2) will hold.

Choose a sequence $x_n \in g_n(h_1(\Sigma^d))$. Instead of ϕ_n consider

$$\tilde{\phi}_n = s_{h_2}^n \circ L_n \circ g_n$$

where $L_n(w) = \psi(x_n) + \psi'(x_n)(w - x_n)$

Observe first that

$$\text{dist}_{C^0}(\phi_n, \tilde{\phi}_n) \to 0 \quad \text{for } n \to \infty \qquad (6.3.5)$$

Indeed,

$$\phi_n(z) - \tilde{\phi}_n(z) = s_{h_2}^n(\psi(g_n(z))) - s_{h_2}^n(L_n(g_n(z))).$$

As $|g_n(z) - x_n| \to 0$ for $n \to \infty$, we have by the C^1-smoothnes of ψ

$$\frac{\psi(g_n(z)) - L_n(g_n(z))}{g_n(z) - x_n} \to 0.$$

So due to the bounded distortion property for the iterates of s_{h_2}, using also the property $\psi'(x_0) \neq 0$ we get

$$\frac{s_{h_2}^n(\psi(g_n(z)) - s_{h_2}^n(L_n(g_n(z))))}{s_{h_2}^n(\psi(g_n(z))) - s_{h_2}^n(\psi(x_n))} \to 0$$

hence (6.3.5). We have proved by the way that all $\tilde{\phi}_n$ are well defined on a neighbourhood of $h_1(\Sigma^d)$, similarly as we have got (6.3.4).

Thus we can consider $\tilde{\phi}_n$'s all of which are $C^{r+\varepsilon}$. We need to prove that their r-th derivatives are uniformly bounded in C^ε. Then by Arzela-Ascolli theorem we can choose a subsequence $\tilde{\phi}_{n_k}^{(r)}$ uniformly convergent to a C^ε function. (Here we use $\varepsilon > 0$.) By the Calculus theorem that the limit of derivatives is the derivative of the limit we will obtain the assertion that a uniformly convergent subsequence of $\tilde{\phi}_n$ has the limit $C^{r+\varepsilon}$smooth.

We shall use our calculations of $(F_m \circ \cdots \circ F_1)^{(r)}$ preceding Proof of Theorem 6.3.2. We can assume that $r \geq 2$, as for $r = 1$ the Theorem has been already proven (see Theorem 6.1.6). For $m = 2n + 1$ we set as $F_1, \ldots, F_n$ the branches of $s_{h_1}^{-1}$ which composition gives g_n. We set $F_{n+1} = L_n$. Finally for $j = n + 2, \ldots, 2n + 1$ we set $F_j = s_{h_2}$.

For every sequence $j_1, \ldots, j_{r-1}$ we assign the number

$$T(j_1, \ldots, j_{r-1}) = \sum\{j_i : j_i \leq n\} + \sum\{m - j_i : j_i \geq n + 1\}.$$

For any x, z in a neighbourhood of $h_1(\Sigma^d)$ sufficiently close to each other and $\alpha = (j_1, \ldots, j_{r-1})$ we have

$$|W_\alpha^r(x) - W_\alpha^r(z)| = |(\frac{\Phi_\alpha(x)}{\Phi_\alpha(z)} - 1)P_\alpha(x) + (P_\alpha(x) - P_\alpha(z))\Phi_\alpha(z)|. \quad (6.3.6)$$

By (6.3.2), organizing the products there in $\prod_{i=1}^{j_1'-1} \prod_{i=1}^{j_2'-1} \cdots \prod_{i=1}^{m}$ (after multiplying by missing terms $F_{j_s'}'$), using bounded distortion of iterates of $s_{h_n u}, \nu = 1, 2$, we obtain

$$\left|\left(\frac{\Phi_\alpha(x)}{\Phi_\alpha(z)} - 1\right)\right| \leq \text{Const } r|x - z|^\varepsilon.$$

Observe also that, using $|x_j - z_j| \leq \text{Const } |x - z|$,

$$|P_\alpha(x) - P_\alpha(z)| \leq \text{Const } |x - z|^\varepsilon.$$

and $P_\alpha(x)$ is bounded by a constant independent of n (depending only on r). Finally we have

$$|\Phi_\alpha(z)| \leq \text{Const } \lambda^{T(\alpha)} \quad (6.3.7)$$

where λ is an arbitrary constant such that $1 < \lambda^{-1} < \inf |s_{h_1}'|, \inf |s_{h_2}'|$

We have used here (6.3.2). The crucial observation leading from (6.3.2) to (6.3.7) was the existence of a constant $C > 0$ such that for every $0 < i \leq j \leq n$

$$C^{-1} < (F_i \circ \cdots \circ F_j)'(z_{j-1}) \cdot (F_{m-i} \circ \cdots \circ F_{m-j})'(z_{m-j-1}) < C$$

following from (6.3.3). We need to refer also again to the bounded distortion property for the iterates of s_{h_ν} as z's do not need to belong to $h_\nu(\Sigma^d)$ unlike x's in (6.3.3).

Thus by (6.3.6) and the estimates following it we obtain

$$|(s_{h_2}^n \circ L_n \circ g_n(x) - s_{h_2}^n \circ L_n \circ g_n(z))^{(r)}|$$
$$\leq \sum_{j_1,\ldots,j_{r-1}} \text{Const}\, |x - z|^\varepsilon \lambda^{T(j_1,\ldots,j_{r-1})}$$
$$\leq \text{Const}\, |x - z|^\varepsilon \sum_{T=0}^\infty 2T^r \lambda^T \leq \text{Const}\, |x - z|^\varepsilon$$

because $\text{Card}\{(j_1,\ldots,j_{r-1}) : T(j_1,\ldots,j_{r-1}) \leq T\} \leq 2T^r$.

The proof of Theorem 6.3.2 in the $C^{r+\varepsilon}$ case for every $r = 1, 2, \ldots, \infty$ has been finished. We need to consider separately the C^ω case. The maps s_{h_ν} extend holomorphically to neighbourhoods of $h_\nu(\Sigma^d)$ in $\mathbb{C}$, the complex plane in which the interval I is embedded. Similarly as in the $C^{r+\varepsilon}$, $r = 1, \ldots, \infty$, case we see that there are neighbourhoods U_ν of $h_\nu(\Sigma^d)$ in $\mathbb{C}$ such that $\tilde{\phi}_n$ are well defined on U_1 and $\tilde{\phi}_n(U_1) \subset U_2$. By the definition they are holomorphic. Now we can use Montel's Theorem. So there exists a subsequence $\tilde{\phi}_{n_j}$, $n_j \to \infty$ as $j \to \infty$, uniformly convergent on compact subsets of U_1 to a holomorphic map. The proof is done, it happened simpler for $r = \omega$ than for $n \neq \omega$. For similar considerations see also Section 8.5.   ♣

Summary. We have the following situation: Just in $\mathcal{H}$ the equivalence of geometries and even the exponential equivalence of geometries do not induce any reasonable smoothness. In $\mathcal{H}e$ the exponential equivalence of geometries already work, it implies $C^{1+\varepsilon}$-equivalence. In $\mathcal{H}b$ even the equivalence of geometries starts to work—it implies the canonical conjugacy to be 1-quasisymmetric— this we have not discussed, see Exercise 2. In $\mathcal{H}ed$ the equivalence of geometries which means then the same as the exponential equivalence yields $C^{1+\varepsilon}$-equivalence. Then the higher smoothness of $\mathcal{H}$ forces the same smoothness of the conjugacy.

We will show in Chapter 9 that in C^ω in a subclass of non-linear Cantor sets even a weaker equivalence of geometries, not taking gaps into account, forces C^ω-equivalence (we mentioned this already at the end of Section 6.1).

6.4 Scaling function and smoothness. Cantor set valued scaling function

The question arises which scaling functions appear in which classes $C^{r+\varepsilon}$ (compare Example 6.2.14). We will give some answer below.

For simplification we assume $I = [0, 1]$.

Definition 6.4.1. Scaling with values in Cantor sets. Given a scaling function S on Σ^{d*} we define a scaling function $\hat{S}$ with values in $\mathcal{H}$ rather than Simp_{2d-2}. For each $j = (\ldots, j_{-2}, j_{-1}) \in \Sigma^{d*}$ we define $\hat{S}(j) \in \mathcal{H}$ by induction as follows.

Suppose for every $j \in \Sigma^{d*}$ and $i_0, \ldots, i_n$ the interval $I(j)_{i_0,\ldots,i_n}$ is already defined. (For empty string we set $[0,1]$.) Then for every $i_{n+1} = 1, 2, \ldots, d$ we define $I(j)_{i_0,\ldots,i_n,i_{n+1}}$ as the $2i_{n+1} - 1$'th interval of the partition of $I(j)_{i_0,\ldots,i_n}$ determined by the proportions $S(j, i_0, \ldots, i_n)_i, i = 1, 2, \ldots, 2d-1$. We conclude with $\hat{S}(j)(i_0, i_1, \ldots) = \bigcap_{n=0}^{\infty} I(j)_{i_0,\ldots,i_n}$.

Denote the Cantor set $\hat{S}(j)(\Sigma^d)$ by $\text{Can}(j)$.

Theorem 6.4.2. *For a scaling function S and $r = 1, 2, \ldots, \infty, \varepsilon : 0 \leq \varepsilon \leq 1$ with $r + \varepsilon > 1$, or $r = \omega$, the following conditions are equivalent*

1. There exists a $C^{r+\varepsilon}$, or C^ω (real-analytic) embedding $h \in \mathcal{H}ed$ with scaling function S (we assume here that in the definition of $C^{r+\varepsilon}$, see Definition 6.3.1, s_h maps each component of its domain diffeomorphically onto $[0,1]$) .

2. For every $j, j' \in \Sigma^{d*}$ there exists a $C^{r+\varepsilon}$, or C^ω respectively, diffeomorphism $F_{j'|j} : [0,1] \to [0,1]$ mapping $\text{Can}(j)$ to $\text{Can}(j')$.

Proof. Let us prove 1. $\Rightarrow$ 2. For any $j \in \Sigma^{d*}$ and $n \geq 1$ denote $j(n) = (j_{-n}, \ldots, j_{-1})$. Write

$$F_{j(n)} := ((s_h)^n|_{I_{j_{-n},\ldots,j_{-1}}}) \circ A_{j(n)}^{-1},$$

where $A_{j(n)}$ is the affine rescaling of $I_{j_{-n},\ldots,j_{-1}}$ to $[0,1]$. Given $j, j' \in \Sigma^{d*}$ and $n, n' \geq 1$ define

$$F_{j'(n')|j(n)} := F_{j'(n')}^{-1} \circ F_{j(n)}.$$

Finally define

$$F_{j'|j} := \lim_{n,n' \to \infty} F_{j'(n')|j(n)}.$$

The convergence, even exponential, easily follows from $s_h \in C^{1+\varepsilon}$. The fact that $F_{j'|j}$ maps $\text{Can}(j)$ to $\text{Can}(j')$, follows from definitions.

In the case of C^ω there is a neighbourhood U of $[0,1]$ in the complex plane so that all $(s_h)^n|_{I_{j_{-n},\ldots,j_{-1}}}^{-1}$ extend holomorphically, injectively, to U. This is so, since $(h(\Sigma^d), \hat{s}_h)$, where $\hat{s}_h$ is a holomorpic extension of s_h, is a conformal expanding repeller. With the use of Koebe Distortion Lemma, Ch. 5, one concludes that all $F_{j'(n')|j(n)}$ have a common domain in $\mathbb{C}$, containing $[0,1]$, on which they are uniformly bounded. So, for given j, j' a subsequence is convergent to a holomorphic function, hence $F_{j'|j}$ is analytic.

Consider now the $C^{r+\varepsilon}$ case.

Let us prove first the following

Claim 6.4.3. Let $F_1, F_2, \ldots$ be C^{r+1} maps of the unit interval $[0,1]$ for $r \geq 1, 0 \leq \varepsilon \leq 1, r + \varepsilon > 1$. Assume all F_m are uniform contractions, i.e there

exist $0 < \lambda_1 \le \lambda_2 < 1$ such that for every m and every $x \in [0,1]$ it holds $\lambda_1 \le |F'_m(x)| \le \lambda_2$. then there exists $C > 0$ such that for all m

$$||F_m \circ \cdots \circ F_1||_{C^{r+\varepsilon}} \le C||F_m \circ \cdots \circ F_1||_{C^1}.$$

(We set the convention that we omit supremum of the modulus of the functions in the norms in $C^{r+\varepsilon}$, we consider only derivatives.)

Proof of the Claim. Consider first $\varepsilon > 0$. We use (6.3.6) and the estimates which follow it. (6.3.7) is replaced by

$$|\Phi_\alpha(z)| \le \text{Const}\, |(F_m \circ \cdots \circ F_1)'(z)|\lambda_2^{\hat{T}(\alpha)},$$

where for $\alpha = (j_1, \ldots, j_{r-1})$ we define $\hat{T}(\alpha) = j_1 + .. + j_{r-1}$. We conclude for $r \ge 2$ with

$$|(F_m \circ \cdots \circ F_1)^{(r)}(x) - (F_m \circ \cdots \circ F_1)^{(r)}(z)| \le \text{Const}\, |x-z|^\varepsilon |(F_m \circ \cdots \circ F_1)'(z)| \sum_\alpha \lambda_2^{\hat{T}(\alpha)}$$

$$\le \text{Const}\, |x-z|^\varepsilon |(F_m \circ \cdots \circ F_1)'(z)| \sum_{T=0}^{\infty} T^r \lambda_2^T \le \text{Const}\, |(F_m \circ \cdots \circ F_1)'(z)||x-z|^\varepsilon.$$

For $r = 1$ there is no summation over α and the assertion is immediate.

For $\varepsilon = 0$ we get

$$|(F_m \circ \cdots \circ F_1)^{(r)}(z)| \le \sum_\alpha |\Phi_\alpha(z)P_\alpha(z)| \le \text{Const} \sum_\alpha |(F_m \circ \cdots \circ F_1)'(z)|\lambda_2^{\hat{T}(\alpha)} \le$$

$$\text{Const}\, |(F_m \circ \cdots \circ F_1)'(z)|.$$

The Claim is proved.   ♣

We apply the Claim to $F_1, F_2, \ldots$ being inverse branches of s_h on $[0,1]$. Let λ be supremum of the contraction rate $|s'_h|^{-1}$. Given $j \in \Sigma^{d*}$ and integers $n, m \ge 0$ we get for $z \in I_{j_{-n}, \ldots j_{-1}}$

$$||(s_h^m|_{I_{j_{-(n+m)}, \ldots, j_{-1}}})^{-1}||_{C^{r+\varepsilon}} \le C|((s_h^m|_{I_{j_{-(n+m)}, \ldots j_{-1}}})^{-1})'(z)|.$$

If we rescale the domain and range to $[0,1]$ we obtain, using bounded distortion of s_h^m,

$$||F_{j(n+m)|j(n)}||_{C^{r+\varepsilon}} \le C\frac{|I_{j_{-n}, \ldots, j_{-1}}|^{r+\varepsilon}}{|I_{j_{-(n+m)}, \ldots, j_{-1}}|}|((s_h^m|_{I_{j_{-(n+m)}, \ldots j_{-1}}})^{-1})'(z)| \le$$

$$\text{Const}\, |I_{j_{-n}, \ldots j_{-1}}|^{r+\varepsilon-1}. \tag{6.4.1}$$

The right hand side expression in this estimate does not depend on m and tends (exponentially fast) to 0 as $n \to \infty$, for $r > 1$.

Note that

$$F^{-1}_{j(n+m)} = F_{j(n+m)|j(n)} \circ F^{-1}_{j(n)}, \tag{6.4.2}$$

therefore for the sequence $F_{j(n)}^{-1}$ we verified a condition that reminds Cauchy's condition. However to conclude convergence in $C^{r+\varepsilon}$, we still need to do some job.

For $r = 1$ we have uniform exponential convergence of $|(F_{j(n)}^{-1})'(z)|$ since $|(F_{j(n+m)|j(n)})'| \to 1$ uniformly exponentially fast as $n \to \infty$. This holds since $F_{j(n)}([0,1]) = [0,1]$, by integration of the second derivative, or, in the case of merely $C^{1+\varepsilon}$, since distortion of $F_{j(n+m)|j(n)}$ tends exponentially to 1 as $n \to$.

For $r > 1, \varepsilon = 0$ the derivatives of $F_{j(n)}^{-1}$ of orders $2, \ldots, r$ tend uniformly to 0 since $F_{j(n+m)|j(n)}$ tend uniformly to identity in C^r as $n \to \infty$. One can see this using our formula for composition of two maps, as in (6.4.2), or, simpler, by substituting Taylor expansion series up to order r of one map in the other.

For $\varepsilon > 0$ the sequence $F_{j(n)}^{-1}$ has been proved in (6.4.1) to be uniformly bounded in $C^{r+\varepsilon}$ and every convergent subsequence has the same limit, being the limit in C^r. Therefore this is a limit in $C^{r+\varepsilon}$.

If we denote the limit by G_j we conclude that

$$F_{j'|j} = G_{j'} \circ G_j^{-1} \qquad (6.4.3)$$

defined above is $C^{r+\varepsilon}$.

The proof of 2. $\Rightarrow$ 1. The embedding h in Proof of Theorem 6.2.10 is the right one. Indeed, $\hat{S}(\ldots, 1, 1)$ coincides with h by construction and $s_h = s_{\hat{S}} = F_{(\ldots,1,1)|(\ldots,1,i)} \circ A_i$, where A_i is rescaling to $[0,1]$ of $I_i, i = 1, \ldots, d$ in the ratio geometry of $\hat{S}(\ldots, 1, 1)$. ♣

Remark 6.4.4. Theorem 6.4.2 (more precisely smoothness of G_j in (6.4.3)), yields a new proof of Theorem 6.3.2, in full generality, that is including the case $\varepsilon = 0$. Indeed one can define $\phi = G_j(h_2)^{-1} \circ G_j(h_1)$ for an arbitrary $j \in \Sigma^{d*}$, where $G_j(h_i), i = 1, 2$ means G_j for h_i.

In the case the ranges of s_{h_1}, s_{h_2} are not the whole $[0,1]$, we define G_j as limit of $F_{j(n+n_0)|j(n_0)}$ so ϕ is defined only on some $I_{j_{-n_0},\ldots,j_{-1}}$, for n_0 large enough that this F makes sense. Then we define ϕ on a neighbourhood of $h_1(\Sigma^d)$ as $s_{h_2}^{n_0} \circ \phi \circ (s_{h_1}|_{I_{j_{-n_0},\ldots,j_{-1}}})^{-n_0}$.

Theorem 6.4.5. *For every $r = 1, 2, \ldots$ and $\varepsilon : 0 \le \varepsilon < 1$ with $r + \varepsilon > 1$ there is a scaling function S such that there is $h \in \mathcal{H}ed$, a $C^{r+\varepsilon}$ embedding with the scaling function S, but there is no $C^{r+\varepsilon'}$ embedding with $\varepsilon' > \varepsilon$. There is also S admitting a C^∞ embedding but not real-analytic.*

This Theorem adresses in particular Example 6.2.14, giving a different approach.

Proof. Consider $d > 1$ disjoint closed intervals I_j in $[0,1]$, with I_1 having 0 as an end point, and f mapping each I_j onto $[0,1]$, so that $f|_{I_j}$ is affine for each $j = 2, \ldots, d$ and $C^{r+\varepsilon}$ on I_1 but not $C^{r+\varepsilon'}$, say at 0 (or C^∞ but not analytic

at 0). This produces $h \in C^{r+\varepsilon}\mathcal{H}$. Choose any sequence $j \in \Sigma^{d*}$ not containing
1's, say $j = (\ldots, 2, 2, 2)$. Then, for the arising scaling function S, we have

$$\hat{S}(j) = h \quad \text{and} \quad \hat{S}(j1) = A \circ (f|_{I_1})^{-1} \circ h,$$

where A is the affine rescaling of I_1 to $[0,1]$.

So $f|_{I_1} \circ A^{-1} : [0,1] \to [0,1]$ maps the Cantor set $\mathrm{Can}(j1)$ to $\mathrm{Can}(j)$. Its
restriction to $\mathrm{Can}(j1)$ cannot extend $C^{r+\varepsilon'}$ since its derivatives up to order r
are computable already on C and $f^{(r)}$ is not ε'-Hölder, by construction. So
S cannot admit $C^{r+\varepsilon'}$ embedding by Theorem 6.4.2. The case of C^{∞} but not
analytic is dealt with similarly.   ♣

6.5   Cantor sets generating families

We shall discuss here a general construction of a $C^{1+\varepsilon}$ Cantor repeller in $\mathbb{R}$
which will be used in the next section.

Definition 6.5.1. We call a family of maps $F = \{f_{n,j} : n = 0, 1, \ldots, \ j = 1, .., d\}$ of a closed interval $I \subset \mathbb{R}$ into itself a *Cantor set generating family* if
the following conditions are satisfied:

All $f_{n,j}$ are $C^{1+\varepsilon}$-smooth and uniformly bounded in the $C^{1+\varepsilon}$-norm, they
preserve an orientation in $\mathbb{R}$. There exist numbers $0 < \lambda_1 < \lambda_2 < 1$ such that
for every n, j $\lambda_1 < |(f_{n,j})'|$ and $\frac{|f_{n,j}(I)|}{|I|} < \lambda_2$ (a natural stronger assumption
would be $|f_{n,j})'| < \lambda_2$ but we need the weaker one for a later use).

For every n all the intervals $f_{n,j}(I)$ are pairwise disjoint and ordered according-
ing to j's and the gaps between them are bounded away from 0.

Given a Cantor set generating family $F = \{f_{n,j} : n = 0, 1, \ldots, \ j = 1, .., d\}$
we write

$$I_{j_0, \ldots, j_n}(F) := (f_{0,j_0} \circ \cdots \circ f_{n,j_n})(I)$$

Then we obtain the announced Cantor set as

$$C(F) := \bigcap_{n=0}^{\infty} E_n(F), \quad wh\!ere \ E_n(F) = \bigcup_{(j_0, \ldots, j_n)} I_{j_0, \ldots, j_n}(F)$$

and the corresponding coding $h(F)$ defined by

$$h(F)((j_0, j_1, \ldots)) = \bigcap_{n \to \infty} I_{j_0, \ldots, j_n}(F).$$

It is easy to see that $h(F)$ has bounded geometry (we leave it as an exercise
to the reader).

Theorem 6.5.2. *Let $F_{\nu} = \{f_{\nu,n,j} : n = 0, 1, \ldots, \ j = 1, .., d\}$ be two Cantor set
generating families, for $\nu = 1$ and $\nu = 2$. Suppose that for each $j = 1, \ldots, d$*

$$\lim_{n \to \infty} \mathrm{dist}_{C_0}(f_{1,n,j}, f_{2,n,j}) = 0.$$

and the convergence is exponential.

Then $h(F_1)$ and $h(F_2)$ are $C^{1+\varepsilon}$-equivalent.

Proof. Observe that the notation is consistent with that at the beginning of Section 6.1, except the situation is more general, it is like that in Remark 6.2.6.

For every $s \leq t$, $\nu = 1, 2$, we denote $(f_{\nu,(s,j_s)} \circ \cdots \circ f_{\nu,(t,j_t)})(I)$ by $I_{\nu,(s,j_s),\ldots,(t,j_t)}$. For every such I_w we denote the left end by lI_w and the right end by rI_w. Observe that although we have not assumed $|f'_{\nu,n,j}| < \lambda_2$ we can deduce from our weaker assumptions (using the bounded distortion property for the iterates) that there exists $k \geq 1$ so that for every $l \geq 0$ and $j_i, i = 0, \ldots, k-1$ we have $|(f_{\nu,l+k-1,j_{k-1}} \circ \cdots \circ f_{\nu,l+i,j_i} \circ \cdots \circ f_{\nu,l,j_0})'| < \lambda_2 < 1$. In future to simplify our notation we assume however that $k = 1$. The general case can be dealt with for example by considering the new family of k compositions of the maps of the original family.

For every $w = ((s, j_s), (s+1, j_{s+1}), \ldots, (t, j_t))$, $w' = ((s+1, j_{s+1}), \ldots, (t, j_t))$ we have

$$
\begin{aligned}
|lI_{1,w} - lI_{2,w}| &\leq |f_{1,s,j_s}(lI_{1,w'}) - f_{1,s,j_s}(lI_{2,w'})| \\
&\quad + |f_{1,s,j_s}(lI_{2,w'}) - f_{2,s,j_s}(lI_{2,w'})| \leq |lI_{1,w'} - lI_{2,w'}| + \text{Const} \exp -\delta s
\end{aligned}
\tag{6.5.1}
$$

for some $\delta > 0$ lower bound of the exponential convergence in the assumptions of Theorem.

Thus for every $w = ((m, j_m), \ldots, (n, j_n))$ we obtain for $t = n$, by induction for $s = n-1, n-2, \ldots, m$

$$
|lI_{1,w)} - lI_{2,w}| \leq \text{Const} \exp -\delta m
\tag{6.5.2}
$$

For every $j = 1, \ldots, d$ we obtain the similar estimate with w replaced by $w, (n+1), j$. We obtain also the similar inequalities for the right ends.

As a result of all that we obtain

$$
\left| \frac{|I_{1,w,(n+1,j)}|}{|I_{1,w}|} - \frac{|I_{2,w,(n+1,j)}|}{|I_{1,w}|} \right| \leq \text{Const} \, \lambda_1^{-(n-m)} \exp -\delta m
$$

Now iterating by $f_{\nu,m-1}, f_{\nu,m-2}, \ldots, f_{\nu,0}$ for $\nu = 1, 2$ almost does not change proportions as we are already in a small scale, more precisely we get

$$
\left| \frac{I_{j_0,\ldots,j_n,j}(F_1)}{I_{j_0,\ldots,j_n}(F_1)} - \frac{I_{j_0,\ldots,j_n,j}(F_2)}{I_{j_0,\ldots,j_n}(F_2)} \right| \leq \text{Const} \left((\lambda_1^{-(n-m)} \exp -\delta m) + \lambda_2^{(n-m)\varepsilon} \right).
\tag{6.5.3}
$$

The same holds for gaps in numerators including "false" gaps i.e. for $j = 0, \ldots, d$.

Now we pick $m = (1 - \kappa)n$ where κ is a constant such that $0 < \kappa < 1$ and

$$
\kappa \log \lambda_1^{-1} - (1 - \kappa)\delta := \vartheta < 0
$$

Then the bound in (6.5.3) replaces by $(\exp \vartheta n) + \lambda_2^{(\varepsilon\kappa)n}$ which converges to 0 exponentially fast for $n \to \infty$.

So our Theorem follows from Theorem 6.1.6, more precisely from its variant described in Remark 6.2.6.

We have also the following

Theorem 6.5.3. *Let* $F = \{f_{n,j} : n = 0, 1, \ldots, \ j = 1, .., d\}$ *be a Cantor set generating family such that for every* j

$$f_{n,j} \to f_{\infty,j} \qquad uniformly \ \ as \ n \to \infty.$$

Then the shift map on the Cantor set $C(F)$ *extends* $C^{1+\varepsilon}$.

Proof. For any Cantor set generating family Φ, every $w = (j_0, \ldots, j_n), j \in \{0, \ldots, 2d\}$ we use the notation $A_j(\Phi, w)$ similarly as in Definition 6.1.1, i.e. for j odd $A_j(\Phi, w) = \frac{I_{wj'}(\Phi)}{I_w(\Phi)}$ where $j' = \frac{j+1}{2}$. The similar definition is for j's even with gaps in the numerators. Again we are in the situation of Remark 6.2.6 including $j = 0, d$.

Consider together with F the family $F' = \{f'_{n,j} : n = 0, 1, \ldots, \ j = 1, .., d\}$ where $f'_{n,j} = f_{n+1,j}$. For every $w = (j_0, \ldots, j_n), j \in \{0, \ldots, 2d\}$ say j odd and $i \in \{1, \ldots, d\}$ we rewrite for clarity the definitions:

$$A_(F, iw) = \frac{|I_{iwj'}(F)|}{|I_{iw}(F)|} = \frac{|f_{0,i} \circ f_{1,j_0} \circ \cdots \circ f_{n+1,j_n} \circ f_{n+2,j}(I)|}{|f_{0,i} \circ f_{1,j_0} \circ \cdots \circ f_{n+1,j_n}(I)|}$$

$$A_j(F', w) = \frac{|f_{1,j_0} \circ \cdots \circ f_{n+1,j_n} \circ f_{n+2,j}(I)|}{|f_{1,j_0} \circ \cdots \circ f_{n+1,j_n}(I)|}$$

We have

$$\left| \frac{A_j(F, iw)}{A_j(F', w)} - 1 \right| \leq \mathrm{Const} \exp{-\delta n}$$

for some constant $\delta > 0$ related to the distortion of $f_{0,i}$ on the interval $f_{1,j_0} \circ \cdots \circ f_{n+1,j_n}(I)|$.

So

$$|A_j(F, iw) - A_j(F', w)| \leq \mathrm{Const} \exp{-\delta n}$$

But

$$|A_j(F', w) - A_j(F, w)| \leq \mathrm{Const} \exp{-\delta n}$$

for some $\delta' > 0$ because the pair of the families F, F' satisfies the assumptions of Theorem 6.5.2.

Thus $|A_j(F, iw) - A_j(F, w)|$ converge to 0 uniformly exponentially fast in length of w. So we can apply Theorem 6.2.4, more precisely the variant from Remark 6.2.6. Proof of Theorem 6.5.3 is over.

6.6 Quadratic-like maps of the interval, an application to Feigenbaum's universality

We show here how to apply the material of the previous Section 6.5 to study "attracting" Cantor sets, being closures of forward orbits of critical points, appearing for Feigenbaum-like and more general so-called infinitely renormalizable unimodal maps of the interval. The original map on such a Cantor set is not expanding at all, but one can view these sets almost as expanding repellers by constructing for them so-called generating families of expanding maps

We finish this Chapter with a beautiful application: First Feigenbaum's universality. It was numerically discovered by M.J. Feigenbaum and independently by P. Coullet and Ch. Tresser).

Rigorously this universality has been explained "locally" by O. Lanford, who proved the existence of the renormalization operator fixed point, later on for large classes of maps by D.Sullivan who applied quasi-conformal maps techniques, and next, more completely, by several other mathematicians, in particular in fundamental contribution by C. McMullen, [McMullen 1996] We refer the reader to the Sullivan's breakthrough paper [Sullivan 1991]: "Bounds, Quadratic Differentials and Renormalization Conjectures". Fortunately a small piece of this can be easily explained with the use of elementary Theorems 6.5.2 and 6.5.3; we shall explain it below.

Let us start with a standard example: the one-parameter family of maps of the interval $I = [0, 1]$ into itself $f_\lambda(x) = \lambda x(1-x)$. For $1 < \lambda < 3$ there are two fixed points in $[0, 1]$ a source at 0 i.e. $|f'_\lambda(0)| > 1$ and a sink x_λ, $|f'_\lambda(x_\lambda)| < 1$, attracting all the points except 0,1 under iterations of f_λ. For $\lambda = 3$ this sink changes to a neutral fixed point, namely $|f'_\lambda(x_\lambda)| = 1$, more precisely $f'_\lambda(x_\lambda) = -1$. For λ growing beyond 3 this point changes to a source and nearby an attracting periodic orbit of period 2 gets born. f^2 maps the interval $I_0 = [x'_\lambda, x_\lambda]$ into itself (x'_λ denotes the point symmetric to x_λ with respect to the critical point $1/2$).
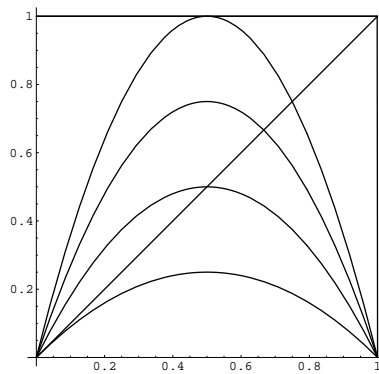

Figure 6.2: Logistic family

If λ continues to grow the left point of this period 2 orbit crosses $1/2$, the derivative of f_λ^2 at this point changes from positive to negative until it reaches the value -1. The periodic orbit starts to repel and an attracting periodic orbit of period 4 gets born. For f^2 on I_0 this means the same bifurcation as before: a periodic orbit of period 2 gets born. The respective interval containing $1/2$ invariant for f^4 will be denoted by I_2. Etc. Denote the values of λ where the consecutive orbits of periods 2^n get born by λ_n. For the limit parameter $\lambda_\infty = \lim_{n\to\infty} \lambda_n$ there are periodic orbits of all periods 2^n all of them sources, see the figure below
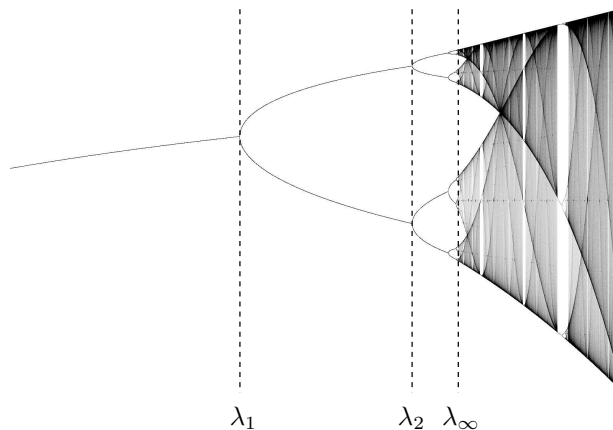
Figure 6.3: Bifurcation diagram

In effect, for λ_∞ we obtain a Cantor set $C(f_{\lambda_\infty}) = \bigcap_{n=1}^{\infty} \bigcup_{k=0}^{2^n-1} f_{\lambda_\infty}^k(I_n)$. This Cantor set attracts all points except the abovementioned sources. It contains the critical point $1/2$ and is precisely the closure of its forward orbit.

Instead of the quadratic polynomials one can consider quite an arbitrary one-parameter family g_λ of C^2 maps of the unit interval with one critical point where the second derivative does not vanish and such that $g_\lambda(0) = g_\lambda(1) = 0$ so that, roughly, the parameter raises the graph. Again one obtains period doubling bifurcations and for the limit parameter $\lambda_\infty(g)$ one obtains the same topological picture as above. We say the map is *Feigenbaum-like*. The Feigenbaum's and Coullet, Tresser's numerical discovery was that the deeper ratios in the Cantor set the weaker dependence of the ratios on the family and that the ratios at the critical point stabilize with the growing magnifications. Moreover the limit quantities do not depend on g.

Another numerical discovery, not to be discussed here, see for example [Avila, Lyubich & de Melo 2003] for a rigorous explanation, was that λ_n/λ_{n+1} has a limit as $n \to \infty$. Moreover this limit does not depend on g. We call it second Feigenbaum's universality.

Let us pass to the description of a general situation:

Definition 6.6.1. For any closed interval $[a, b]$ we call a mapping $f : [a, b] \to [a, b]$ *smooth quadratic-like* if $f(a) = f(b) = a$ and f can be decomposed into $f = Q \circ h$ where Q is a quadratic polynomial and h is a smooth diffeomorphism of I. The word smooth will be applied below for C^2. Here we allow $a > b$, in such a case the interval $[b, a]$ is under the consideration of course and its right end rather than the left is a fixed point and the map has minimum at the critical point. If $a = 0, b = 1$ we say that f is *normalized*.

We call f *infinitely renormalizable* if there exists a decreasing sequence of intervals $I_n, n = 0, 1, 2, \ldots$ all containing the critical point c_f and a sequence of integers $d_n \geq 2$ such that for every n all $f^j(I_n)$ have pairwise disjoint interiors for $j = 0, 1, \ldots, D_n - 1$ where $D_n := \prod_{i=0,\ldots,n} d_i$ and $f^{D_n}(I_n)$ maps I_n into itself.

We call the numbers d_n and the order in which the intervals $f^j(I_n)$ are placed in I a *combinatorics* of f. Finally we say that an infinitely renormalizable f has *bounded combinatorics* if all d_n are uniformly bounded. We write $C(f) = \bigcap_{n=0}^{\infty} \bigcup_{k=0}^{D_n - 1} f^k(I_n)$.

It may happen that the maps f^{D_n} on I_n are not quadratic-like because the assumption $f(a) = f(b) = a$ is not satisfied.

Consider however an arbitrary $f : [a, b] \to [a, b]$ which is smooth quadratic-like and *renormalizable* what means that there exists $I_0 \subset [a, b]$ containing c_f and an integer $d > 1$ such that all $f^j(I_0)$ have pairwise disjoint interiors for $j = 0, 1, \ldots, d - 1$. Then I_0 can be extended to an interval I_0' for which still all $f^j(I_0')$ have pairwise disjoint interiors f^d maps I_0' into itself and f^d on I_0' is quadratic-like. The proof is not hard, the reader can do it as an exercise or look into [Collet & Eckmann 1980]. The periodic end of I_0' is called a *restrictive central point*.

We define the *rescaling map* R_f as such an affine map which transforms I_0' onto I and

$$f_1 := R_f \circ f^d \circ R_f^{-1} \tag{6.6.1}$$

is normalized. We call the operator $f \mapsto f_1$ the *renormalization operator* and denote it by $\mathcal{R}$. (Caution: d, I_0' and so $\mathcal{R}$ have not been uniquely defined but this will not hurt the correctness of the considerations which follow, in particular in the infinitely renormalizable case $C(f)$ does not depend on these objects as the closure of the forward orbit of the critical point, see the remark ending Proof of Theorem 6.6.3.)

Now for an arbitrary smooth quadratic-like map f of $I = [0, 1]$ infinitely renormalizable with a bounded combinatorics, we consider a sequence of maps f_n defined by induction: $f_0 = f$, $f_n = \mathcal{R}(f_{n-1})$. The domain I_0' for the renormalization of f_n is denoted by I^n and we have the affine rescaling map $R_n := R_{f_n}$ from I^n onto I and $f_{n+1} = \mathcal{R}(f_n) = R_n \circ f^{d_n} \circ R_n^{-1}$.

Now we can formulate the fundamental Sullivan-McMullen's theorem:

Theorem 6.6.2. *Suppose f and g are two C^2-quadratic-like maps of $I = [0, 1]$ both infinitely renormalizable with the same bounded combinatorics. Then*

$\mathrm{dist}(R_{f_n}, R_{g_n}) \to 0$ *as* $n \to \infty$. *Moreover both sequences* f_n *and* g_n *stay uniformly bounded as* $C^{1+\varepsilon}$-*quadratic-like maps (i.e.* h's *and* h^{-1}'s *in the* $Q \circ h$ *decomposition stay uniformly bounded in* $C^{1+\varepsilon}$*) and*

$$\mathrm{dist}_{C^0}(f_n, g_n) \to 0.$$

In the case f, g are real-analytic the convergence is exponentially fast, even in the C^0-topology in complex functions on a neighbourhood of I in $\mathbb{C}$.

The intuitive meaning of the above is that the larger magnification of a neighbourhood of 0 the more the same the respective iterates of f and g look like. The same geometry of the depths of the Cantor sets would mean that the similar looks close to zero propagate to the Cantor sets.

Now we can fulfill our promise and relying on the results of this section prove this propagation property, i.e. relying on Theorem 6.6.2 prove rigorously the Feigenbaum universality:

Theorem 6.6.3. *Suppose* f *and* g *are two* C^2-*quadratic-like maps of* $I = [0, 1]$ *both infinitely renormalizable with the same bounded combinatorics. Suppose also that the convergences in the assertion of Theorem 6.6.2 are exponential. Then* $C(f)$ *and* $C(g)$ *are* $C^{1+\varepsilon}$-*equivalent Cantor sets.*

Proof. Related to f we define a generating family (Definition 6.5.1) $F = \{f_{n,j}, n = 0, 1, \ldots, j = 1, \ldots, d_n\}$. Namely we define

$$f_{n,j} = f_n^{-(d_n - j + 1)} \circ R_n^{-1} \tag{6.6.2}$$

where each $f_n^{-(d_n - j + 1)}$ means the branch leading to an interval containing $f^{j-1}(I^n)$.

The $C^{1+\varepsilon}$ uniform boundedness of $f_{n,j}$'s follows immediately from the boundedness asserted in Theorem 6.6.2 if we know (see the next paragraph) that all I^n's have lengths bounded away from 0. Indeed if we denote $f_n = Q \circ h_n$ we have

$$f_{n,j} = h_n^{-1} \circ Q^{-1} \circ \cdots \circ h_n^{-1} \circ Q^{-1} \circ R_n^{-1}$$

with all h_n^{-1} uniformly bounded in $C^{1+\varepsilon}$ and Q^{-1} as well because their domains are far from the critical value $f(c_{f_n})$. Also $|(R_n)'|$'s are uniformly bounded.

Now $f_n^{d_n}(I^n) \subset I^n$ with I^n arbitrarily small and d_n's uniformly bounded together with the asserted in Theorem 6.6.2 uniform boundedness of f_n's would result in the existence of a periodic sink attracting c_f. Indeed, $|(f_n)'|$ would be small on I^n so as $|(f^{d_n-1})'|$ is bounded on $f_n(I^n)$ by a constant not depending on n. So $|(f^{d_n})'|$ on I^n would be small hence its graph has a unique intersection with the diagonal which the sink attracting I^n.

This is almost the end of the proof because we construct the analogous generating family G for g and refer to Theorem 6.1.6. The convergence assumed there, can be proved similarly as we proved the uniform $C^{1+\varepsilon}$-boundness above. This concerns also the assumptions involving λ_1 and λ_2 in the definition of the generating families. Still however some points should be explained:

1. For each n the intervals $f_{n,j}(I)$ in Definition 6.5.1 were ordered in $\mathbb{R}$ according the order $<$ in the integers j. Here it is not so. Moreover $f_{n,j}$ here do not all preserve the orientation in $\mathbb{R}$. Finally d_n's do not be all equal to the same integer d. Fortunately all done before is correct also in this situation.

2. The intervals $f_{n,j}(I)$ may have common ends here, in particular the assumption about gaps in the definition of the generating family may happen not to be satisfied. In that instant we replace I by a slightly smaller interval and restrict all $f_{n,j}$'s to it. We can do it because for each $J = f_{n,j}(I)$ we have $\mathrm{dist}(C(f), \mathrm{ends~of~}J) > \mathrm{Const} > 0$. This is so because for every normalized renormalizable f if $f(c_f)$ is close to 1 then a very large d is needed in order to have $f^d(c_f) \in I_0$ unless $\sup |f'|$ is very large. But all d_n are uniformly bounded in our infinitely renormalizable case and the derivatives $|(f_n)'|$ are uniformly bounded. So for every n, $f_n(c_{f_n})$ is not very close to 1 and $f_n^2(c_{f_n})$ is not very close to 0 and $C(f_n) \subset [f_n(c_{f_n})~f_n^2(c_{f_n})]$.

We managed to present $C(f)$ and $C(g)$ as subsets of Cantor sets $C(F), C(G)$ for generating families. But by the construction every interval $I_{j_0,\ldots,j_n}(F)$ in the definition of $C(F)$ contains an interval of the form $f^j(I_n)$, $0 \le j < D_n$ hence every component of $C(F)$ contains a component of $C(f)$. So $C(f) = C(F)$ and similarly $C(g) = C(G)$. Hence $C(f)$ and $C(g)$ are Cantor sets indeed and everything concerning $C(F), C(G)$ we proved concerns them as well. Observe by the way that by the definition every $f^j(I_n)$ contains $f^j(c_f)$ hence $C(f)$ can be defined in the intrinsic way, independently of the choice of I_n's, as $\mathrm{cl} \bigcup_{j=0}^{\infty} f^j(c_f)$.

The following specification of Theorems 6.6.2 and 6.6.3 holds:

Theorem 6.6.4. *Let f be a C^2 quadratic-like map of $[0,1]$ infinitely renormalizable with a bounded combinatorics. Suppose it is periodic i.e. that for some $n_2 > n_1 \ge 0$ f_{n_1} and f_{n_2} have the same combinatorics. Then there exists g a real-analytic quadratic-like map of $[0,1]$ such that for $t := n_2 - n_1$, $\mathcal{R}^t(g) = g$ and $\mathrm{dist}_{C^0}(f_n, g_{n-n_1}) \to 0$ as $n \to \infty$.*

If the convergence is exponential then the shift map on $C(f_{n_1}^t)$ extends $C^{1+\varepsilon}$.

On the proof. The existence of g is another fundamental result in this theory, which we shall not prove in this book. (The first, computer assisted, proof was provided by O. Lanford [Lanford 1982] for $d = 2$, i.e. for the Feigenbaum-like class.) Then the convergence follows from Theorem 5.4.29. Indeed, from $\mathcal{R}^t(g) = g$ we obtain the convergence of $(f_{n_1}^t)_{n,j}$ to g. If the convergences are exponential (which is the case if f is real-analytic) then the shift map extends $C^{1+\varepsilon}$ due to Theorem 6.5.3. Notice that instead of $C(f)$ we consider $C(f_{n_1}^t)$. This is so because

$$\prod_{j=d_{n_1}}^{d_{n_1}+t-1} d_j = \prod_{j=d_{n_1}+t}^{d_{n_1}+2t-1} d_j = \cdots := d$$

and it makes sense to speak about the shift map on Σ^d. For f itself if we denote $\prod_{j=0}^{\infty} \{1, \ldots, d_j\}$ by $\Sigma(d_0, d_1, \ldots)$ we can speak only about the left side shift map from $\Sigma(d_0, d_1, \ldots)$ to $\Sigma(d_1, \ldots)$.

Observe again that the embedding of Σ^d into I does not need to preserve the order but it does not hurt the validity of Theorem 6.5.3.

The set $C(f)$ is presented as the union of $D = \prod_{j=0}^{n_1-1} d_j$ Cantor sets which are embeddings of Σ^d, of the form $f^j(C(f_{n_1}^t)), j = 0, \ldots, n_1 - 1$, each of which has an exponentially determined geometry and Hölder continuous scaling function.

Remarks 6.6.5. 1. Observe for f being any smooth quadratic-like infinitely renormalizable map of I and the corresponding generating family F, that as some $f_{n,j}$ may change the orientation, the corresponding intervals $I_{j_0,\ldots,j_n,j}(F)$ have the order in $I_{j_0,\ldots,j_n}(F)$ the same or opposite to that of $I_j(F)$'s in I depending as there is even or odd number of $j_i, i = 0, \ldots, n$ such that f_{i,j_i} changes the orientation.

2. Remind that $C(f)$ has a 1-to-1 coding $h : \Sigma(d_0, d_1, \ldots) \to C(f)$ defined by $h(j_0, j_1, \ldots) = \bigcap_{n\to\infty} I_{j_0,\ldots,j_n}(F)$. Let us write here $j = 0, \ldots, d_n - 1$ rather than $j = 1, \ldots, d_n$. Then f yields on $\Sigma(d_0, d_1, \ldots)$ the map $\Phi(f)(j_0, j_1, \ldots) = (0, 0, \ldots, j_i + 1, j_{i+1}, \ldots)$, where i is the first integer such that $j_i \neq d_i - 1$, or $\Phi(f)(j_0, j_1, \ldots) = (0, 0, 0 \ldots)$ if for all i we have $j_i = d_i - 1$. Φ is sometimes called the *adding machine*. If all $d_n = p$ the map Φ is just the adding of the unity in the group of p-adic numbers. For d_n different we have the group structure on $\Sigma(d_0, d_1, \ldots)$ of the inverse limit of the system $\cdots \to \mathbb{Z}_{d_2 d_1 d_0} \to \mathbb{Z}_{d_1 d_0} \to \mathbb{Z}_{d_0}$ and $\Phi(f)$ is also adding the unity.

If we denote the shift map from $\Sigma(d_0, d_1, \ldots)$ to $\Sigma(d_1, \ldots)$ by s we obtain the equality

$$\Phi(f_1) \circ s = s \circ \Phi(f)^{d_0}$$

(the indexing in (6.6.2) has been adjusted to assure this). On I^0 this corresponds to (6.6.1).

3. The combinatorics of an infinitely renormalizable f is determined by the so-called kneading sequence $K(f)$ defined as a sequence of letters L and R, where $n = 1, 2, \ldots$ such that at the n'th place we have L or R depending as $f^n(c_f)$ is left or right of c_f in $\mathbb{R}$ (we leave it as an exercise to the reader). So in Theorems 6.6.2–6.6.4 we can write: the same kneading sequences, instead of: the same combinatorics.

Also the property: renormalizable (and hence: infinitely renormalizable) can be guessed from the look of the kneading sequence. A renormalization with I_0 and $f^d(I_0) \subset I_0$ implies of course that the kneading sequence is of the form $AB_1 AB_2 AB_3 \ldots$, where each B_i is L or R and A is a block built from L's and R's of the length $d-1$. The converse is also true, the proof is related to the proof of the existence of the restrictive central point. One can do it as an exercise or to look into [Collet & Eckmann 1980].

4. Let us go back now to the example f_{λ_∞}, or more general $g_{\lambda_\infty(g)}$ mentioned at the beginning of this Section. We have $d_n = 2$ for all n, (R_n change orientation). So we can apply Theorems 6.6.3 and 6.6.4 which explain Feigenbaum's and Coullet-Tresser's discoveries.

Observe that $g_{\lambda_\infty(g)}$ is exceptional among smooth quadratic-like infinitely renormalizable maps. Namely except a sequence of periodic sources every point

is being attracted to $C(f)$. Topological entropy is equal to 0. For every infinitely renormalizable map with a different kneading sequence there is an invariant repelling Cantor set (in fact some of its points can be blown up to intervals). Topological entropy is positive on it. One says that such a map is already *chaotic*, while $g_{\lambda_\infty(g)}$ is on the *boundary of chaos*.

Exercises

6.1. For maps as in Definition 6.6.1, prove the existence of the restrictive central point.

Hint: Consider the so-called Guckenheimer set,

$$G_d = \{x : \mathrm{dist}_f(f^d(x), c_f) < \mathrm{dist}_f(x, c_f) \text{ and}$$
$$\mathrm{dist}_f(f^j(x), c_f) > \mathrm{dist}_f(x, c_f) \text{ for } j = 1, \ldots, d-1\}$$

where $\mathrm{dist}_f(x, y) = |h(x) - h(y)|$ in the decomposition $f = Q \circ h$.

6.2. Suppose f and g are smooth quadratic-like maps of $I = [0, 1]$ both infinitely renormalizable with the same bounded combinatorics as in Theorem 6.6.2. Using the fact that $\mathrm{dist}_{C^0}(f_n, g_n) \to 0$ asserted there, but not assuming the convergence is exponential prove that the standard conjugacy ϕ between $C(f)$ and $C(g)$ is 1-quasisymmetric, more precisely that for every $x, y, z \in C(f), x > y > z$, $|x - y|/|y - z| < \mathrm{Const}$ we have $\frac{|\phi(x)-\phi(y)|/|\phi(y)-f(z)|}{|x-y|/|y-z|} \to 1$ as $x - z \to 0$. In particular if the scaling function $S(f)$ exists for f then it exists for g and $S(f) = S(g)$.

Hint: One can modify Proof of Theorem 6.5.2. Instead of $\exp -\delta s$ in (6.5.1) one has some a_n converging to 0 as $n \to \infty$. Then in (6.5.2) we estimate by $\sum_{s=m}^n a_s$ and then consider $m = m(n)$ so that $n - m \to \infty$ but $\sum_{s=m}^n a_s \to 0$ as $n \to \infty$.

6.3. Let f and g be unimodal maps of the interval $[0, 1]$ (f unimodal means continuous, having unique critical point c, being strictly increasing left to it and strictly decreasing right to it, $f(c) = 1$), having no interval J on which all iterates are monotone. Prove that f and g are topologically conjugate iff they have the same kneadings sequences (see Remark 6.6.5, item 3.)

6.4. Prove that for $f \in C^3$ a unimodal map of the interval with no attracting (from both or one side) periodic orbit, if Schwarzian derivative $S(f)$ is negative, then there are no homtervals, i.e. intervals on which all iterates of f are monotone.

Hint: First prove that there is no homterval whose forward orbit is disjoint with a neighbourhood of the critical point c_f (A. Schwartz's Lemma; one does not use $S(f) < 0$ here, C^{1+1} is enough).

Next use the property implied by $S(f) < 0$, that for all n and every interval J on which $(f^n)'$ is non-zero, $(f^n)'$ is monotone on J.

For details see for example [Collet-Eckmann]

6.5. Prove the $C^{r+\varepsilon}$ version of the so-called Folklore Theorem, saying that if $0 = a_0 < a_1 < \cdots < a_{n-1} < a_n = 1$ and for each $i = 0, \ldots, n-1$, $f_i : [a_i, a_{i+1}] \to [0, 1]$ onto, each f_i is $C^{r+\varepsilon}$ for $r \geq 2, 0 \leq \varepsilon \leq 1, r + \varepsilon > 2$ and $|f_i'| \geq$ Const > 1, then for f defined as f_i on each (a_i, a_{i+1}), there exists an f invariant probability μ equivalent to Lebesgue measure, with the density bounded away from 0, of class $C^{r-1+\varepsilon}$.

Formulate and prove an analogous version for Cantor sets $h(\Sigma^d)$ with "shifts" $h \circ s \circ h^{-1}$, as in Section 6.2.

Hint: The existence of μ follows from Hölder property of the potential function $\phi = -\log|f'|$, see Chapter 4. μ is the invariant Gibbs measure. Its density is $\lim_{n \to \infty} \mathcal{L}_\phi^n(\mathbb{1})(x) = \sum_{y \in f^{-n}(x)} |(f^n)'(y)|^{-1}$. Each summand considered along an infinite backward branch, after rescaling, converges in $C^{r-1+\varepsilon}$, see Theorem 5.4.23, smoothness of G_j.

A slightly different proof can be found for example in [Boyarsky & Góra 1997].

Bibliographical notes

As we already mentioned, this Chapter bases mainly on [Sullivan 1988], [Sullivan 1991] and xcitPT. A weak version of Theorem 6.5.2 was independently proved by W. Paluba in [Paluba 1989].

A version of most of the theory presented in this Chapter was published also by A. Pinto and D. Rand in [Pinto & Rand 1988], [Pinto & Rand 1992]. They proved moreover that the canonical conjugacy between two real-analytic quadratic-like maps as in Theorem 6.6.2 is $C^{2+0.11}$, using numerical results on the speed of contraction (leading eigenvalues) of the renormalization operator at the Feigenbaum fixed point.

In Proof of Theorem 6.6.3 we were proving for the families F and G that the assumptions of Theorem 5.4.26 were satisfied i.e. that F and G were Cantor set generating families. This implied that the Cantor sets $C(F), C(G)$, more precisely $h(F), h(G)$ have bounded geometries. In fact this can be proved directly (though it is by no mean easy) without referring to the difficult Theorem 6.6.2, see for example [de Melo & van Strien 1993].

Moreover this bounded geometry phenomenon is in fact the first step (real part) in the proof of the fundamental Theorem 6.6.2 (which includes also a complex part), see [Sullivan 1991]. Instead of C^2 one can assume weaker C^{1+z}, z for Zygmund, see [Sullivan 1991] or [de Melo & van Strien 1993].

The exponential convergence in Theorem 6.6.2 for analytic f, g was proved by C. McMullen in [McMullen 1996]. Recently the exponential convergence for $f, g \in C^2$ was proved, by W. de Melo and A. Pinto, see [de Melo & Pinto 1999].

The first proof of the existence of g as in Theorem 6.6.4 and the exponential convergence of $\mathcal{R}^n(f)$ to g was provided by O. Lanford [Lanford 1982] for f very close to g, in the case of Feigenbaum-like maps. His prove did not use the bounded geometry of the Cantor set.

For each $k \geq 3$ the convergence in C^k in Theorem 6.6.2 for all $f, g \in C^k$, (symmetric) was proved in [Avila, Martens & de Melo 2001].

For deep studies concerning the hyperbolicity of the renormalization operator at periodic points and laminations explaining the second Feigenbaum universality, see recent papers [Lyubich 1999], [Avila, Lyubich & de Melo 2003], [Smania 2005], [de Faria *et al.* 2006].

Chapter 7

Fractal dimensions

In the first section of this chapter we provide a more complete treatment of outer measure begun in Chapter 1. The rest of this chapter is devoted to present basic definitions related to Hausdorff and packing measures, Hausdorff and packing dimensions of sets and measures and ball (or box) -counting dimensions.

7.1 Outer measures

In Section 1.1 we have introduced the abstract notion of measure. In the beginning of this section we want to show how to construct measures starting with functions of sets called *outer measures* which are required to satisfy much weaker conditions. Our exposition of this material is brief and the reader should find its complete treatment in all handbooks of geometric measure theory (see for example [Falconer 1997], [Mattila 1995] or [Pesin 1997]).

Definition 7.1.1. An *outer measure* on a set X is a function μ defined on all subsets of X taking values in $[0, \infty]$ such that

$$\mu(\emptyset) = 0, \tag{7.1.1}$$
$$\mu(A) \leq \mu(B) \text{ if } A \subset B \tag{7.1.2}$$

and

$$\mu\Big(\bigcup_{n=1}^{\infty} A_n \Big) \leq \sum_{n=1}^{\infty} \mu(A_n) \tag{7.1.3}$$

for any countable family $\{A_n : n = 1, 2, \ldots\}$ of subsets of X.

A subset A of X is called μ-*measurable* or simply *measurable with respect to the outer measure* μ if and only if

$$\mu(B) \geq \mu(B \cap A) + \mu(B \setminus A) \tag{7.1.4}$$

for all sets $B \subset X$. Check that the opposite inequality follows immediately from (7.1.3). Check also that if $\mu(A) = 0$ then A is μ-measurable.

Theorem 7.1.2. *If μ is an outer measure on X, then the family $\mathcal{F}$ of all μ-measurable sets is a σ-algebra and the restriction of μ to $\mathcal{F}$ is a measure.*

Proof. Obviously $X \in \mathcal{F}$. By symmetry of (7.1.4), $A \in \mathcal{F}$ if and only if $A^c \in \mathcal{F}$. So, the conditions (1.1.1) and (1.1.2) of the definition of σ-algebra are satisfied. To check condition (1.2.5) that $\mathcal{F}$ is closed under countable union, suppose that $A_1, A_2, \ldots \in \mathcal{F}$ and let $B \subset X$ be any set. Applying (7.1.4) in turn to $A_1, A_2, \ldots$ we get for all $k \geq 1$

$$
\begin{aligned}
\mu(A) &\geq \mu(B \cap A_1) + \mu(B \setminus A_1) \\
&\geq \mu(B \cap A_1) + \mu((B \setminus A_1) \cap A_2) + \mu(B \setminus A_1 \setminus A_2) \\
&\geq \ldots \\
&\geq \sum_{j=1}^{k} \mu\left(\left(B \setminus \bigcup_{i=1}^{j-1} A_i\right) \cap A_j\right) + \mu\left(B \setminus \bigcup_{j=1}^{k} A_j\right) \\
&\geq \sum_{j=1}^{k} \mu\left(\left(B \setminus \bigcup_{i=1}^{j-1} A_i\right) \cap A_j\right) + \mu\left(B \setminus \bigcup_{j=1}^{\infty} A_j\right)
\end{aligned}
$$

and therefore

$$
\mu(A) \geq \sum_{j=1}^{\infty} \mu\left(\left(B \setminus \bigcup_{i=1}^{j-1} A_i\right) \cap A_j\right) + \mu\left(B \setminus \bigcup_{j=1}^{\infty} A_j\right) \tag{7.1.5}
$$

Since

$$
B \cap \bigcup_{j=1}^{\infty} A_j = \bigcup_{j=1}^{\infty} \left(B \setminus \bigcup_{i=1}^{j-1} A_i\right) \cap A_j
$$

using (7.1.3) we thus get

$$
\mu(A) \geq \mu\left(\bigcup_{j=1}^{\infty} \left(B \setminus \bigcup_{i=1}^{j-1} A_i\right) \cap A_j\right) + \mu\left(B \setminus \bigcup_{j=1}^{\infty} A_j\right)
$$

Hence condition (1.1.3) is also satisfied and $\mathcal{F}$ is a σ-algebra. To see that μ is a measure on $\mathcal{F}$ i.e. that condition (1.1.4) is satisfied, consider mutually disjoint sets $A_1, A_2, \ldots \in \mathcal{F}$ and apply (7.1.5) with $B = \bigcup_{j=1}^{\infty} A_j$ to get

$$
\mu\left(\bigcup_{j=1}^{\infty} A_j\right) \geq \sum_{j=1}^{\infty} \mu(A_j)
$$

Combining this with (7.1.3) we conclude that μ is a measure on $\mathcal{F}$.   ♣

Now, let (X, ρ) be a metric space. An outer measure μ on X is said to be a *metric outer measure* if and only if

$$
\mu(A \cup B) = \mu(A) + \mu(B) \tag{7.1.6}
$$

for all *positively separated* sets $A, B \subset X$ that is satisfying the following condition

$$\rho(A, B) = \inf\{\rho(x, y) : x \in A, y \in B\} > 0$$

Recall that the Borel σ-algebra on X is that generated by open, or equivalently closed, sets. We want to show that if μ is a metric outer measure then the family of all μ-measurable sets contains this σ-algebra. The proof is based on the following version of Carathéodory's lemma.

Lemma 7.1.3. *Let μ be a metric outer measure on (X, ρ). Let $\{A_n : n = 1, 2, \ldots\}$ be an increasing sequence of subsets of X and denote $A = \bigcup_{n=1}^{\infty} A_n$. If $\rho(A_n, A \setminus A_{n+1}) > 0$ for all $n \geq 1$, then $\mu(A) = \lim_{n \to \infty} \mu(A_n)$.*

Proof. By (7.1.3) it is enough to show that

$$\mu(A) \leq \lim_{n \to \infty} \mu(A_n) \tag{7.1.7}$$

If $\lim_{n \to \infty} \mu(A_n) = \infty$, there is nothing to prove. So, suppose that

$$\lim_{n \to \infty} \mu(A_n) = \sup_n \mu(A_n) < \infty \tag{7.1.8}$$

Let $B_1 = A_1$ and $B_n = A_n \setminus A_{n-1}$ for $n \geq 2$. If $n \geq m + 2$, then $B_m \subset A_m$ and $B_n \subset A \setminus A_{n-1} \subset A \setminus A_{m+1}$. Thus B_m and B_n are positively separated and applying (7.1.6) we get for every $j \geq 1$

$$\mu\left(\bigcup_{i=1}^{j} B_{2i-1}\right) = \sum_{i=1}^{j} \mu(B_{2i-1}) \quad \text{and} \quad \mu\left(\bigcup_{i=1}^{j} B_{2i}\right) = \sum_{i=1}^{j} \mu(B_{2i}) \tag{7.1.9}$$

We have also for every $n \geq 1$

$$\mu(A) = \mu\left(\bigcup_{k=n}^{\infty} A_k\right) = \mu\left(A_n \cup \bigcup_{k=n+1}^{\infty} B_k\right)$$

$$\leq \mu(A_n) + \sum_{k=n+1}^{\infty} \mu(B_k) \leq \lim_{l \to \infty} \mu(A_l) + \sum_{k=n+1}^{\infty} \mu(B_k) \tag{7.1.10}$$

Since the sets $\bigcup_{i=1}^{j} B_{2i-1}$ and $\bigcup_{i=1}^{j} B_{2i}$ appearing in (6.1.9) are both contained in A_{2j}, it follows from (7.1.8) and (7.1.9) that the series $\sum_{k=1}^{\infty} \mu(B_k)$ converges. Therefore (7.1.7) follows immediately from (7.1.10). The proof is finished. ♣

Theorem 7.1.4. *If μ is a metric outer measure on (X, ρ) then all Borel subsets of X are μ-measurable.*

Proof. Since the Borel sets form the least σ-algebra containing all closed subsets of X, it follows from Theorem 7.1.2 that it is enough to check (7.1.4) for every closed set $A \subset X$ and every $B \subset X$. For all $n \geq 1$ let $B_n = \{x \in B \setminus A : \rho(x, A) \geq 1/n\}$. Then $\rho(B \cap A, B_n) \geq 1/n$ and by (7.1.6)

$$\mu(B \cap A) + \mu(B_n) = \mu((B \cap A) \cup B_n) \leq \mu(B) \tag{7.1.11}$$

The sequence $\{B_n\}_{n=1}^{\infty}$ is increasing and, since A is closed, $B \setminus A = \bigcup_{n=1}^{\infty} B_n$. In order to apply Lemma 7.1.3 we shall show that

$$\rho(B_n, (B \setminus A) \setminus B_{n+1}) > 0$$

for all $n \geq 1$. And indeed, if $x \in (B \setminus A) \setminus B_{n+1}$, then there exists $z \in A$ with $\rho(x, z) < 1/(n+1)$. Thus, if $y \in B_n$, then

$$\rho(x, y) \geq \rho(y, z) - \rho(x, z) > 1/n - 1/(n+1) = \frac{1}{n(n+1)}$$

and consequently $\rho(B_n, (B \setminus A) \setminus B_{n+1}) > 1/n(n+1) > 0$. Applying now Lemma 7.1.3 with $A_n = B_n$ shows that $\mu(B \setminus A) = \lim_{n \to \infty} \mu(B_n)$. Thus (7.1.4) follows from (7.1.11). The proof is finished.   ♣

7.2   Hausdorff measures

Let $\phi : [0, \infty) \to [0, \infty)$ be a non-decreasing function continuous at 0, positive on $(0, \infty)$ and such that $\phi(0) = 0$. Let (X, ρ) be a metric space. For every $\delta > 0$ define

$$\Lambda_{\phi}^{\delta}(A) = \inf\Big\{\sum_{i=1}^{\infty} \phi(\mathrm{diam}(U_i))\Big\} \tag{7.2.1}$$

where the infimum is taken over all countable covers $\{U_i : i = 1, 2, \ldots\}$ of A of diameter not exceeding δ. Conditions (7.1.1) and (7.1.2) are obviously satisfied with $\mu = \Lambda_{\phi}^{\delta}$. To check (7.1.3) let $\{A_n : n = 1, 2, \ldots\}$ be a countable family of subsets of X. Given $\varepsilon > 0$ for every $n \geq 1$ we can find a countable cover $\{U_i^n : i = 1, 2, \ldots\}$ of A_n of diameter not exceeding δ such that $\sum_{i=1}^{\infty} \phi(\mathrm{diam}(U_i^n)) \leq \Lambda_{\phi}^{\delta}(A_n) + \varepsilon/2^n$. Then the family $\{U_i^n : n \geq 1, i \geq 1\}$ covers $\bigcup_{n=1}^{\infty} A_n$ and

$$\Lambda_{\phi}^{\delta}\Big(\bigcup_{n=1}^{\infty} A_n\Big) \leq \sum_{n=1}^{\infty} \sum_{i=1}^{\infty} \phi(\mathrm{diam}(U_i^n)) \leq \sum_{n=1}^{\infty} \Lambda_{\phi}^{\delta}(A_n) + \varepsilon$$

Thus, letting $\varepsilon \to 0$, (7.1.3) follows proving that Λ_{ϕ}^{δ} is an outer measure. Define

$$\Lambda_{\phi}(A) = \lim_{\delta \to 0} \Lambda_{\phi}^{\delta}(A) = \sup_{\delta > 0} \Lambda_{\phi}^{\delta}(A) \tag{7.2.2}$$

The limit exists, but may be infinite, since $\Lambda_{\phi}^{\delta}(A)$ increases as δ decreases. Since all Λ_{ϕ}^{δ} are outer measures, the same argument also shows that Λ_{ϕ} is an outer measure. Moreover Λ_{ϕ} turns out to be a metric outer measure, since if A and B are two positively separated sets in X, then no set of diameter less than $\rho(A, B)$ can intersect both A and B. Consequently

$$\Lambda_{\phi}^{\delta}(A \cup B) = \Lambda_{\phi}^{\delta}(A) + \Lambda_{\phi}^{\delta}(B)$$

for all $\delta < \rho(A, B)$ and letting $\delta \to 0$ we get the same formula for Λ_{ϕ} which is just (7.1.6) with $\mu = \Lambda_{\phi}$. The metric outer measure Λ_{ϕ} is called the *Hausdorff*

outer measure associated to the function ϕ. Its restriction to the σ-algebra of Λ_ϕ-measurable sets, which by Theorem 7.1.4 includes all the Borel sets, is called the *Hausdorff measure* associated to the function ϕ.

As an immediate consequence of the definition of Hausdorff measure and the properties of the function ϕ we get the following.

Proposition 7.2.1. *The Hausdorff measure Λ_ϕ is non-atomic.*

Remark 7.2.2. A particular role is played by functions ϕ of the form $t \to t^\alpha$, $t, \alpha > 0$ and in this case the corresponding outer measures are denoted by Λ_α^δ and Λ_α.

Remark 7.2.3. Note that if ϕ_1 is another function but such that ϕ_1 and ϕ restricted to an interval $[0, \varepsilon)$, $\varepsilon > 0$, are equal, then the outer measures Λ_{ϕ_1} and Λ_ϕ are also equal. So, in fact, it is enough to define the function ϕ only on an arbitrarily small interval $[0, \varepsilon)$.

Remark 7.2.4. Notice that we get the same values for $\Lambda_\phi^\delta(A)$, and consequently also for $\Lambda_\phi(A)$, if the infimum in (7.2.1) is taken only over covers consisting of sets contained in A. This means that the Hausdorff outer measure $\Lambda_\phi(A)$ of A is its intrinsic property, i.e. does not depend on in which space the set A is contained. If we treated A as the metric space $(A, \rho|_A)$ with the metric $\rho|_A$ induced from ρ, we would get the same value for the Hausdorff outer measure.

If we however took the infimum in (7.2.1) only over covers consisting of balls, we could get different "Hausdorff measure" which (dependently on ϕ) would need not be even equivalent with the Hausdorff measure just defined. To assure this last property ϕ is from now on assumed to satisy the following condition.

There exists a function $C : (0, \infty) \to [1, \infty)$ such that for every $a \in (0, \infty)$ and every $t > 0$ sufficiently small (dependently on a)

$$C(a)^{-1}\phi(t) \leq \phi(at) \leq C(a)\phi(t) \tag{7.2.3}$$

Since $(ar)^t = a^t r^t$, all functions ϕ of the form $r \to r^t$, considered in Remark 6.2.2, satisfy (7.2.3) with $C(a) = a^t$. Check that all functions $r \to r^t \exp(c\sqrt{\log 1/r \log \log \log 1/r}$, $c \geq 0$ also satisfy (7.2.3) with a suitable function C.

Definition 7.2.5. A countable collection $\{(x_i, r_i) : i = 1, 2, \ldots\}$ of pairs $(x_i, r_i) \in X \times (0, \infty)$ is said to *cover* a subset A of X if $A \subset \bigcup_{i=1}^\infty B(x_i, r_i)$, and is said to be *centered* at the set A if $x_i \in A$ for all $i = 1, 2, \ldots$. The *radius* of this collection is defined as $\sup_i r_i$ and its diameter as the diameter of the family $\{B(x_i, r_i) : i = 1, 2, \ldots\}$.

For every $A \subset X$ and every $r > 0$ let

$$\Lambda_\phi^{Br}(A) = \inf\left\{\sum_{i=1}^\infty \phi(r_i)\right\} \tag{7.2.4}$$

where the infimum is taken over all collections $\{(x_i, r_i) : i = 1, 2, \ldots\}$ centered at the set A, covering A and of radii not exceeding r. Let

$$\Lambda_\phi^B(A) = \lim_{r \to 0} \Lambda_\phi^{Br}(A) = \sup_{r > 0} \Lambda_\phi^{Br}(A) \qquad (7.2.5)$$

The limit exists by the same argument as used for the limit in (7.2.2). We shall prove the following.

Lemma 7.2.6. *For every set $A \subset X$*

$$1 \le \frac{\Lambda_\phi(A)}{\Lambda_\phi^B(A)} \le C(2)$$

Proof. Since the diameter of any ball does not exceed its double radius, since the diameter of any collection $\{(x_i, r_i) : i = 1, 2, \ldots\}$ also does not exceed its double radius and since the function ϕ is non- decreasing and satisfies (7.2.3), we see that for every $r > 0$ small enough

$$\sum_{i=1}^{\infty} \phi(\operatorname{diam}(B(x_i, r_i))) \le \sum_{i=1}^{\infty} \phi(2r_i) \le C(2) \sum_{i=1}^{\infty} \phi(r_i)$$

and therefore $\Lambda_\phi^{2r}(A) \le C(2)\Lambda_\phi^{Br}(A)$. Thus, letting $r \to 0$,

$$\Lambda_\phi(A) \le C(2)\Lambda_\phi^B(A) \qquad (7.2.6)$$

On the other hand, let $\{U_i : i = 1, 2, \ldots\}$ be a countable cover of A consisting of subsets of A. For every $i \ge 1$ choose $x_i \in U_i$ and put $r_i = \operatorname{diam}(U_i)$. Then the collection $\{(x_i, r_i) : i = 1, 2, \ldots\}$ covers A, is centered at A and

$$\sum_{i=1}^{\infty} \phi(r_i) = \sum_{i=1}^{\infty} \phi(\operatorname{diam}(U_i))$$

which implies that $\Lambda_\phi^{B\delta}(A) \le \Lambda_\phi^\delta(A)$ for every $\delta > 0$. Thus $\Lambda_\phi^B(A) \le \Lambda_\phi(A)$ which combined with (7.2.6) finishes the proof.   ♣

Remark 7.2.7. The function of sets Λ_ϕ^B need not to be an outer measure since condition (7.1.2) need not to be satisfied. Since we will be never interested in exact computation of Hausdorff measure, only in establishing its positiveness or finiteness or in comparing the ratio of its value with some other quantities up to bounded constants, we will be mostly dealing with $\Lambda_\phi^{B\delta}$ and Λ_ϕ^B using nevertheless always the symbols $\Lambda_\phi^\delta(A)$ and $\Lambda_\phi(A)$.

7.3   Packing measures

Let, as in the previous section, $\phi : [0, \infty) \to [0, \infty)$ be a non-decreasing function such that $\phi(0) = 0$ and let (X, ρ) be a metric space. A collection $\{(x_i, r_i) : i =$

$1, 2, \ldots\}$ centered at a set $A \subset X$ is said to be a *packing* of A if and only if for any pair $i \neq j$

$$\rho(x_i, x_j) \geq r_i + r_j$$

This property is not generally equivalent to requirement that all the balls $B(x_i, r_i)$ are mutually disjoint. It is obviously so if X is a Euclidean space. For every $A \subset X$ and every $r > 0$ let

$$\Pi_\phi^{*r}(A) = \sup\left\{\sum_{i=1}^\infty \phi(r_i)\right\} \tag{7.3.1}$$

where the supremum is taken over all packings $\{(x_i, r_i) : i = 1, 2, \ldots\}$ of A of radius not exceeding r. Let

$$\Pi_\phi^*(A) = \lim_{r \to 0} \Pi_\phi^{*r}(A) = \inf_{r > 0} \Pi_\phi^{*r}(A) \tag{7.3.2}$$

The limit exists since $\Pi_\phi^{*r}(A)$ decreases as r decreases. In opposite to Λ_ϕ^B the function Π_ϕ^* satisfies condition (7.1.2), however it also need not to be an outer measure since this time condition (7.1.3) need not to be satisfied. To obtain an outer measure we put

$$\Pi_\phi(A) = \inf\left\{\sum \Pi_\phi^*(A_i)\right\}, \tag{7.3.3}$$

where the supremum is taken over all covers $\{A_i\}$ of A. The reader will check easily, with similar arguments as in the case of Hausdorff measures, that Π_ϕ is already an outer measure and even more, a metric outer measure on X. It will be called the *outer packing measure* associated to the function ϕ. Its restriction to the σ-algebra of Π_ϕ-measurable sets, which by Theorem 7.1.4 includes all the Borel sets, will be called *packing measure* associated to the function ϕ.

Proposition 7.3.1. *For every set $A \subset X$ it holds $\Lambda_\phi(A) \leq C(2)\Pi_\phi(A)$.*

Proof. First we shall show that for every set $A \subset X$ and every $r > 0$

$$\Lambda_\phi^{2r}(A) \leq C(2)\Pi_\phi^{*r}(A) \tag{7.3.4}$$

Indeed, if there is no finite maximal (in the sense of inclusion) packing of the set A of the form $\{(x_i, r)\}$, then for every $k \geq 1$ there exists a packing $\{(x_i, r) : i = 1, \ldots, k\}$ of A and therefore $\Pi_\phi^{*r}(A) \geq \sum_{i=1}^k \phi(r) = k\phi(r)$. Since $\phi(r) > 0$, this implies that $\Pi_\phi^{*r}(A) = \infty$ and (7.3.4) holds. Otherwise, let $\{(x_i, r) : i = 1, \ldots, l\}$ be a maximal packing of A. Then the collection $\{(x_i, 2r) : i = 1, \ldots, l\}$ covers A and therefore

$$\Lambda_\phi^{2r}(A) \leq \sum_{i=1}^l \phi(2r) \leq C(2)l\phi(r) \leq C(2)\Pi_\phi^{*r}(A)$$

that is (7.3.4) is satisfied. Thus letting $r \to 0$ we get

$$\Lambda_\phi(A) \leq C(2)\Pi_\phi^*(A) \tag{7.3.5}$$

So, if $\{A_n\}_{n \geq 1}$ is a countable cover of A then,

$$\Lambda_\phi(A) \leq \sum_{n=1}^{\infty} \Lambda_\phi(A_i) \leq C(2) \sum_{n=1}^{\infty} \Pi_\phi^*(A_i)$$

Hence, applying (7.3.3), the lemma follows.   ♣

7.4   Dimensions

Let, similarly as in the two previous sections, (X, ρ) be a metric space. Recall (comp. Remark 6.2.2) that Λ_t, $t > 0$, is the Hausdorff outer measures on X associated to the function $r \to r^t$ and all Λ_t^δ are of corresponding meaning. Fix $A \subset X$. Since for every $0 < \delta \leq 1$ the function $t \to \Lambda_t^\delta(A)$ is non-increasing, so is the function $t \to \Lambda_t(A)$. Furthermore, if $s < t$, then for every $0 < \delta$

$$\Lambda_s^\delta(A) \geq \delta^{s-t} \Lambda_t^\delta(A)$$

which implies that if $\Lambda_t(A)$ is positive, then $\Lambda_s(A)$ is infinite. Thus there is a unique value, $\mathrm{HD}(A)$, called the *Hausdorff dimension* of A such that

$$\Lambda_t(A) = \begin{cases} \infty & \text{if } 0 \leq t < \mathrm{HD}(A) \\ 0 & \text{if } \mathrm{HD}(A) < t < \infty \end{cases} \tag{7.4.1}$$

Note that similarly as Hausdorff measures (comp. Remark 6.2.4), Hausdorff dimension is consequently also an intrinsic property of sets and does not depend on their complements. The following is an immediate consequence of the definitions of Hausdorff dimension and outer Hausdorff measures.

Theorem 7.4.1. *The Hausdorff dimension is a monotonic function of sets, that is if $A \subset B$ then $\mathrm{HD}(A) \leq \mathrm{HD}(B)$.*

We shall prove the following.

Theorem 7.4.2. *If $\{A_n\}_{n \geq 1}$ is a countable family of subsets of X then*

$$\mathrm{HD}(\cup_n A_n) = \sup_n \{\mathrm{HD}(A_n)\}.$$

Proof. Inequality $\mathrm{HD}(\cup_n A_n) \geq \sup_n \{\mathrm{HD}(A_n)\}$ is an immediate consequence of Theorem 7.4.1. Thus, if $\sup_n \{\mathrm{HD}(A_n)\} = \infty$ there is nothing to prove. So, suppose that $s = \sup_n \{\mathrm{HD}(A_n)\}$ is finite and consider an arbitrary $t > s$. In view of (7.4.1), $\Lambda_t(A_n) = 0$ for every $n \geq 1$ and therefore, since Λ_t is an outer measure, $\Lambda_t(\cup_n A_n) = 0$. Hence, by (7.4.1) again, $\mathrm{HD}(\cup_n A_n) \leq t$. The proof is finished.   ♣

As an immediate consequence of this theorem, Proposition 7.2.1 and formula (7.4.1) we get the following.

Proposition 7.4.3. *The Hausdorff dimension of any countable set is equal to 0.*

In exactly the same way as Hausdorff dimension HD one can define *packing** *dimension* PD* and *packing dimension* PD using respectively $\Pi_t^*(A)$ and $\Pi_t(A)$ instead of $\Lambda_t(A)$. The reader can check easily that results analogous to Theorem 7.4.1, Theorem 7.4.2 and Proposition 7.4.3 are also true in these cases. As an immediate consequence of these definitions and Proposition 7.3.1 we get the following.

Lemma 7.4.4. $\mathrm{HD}(A) \leq \mathrm{PD}(A) \leq \mathrm{PD}^*(A)$ *for every set* $A \subset X$.

Now we shall define the third basic dimension – *ball-counting dimension* frequently also called box-counting dimension, Minkowski dimension or capacity. Let A be an arbitrary subset of the metric space (X, ρ). We first need the following.

Definition 7.4.5. For every $r > 0$ consider the family of all collections $\{(x_i, r_i)\}$ (see Definition 6.2.5) of radius not exceeding r which cover A and are centered at A. Put $N(A, r) = \infty$ if this family is empty. Otherwise define $N(A, r)$ to be the minimum of all cardinalities of elements of this family. Note that one gets the same number if one considers the subfamily of collections of radius exactly r and even only its subfamily of collections of the form $\{(x_i, r)\}$.

Now the *lower ball-counting dimensions* and *upper ball-counting dimension* of A are defined respectively by

$$\underline{\mathrm{BD}}(A) = \liminf_{r \to 0} \frac{\log N(A, r)}{-\log r} \quad \overline{\mathrm{BD}}(A) = \limsup_{r \to 0} \frac{\log N(A, r)}{-\log r}. \tag{7.4.2}$$

If $\underline{\mathrm{BD}}(A) = \overline{\mathrm{BD}}(A)$, the common value is called simply ball-counting dimension and is denoted by $\mathrm{BD}(A)$. The reader will easily prove the next theorem which explains the reason of the name box-counting dimension. The other names will not be discussed here.

Proposition 7.4.6. *Fix* $n \geq 1$. *For every* $r > 0$ *let* $\mathcal{L}(r)$ *be any partition (up to boundaries) of* $\mathbb{R}^n$ *into closed cubes of sides of length* r. *For any set* $A \subset \mathbb{R}^n$ *let* $L(A, r)$ *denotes the number of cubes in* $\mathcal{L}(r)$ *which intersect* A. *Then*

$$\underline{\mathrm{BD}}(A) = \liminf_{r \to 0} \frac{\log L(A, r)}{-\log r} \quad \overline{\mathrm{BD}}(A) = \limsup_{r \to 0} \frac{\log L(A, r)}{-\log r}$$

Remark 7.4.7. Ball-counting dimension has properties which distinguish it qualitatively from Hausdorff and packing dimensions. For instance $\underline{\mathrm{BD}}(\overline{A}) = \underline{\mathrm{BD}}(A)$ and $\overline{\mathrm{BD}}(\overline{A}) = \overline{\mathrm{BD}}(A) =$. So, in particular there exist countable sets of positive ball-counting dimension, for example the set of rational numbers in the interval $[0, 1]$. Even more, there exist compact countable sets with this property like the set $\{1, 1/2, 1/3, \ldots, 0\} \subset \mathbb{R}$. On the other hand in many cases (see Theorem 7.6.7) all these dimensions coincide.

Now we shall provide other characterizations of ball-counting dimension, which in particular will be used to prove Lemma 7.4.9 and consequently Theorem 7.4.10 which establishes most general relations between the dimensions considered in this section.

Let $A \subset X$. For every $r > 0$ define $P(A, r)$ to be the supremum of cardinalities of all packings of the set A of the form $\{(x_i, r)\}$. First we shall prove the following.

Lemma 7.4.8. *For every set $A \subset \mathbb{R}^n$ and every $r > 0$*

$$N(A, 2r) \leq P(A, r) P(A, r) \leq N(A, r).$$

Proof. Let us start with the proof of the first inequality. If $P(A, r) = \infty$, there is nothing to prove. Otherwise, let $\{(x_i, r) : i = 1, \ldots, k\}$ be a packing of A with $k = P(A, r)$. Then this packing is maximal in the sense of inclusion and therefore the collection $\{(x_i, 2r) : i = 1, \ldots, l\}$ covers A. Thus $N(A, 2r) \leq l = P(A, r)$. The first part of Lemma 7.4.8 is proved.

If $N(A, r) = \infty$, the second part is obvious. Otherwise consider a finite packing $\{(x_i, r) : i = 1, \ldots, k\}$ of A and a finite cover $\{(y_j, r) : j = 1, \ldots, l\}$ of A centered at A. Then for every $1 \leq i \leq k$ there exists $1 \leq j = j(i) \leq l$ such that $x_i \in B(y_j(i), r)$ and every ball $B(y_j, r)$ can contain at most one element of the set $\{x_i : i = 1, \ldots, k\}$. So, the function $i \to j(i)$ is injective and therefore $k \leq l$. The proof is finished.   ♣

As an immediate consequence of Lemma 7.4.8 we get the following.

$$\underline{\mathrm{BD}}(A) = \liminf_{r \to 0} \frac{\log P(A, r)}{-\log r} \quad \overline{\mathrm{BD}}(A) = \limsup_{r \to 0} \frac{\log P(A, r)}{-\log r}. \qquad (7.4.3)$$

Now we are in a position to prove the following.

Lemma 7.4.9. *For every set $A \subset X$ we have $\mathrm{PD}^*(A) = \overline{\mathrm{BD}}(A)$.*

Proof. Take $t < \overline{\mathrm{BD}}(A)$. In view of (7.4.3) there exists a sequence $\{r_n : n = 1, 2, \ldots\}$ of positive reals converging to zero and such that $P(A, r_n) \geq r_n^{-t}$ for every $n \geq 1$. Then $\Pi_t^{*r_n}(A) \geq r^t P(A, r_n) \geq 1$ and consequently $\Pi_t^*(A) \geq 1$. Hence $t \leq \mathrm{PD}^*(A)$ and therefore $\overline{\mathrm{BD}}(A) \leq \mathrm{PD}^*(A)$.

In order to prove the converse inequality consider $s < t < \mathrm{PD}^*(A)$. Then $\Pi_t^*(A) = \infty$ and therefore for every $n \geq 1$ there exists a finite packing $\{(x_{n,i}, r_{n,i}) : i = 1, \ldots, k(n)\}$ of A of radius not exceeding 2^{-n} and such that

$$\sum_{i=1}^{k(n)} r_{n,i}^t > 1 \qquad (7.4.4)$$

Now for every $m \geq n$ let

$$l_{n,m} = \#\{i \in \{1, \ldots, k(n)\} : 2^{-(m+1)} < r_{n,i} \leq 2^{-m}\}$$

Then by (7.4.4)

$$\sum_{m=n}^{\infty} l_{n,m} 2^{-mt} > 1 \tag{7.4.5}$$

Suppose that $l_{n,m} < 2^{ms}(1 - 2^{(s-t)})$ for every $m \geq n$. Then

$$\sum_{m=n}^{\infty} l_{n,m} 2^{-mt} < (1 - 2^{(s-t)}) \sum_{m=0}^{\infty} 2^{m(s-t)} = 1,$$

what contradicts (7.4.5). Thus for every $n \geq 1$ there exists $m = m(n) \geq n$ such that

$$l_{n,m} \geq 2^{ms}(1 - 2^{(s-t)})$$

Hence $P(A, 2^{-(m+1)}) \geq 2^{ms}(1 - 2^{(s-t)})$, so

$$a c \log P(A, 2^{-(m+1)})(m+1) \log 2 \geq \frac{sm \log 2 + \log(1 - 2^{s-t})}{(m+1) \log 2}$$

Thus, letting $n \to \infty$ (then also $m = m(n) \to \infty$) we obtain $\overline{\mathrm{BD}}(A) \geq s$. ♣

Combining now Lemma 7.4.4 and Lemma 7.4.9 and checking easily that $\mathrm{HD}(A) \leq \underline{\mathrm{BD}}(A)$ we obtain the following main general relation connecting all the dimensions under consideration.

Theorem 7.4.10. *For every set $A \subset X$*

$$\mathrm{HD}(A) \leq \min\{\mathrm{PD}(A), \underline{\mathrm{BD}}(A)\} \leq \max\{\mathrm{PD}(A), \underline{\mathrm{BD}}(A)\} \leq \overline{\mathrm{BD}}(A) = \mathrm{PD}^*(A)$$

We finish this section with the following definition.

Definition 7.4.11. Let μ be a Borel measure on (X, ρ). We write

$$\mathrm{HD}_\star(\mu) = \inf\{\mathrm{HD}(Y) : \mu(Y) > 0\} \quad \text{and} \quad \mathrm{HD}^\star(\mu) = \inf\{\mathrm{HD}(Y) : \mu(X \backslash Y) = 0\}.$$

In case $\mathrm{HD}_\star(\mu) = \mathrm{HD}^\star(\mu)$, we call it *Hausdorff dimension* of the measure μ and write $\mathrm{HD}(\mu)$.

An analogous definition can be formulated for packing dimension, with notation $\mathrm{PD}_\star(\mu), \mathrm{PD}^\star(\mu), PD(\mu)$ and the name *packing dimension* of the measure μ.

7.5 Besicovitch covering theorem

In this section we prove only one result, the Besicovitch covering theorem. Although this theorem seems to be almost always omitted in the classical geometric measure theory, we however consider it as one of most powerful geometric tools when dealing with some aspects of fractal sets. We refer the reader to Section 7.6 to verify our opinion.

Theorem 7.5.1 (Besicovitch covering theorem)**.** *Let $n \geq 1$ be an integer. Then there exists a constant $b(n) > 0$ such that the following claim is true.*

If A is a bounded subset of $\mathbb{R}^n$ then for any function $r : A \to (0, \infty)$ there exists $\{x_k : k = 1, 2, \ldots\}$ a countable subset of A such that the collection $\mathcal{B}(A, r) = \{B(x_k, r(x_k)) : k \geq 1\}$ covers A and can be decomposed into $b(n)$ packings of A.

In particular it follows from Theorem 7.5.1 that $\#\{B \in \mathcal{B} : x \in B\} \leq b(n)$. Exactly the same proof (world by world) goes if open balls in Theorem 7.5.1 are replaced by closed ones.

For any $x \in \mathbb{R}^n$, any $0 < r \leq \infty$ and any $0 < \alpha < \pi$ by $\mathrm{Con}(x, \alpha, r)$ we will denote any solid central cone with vertex x, radius r and angle (Lebesgue measure on the unit sphere S^{n-1}) α. The proof of Theorem 7.5.1 is based on the following obvious geometric observation.

Observation 7.5.2. Let $n \geq 1$ be an integer. Then there exists $\alpha(n) > 0$ so small that the following holds.

If $x \in \mathbb{R}^n$, $0 < r < \infty$, if $z \in B(x, r) \setminus B(x, r/3)$ and $x \in \mathrm{Con}(z, \alpha(n), \infty)$ then the set $\mathrm{Con}(z, \alpha(n), \infty) \setminus B(x, r/3)$ consists of two connected components (one of z and one of "∞") and that containing z is contained in $B(x, r)$.

Proof of Theorem 7.5.1. We will construct the sequence $\{x_k : k = 1, 2, \ldots\}$ inductively. Let

$$a_0 = \sup\{r(x) : x \in A\}$$

If $a_0 = \infty$ then one can find $x \in A$ with $r(x)$ so large that $B(x, r(x)) \supset A$ and the proof is finished.

If $a_0 < \infty$ choose $x_1 \in A$ so that $r(x_1) > a_0/2$. Fix $k \geq 1$ and assume that the points $x_1, x_2, \ldots, x_k$ have been already chosen. If $A \subset B(x_1, r(x_1)) \cup \ldots \cup B(x_k, r(x_k))$ then the selection process is finished. Otherwise put

$$a_k = \sup\{r(x) : x \in A \setminus \big(B(x_1, r(x_1)) \cup \ldots \cup B(x_k, r(x_k))\big)\}$$

and take

$$x_{k+1} \in A \setminus \big(B(x_1, r(x_1)) \cup \ldots \cup B(x_k, r(x_k))\big) \qquad (7.5.1)$$

such that

$$r(x_{k+1}) > a_k/2 \qquad (7.5.2)$$

In order to shorten notation from now on throughout this proof we will write r_k for $r(x_k)$. By (7.5.1) we have $x_l \notin B(x_k, r_k)$ for all pairs k, l with $k < l$. Hence

$$\|x_k - x_l\| \geq r(x_k) \qquad (7.5.3)$$

It follows from the construction of the sequence (x_k) that

$$r_k > a_{k-1}/2 \geq r_l/2 \qquad (7.5.4)$$

and therefore $r_k/3 + r_l/3 < r_k/3 + 2r_k/3 = r_k$. Joining this and (6.5.3) we obtain

$$B(x_k, r_k/3) \cap B(x_l, r_l/3) = \emptyset \qquad (7.5.5)$$

for all pairs k, l with $k \neq l$ since then either $k < l$ or $l < k$.

Now we shall show that the balls $\{B(x_k, r_k) : k \geq 1\}$ cover A. Indeed, if the selection process stops after finitely many steps this claim is obvious. Otherwise it follows from (7.5.5) that $\lim_{k \to \infty} r_k = 0$ and if $x \notin \bigcup_{k=1}^{\infty} B(x_k, r_k)$ for some $x \in A$ then by construction $r_k > a_{k-1}/2 \geq r(x)$ for every $k \geq 1$. The contradiction obtained proves that $\bigcup_{k=1}^{\infty} B(x_k, r_k) \supset A$.

The main step of the proof is given by the following.

Claim. For every $z \in \mathbb{R}^n$ and any cone $\mathrm{Con}(z, \alpha(n), \infty)$ ($\alpha(n)$ given by Observation 6.5.2)

$$\#\{k \geq 1 : z \in B(x_k, r_k) \setminus B(x_k, r_k/3) x_k \in \mathrm{Con}(z, \alpha(n), \infty)\} \leq 1 + 16^n$$

Denote by Q the set of integers whose cardinality is to be estimated. If $Q = \emptyset$, there is nothing to prove. Otherwise let $i = \min Q$. If $k \in Q$ and $k \neq i$ then $k > i$ and therefore $x_k \notin B(x_i, r_i)$. In view of this, Observation 6.5.2 applied with $x = x_i$, $r = r_i$, and the definition of Q, we get $\|z - x_k\| \geq 2r_i/3$, whence

$$r_k \geq \|z - x_k\| \geq 2r_i/3 \tag{7.5.6}$$

On the other hand by (7.5.4) we have $r_k < 2r_i$ and therefore $B(x_k, r_k/3) \subset B(z, 4r_k/3) \subset B(z, 8r_i/3)$. Thus, using (7.5.5), (7.5.6) and the fact that the n-dimensional volume of balls in $\mathbb{R}^n$ is proportional to the nth power of radii we obtain $\#Q \leq (8r_i/3)^n/(2r_i/9)^n = 12^n$. The proof of the claim is finished.

Clearly there exists an integer $c(n) \geq 1$ such that for every $z \in \mathbb{R}^n$ the space $\mathbb{R}^n$ can be covered by at most $c(n)$ cones of the form $\mathrm{Con}(z, \alpha(n), \infty)$. Therefore it follows from the claim that for every $z \in \mathbb{R}^n$

$$\#\{k \geq 1 : z \in B(x_k, r_k) \setminus B(x_k, r_k/3)\} \leq c(n)12^n$$

Thus applying (7.5.5)

$$\#\{k \geq 1 : z \in B(x_k, r_k) \leq 1 + c(n)12^n \tag{7.5.7}$$

Since the ball $\overline{B}(0, 3/2)$ is compact, it contains a finite subset P such that $\bigcup_{x \in P} B(x, 1/2) \supset \overline{B}(0, 3/2)$. Now for every $k \geq 1$ consider the composition of the map $\mathbb{R}^n \ni x \to r_k x \in \mathbb{R}^n$ and the translation determined by the vector from 0 to x_k. Call by P_k the image of P under this translation. Then $\#P_k = \#P$, $P_k \subset \overline{B}(x_k, 3r_k/2)$ and

$$\bigcup_{x \in P_k} B(x, r_k/2) \supset \overline{B}(0, 3r_k/2) \tag{7.5.8}$$

Consider now two integers $1 \leq k < l$ such that

$$B(x_k, r_k) \cap B(x_l, r_l) \neq \emptyset \tag{7.5.9}$$

Let $y \in \mathbb{R}^n$ be the only point lying on the interval joining x_l and x_0 at the distance $r_k - r_l/2$ from x_k. As $x_l \notin B(x_k, r_k)$, by (6.5.9) we have $\|y - x_l\| \leq$

$r_l + r_l/2 = 3r_l/2$ and therefore by (7.5.8) there exists $z \in P_l$ such that $\|z - y\| < r_l/2$. Consequently $z \in B(x_k, r_l/2 + r_k - r_l/2) = B(x_k, r_k)$. Thus applying (7.5.7) with z being the elements of P_l, we obtain the following

$$\#\{1 \leq k \leq l - 1 : B(x_k, r_k) \cap B(x_l, r_l) \neq \emptyset\} \leq \#P(1 + c(n)12^n) \qquad (7.5.10)$$

for every $l \geq 1$.

Putting $b(n) = \#P(1 + c(n)12^n) + 1$ this property allows us to decompose the set $\mathbb{N}$ of positive integers into $b(n)$ subsets $\mathbb{N}_1, \mathbb{N}_2, \ldots, \mathbb{N}_{b(n)}$ in the following inductive way. For every $k = 1, 2, \ldots, b(n)$ set $\mathbb{N}_k(b(n)) = \{k\}$ and suppose that for every $k = 1, 2, \ldots, b(n)$ and some $j \geq b(n)$ mutually disjoint families $\mathbb{N}_k(j)$ have been already defined so that

$$\mathbb{N}_1(j) \cup \mathbb{N}_{b(n)}(j) = \{1, 2, \ldots, j\}$$

Then by (7.5.10) there exists at least one $1 \leq k \leq b(n)$ such that $B(x_{j+1}, r_{j+1}) \cap B(x_i, r_i) = \emptyset$ for every $i \in \mathbb{N}_k(j)$. We set $\mathbb{N}_k(j + 1) = \mathbb{N}_k(j) \cup \{j + 1\}$ and $\mathbb{N}_l(j + 1) = \mathbb{N}_l(j)$ for all $l \in \{1, 2, \ldots, b(n)\} \setminus \{k\}$. Putting now for every $k = 1, 2, \ldots, b(n)$

$$\mathbb{N}_k = \mathbb{N}_k(b(n)) \cup \mathbb{N}_k(b(n) + 1) \cup \ldots$$

we see from the inductive construction that these sets are mutually disjoint, that they cover $\mathbb{N}$ and that for every $k = 1, 2, \ldots, b(n)$ the families of balls $\{B(x_l, r_l) : l \in \mathbb{N}_k\}$ are also mutually disjoint. The of proof the Besicovitch covering theorem is finished.   ♣

We would like to emphasize here once more that the same statement remains true if open balls are replaced by closed ones. Also if instead of balls one considers n-dimensional cubes. Then although the proof is based on the same idea, however technically is considerably easier.

7.6   Frostman type lemmas

In this section we shall explain how a knowledge about a measure of small balls versus diameter yields an information about dimensions of support of the measure.

Let a function $\phi : [0, \infty) \to [0, \infty)$ satisfy the same conditions as in Section 7.2 including (7.2.3) and moreover let ϕ be continuous. We start with the following.

Theorem 7.6.1. *Let $n \geq 1$ be an integer and let $b(n)$ be the constant claimed in Theorem 7.5.1 (Besicovitch covering theorem). Assume that μ is a Borel probability measure on $\mathbb{R}^n$ and A is a bounded Borel subset of $\mathbb{R}^n$. If there exists $C \in (0, \infty]$, $(1/\infty = 0)$, such that*
(a) for all (but countably many maybe) $x \in A$

$$\limsup_{r \to 0} \frac{\mu(B(x, r))}{\phi(r)} \geq C$$

then $\Lambda_\phi(E) \le \frac{b(n)}{C}\mu(E)$ for every Borel set $E \subset A$. In particular $\Lambda_\phi(A) < \infty$.

or

(b) for all $x \in A$

$$\limsup_{r \to 0} \frac{\mu(B(x,r))}{\phi(r)} \le C < \infty$$

then $\mu(E) \le C\Lambda_\phi(E)$ for every Borel set $E \subset A$.

Proof. (a) In view of Proposition 7.2.1 we can assume that E does not intersect the exceptional countable set. Fix $\varepsilon > 0$ and $r > 0$. Since μ is a regular measure, there exists an open set $G \supset E$ such that $\mu(G) \le \mu(E) + \varepsilon$. By openness of G and by assumption (a), for every $x \in E$ there exists $0 < r(x) < r$ such that $B(x, r(x)) \subset G$ and $(1/C + \varepsilon)\mu(B(x, r)) \ge \phi(r)$. Let $\{(x_k, r(x_k)) : k \ge 1\}$ be the cover of E obtained by applying Theorem 7.5.1 (Besicovitch covering theorem) to the set E. Then

$$\Lambda_\phi^r(E) \le \sum_{k=1}^\infty \phi(r(x_k)) \le \sum_{k=1}^\infty (C^{-1} + \varepsilon)\mu(B(x_k, r(x_k)))$$

$$\le b(n)(C^{-1} + \varepsilon)\mu\left(\bigcup_{k=1}^\infty B(x_k, r(x_k))\right) \le b(n)(C^{-1} + \varepsilon)(\mu(E) + \varepsilon)$$

Letting $r \to 0$ we thus obtain $\Lambda_\phi(E) \le b(n)(1/C + \varepsilon)(\mu(E) + \varepsilon)$ and therefore letting $\varepsilon \to 0$ the part (a) follows (note that the proof is correct with $C = \infty$!).

(b) Fix an arbitry $s > C$. Since for every $r > 0$ the function $x \to \mu(B(x,r))/\phi(r)$ is measurable and since the supremum of a countable sequence of measurable functions is also a measurable function, we conclude that for every $k \ge 1$ the function $\psi_k : A \to \mathbb{R}$ is measurable, where

$$\psi_k(x) = \sup\left\{\frac{\mu(B(x,r))}{\phi(r)} : r \in Q \cap (0, 1/k]\right\}$$

and Q denotes the set of rational numbers. For every $k \ge 1$ let $A_k = \psi_k^{-1}((0, s])$. In view of measurability of the functions ψ_k all the sets A_k are measurable. Take an arbitrary $r \in (0, 1/k]$. Then there exists a sequence $r_j : j = 1, 2, \ldots\}$ of rational numbers converging to r from above. Since the function ϕ is continuous and the function $t \to \mu(B(x,t))$ is non-decreasing, we have for every $x \in A_k$

$$ac\mu(B(x,r))\phi(r) \le \lim_{j \to \infty} \frac{\mu(B(x, r_j))}{\phi(r_j)} \le s$$

So, if $F \subset A_k$ is a Borel set and if $\{(x_i, r_i) : i = 1, 2, \ldots\}$ is a collection centered at the set F, covering F and of radius not exceeding $0 < r \le 1/k$, then

$$\sum_{i=1}^\infty \phi(r_i) \ge s^{-1} \sum_{i=1}^\infty \mu(B(x_i, r_i)) \ge s^{-1}\mu(F)$$

Hence, $\Lambda_\phi^r(F) \ge s^{-1}\mu(F)$ and letting $r \to 0$ we get

$$\Lambda_\phi(E) \ge \Lambda_\phi(F) \ge s^{-1}\mu(F)$$

By the assumption of (b), $\cup_k A_k = A$ and therefore, putting $B_k = A_k \setminus (A_1 \cup A_2 \cup \ldots \cup A_{k-1})$, $k \geq 1$, we see that the family $\{B_k : k \geq 1\}$ is a countable partition of A into Borel sets. Therefore, if $E \subset A$ then

$$\Lambda_\phi(E) = \sum_{k=1}^\infty \Lambda_\phi(E \cap A_k) \geq s^{-1} \sum_{k=1}^\infty \mu(E \cap A_k) = s^{-1}\mu(E)$$

So, letting $s \searrow C$ finishes the proof. ♣

In an analogous way, using Besicivitch covering theorem, the decomposition into packings, one can prove the following.

Theorem 7.6.2. *Let $n \geq 1$ be an integer and let $b(n)$ be the constant claimed in Theorem 7.5.1 (Besicovitch covering theorem). Assume that μ is a Borel probability measure on $\mathbb{R}^n$ and A is a bounded subset of $\mathbb{R}^n$. If there exists $C \in (0, \infty]$, $(1/\infty = 0)$, such that*
(a) for all $x \in A$

$$\liminf_{r \to 0} \frac{\mu(B(x,r))}{\phi(r)} \leq C$$

then $\mu(E) \leq b(n)C\Pi_\phi(E)$ for every Borel set $E \subset A$.
or
(b) for all $x \in A$

$$\liminf_{r \to 0} \frac{\mu(B(x,r))}{\phi(r)} \geq C < \infty$$

then $\Pi_\phi(E) \leq C^{-1}\mu(E)$ for every Borel set $E \subset A$. In particular $\Pi_\phi(A) < \infty$.

Note that each Borel measure μ defined on a Borel subset B of R^n can be in a canonical way considered as a measure on $\mathbb{R}^n$ by putting $\mu(A) = \mu(A \cap B)$ for every Borel set $A \subset \mathbb{R}^n$.

As a simple consequence of Theorem 7.6.1 we shall prove

Theorem 7.6.3 (Frostman Lemma)**.** *Suppose that μ is a Borel probability measure on $\mathbb{R}^n$, $n \geq 1$, and A is a bounded Borel subset of $\mathbb{R}^n$.*
(a) If $\mu(A) > 0$ and there exists θ_1 such that for every $x \in A$

$$\liminf_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} \geq \theta_1$$

then $\mathrm{HD}(A) \geq \theta_1$.
(b) If there exists θ_2 such that for every $x \in A$

$$\liminf_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} \leq \theta_2$$

then $\mathrm{HD}(A) \leq \theta_2$.

Proof. (a) Take any $0 < \theta < \theta_1$. Then, by the assumption, $\limsup_{r \to 0} \mu(B(x,r))/r^\theta \leq 1$. Therefore applying Theorem 7.6.1(b) with $\phi(t) = t^\theta$, we obtain $\Lambda_\theta(A) \geq \mu(A) > 0$. Hence $\mathrm{HD}(A) \geq \theta$ by definition (7.4.1) and consequently $\mathrm{HD}(A) \geq \theta_1$.

(b) Take now an arbitrary $\theta > \theta_2$. Then by the assumption $\limsup_{r \to 0} \mu(B(x,r))/r^\theta \geq 1$. Therefore applying Theorem 7.6.1(a) with $\phi(t) = t^\theta$ we obtain $\Lambda_\theta(A) < \infty$, whence $\mathrm{HD}(A) \leq \theta$ and consequently $\mathrm{HD}(A) \leq \theta_1$. The proof is finished.   ♣

Similarly one proves a consequence of Theorem 7.6.2.

Theorem 7.6.4. *Suppose that μ is a Borel probability measure on $\mathbb{R}^n$, $n \geq 1$, and A is a bounded Borel subset of $\mathbb{R}^n$.*

(a) If $\mu(A) > 0$ and there exists θ_1 such that for every $x \in A$

$$\limsup_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} \geq \theta_1$$

then $\mathrm{PD}(A) \geq \theta_1$.

(b) If there exists θ_2 such that for every $x \in A$

$$\limsup_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} \leq \theta_2$$

then $\mathrm{PD}(A) \leq \theta_2$.

Let μ be a Borel probability measure on a metric space X. For every $x \in X$ we define the *lower and upper pointwise dimension* of μ at x by putting respectively

$$\underline{d}_\mu(x) = \liminf_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} \quad \text{and} \quad \overline{d}_\mu(x) = \limsup_{r \to 0} \frac{\log \mu(B(x,r))}{\log r}.$$

Suppose now that $X \subset \mathbb{R}^d$ with Euclidean metric. Then the following theorem on Hausdorff and packing dimensions of μ, defined in Definition 6.4.10, follows easily from Theorems 7.6.3 and 7.6.4.

Theorem 7.6.5.

$$\mathrm{HD}_\star(\mu) = \operatorname{ess\,inf} \underline{d}_\mu, \quad \mathrm{PD}_\star(\mu) = \operatorname{ess\,inf} \overline{d}_\mu \quad and$$
$$\mathrm{HD}^\star(\mu) = \operatorname{ess\,sup} \underline{d}_\mu(x), \quad \mathrm{PD}^\star(\mu) = \operatorname{ess\,sup} \overline{d}_\mu(x).$$

Proof. Recall that the μ-essential infimum $\operatorname{ess\,inf}$ of a measurable function ϕ and the μ-essential supremum $\operatorname{ess\,sup}$ are defined by

$$\operatorname{ess\,inf}(\phi) = \sup_{\mu(N)=0} \inf_{x \in X \setminus N} \phi(x) \quad \text{and} \quad \operatorname{ess\,sup}(\phi) = \inf_{\mu(N)=0} \sup_{x \in X \setminus N} \phi(x).$$

So, to begin with, for $\theta_1 := \operatorname{ess\,inf} \phi$ we have

$$\mu\{x : \phi(x) < \theta_1\} = 0 \quad \text{and} \quad (\forall \theta > \theta_1)\mu\{x : \phi(x) < \theta\} > 0.$$

Indeed, if $\mu\{x : \phi(x) < \theta_1\} > 0$ then there eists $\theta < \theta_1$ with $\mu\{x : \phi(x) \le \theta\} > 0$ hence for every N with $\mu(N) = 0$ we have $\inf_{X \setminus N} \phi \le \theta$ hence ess inf $\phi \le \theta$, a contradiction. If there exists $\theta > \theta_1$ with $\mu\{x : \phi(x) < \theta\} = 0$ then for $N = \{x : \phi(x) < \theta\}$ we have $\inf_{X \setminus N} \phi \ge \theta$ hence ess inf $\phi \ge \theta$, a contradiction.

This applied to $\phi = \underline{d}_\mu$ yields for every A with $\mu(A) > 0$ the existence of $A' \subset A$ with $\mu(A') = \mu(A) > 0$ such that for every $x \in A'$ $\underline{d}_\mu(x) \ge \theta_1$ hence $\mathrm{HD}(A) \ge \mathrm{HD}(A') \ge \theta_1$ by Theorem 7.6.3(a), hence $\mathrm{HD}_\star(\mu) \ge \theta_1$.

On the other hand for every $\theta > \theta_1$ $\mu\{x : \underline{d}_\mu(x) < \theta\} > 0$ and by Theorem 7.6.3(b) $\mathrm{HD}(\{x : \underline{d}_\mu(x) < \theta\}) \le \theta$, therefore $\mathrm{HD}_\star(\mu) \le \theta$. Letting $\theta \to \theta_1$ we get $\mathrm{HD}_\star(\mu) \le \theta_1$. We conclude that $\mathrm{HD}_\star(\mu) = \theta_1$.

Similarly one proceeds to prove $\mathrm{HD}^\star(\mu) = \mathrm{ess\,sup}\,\underline{d}_\mu(x)$ and to deal with packing dimension, refering to Theorem 7.6.4.   ♣

Then by definition of essinf there exists $Y \subset X \subset \mathbb{R}^n$ be a Borel set such that $\mu(Y) = 1$ and for every $x \in Y$ $\underline{d}_\mu(x) \ge \theta_1$. Hence for every $A \subset X$ with $\mu(A) > 0$, we have $\mu(A \cap Y) > 0$ and for every $x \in A \cap Y$, $\underline{d}_\mu(x) \ge \theta_1$. So using Theorem 7.6.3(a) we get $\mathrm{HD}(A) \ge \mathrm{HD}(A \cap Y) \ge \theta_1$. Hence by the definition of $\mathrm{HD}_\star$ we get $\mathrm{HD}_\star \ge \theta_1$. Other parts of Theorem 7.6.5 follow from the definitions and Theorems 7.6.4 and 7.6.3(a) similarly.   ♣

Definition 7.6.6. Let X be a Borel bounded subset of $\mathbb{R}^n$, $n \ge 1$. A Borel probability measure on X is said to be a *geometric measure* with an exponent $t \ge 0$ if and only if there exists a constant $C \ge 1$ such that

$$C^{-1} \le \frac{\mu(B(x,r))}{r^t} \le C$$

for every $x \in X$ and every $0 < r \le 1$.

We shall prove the following.

Theorem 7.6.7. *If X is a Borel bounded subset of $\mathbb{R}^n$, $n \ge 1$, and μ is a geometric measure on X with an exponent t, then $\mathrm{BD}(X)$ exists and*

$$\mathrm{HD}(X) = \mathrm{PD}(X) = \mathrm{BD}(X) = t$$

Moreover the three measures μ, Λ_t and Π_t on X are equivalent with bounded Radon-Nikodym derivatives.

Proof. The last part of the theorem follows immediately from Theorem 7.6.1 and Theorem 7.6.2 applied for $A = X$. Consequently also $t = \mathrm{HD}(X) = \mathrm{PD}(X)$ and therefore, in view of Theorem 7.4.10, we only need to show that $\overline{\mathrm{BD}}(X) \le t$. And indeed, let $\{(x_i, r) : i = 1, \dots, k\}$ be a packing of X. Then

$$kr^t \le C \sum_{i=1}^k \mu(B(x_i, r)) \le C$$

and therefore $k \le C r^{-t}$. Thus $P(X, r) \le C r^{-t}$, whence $\log P(X, r) \le \log C - t \log r$. Applying now formula (7.4.3) finishes the proof.   ♣

In particular it follows from this theorem that every geometric measure admits exactly one exponent. Lots of examples of geometric measures will be provided in the next chapters.

Bibliographical notes

The history of notions and development of the geometric measure theory is very long, rich and complicated and its outline exceeds the scope of this book. We refer the interested reader to the books [Falconer 1997] and [Mattila 1995].

Chapter 8

Conformal expanding repellers

Conformal expanding repellers (abbreviation: CER's) were defined already in Chapter 5 and some basic properties of expanding sets and repellers in dimension 1 were discussed in Section 5.2. A more advanced geometric theory in the real 1-dimensional case was done in Chapter 6.

Now we have a new tool: Frostman Lemma and related facts from Chapter 7. Equipped with the theory of Gibbs measures and with the pressure function we are able to develop a geometric theory of CER's with Hausdorff measures and dimension playing the crucial role. We shall present this theory for $C^{1+\varepsilon}$ conformal expanding repellers in $\mathbb{R}^d$. The main case of our interest will be $d = 2$. Remind (Section 5.2 that the assumed conformality, forces for $d = 2$ that f is holomorphic or anti-holomorphic and for $d \geq 3$ that f is locally a Möbius map. Conformality for $d = 1$ is meaningless, so we assume $C^{1+\varepsilon}$ in order to be able to rely on the Bounded Distortion for Iteration lemma.

We shall outline a theory of Gibbs measures from the point of view of multifractal spectra of dimensions (Section 8.2) and pointwise fluctuations due to the Law of Iterated Logarithm (Section 8.3) .

For $d = 2$ we shall apply this theory to study the boundary $\operatorname{Fr}\Omega$ of a simply connected domain Ω, in particular a simply connected immediate basin of attraction to a sink for a rational mapping of the Riemann sphere.

To simplify our considerations we shall restrict usually to the cases where the mapping on the boundary is expanding, and sometimes we assume that the boundary is a Jordan curve, for example for the mapping $z \mapsto z^2 + c$ for $|c|$ small.

In Section 8.5 we study harmonic measure on $\operatorname{Fr}\Omega$. We adapt the results of Section 8.3 to study its pointwise fluctuations and we prove that except special cases these fluctuations take place. We shall derive from this an information about the fluctuations of the radial growth of the derivative of the Riemann mapping R from the unit disc $\mathbb{D}$ to Ω. In Section 8.6 we discuss integral means

$\int_{\partial \mathbb{D}} |R'(rz)|^t \, |dz|$ as $r \nearrow 1$. In Section 8.7 we provide other examples of Ω, von Koch snowflake and Carleson's (generalized) snowflakes.

8.1   Pressure function and dimension

Let $f : X \to X$ be a topologically mixing conformal expanding repeller in $\mathbb{R}^d$. As before we abbreviate notation of the pressure $\mathrm{P}(f, \phi)$, to $\mathrm{P}(\phi)$. We start with the following technical lemma.

Lemma 8.1.1. *Let m be a Gibbs state (not necessarily invariant) on X and let $\phi : X \to \mathbb{R}$ be a Hölder continuous function. Assume $\mathrm{P}(\phi) = 0$. Then there is a constant $E \geq 1$ such that for all r small enough and all $x \in X$ there exists $n = n(x, r)$ such that*

$$\frac{\log E + S_n \phi(x)}{-\log E - \log |(f^n)'(x)|} \leq \frac{\log m(B(x, r))}{\log r} \leq \frac{-\log E + S_n \phi(x)}{\log E - \log |(f^n)'(x)|}. \qquad (8.1.1)$$

Proof. Take an arbitrary $x \in X$. Fix $r \in (0, C^{-1}\xi)$ and let $n = n(x, r) \geq 0$ be the largest integer so that

$$|(f^n)'(x)|rC \leq \xi, \qquad (8.1.2)$$

where $C = C_{\mathrm{MD}}$ is the multiplicative distortion constant (corresponding to the Hölder continuous function $\log |f'|$), as in the Distortion Lemma for Iteration (Lemma 5.2.2), see Definition 5.2.1. Then

$$f_x^{-n}(B(f^n(x), \xi)) \supset B(x, \xi|(f^n)'(x)|^{-1}C^{-1}) \supset B(x, r). \qquad (8.1.3)$$

Now take n_0 such that $\lambda^{n_0 - 1} \geq C^2$. We then obtain

$$|(f^{n+n_0})'|rC^{-1} \geq \xi. \qquad (8.1.4)$$

Hence, again by the Distortion Lemma for Iteration

$$f_x^{-n-n_0}(B(f^{n+n_0}(x), \xi)) \subset B\big(x, \xi|(f^{n+n_0})'(x)|^{-1}C\big) \subset B(x, r). \qquad (8.1.5)$$

By the Gibbs property of the measure m, see (4.1.1), for a constant $E \geq 1$ (the constant C in (4.1.1)) we can write

$$E^{-1} \leq \frac{\exp S_n \phi(x)}{m(f_x^{-n}(B(f^n(x), \xi)))} \quad \text{and} \quad \frac{\exp S_{n+n_0} \phi(x)}{m(f_x^{-(n+n_0)}(B(f^{n+n_0}(x), \xi)))} \leq E.$$

Using this, (8.1.3), (8.1.5), the inequality $S_{n+n_0}\phi(x) \geq S_n\phi(x) + n_0 \inf \phi$, and finally increasing E so that the new $\log E$ is larger than the old $\log E - n_0 \inf \phi$, we obtain

$$\log E + S_n \phi(x) \geq \log m(B(x, r)) \geq -\log E + S_n \phi(x). \qquad (8.1.6)$$

Using now (8.1.2) and (8.1.4), denoting $L = \sup |f'|$, and applying logarithms, we obtain

$$\frac{\log E + S_n \phi(x)}{\log |(f^n)'(x)|^{-1} - n_0 \log L + \log \xi} \leq \frac{\log m(B(x, r))}{\log r} \leq \frac{-\log E + S_n \phi(x)}{\log |(f^n)'(x)|^{-1}\xi}.$$

Increasing further E so that $\log E \geq n_0 \log L - \log \xi$, we can rewrite it in the "symmetric" form of (8.1.1). ♣

When we studied the pressure function $\phi \mapsto \mathrm{P}(\phi)$ in Chapters 2 and 4 the linear functional $\psi \mapsto \int \psi d\mu_\phi$ appeared. This was the Gateaux differential of P at ϕ (Theorem 2.6.5, Proposition 2.6.6 and (4.6.5)). Here the presence of an ambient smooth structure (1-dimensional or conformal) distingushes ψ's of the form $-t \log |f'|$. We obtain a link between the ergodic theory and the geometry of the embedding of X into $\mathbb{R}^d$.

Definition 8.1.2. Let μ be an ergodic f-invariant probability measure on X. Then by Birkhoff's Ergodic Theorem, for μ-almost every $x \in X$, the limit $\lim_{n \to \infty} \frac{1}{n} \log |(f^n)'(x)|$ exists and is equal to $\int \log |f'| d\mu$. We call this number the *Lyapunov characteristic exponent* of the map f with respect to the measure μ and we denote it by $\chi_\mu(f)$. In our case of expanding maps considered in this Chapter we obviously have $\chi_\mu(f) > 0$.

This definition does not demand the expanding property. It makes sense for an arbitrary invariant subset X of $\mathbb{R}^d$ or the Riemann sphere $\bar{\mathbb{C}}$, for f conformal (or differentiable in the real case) defined on a neighbourhood of X. There is no problem with the integrability because $\log |f'|$ is upper bounded on X. We do not exclude the possibility that $\chi_\mu = -\infty$. The notion of a Lyapunov characteristic exponent will play a crucial role also in subsequent chapters where non-expanding invariant sets will be studied.

Theorem 8.1.3 (Volume Lemma, expanding map and Gibbs measure case). *Let m be a Gibbs state for a topologically mixing conformal expanding repeller $X \in \mathbb{R}^d$ and a Hölder continuous potential $\phi : X \to \mathbb{R}$. Then for m-almost every point $x \in X$ there exists the limit*

$$\lim_{r \to 0} \frac{\log m(B(x,r))}{\log r}.$$

Moreover, this limit is almost everywhere constant and is equal to $\mathrm{h}_\mu(f)/\chi_\mu(f)$, where μ denotes the only f-invariant probability measure equivalent to m.

Proof. We can assume that $\mathrm{P}(\phi) = 0$. We can achieve it by subtracting $\mathrm{P}(\phi)$ from ϕ; the Gibbs measure class will stay the same (see Proposition 4.1.4). In view of the Birkhoff Ergodic Theorem, for μ-a.e $x \in X$ we have

$$\lim_{n \to \infty} \frac{1}{n} S_n \phi(x) = \int \phi \, d\mu \quad \text{and} \quad \lim_{n \to \infty} \frac{1}{n} \log |(f^n)'(x)| = \chi_\mu(f).$$

Combining these equalities with (8.2.1), along with the observation that $n = n(x,r) \to \infty$ as $r \to 0$, and using also the equality $\mathrm{h}_\mu(f) + \int \phi d\mu = \mathrm{P}(\phi) = 0$, we conclude that

$$\lim_{r \to 0} \frac{\log \mu(B(x,r))}{\log r} = \frac{\mathrm{h}_\mu(f)}{\chi_\mu(f)}.$$

The proof is finished. ♣

As an immediate consequence of this lemma and Theorem 7.6.5 we get the following.

Theorem 8.1.4. *If μ is an ergodic Gibbs state for a conformal expanding repeller $X \in \mathbb{R}^d$ and a Hölder continuous potential ϕ on X, then there exist Hausdorff and packing dimensions of μ and*

$$\mathrm{HD}(\mu) = \mathrm{PD}(\mu) = \mathrm{h}_\mu(f)/\chi_\mu(f). \qquad (8.1.7)$$

Using the above technique we can find a formula for the Hausdorff dimension and other dimensions of the whole set X. This is the solution of the non-linear problem, corresponding to the formula for Hausdorff dimension of the linear Cantor sets, discussed in the introduction.

Definition 8.1.5 (Geometric pressure). Let $f : X \to X$ be a topologically mixing conformal expanding repeller in $\mathbb{R}^d$. We call the pressure function

$$\mathrm{P}(t) := \mathrm{P}(-t \log |f'|)$$

a geometric pressure function.

As f is Lipschitz continuous (or as f is forward expanding), the function $\mathrm{P}(t)$ is finite (see comments at the beginning of Section 2.6). As $|f'| \geq \lambda > 1$, it follows directly from the definition that $\mathrm{P}(t)$ is strictly decreasing from $+\infty$ to $-\infty$. In particular there exists exactly one parameter t_0 such that $\mathrm{P}(t_0) = 0$.

Figure 8.1: Geometric pressure function
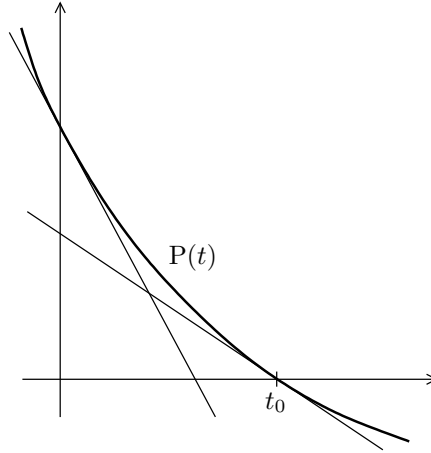
We prove first the following.

Theorem 8.1.6 (Existence of geometric measures). *Let t_0 be defined by $\mathrm{P}(t_0) = 0$. Write ϕ for $-t_0 \log |f'|$ restricted to X. Then each Gibbs state m corresponding to the function ϕ is a geometric measure with the exponent t_0. In particular $\lim_{r \to 0} \frac{\log m(B(x,r))}{\log r} = t_0$ for every $x \in X$.*

Proof. We put in (8.1.1) $\phi = -t_0 \log |f'|$. Then using (8.1.2) (8.1.4) and $\sup |f'| \leq L$ to replace $|(f^n)'(x)|^{-1}$ by r we obtain

$$\frac{\log E + t_0 \log r}{-\log E + \log r} \leq \frac{\log m(B(x,r))}{\log r} \leq \frac{-\log E + t_0 \log r}{\log E + \log r}$$

with a corrected constant E. Hence

$$\frac{\log E + t_0 \log r}{\log r} \leq \frac{\log m(B(x,r))}{\log r} \leq \frac{-\log E + t_0 \log r}{\log r} \qquad (8.1.8)$$

for further corected E. In consequence

$$t_0 \leq \frac{\log\big(m(B(x,r))/E\big)}{\log r} \qquad \frac{\log\big(Em(B(x,r))\big)}{\log r} \leq t_0,$$

hence

$$m(B(x,r))/E \leq r^{t_0} \quad \text{and} \quad Em(B(x,r)) \geq r^{t_0}.$$

(In the denominators we passed in Proof of Lemma 8.1.1 from r to $|(f^n)'(x)|^{-1}$ and here we passed back, so at this point the proof could be shortened. Namely we could deduce (8.1.8) directly from (8.1.6). However we needed to pass from $|(f^n)'(x)|^{-1}$ to r also in numerators and this point could not be simplified). ♣

As an immediate consequence of this theorem and Theorem 7.6.7 we get the following.

Corollary 8.1.7. *The Hausdorff dimension of X is equal to t_0. Moreover it is equal to the packing and Minkowski dimensions. All Gibbs states corresponding to the potential $\phi = -t_0 \log |f'|$, as well as t_0-dimensional Hausdorff and packing measures are mutually equivalent with bounded Radon-Nikodym derivatives.*

Remarks and Summary

The straight line tangent to the graph of P(t) at each $t \in \mathbb{R}$ is the graph of the affine function

$$L_t(s) := \mathrm{h}_{\mu_t}(f) + s\chi_{\mu_t}(f),$$

where μ_t is the invariant Gibbs measure for the potential $-t \log |f'|$. Indeed, by the Variational Principle (Theorem 2.4.1) $L_t(t) = \mathrm{P}(t)$ and $L_t(s) \leq \mathrm{P}(t)$ for all $s \in \mathbb{R}$, compare Section 2.6. The points where the graph of L_t intersects the domain and range axes are respectively HD(μ_t), by req(7.1.6a) and Theorem 4.6.5, and $\mathrm{h}_{\mu_t}(f)$. The derivative is equal to $-\chi_{\mu_t}(f)$. Corollary 8.1.7 says in particular that HD(μ_{t_0}) = HD(X).

For example at Figure 8.1 tangent through the point of intersection of the graph of P(t) with the range axis intersects the domain axis at the Hausdorff dimension of the measure with maximal entropy.

Similarly as in Theorem 8.1.6 one can prove that for every $x \in X$ and $t \in \mathbb{R}$ we have for all r small

$$\mu_t(B(x,r)) \sim r^t \varepsilon^{-\mathrm{P}(t)},$$

where $\sim$ means the mutual ratios are bounded. Compare (4.1.1). This justifies the name: geometric pressure. This topic will be further developped in the next section on the multifractal spectra. In Section 11.5 we shall introduce geometric pressure in the case Julia set contains critical points.

More on Volume Lemma.

We end this section with a version of the Volume Lemma for a Borel probability invariant measure on the expanding repeller (X, f). In Chapter 10 we shall prove this without the expanding assumption assuming only positivity of Lyapunov exponent (though assuming also ergodicity) and the proof will be difficult. So we prove first a simpler version, which will be needed already in the next section. We start with a simple fact following from Lebesgue Theorem on the differentiability a.e. ([Lojasiewicz 1988, Th.7.1.4]) We provide a proof since it is very much in the spirit of Chapter 7.

Lemma 8.1.8. *Every non-decreasing function $k : I \to \mathbb{R}$ defined on a bounded closed interval $I \subset \mathbb{R}$ is Lipschitz continuous at Lebesgue almost every point in I. In other words, for every $\varepsilon > 0$ there exist $L > 0$ and a set $A \subset I$ such that $|I \setminus A| < \varepsilon$, where $|\cdot|$ is the Lebesgue measure in $\mathbb{R}$, and at each $r \in A$ the function k is Lipschitz continuous with the Lipschitz constant L.*

Proof. Suppose on the contrary, that

$$B = \{x \in I : \sup\{y \in I : x \neq y, \ \frac{|k(x) - k(y)|}{|x - y|}\} = \infty\}$$

has positive Lebesgue measure. Write $I = [a, b]$. We can assume, by taking a subset, that B is compact and contains neither a nor b. For every $x \in B$ choose $x' \in I, x' \neq x$ such that

$$\frac{|k(x) - k(x')|}{|x - x'|} > 2\frac{k(b) - k(a)}{|B|}. \tag{8.1.9}$$

Replace each pair x, x' by y, y' with $(y, y') \supset [x, x']$, and y, y' so close to x, x' that (8.1.9) still holds for y, y' instead of x, x'. In case when x or x' equals a or b we do not make the replacement.) We shall use for y, y' the old notation x, x' assuming $x < x'$.

Now from the family of intervals (x, x') choose a finite family $\mathcal{I}$ covering our compact set B. From this family it is possible to choose a subfamily of intervals whose union still covers B and which consists of two subfamilies $\mathcal{I}^1$ and $\mathcal{I}^2$ of pairwise disjoint intervals. Indeed. Start with $I_1 = (x_1, x_1') \in \mathcal{I}$ with minimal possible $x = x_1$ and maximal in $\mathcal{I}$ in the sense of inclusion. Having found $I_1 = (x_1, x_1'), \ldots, I_n = (x_n, x_n')$ we choose I_{n+1} as follows. Consider $\mathcal{I}_{n+1} := \{(x, x') \in \mathcal{I} : x \in \bigcup_{i=1,\ldots,n} I_i, x' > \sup_{i=1,\ldots,n} x_i'\}$. If $\mathcal{I}_{n+1}$ is non-empty, we set (x_{n+1}, x_{n+1}') so that $x_{n+1}' = \max\{x' : (x, x') \in \mathcal{I}_{n+1}\}$. If $\mathcal{I}_{n+1} = \emptyset$, we set (x_{n+1}, x_{n+1}') so that x_{n+1} is minimal possible to the right of $\max\{x_i' : i = 1, \ldots, n\}$ or equal to it, and maximal in $\mathcal{I}$.

In this construction the intervals (x_n, x'_n) with even n are pairwise disjoint, since each (x_{n+2}, x'_{n+2}) has not been a member of $\mathcal{I}_{n+1}$. The same is true for odd n's. We define $\mathcal{I}^i$ for $i = 1, 2$ as the family of (x_n, x'_n) for even, respectively odd, n.

In view of the pairwise disjointness of the intervals of the families $\mathcal{I}^1$ and $\mathcal{I}^2$, monotonicity of k and (8.1.9), we get that

$$k(b) - k(a) \geq \sum_{n \in \mathcal{I}^1} k(x'_n) - k(x_n) > 2\frac{k(b) - k(a)}{|B|} \sum_{n \in \mathcal{I}^1} (x'_n - x_n)$$

and the similar inequality for $n \in \mathcal{I}^2$. Hence, taking into account that $\mathcal{I}^1 \cup \mathcal{I}^2$ covers B, we get

$$2(k(b) - k(a)) > 2\frac{k(b) - k(a)}{|B|} \sum_{n \in \mathcal{I}^1 \cup \mathcal{I}^2} (x'_n - x_n) \geq 2\frac{k(b) - k(a)}{|B|}|B| = 2(k(b) - k(a)),$$

which is a contradiction. ♣

Corollary 8.1.9. *For every Borel probability measure ν on a compact metric space (X, ρ) and for every $r > 0$ there exists a finite partition $\mathcal{P} = \{P_t, t = 1, \ldots, M\}$ of X into Borel sets of positive measure ν and with $\mathrm{diam}(P_t) < r$ for all t, and there exists $C > 0$ such that for every $a > 0$*

$$\nu(\partial_{\mathcal{P}, a}) \leq Ca, \tag{8.1.10}$$

where $\partial_{\mathcal{P}, a} := \bigcap_t \left(\bigcup_{s \neq t} B(P_s, a) \right)$.

Proof. Let $\{x_1, \ldots, x_N\}$ be a finite $r/4$-net in X. Fix $\varepsilon \in (0, r/4N)$. For each function $t \mapsto k_i(t) := \nu(B(x_i, t))$, $t \in I = [r/4, r/2]$, apply Lemma 8.1.8 and find appropriate L_i and A_i, for all $i = 1, \ldots, N$. Let $L = \max\{L_i, i = 1, \ldots, N\}$ and let $A = \bigcap_{i=1,\ldots,N} A_i$. The set A has positive Lebesgue measure by the choice of ε. So, we can choose its point r_0 different from $r/4$ and $r/2$. Therefore, for all $a < a_0 := \min\{r_0 - r/4, r/2 - r_0\}$ and for all $i \in \{1, 2, \ldots, n\}$, we have $\nu(B(x_i, r_0 + a) \setminus B(x_i, r_0 - a)) \leq 2La$. Hence, putting

$$\Delta(a) = \bigcup_i \left(B(x_i, r_0 + a) \setminus B(x_i, r_0 - a) \right),$$

we get $\nu(\Delta(a)) \leq 2LNa$. Define $\mathcal{P} = \{\bigcap_{i=1}^N B^{\kappa(i)}(x_i, r_0)\}$ as a family over all functions $\kappa : \{1, \ldots, N\} \to \{+, -\}$, where $B^+(x_i, r_0) := B(x_i, r_0)$ and $B^-(x_i, r_0) := X \setminus B(x_i, r_0)$, except κ yielding sets of measure 0, in particular except empty intersections. After removing from X of a set of measure 0, the partition $\mathcal{P}$ covers X. Since $r_0 \geq r/4$, the balls $B(x_i, r_0)$ cover X. Hence, for each non-empty $P_t \in \mathcal{P}$ at least one value of κ is equal to $+$. Hence $\mathrm{diam}(P_t) \leq 2r_0 < r$.

Note now that $\partial_{\mathcal{P}, a} \subset \Delta(a)$. Indeed, let $x \in \partial_{\mathcal{P}, a}$. Since $\mathcal{P}$ covers X there exists t_0 such that $x \in P_{t_0}$ so $x \notin P_t$ for all $t \neq t_0$. However, since $x \in$

$\bigcup_{t \neq t_0} B(P_t, a)$, there exists $t_1 \neq t_0$ such that $\mathrm{dist}(x, P_{t_1}) < a$. Let $B = B(x_i, r_0)$ be such that $P_{t_0} \subset B^+$ and $P_{t_1} \subset B^-$, or *vice versa*. In the case when $x \in P_{t_0} \subset B^+$, by the triangle inequality $\rho(x, x_i) > r_0 - a$ and since $\rho(x, x_i) < r_0$, we get $x \in \Delta(a)$. In the case $x \in P_{t_0} \subset B^-$ we have $x \in B(x_i, r_0+a) \backslash B(x_i, r_0) \subset \Delta(a)$.

We conclude that $\nu(\partial_{\mathcal{P},a}) \leq \nu(\Delta(a)) \leq 2LNa$ for all $a < a_0$. For $a \geq a_0$ it suffices to take $C \geq 1/a_0$. So the corollary is proved, with $C = \max\{2LN, 1/a_0\}$.

♣

Remark. If X is embedded for example in a compact manifold Y, then we can view ν as a measure on Y, we find a partition $\mathcal{P}$ of Y and then $\partial_{\mathcal{P},a} = B(\bigcup_{t=1,\dots,M} \partial P_t, a)$, provided $M \geq 2$. This justifies the notation $\partial_{\mathcal{P},a}$.

Corollary 8.1.10. *Let ν be a Borel probability measure on a compact metric space (X, ρ) and let $f : X \to X$ be an endomorphism measurable with respect to the Borel σ-algebra on X and preserving measure ν. Then for every $r > 0$ there exists a finite partition $\mathcal{P} = \{P_t, t = 1, \dots, M\}$ of X into Borel sets of positive measure ν and with $\mathrm{diam}(P_t) < r$ such that for every $\delta > 0$ and ν-a.e. $x \in X$ there exists $n_0 = n_0(x)$ such that for every $n \geq n_0$*

$$B(f^n(x), \exp(-n\delta)) \subset \mathcal{P}(f^n(x)) \qquad (8.1.11)$$

Proof. Let $\mathcal{P}$ be the partition from Corollary 8.1.9. Fix an arbitrary $\delta > 0$. Then by Corollary 8.1.9

$$\sum_{n=0}^{\infty} \nu(\partial_{\mathcal{P}, \exp(-n\delta)}) \leq \sum_{n=0}^{\infty} C \exp(-n\delta) < \infty.$$

Hence by the f-invariance of ν, we obtain

$$\sum_{n=0}^{\infty} \nu(f^{-n}(\partial_{\mathcal{P}, \exp(-n\delta)})) < \infty.$$

Applying now the Borel-Cantelli lemma for the family $\{f^{-n}(\partial_{\mathcal{P}, \exp(-n\delta)})\}_{n=1}^{\infty}$ we conclude that for ν-a.e $x \in X$ there exists $n_0 = n_0(x)$ such that for every $n \geq n_0$ we have $x \notin f^{-n}(\partial_{\mathcal{P}, \exp(-n\delta)})$, so $f^n(x) \notin \partial_{\mathcal{P}, \exp(-n\delta)}$. Hence, by the definition of $\partial_{\mathcal{P}, \exp(-n\delta)}$, if $f^n(x) \in P_t$ for some $P_t \in \mathcal{P}$, then $f^n(x) \notin \bigcup_{s \neq t} B(P_s, \exp(-n\delta))$. Thus

$$B(f^n(x), \exp -n\delta) \subset P.$$

We are done.   ♣

Theorem 8.1.11 (Volume Lemma, expanding map and an arbitrary measure case). *Let ν be an f-invariant Borel probability measure on a topologically exact conformal expanding repeller (X, f), where $X \subset \mathbb{R}^d$. Then*

$$\mathrm{HD}_\star(\nu) \leq \frac{\mathrm{h}_\nu(f)}{\chi_\nu(f)} \leq \mathrm{HD}^\star(\nu). \qquad (8.1.12)$$

If in addition ν is ergodic, then for ν-a.e. $x \in X$

$$\lim_{r \to 0} \frac{\log \nu(B(x,r))}{\log r} = \frac{h_\nu(f)}{\chi_\nu(f)} = HD(\nu). \tag{8.1.13}$$

Proof. Fix the partition $\mathcal{P}$ coming from Corollary 8.1.9 with $r = \min\{\xi, \eta\}$, where $\eta >$ was defined in (3.0.1). Then, as we saw in Chapter 4

$$\mathcal{P}^{n+1}(x) \subset f_x^{-n}(B(f^n(x), \xi)). \tag{8.1.14}$$

for every $x \in X$ and all $n \geq$. We shall work now to get a sort of opposite inclusion. Consider an arbitrary $\delta > 0$ and x so that (8.1.11) from Corollary 8.1.10 is satisfied for all $n \geq n_0(x)$. For every $0 \leq i \leq n$ define $k(i) = [i\frac{\delta}{\log \lambda} + \frac{\log \xi}{\log \lambda}] + 1$, $\lambda > 1$ being the expanding constant for $f : X \to X$ (see (3.0.1)). Hence $\exp(-i\delta) \geq \xi\lambda^{-k}$ and therefore $f_{f^i(x)}^{-k}(B(f^{i+k}(x), \xi)) \subset B(f^i(x), \exp -i\delta)$. So, using (8.1.11) for i in place of n, we get

$$f_x^{-(i+k)}(B(f^{i+k}(x), \xi)) \subset f_x^{-i}(\mathcal{P}(f^i(x)))$$

for all $i \geq n_0(x)$. From this estimate for all $n_0 \leq i \leq n$, we conclude that

$$f_x^{-(n+k(n))}(B(f^{n+k(n)}(x), \xi) \subset \mathcal{P}_{n_0}^{n+1}(x).$$

Notice that for ν-a.e. x there is $a > 0$ such that $B(x, a) \subset \mathcal{P}^{n_0}(x)$, by the definition of $\partial_{\mathcal{P},}$. Therefore for all n large enough

$$f_x^{-(n+k(n))}(B(f^{n+k(n)}(x), \xi)) \subset \mathcal{P}^n(x). \tag{8.1.15}$$

It follows from (8.1.15) and (8.1.14) with $n + k(n)$ in place of n, that

$$\lim_{n \to \infty} -\frac{1}{n} \log \nu(\mathcal{P}^n(x)) \leq \liminf_{n \to \infty} \frac{-\log \nu\left(f_x^{-(n+k(n))}(B(f^{n+k(n)}(x), \xi))\right)}{n}$$

$$\leq \limsup_{n \to \infty} \frac{-\log \nu(f_x^{-(n+k(n))}(B(f^{n+k(n)}(x), \xi)))}{n}$$

$$\leq \lim_{n \to \infty} -\frac{1}{n} \log \nu(\mathcal{P}^n(x))(\mathcal{P}^{n+k(n)+1})(x).$$

The limits on the most left and most right-hand sides of these inequalities exist for ν-a.e. x by the Shennon-McMillan-Breiman Theorem (Theorem 1.5.4), see also (1.5.2), and their ratio is equal to $\lim_{n\to\infty} \frac{n}{n+k(n)} = 1 + \frac{\delta}{\log \lambda}$. Letting $\delta \to 0$ we obtain the existence of the limit and the equality

$$h_\nu(f, \mathcal{P}, x) := \lim_{n \to \infty} -\frac{1}{n} \log \nu(\mathcal{P}^n(x)) = \lim_{n \to \infty} \frac{-\log \nu(f_x^{-n}(B(f^n(x), \xi)))}{n}. \tag{8.1.16}$$

In view of Birkhoff's Ergodic Theorem, the limit

$$\chi_\nu(f, x) := \lim_{n \to \infty} \frac{1}{n} \log |(f^n)'(x)|, \tag{8.1.17}$$

exists for ν-a.e. $x \in X$. Dividing side by side (8.1.16) by (8.1.17) and using (8.1.2)-(8.1.5), we get

$$\lim_{r \to 0} \frac{\log \nu(B(x,r))}{\log r} = \frac{\mathrm{h}_\nu(f, \mathcal{P}, x)}{\chi_\nu(f, x)}.$$

Since by the Shennon-McMillan-Breiman Theorem (formula (1.5.3)) and Birkhoff's Ergodic Theorem,

$$\frac{\int \mathrm{h}_\nu(f, \mathcal{P}, x)\, d\nu(x)}{\int \chi_\nu(f, x)\, d\nu} = \frac{\mathrm{h}_\nu(f, \mathcal{P})}{\chi_\nu(f)} = \frac{\mathrm{h}_\nu(f)}{\chi_\nu(f)}.$$

The latter equality holds since f is expansive and $\mathrm{diam}(\mathcal{P})$ is less than the expansivness constant of f, which exceeds η.

There thus exists a positive measure set where $\frac{\mathrm{h}_\nu(f, \mathcal{P}, x)}{\chi_\nu(f, x)} \leq \frac{\mathrm{h}_\nu(f)}{\chi_\nu(f)}$ and a positive measure set where the opposite inequality holds. Therefore

$$\lim_{r \to 0} \frac{\log \nu(B(x,r))}{\log r} \leq \frac{\mathrm{h}_\nu(f)}{\chi_\nu(f)}$$

and the opposite inequality also holds on a positive measure set. In view of definitions of $\mathrm{HD}_\star$ and $\mathrm{HD}^\star$ (Definition 7.4.11) and by Theorem 7.6.5, this finishes the proof of the inequalities (8.1.12) in our Theorem. In the ergodic case $\mathrm{h}_\nu(f, \mathcal{P}, x) = \mathrm{h}_\nu(f)$ and $\chi_\nu(f, x) = \chi_\nu(f)$ for ν-a.e. $x \in X$. So (8.1.13) holds. ♣

8.2 Multifractal analysis of Gibbs state

In the previous section we linked to a (Gibbs) measure only one dimension number, $\mathrm{HD}(m)$. Here one of our aims is to introduce 1-parameter families of dimensions, so-called spectra of dimensions. In these definitions we do not need the mapping f. Let ν be a Borel probability measure on a metric space X. Recall from Section 7.6 that given $x \in X$ we defined the lower and upper pointwise dimension of ν at x by putting respectively

$$\underline{d}_\nu(x) = \liminf_{r \to 0} \frac{\log \nu(B(x,r))}{\log r} \text{ and } \overline{d}_\nu(x) = \limsup_{r \to 0} \frac{\log \nu(B(x,r))}{\log r}.$$

If $\underline{d}_\nu(x) = \overline{d}_\nu(x)$, we call the common value the pointwise dimension of ν at x and we denote it by $d_\nu(x)$. The function d_ν is called the *pointwise dimension* of the measure ν, cf. Chapter 7. For any $\alpha \leq 0 \leq \infty$ write

$$X_\nu(\alpha) = \{x \in X : d_\nu(x) = \alpha\}.$$

The domain of d_ν namely the set $\bigcup_\alpha X_\nu(\alpha)$ is called *a regular part* of X and its complement $\hat{X}$ a *singular part*. The decomposition of the set X as

$$X = \bigcup_{0 \leq \alpha \leq \infty} X_\nu(\alpha) \cup \hat{X}.$$

is called the *multifractal decomposition with respect to the pointwise dimension*.

Define the $F_\nu(\alpha)$-*spectrum for pointwise dimensions* (another name: *dimension spectrum for pointwise dimensions*, a function related to Hausdorff dimension by

$$F_\nu(a) = \mathrm{HD}(X_\nu(\alpha)),$$

where we define the domain of F_ν as $\{\alpha : X_\nu(\alpha) \neq \emptyset\}$.

Note that by Theorem 8.1.6 if (X, f) is a topologically exact expanding conformal repeller and $\nu = \mu_{-\mathrm{HD}(X)\log|f'|}$ then all $X_\nu(\alpha)$ are empty except $X_\nu(\mathrm{HD}(X))$. In particular the domain of F_ν is in this case just one point $\mathrm{HD}(X)$.

Let for every real $q \neq 1$

$$R_q(\nu) := \frac{1}{q-1} \lim_{r \to 0} \frac{\log \sum_{i=1}^N \nu(B_i)^q}{\log r},$$

where $N = N(r)$ is the total number of boxes B_i of the form $B_i = \{(x_1, \ldots, x_d) \in \mathbb{R}^d : rk_j \leq x_j \leq r(k_j + 1), \ j = 1, \ldots, d\}$ for integers $k_j = k_j(i)$ such that $\nu(B_i) > 0$. This function is called *Rényi spectrum for dimensions*, provided the limit exists. It is easy to check (Exercise 8.1) that it is equal to the *Hentschel-Procaccia spectrum*

$$HP_q(\nu) := \frac{1}{q-1} \lim_{r \to 0} \frac{\log \inf_{\mathcal{G}_r} \sum_{B(x_i, r) \in \mathcal{G}_r} \nu(B(x_i, r))^q}{\log r},$$

where infimum is taken over all $\mathcal{G}_r$ being finite or countable coverings of the (topological) support of ν by balls of radius r centered at $x_i \in X$, or

$$HP_q(\nu) := \frac{1}{q-1} \lim_{r \to 0} \frac{\log \int_X \nu(B(x, r))^{q-1} d\nu(x)}{\log r}$$

provided the limits exist. For $q = 1$ we define the *information dimension $I(\nu)$* as follows. Set

$$H_\nu(r) = \inf_{\mathcal{F}_r} \left(-\sum_{B \in \mathcal{F}_r} \nu(B) \log \nu(B) \right),$$

where infimum is taken over all partitions $\mathcal{F}_r$ of a set of full measure ν into Borel sets B of diameter at most r. We define

$$I(\nu) = \lim_{r \to 0} \frac{H_\nu(r)}{-\log r}$$

provided the limit exists. A complement to Theorem 7.6.5 is that

$$\mathrm{HD}_\star(\nu) \leq I(\nu) \leq \mathrm{PD}^\star(\nu). \tag{8.2.1}$$

For the proof see Exercise 8.5. Note that for Rényi and HP dimensions it does not make any difference whether we consider coverings of the topological support (the smallest closed set of full measure) of a measure or any set of full

measure, since all balls have the same radius r, so we can always choose locally finite (number independent of r) subcovering. These are "box type" dimension quantities.

A priori there is no reason for the function $F_\nu(\alpha)$ to behave nicely. If ν is an f-invariant ergodic measure for (X, f), a topologically exact conformal expanding repeller, then at least we know that for $\alpha_0 = \mathrm{HD}(\nu)$, we have $d_\nu(x) = \alpha_0$ for ν-a.e. x (by the Volume Lemma: Theorem 8.1.3 and Theorem 8.1.4 for a Gibbs measure ν of a Hölder continuous function and by Theorem 8.1.11 in the general case). So, in particular we know at least that the domain of $F_\alpha(\nu)$ is nonempty. However for $\alpha \neq \alpha_0$ we have then $\nu(X_\nu(\alpha)) = 0$ so $X_\nu(\alpha)$ are not visible for the measure ν. Whereas the function $HP_q(\nu)$ can be determined by statistical properties of ν-typical (a.e.) trajectory, the function $F_\nu(\alpha)$ seems intractable. However if $\nu = \mu_\phi$ is an invariant Gibbs measure for a Hölder continuous function (potential) ϕ, then miraculously the above spectra of dimensions happen to be real-analytic functions and $-F_{\mu_\phi}(-p)$ and $HP_q(\mu_\phi)$ are mutual Legendre transforms. Compare this with the pair of Legendre-Fenchel transforms: pressure and -entropy, Remark 2.6.3. Thus fix an invariant Gibbs measure μ_ϕ corresponding to a Hölder continuous potential ϕ. We can assume without loosing generality that $\mathrm{P}(\phi) = 0$. Indeed, starting from an arbitrary ϕ, we can achieve this without changing μ_ϕ by subtracting from ϕ its topological pressure (as at the beginning of the proof of Theorem 8.1.3). Having fixed ϕ, in order to simplify notation, we denote $X_{\mu_\phi}(\alpha)$ by X_α and F_{μ_ϕ} by F. We define a two-parameter family of auxiliary functions $\phi_{q,t} : X \to \mathbb{R}$ for $q, t \in \mathbb{R}$, by setting

$$\phi_{q,t} = -t \log |f'| + q\phi.$$

Lemma 8.2.1. *For every $q \in \mathbb{R}$ there exists a unique $t = T(q)$ such that $\mathrm{P}(\phi_{q,t}) = 0$.*

Proof. This lemma follows from the fact the function $t \mapsto \mathrm{P}(\phi_{q,t})$ is decreasing from ∞ to $-\infty$ for every q (see comments preceding Theorem 8.1.6 and at the beginning of Section 2.6) and the Darboux theorem. ♣

We deal with invariant Gibbs measures $\mu_{\phi_{q,T(q)}}$ which we denote for abbreviation by μ_q and with the measure μ_ϕ so we need to know a relation between them. This is explained in the following.

Lemma 8.2.2. *For every $q \in \mathbb{R}$ there exists $C > 0$ such that for all $x \in X$ and $r > 0$*

$$C^{-1} \leq \frac{\mu_q(B(x,r))}{r^{T(q)} \mu_\phi(B(x,r))^q} \leq C. \tag{8.2.2}$$

Proof. Let $n = n(x, r)$ be defined as in Lemma 8.1.1. Then, by (8.1.6), (8.1.2) and (8.1.4), the ratios

$$\frac{\mu_\phi(B(x,r))}{\exp S_n \phi(x)}, \quad \frac{\mu_q(B(x,r))}{|(f^n)'(x)|^{-T(q)} \exp q S_n \phi(x)}, \quad \frac{r}{|(f^n)'(x)|^{-1}}$$

are bounded from below and above by positive constants independent of x, r. This yields the estimates (8.2.2) ♣

Let us prove the following.

Lemma 8.2.3. *For any f-invariant ergodic probability measure τ on X and for τ-a.e. $x \in X$ we have*

$$d_{\mu_\phi}(x) = \frac{\int \phi d\tau}{-\int \log|f'| d\tau}.$$

Proof. Using formula (8.1.1) in Lemma 8.1.1 and Birkhoff 's Ergodic Theorem, we get

$$d_{\mu_\phi}(x) = \lim_{n \to \infty} \frac{S_n \phi(x)}{\log|(f^n)'(x)|^{-1}} = \frac{\lim_{n \to \infty} \frac{1}{n} S_n \phi(x)}{\lim_{n \to \infty} \frac{1}{n} \log|(f^n)'(x)|^{-1}} = \frac{\int \phi d\tau}{-\int \log|f'| d\tau}.$$

♣

One can conclude from this, that the singular part $\hat{X}$ of X has zero measure for every f-invariant τ. Yet the set $\hat{X}$ is usually big, see Exercise 8.4.

On the Legendre transform. Let $k = k(q) : I \to \mathbb{R} \cup \{-\infty, \infty\}$ be a continuous convex function on $I = [\alpha_1(k), \alpha_2(k)]$ where $-\infty \leq \alpha_1(k) \leq \alpha_2(k) \leq \infty$, excluded the case I is only $-\infty$ or only ∞. I.e. I is either a point in $\mathbb{R}$ or a closed interval or a closed semi-line jointly with $-\infty$ or with ∞, or else $\mathbb{R} \cup \{-\infty, \infty\}$). We assume also that k on (α_1, α_2) is finite.

The Legendre transform of k is the function g of a new variable p defined by

$$g(p) = \sup_{q \in I}\{pq - k(q)\}.$$

Its domain is defined as the closure in $\mathbb{R} \cup \{-\infty, \infty\}$ of the set of points p in $\mathbb{R}$, where $g(p)$ is finite, and g is extended to the boundary by the continuity.

It can be easily proved (Exercise 8.2) that the domain of g is also either a point, or a closed interval or a semi-line or $\mathbb{R}$ (with $\pm\infty$). More precisely the domain is $[\alpha_1(g), \alpha_2(g)]$, where $\alpha_1(g) = -\infty$ if $\alpha_1(k)$ is finite, or $\alpha_1(g) = \lim_{x \to -\infty} k'(x)$ if $\alpha_1(k) = -\infty$. The derivative means here a one side derivative, it does not matter left or right.

Similarly one describes $\alpha_2(g)$ replacing $-\infty$ by ∞.

It is also easy to show that g is a continuous convex function (on its domain) and that the Legendre transform is involutive. We then say that the functions k and g form a Legendre transform pair.

Proposition 8.2.4. *If two convex functions k and g form a Legendre transform pair then $g(k'(q)) = qk'(q) - k(q)$, where $k'(q)$ is any number between the left and right hand side derivative of k at q, defined as $-\infty, \infty$ at $q = \alpha_1(k), \alpha_2(k)$ respectively, if $\alpha_1(k), \alpha_2(k)$ are finite. The formula holds also at $\alpha_i(g)$ if the arising $0 \cdot \infty$ and $\infty - \infty$ are defined appropriately.*

Note that if k is C^2 with $k'' > 0$, therefore strictly convex, then also $g'' > 0$ at all points $k'(q)$ for $\alpha_1(k) < q < \alpha_2(k)$, therefore g is strictly convex on $[k'(\alpha_1(k)), k'(\alpha_2(k))]$. Outside this interval g is affine in its domain. If the domain of k is one point then g is affine on $\mathbb{R}$ and *vice versa*.

We are now in position to formulate our main theorem in this section gathering in particular some facts already proven.

Theorem 8.2.5.   (a) *The pointwise dimension $d_{\mu_\phi}(x)$ exists for μ_ϕ-almost every $x \in X$ and*

$$d_{\mu_\phi}(x) = \frac{\int \phi d\mu_\phi}{-\int \log |f'| d\mu_\phi} = \mathrm{HD}(\mu_\phi) = \mathrm{PD}(\mu_\phi).$$

(b) *The function $q \mapsto T(q)$ for $q \in \mathbb{R}$, is real analytic, $T(0) = \mathrm{HD}(X)$, $T(1) = 0$,*

$$T'(q) = \frac{\int \phi d\mu_q}{\int \log |f'| d\mu_q} < 0$$

and $T''(q) \geq 0$.

(c) *For all $q \in \mathbb{R}$ we have $\mu_q(X_{-T'(q)}) = 1$, where μ_q is the invariant Gibbs measure for the potential $\phi_{q,T(q)}$, and $\mathrm{HD}(\mu_q) = \mathrm{HD}(X_{-T'(q)})$.*

(d) *For every $q \in \mathbb{R}$, $F(-T'(q)) = T(q) - qT'(q)$, i.e. $p \mapsto -F(-p)$ is Legendre transform of $T(q)$. In particular F is continuous at $-T'(\pm\infty)$ the boundary points of its domain, as the Legendre transform is, and for $\alpha \notin [-T'(\infty), -T'(-\infty)]$ the sets $X_{\mu_\phi}(\alpha)$ are empty, so these α's do not lie in the domain of F (see the definition), as they do not belong to the domain of the Legendre transform.*

(This emptyness property is called completness of the F-spectrum.)

If the measures μ_ϕ and $\mu_{-\mathrm{HD}(X) \log |f'|}$ (the latter discussed in Theorem 8.1.6 and Corollary 8.1.7) do not coincide, then $T'' > 0$ and $F'' < 0$, i.e. the functions T and F are respectively strictly convex on $\mathbb{R}$, and strictly concave on $[-T'(\infty), -T'(-\infty)]$ which is a bounded interval in $\mathbb{R}^+ = \{\alpha \in \mathbb{R} : \alpha > 0\}$. If $\mu_\phi = \mu_{-\mathrm{HD}(X) \log |f'|}$ then T is affine and the domain of F is one point $-T'$.

(e) *For every $q \neq 1$ the HP and Rényi spectra exist (i.e. limits in the definitions exist) and $\frac{T(q)}{1-q} = HP_q(\mu_\phi) = R_q(\mu_\phi)$. For $q = 1$ the information dimension $I(\mu_\phi)$ exists and*

$$\lim_{q \to 1, q \neq 1} \frac{T(q)}{1-q} = -T'(1) = \mathrm{HD}(\mu_\phi) = \mathrm{PD}(\mu_\phi) = I(\mu_\phi).$$

Insert Figures: graph of T, graph of F [Pesin 1997, p. 219, 220]

Figure 8.2:

Proof. **1.** Since $P(\phi) = 0$, the part (a) is an immediate consequence of Theorem 8.1.3 and its second and third equalities follow from Theorem 8.1.4. The first equality is also a special case of Lemma 8.2.3 with $\tau = \mu_\phi$.

2. We shall prove some statements of the part (b). The function $\phi_{q,t} = -t \log |f'| + q\phi$, from $\mathbb{R}^2$ to $C^\theta(X)$, where θ is a Hölder exponent of the function ϕ, is affine. Since by a result of Ruelle, compare Section 5.4, the topological pressure function $P : C^\theta \to \mathbb{R}$ is real analytic, then the composition which we denote $P(q,t)$ is real analytic. Hence the real analyticity of $T(q)$ follows immediately from the Implicit Function Theorem once we verify the non-degeneracy assumption. In fact C^2-smoothness of $P(q,t)$ is sufficient to proceed further (here only C^1), which has been proved in Theorem 4.7.4.

Indeed, due to Theorem 4.6.5 for every $(q_0, t_0) \in \mathbb{R}^2$

$$\frac{\partial P(q,t))}{\partial t}\big|_{(q_0,t_0)} = -\int_X \log |f'| d\mu_{q_0,t_0} < 0, \qquad (8.2.3)$$

where μ_{q_0,t_0} is the invariant Gibbs state of the function ϕ_{q_0,t_0}. Differentiating with respect to q the equality $P(q,t) = 0$ we obtain

$$0 = \frac{\partial P(q,t)}{\partial t}\big|_{(q,T(q))} \cdot T'(q) + \frac{\partial P(q,t))}{\partial q}\big|_{(q,T(q))} \qquad (8.2.4)$$

hence we obtain the standard formula

$$T'(q) = -\frac{\partial P(q,t))}{\partial q}\big|_{(q,T(q))} \Big/ \frac{\partial P(q,t)}{\partial t}\big|_{(q,T(q))},$$

Again using (4.6.5) and $P(\phi_{q,T(q)}) = 0$, we obtain

$$T'(q) = \frac{\int \phi d\mu_q}{\int \log |f'| d\mu_q} \leq \frac{-h_{\mu_q}(f)}{\int \log |f'| d\mu_q} < 0, \qquad (8.2.5)$$

the latter true since the entropy of any invariant Gibbs measure for Hölder function is positive, see for example Theorem 4.2.12.

The equality $T(0) = HD(X)$ is just Corollary 8.1.7. $T(1) = 0$ follows from the equality $P(\phi) = 0$.

3. The inequality $T''(q) \geq 0$ follows from the convexity of $P(q,t)$, see Theorem 2.6.2. Indeed the assumption that the part of $\mathbb{R}^3$ above the graph of $P(q,t)$ is convex implies that its intersection with the plane (q,t) is also convex. Since $\frac{\partial P(q,t))}{\partial t}\big|_{(q_0,t_0)} < 0$, this is the part of the plane above the graph of T. Hence T is a convex function.

We avoided in the above consideration an explicit computation of T''. However to discuss strict convexity (a part of (d)) it is necessary to compute it.

Differentiating (8.2.4) with respect to q we obtain the standard formula

$$T''(q) = \frac{T'(q)^2 \frac{\partial^2 \mathrm{P}(q,t)}{\partial t^2} + 2T'(q)\frac{\partial^2 \mathrm{P}(q,t)}{\partial q \partial t} + \frac{\partial^2 \mathrm{P}(q,t)}{\partial q^2}}{-\frac{\partial \mathrm{P}(q,t)}{\partial t}} \qquad (8.2.6)$$

with the derivatives of P taken at $(q, T(q))$. The numerator is equal to

$$\left(T'(q)\frac{\partial}{\partial t} + \frac{\partial}{\partial q}\right)^2 \mathrm{P}(q,t) = \sigma^2_{\mu_q}(-T'(q)\log|f'| + \phi)$$

by Theorem 4.7.4, since this is the second order derivative of $P : C(X) \to \mathbb{R}$ in the direction of the function $-T'(q)\log|f'| + \phi$.

The inequality $\sigma^2 \geq 0$, true by definition, implies $T'' \geq 0$ since the denominator in (8.2.6) is positive by (8.2.3).

By Theorem 1.11.3 $\sigma^2_{\mu_q}(-T'(q)\log|f'| + \phi) = 0$ if and only if the function $-T'(q)\log|f'| + \phi$ is cohomologous to a constant, say to a. It follows then from the equality in (8.2.5) that $a = \int a\,d\mu_q = \int(-T'(q)\log|f'| + \phi)d\mu_q = 0$. Therefore $T'(q)\log|f'|$ is cohomologous to ϕ and, as $\mathrm{P}(\phi) = 0$, also $\mathrm{P}(T'(q)\log|f'|) = 0$. Thus, by Theorem 8.1.6 and Corollary 8.1.7, $T'(q) = -\mathrm{HD}(X)$ and consequently ϕ is cohomologous to the function $-\mathrm{HD}(X)\log|f'|$. This implies that $\mu_\phi = \mu_{-\mathrm{HD}(X)\log|f'|}$, the latter being the equilibrium (invariant Gibbs) state of the potential $-\mathrm{HD}(X)\log|f'|$. Therefore, in view of our formula for T'', if $\mu_\phi \neq \mu_{-\mathrm{HD}(X)\log|f'|}$, then $T''(q) > 0$ for all $q \in \mathbb{R}$.

4. We prove (c). By Lemma 8.2.3 applied to $\tau = \mu_q$, there exists a set $\tilde{X}_q \subset X$, of full measure μ_q, such that for every $x \in \tilde{X}_q$ there exists

$$d_{\mu_\phi}(x) = \lim_{r \to 0} \frac{\log \mu_\phi(B(x,r))}{\log r} = \frac{\int \phi\,d\mu_q}{-\int \log|f'|d\mu_q} = -T'(q).$$

the latter proved in (b). Hence $\tilde{X}_q \subset X_{-T'(q)}$. Therefore $\mu_q(X_{-T'(q)}) = 1$.

By Lemma 8.2.2 for every $B = B(x,r)$

$$|\log \mu_q(B) - T(q)\log r - q\log \mu_\phi(B)| < C$$

for some constant $C \in \mathbb{R}$. Hence

$$\left|\frac{\log \mu_q(B)}{\log r} - T(q) - q\frac{\log \mu_\phi(B)}{\log r}\right| \to 0 \qquad (8.2.7)$$

as $r \to 0$.

Using (8.2.7), observe that for every $x \in X_{-T'(q)}$, in particular for every $x \in \tilde{X}_q$,

$$\lim_{r \to 0} \frac{\log \mu_q(B)}{\log r} = T(q) + q\lim_{r \to 0}\frac{\log \mu_\phi(B)}{\log r} = T(q) - qT'(q).$$

Although $\tilde{X}_q$ can be much smaller than $X_{-T'(q)}$, miraculously their Hausdorff dimensions coincide. Indeed the measure μ_q restricted to either $\tilde{X}_q$ or to $X_{-T'(q)}$ satisfies the assumptions of Theorem 7.6.3 with $\theta_1 = \theta_2 = T(q) - qT'(q)$. Therefore

$$\mathrm{HD}(\tilde{X}_q) = \mathrm{HD}(X_{-T'(q)}) = T(q) - qT'(q) \tag{8.2.8}$$

and consequently

$$F(-T'(q)) = T(q) - qT'(q).$$

Remarks. a) If we take a set larger than $X_{-T'(q)}$, namely replacing in the definition of $X_\nu(\alpha)$ the dimension d_ν by the lower dimension $\underline{d}_\nu$ we still obtain the same Hausdorff dimension, again by Theorem 7.6.3.

b) Some authors replace in the definition of $X_\nu(\alpha)$ the value $d_\nu(x)$ by $\underline{d}_\nu(x)$. Then there is no singular part. In view of a) the $F_\nu(\alpha)$ spectrum is the same for $\nu = \mu_\phi$.

c) Notice that (8.2.8) means that $\mathrm{HD}(X_{-T'(q)})$ is the value where the straight line tangent to the graph of T at $(q, T(q))$ intersects the range axis.

In the next steps of the proof the following will be useful.

Claim (Variational Principle for T). For any f-invariant ergodic probability measure τ on X, consider the following linear equation of variables q, t

$$\int \phi_{q,t}\, d\tau + \mathrm{h}_\tau(f) = 0$$

that is

$$t = t_\tau(q) = \frac{\mathrm{h}_\tau(f)}{\int \log|f'|\, d\tau} + q\frac{\int \phi\, d\tau}{\int \log|f'|\, d\tau}. \tag{8.2.9}$$

Then for every $q \in \mathbb{R}$

$$T(q) = \sup_\tau\{t_\tau(q)\} = t_{\mu_q}(q),$$

where the supremum is taken over all f-invariant ergodic probability measures τ on X.

Proof of the Claim. Since $\int \phi_{q,t}\, d\tau + \mathrm{h}_\tau(f) \leq \mathrm{P}(\phi_{q,t})$ and since $\frac{\partial\, \mathrm{P}(q,t)}{\partial t} < 0$ (compare the proof of convexity of T), we obtain

$$t_\tau(q) \leq T(q).$$

On the other hand by (8.2.9), and using $\mathrm{P}(\phi_{q,T(q)} = 0$, we obtain

$$t_{\mu_q}(q) = \frac{\mathrm{h}_{\mu_q}(f) + q\int \phi\, d\mu_q}{\int \log|f'|\, d\mu_q} = \frac{T(q)\int \log|f'|\, d\mu_q}{\int \log|f'|\, d\mu_q} = T(q).$$

The Claim is proved. ♣

5. We continue Proof of Theorem 8.2.5. We shall prove the missing parts of (d). We have already proved that

$$F(-T'(q)) = \mathrm{HD}(X_{-T'(q)}) = \mathrm{HD}(\mu_q) = T(q) - qT'(q).$$

Note that $[-T'(\infty), -T'(-\infty)] \subset \mathbb{R}^+ \cup \{0, \infty\}$ since $T'(q) < 0$ for all q. Note finally that

$$-T'(-\infty) = \lim_{q \to -\infty} \frac{-\int \phi d\mu_q}{\int \log|f'| d\mu_q} \le \frac{\sup(-\phi)}{\inf \log|f'|} < \infty$$

and

$$-T'(\infty) = \lim_{q \to \infty} \frac{-\int \phi d\mu_q}{\int \log|f'| d\mu_q}.$$

The expressions under lim are positive, (see (8.2.5)). It is enough now to prove that they are bounded away from 0 as $q \to \infty$. To this end choose q_0 such that $T(q_0) < 0$. By our Claim (Variational Principle for T) $t_{\mu_q}(q_0) \le T(q_0)$. Since $t_{\mu_q}(0) \ge 0$, we get

$$-q_0 \frac{\int \phi d\mu_q}{\int \log|f'| d\mu_q} = t_{\mu_q}(0) - t_{\mu_q}(q_0) \ge |T(q_0)|.$$

Hence $\frac{-\int \phi d\mu_q}{\int \log|f'| d\mu_q} \ge |T(q_0)|/q_0 > 0$ for all q.

6. To end the proof of (d) we need to prove the formula for F at $-T'(\pm\infty)$ (in case T is not affine) and to prove that for $\alpha \notin [-T'(\infty), -T'(-\infty)]$ the sets $X_{\mu_\phi}(\alpha)$ are empty. First note the following.

6a. For any f-invariant ergodic probability measure τ on X, there exists $q \in \mathbb{R} \cup \{\pm\infty\}$ such that

$$\frac{\int \phi d\tau}{\int \log|f'| d\tau} = \frac{\int \phi d\mu_q}{\int \log|f'| d\mu_q}. \tag{8.2.10}$$

($\lim_{q \to \pm\infty}$ in the $\pm\infty$ case).

Indeed, by the Claim the graphs of the functions $t_\tau(q)$ and $T(q)$ do not intersect transversally (they can be only tangent) and hence the first graph which is a straight line, is parallel to a tangent to the graph of T at a point $(q_0, T(q_0))$, or one of its asymptotes, at $-\infty$ or $+\infty$. Now (8.2.10) follows from the same formula (8.2.9) for $\tau = \mu_{q_0}$, since the graph of $t_{\mu_{q_0}}$ is tangent to the graph of T just at $(q_0, T(q_0))$. (Note that the latter sentence proves the formula $T'(q) = \frac{\int \phi d\mu_q}{\int \log|f'| d\mu_q}$ in a different way than in 2. , namely *via* the Variational Principle for T.).

6b. Proof that $X_\alpha = \emptyset$ for $\alpha \notin [-T'(\infty), -T'(-\infty)]$. Suppose there exists $x \in X$ with $\alpha := d_{\mu_\phi}(x) \notin [-T'(\infty), -T'(-\infty)]$. Consider any sequence of integers $n_k \to \infty$ and real numbers b_1, b_2 such that

$$\lim_{k \to \infty} \frac{1}{n_k} S_n \phi(x) = b_1, \quad \lim_{k \to \infty} \frac{1}{n_k}(-\log|(f^n)'(x)|) = b_2$$

and $b_1/b_2 = \alpha$. Let τ be any weak*-limit of the sequence of measures

$$\tau_{n_k} := \frac{1}{n_k} \sum_{j=0}^{n_k-1} \delta_{f^j(x)},$$

where $\delta_{f^j(x)}$ is the Dirac measure supported at $f^j(x)$, compare Remark 2.1.15. Then $\int \phi d\tau = b_1$ and $\int (-\log|f'|) d\tau = b_2$.

Due to Choquet Theorem (Section 2.1) (or due to the Decomposition into Ergodic Components Theorem, Theorem 1.8.11) we can assume that τ is ergodic. Indeed, τ is an "average" of ergodic measures. So among all ergodic measure ν involved in the average, there is ν_1 such that $\frac{\int \phi d\nu_1}{\int -\log|f'|d\nu_1} \leq \alpha$ and ν_2 such that $\frac{\int \phi d\nu_2}{\int -\log|f'|d\nu_2} \geq \alpha$. If $\alpha < -T'(\infty)$ we consider ν_1 as an ergodic τ, if $\alpha > -T'(-\infty)$ we consider ν_2. For the ergodic τ found in this way, the limit α can be different than for the original τ, but it will not belong to $[-T'(\infty), -T'(-\infty)]$ and we shall use the same symbol α to denote it. By Birkhoff's Ergodic Theorem applied to the functions ϕ and $\log|f'|$, for τ-a.e. x we have $\lim_{n\to\infty} \frac{S_n(\phi)(x)}{-\log|(f^n)'(x)|} = \alpha$. Hence, applying Lemma 8.2.3, we get

$$\alpha = d_{\mu_\phi}(x) = \frac{\int \phi d\tau}{-\int \log|f'| d\tau}.$$

Finally notice that by (8.2.10) there exists $q \in \mathbb{R}$ such that $\alpha = \frac{\int \phi d\mu_q}{-\int \log|f'|d\mu_q}$, whence $\alpha \in [-T'(\infty), -T'(-\infty)]$. This contradiction finishes the proof.   ♣

Remark. We have proved in fact that for all $x \in X$ any limit number of the quotients $\log \mu_\phi(B(x,r)/\log r$ as $r \to 0$ lies in $[-T'(\infty), -T'(-\infty)]$, the fact stronger than $d_{\mu_\phi}(x) \in [-T'(\infty), -T'(-\infty)]$ for all x in the regular part of X.

6c. On $F(-T'(\pm\infty))$. Consider any τ being a weak*-limit of a subsequence of μ_q as q tends to, say, ∞. We shall try to proceed with τ similarly as we did with μ_q, though we shall meet some difficulties. We do not know whether τ is ergodic (and choosing an ergodic one from the ergodic decomposition we may loose the convergence $\mu_q \to \tau$). Nevertheless using Birkhoff Ergodic Theorem and proceeding as in the proof of Lemma 8.2.3, we get

$$\frac{\int \lim_{n\to\infty} \frac{1}{n} S_n \phi(x) \, d\tau(x)}{-\int \lim_{n\to\infty} \frac{1}{n} \log|(f^n)'(x)| \, d\tau(x)} = \frac{\int \phi \, d\tau}{-\int \log|f'| \, d\tau} = \lim_{q\to\infty} \frac{\int \phi d\mu_q}{-\int \log|f'|d\mu_q}$$

$$= \lim_{q\to\infty} (-T'(q)) = -T'(\infty)$$

with the convergence over a subsequence of q's. Since we know already that

$$d_{\mu_\phi}(x) = \frac{\lim_{n\to\infty} \frac{1}{n} S_n \phi(x)}{-\lim_{n\to\infty} \frac{1}{n} \log|(f^n)'(x)|} \geq -T'(\infty),$$

we obtain for every x in a set $\tilde{X}_\tau$ of full measure τ that the limit $d_\tau(x) = -T'(\infty)$. We conclude with $\tilde{X}_\tau \subset X_{-T'(\infty)}$.

Now we use the Volume Lemma for the measure τ. There is no reason for it to be Gibbs, neither ergodic, so we need to refer to the version of Volume Lemma coming from Theorem 8.1.11. We obtain

$$\mathrm{HD}(X_{-T'(\infty)}) \geq \mathrm{HD}^{\star}(\tau) \geq \frac{\mathrm{h}_\tau(f)}{\int \log|f'|\,d\tau} \geq \liminf_{q\to\infty} \frac{\mathrm{h}_{\mu_q}(f)}{\chi_{\mu_q}(f)}$$
$$= \lim_{q\to\infty} T(q) - qT'(q) = F(-T'(\infty)).$$

We have used here the upper semicontinuity of the entropy function $\nu \to \mathrm{h}_\nu(f)$ at τ due to the expanding property (see Theorem 2.5.6).

It is only left to estimate $\mathrm{HD}(X_{-T'(\infty)})$ from above. As for μ_q, we have for every q and $x \in X_{-T'(\infty)}$ (see (8.2.7)) that

$$\lim_{r\to 0} \frac{\log\mu_q(B)}{\log r} = T(q) + q\lim_{r\to 0} \frac{\log\mu_\phi(B)}{\log r} = T(q) - qT'(\infty) \leq T(q) - qT'(q),$$

Hence $\mathrm{HD}(X_{-T'(\infty)}) \leq T(q) - qT'(q)$. Letting $q \to \infty$ we obtain $\mathrm{HD}(X_{-T'(\infty)}) \leq F(-T'(\infty))$.

7. HP and Rényi spectra. Recall that topological supports of μ_ϕ and μ_q are equal to X, since these measures as Gibbs states for Hölder functions, do not vanish on open subsets of X due to Proposition 4.2.10. For every $\mathcal{G}_r$ a finite or countable covering X by balls of radius r of multiplicity at most C we have

$$1 \leq \sum_{B\in\mathcal{G}_r} \mu_q(B) \leq C.$$

Hence, by Lemma 8.2.2

$$C^{-1} \leq r^{T(q)} \sum_{B\in\mathcal{G}_r} \mu_\phi(B)^q \leq C$$

with an appropriate another constant C. Taking logarithms and, for $q \neq 1$, dividing by $(1-q)\log r$ yields (e) for $q \neq 1$.

8. Information dimension. For $q = 1$ we have $\lim_{q\to 1, q\neq 1} \frac{T(q)}{1-q} = -T'(1)$ by the definition of derivative. It is equal to $\mathrm{HD}(\mu_\phi) = \mathrm{PD}(\mu_\phi)$ by (a) and (b) and equal to $I(\mu_\phi)$ by Exercise 8.5   ♣

8.3   Fluctuations for Gibbs measures

In Section 8.2, given an invariant Gibbs measure μ_ϕ we studied a fine structure of X, a stratification into sets of zero measure (except the stratum of typical points), treatable with the help of Gibbs measures of other functions. Here we shall continue the study of typical (μ_ϕ-a.e.) points. We shall replace Birkhoff's Ergodic Theorem by a more refined one: Law of Iterate Logarithm (Section 1.11), Volume Lemma in a form more refined than Theorem 8.1.11 and Frostman Lemma in the form of Theorem 7.6.1 – theorem 7.6.2.

For any two measures μ, ν on a σ-algebra $(X, \mathcal{F})$, not necessarily finite, we use the notation $\mu \ll \nu$ for μ absolutely continuous with respect to ν, the same as in Section 1.1, and $\mu \perp \nu$ for μ is singular with respect to ν, that is if there exist measurable disjoint sets $X_1, X_2 \subset X$ of full measure, that is $\mu(X \setminus X_1) = \nu(X \setminus X_2) = 0$, generalizing the notation for finite measures, see Section 1.2. We write $\mu \asymp \nu$ if the measures are equivalent, that is if $\mu \ll \nu$ and $\nu \ll \mu$.

The symbol $\log_k$ means the iteration of the log function k times. As in Chapter 7 Λ_α means the Hausdorff measure with the gauge function α, Λ_κ abbreviates Λ_{t^κ} and HD means Hausdorff dimension.

Theorem 8.3.1. *Let $f : X \to X$ be a topologically exact conformal expanding repeller. Let $\phi : X \to \mathbb{R}$ be a Hölder continuous function and let μ_ϕ be its invariant Gibbs measure. Denote $\kappa = \mathrm{HD}(\mu_\phi)$.*
   Then either

(a) *the following conditions, equivalent to each other, hold*

   (a1) *ϕ is cohomologous to $-\kappa \log |f'|$ up to an additive constant, i.e. $\phi + \kappa \log |f'|$ is cohomologous to a constant in Hölder functions; then this constant must be equal to the pressure $\mathrm{P}(f, \phi)$ so we can say that $\psi := \phi + \kappa \log |f'| - \mathrm{P}(f, \phi)$ is a coboundary (see Definition 1.11.2 and Remark 3.4.6),*

   (a2) *$\mu_\phi \asymp \Lambda_\kappa$ on X,*

   (a3) *$\kappa = \mathrm{HD}(X)$*

or

(b) *$\psi = \phi + \kappa \log |f'|$ is not cohomologous to a constant, $\mu_\phi \perp \Lambda_\kappa$, and moreover, there exists $c_0 > 0$, $(c_0 = \sqrt{2\sigma_{\mu_\phi}^2(\psi)/\chi_{\mu_\phi}(f)})$, such that with the gauge function $\alpha_c(r) = r^\kappa \exp(c\sqrt{\log 1/r \log_3 1/r})$:*

   (b1) *$\mu_\phi \perp \Lambda_{\alpha_c}$ for all $0 < c < c_0$, and*

   (b2) *$\mu_\phi \ll \Lambda_{\alpha_c}$ for all $c > c_0$.*

Remark. Also $\mu_\phi \perp \Lambda_{\alpha_{c_0}}$ holds, see Exercise 8.8.

Proof. Note first that by Theorem 8.1.4

$$\int \psi \, d\mu_\phi = \int \phi \, d\mu_\phi + \mathrm{HD}(\mu_\phi)\chi_{\mu_\phi} - \mathrm{P}(\phi) = \int \phi \, d\mu_\phi + \mathrm{h}_{\mu_\phi}(f) - \mathrm{P}(\phi) = 0,$$
$$(8.3.1)$$

since μ_ϕ is an equilibrium state. If $\phi + \kappa \log |f'|$ is cohomologous to a constant a, then for a Hölder function u we have $\int (\phi + \kappa \log |f'| - a) d\mu_\phi = \int (u \circ f - u) d\mu_\phi = 0$ hence $a = \mathrm{P}(\phi)$. Therefore indeed ψ is a coboundary.

By Proposition 4.1.4 the property (a1) is equivalent to $\mu_\phi = \mu_{-\kappa \log |f'|}$ (the potentials cohomologous up to an additive constant have the same invariant

Gibbs measures, and vice versa). Finally, since two cohomologous continuous functions have the same pressure (by definition), $P(-\kappa \log |f'|) = P(\phi - P(\phi)) = 0$, so, by Corollary 8.1.7, $\kappa = \mathrm{HD}(X)$ and $\mu_\phi = \mu_{-\kappa \log |f'|} \asymp \Lambda_\kappa$. We have proved that (a1) implies (a2) and (a3).

(a2) implies that Λ_κ is nonzero finite on X, hence $\mathrm{HD}(X) = \kappa$ i.e. (a3). Finally (a3), i.e. $\kappa = \mathrm{HD}(\mu_\phi) = \mathrm{HD}(X)$ implies $\mathrm{h}_{\mu_\phi}(f) - \kappa \chi_{\mu_\phi}(f) = 0$ by Theorem 8.1.4 and $P(-\kappa \log |f'|) = 0$ by Corollary 8.1.7. Hence μ_ϕ is an invariant equilibrium state for $-\kappa \log |f'|$. By the uniqueness of equilibrium measure (Chapter 4), $\mu_\phi = \mu_{-\kappa \log |f'|}$, hence (a1). (This implication can be called *uniqueness of the measure maximizing Hausdorff dimension.*

Let us discuss now the part (b). Suppose that ψ is not cohomologous to a constant. In this case $\sigma^2_{\mu_\phi}(\psi) > 0$, see Theorem 1.11.3. We can assume that $P(\phi) = 0$ because subtracting the constant $P(\phi)$ from the original ϕ does not change the Gibbs measure.

Let us invoke (8.1.6) and the conclusion from (8.1.2) and (8.1.4), namely

$$K^{-1} \exp S_n \phi(x) \leq \mu(B(x,r)) \leq K \exp S_n \phi(x) \qquad (8.3.2)$$

and

$$K^{-1} |(f^n)'(x)|^{-1} \leq r \leq K |(f^n)'(x)|^{-1} \qquad (8.3.3)$$

for a constant $K \geq 1$ not depending on x and $r > 0$ and for $n = n(x,r)$ defined by (8.1.2).

Note that for $F(t) := \sqrt{t \log_2 t}$, for every $s_0 \geq 0$ there exists t_0 such that for all $s : -s_0 \leq s \leq s_0, s \neq 0$ and $t \geq t_0$ we have $|(F(t+s) - F(t))/s| < 1$. This follows from Lagrange Theorem and $dF/dt \to 0$ as $t \to \infty$, easy to calculate.

Substituting $t = \log |(f^n)'(x)|$ and denoting $\sqrt{\log(|(f^n)'(x)|) \log_3(|(f^n)'(x)|)}$ by $g_n(x)$, we get for $r > 0$ small enough

$$\frac{\mu_\phi(B(x,r))}{r^\kappa \exp(c\sqrt{\log 1/r \log_3 1/r})} \leq \frac{K \exp(S_n \phi(x)}{(K|(f^n)'(x)|)^{-\kappa} \exp(cF(\log |(f^n)'(x)| - \log K))}$$

$$= \frac{Q \exp(S_n \phi(x)}{|(f^n)'(x)|^{-\kappa} \exp(c g_n(x))}$$

for $Q := K^{\kappa + 1 + c} \exp c$, and similarly

$$\frac{\mu_\phi(B(x,r))}{r^\kappa \exp(c\sqrt{\log 1/r \log_3 1/r})} \geq \frac{Q^{-1} \exp(S_n \phi(x)}{|(f^n)'(x)|^{-\kappa} \exp(c g_n(x))}.$$

We rewrite these inequalities in the form

$$-\log Q + g_n(x) \left(\frac{S_n \phi(x) + \kappa \log |(f^n)'(x)|}{g_n(x)} - c \right)$$

$$\leq \log \left(\frac{\mu_\phi(B(x,r))}{r^\kappa \exp(c\sqrt{\log 1/r \log_3 1/r})} \right)$$

$$\leq \log Q + g_n(x) \left(\frac{S_n \phi(x) + \kappa \log |(f^n)'(x)|}{g_n(x)} - c \right). \qquad (8.3.4)$$

We have $S_n \phi + \kappa \log |(f^n)'| = S_n \psi$, so we need to evaluate the following upper limit.

$$\limsup_{n \to \infty} \frac{S_n \psi(x)}{\sqrt{\log |(f^n)'(x)| \log_3 |(f^n)'(x)|}}$$

By the Law of Iterated Logarithm, see (1.11.3) and Theorems 4.7.1 and 1.11.1, for μ_ϕ-a.e. $x \in X$, and writing $\sigma^2 = \sigma^2_{\mu_\phi}$, we have

$$\limsup_{n \to \infty} \frac{S_n \psi(x)}{\sqrt{n \log_2(n)}} = \sqrt{2\sigma^2}. \tag{8.3.5}$$

Applying Birkhoff Ergodic Theorem to the function $\log |f'|$, for μ_ϕ-a.e. $x \in X$, denoting $c_n = \log |(f^n)'(x)| = S_n \log |f'|(x)$ we obtain

$$\lim_{n \to \infty} \frac{\sqrt{c_n \log_2 c_n}}{\sqrt{n \log_2 n}} = \sqrt{\chi_\mu} \lim_{n \to \infty} \frac{\sqrt{\log_2 c_n}}{\sqrt{\log_2 n}} = \sqrt{\chi_{\mu_\phi}}. \tag{8.3.6}$$

Here $\lim_{n \to \infty} \frac{\sqrt{\log_2 c_n}}{\sqrt{\log_2 n}} = 1$, since

$$\frac{\log_2 c_n}{\log_2 n} - 1 = \frac{\log(\log(c_n)/\log(n))}{\log_2 n} \to 0$$

true, since the numerator is bounded, in fact it tends to 0. Indeed, the assumption that $c_n/n \to \chi_\mu$, in particular that c_n/n is bounded and bounded away from 0, implies $\log(c_n)/\log(n) \to 1$ hence its logarithm tends to 0.

Combining (8.3.5) with (8.3.6) we obtain for μ_ϕ-a.e. x the following formula

$$\limsup_{n \to \infty} \frac{S_n \psi(x)}{\sqrt{\log |(f^n)'(x)| \log_3 |(f^n)'(x)|}} = \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}} = c_0. \tag{8.3.7}$$

Therefore, due to $g_n \to \infty$ as $n \to \infty$, for $c < c_0$, both, the left and the right hand side expressions in (8.3.4) tend to ∞. Hence the middle expression in (8.3.4) also tends to ∞. Analogously for $c > c_0$ these expressions tend to $-\infty$. Applying exp we get rid of log and obtain

$$\limsup_{r \to 0} \frac{\mu_\phi(B(x,r))}{r^\kappa \exp(c\sqrt{\log 1/r \log_3 1/r})} = \begin{cases} \infty & \text{if } c < \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}} \\ 0 & \text{if } c > \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}} \end{cases} \tag{8.3.8}$$

Therefore, by Theorem 7.6.1, $\mu_\phi \perp \Lambda_{\alpha_c}$ for all $c < \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}}$ and $\mu_\phi \ll \Lambda_{g_c}$ for all $c > \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}}$. The proof is finished. ♣

Note that this proof is done without the use of Markov partitions, unlike in [PUZ], though it is virtually the same.

The last display, (8.3.8), is known as a LIL Refined Volume Lemma, here in the expanding map, Gibbs measure case, compare Theorem 8.1.3.

Above, (8.3.8) has been obtained from (8.3.7) via (8.3.4). Instead, using (8.3.2), (8.3.3) one can obtain from (8.3.7) the following, equivalent to (8.3.8)

Lemma 8.3.2 (LIL Refined Volume Lemma). *For μ_ϕ-a.e. x*

$$\limsup_{r \to 0} \frac{\log(\mu_\phi(B(x,r))/r^\kappa)}{\sqrt{\log 1/r \log_3 1/r}} = \sqrt{\frac{2\sigma^2}{\chi_{\mu_\phi}}} = c_0.$$

8.4 Boundary behaviour of the Riemann map

In this and the next section we shall apply the results of Section 8.3 to the conformal expanding repeller (X, f) for X at least two-points set, being the boundary $\operatorname{Fr}\Omega$ of a connected simply-connected open domain Ω in the Riemann sphere $\overline{\mathbb{C}}$. A model example is Ω the immediate basin of attraction to an attracting fixed point for a rational mapping, in particular basin of attraction to ∞ for a polynomial with $X = J(f)$, the Julia set. We will assume the expanding property only for technical reasons (and the nature of Chapter 8); for a more general case see [Przytycki 1986] and [Przytycki, Urbański & Zdunik 1989], [Przytycki, Urbański & Zdunik 1991]. In this section we shall consider a large class of invariant measures. In the next section we shall apply the results to harmonic measure. We shall interpret the results in the terms of the radial growth of $|R'(t\zeta)|$ for $R : \mathbb{D} \to \Omega$ a Riemann map, i.e. a holomorphic bijection from the unit disc $\mathbb{D}$ to Ω, for a.e. $\zeta \in \partial\mathbb{D}$ and $t \nearrow 1$.

We start with general useful facts. Let Ω be an arbitrary open connected simply-connected domain in $\overline{\mathbb{C}}$. Denote by $R : \mathbb{D} \to \Omega$ a Riemann mapping, as above,

Lemma 8.4.1. *For any sequence $x_n \in \mathbb{D}$, $x_n \to \partial\mathbb{D}$ iff $R(x_n) \to \operatorname{Fr}\Omega$.*

Proof. If a subsequence of $R(x_n)$ does not converge to $\operatorname{Fr}\Omega$ then we find its convergent subsequence $R(x_{n_i}) \to y \in \mathbb{D}$. So $x_{n_i} \to R^{-1}(y) \in \mathbb{D}$ which contradicts $x_n \to \partial\mathbb{D}$. The converse implication can be proved similarly. ♣

Let now U be a neighbourhood of $\operatorname{Fr}\Omega$ in $\overline{\mathbb{C}}$ and $f : \Omega \cap U \to \Omega$ be a continuous map, which extends continuously on $\operatorname{cl}(\Omega \cap U)$, mapping $\operatorname{Fr}\Omega$ in $\operatorname{Fr}\Omega$. Define $g : R^{-1}(\Omega \cap U) \to \mathbb{D}$ by $g = R^{-1} \circ f \circ R$.

Lemma 8.4.2. *For any sequence $x_n \in R^{-1}(\Omega \cap U)$, $x_n \to \partial\mathbb{D}$ iff $g(x_n) \to \partial\mathbb{D}$.*

Proof. The implication to the right follows from Lemma 8.4.1 and the continuity of f at $\operatorname{Fr}\Omega$. Conversely, if $g(x_n) \to \partial\mathbb{D}$, then by Lemma 8.4.1 $R(g(x_n)) = f(R(x_n)) \to \operatorname{Fr}\Omega$. Hence $R(x_n) \to \operatorname{Fr}\Omega$, otherwise a subsequence of $R(x_n)$ converges to $x \in \Omega$ and $f(x) \in \operatorname{Fr}\Omega$ which contradicts $f(\Omega \cap U) \subset \Omega$. Hence, again by Lemma 8.4.1, $x_n \to \partial\mathbb{D}$. ♣

Proposition 8.4.3 (on desingularization). *Suppose f as above extends holomorphically to U, a neighbourhood of $\operatorname{Fr}\Omega$. Then $g = R^{-1} \circ f \circ R$ on $R^{-1}(\Omega \cap U)$ extends holomorphically to g_1 on a neighbourhood of $\partial\mathbb{D}$, satisfying $I \circ g_1(z) = g_1 \circ I$ for the inversion $I(z) = \bar{z}^{-1}$. This g_1 has no critical points in $\partial\mathbb{D}$.*

Proof. Let $W_1 = \{z : r_1 < |z| < 1\}$ for $r_1 < 1$ large enough that $\mathrm{cl}\, W_1 \subset R^{-1}(\Omega \cap U)$ and W_1 contains no critical points for g. It is possible since f has only a finite number of critical points in every compact subset of U hence in a neighbourhood of $\mathrm{Fr}\,\Omega$, hence g has a finite number of critical points in a neighbourhood of $\partial \mathbb{D}$ in $\mathbb{D}$. Let $W_2 = \{z : r_2 < |z| < 1\}$ for $r_2 < 1$ large enough that if $z \in W_2 \cap g(x)$, then $x \in W_1$. Consider V a component of $g^{-1}(W_2)$. By the above definitions g is a covering map on V. V contains a neighbourhood of $\partial \mathbb{D}$ since by Lemma 8.4.2 V contains points arbitrarily close to $\partial \mathbb{D}$ and if $x_1 \in V$ and $x_2 \in g^{-1}(W_2)$ with x_1, x_2 close enough to $\partial \mathbb{D}$ then an arc δ joining x_1 to x_2 (an interval in polar coordinates) is also close enough to $\partial \mathbb{D}$ that $g(\delta) \subset W_2$. Hence $x_2 \in V$. Let d be the degree of g on V. Then there exists a lift $\tilde{g} : V \to W_3 := \{z : r_2^{1/d} < |z| < 1$, namely a univalent holomorpic mapping such that $(\tilde{g}(x))^d = g$.

The mapping $\tilde{g}$ extends continuously from V to $\tilde{g}_1$ on $V \cup \partial \mathbb{D}$ by Carathéodory's theorem (see for example [Collingwood & Lohwater 1966, Chap. 3.2]). Formally this theorem says that a holomorphic bijection between two Jordan domains extends to a homeomorphism between the closures. However the proof for annuli (W_3 and V) is the same. We use the fact that $\partial \mathbb{D}$ are the corresponding components of the boundaries. (One can also intersect V with small discs B with origins in $\partial \mathbb{D}$, consider $g|_{B \cap V}$ on the topological discs $B \cap V$ and get the continuity of the extensions to $\partial \mathbb{D}$ directly from Carathéodory's theorem.) Finally define the extension of g to $V \cup \partial \mathbb{D}$ by $g_1(x) = (\tilde{g}_1)^d$. It extends holomorphically to a neighbourhood of $\partial \mathbb{D}$ by Schwarz reflection principle. $g_1'(z) \neq 0$ for $z \in \partial \mathbb{D}$ since $g_1(V) \subset \mathbb{D}$ and $g_1(V^*) \subset \mathbb{C} \setminus \mathrm{cl}\,\mathbb{D}$, where V^* is the image of V by the inversion I. ♣

Remark 8.4.4. We can consider g_1 on a neighbourhood of $\partial \mathbb{D}$ as stretching the possibly wild set $\mathrm{Fr}\,\Omega$ lifting (a part of) f and extending to g_1 not having critical points. The lemma on desinularization applies to all periodic simply connected Fatou domains for rational mappings, in particular to Siegel discs and basins of attraction to periodic orbits. In the latter case the following applies.

Proposition 8.4.5. *Let $f : U \to \overline{\mathbb{C}}$ be a holomorphic mapping preserving $\mathrm{Fr}\,\Omega$ and mapping $U \cap \Omega$ in Ω as before. Assume also that*

$$\bigcap_{n \geq 0} f^{-n}(U \cap \mathrm{cl}\,\Omega) = \mathrm{Fr}\,\Omega. \tag{8.4.1}$$

Then the extension g_1 of $g = R^{-1} \circ f \circ R$ provided by Proposition 8.4.3 is expanding on $\partial \mathbb{D}$, moreover $(\partial \mathbb{D}, g_1)$ is a conformal expanding repeller.

Proof. By (8.4.1) for every $x \in U \cap \Omega$ there exists $n > 0$ such that $f^n(x) \notin U$. Hence, due to Lemma 8.4.1, there exists $r_1 < 1$ such that $W_1 = \{z : r_1 \leq |z| < 1\} \subset R^{-1}(U \cap \Omega)$ and for every $z \in W_1$ there exists $n > 0$ for which $g^n(z) \notin W_1$.

Next observe that by Lemma 8.4.2 there exists $r_2 : r_1 < r_2 < 1$ such that if $|g(z)| > r_2$ then $|z| > r_1$. Moreover there exists $r_3 < 1$ such that if $r_3 < |z| < 1$ then for all $n \geq 0$ $|g^{-n}(z)| < r_2$. By $g^{-n}(z)$ we understand here any point

in this set. Indeed, suppose there exist sequences $r_n \nearrow 1$ $r_n < |z_n| < 1$ and $m_n > 0$ such that $r_1 \leq |g^{-m_n}(z_n)| \leq r_2$ and $r_2 < |g^{-m}(z_n)|$ for all $0 \leq m < m_n$. Then for z_0 a limit point of the sequence $g^{-m_n}(z_n)$ we have $|g^m(z)| \geq r_1$ for all $m \geq 0$ which contradicts the first paragraph of the proof.

Moreover, for every $0 < r < 1$ there exists $n(r) > 0$ such that if $r_3 < |z| < 1$ and $n \geq n(r)$ then $|g^{-n}(z)| \geq r$. Otherwise a limit point $z_0 = \lim_{m_n \to \infty} g^{-m_n}(z_n)$ for $r_3 < |z_n|$ would satisfy $g^m(z_0) \leq r_2$ for all $m \geq 0$ a contradiction. By the symmetry given by I the same holds for $1 < |z| < r_3^{-1}$. Hence $\bigcap_{n \geq 0} g^{-n}(\{z : r_3 < |z| < r_3^{-1}\}) = \partial\mathbb{D}$, i.e. $\partial\mathbb{D}$ is a repeller for g, see Ch.4 S.1.

Let z_n be a g_1-trajectory in $\partial\mathbb{D}$, $g(z_n) = z_{n-1}, n = 0, -1, \ldots$. Then for all $n \geq 0$ there exist univalent branches g_1^{-n} on $B(z_0, r_3)$ mapping z_0 to z_{-n} and such that $g_1^{-n}(B(z_0, r_3)) \subset \{z : r_2 < |z| < r_2^{-1}\}$. Moreover $g_1^{-n}(B(z_0, r_3)) \to \partial\mathbb{D}$. Fixed z_0 consider all branches $G_{z_0, \nu, n}$ of g_1^{-n} on $B(z_0, r_3)$ indexed by ν and n. This family is normal and limit functions have values in $\partial\mathbb{D}$. Since $\partial\mathbb{D}$ has empty interior, all the limit functions are constant. Hence there exists $n(z_0)$ such that for all $n \geq n(z_0)$ and $G_{\nu,n}$ for all $z \in B(z_0, r_3/2)$ we have $|G'_{z_0 \nu, n}(z)| < 1$. If we take a finite family of points z_0 such that the discs $B(z_0, r_3/2)$ cover $\partial\mathbb{D}$, then for all $G_{z_0, \nu, n}$ with $n \geq \max\{n(z_0)\}$ and $z \in B(z_0, r_3/2)$ $|G'_{z_0 \nu, n}(z)| < 1$. Hence for all $z \in \partial\mathbb{D}$ and $n \geq \max\{n(z_0)\}$ $|(g^n)'(z)| > 1$ which is the expanding property. ♣

Now we pass to the main topic of this Section, the boundary behaviour of R. We shall denote g_1, the extension of g, just by g.

Definition 8.4.6. We say that for $z \in \partial\mathbb{D}$, $x \to z$ *non-tangentially* if $x \in \mathbb{D}$, x converges to z and there exists $0 < \alpha < \pi/2$ such that for x close enough to z, x belongs to the so-called Stoltz angle

$$S_\alpha(z) = z \cdot (1 + \{x \in \mathbb{C} \setminus \{0\} : \pi - \alpha \leq \text{Arg}(x) \leq \pi + \alpha\}).$$

We say that $x \to z$ *radially* if $x = tz$ for $t \nearrow 1$. For any ϕ a real or complex valued function on $\mathbb{D}$ it is said that ϕ has a nontangential or radial limit at $z \in \partial\mathbb{D}$ if $\phi(x)$ has a limit for $x \to z$ nontangentially or radially respectively.

Theorem 8.4.7. *Assume that (X, f) is a conformal expanding repeller for $X = \text{Fr}\,\Omega \subset \bar{\mathbb{C}}$ for a domain $\Omega \subset \mathbb{C}$. Let $R : \mathbb{D} \to \Omega$ be a Riemann mapping. Then*

$$\limsup_{|x| \to 1} \frac{\log |R'(x)|}{-\log(1 - |x|)} < 1.$$

(This is better than generally true non-sharp inequality, following from Remark 5.2.5). In particular R extends to a Hölder continuous function on $\text{cl}\,\mathbb{D}$. Denote the extension by the same symbol R. Let g be as before and let its extension (in Proposition 8.4.3) be also denoted by g. Then the equality $f \circ R = R \circ g$ extends to $\text{cl}\,\mathbb{D}$.

If μ is a g-invariant ergodic probability measure on $\partial\mathbb{D}$, then the non-tangential limit

$$\lim_{x \to z} \frac{\log |R'(x)|}{-\log(1-|x|)}$$

exists for μ-almost every point $z \in \partial\mathbb{D}$ and is constant almost everywhere. Denote this constant by $\chi_\mu(R)$. Then

$$\chi_\mu(R) = 1 - \frac{\chi_{\mu \circ R^{-1}}(f)}{\chi_\mu(g)}, \tag{8.4.2}$$

where the measure $\mu \circ R^{-1} = R_*(\mu)$ is well defined (and Borel) due to the continuity of R on $\partial\mathbb{D}$.

Proof. Fix $\delta > 0$ such that for every $z \in \partial\mathbb{D}$ there exists a backward branch g_z^{-n} of g^{-n} on $B(g^n(z), \delta)$ mapping $g^n(z)$ to z. Such δ exists since g is expanding, by Proposition 8.4.5, compare the Proof of Proposition 8.4.3.

By the expanding property of g or by Koebe Distortion Lemma we can assume that the distortion for all g_z^{-n} is bounded on $B(g^n(z), \delta)$ by a constant K.

For $x \in S_\alpha(z)$ and $|x - z| < \delta/2$ denote by $n = n(x, z, \delta)$ the least non-negative integer such that $|g^{n+1}(x) - g^{n+1}(z)| \geq \delta/2$. Such n exists if δ is small enough, again since g is expanding. We get for α as in Definition 8.4.6,

$$\frac{1 - |g^n(x)|}{|g^n(z) - g^n(x)|} \geq \frac{1}{\pi}\left(\frac{\pi}{2} - \alpha\right)K^{-1}. \tag{8.4.3}$$

Otherwise there exists $w \in \partial\mathbb{D}$ such that $|w - g^n(x)| < |g^n(z) - g^n(x)|\alpha K^{-1} < \delta/2$. Then $w \in B(g^n(z), \delta)$ so w is in the domain of g_z^{-n} and we obtain $1 - |x| \leq |g_z^{-n}(w) - x| < |z - x|\alpha$, a contradiction. We used here the fact that $g_z^{-n}(g^n(x)) = x$, true since $|g^j(z) - g^j(x)| < \delta/2$ for all $j = 0, 1, \ldots, n$ and g is expanding (two different preimages of a point are far from one another).

From the above bound of distortion it follows also that

$$K^{-1} \leq \frac{|(g^n)'(x)|}{|(g^n)'(z)|} \leq K, \tag{8.4.4}$$

and, writing $\|g'\| = \sup_{1-\delta/2 \leq |x| \leq 1} |g'(x)|$,

$$(K\|g'\|)^{-1}\delta/2 \leq |z - x| \cdot |(g^n)'(x)| \leq K\delta/2. \tag{8.4.5}$$

By $f^n \circ R = R \circ g^n$ we have $R'(x) = ((f^n)'(R(x)))^{-1}R'(g^n(x))(g^n)'(x)$. Due to (8.4.3), $1 - |g^n(x)| \geq \delta/2\|g'\|^{-1}\alpha K^{-1}$, hence there exists a constant $C > 0$ such that for all $z \in \partial\mathbb{D}$ and x, n as above

$$C^{-1} \leq |R'(g^n(x))| \leq C.$$

We conclude with

$$|R'(x)| \leq \lambda_f^{-n} C \|g'\|^n,$$

where λ_f is the expanding constant for f. Hence, with the use of (8.4.5) to the denominator, we obtain

$$\limsup_{|x|\to 1} \frac{\log|R'(x)|}{-\log 1 - |x|} \le \limsup_{x\to z} \frac{-n\log\lambda_f + \log|(g^n)'(z)|}{\log|(g^n)'(z)|} \le 1 - \frac{\log\lambda_f}{||g'||} < 1.$$

If we consider $x_1, x_2 \in \mathbb{D}$ close to each other and also close to $\partial\mathbb{D}$, we find $y \in \mathbb{D}$ and $z_1, z_2 \in \partial\mathbb{D}$ such that $|y| \le \min\{|x_1|, |x_2|\}$, $|x_i - y| \le 2|x_1 - x_2|$ for $i = 1, 2$ and the intervals joining x_i to y are in the Stoltz angles $S_{\pi/4}(z_i)$. By integration of $|R'|$ along these intervals one obtains Hölder continuity of R on $\mathbb{D}$ with an arbitrary exponents smaller than $a := 1 - \frac{\log\lambda_f}{||g'||}$ (a more careful consideration yields the exponent a) and a definite Hölder norm, thus Hölder extending to $\mathrm{cl}\,\mathbb{D}$.

Now we pass to $\chi_\mu(R)$. Since the Riemann map extends to $R : \mathrm{cl}\,D^1 \to \mathrm{Fr}\,\Omega$ uniformly continuous, $R(g^n(x))$ lies close to $R(g^n(z))$. Let $f_{R(z)}^{-n}$ be a holomorphic inverse branch of f^n defined on some small neighbourhood of $R(g^n(z))$, containing $R(g^n(x))$ and sending $R(g^n(z)) = f^n(R(z))$ to $R(z)$. Then $f_{R(z)}^{-n}(R(g^n(x)) = x$ and applying Koebe's Distortion Theorem or bounded distortion for iterates, we obtain

$$\hat{K}^{-1} \le \frac{|(f^n)'(R(x))|}{|(f^n)'(R(z))|} \le \hat{K}, \tag{8.4.6}$$

for some constant $\hat{K}$ independent of z, x and n.

By Birkhoff's Ergodic Theorem there exists a Borel set $Y \in \partial\mathbb{D}$ such that $\mu(Y) = 1$ and

$$\lim_{k\to\infty} \frac{1}{k}\log|(g^k)'(z)| = \chi_\mu(g) \quad \text{and} \quad \lim_{n\to\infty} \frac{1}{k}\log|(f^k)'(R(z))| = \chi_{\mu\circ R^{-1}}(f).$$

for all $z \in Y$.

We conclude that for all $z \in Y$ and $x \in S_\alpha(z)$,

$$\lim_{x\to z} \frac{-\log|R'(x)|}{\log(1-|x|)} = \lim_{x\to z} \frac{\log|(f^n)'(R(z))|^{-1} + \log|(g^n)'(x)|}{\log(1-|x|)} = 1 - \frac{\chi_{\mu\circ R^{-1}}(f)}{\chi_\mu(g)}.$$

$$\clubsuit$$

8.5   Harmonic measure; "fractal vs.analytic" dichotomy

We continue to study $\mathrm{Fr}\,\Omega \subset \mathbb{C}$ the boundary of a simply connected domain $\Omega \subset \bar{\mathbb{C}}$ and the boundary behaviour of a Riemann map $R : \mathbb{D} \to \Omega$, in presence of a map f as in the previous section, with the use of *harmonic measure*. Though most of the theory holds under the weak assumption that f is boundary repelling to the side of Ω, as in Proposition 8.4.5. We call such domain an RB-domain.

We assume in most of this Section, for simplicity, a stronger property that f is expanding on $\operatorname{Fr}\Omega$, and sometimes that Ω is a Jordan domain, that is $\operatorname{Fr}\Omega$ is a Jordan curve.

Harmonic measure $\omega(x, A) = \omega_\Omega(x, A)$ for $x \in \Omega$ and $A \subset \operatorname{Fr}\Omega$ Borel sets, is a harmonic function with respect to x and a Borel probability measure with respect to A, such that for every continuous $\phi : \partial\Omega \to \mathbb{R}$ the function $\tilde{\phi}(x) := \int \phi(z)\,d\omega(x, z)$ is a harmonic extension of ϕ to Ω, continuous on $\operatorname{cl}\Omega$. Its existence is called solution of Dirichlet problem. For simply connected Ω with non-one point boundary it always exists. If $R(0) = x_0$ then $\omega(x_0, \cdot) = R_*(l)$, where l is the normalized length measure on $\partial\mathbb{D}$. Of course $R_*(l)$ makes sense if R is continuous on $\operatorname{cl}\mathbb{D}$. However it makes sense also in general, if we consider the extension of R by the radial limit, which exists l-a.e. by Fatou Theorem, [Pommerenke 1992], [Collingwood & Lohwater 1966].

Since all the Riemann maps differ by compositions with homographies (Möbius maps) preserving the unit circle, all the harmonic measures $\omega(x, \cdot)$ for $x \in \Omega$ are equivalent and corresponding Radon-Nikodym derivatives are bounded away from zero and infinity. If we are interested only in this equivalence class we write ω without specifying the point x, and call it a harmonic measure, or harmonic measure equivalence class on $\operatorname{Fr}\Omega$ viewed from Ω.

Harmonic measure $\omega(x, \cdot)$ can be defined as the probability distribution of the first hit of $\operatorname{Fr}\Omega$ by the Brownian motion starting from x. This is a very intuitive and inspiring point of view.

For more information about harmonic measures in $\mathbb{C}$ we refer the reader for example to [Pommerenke 1992] or [Tsuji 1959].

In the presence of f boundary repelling to the side of Ω the lift g defined in Proposition 8.4.3, extended to $\partial\mathbb{D}$, is expanding by Proposition 8.4.5, hence by Chapter 4 there exists a g-invariant measure μ equivalent to l which is a Gibbs measure for the potential $-\log|g'|$ (with real-analytic density, see Ch.5.2). So the equivalence class ω contains an f-invariant measure, that is $R_*(\mu)$, allowing to apply ergodic theory.

If Ω is a simply connected basin of attraction to ∞ for a polynomial f of degree $d \geq 2$, then $\omega = \omega(\infty, \cdot)$ is a measure of maximal entropy, $\log d$, see xcit[Brolin]. This measure is often called balanced measure.

A major theorem is Makarov's theorem [Makarov 1985] that $\mathrm{HD}(\omega) = 1$. This is a general result true for any simply connected domain Ω as above with no dynamics involved. We shall provide here a simple proof in the dynamical context, in presence of expanding f for Jordan $\operatorname{Fr}\Omega$.

We start with a general simple observation

Lemma 8.5.1. *If for l-a.e. $z \in \partial\mathbb{D}$ there exists a radial limit $\chi(R)(z) := \lim_{x \to z} \frac{-\log|R'(x)|}{\log(1-|x|)}$, then $\int \chi(R)(z)\,dl = 0$.*

(In fact the assumption on the existence of the limit for l-a.e. z, equal to 0, is always true by Makarov's theory.)

Proof. We have

$$\int \chi(R)\,dl = \int \lim_{r\to 1} \frac{\log|R'(rz)|}{-\log(1-r)}\,dl(z)$$
$$= \lim_{r\to 1} \frac{1}{-\log(1-r)} \int \log|R'(rz)|\,dl(z) = 0.$$

We could change above the order of integral and limit, due to the bounds $-2 \leq \frac{\log|R'(rz)|}{-\log(1-r)} \leq 2$ for all r sufficiently close to 1, following from Koebe Distortion Lemma, see Section 5.2. The latter expression is equal to 0 since $\log|R'(rz)|$ is a harmonic function so the integral is equal to $\log|R'(0)|$ which does not depend of r. ♣

Corollary 8.5.2. *Suppose that f is a holomorphic mapping preserving $\mathrm{Fr}\,\Omega$ repelling to the side of Ω. Then for μ the g-invariant measure equivalent to the length measure l*

$$\chi_{R_*(\mu)}(f) = \chi_\mu(g) > 0 \qquad (8.5.1)$$
$$\mathrm{h}_{R_*(\mu)}(f) = \mathrm{h}_\mu(g) \qquad (8.5.2)$$

and $\mathrm{HD}(\omega) = 1$, for ω, the harmonic measure on $\mathrm{Fr}\,\Omega$ viewed from Ω.

Proof. We prove this Corollary only in the case $(\mathrm{Fr}\,\Omega, f)$ is an expanding conformal repeller and Ω is Jordan domain. Then, as we already mentioned in the introduction to this Section, $R_*(\mu)$ is a probability f-invariant measure in the class of harmonic measure ω.

In view of Theorem 8.4.7 $\chi(R)$ exists and is constant l-a.e. equal to $\chi_\mu(R)$, hence by Lemma 8.5.1 it is equal to 0. Hence by (8.4.2) we get (8.5.1). The property (7.5.2) is immediate in the Jordan case since R is a homeomorphism from $\partial\mathbb{D}$ to $\mathrm{Fr}\,\Omega$ by Carathéodory's theorem, conjugating g with f.

Hence

$$\frac{\mathrm{h}_{R_*(\mu)}(f)}{\chi_{R_*(\mu)}} = \frac{\mathrm{h}_\mu(g)}{\chi_\mu(g)}.$$

Since $\mathrm{HD}(\mu) = 1$, an immediate application of Theorem 8.1.11 for f and g (Volume Lemma) finishes the proof. ♣

From now on we assume that Ω is Jordan and f expanding. Then the f-invariant measure $R_*(\mu)$, the R_*-image of the Gibbs g-invariant measure μ, is itself a Gibbs measure, see below, and we can apply the results of Section 8.3, namely Theorem 8.3.1.

Theorem 8.5.3. *The harmonic measure class ω on $\mathrm{Fr}\,\Omega$ contains an f-invariant Gibbs measure for the map $f : \mathrm{Fr}\,\Omega \to \mathrm{Fr}\,\Omega$ and the Hölder continuous potential $-\log|g'| \circ R^{-1}$. The pressure satisfies $P(f, -\log|g'| \circ R^{-1}) = 0$.*

Proof. Recall that Jacobian $J_l(g)$ of $g : \partial\mathbb{D} \to \partial\mathbb{D}$ with respect to the length measure l is equal to $|g'|$, hence l is a Gibbs measure for $\phi = -\log|g'|$ containing in its class a g-invariant Gibbs measure μ. The pressure satisfies $P = P(g, \phi) = 0$ by direct checking of the condition (4.1.1) or since $J_l(g) = e^{\phi - P} = |g'|e^{-P}$.

Since R is a topological conjugacy between $g : \partial\mathbb{D} \to \partial\mathbb{D}$ and $f : \operatorname{Fr}\Omega \to \operatorname{Fr}\Omega$, we automatically get the Gibbs property (4.1.1) for the measure $R_*(l)$ in the class of harmonic measure ω, for f and $\phi \circ R^{-1}$. We get also $P(f, \phi \circ R^{-1}) = P(g, \phi) = 0$. We obtain Gibbs f-invariant measure $R_*(\mu)$ in the class of ω for the potential function $\phi \circ R^{-1}$ which is Hölder since R^{-1} is Hölder.

(Note that in Theorem 8.4.7 we proved that R is Hölder, not knowing a priori that R extends continuously to $\partial\mathbb{D}$. Here we assume that $\operatorname{Fr}\Omega$ is Jordan, so R extends to a homeomorphism by Carathéodory's theorem, hence R^{-1} makes sense. Therefore the proof that R^{-1} is Hölder is straightforward: go from small scale to large scale by f^n, then back on the R^{-1} image by g^{-n}, the appropriate branch, and use bounded distortion for iterates, Ch.5.2.) ♣

Theorem 8.5.4. *Let $f : \operatorname{Fr}\Omega \to \operatorname{Fr}\Omega$ be a conformal expanding repeller, where Ω is a Jordan domain. Then either*

(a) *$\omega \asymp \Lambda_1$ on $\partial\Omega$, which is equivalent to the property that the functions $\log|g'|$ and $\log|f' \circ R|$ are cohomologous, and else equivalent to $\operatorname{HD}(\partial\Omega) = 1$, or*

(b) *$\omega \perp \Lambda_1$, which implies the existence of $c_0 > 0$ such that with the gauge function $\alpha_c(t) = t\exp(c\sqrt{\log(1/t)\log_3(1/t)})$,*

$$\omega \perp \Lambda_{\alpha_c} \quad \text{for all } \ 0 \le c < c_0$$

and

$$\omega \ll \Lambda_{\alpha_c} \quad \text{for all } c > c_0.$$

Proof. The property that $\log|g'|$ and $\log|f' \circ R|$ are cohomologous implies that the functions $-\log|g' \circ R^{-1}|$ and $-\log|f'|$ are cohomologous (with respect to the map $f : \partial\Omega \to \partial\Omega$). By Theorem 8.5.3 ω contains in its equivalence class an invariant Gibbs state of the potential $-\log|g' \circ R^{-1}|$. By Corollary 8.5.2 $\kappa = \operatorname{HD}(\omega) = 1$. Since $\operatorname{P}(f, -\log|f'|) = \operatorname{P}(f, -\log|g' \circ R^{-1}|) = \operatorname{P}(g, -\log|g'|) = 0$, it follows from Corollary 8.1.7 that the cohomology is equivalent to $\operatorname{HD}(\operatorname{Fr}\Omega) = 1$, and to the property that ω is equivalent to the 1-dimensional Hausdorff measure on $\operatorname{Fr}\Omega$. So, the part (a) of Theorem 8.5.4 is proved.

Suppose now that $\log|g'|$ and $\log|f' \circ R|$ are not cohomologous. Then $-\log|g' \circ R^{-1}|$ and $-\log|f'|$ are not cohomologous. Let μ be the invariant Gibbs state of $-\log|g' \circ R^{-1}|$ in the class of ω. By $\kappa = 1$ we get the part (b) immediately from Theorem 8.3.1(b) for $X = \operatorname{Fr}\Omega$. ♣

Now we shall take a closer look at the case a), of rectifiable Jordan curve $\operatorname{Fr}\Omega$. In particular we shall conclude that this curve must be real-analytic.

Theorem 8.5.5. *If $f : \operatorname{Fr}\Omega \to \operatorname{Fr}\Omega$ is a conformal expanding repeller, Ω is a Jordan domain and $\operatorname{HD}(\operatorname{Fr}\Omega) = 1$ (or any other condition in the case (a) in Theorem 8.5.4, then $\operatorname{Fr}\Omega$ is a real-analytic curve.*

If we assume additionally that f extends holomorphically onto $\overline{\mathbb{C}}$, i.e. f is a rational function, and Ω is completely invariant, namely $f^{-1}(\Omega) = \Omega$, then R is a homography, $\mathrm{Fr}\,\Omega$ is a geometric circle and f is a finite Blaschke product in appropriate holomorphic coordinates on $\overline{\mathbb{C}}$, i.e.

$$f(z) = \theta \prod_{i=1}^{d} \frac{z - a_i}{1 - \bar{a}_i z}$$

with d the degree of f, $|\theta| = 1$ and $|a_i| < 1$.

Finally, if f is a polynomial and Ω completely invariant, then in appropriate coordinates $f(z) = z^d$.

For a stronger version, where Ω is only assumed to be forward invariant rather than completely invariant, and for a counterexample, see Exercise 8.12.

Proof. The condition (a2) in Theorem 8.5.4 means that $R : \partial\mathbb{D} \to \mathrm{Fr}\,\Omega$ transports the length measure on $\partial\mathbb{D}$ to the measure equivalent to the Hausdorff measure Λ_1 on $\mathrm{Fr}\,\Omega$.

The idea now is to look at $\mathrm{Fr}\,\Omega$ from outside. We denote $D_1 = \mathbb{D}$, $R_1 =: \mathbb{D} \to \Omega$ and denote $S^1 = \partial\mathbb{D}$. Consider a Riemann map $R_2 : D_2 := \{z : |z| > 1\} \to \overline{\mathbb{C}} \setminus \mathrm{cl}\,\Omega = \Omega^*$. By Carathéodory's Theorem R_2 (analogously to R_1) extends to a homeomorphism from $\mathrm{cl}\,D_2$ to $\mathrm{cl}\,\Omega^*$. Denote the extensiond to $\mathrm{cl}\,\mathbb{D}_i$ by the same symbols R_i.

The map g_1 extending $R_1^{-1} \circ f \circ R_1$ (see Proposition 8.4.3), as being expanding, is a local homeomorphism on a neighbourhood of S^1 in $\mathrm{cl}\,D_1$. Since Ω is a Jordan domain, R_1 is a homeomorphism between closures, $\mathrm{cl}\,D_1$ to $\mathrm{cl}\,\Omega$. So f is a local homeomorphism an open neighborhood U of $\mathrm{Fr}\,\Omega$ in $\mathrm{cl}\,\mathrm{Fr}\,\Omega$. In conclusion, since f has no critical points in $\mathrm{Fr}\,\Omega$, there exists an open neighborhood U of $\mathrm{Fr}\,\Omega$ such that f is defined on $U \cap \Omega*$ and maps it into Ω^*.

Indeed, if $\Omega^* \ni z_n \to z \in \mathrm{Fr}\,\Omega$ and $\mathrm{cl}\,\Omega \ni f(z_n) \to f(z)$, then, since f is a local homeomorphism on a neighbourhood of $\mathrm{Fr}\,\Omega$ in $\mathrm{cl}\,\Omega$, see the paragraph above, there exists $\mathrm{cl}\,\Omega \ni w_n \to z$ such that $f(w_n) \to f(z)$. This contradicts the assumption that f has no critical points in $\mathrm{Fr}\,\Omega$, i.e. f is a local homeomorphism in a neighbourhood of $\mathrm{Fr}\,\Omega$ in $\mathbb{C}$.

Therefore, analogously to g_1, we can define $g_2 = R_2^{-1} \circ f \circ R_2$, the lift of f via the Riemann map R_2 on the set D_2 intersected with a sufficiently thin open annulus surrounding S^1, and consider the extensions of R_2 and g_2 to the closure $\mathrm{cl}\,D_2$, see Figure .....
Set

$$h = R_2^{-1} \circ R_1|_{S^1} : S^1 \to S^1.$$

Composing, if necessary, R_2 with a rotation we may assume that $h(1) = 1$. Our first objective is to demonstrate that h is real-analytic.

Indeed, let $\mu_i = u_i l$ be g_i-invariant Gibbs measures for potentials $-\log|g_i'|$, i.e. g_i-invariant measures equivalent to length measure l, for $i = 1, 2$ respectively. In view of Section 5.2, the densities u_1 and u_2 are both real-analytic.
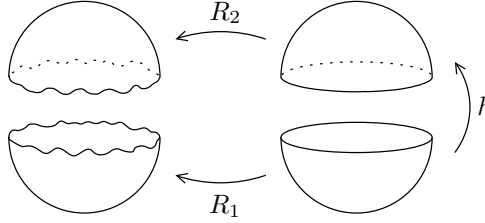
Figure 8.3: Broken egg argument

Now we refer to F. and M. Riesz theorem (or Riesz-Privalov, see for example [Pommerenke 1992, Ch.6.3]), which says that $\operatorname{Fr}\Omega$ rectifiable Jordan curve implies that the map $R_2 : \partial\mathbb{D} \to \operatorname{Fr}\Omega$ transports the length measure on S^1 to the measure equivalent to Λ_1 on $\operatorname{Fr}\Omega$. (Recall that we stated the similar fact on R_1 at the beginning of the proof, which followed directly from the assumptions, without referring to Riesz theorem.) We conclude that $h_*(\mu_1)$ is equivalent to μ_2. Since h establishes conjugacy between g_1 and g_2 the measure $h_*(\mu_1)$ is g_2-invariant.

Now comes the main point. The measures μ_2 and $h(\mu_1)$ are ergodic, hence equal, by Theorem 1.2.6, i.e.

$$h(\mu_1) = \mu_2.$$

Therefore, writing $a(t) = \frac{1}{2\pi} \log h(e^{2\pi it})$, $a : [0,1] \to [0,1]$, denoting $b_1(t) = \int_0^t u_1(e^{2\pi it})\, dt$ and $b_2(t) = \int_0^t u_2(e^{2\pi it})\, dt$, noting that by $h(1) = 1$ we have $a(0) = 0$, we get for all $t : 0 \le t \le 1$

$$b_1(t) = b_2(a(t)).$$

The functions b_i are real-analytic and invertible since u_i are positive. Therefore we can write inverse functions and conclude that $a = b_2^{-1} \circ b_1$ is real-analytic. Hence h is real analytic.

The function h extends to holomorphic function on a neighbourhood of S^1 and we can replace R_2 by $R_3 = R_2 \circ h$ in a neighbourhood of S^1 in D_2. By definition R_1 considered on $\operatorname{cl} D_1$ and R_3 outside D_1 coincide on S^1. So by Peinleve's Lemma they glue together to a holomorphic mapping R on a neighbourhood of S^1. So $R(S^1)$ is a real-analytic curve and the proof of the first part is finished.

Suppose now that f extends to a rational function on $\overline{\mathbb{C}}$ and Ω is completely invariant. Then also Ω^* is completely invariant and both domains are basins of attraction to sinks, $p_1 \in \Omega$ and $p_2 \in \overline{\mathbb{C}} \setminus \operatorname{cl}\Omega$ respectively (use Brouwer theorem and Schwarz lemma). Let R_i defined above satisfy $R_1(0) = p_1$ and $R_2(\infty) = p_2$. The maps $g_i = R_i^{-1} \circ f \circ R_i$ preserving D_i and S^1 must be Blaschke products. Indeed. Let $a_1, \ldots, a_d$ be the zeros of g_1 in D_1 with counted multiplicities. Their number is d since d is the degree of f and $R_1(a_i)$ are f-preimages of p. Denote $B_1(z) = \prod_{i=1}^d \frac{z - a_i}{1 - \bar{a}_i z}$. Each factor $\frac{z - a_i}{1 - \bar{a}_i z}$ is a homography preserving S^1, so their product also preserves S^1.

For B_1 as above g_1/B_1 is holomorphic on D_1, has no zeros there, and its continuous extension to S^1 (see Section 8.4) preserves S^1 Hence by Maximum Principle applied to g_1/B_1 and B_1/g_1 the function g_1/B_1 is a constant λ_1. So $g_1 = \lambda_1 B$ for $|\lambda_1| = 1$. In fact, as one of the zeros of B is 0, as $0 = R_1^{-1}(p_1)$ is a fixed point for g_1, we can write

$$g_1(z) = \lambda_1 z \prod_{i=2}^{d} \frac{z - a_i}{1 - \bar{a}_i z}.$$

Similarly we prove that

$$g_2(z) = \lambda_2 z \prod_{i=2}^{d} \frac{z - a_i'}{1 - \bar{a}_i' z}.$$

for $1/\bar{a}_i'$ the poles of g_2 in D_2.

Note that each Blaschke product B, for which 0 is a fixed point, preserves the length measure l on $\partial\mathbb{D}$. Indeed, let ϕ be an arbitrary real continuous function on $\partial\mathbb{D}$ and $\tilde\phi$ its harmonic extension to $\mathbb{D}$. Then

$$\int \phi \, dl = \tilde\phi(0) = \tilde\phi(B(0)) = \int \phi \circ B \, dl, \qquad (8.5.3)$$

since $\tilde\phi \circ B$ is harmonic as a composition of a holomorphic mapping with a harmonic function. We conclude that both g_1 and g_2 preserve the length measure l. Hence $h = \mathrm{id}$ and $R_1 = R_2$ on S^1 glue together to a homography R on $\bar{\mathbb{C}}$, g_1 and g_2 extend each other holomorphically to $g := g_1 = g_2$ on $\bar{\mathbb{C}}$, and $f = R \circ g \circ R^{-1}$.

Finally, if f is a polynomial, then ∞ is a pole of multiplicity d, hence $g(z) = z^d$. ♣

Example 8.5.6. In Section 5.1, Example 5.1.10, we provided an example of an expanding repeller, being an invariant Jordan curve for $f_c(z) = z^d + c$ for $d = 2$ and $c \approx 0$. Similarly, for any $d \geq 2$ there exists an invariant Jordan curve J_c, being Julia set for f_c, cutting the Riemann sphere $\bar{\mathbb{C}}$ into two components, Ω and Ω^* which are basins of attraction to a fixed point p_c near 0 and to the fixed point at ∞. The existence of the expanding repeller J_c, follows from Proposition 5.1.7. The rest of the scenario is an easy exercise. We can conclude from Theorem 8.5.5 that $c \neq 0$ implies $\mathrm{HD}(J_c) > 1$.

Now we present another proof of Theorem 2, avoiding Riesz Theorem, so more applicable in other situations, see for example Exercise 8.14.

Proof of Theorem 8.5.5, a second method. It is comfortable to use now the half-plane rather than disc, so we consider a univalent conformal map $R : \{z \in \mathbb{C} : \Im z > 0\} \to \Omega$ extending to a homeomorphism $R : \mathrm{cl}\{\Im z \geq 0\} \cup \infty \to \mathrm{cl}\,\Omega$.

By our the assumptions R is absolutely continuous on the real axis $\mathbb{R}$. Denote the restriction of R to this axis by Ψ. Then $\Psi(x)$ is differentiable a.e. and it is equal to the integral of its derivative, see [Pommerenke 1992, Ch.6.3].

Therefore $\Psi' \neq 0$ on a set of positive Lebesgue measure in $\mathbb{R}$. By Egorov's theorem $\frac{\Psi(x+h)-\Psi(x)}{h} - \Psi'(x) \to 0$ uniformly for $|h| \to 0, h \neq 0$ except for a set of an arbitrarily small measure (for a finite measure equivalent to Lebesgue). To be concrete: there exists $c > 0$ and a sequence of numbers $\varepsilon_n \searrow 0$ such that the following set has positive Lebesgue measure

$$Q = \{x \in \mathbb{R} : c \leq |\Psi'(x)| \leq 1/c, \, |\Psi(x+h) - \Psi(x) - \Psi'(x)h| \leq |h|/n \text{ if } |h| \leq \varepsilon_n\}.$$

Let μ denote, as before, the probability g-invariant measure on $\mathbb{R}$ equivalent to Lebesgue (remember that we have replaced the unit disc by the upper half-plane, we use however the same notation R, g and μ). We will prove that R extends to a holomorphic map on a neighbourhood in $\mathbb{C}$ of any point in $\mathbb{R}$, i.e. it is real-analytic on $\mathbb{R}$, by using the formula

$$R = f^n \circ R \circ g^{-n}.$$

The point is to choose the right backward branches g^{-n} so that R in the middle in the above identity is almost affine. We shall use the natural extension $(\check{\mathbb{R}}, \tilde{\mu}, \tilde{g})$, see Section 1.7, where $\check{\mathbb{R}}$ can be understood as the space of g-trajectories and $\pi = \pi_0$ maps $\check{\mathbb{R}}$ to $\mathbb{R}$ and is defined by $\pi(x_n, \, n = \ldots, -1, 0, 1, \ldots) = x_0$. (We shall use this method more extensively in Chapter 10.)

Since g is ergodic, $\tilde{g}^{-1}$ is ergodic , see Section 1.2 and Exercise 1.14, and in conclusion there exists $x_0 \in \mathbb{R}$ and a sequence G_j of backward branches of g^{-n_j} defined on an interval I with x_0 in the middle, $r := |I|/2$, such that $x_j := G_j(x_0) \in Q$ for all $j = 1, 2, \ldots$. Define affine maps

$$A_j(y) := \Psi'(x_j)(y - x_j) + \Psi(x_j) \tag{8.5.4}$$

from $\mathbb{R}$ to $\mathbb{C}$.

First we show that we have uniform convergence on I as $j \to \infty$

$$\Psi_j := f^{n_j} \circ A_j \circ G_j \to \Psi. \tag{8.5.5}$$

Fixed G_j and $x \in I$ denote $y := g_j(x_0)$ and $y + h := G_j(x)$. If $\lambda_g^{-n_j} \operatorname{diam}_s(I) < \varepsilon_n$ for λ_g the expanding constant for g, where diam_s denotes the diameter in the spherical metric, then by the definition of the set Q we obtain, taking into account that $\Psi(y) = A_j(y)$,

$$\left| \frac{\Psi(y+h) - \Psi(y)}{A_j(y+h) - \Psi(y)} - 1 \right| \leq \frac{(1/n_j)|h|}{|\Psi'(y)h|} \leq \frac{1/n_j}{c}. \tag{8.5.6}$$

Then by bounded distortion for iterates of f, Lemma 5.2.2, we obtain for a constant $C \geq 1$ depending on f

$$\left| \frac{f^{n_j}\Psi(y+h) - f^{n_j}\Psi(y)}{f^{n_j}A_j(y+h) - f^{n_j}\Psi(y)} - 1 \right| \leq e^{Cr}/n_j c. \tag{8.5.7}$$

To use Lemma 5.2.2 we need to check its assumptions (we consider $x = \Psi(y), y_1 = \Psi(y+h), y_2 = A_j(y+h)$ in the notation of Lemma 5.2.2), namely to check that for all $k = 0, 1, \ldots, n_j$

$$|f^k\Psi(y+h) - f^k\Psi(y)| < r \text{ and } |f^kA_j(y+h) - f^k\Psi(y)| < r \tag{8.5.8}$$

The first estimate follows immediately from the expanding property of f, namely the estimate $|f^k \Psi(y+h) - f^k \Psi(y)| \leq \lambda_f^{n_j-k} \operatorname{diam} \Psi(I) < r$, where λ_f is the expanding constant for f.

The second estimate can be proved by induction, jointly with (8.5.7) for all $f^k, k = 0, 1, \ldots, n_j$ in place of f^{n_j} in (8.5.7). For each k_0, having assumed (8.5.8) for all $k \leq k_0$, we obtain (8.5.7) for f^{k_0} in place of f^{n_j}, by Lemma 5.2.2. In particular the bound is by $1 - \lambda_f^{-1}$ if n_j is large enough.

Hence in the fraction, writing $k = k_0$, we get in the denominator $|f^k A_j(y + h) - f^k \Psi(y)| \leq \operatorname{diam} \Psi(I)$, since the numerator is bounded by $\lambda_f^{-(n_j-k)} \operatorname{diam} \Psi(I) \leq \lambda_f^{-1} \operatorname{diam} \Psi(I)$. Hence $|f^{k+1} A_j(y+h) - f^{k+1} \Psi(y)| < K \operatorname{diam} \Psi(I) = r$

Note that in the course of induction we verify that the consecutive points $f^k A_j(y+h)$ as being close to $\operatorname{Fr} \Omega$ belong to the domain of f.

Now we calculate using $f^{n_j} \circ \Psi \circ G_j = \Psi$ for all j and (8.5.7) that

$$
\begin{aligned}
|\Psi_j(x) - \Psi(x)| &= |\Psi_j(x) - \Psi_j(x_0) - (\Psi(x) - \Psi(x_0))| \\
&= \left| \frac{f^{n_j} \Psi(y+h) - f^{n_j} \Psi(y)}{f^{n_j} A_j(y+h) - \Psi(x_0)} - 1 \right| \cdot |f^{n_j} A_j(y+h) - \Psi(x_0)| \\
&\leq e^{Cr}/n_j c)|f^{n_j} A_j(y+h) - \Psi(x_0)|.
\end{aligned}
$$

which tends to 0 for $j \to \infty$.

Now consider Ψ_j as defined on a complex neighbourhood of I. To this aim consider A_j as affine maps of $\mathbb{C}$, given by the same formula (8.5.4) as before. By (8.5.8) considered for complex x and consequently complex h the maps Ψ_j are well defined and uniformly bounded. Thus, we can apply Montel theorem and choose a convergent subsequence from Ψ_j . The limit must be a holomorphic extension of Ψ by uniqueness because it is equal to Ψ on I.

Finally Ψ extends holomorphically to a neighbourhood of every $z \in \mathbb{R} \cup \infty$ since by the topological exactness of g there exists $x \in I$ and an integer $n \geq 0$ such that $g^n(x) = z$. So, on a neighbourhood of z we define the extension $\Psi = f^n \circ \Psi \circ g_x^{-n}$ where Ψ in the middle has been already defined in a neighbourhood of I.   ♣

Now we shall prove the following corresponding fact on the radial behaviour of Riemann mapping .

Theorem 8.5.7. *Let $f : \operatorname{Fr} \Omega \to \operatorname{Fr} \Omega$ be a conformal expanding repeller with Ω a Jordan domain. Depending on whether $c(\omega) = 0$ or $c(\omega) \neq 0$, either $\partial\Omega$ is real-analytic and the Riemann map $R : D^1 \to \Omega$ and its derivative R' extend holomorphically beyond ∂D^1 or for almost every $z \in \partial D^1$*

$$
\limsup_{r \to 1} |R'(rz)| \exp c\sqrt{\log(1/1-r)\log_3(1/1-r)} = \begin{cases} \infty & \text{if } c \leq c(\omega) \\ 0 & \text{if } c > c(\omega) \end{cases} \quad (8.5.9)
$$

and

$$\limsup_{r \to 1}\big(|R'(rz)| \exp c\sqrt{\log(1/1-r)\log_3(1/1-r)}\big)^{-1} = \begin{cases} \infty & \text{if } c \le c(\omega) \\ 0 & \text{if } c > c(\omega) \end{cases}$$

$$(8.5.10)$$

Moreover the radial limsup can be replaced by the nontangential one.

Proof. Let $n > 0$ be the least integer for which $g^n(rz) \in B(0, r_0)$ for some fixed $r_0 < 1$. We have $R'(rz) = ((f^n)'(R(rz)))^{-1} \cdot R'(g^n(rz)) \cdot (g^n)'(rz)$. Hence, for some constant $K > 0$ independent of r and z

$$K^{-1} \le \frac{|R'(rz)|}{|((f^n)'(R(rz)))^{-1}| \cdot |R'(g^n(rz))|} \le K.$$

By the bounded distortion theorem the rz in the denominator can be replaced z and n depends on r as described by (8.1.2) with r replaced by $1 - r$. Now we proceed as in the proof of Theorem 8.3.1 replacing deviations of $S_n(\phi) - P(\phi)n + \kappa \log |(f^n)'(x)|$ by the deviations of $\log |(g^n)'(x)| - \log |(f^n)'(x)|$. The proof is finished. ♣

8.6 Pressure versus integral means of the Riemann map

In this section we establish a close relation between integral means of derivatives of the Riemann map to a domain Ω and topological pressure of the function $-t \log |f'|$ for a mapping f on the boundary of Ω. This links holomorphic dynamics with analysis, as in the notion of β below f is not involved. Given $t \in \mathbb{R}$ define

$$\beta(t) = \limsup_{r \to 1} \frac{\log \int_{\partial \mathbb{D}} |R'(rz)|^t dl(z)}{-\log(1 - r)}, \qquad (8.6.1)$$

the integral with respect to the length measure. We shall prove the following.

Theorem 8.6.1. *Assume that* $(\mathrm{Fr}\,\Omega, f)$ *is a conformal expanding repeller (as in Theorem 8.4.7). If the lifted (desingularized) map* $g : \partial \mathbb{D} \to \partial \mathbb{D}$ *is of the form* $z \mapsto z^d$, $d \ge 2$, *then*

$$\beta(t) = t - 1 + \frac{\mathrm{P}(f, -t \log |f'|)}{\log d}. \qquad (8.6.2)$$

In particular in (8.6.1) limsup can be replaced by lim.

Proof. Fix $0 < r < 1$. Fix $n = n(r)$ to be the first integer for which $|g^n(rz)| < r_0$ for $z \in \partial \mathbb{D}$, where $r_0 < 1$ is a constant such that f is defined on a neighbourhood of $\mathrm{cl}\,R(\{r_0 \le |w| \le 1\})$. Note that n is independent of z and that there exists a constant $A \ge 1$ such that $A^{-1} \le |R'(w)| \le A$ for all $w \in B(0, r_0)$.

Then, for all $z \in \partial\mathbb{D}$

$$|R'(rz)|^t = |R'(g^n(rz))|^t \frac{(|g^n|)'(rz)|^t}{|(f^n)'(R(rz))|^t}.$$

Divide $\partial\mathbb{D}$ into d^n arcs $I_j, j = 0, \ldots, d^n - 1$ with the end points $z_j := e^{(2\pi i)j/d^n}$ and z_{j+1}. Note that $\{z_j := j = 0, \ldots, d^n - 1\} = g^{-n}(\{1\})$.

By Hölder continuity of the continuous extension of R to $\mathrm{cl}\,\mathbb{D}$, see Theorem 8.4.7, $f' \circ R$ is Hölder continuous on $\mathrm{cl}\,\mathbb{D}$. Hence there is a constant $K > 0$ such that the ratio $|(f^n)'(R(w_1))/(f^n)'(R(w_2))|$ is bounded by K for all n all j and $w_1, w_2 \in rI_j$, see Chapter 3. Hence

$$\int_{I_j} |(f^n)'(R(rz))|^{-t} dl(z) \asymp (2\pi r d^{-n} |(f^n)'(R(rz_j))|^{-t}|,$$

where $\asymp$ means the equality up to a bounded factor.

By our definition of n, $r_0^d \leq r^{d^n} \leq r_0$; hence $d \log(r_0) \leq d^n \log r \leq \log(r_0)$. Since there exists a constant $B \geq 1$ such that $B^{-1}(1 - r) \leq -\log r \leq B(1 - r)$ for all r sufficiently close to 1, we get $B^{-1} \log 1/r_0 \leq d^n(1 - r) \leq Bd \log 1/r_0$. Therefore $-\log B + \log\log 1/r_0 \leq n \log d + \log(1 - r) \leq \log B + \log\log 1/r_0 + \log d$. Hence $n \log d - C \leq -\log(1 - r) \leq n \log d + C$ for some constant C. Thus, using $|(g^n)'(rz)| = d^n |rz|^{d^n - 1} \asymp d^n$,

$$\lim_{r \to 1} \frac{\log \int_{\partial\mathbb{D}} |R'(rz)|^t dl(z)}{-\log(1 - r)} = \lim_{n \to \infty} \frac{1}{n \log d} \log \Big(\sum_{j=0}^{d^n - 1} 2\pi r d^{-n} d^{nt} |(f^n)'(R(rz_j))|^{-t} \Big)$$

$$= -1 + t + \sum \lim_{n \to \infty} \frac{1}{n \log d} \log \sum_j |f^n)'(R(rz_j))|^{-t}$$

$$= t - 1 + \frac{\mathrm{P}(g, -t \log|f'| \circ R)}{\log d} = t - 1 + \frac{\mathrm{P}(f, -t \log|f'|)}{\log d}$$

Above, to get pressures, we use the equalities $|(f^n)'(R(rz_j))|^{-t} = \exp S_n(-\log|f'| \circ R)(rz_j)$, where $S_n(\phi) = \sum_{k=0}^{n-1} \phi \circ g^k$ with $\phi = -\log|f'| \circ R$, and apply the definition of pressure $\mathrm{P}_x(T, \phi)$ provided in Proposition 3.4.3 To get $\mathrm{P}(g, -t \log|f'| \circ R)$ we replace n-th preimages rz_j of the point $g^n(rz_j)$ (not depending on j) by preimages of $g^n(z_j) = 1$, therefore computing $\mathrm{P}_1(g, \phi)$. As ϕ is Hölder continuous we can apply Lemma 3.4.2. To get $\mathrm{P}(f, -t \log|f'|)$ we replace preimages of $R(g^n(rz_j))$ by preimages of $R(1)$, therefore dealing with $\mathrm{P}_{R(1)}(f, -\log|f'|)$, and refer to the Hölder continuity of $-t \log|f'|$. Limsup can be replaced by lim in $\beta(t)$ since lim in $\mathrm{P}_x(T, \phi)$ exists in Proposition 3.4.3. The proof is finished.   ♣

Remark 8.6.2. The equality (8.2.7) holds even if we do not assume that f is expanding on $\mathrm{Fr}\,\Omega$; it is sufficient to assume boundary repelling to the side of Ω, as in Proposition 8.4.5. To this aim we need to define pressure appropriately. The above proof works for $P_x(f, -t \log|f'|)$ for an arbitrary $x \in \Omega$ close to $\mathrm{Fr}\,\Omega$, see also [Binder, Makarov & Smirnov 2003], Lemma 2.

This pressure does not depend on $x \in \Omega$ by Koebe Distortion Lemma for iteration of branches of f^{-1} in Ω, see Section 5.2. This notion makes sense and is independent of x also for $x \in \operatorname{Fr}\Omega$ for "most" x, see [Przytycki 1999] for the case Ω is a basin of infinity for a polynomial. Compare Section 11.5.

Remark 8.6.3. If f is of degree d on Ω simply connected and f expanding on $\operatorname{Fr}\Omega$ then

$$F(\alpha) := \inf_{t \in \mathbb{R}} \left(t + \frac{\alpha P(t)}{\log d} \right) \qquad (8.6.3)$$

for $P(t) := P(f, -t \log|f'|)$ is the spectrum of dimensions of measure with maximal entropy $F_{\mu_{\max}}(\alpha)$, see the beginning of Section 8.2 and Exercise 8.6.

If f is a polynomial and Ω basin of ∞ then measure with maximal entropy is the harmonic measure ω (from ∞, see [Brolin 1965]) hence (8.6.3) is the formula for the spectrum of dimensions of harmonic measure related to Hausdorff dimension.

One can ask under what conditions the same formula holds for a simply connected Ω in absence of f, where in place of $P(t)/\log d$ one puts $\beta(t) - t + 1$, cf. (8.6.1).

Remark 8.6.4. The following conjecture is of interest. For $B(t) := \sup \beta(t)$, the supremum being taken over all simply connected domains with non one point boundary, and for $B_{\text{poly}}(t) := \sup_\Omega \beta(t)$ supremum taken over Ω being simply connected basins of attraction to ∞ for polynomials

$$B(t) = B_{\text{poly}}(t).$$

It is known, that $B_t = B_{\text{snowflake}}(t)$, where $B_{\text{snowflake}}(t)$ is defined as the $\sup \beta(t)$ with supremum taken over Ω being complements of Carleson's snowflakes, see next section, Section 8.7.

Remark 8.6.5. The following is called Brennan conjecture: $B_{\text{BSC}}(-2) = 1$ (BSC means supremum over bounded simply connected domains).

This has been verified for Ω simply connected basins of ∞ for quadratic polynomials in [Barański, Volberg, & Zdunik 1998], the variant saying that $\int\int_{\mathbb{D}} |R'|^{-2+\varepsilon} |dz|^2 < \infty$.

A stronger conjecture is that

$$B(t) = |t|^2/4 \quad \text{for} \quad |t| \le 2 \quad\quad |t| - 1 \quad \text{for} \quad |t| \ge 2.$$

8.7 Geometric examples. Snowflake and Carleson's domains

This last section of this chapter is devoted to apply the results of previous sections to geometric examples like the Koch's snowflake and Carleson's example. Following the idea of the proof of Theorems 8.3.1, 8.5.4, 8.5.5 and coping with

additional technicalities, see [Przytycki, Urbański & Zdunik 1991, Theorem C, Section 6], one can prove the following.

Theorem 8.7.1. *Let Ω be a simply connected domain in $\mathbb{C}$ with the boundary $\mathrm{Fr}\,\Omega = \partial\Omega$ being a Jordan curve. Let ∂_j, $j = 1, 2 \ldots, k$ be a finite family of compact arcs in $\partial\Omega$ with pairwise disjoint interiors. Denote $\bigcup \partial_j$ by ∂ (we do not assume that this curve is connected). Assume that there exists a family of conformal maps f_j, $j = 1, \ldots, k$, (which may reverse the orientation on $\mathbb{C}$) on neighbourhoods U_j of ∂_j. For every j assume that $f_j(\Omega \cap U_j) \subset \Omega$, $|f_j'| > 1$ on U_j and*

$$f_j(\partial\Omega \cap U_j) \subset \partial\Omega. \tag{8.7.1}$$

Assume also the Markov partition property: for every $j = 1, \ldots k$, $f_j(\partial_j) = \bigcup_{s \in I_j} \partial_s$ for some subset $I_j \subset \{1, 2, \ldots, k\}$. Consider the $k \times k$ matrix $A = A_{jk}$ where $A_{jk} = 1$ if $k \in I_j$ and $A_{jk} = 0$ if $k \notin I_j$. Assume that A is aperiodic, i.e. there exists n such that all the entries of A^n are positive. (cf. Section 3.3). Then there exists a transition parameter $c(\omega, \partial) \geq 0$ such that for the harmonic measure ω on $\partial\Omega$ viewed from Ω, restricted to ∂ the claims of Theorem 8.5.4 and Theorem 8.5.5 (the analyticity of ∂ in the case $c(\omega, \partial) = 0$), hold for ∂.

Here (8.7.1) is a crucial assumption allowing to prove Theorem 8.7.1. To have it satisfied one needs sometimes to construct a sophisticated Markov partition of $\partial\Omega$ rather than a natural one, see the snowflake example below, Figure 8.4 and Chapter 0. See the discussion in [Makarov 1986].

Example 8.7.2 (the snowflake)**.** To every side of an equilateral triangle, in the middle we glue from outside a three times smaller triangle. To every side of the resulting polygon we glue again an equilateral triangle three times smaller, and so on infinitely many times. The triangles do not overlap in this construction and the boundary of the resulting domain Ω is a Jordan curve. This Ω is called the Koch's snowflake. It was first described by Helge Koch in 1904.

Denote the curve in $\partial\Omega$ joining a point $x \in \partial\Omega$ to $y \in \partial\Omega$ in the clockwise direction just by xy. For every $\partial_i := A_i A_{i+1(mod\,12)} \subset \partial\Omega$, $i = 0, 1, \ldots, 11$, we consider its covering by the curves 12, 23, 34, 45, 56 in Ω, see Figure 8.5. This covering together with the affine maps

$$12,\ 34 \rightarrow 16\ (\text{ preserving orientation on } \partial\Omega)$$
$$23 \rightarrow 61\ (\text{ reversing orientation })$$
$$56 \rightarrow 36\ (\text{ preserving orientation })$$
$$45 \rightarrow 63\ (\text{ reversing orientation })$$

gives a Markov partition of ∂_i satisfying the assumptions of Theorem 8.7.1.
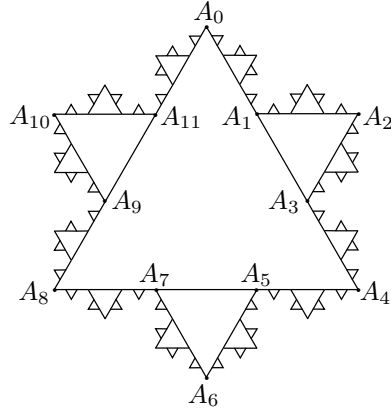
Figure 8.4: Snowflake
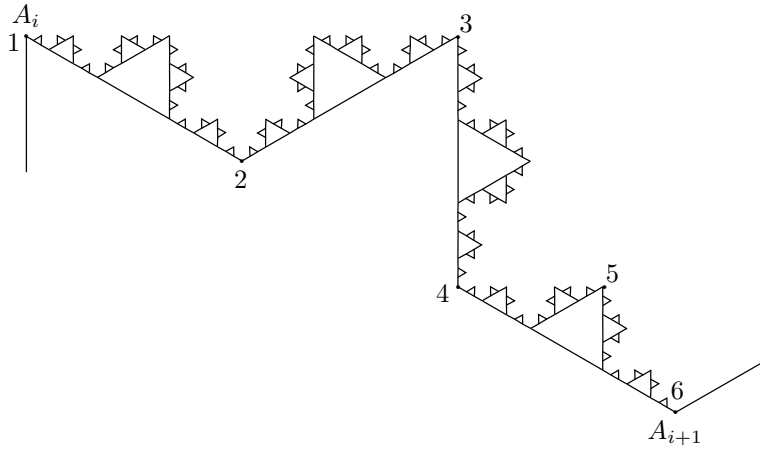
Figure 8.5: A fragment of the snowflake

Since $\partial\Omega$ (and every its subcurve) is definitely not real-analytic (HD($\partial\Omega$) = $\log 4/\log 3$), the assertion of Theorem 8.7.1 is valid with $c(\omega, \partial_i) > 0$. We may denote $c(\omega, \partial_i)$ by $c(\omega)$ since it is independent of ∂_i by symmetry.

Example 8.7.3 (Carleson's domain)**.** We recall Carleson's construction from [Carleson 1985]. We fix a broken line γ with the first and last segment lying in the same straight line in $\mathbb{R}^2$, with no other segments intersecting the segment $\overline{1, d-1}$, see Figure 8.6).

Then we take a regular polygon Ω^1 with vertices $T_0, T_1, \ldots, T_n$ and glue to every side of it, from outside, the rescaled, not mirror reflected, curve γ
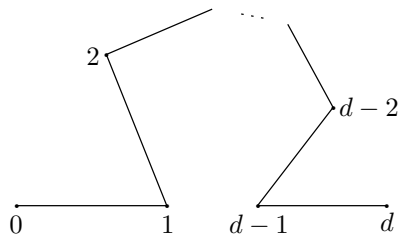
Figure 8.6: Construction of Carleson's domain

so that the ends of the glued curve coincide with the ends of the side. The resulting curve bounds a second polygon Ω^2. Denote its vertices by $A_0, A_1, \ldots$ (Figure 8.7). Then we glue again the rescaled γ to all sides of Ω^2 and obtain a third order polygon Ω^3 with vertices $B_0, B_1, \ldots$. Then we build Ω^4 with vertices $C_0, C_1, \ldots \Omega^5$ with $D_0, D_1, \ldots$ etc.
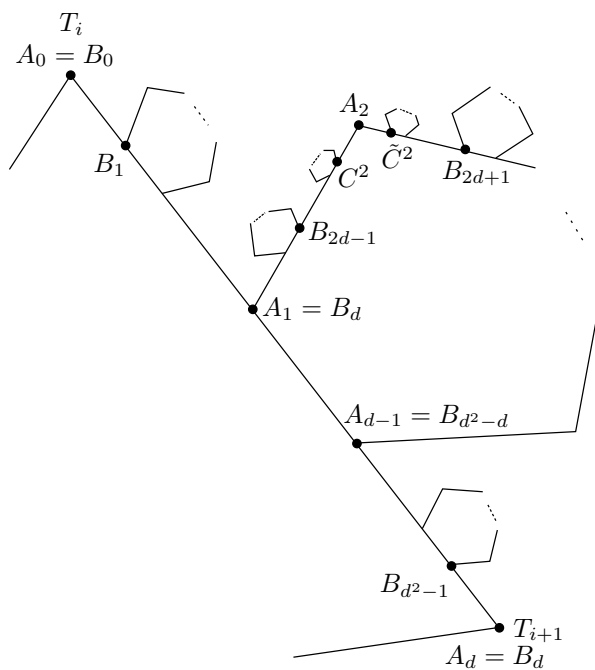
Figure 8.7: Carleson's domain

Assume that there is no self-intersecting of the curves $\partial\Omega^n$ in this construction. Moreover assume that in the limit we obtain a Jordan curve $\mathcal{L} = \mathcal{L}(\Omega^1, \gamma) = \partial\Omega$. The natural Markov partition of each curve T_iT_{i+1} in $\mathcal{L}$ into

curves $A_j A_{j+1}$ with $f(A_j A_{j+1}) = T_i T_{i+1}$, considered by Carleson does not satisfy the property (8.7.1) so we cannot succeed with it. Instead we proceed as follows: Define in an affine fashion

$$f(B_{d(j-1)+1} B_{dj-1}) = A_1 A_{d-1}$$

for every $j = 1, 2 \ldots, d$. Divide now every arc $B_{dj-1} A_j$ for $j = 1, 2 \ldots, d$ and $A_j B_{dj+1}$, $j = 1, 2 \ldots, d$ into curves with ends in the vertices of the polygon $\Omega^4 : C^j \in B_{dj-1} A_j$, $\tilde{C}^j \in A_j B_{dj+1}$ respectively, the closest to $A_j (\neq A_j)$. Let for $j = 1, 2, \ldots, d-1$,

$$f(C^j A_j) = B_{dj-1} A_j, \quad f(B_{dj-1} C^j) = A_{d-1} B_{d^2-1},$$
$$f(A_j \tilde{C}^j) = A_j B_{dj+1}, \quad f(\tilde{C}^j B_{dj+1}) = B_1 A_1.$$

This gives a Markov partition of $B_1 B_{d^2-1}$ with aperiodic transition matrix, see the discussion after Definition 3.3.3 and Theorem 3.5.7. We can consider instead of the broken line γ in the construction of Ω, the line $\gamma^{(2)}$, consisting of d^2 segments, which arises by glueing to every side of γ a rescaled γ. Consecutive gluing of the rescaled $\gamma^{(2)}$ to the polygon Ω^1 gives consecutively Ω^3, Ω^5 etc. The same construction as above gives a Markov partition of $D_1 D_{d^4-1}$ in $T_i T_{i+1}$. By continuing this procedure we approximate $T_i T_{i+1}$, so from Theorem 8.7.1 and from the symmetry we deduce that there exists a transition parameter $c(\omega)$ such that the assertion of Theorem 8.5.4(b) is satisfied. Observe that Carleson's assumption that the broken line $1, 2, \ldots, d-1$ does not intersect $\overline{1, d-1}$ has not been needed in these considerations. Also the assumption that Ω^1 is a regular polygon can be omitted; one can prove that $c(\omega)$ does not depend on $T_i T_{i+1}$ by considering a Markov partition with aperiodic transition matrix, which involves all the sides of Ω^1 simultaneously.

Exercises

Multifractal analysis

8.1. Prove the equalities of Rényi and Hentschel-Procaccia spectra.

8.2. Prove Proposition 8.2.4 about Legendre transform pairs and remarks preceding and following it.

8.3. Prove for $\alpha = -T'(1)$ that $F(\alpha) = \alpha$ and $F'(\alpha) = 1$ (see Fig.1.) and $F'(-T'(\pm\infty)) = \pm\infty$.

8.4. Prove that if ϕ is not cohomologous to $-\operatorname{HD}(X) \log|f'|$ then the singular part $\hat{X}$ of X is nonempty. Moreover $\operatorname{HD}(\hat{X}) = \operatorname{HD}(X)$.

Hint: Using the Shadowing Lemma from Chapter 3, find trajectories that have blocks close to blocks of trajectories typical for $\mu_{-\operatorname{HD}(X)\log|f'|}$ of length

N interchanging with blocks close to blocks typical for μ_ϕ of length εN, for N arbitrarily large and $\varepsilon > 0$ arbitrarily small.

8.5. Define the *lower* and *upper information dimension* $\underline{I}(\nu)$ and $\overline{I}(\nu)$ replacing in the definition of $I(\nu)$ the limit $\lim_r$ by the lower and upper limits respectively. Prove that $\mathrm{HD}_\star(\nu) \leq \underline{I}(\nu) \leq \overline{I}(\nu) \leq \mathrm{PD}^\star(\nu)$, see (8.2.1).

Sketch of the proof. For an arbitrary $\varepsilon > 0$ there exist $C > 0$ and $A \subset X$, with $\nu(X \setminus A) \leq \varepsilon$ such that for all r small enough there exists a partition $\mathcal{F}_r$ of A, satisfying $H_\nu(r) + \varepsilon \geq -\sum_{B \in \mathcal{F}_r} \nu(B) \log \nu(B) \geq \sum_{B \in \mathcal{F}_r} \nu(B) \mathrm{HD}_\star(\nu) \log \frac{1}{C \operatorname{diam} B} \geq \mathrm{HD}_\star(\nu)(1 - \varepsilon) \log \frac{1}{Cr}$.

On the other hand for the partition $\mathcal{B}_r$ of X into intersections with boxes (cubes) of sides of length r (compare Proposition 7.4.6 and the partition involved in the definition of Rényi dimension, but consider here disjoint cubes, that is open from one side), we have

$$\overline{I}(\nu) = \limsup_{r \to 0} \frac{H_\nu(r)}{-\log r} \leq \limsup_{r \to 0} \frac{-\sum_{B \in \mathcal{B}_r} \nu(B) \log \nu(B)}{-\log r}$$

$$\leq \limsup_{r \to 0} \frac{\int \log \nu(B_r(x)) \, d\nu(x)}{\log r} \leq \int \left(\limsup_{r \to 0} \frac{\log \nu(B_r(x))}{\log r} \right) d\nu(x) \leq \mathrm{PD}^\star(\nu),$$

where $B_r(x)$ denotes the cube of side r containing x.

Prove that it has been eligible here to use cubes instead of balls standing in the definition of $\overline{d}_\nu(x)$. For this aim prove that for ν-a.e. $x \in X$, we have $\lim \frac{\log \nu(B_r(x))}{\log \nu(B(x,r))} = 1$. Use Borel-Cantelli lemma.

Prove that we could use Fatou's lemma (changing the order of limsup and integral) indeed, due to the existence of a ν-integrable function which bounds from above all the functions $\log \nu(B(x,r))/\log r$ (or $\log \nu(B_r(x))/\log r$). Use again Borel-Cantelli lemma, for, say, $r = 2^{-k}$.

8.6. Let $\mu = \mu_\phi$ be a measure of maximal entropy on a topologically exact conformal expanding repeller X such that every point $x \in X$ has exactly d preimages (so $\phi = -\log d$). Prove (deduce from Theorem 8.2.5) that $F(\alpha) = \inf_{t \in \mathbb{R}} \left(t + \frac{\alpha \mathrm{P}(t)}{\log d} \right)$, more concretely $F(\alpha) = T + \frac{\alpha \mathrm{P}(T)}{\log d}$, where $\alpha = -\frac{\log d}{\mathrm{P}'(T)}$.

8.7. Let $\phi_i : X \to \mathbb{R}$ be Hölder continuous functions for $i = 1, \ldots, k$ and μ_{ϕ_i} their Gibbs measures. Define $X_{\alpha_1, \ldots, \alpha_k} = \{x \in X : d_{\mu_i}(x) = \alpha_i \text{ for all } i = 1, \ldots, k\}$. Define $\phi_{q_1, \ldots, q_k, t} = -t \log |f'| + \sum_i q_i \phi_i$ and $T(q_1, \ldots, q_k)$ as the only zero of the function $t \mapsto \mathrm{P}(\phi_{q_1, \ldots, q_k, t})$. Prove the same properties of T as in Theorem 8.2.5, in particular that

$$\mathrm{HD}(X_{\alpha_1, \ldots, \alpha_k}) = \inf_{(q_1, \ldots, q_k) \in \mathbb{R}^k} \sum_i q_i \alpha_i + T(q_1, \ldots, q_k)$$

wherever the infimum is finite.

Fluctuations for Gibbs measures

8.8. Prove $\mu_\phi \perp \Lambda_{\alpha_{c_0}}$ in the case b) of Theorem 8.3.1.

Hint. Use a function more refined than $\sqrt{2\sigma^2 n \log\log n}$, see the Kolmogorov test after Theorem 1.11.1. Use LIL (upper bound) for $S_n(\log|\phi'| - \chi_{\mu_\phi})$ (Birkhoff Ergodic theorem as used above is not suficient). for details see [PUZ].

8.9. Prove a Theorem analogous to Theorem 8.3.1, comparing μ_ϕ with packing measures. In particular prove that, for ψ not a coboundary, for the gauge function $\alpha_c(r) = r^\kappa \exp(-c\sqrt{\log 1/r \log_3 1/r})$ and $c_0 = \sqrt{2\sigma^2_{\mu_\phi}(\psi)/\chi_{\mu_\phi}(f)}$ it holds $\mu_\phi \ll \Pi_{\alpha_c}$ for all $0 < c < c_0$, and $\mu_\phi \perp \Pi_{\alpha_c}$ for all $c > c_0$.

Harmonic measure

8.10. Prove (8.5.2), namely $\mathrm{h}_{R_*(\mu)}(f) = \mathrm{h}_\mu(g)$ in the case f is expanding but not assuming that Ω is Jordan. To this end prove that R is finite-to-one on $\partial\mathbb{D}$.

8.11. Prove that if Ω is a Jordan domain with boundary preserved by a conformal expanding map f defined on its neighbourhood, and harmonic measures ω_Ω and $\omega_{\overline{\mathbb{C}}\setminus\mathrm{cl}\,\Omega}$ on $\mathrm{Fr}\,\Omega$ (i.e harmonic measures on $\mathrm{Fr}\,\Omega$ viewed from inside and outside) are equivalent, then they are equivalent to the Hausdorff measure Λ_1 (hence $\mathrm{Fr}\,\Omega$ is real analytic).

Remark. A part of this theorem holds without assuming the existence of f, see [Bishop *et al.* 1989]. It has an important intuitive meaning. Harmonic measure is supported on a set exposed to the side from which it is defined, easily accessible by Brownian motion. These sets in $\mathrm{Fr}\,\Omega$ viewed from inside and outside are very different except $\mathrm{Fr}\,\Omega$ is rectifiable.

8.12. Prove that if $(\mathrm{Fr}\,\Omega, f)$ is an expanding conformal repeller for a rational function f, $\mathrm{Fr}\,\Omega$ is an analytic Jordan curve and Ω is a basin of attraction to a sink, then $\mathrm{Fr}\,\Omega$ is a geometric circle. (The assumption Ω is a basin of attraction is weaker than the assumption that Ω is completely invariant in Theorem 8.5.5.)

Hint: Due to the analyticity of $\mathrm{Fr}\,\Omega$ a Riemann map $R : \mathbb{D} \to \Omega$ extends holomorphically to a neighbourhood U of $\mathrm{cl}\,\mathbb{D}$.Consider g a Blaschke product extending $R^{-1}fR$ defined on $\mathbb{D}$. We can assume g has a sink at ∞. Extend next R to $\mathbb{C}$ holomorphically by $f^n \circ R \circ g^{-n}$, with branches g^{-n} and n large enough that $g^{-n}(z) \in U$. Check that the extension does not depend on the choice of the branches g^{-n}. If g is not of the form $g(z) = Az^d$ then the above formula defines R on $\overline{\mathbb{C}}$. If $g(z) = Az^d$ prove separately that R does no have an essential singularity at ∞. Finally prove that the extended R is invertible. For details see [Brolin 1965, Lemma 9.1].

If we do not assume anything about f-invariance of Ω or Ω^* then Jordan $\mathrm{Fr}\,\Omega$ need not be a geometric circle. Consider for example the mapping $F(x,y) = (4x, 4y)$ on the 2-torus $\mathbb{R}^2/\mathbb{Z}^2$ and its factor, so called Lattés map, $f := PFP^{-1}$ on the Riemann sphere, where P is Weierstrass elliptic function. Then $P(\{y = 1/4 + \mathbb{Z}\})$ is an f-invariant expanding repelling Jordan curve, but it is not a geometric circle (we owe this example to A. Eremenko).

8.13. Prove that if for two conformal expanding repellers (J_1, f_1) and (J_2, f_2) in $\mathbb{C}$ being Jordan curves, the multipliers at all periodic orbits in J corresponding by a conjugating homeomorphism h, coincide, i.e. for each periodic point $q \in J_1$

of period n we have $|(f_1^n)'(q)| = |(f_2^n)'(h(q))|$, then the conjugacy extends to a conformal map to neighbourhoods.

8.14. Let $A : \mathbb{R}^d/Z^d \to \mathbb{R}^d/Z^d$ be a hyperbolic toral automorphism given by an integer matrix of determinant 1. Let $\Phi(x_1, \ldots, x_d) = (\varepsilon^{2\pi i x_1}, \ldots, \varepsilon^{2\pi i x_d})$ maps this torus to the torus $T^d = \{|z_1| = \cdots = |z_d| = 1\} \subset \mathbb{C}^d$. It extends to $\mathbb{C}^d/\mathbb{Z}^d$. Define $B = \Phi A \Phi^{-1}$. Let f be a holomorphic perturbation of B on a neighbourhood of T^d. Prove that close to T^d there is a topological torus S invariant for f such that A on T^d and f on S are topologically conjugate by a homeomorphism h close to identity. Prove that if for each A-periodic orbit $p, A(p), \ldots, A^{n-1}(p)$ of period n absolute values of eigenvalues of differentials $DA^n(p)$ and of $Df^n(h(p))$ coincide (one says that Lyapunov spectra of periodic orbits coincide), then h extends to a holomorphic mapping on a neighbourhood of T^d.

Bibliographical notes

The section on multifractal analysis relies mainly on the monographs by Y. Pesin [Pesin 1997] and K. Falconer [Falconer 1997] (though details are modified, for example we do not use Markov partition). The reader can find there comprehensive expositions and further references. The development of this theory has been stimulated by physicists, the paper often quoted is [Hasley *et al.* 1986].

Proofs of Propositions 8.4.3 and 8.4.5 are slight modifications of proofs in [Przytycki 1986, Ch.7]. For Proposition 8.4.3 see also [Ghys 1984]. It is commonly used in the study of Siegel discs (Herman) and hedgehogs for Cremer points (Perez-Marco). The assumption that f is expanding, for the Riemann map R to be Hölder, is not necessary. A non-uniform hyperbolicity, namely Collet-Eckmann, or Topological Collet-Eckmann is sufficient, see [Graczyk & Smirnov 1998], [Przytycki & Rohde 1998] or [Przytycki 2000, Proposition 5.2]. A condition intermediate between expanding and non-uniform hyperbolicity (all critical points in $\operatorname{Fr}\Omega$ eventually periodic) in case Ω is a basin of attraction of a rational map is equivalent to John property of Ω, stronger than Hölder, see [Carleson, Jones & Yoccoz 1994].

The formula for $\chi_\mu(R)$ in Theorem 8.4.7 holds for $(\partial\Omega, f)$ repelling to the side of Ω, as in Proposition 8.4.5, provided μ has positive entropy. The expanding assumption for f is not needed. See [Przytycki 1986, Theorem 1].

The proofs of Theorem 8.5.4 and Theorem 8.5.5 in full generality can be found in [Przytycki 1986] and [Przytycki, Urbański & Zdunik 1989] and [Przytycki, Urbański & Zdunik 1 The proof of Theorem 8.5.5 is virtually taken from [Sullivan 1982], see also [Przytycki 1986b]. The idea of the proof is similar as for quasi-Fuchsian groups (either Hausdorff dimension of the limit quasicircle is bigger than 1, or the group is Fuchsian) in [Bowen 1979]. It is a simple example of the strategy used in a proof of Mostow Rigidity Theorem, see for example [Sullivan 1982]. In the general polynomial f case, with the basin Ω of attraction to ∞ simply connected the dichotomy that either $\operatorname{HD}(\operatorname{Fr}\Omega) > 1$ or $f(z) = z^d$ was proved by A. Zdunik in [Zdunik 1990], [Zdunik 1991]. A more careful look proves that for any Ω with f defined on a neighbourhood of $\operatorname{Fr}\Omega$ with bondary repelling to

the side Ω as in Propositions 8.4.5 and Corollary 8.5.2 either HD(Fr Ω) > 1, in fact even hyperbolic dimension HyD(X) > 1, see [Przytycki 2006], (for the definition see Section 11.2), or Fr(Ω) is a real analytic Jordan curve or interval, see [Zdunik 1991]. In case f extends to a rational mapping of $\overline{\mathbb{C}}$ it is either a finite Blaschke product in appropriate coordinates, as in Theorem 8.5.5, or its 2:1 factor (Tchebyshev polynomial in case f is a polynomial).

The references to the Remarks 8.6.2–8.6.4 include [Carleson & Jones 1992], [Makarov 1999], [Binder, Makarov & Smirnov 2003], [Beliaev & Smirnov 2005], where further references are provided.

Chapter 9

Sullivan's classification of conformal expanding repellers

This chapter relies on ideas of the proof of the rigidity theorem drafted by D. Sullivan in Proceedings of Berkeley's ICM in 1986, see [Sullivan 1986]. In Chapter 6, Example 6.1.10 shows that two expanding repellers can be Lipschitz conjugate, but not analytically (even not differentially) conjugate.

So in Chapter 6 we provided an additional invariant, the scaling function for an expanding repeller in the line, taking in account "gaps", and proved that it already determined the $C^{1+\varepsilon}$-structure.

In this chapter we distinguish, following Sullivan, a class of conformal expanding repellers, abbr. CER's, called *non-linear*, and prove that the class of equivalence of the geometric measure, in particular the class of Lipschitz conjugacy, determines the conformal structure.

This is amazing: a holomorphic structure preserved by a map is determined by a measure.

9.1   Equivalent notions of linearity

Definition 9.1.1. Consider a CER (X, f) for compact $X \subset \mathbb{C}$. Denote by Jf the Jacobian of f with respect to the Gibbs measure μ_X equivalent to a geometric measure m_X on X. We call (X, f) *linear* if one of the following conditions holds:

a) The Jacobian Jf, is locally constant.

b) The function $\mathrm{HD}(X) \log |f'|$ is cohomologous to a locally constant function on X.

c) The conformal structure on X admits a conformal affine refinement so that f is affine (i.e., see Sec. 4.3, there exists an atlas $\{\varphi_t\}$ that is a family

of conformal injections $\phi_t : U_t \to \mathbb{C}$ where $\bigcup_t U_t \supset X$ such that all the maps $\phi_t \phi_s^{-1}$ and $\phi_t f \phi_s^{-1}$ are affine).

Recall that as the conformal map f may change the orientation of $\mathbb{C}$ on some components of its domain we can write $|f'|$ but not f' unless f is holomorphic.

Proposition 9.1.2. *The conditions a), b) and c) are equivalent.*

Before we shall prove this proposition we distinguish among CER's *real-analytic* repellers:

Definition 9.1.3. We call (X, f) *real-analytic* if X is contained in the union of a finite family of real analytic open arcs and closed curves.

Lemma 9.1.4. *If there exists a connected open domain U in $\mathbb{C}$ intersecting X for a CER (X, f) and if there exists a real analytic function k on it equal identically 0 on $U \cap X$ but not on U then (X, f) is real-analytic.*

Proof. Pick an arbitrary $x \in U \cap X$. Then in a neighbourhood V of x the set $E = \{k = 0\}$ is a finite union of pairwise disjoint real-analytic curves and of the point x. This follows from the existence of a finite decomposition of the germ of E at x into irreducible germs and the form of each such germ, see for example Proposition 5.8. in the Malgrange book [Malgrange 1967]. As the sets $f^n(X \cap V)$, $n \geq 0$ cover X, X is compact and f is open on X we conclude that X is contained in a finite union of real-analytic curves γ_j and a finite set of points A such that the closures of γ_j can intersect only in A.

Suppose that there exists a point $x \in X$ such that X is not contained in any real-analytic curve in every neighbourhood of x. Then the same is true for every point $z \in X \cap f^{-n}\{x\}$, $n \geq 0$, hence for an infinite number of points (because pre-images of x are dense in X by the topological exactness of f, see Ch. ?). But we proved above that the number of such points is finite so we arived at a contradiction. We conclude that X is contained in a 1-dimensional real-analytic submanifold of $\mathbb{C}$.   ♣

Proof of Proposition 9.1.2.
   a)$\Rightarrow$ b). Let u be the eigenfunction $\mathcal{L}u = u$ for the transfer operator $\mathcal{L} = \mathcal{L}_\phi$ for the function $\phi = -\kappa \log |f'|$, where $\kappa = \mathrm{HD}(X)$, as in Sec. 3.3. Here the eigenvalue $\lambda = \exp P(f, \phi)$ is equal to 1, see Sec. 7.2.

For an arbitrary $z \in X$ we have in its neighbourhood in X

$$\mathrm{Const} = \log Jf = \kappa \log |f'(x)| + \log u(f(x)) - \log u(x) \tag{9.1.1}$$

b)$\Rightarrow$ c). The function u extends to a real-analytic function $u_{\mathbb{C}}$ in a neighbourhood of X, see Sec. 4.4, so the function $\log Jf$ extends to a real-analytic function $\log Jf_{\mathbb{C}}$ by the right hand side equality in the formula (9.1.1), for $u_{\mathbb{C}}$ instead of u. We have two cases: either $\log Jf_{\mathbb{C}}$ is not locally constant on every neighbourhood of X and then by Lemma 9.1.4 (X, f) is real-analytic or $\log Jf_{\mathbb{C}}$ is locally constant. Let us consider first the latter case.

Fix $z \in X$. Choose an arbitrary sequence of points $z_n \in X$, $n \geq 0$ such that $f(z_n) = z_{n-1}$ and choose branches f_ν^{-n} mapping z to z_n. Due to the expanding property of f they are all well defined on a common domain around z. For every x close to z denote $x_n = f_\nu^{-n}(x)$. We have $\operatorname{dist}(x_n, z_n) \to 0$ so by (9.1.1) for $\log J f_{\mathbb{C}}$

$$
\begin{aligned}
&\sum_{n=1}^{\infty} \kappa(\log |f'(x_n)| - \log |f'(z_n)|) \\
&= \log u_{\mathbb{C}}(x) - \log u_{\mathbb{C}}(z) + \lim_{n \to \infty} (\log u_{\mathbb{C}}(z_n) - \log u_{\mathbb{C}}(x_n)) \\
&= \log u_{\mathbb{C}}(x) - \log u_{\mathbb{C}}(z).
\end{aligned}
\tag{9.1.2}
$$

We conclude that $\log u_{\mathbb{C}}(x)$ is a harmonic function in a neighbourhood of z in $\mathbb{C}$ as the limit of a convergent series of harmonic functions; we use the fact that the compositions of harmonic functions with the conformal maps f_ν^{-n} are harmonic. Close to z we take a so-called harmonic conjugate function h so that $\log u(x) + ih(x)$ is holomorphic.

Write $F_z = \exp(\log u + ih)$ and denote by $\tilde{F}_z$ a primitive function for F_z in a neighbourhood of z. This is a chart because $F_z(z) \neq 0$. The *atlas* given by the charts $\tilde{F}_z$ is affine (conformal) by the construction. We have due to (9.1.1) for the extended u

$$
|(\tilde{F}_{f(z)} \circ f \circ \tilde{F}_z^{-1})'(F_z(x))| = u_{\mathbb{C}}(f(x))|f'(x)|/u_{\mathbb{C}}(x) = \mathrm{Const}
$$

so the differential of f is locally constant in our atlas.

In the case (X, f) is real-analytic we consider just the charts ϕ_t being primitive functions of u on real-analytic curves containing X into $\mathbb{R}$ with unique complex extensions to neighbourhoods of these curves into a neighbourhood of $\mathbb{R}$ in $\mathbb{C}$. The equality $\log J f_{\mathbb{C}} = \mathrm{Const}$ holds on these curves so the derivatives of $\phi_t f \phi_s^{-1}$ are locally constant.

c) $\Rightarrow$ a). Denote the maps $\phi_t f \phi_s^{-1}$ by $\tilde{f}_{t,s}$. In a neighbourhood (in X) of an arbitrary $z \in X$ we have

$$
\begin{aligned}
u(x) &= \lim_{n \to \infty} \mathcal{L}^n(1)(x) = \lim_{n \to \infty} \sum_{y \in f^{-n}(x)} |(f^n)'(y)|^{-\kappa} \\
&= \lim_{n \to \infty} |\phi'(x)|^\kappa \sum_y |\phi'(y)|^{-\kappa} |\tilde{f}'(y)|^{-n\kappa} \\
&= \mathrm{Const} \lim_{n \to \infty} |\phi'(x)|^\kappa \sum_y \tilde{f}'(y)|^{-n\kappa} = |\phi'(x)|^\kappa \, \mathrm{Const}
\end{aligned}
\tag{9.1.3}
$$

To simplify the notation we omitted the indices at ϕ and $\tilde{f}$ here, of course they depend on z and y's more precisely on the branches of f^{-n} on our neighbourhood of z mapping z to y's. Const also depends on z. We could omit the functions $\phi'(y)$ in the last line of (9.1.3) because the diameters of the domains of $\phi'(y)$ which were involved converged to 0 when $n \to \infty$ due to the expanding property of f, so these functions were almost constant.

Hence due to (9.1.3) in a neighbourhood of every $x \in X$ we get

$$Jf(x) = \text{Const } u(f(x))|f'(x)|^{\kappa}/u(x) = \text{Const } |\tilde{f}'(x)|^{\kappa} = \text{Const} \qquad \clubsuit$$

Remark 9.1.5. In the b)$\Rightarrow$c) part of the proof of Proposition 9.1.2 as $-\kappa \log|f'|$ is harmonic we do not need to refer to Sec. 4.4 for the real-analyticity of u. The formula (9.1.2) gives a harmonic extension of u to a neighbourhood of an arbitrary $z \in X$, depending on the choice of the sequence (z_n). If two extensions u_1, u_2 do not coincide on a neighbourhood of z then in a neighbourhood of z, $X \subset \{u_1 - u_2 = 0\}$.

If the equation (9.1.1) does not extend to a neighbourhood of z then again $X \subset \{v = \text{Const}\}$ for a harmonic function v extending the right hand side of (9.1.1).

In each of the both cases (X, f) happens to be real-analytic and to prove it we do not need to refer to Malgrange's book as in the proof of Lemma 9.1.4. Indeed, for any non-constant harmonic function k on a neighbourhood of $x \in X$ such that $X \subset \{k = 0\}$ we consider a holomorphic function F such that $k = \Re F$ and $F(x) = 0$. Then $E = \{k = 0\} = \{\Re F = 0\}$. If F has a d-multiple zero at x then it is a standard fact that E is a union of d analytic curves intersecting at x within the angle $\frac{\pi}{d}$.

We end this Section with giving one more condition implying the linearity.

Lemma 9.1.6. *Suppose for a CER (X, f) that there exists a Hölder continuous line field in the tangent bundle on a neighbourhood of X invariant under the differential of f. In other words there exists a complex valued nowhere zero Hölder continuous function α such that for every x in a neighbourhood of X*

$$\text{Arg}\,\alpha(x) + \text{Arg}\,f'(x) = \text{Arg}\,\alpha(f(x)) + \varepsilon(x)\pi \qquad (9.1.4)$$

where $\varepsilon(x)$ is a locally constant function equal 0 or 1. This is in the case f preserves the orientation at x, if it reverses the orientation we replace in (9.2.1) $\text{Arg}\,f'$ by $-\text{Arg}\,\bar{f}'$.

Then (X, f) is linear.

Proof. As in Proof of Proposition 9.1.2, the calculation (9.1.2), if f is holomorphic we have for x in a neighbourhood of $z \in X$ in $\mathbb{C}$

$$\text{Arg}\,\alpha(z) - \text{Arg}\,\alpha(x) = \sum_{n=1}^{\infty}(\text{Arg}(f'(z_n)) - \text{Arg}(f'(x_n))),$$

if we allow f to reverse the orientation then we replace $\text{Arg}\,f'$ by $-\text{Arg}\,\bar{f}'$ in the above formula for such n that f changes the orientation in a neighbourhood of x_n. So $\text{Arg}\,\alpha(x)$ is a harmonic function. Close to z we find a conjugate harmonic function h so we get a family of holomorphic functions $F_z = \exp(-h + i\,\text{Arg}\,\alpha$ which primitive functions give an atlas we have looked for.

Remark 9.1.7. The condition for (X, f) in Lemma 9.1.6 is stronger than the linearity property. Indeed we can define f on the union of the discs $D_1 = \{|z| < 1\}$ and $D_2 = \{|z - 3| < 1\}$ by $f(z) = 5 \exp 2\pi \vartheta i$ on D_1 where ϑ is irrational, and $f(z) = 5(z - 3)$ on D_2. This is an example of an iterated function system from Sec. 4.5. We get a CER (X, f) where $X = \bigcap_{n=0}^{\infty} f^{-n}(\{|z| < 5\})$. It is linear because it satisfies the condition c). Meanwhile $0 \in X, f(0) = 0$ and $f'(0) = 5 \exp 2\pi \vartheta i$, so the equation (9.1.4) has no solution at $x = 0$ even for any iterate of f.

Remark 9.1.8. If we assume in place of (9.1.4) that $\operatorname{Arg} f'(x) - \operatorname{Arg} \alpha(f(x)) - \operatorname{Arg} \alpha(x)$ is locally constant, then we get the condition equivalent to the linearity.

9.2 Rigidity of nonlinear CER's

In this section we shall prove the main theorem of Chapter 9:

Theorem 9.2.1. *Let $(X, f), ((Y, g)$ be two non-linear conformal expanding repellers in $\mathbb{C}$. Let h be an invertible mapping from X onto Y preserving Borel σ-algebras and conjugating f to g, $h \circ f = g \circ h$. Suppose that one of the following assumption is satisfied:*

1. h and h^{-1} are Lipschitz continuous.

2. h and h^{-1} are continuous and preserve so-called Lyapunov spectra, namely for every periodic $x \in X$ and integer n such that $f^n(x) = x$ we have $|(f^n)'(x)| = |(g^n)'(h(x))|$.

3. h_* maps a geometric measure m_X on X to a measure equivalent to a geometric measure m_Y on Y.

Then h extends from X (or from a set of full measure m_X in the case 3.) to a conformal homeomorphism on a neighbourhood of X.

We start the proof with a discussion of the assumptions. The equivalence of the conditions 1. and 2. has been proved in Sec. 4.3. The condition 1. implies 3. by the definition of geometric measures 5.6.5. One of the steps of the proof of Theorem will assert that 3. implies 1. under the non-linearity assumption. Without this assumption the assertion may happen false. A positive result is that if h is continuous then for a constant $C > 0$ and every $x_1, x_2 \in X$

$$C < \frac{|h(x_1) - h(x_2)|^{\operatorname{HD}(Y)}}{|x_1 - x_2|^{\operatorname{HD}(X)}} < C^{-1}.$$

(We leave the proof to the reader.)

It may happen that $\operatorname{HD}(X) \neq \operatorname{HD}(Y)$ for example if X is a $1/3$ – Cantor set and for g we remove each time half of the interval from the middle.

A basic observation to prove Theorem 9.2.1 is that

$$Jg \circ h = Jf \text{ and moreover } Jg^j \circ h = Jf^j \tag{9.2.1}$$

for every integer $j > 0$. This follows from $g^j \circ h = h \circ f^j$ and $Jh \equiv 1$. We recall that we consider Jacobians with respect to the Gibbs measures equivalent to geometric measures.

Observe finally that (X, f) linear implies (Y, g) linear. Indeed, if (X, f) is linear then Jf hence Jg admit only a finite number of values in view of $Jg \circ h = Jf$. As Jg is continuous this implies that Jg is locally constant i.e. (Y, g) is linear.

Lemma 9.2.2. *If a CER (X, f) is non-linear then there exists $x \in X$ such that* $\operatorname{grad} Jf_{\mathbb{C}}(x) \neq 0$.

Proof. If $\operatorname{grad} Jf_{\mathbb{C}} \equiv 0$ on X then as $Jf_{\mathbb{C}}$ is real- analytic we have either $\operatorname{grad} Jf_{\mathbb{C}} \equiv 0$ on a neighbourhood of X in $\mathbb{C}$ or by Lemma 9.1.4 (X, f) is real-analytic and $\operatorname{grad} Jf_{\mathbb{C}} \equiv 0$ on real- analytic curves containing X. In both cases by integration we obtain Jf locally constant on X what contradicts the non-linearity assumption.

Now we shall prove Theorem in the simplest case to show the reader the main idea working later also in the general case.

Proposition 9.2.3. *The assertion of Theorem 9.2.1 holds if we suppose additionally that (X, f) and $Y, g)$ are real-analytic and the conjugacy h is continuous.*

Proof. Let M, N be real analytic manifolds containing X, Y respectively. By the non-linearity of X and Lemma 9.2.2 there exists $x \in X$ and its neighbourhood U in M such that $F := Jf_{\mathbb{C}}|_U : U \to \mathbb{R}$ has a real-analytic inverse $F^{-1} : F(U) \to U$. Then in view of (9.2.1) $h^{-1} = F^{-1} \circ Jg_{\mathbb{C}}$ on $h(U \cap X)$ so h^{-1} on $h(U \cap X)$ extends to a real analytic map on a neighbourhood of $h(U \cap X)$ in N.

Now we use the assumption that h^{-1} is continuous so $h(U \cap X)$ contains an open set v in Y. There exists a positive integer n such that $g^n(V) = Y$ hence for every $y \in Y$ there exists a neighbourhood W of y in N such that a branch g_ν^{-n} of g^{-n} mapping y and even $W \cap Y$ into V is well defined. So we have $h^{-1} = f^n \circ h^{-1} \circ g_\nu^{-n}$ extended on W to a real-analytic map. This gives a real-analytic extension of h^{-1} on a neighbourhood of Y because two such extensions must coincide on the intersections of their domains by the real-analyticity and the fact that Y has no isolated points.

Similarly using the non-linearity of (Y, g) and the continuity of h we prove that h extends analytically. By the analyticity and again lack of isolated points in X and Y the extentions are inverse to each other, so h extends even to a biholomorphic map.

Now we pass to the general case.

Lemma 9.2.4. *Suppose that there exists $x \in X$ such that $\operatorname{grad} Jf_{\mathbb{C}}(x) \neq 0$ in the case X is real-analytic, or there exists an integer $k \geq 1$ such that $\det(\operatorname{grad} Jf_{\mathbb{C}}, \operatorname{grad}(Jf_{\mathbb{C}} \circ f^k)) \neq 0$ in the other case.*

(In other words we suppose that $Jf_{\mathbb{C}}$, respect. $(Jf_{\mathbb{C}}, Jf_{\mathbb{C}} \circ f^k)$, give a coordinate system on a real, respect. complex neighbourhood of x.)

Suppose the analogous property for (Y, g).

Let $h : X \to Y$ *satisfy the property 3. assumed in Theorem 9.2.1. Then h extends from a set of full geometric measure in X to a bi-Lipschitz homeomorphism of X onto Y conjugating f with g.*

Proof. We can suppose that $\mathrm{HD}(X) \geq \mathrm{HD}(Y)$, recall that HD denotes Hausdorff dimension. Pick x with the property assumed in the Lemma. Let U be its neighbourhood in M (as in Proof of Proposition 9.2.3) or in $\mathbb{C}$ if (X, f) is not real-analytic, so that $F := (Jf_{\mathbb{C}}, Jf_{\mathbb{C}} \circ f^k)$ is an embedding on U. Let $y \in Y$ be a density point of the set $h(U \cap X)$ with respect to the Gibbs measure μ_Y equivalent to the geometric measure m_Y. (Recall that we have proved that almost every point is a density point for an arbitrary probability measure on a euclidean space in Chapter 7 relying on Besicovitch's Theorem.) So if we denote $(Jg_{\mathbb{C}}, Jg_{\mathbb{C}} \circ g^k)$ in a neighbourhood (real or complex) of y by G, we have for every $\delta > 0$ such $\varepsilon_0 = \varepsilon_0(\delta) > 0$ that for every $0 < \varepsilon < \varepsilon_0$:

$$\frac{\mu_Y(B(y, \varepsilon) \cap h(U \cap X))}{\mu_Y(B(y, \varepsilon))} > 1 - \delta$$

and

$$h^{-1} = F^{-1} \circ G \qquad \text{on} \ \ h(U \cap X).$$

(Observe that the last equality may happen false outside $h(U \cap X)$ even very close to y because h^{-1} may map such points to $(Jf_{\mathbb{C}}, Jf_{\mathbb{C}} \circ f^k)^{-1} \circ G$ with a branch of $(Jf_{\mathbb{C}}, Jf_{\mathbb{C}} \circ f^k)^{-1}$ different from F^{-1}.)

Now for every $\varepsilon > 0$ small enough there exists an integer n such that $\operatorname{diam} g^n B(y, \varepsilon)$ is greater than a positive constant , $g^n|_{B(y,\varepsilon)}$ is injective and the distortion of g^n on $B(y, \varepsilon)$ is bounded by a constant C, both constants depending only on (Y, g). Then if $\varepsilon < \varepsilon_0(\delta)$ we obtain for $Y_\delta := g^n(h(U \cap X) \cap B(y, \varepsilon))$,

$$\frac{\mu_Y(g^n(B(y, \varepsilon)) \setminus Y_\delta)}{\mu_Y(g^n(B(y, \varepsilon)))} < C \frac{\mu_Y(B(y, \varepsilon) \setminus h(U \cap X))}{\mu_Y(B(y, \varepsilon))} < C\delta.$$

So

$$\frac{\mu_Y(Y_\delta)}{\mu_Y(g^n(B(y, \varepsilon)))} > 1 - C\delta. \tag{9.2.2}$$

We have

$$|(f^n)'(h^{-1}(y))|^{\mathrm{HD}(X)} \leq \operatorname{Const} Jf(h^{-1}(y))$$
$$= \operatorname{Const} Jg(y) \leq \operatorname{Const} |(f^n)'(y)|^{\mathrm{HD}(Y)}.$$

As we assumed $\mathrm{HD}(X) \geq \mathrm{HD}(Y)$ we obtain

$$|(f^n)'(h^{-1}(y))| \leq \operatorname{Const} |(f^n)'(y)|^{\mathrm{HD}(Y)/\mathrm{HD}(X)} \leq \operatorname{Const} |(f^n)'(y)| \tag{9.2.3}$$

Then due to the bounded distortion property for iteration of f and g we obtain that $h^{-1} = f^n h^{-1} g^{-1}$ is Lipschitz on Y_δ with Lipschitz constant independent of δ, more precisely bounded by $\operatorname{Const} \sup \|D(F^{-1} \circ G\|$, where $F^{-1} \circ G$

is considered on a real (complex) neighbourhood of y and Const is that from (9.2.3).

There exists an integer $K > 0$ such that for every n, $g^K g^n B(y, \varepsilon(n))$ covers Y. Because Jg is bounded, separated from 0, this gives h^{-1} on $g^K(Y_\delta)$ Lipschitz with a Lipschitz constant independent from δ and $\mu(g^K(Y_\delta)) > 1 - \text{Const } \delta$ for δ arbitrarily small. We conclude that h^{-1} is Lipschitz on a set of full measure μ_Y so it has a Lipschitz extension to Y.

We conclude also that $\text{HD}(X) = \text{HD}(Y)$. Otherwise $\text{diam } h^{-1}(Y_\delta) \to 0$, so because $\text{supp}\mu_X = X$ we would get $\text{diam } X = 0$. So we can interchange above the roles of (X, f) and (Y, g) and prove that h is Lipschitz.

The next step will assert that for non-linear repellers the assumptions of Lemma 9.2.4 about the existence of coordinate systems are satisfied.

Lemma 9.2.5. *If (X,f) is a non-linear CER then there exists $x \in X$ such that either $\text{grad } Jf_\mathbb{C}(x) \neq 0$ in the case X is real-analytic, or there exists an integer $k \geq 1$ such that $\det(\text{grad } Jf_\mathbb{C}, \text{grad}(Jf_\mathbb{C} \circ f^k)) \neq 0$ in the case (X,f) is not real-analytic.*

Proof. We know already from Lemma 9.2.2 that there exists $\hat{x} \in X$ such that $\text{grad } Jf_\mathbb{C}(z) \neq 0$ so we may restrict our considerations to the case (X, f) is not real-analytic.

Suppose Lemma is false. Then for all $k > 0$ the functions

$$\Phi_k := \det(\text{grad } Jf_\mathbb{C}, \text{grad}(Jf_\mathbb{C} \circ f^k))$$

are identically equal to 0 on X. Let W be a neighbourhood of $\hat{x}$ in $\mathbb{C}$ where $\text{grad } Jf_\mathbb{C} \neq 0$.

Let us consider on W the line field $\mathcal{V}$ orthogonal to $\text{grad } Jf_\mathbb{C}$. Due to the topological exactness of f on X for every $x \in X$ there exists $y \in W \cap X$ and $n \geq 0$ such that $f^n(y) = x$.

Thus define at x

$$\mathcal{V}_x := Df^n(\mathcal{V}_y) \tag{9.2.4}$$

We shall prove now that if $x = f^k(y) = f^l(z)$ for some $y, z \in W \cap X$, $k, l \geq 0$, then

$$Df^k(\mathcal{V}_y) = Df^l(\mathcal{V}_z). \tag{9.2.5}$$

If (9.2.5) is false, then close to x there exist $x' \in X$ and $m \geq 0$ such that $f^m(x') \in W$ (we again refer to the topological exactness of f) and $Df^k(\mathcal{V}_{y'}) \neq Df^l(\mathcal{V}_{z'})$, where $f^k(y') = f^l(z') = x'$, $y' \in X$ is close to y and $z' \in X$ is close to z. We obtain $Df^{k+m}(\mathcal{V}_{y'}) \neq Df^{l+m}(\mathcal{V}_{z'})$ so either $Df^{k+m}(\mathcal{V}_{y'}) \neq \mathcal{V}_{f^m(x')}$ or $Df^{l+m}(\mathcal{V}_{z'}) \neq \mathcal{V}_{f^m(x')}$. Consider the first case (the second is of course similar). We obtain that Jf and $Jf \circ f^{k+m}$ give a coordinate system in a neighbourhood of y' i.e. $\Phi_{k+m}(y') \neq 0$ contrary to the supposition.

Thus the formula (9.2.4) defines a line field at all points of X which is Df-invariant. Observe however that the same formula defines a real-analytic extension of the line field to a neighbourhood of x in $\mathbb{C}$ because $\mathcal{V}$ is real-analytic on a neighbourhood of $y \in W$ and f is analytic. Each two such germs

of extensions related to two different pre-images of x must coincide because they coincide on X, otherwise (X, f) would be real-analytic. Now we can choose a finite cover $B_j = B(x_j, \delta_j)$ of a neighbourhood of X with discs, $x_j \in X$ so that for the respective F_j-branches of f^{-n_j} leading x_j into W, we have $F_j(3B_j) \subset W$ where $3B_j := B(x_j, 3\delta_j)$. Hence the formula (9.2.4) defines $\mathcal{V}$ on $3B_j$. So if $B_i \cap B_j \neq \emptyset$, then we have $3B_i \subset B_j$ or vice versa. So $3B_i \cap 3B_j \cap X \neq 0$ hence the extensions of $\mathcal{V}$ on $3B_i$ and on $3B_j$, in particular on B_i and on B_j, coincide on the intersection. This is so because they coincide on the intersection with X and $(X, f$ is not real-analytic.

(We made the trick with 3δ because it can happen that $B_i \cap B_j \neq \emptyset$ but $B_i \cap B_j \cap X = \emptyset$.)

Thus $\mathcal{V}$ extends real-analytically to a neighbourhood of X. This field is Df-invariant on a neighbourhood of X because we can define it in a neighbourhood of $x \in X$ and $f(x)$ by (9.2.4) taking the same $y \in W \cap X$ where $f^n(y) = x$, $f^{n+1}(y) = f(x)$. So by Lemma 9.1.6 (X, f) is linear what contradicts the assumption that (X, f) is non-linear.

Corollary 9.2.6. *If for $(X, f), (Y, g)$ the assumptions of Theorem 9.2.1 are satisfied and if (Y, g) is real-analytic then (X, f) is real-analytic too.*

Proof. Due to Lemma 9.2.5 the assumptions of Lemma 9.2.4 are satisfied. So $h^{-1} = F^{-1} \circ G$ on a neighbourhood of $y \in Y$ by the continuity of h^{-1}, (see the notation in Proof of Lemma 9.2.4). Denote a real-analytic manifold Y is contained in by N. Then $Jg_{\mathbb{C}} \neq$ Const on any neighbourhood of y in N. Otherwise h^{-1} would be constant, but y is not isolated in Y so h^{-1} would not be injective.

Remind that we can consider $F^{-1} \circ G$ as a real analytic extension of h^{-1} to a neighbourhood V of y in N. So the differential of $F^{-1}G$ is 0 at most at isolated points, so different from 0 at a point $y' \in V \cap Y$. We conclude due to the continuity of h that in a neighbourhood of $h^{-1}(y')$, X is contained in a real-analytic curve. So (X, f) is a real-analytic repeller.

Now we shall collect together what we have done and make a decisive step in proving Theorem 9.2.1, namely we shall prove that the conjugacy extends to a real-analytic diffeomorphism.

Proof of Theorem 9.2.1. If both (X, f) and (Y, g) are real-analytic then the conjugacy extends real-analytically to a real-analytic manifold so complex analytically to its neighbourhood by Proposition 9.2.3. Its assumptions hold by Lemmas 9.2.4 and 9.2.2. If both (X, f) and (Y, g) are not real-analytic (a mixed situation is excluded by Corollary 9.2.6), then by Lemma 9.2.4 which assumptions hold due to Lemma 9.2.5 we can assume the conjugacy h is a homeomorphism of X onto Y. But h^{-1} extends to a neighbourhood of $y \in Y$ in $\mathbb{C}$ to a real-analytic map. We use here again the notation of Lemma 9.2.4 and proceed precisely like in Proposition 9.2.3, Lemma 9.2.4 and Corollary 9.2.6 by writing $h^{-1} = F^{-1} \circ G$. This gives a real-analytic extension of h^{-1} to a neighbourhood of an arbitrary $y \in Y$ by the formula $f^n \circ h^{-1} \circ g_\nu^{-1}$ precisely as in Proof of Proposition 9.2.3.

For two different branches F_1, F_2 of g^{-n_1}, g^{-n_2} respectively, mapping y into the domain of $F^{-1} \circ G$ germs of the extensions must coincide because they coincide on the intersection with Y, see Lemma 9.1.4.

Now we build a real-analytic extension of h^{-1} to a neighbourhood of Y similarly as we extended $\mathcal{V}$ in Proof of Lemma 9.2.5, again using the assumption (Y, g) is not real-analytic. Similarly we extend h.

Denote the extensions by $\tilde{h}, \tilde{h^{-1}}$. We have $\tilde{h^{-1}} \circ \tilde{h}$ and $\tilde{h} \circ \tilde{h^{-1}}$ equal to the identity on X, Y respectively. The these compositions extend to the identities to neighbourhoods, otherwise (X, f) or (Y, g) would be real-analytic. We conclude that $\tilde{h}$ is a real-analytic diffeomorphism. Finally observe that $g\tilde{h} = \tilde{h}f$ on a neighbourhood of X because this equality holds on X itself and our functions are real-analytic, otherwise (X, f) would be real-analytic.

The only thing we should still prove is the following

Lemma 9.2.7. *If (X, f) is a non-linear CER, not real-analytic , and there is a real-analytic diffeomorphism h on a neighbourhood of X to a neighbourhood of Y for another CER (Y, g) such that $h(X) = Y$ and h conjugates f with g in a neighbourhood of X then h is conformal.*

Proof. Suppose for the simplification that f, g and h preserve the orientation of $\mathbb{C}$, we will comment the general case at the end.

For any orientation preserving diffeomorphism Φ of a domain in $\mathbb{C}$ into $\mathbb{C}$ denote the complex dilatation function by ω_Φ . We recall that $\omega_\Phi := \frac{d\Phi}{d\bar{z}} / \frac{d\Phi}{dz}$. (The reader not familiar with the complex dilatation and its properties is advised to read the first 10 pages of the classical Ahlfors book [Ahlfors].) The geometric meaning of the argument of $\omega_\Phi(z)$ may be explained by the equality $\frac{1}{2}\omega_\Phi = \alpha$ where α corresponds to the the direction in which the differential $D\Phi$ at z attains its maximum. In another words it is the direction of the smaller axis of the ellipse in the tangent space at z which is mapped by $D\Phi$ to the unit circle. Of course this makes sense if $\omega(z) \neq 0$. Observe finally that $\omega(z) = 0$ iff $\frac{d\Phi}{d\bar{z}} = 0$. Let go back now to our concrete maps.

If $\frac{dh}{d\bar{z}} \equiv 0$ on X then as $\frac{dh}{d\bar{z}}$ is a real-analytic function we have $\frac{dh}{d\bar{z}} \equiv 0$ on a neighbourhood of X, otherwise (X, f) would be real-analytic. But this means that h is holomorphic what proves our Lemma. It rests to prove that the case $\frac{dh}{d\bar{z}} \not\equiv 0$ on X is impossible.

Observe that if $\frac{dh}{d\bar{z}}(x) = 0$ then $\frac{dh}{d\bar{z}}(f(x)) = 0$ because $h = ghf_\nu^{-1}$ on a neighbourhood of $f(x)$ for the branch f_ν^{-1} of f^{-1} mapping $f(x)$ to x and because g and f_ν^{-1} are conformal. So if there exists $x \in X$ such that $\frac{dh}{d\bar{z}}(x) \neq 0$ then this holds also for all x's from a neighbourhood and as a consequence of the topological exactness of f for all x in a neighbourhood of X. Thus we have a complex-valued function ω_h nowhere zero on a neighbourhood of X.

Recall now that for any two orientation preserving diffeomorphisms Φ and Ψ, if Ψ is holomorphic then

$$\omega_{\Psi \circ \Phi} = \omega_\Phi$$

and if Φ is conformal then

$$\omega_\Psi \circ \Phi = \left(\frac{\Phi'}{|\Phi'|}\right)^2 \omega_{\Psi \circ \Phi} = \omega_\Phi$$

Applying it to the equation $h \circ f = g \circ h$ we obtain

$$\omega_h \circ f = \left(\frac{f'}{|f'|}\right)^2 \omega_{h \circ f} = \left(\frac{f'}{|f'|}\right)^2 \omega_{g \circ h} = \left(\frac{f'}{|f'|}\right)^2 \omega h.$$

Thus $\alpha(x) := \frac{1}{2}\omega_h(x)$ satisfies the equation (9.1.4) and by Lemma 9.1.6 (X, f) happens linear what contradicts our assumption that it is non-linear.

In the case a diffeomorphism reverses the orientation we write everywhere above $\omega_{\bar\Phi}$ instead of ω_Φ and if Φ is conformal reversing orientation we write $\overline{\overline{\Phi'}}$ instead of Φ'. Additionally some omegas should be conjugated in the formulas above. We also arrive at (9.1.4). (In this situation the complex notation is not comfortable. Everything becomes trivial if we act with differentials on line fields. We leave writing this down to the reader.)

Example 9.2.8. If $f_c(z) = z^2 + c$ for $c \in \mathcal{M}_0$, see Example 5.1.9 and Example 8.5.6 (for $z^d + c$), then Julia set $J(f_c) = X_{f_c}$ is a Jordan curve and (X_{f_c}, f_c) is non-linear, except for $c = 0$.

Indeed, if it is linear then by Definition 9.1.1 a), the function $-\operatorname{HD}(X_{f_c})\log|f'|$ is cohomologous to constant on X_{f_c} because this set is connected. Hence, by Theorem 8.5.5, $f_c(z) = z^2$, i.e. $c = 0$.

In fact $(J(f), f|_{J(f)})$ is non-linear for every rational maps f without critical points in its Julia set $J(f)$, in particular f expanding on $J(f)$, except for $f(z) = z^d$, $|d| \geq 2$. This follows from [Zdunik 1990], compare [Przytycki & Urbański 1999, Section 3].

Example 9.2.9. Let X be a Cantor set in the line $\mathbb{R}$ which is image by h of Σ^d as in Section 6.1, i.e. $h \in \mathcal{H}$. Consider the map $h \circ s \circ h^{-1}$, where s is the shift to the left on Σ^d. Suppose that this map extends to s_h which is locally affine, that is the scaling function stabilizes, $S_n/S_{n+1} \equiv 1$ for all n large enough, cf. Theorem 6.2.4. Then the repeller (X, s_h) is linear, by Definition 9.1.1 c).

Remark 9.2.10. In presence of critical points in $J(f)$ for f non-exceptional (that is, with parabolic orbifold) $J(f)$ contains non-linear invariant expanding repellers for f. See [Przytycki & Urbański 1999, Section 3], [Zdunik 1990] and [Prado 1997].

Bibliographical notes

As we already mentioned this chapter relies on ideas by Dennis Sullivan, see [Sullivan 1986]. Written in 1991, it was followed by many papers applying its ideas, see for example [Przytycki & Urbański 1999], [Mauldin, Przytycki & Urbanski 2001], [Urbanski 2001] in $\mathbb{R}^d, d \geq 3$. See also [Mauldin & Urbanski 2003, section 7.3].

Recent year this rigidity has been intensively discussed in iteration of entire and meromorphic maps.

Chapter 10

Conformal maps with invariant probability measures of positive Lyapunov exponent

10.1 Ruelle's inequality

Let X be a compact subset of the closed complex plane $\overline{\mathbb{C}}$ and let $\mathcal{A}(X)$ denote the set of all continuous maps $f : X \to X$ that can be analytically extended to an open neighbourhood $U(f)$ of X. In this section we only work with the standard spherical metric on $\overline{\mathbb{C}}$, normalized so that the area of $\overline{\mathbb{C}}$ is 1. In particular all the derivatives are computed with respect to this metric.

Let us recall and extend Definition 8.1.2. Let μ be an f-invariant Borel probability measure on X. Since $|f'|$ is bounded, the integral $\int \log |f'| \, d\mu$ is well-defined and moreover $\int \log |f'| \, d\mu < +\infty$. The number

$$\chi_\mu = \chi_\mu(f) = \int \log |f'| \, d\mu$$

is called the *Lyapunov characteristic exponent* of μ and f. Note that $\int \log |f'| d\mu = -\infty$ is not excluded. In fact it is possible, for example if $X = \{0\}$ and $f(z) = z^2$.

On the other hand for every rational function $f : \overline{\mathbb{C}} \to \overline{\mathbb{C}}$ and every f-invariant μ supported on the Julia set $J(f)$, see Chapter 0, Example 0.6, it holds $\chi_\mu \geq 0$. For the proof see [Przytycki 1993].

By Birkhoff Ergodic Theorem (Th. 1.2.5) the *Lyapunov characteristic exponent*

$$\chi_\mu(x) = \lim_{n \to \infty} \frac{1}{n} \log |(f^n)'(x)|$$

exists for a.e. x and $\int \chi_\mu(x)\, d\mu(x) = \chi_\mu$. (In fact one allows $\log|f'|$ with integral $-\infty$ here, so one need extend slightly Th. 1.2.5. This is not difficult.)

The section is devoted to prove the following.

Theorem 10.1.1 (Ruelle's inequality). *If $f \in \mathcal{A}(X)$, then $\mathrm{h}_\mu(f) \le 2\int \max\{0, \chi_\mu(x)\}\, d\mu$. For ergodic μ this yields $\mathrm{h}_\mu(f) \le 2\max\{0, \chi_\mu\}$.*

Proof. Consider a sequence of positive numbers $a_k \searrow 0$, and $\mathcal{P}_k, k = 1, 2, \dots$ an increasing sequence of partitions of the sphere $\overline{\mathbb{C}}$ consisting of elements of diameters $\le a_k$ and of (spherical) areas $\ge \frac{1}{4}a_k^2$. Check that such partitions exist.

For every $g \in \mathcal{A}(X)$, $x \in X$ and $k \ge 1$ let

$$N(g, x, k) = \#\{P \in \mathcal{P}_k : g(P_k(x) \cap U(g)) \cap P \ne \emptyset\}$$

Our first aim is to show that for every $k > k(g)$ large enough

$$N(g, x, k) \le 4\pi(|g'(x)| + 2)^2 \tag{10.1.1}$$

Indeed, fix $x \in X$ and consider k so large that $\mathcal{P}_k(x) \subset U(g)$ and a Lipschitz constant of $g|_{\mathcal{P}_k(x)}$ does not exceed $|g'(x)|+1$. Thus the set $g(\mathcal{P}_k(x))$ is contained in the ball $B(g(x), (|g'(x)| + 1)a_k)$. Therefore if $g(\mathcal{P}_k(x)) \cap P \ne \emptyset$, then

$$P \subset B(g(x), (|g'(x)| + 1)a_k + a_k) = B(g(x), (|g'(x)| + 2)a_k)$$

Hence $N(g, x, k) \le \pi(|g'(x)| + 2)^2 a_k^2 / \frac{1}{4}a_k^2 = 4\pi(|g'(x)| + 2)^2$ and (10.1.1) is proved.

Let $N(g, x) = \sup_{k > k(g)} N(g, x, k)$. In view of (10.1.1) we get

$$N(g, x) \le 4\pi(|g'(x)| + 2)^2 \tag{10.1.2}$$

Now note that for every finite partition $\mathcal{A}$ one has

$$\begin{aligned}
\mathrm{h}(g, \mathcal{A}) &= \lim_{n\to\infty} \frac{1}{n+1}\mathrm{H}(\mathcal{A}^n) \\
&= \lim_{n\to\infty} \frac{1}{n+1}\Big(\mathrm{H}(g^{-n}(\mathcal{A})|\mathcal{A}^{n-1}) + \cdots + \mathrm{H}(g^{-1}(\mathcal{A})|\mathcal{A}) + \mathrm{H}(\mathcal{A})\Big) \\
&\le \lim_{n\to\infty} \frac{1}{n}\Big(\mathrm{H}(g^{-n}(\mathcal{A})|g^{-(n-1)}(\mathcal{A})) + \cdots + \mathrm{H}(g^{-1}(\mathcal{A})|\mathcal{A})\Big) \\
&= \mathrm{H}(g^{-1}(\mathcal{A})|\mathcal{A}). \tag{10.1.3}
\end{aligned}$$

(Compare this computation with the one done in Theorem 1.4.5 or in Proof of Theorem 1.5.4, which would result with $\mathrm{h}(g, \mathcal{A}) \le \mathrm{H}(\mathcal{A}|g^{-1}(\mathcal{A}))$.) Going back to our situation, since

$$\mathrm{H}_{\mu_{\mathcal{P}_k(x)}}(g^{-1}(\mathcal{P}_k)|\mathcal{P}_k(x)) \le \log \#\{P \in \mathcal{P}_k : g^{-1}(P) \cap \mathcal{P}_k(x) \ne \emptyset\} = \log N(g, x, k)$$

and by Theorem 1.8.7a, we obtain

$$\begin{aligned}
\mathrm{h}_\mu(g) &\le \limsup_{k\to\infty} \mathrm{H}_\mu(g^{-1}(\mathcal{P}_k)|\mathcal{P}_k) = \limsup_{k\to\infty} \int \mathrm{H}_{\mu_{\mathcal{P}_k(x)}}(g^{-1}(\mathcal{P}_k)|\mathcal{P}_k(x))\, d\mu(x) \\
&\le \limsup_{k\to\infty} \int \log N(g, x, k)\, d\mu(x) \le \int \log N(g, x)\, d\mu(x).
\end{aligned}$$

Applying this inequality to $g = f^n$ ($n \geq 1$ an integer) and employing (9.1.2) we get

$$\mathrm{h}_\mu(f) = \frac{1}{n}\mathrm{h}_\mu(f^n) \leq \frac{1}{n}\int \log N(f^n, x)\, d\mu(x) = \int \frac{1}{n}\log N(f^n, x)\, d\mu(x)$$

$$\leq \int \frac{1}{n}\log 4\pi(|(f^n)'(x)| + 2)^2\, d\mu(x)$$

Since $0 \leq \frac{1}{n}\log(|(f^n)'(x)|+2)^2 \leq 2(\log\big(\sup_X |f'|\big)+1)$ and $\lim_{n\to\infty}\frac{1}{n}\log(|(f^n)'(x)|+2) = \max\{0, \chi_\mu(x)\}$ for μ-a.e $x \in X$, it follows from the Dominated Convergence Theorem (Section 1.1) that

$$h_\mu(f) \leq \lim_{n\to\infty}\int \frac{1}{n}\log(|(f^n)'(x)| + 2)^2\, d\mu(x) = \int \max\{0, 2\chi_\mu(x)\}\, d\mu.$$

The proof is completed.   ♣

10.2   Pesin's theory

In this section we work in the same setting and we follow the same notation as in Section 10.1.

Lemma 10.2.1. *If μ is a Borel finite measure on $\mathbb{R}^n$, $n \geq 1$, a is an arbitrary point of $\mathbb{R}^n$ and the function $z \mapsto \log|z - a|$ is μ-integrable, then for every $C > 0$ and every $0 < t < 1$,*

$$\sum_{n\geq 1}\mu(B(a, Ct^n)) < \infty.$$

Proof. Since μ is finite and since given $t < s < 1$ there exists $q \geq 1$ such that $Ct^n \leq s^n$ for all $n \geq q$, without loosing generality we may assume that $C = 1$. Recall that given $b \in \mathbb{R}^n$, and two numbers $0 \leq r < R$, $R(b, r, R) = \{z \in \mathbb{C} : r \leq |z - b| < R\}$. Since $-\log(t^n) \leq -\log|z - a|$ for every $z \in B(a, t^n)$ we get the following.

$$\sum_{n\geq 1}\mu(B(a, t^n)) = \sum_{n\geq 1}n\mu(R(a, t^{n+1}, t^n)) = \frac{-1}{\log t}\sum_{n\geq 1}-\log(t^n)\mu(R(a, t^{n+1}, t^n))$$

$$\leq \frac{-1}{\log t}\int_{B(a,t)}-\log|z - a|\, d\mu(z) < +\infty$$

The proof is finished.   ♣

Lemma 10.2.2. *If μ is a Borel finite measure on $\overline{\mathbb{C}}$, $n \geq 1$, and $\log|f'|$ is μ integrable, then the function $z \mapsto \log|z-c| \in L^1(\mu)$ for every critical point c of f. If additionally μ is f-invariant, then also the function $z \mapsto \log|z-f(c)| \in L^1(\mu)$.*

Proof. That $\log |z - c| \in L^1(\mu)$ follows from the fact that near c we have $C^{-1}|z - q|^{q-1} \leq |f'(z)| \leq C|z - c|^{q-1}$, where $q \geq 2$ is the order of the critical point c and $C \geq 1$ is a universal constant, and since out of any neighbourhood of the set of critical points of f, $|f'(z)|$ is uniformly bounded away from zero and infinity. In order to prove the second part of the lemma, consider a ray R emanating from $f(c)$ such that $\mu(R) = 0$ and a disk $B(f(c), r)$ such that $f_c^{-1} : B(f(c), r) \backslash R \to \overline{\mathbb{C}}$, an inverse branch of f sending $f(c)$ to c, is well-defined. Let $D = B(f(c), r) \backslash R$. We may additionally require $r > 0$ to be so small that $|z - f(c)| \asymp |f_c^{-1}(z) - c|^q$. It suffices to show that the integral $\int_D \log |z - f(c)| \, d\mu(z)$ is finite. And indeed, by f-invariance of μ we have

$$
\begin{aligned}
\int_D \log |z - f(c)| \, d\mu(z) &= \int_X 1_D(z) \log |z - f(c)| \, d\mu(z) \\
&\asymp \int_X 1_D(z) \log |f_c^{-1}(z) - c|^q \, d\mu(z) \\
&= \int_X (1_D \circ f)(z) \log |z - c|^q \, d\mu(z) \\
&= \int_X 1_{f^{-1}(D)} \log |z - c|^q \, d\mu(z)
\end{aligned}
$$

Notice here that the function $1_D(z) \log |f_c^{-1}(z) - c|^q$ is well-defined on X indeed and that unlike most of our comparability signs, the sign in the formula above means an additive comparability. The finiteness of the last integral follows from the first part of this lemma. ♣

Theorem 10.2.3. *Let $(Z, \mathcal{F}, \nu)$ be a measure space with an ergodic measure preserving automorphism $T : Z \to Z$. Let $f : X \to X$ be a continuous map from a compact set $X \subset \overline{\mathbb{C}}$ onto itself having a holomorphic extention onto a neighbourhood of X ($f \in \mathcal{A}(X)$). Suppose that μ is an f-invariant ergodic measure on X with positive Lyapunov exponent. Suppose also that $h : Z \to X$ is a measurable mapping such that $\nu \circ h^{-1} = \mu$ and $h \circ T = f \circ h$ ν-a.e.. Then for ν-a.e. $z \in Z$ there exists $r(z) > 0$ such that the function $z \mapsto r(z)$ is measurable and the following is satisfied:*

For every $n \geq 1$ there exists $f_{x_n}^{-n} : B(x, r(z)) \to \overline{\mathbb{C}}$, an inverse branch of f^n sending $x = h(z)$ to $x_n = h(T^{-n}(z))$. In addition, for an arbitrary χ, $-\chi_\mu(f) < \chi < 0$, (not depending on z) and a constant $K(z)$

$$
|(f_{x_n}^{-n})'(y)| < K(z) \, e^{\chi n} \quad \text{and} \quad \frac{|(f_{x_n}^{-n})'(w)|}{|(f_{x_n}^{-n})'(y)|} \leq K
$$

for all $y, w \in B(x, r(z))$. K is here the Koebe constant corresponding to the scale $1/2$.

Proof. Suppose first that $\mu\left(\bigcup_{n \geq 1} f^n(\text{Crit}(f))\right) > 0$. Since μ is ergodic this implies that μ must be concentrated on a periodic orbit of an element $w \in$

$\bigcup_{n\geq 1} f^n(\mathrm{Crit}(f))$. This means that $w = f^q(c) = f^{q+k}(c)$ for some $q, k \geq 1$ and $c \in \mathrm{Crit}(f)$, and

$$\mu(\{f^q(c), f^{q+1}(c), \ldots, f^{q+k-1}(c)\}) = 1.$$

Since $\int \log |f'| \, d\mu > 0$, $|(f^k)'(f^q(c))| > 1$. Thus the theorem is obviously true for the set $h^{-1}(\{f^q(c), f^{q+1}(c), \ldots, f^{q+k-1}(c)\})$ of ν measure 1.

So, suppose that $\mu(\bigcup_{n\geq 1} f^n(\mathrm{Crit}(f))) = 0$. Set $R = \min\{1, \mathrm{dist}(X, \overline{\mathbb{C}} \setminus U(f))\}$ and fix $\lambda \in (e^{\frac{1}{4}\chi}, 1)$. Consider $z \in Z$ such that $x = h(z) \notin \bigcup_{n\geq 1} f^n(\mathrm{Crit}(f))$,

$$\lim_{n\to\infty} \frac{1}{n} \log |(f^n)'(h(T^{-n}(z))| = \chi_\mu(f),$$

and $x_n = h(T^{-n}(z)) \in B(f(\mathrm{Crit}(f)), R\lambda^n)$ only for finitely many n's. We shall first demonstrate that the set of points satisfying these properties is of full measure ν. Indeed, the first requirement is satisfied by our hypothesis, the second is due to Birkhoff's ergodic theorem. In order to prove that the set of points satisfying the third condition has ν measure 1 notice that

$$\sum_{n\geq 1} \nu\big(T^n(h^{-1}(B(f(\mathrm{Crit}(f)), R\lambda^n)))\big) = \sum_{n\geq 1} \nu\big(h^{-1}(B(f(\mathrm{Crit}(f)), R\lambda^n))\big)$$
$$= \sum_{n\geq 1} \mu(B(f(\mathrm{Crit}(f)), R\lambda^n)) < \infty,$$

where the last inequality we wrote due to Lemma 10.2.2 and Lemma 10.2.1. The application of the Borel-Cantelli lemma finishes now the demonstration. Fix now an integer $n_1 = n_1(z)$ so large that $x_n = h(T^{-n}(z)) \notin B(f(\mathrm{Crit}(f)), R\lambda^n)$ for all $n \geq n_1$. Notice that because of our choices there exists $n_2 \geq n_1$ such that $|(f^n)'(x_n)|^{-1/4} < \lambda^n$ for all $n \geq n_2$. Finally set $S = \sum_{n\geq 1} |(f^n)'(x_n)|^{-1/4}$, $b_n = \frac{1}{2}S^{-1}|(f^{n+1})'(x_{n+1})|^{\frac{-1}{4}}$, and

$$\Pi = \Pi_{n=1}^\infty (1 - b_n)^{-1}$$

which converges since the series $\sum_{n\geq 1} b_n$ converges. Choose now $r = r(z)$ so small that $16r(z)\Pi K S^3 \leq R$, all the inverse branches $f_{x_n}^{-n} : B(x_0, \Pi r(z)) \to \overline{\mathbb{C}}$ are well-defined for all $n = 1, 2, \ldots, n_2$ and $\mathrm{diam}\big(f_{x_{n_2}}^{-n_2}(B(x_0, r\Pi_{k\geq n_2}(1 - b_k)^{-1}))\big) \leq \lambda^{n_2} R$. We shall show by induction that for every $n \geq n_2$ there exists an analytic inverse branch $f_{x_n}^{-n} : B\big(x_0, r\Pi_{k\geq n}(1 - b_k)^{-1}\big) \to \mathbb{C}$, sending x_0 to x_n and such that

$$\mathrm{diam}\big(f_{x_n}^{-n}(B\big(x_0, r\Pi_{k\geq n}(1 - b_k)^{-1}\big)\big) \leq \lambda^n R.$$

Indeed, for $n = n_2$ this immediately follows from our requirements imposed on $r(z)$. So, suppose that the claim is true for some $n \geq n_2$. Since $x_n = f_{x_n}^{-n}(x_0) \notin B(\mathrm{Crit}(f), R\lambda^n)$ and since $\lambda^n R \leq R$, there exists an inverse branch $f_{x_{n+1}}^{-1} : B(x_n, \lambda^n R) \to \mathbb{C}$ sending x_n to x_{n+1}. Since $\mathrm{diam}\big(f_{x_n}^{-n}(B\big((x_0, r\Pi_{k\geq n}(1-$

$b_k)^{-1})) \leq \lambda^n R$, the composition $f_{x_{n+1}}^{-1} \circ f_{x_n}^{-n} B\big(x_0, r\Pi_{k\geq n}(1-b_k)^{-1}\big) \to \mathbb{C}$ is well-defined and forms the inverse branch of f^{n+1} that sends x_0 to x_{n+1}. By the Koebe distortion theorem we now estimate

$$\text{diam}\big(f_{x_{n+1}}^{-(n+1)}(B\big(x_0, r\Pi_{k\geq n+1}(1-b_k)^{-1}\big))\big)$$
$$\leq 2r\Pi_{k\geq n+1}(1-b_k)^{-1}|(f^{n+1})'(x_{n+1})|^{-1}Kb_n^{-3}$$
$$\leq 16r\Pi KS^3|(f^{n+1})'(x_{n+1})|^{-1}|(f^{n+1})'(x_{n+1})|^{\frac{3}{4}}$$
$$= 16r\Pi KS^3|(f^{n+1})'(x_{n+1})|^{-\frac{1}{4}}$$
$$\leq R\lambda^{n+1},$$

where the last inequality sign we wrote due to our choice of r and the number n_2. Putting $r(z) = r/2$ the second part of this theorem follows now as a combined application of the equality $\lim_{n\to\infty} \frac{1}{n}\log|(f^n)'(x_n)| = \chi_\mu(f)$ and the Koebe distortion theorem.   ♣

As an immediate consequence of Theorem 10.2.3 we get the following.

Corollary 10.2.4. *Assume the same notation and asumptions as in Theorem 10.2.3. Fix $\varepsilon > 0$. Then there exist a set $Z(\varepsilon) \subset Z$, the numbers $r(\varepsilon) \in (0,1)$ and $K(\varepsilon) \geq 1$ such that $\mu(Z(\varepsilon)) > 1 - \varepsilon$, $r(z) \geq r(\varepsilon)$ for all $z \in Z(\varepsilon)$ and with $x_n = h(T^{-n}(z))$*

$$K(\varepsilon)^{-1}\exp(-(\chi_\mu + \varepsilon)n) \leq |(f_{x_n}^{-n})'(y)|$$
$$\leq K(\varepsilon)\exp(-(\chi_\mu - \varepsilon)n) \text{ and } \frac{|(f_{x_n}^{-n})'(w)|}{|(f_{x_n}^{-n})'(y)|} \leq K$$

for all $n \geq 1$, all $z \in Z(\varepsilon)$ and all $y, w \in B(x_0, r(\varepsilon))$. K is here the Koebe constant corresponding to the scale $1/2$.

Remark 10.2.5. In our future applications the system (Z, f, ν) will be usually given by the natural extension of the holomorphic system (f, μ).

10.3   Mañé's partition

In this section, basically following Mañé's book [Mañé 1987], we construct so called Mañé's partition which will play an important role in the proof of a part of the Volume Lemma given in the next section. We begin with the following elementary fact.

Lemma 10.3.1. *If $x_n \in (0,1)$ for every $n \geq 1$ and $\sum_{n=1}^{\infty} nx_n < \infty$, then $\sum_{n=1}^{\infty} -x_n\log x_n < \infty$.*

Proof. Let $S = \{n : -\log x_n \geq n\}$. Then

$$\sum_{n=1}^{\infty} -x_n\log x_n = \sum_{n\notin S} -x_n\log x_n + \sum_{n\in S} -x_n\log x_n \leq \sum_{n=1}^{\infty} nx_n + \sum_{n\in S} -x_n\log x_n$$

Since $n \in S$ means that $x_n \leq e^{-n}$ and since $\log t \leq 2\sqrt{t}$ for all $t \geq 1$, we have

$$\sum_{n \in S} x_n \log \frac{1}{x_n} \leq 2 \sum_{n=1}^{\infty} x_n \sqrt{\frac{1}{x_n}} \leq 2 \sum_{n=1}^{\infty} e^{-\frac{1}{2}n} < \infty$$

The proof is finished.   ♣

The next lemma is the main and simultaneously the last result of this section.

Lemma 10.3.2. *If μ is a Borel probability measure concentrated on a bounded subset M of a Euclidean space and $\rho : M \to (0,1]$ is a measurable function such that $\log \rho$ is integrable with respect to μ, then there exists a countable measurable partition, called Mañé's partition, $\mathcal{P}$ of M such that $\mathrm{H}_\mu(\mathcal{P}) < \infty$ and*

$$\mathrm{diam}(\mathcal{P}(x)) \leq \rho(x)$$

for μ-almost every $x \in M$.

Proof. Let q be the dimension of the Euclidean space containing M. Since M is bounded, there exists a constant $C > 0$ such that for every $0 < r < 1$ there exists a partition $\mathcal{P}_r$ of M of diameter $\leq r$ and which consists of at most Cr^{-q} elements. For every $n \geq 0$ put $U_n = \{x \in M : e^{-(n+1)} < \rho(x) \leq e^{-n}\}$. Since $\log \rho$ is a non-positive integrable function, we have

$$\sum_{n=1}^{\infty} -n\mu(U_n) \geq \sum_{n=1}^{\infty} \int_{U_n} \log \rho \, d\mu = \int_M \log \rho \, d\mu > -\infty$$

so that

$$\sum_{n=1}^{\infty} n\mu(U_n) < +\infty. \tag{10.3.1}$$

Define now $\mathcal{P}$ as the partition whose atoms are of the form $Q \cap U_n$, where $n \geq 0$ and $Q \in \mathcal{P}_{r_n}$, $r_n = e^{-(n+1)}$. Then

$$\mathrm{H}_\mu(\mathcal{P}) = \sum_{n=0}^{\infty} \Big(- \sum_{U_n \supset P \in \mathcal{P}} \mu(P) \log \mu(P) \Big).$$

But for every $n \geq 0$

$$- \sum_{U_n \supset P \in \mathcal{P}} \mu(P) \log \mu(P) = \mu(U_n) \sum_P -\frac{\mu(P)}{\mu(U_n)} \log\Big(\frac{\mu(P)}{\mu(U_n)}\Big) - \mu(U_n) \sum_P \frac{\mu(P)}{\mu(U_n)} \log(\mu(U_n))$$

$$\leq \mu(U_n)(\log C - q \log r_n) - \mu(U_n) \log \mu(U_n)$$

$$\leq \mu(U_n) \log C + q(n+1)\mu(U_n) - \mu(U_n) \log \mu(U_n).$$

Thus, summing over all $n \geq 0$, we obtain

$$\mathrm{H}_\mu(\mathcal{P}) \leq \log C + q + q \sum_{n=0}^{\infty} n\mu(U_n) + \sum_{n=0}^{\infty} -\mu(U_n) \log \mu(U_n).$$

Therefore looking at (10.3.1) and Lemma 9.3.1 we conclude that $H_\mu(\mathcal{P})$ is finite. Also, if $x \in U_n$, then the atom $\mathcal{P}(x)$ is contained in some atom of $\P_{r_n}$ and therefore

$$\operatorname{diam}(\mathcal{P}(x)) \le r_n = e^{-(n+1)} < \rho(x).$$

Now the remark that the union of all the sets U_n is of measure 1 completes the proof.   ♣

10.4   Volume lemma and the formula $\operatorname{HD}(\mu) = \operatorname{h}_\mu(f)/\chi_\mu(f)$

In this section we keep the notation of Sections 10.1 and 10.2 and our main purpose is to prove the following two results which generalize the respective results in Chapter 8.

Theorem 10.4.1. *If $f \in \mathcal{A}(X)$ and μ is an ergodic f-invariant measure with positive Lyapunov exponent, then $\operatorname{HD}(\mu) = \operatorname{h}_\mu(f)/\chi_\mu(f)$.*

Theorem 10.4.2 (Volume Lemma). *With the assumptions of Theorem 10.4.1*

$$\lim_{r \to 0} \frac{\log(\mu(B(x,r)))}{\log r} = \frac{\operatorname{h}_\mu(f)}{\chi_\mu(f)}$$

for μ-a.e. $x \in X$.

In view of theorem 7.6.5, Theorem 10.4.1 follows from Theorem 10.4.2 and we only need to prove the latter one. Let us prove first

$$\liminf_{r \to 0} \frac{\log(\mu(B(x,r)))}{\log r} \ge \frac{\operatorname{h}_\mu(f)}{\chi_\mu(f)} \tag{10.4.1}$$

for μ-a.e. $x \in X$. By Corollary 8.1.10 there exists a finite partition $\mathcal{P}$ such that for an arbitrary $\varepsilon > 0$ and every x in a set X_o of full measure μ there exists $n(x) \ge 0$ such that for all $n \ge n(x)$.

$$B(f^n(x), e^{-\varepsilon n}) \subset \mathcal{P}(f^n(x)). \tag{10.4.2}$$

Let us work from now on in the natural extension $(\tilde{X}, \tilde{f}, \tilde{\mu})$. Let $\tilde{X}(\varepsilon)$ and $r(\varepsilon)$ be given by Corollary 10.2.4, i.e. $\tilde{X}(\varepsilon) = Z(\varepsilon)$. In view of Birkhoff's Ergodic Theorem there exists a measurable set $\tilde{F}(\varepsilon) \subset \tilde{X}(\varepsilon)$ such that $\tilde{\mu}(\tilde{F}(\varepsilon)) = \tilde{\mu}(\tilde{X}(\varepsilon))$ and

$$\lim_{n \to \infty} \frac{1}{n} \sum_{j=1}^{n-1} \chi_{\tilde{X}(\varepsilon)} \circ \tilde{f}^n(\tilde{x}) = \tilde{\mu}(\tilde{X}(\varepsilon))$$

for every $\tilde{x} \in \tilde{F}(\varepsilon)$. Let $F(\varepsilon) = \pi(\tilde{F}(\varepsilon))$. Then $\mu(F(\varepsilon)) = \tilde{\mu}(\pi^{-1}(F(\varepsilon)) \ge \tilde{\mu}(\tilde{F}(\varepsilon)) = \tilde{\mu}(\tilde{X}(\varepsilon))$ converges to 1 if $\varepsilon \searrow 0$. Consider now $x \in F(\varepsilon) \cap X_o$ and

take $\tilde{x} \in \tilde{F}(\varepsilon)$ such that $x = \pi(\tilde{x})$. Then by the above there exists an increasing sequence $\{n_k = n_k(x) : k \geq 1\}$ such that $\tilde{f}^{n_k}(\tilde{x}) \in \tilde{X}(\varepsilon)$ and

$$\frac{n_{k+1} - n_k}{n_k} \leq \varepsilon \qquad (10.4.3)$$

for every $k \geq 1$. Moreover, we can assume that $n_1 \geq n(x)$. Consider now an integer $n \geq n_1$ and the ball $B\big(x, Cr(\varepsilon) \exp(-(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big)$, where $0 < C < (Kr(\varepsilon))^{-1}$ is a constant (possibly depending on x) so small that

$$f^q\big(B(x, Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big) \subset P(f^q(x)) \qquad (10.4.4)$$

for every $q \leq n_1$ and $K(\varepsilon) \geq 1$ is the constant appearing in Corollary 10.2.4. Take now any q, $n_1 \leq q \leq n$, and associate k such that $n_k \leq q \leq n_{k+1}$. Since $\tilde{f}^{n_k}(\tilde{x}) \in \tilde{X}(\varepsilon)$ and since $\pi(\tilde{f}^{n_k}(\tilde{x})) = f^{n_k}(x)$, Corollary 10.2.4 produces a holomorphic inverse branch $f_x^{-n_k} : B(f^{n_k}(x), r(\varepsilon)) \to \overline{\mathbb{C}}$ of f^{n_k} such that $f_x^{-n_k}(f^{n_k}(x)) = x$ and

$$f_x^{-n_k}\big(B(f^{n_k}(x), r(\varepsilon))\big) \supset B\big(x, K(\varepsilon)r(\varepsilon)^{-1} \exp(-(\chi_\mu + \varepsilon)n_k)\big).$$

Since $B(x, Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n) \subset B\big(x, K(\varepsilon)^{-1}r(\varepsilon) \exp -(\chi_\mu + \varepsilon)n_k)\big)$, it follows from Corollary 10.2.4 that

$$f^{n_k}\big(B(x, Cr(\varepsilon) \exp - (\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big) \subset$$
$$\subset B\big(f^{n_k}(x), CKr(\varepsilon)e^{-\chi_\mu(n-n_k)} \exp(\varepsilon(n_k - (2 + \log \|f'\|)n))\big).$$

Since $n \geq n_k$ and since by (10.4.3) $q - n_k \leq \varepsilon n_k$, we therefore obtain

$$f^q\big(B(x, Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big) \subset$$
$$\subset B(f^q(x), CK(\varepsilon)r(\varepsilon)e^{-\chi_\mu(n-n_k)} \exp(\varepsilon(n_k - (2 + \log \|f'\|)n)) \exp((q - n_k) \log \|f'\|)$$
$$\subset B(f^q(x), CK(\varepsilon)r(\varepsilon) \exp\big(\varepsilon(n_k \log \|f'\| + n_k - 2n - n \log \|f'\|)\big)$$
$$\subset B(f^q(x), CK(\varepsilon)r(\varepsilon)e^{-\varepsilon n}) \subset B(f^q(x), e^{-\varepsilon q}).$$

Combining this, (10.4.2), and (10.4.4), we get

$$B\big(x, Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big) \subset \bigvee_{j=0}^{n} f^{-j}(\mathcal{P})(x).$$

Therefore, applying Theorem 1.5.5 (the Shannon-McMillan-Breiman Theorem), we have

$$\liminf_{n \to \infty} -\frac{1}{n} \log \mu\big(B(x, Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)\big) \geq \mathrm{h}_\mu(f, \mathcal{P}) \geq \mathrm{h}_\mu(f) - \varepsilon$$

It means that denoting the number $Cr(\varepsilon) \exp -(\chi_\mu + (2 + \log \|f'\|)\varepsilon)n)$ by r_n, we have

$$\liminf_{n \to \infty} \frac{\log \mu(B(x, r_n))}{\log r_n} \geq \frac{\mathrm{h}_\mu(f) - \varepsilon}{\chi_\mu(f) + (2 + \log \|f'\|)\varepsilon}$$

Now, since $\{r_n\}$ is a geometric sequence and since $\varepsilon > 0$ can be taken arbitrarily small, we conclude that for μ-a.e. $x \in X$

$$\liminf_{n\to\infty} \frac{\log \mu(B(x,r))}{\log r} \geq \frac{h_\mu(f)}{\chi_\mu(f)}$$

This completes the proof of (10.4.1).   ♣

Remark. Since here $X \subset \mathbb{C}$, we could have considered a partition $\mathcal{P}$ of a neighbourhood of X in $\mathbb{C}$ where $\partial_{\mathcal{P},a}$ would have a more standard sense, see Remark after Corollary 8.1.9.

Now let us prove that

$$\limsup_{r\to 0} \frac{\log(\mu(B(x,r)))}{\log r} \leq h_\mu(f)/\chi_\mu(f) \tag{10.4.5}$$

for μ-a.e. $x \in X$.

In order to prove this formula we again work in the natural extension $(\tilde{X}, \tilde{f}, \tilde{\mu})$ and we apply Pesin theory. In particular the sets $\tilde{X}(\varepsilon)$, $\tilde{F}(\varepsilon) \subset \tilde{X}(\varepsilon)$ and the radius $r(\varepsilon)$, produced in Corollary 10.2.4 have the same meaning as in the proof of (10.4.1). To begin with notice that there exist two numbers $R > 0$ and $0 < Q < \min\{1, r(\varepsilon)/2\}$ such that the following two conditions are satisfied.

$$\text{If } z \notin B(\mathrm{Crit}(f), R), \text{ then } f|_{B(z,Q)} \text{ is injective.} \tag{10.4.6}$$
$$\text{If } z \in B(\mathrm{Crit}(f), R), \text{ then } f|_{B(z,Q\,\mathrm{dist}(z,\mathrm{Crit}(f)))} \text{ is injective.} \tag{10.4.7}$$

Observe also that if z is sufficiently close to a critical point c, then $f'(z)$ is of order $(z - c)^{q-1}$, where $q \geq 2$ is the order of critical point c. In particular the quotient of $f'(z)$ and $(z - c)^{q-1}$ remains bounded away from 0 and ∞ and therefore there exists a constant number $B > 1$ such that $|f'(z)| \leq B\,\mathrm{dist}(z, \mathrm{Crit}(f))$. So, in view of Lemma 10.2.2, the logarithm of the function $\rho(z) = Q\min\{1, \mathrm{dist}(z, \mathrm{Crit}(f))$ is integrable and consequently Lemma 10.3.2 applies. Let $\mathcal{P}$ be the Mañé's partition produced by this lemma. Then $B(x, \rho(x)) \supset \mathcal{P}(x)$ for μ-a.e. $x \in X$, say for a subset X_ρ of X of measure 1. Consequently

$$B_n(x, \rho) = \bigcap_{j=0}^{n-1} f^{-j}\big(B(f^j(x), \rho(f^j(x)))\big) \supset \mathcal{P}_0^n(x) \tag{10.4.8}$$

for every $n \geq 1$ and every $x \in X_\rho$. By our choice of Q and the definition of ρ, the function f is injective on all balls $B(f^j(x), \rho(f^j(x)))$, $j \geq 0$, and therefore f^k is injective on the set $B_n(x, \rho)$ for every $0 \leq k \leq n - 1$. Now, let $x \in F(\varepsilon) \cap X_\rho$ and let k be the greatest subscript such that $q = n_k(x) \leq n - 1$. Denote by f_x^{-q} the unique holomorphic inverse branch of f^q produced by Corollary 10.2.4 which sends $f^q(x)$ to x. Clearly $B_n(x, \rho) \subset f^{-q}(B(f^q(x), \rho(f^q(x))))$ and since f^q is injective on $B_n(x, \rho)$ we even have

$$B_n(x, \rho) \subset f_x^{-q}(B(f^q(x), \rho(f^q(x)))).$$

By Corollary 10.2.4 $\operatorname{diam}\big(f_x^{-q}(B(f^q(x), \rho(f^q(x))))\big) \leq K \exp(-q(\chi_\mu - \varepsilon))$. Since by (10.4.3), $n \leq q(1 + \varepsilon)$ we finally deduce that

$$B_n(x, \rho) \subset B\bigg(x, K \exp\bigg(-n\frac{\chi_\mu - \varepsilon}{1 + \varepsilon}\bigg)\bigg).$$

Thus, in view of (10.4.8)

$$B\bigg(x, K \exp\bigg(-n\frac{\chi_\mu - \varepsilon}{1 + \varepsilon}\bigg)\bigg) \supset \mathcal{P}_0^n(x).$$

Therefore, denoting by r_n the radius of the ball above, it follows from Shanon-McMillan-Breiman theorem that for μ-a.e $x \in X$

$$\limsup_{n \to \infty} -\frac{1}{n} \log \mu(B(x, r_n) \leq h_\mu(f, \mathcal{P}) \leq h_\mu(f).$$

So

$$\limsup_{n \to \infty} \frac{\log \mu(B(x, r_n)}{\log r_n} \leq \frac{h_\mu(f)}{\chi_\mu(f) - \varepsilon}(1 + \varepsilon).$$

Now, since $\{r_n\}$ is a geometric sequence and since ε can be taken arbitrarily small, we conclude that for μ-a.e. $x \in X$

$$\limsup_{n \to \infty} \frac{\log \mu(B(x, r)}{\log r} \leq \frac{h_\mu(f)}{\chi_\mu(f)}.$$

This completes the proof of (10.4.5) and because of (10.4.1) also the proof of Theorem 10.4.2. ♣

10.5 Pressure-like definition of the functional $h_\mu + \int \phi \, d\mu$

In this section we prepare some general tools used in the next section to approximate topological pressure on hyperbolic sets. No smoothness is assumed here, we work in purely metric setting only. Our exposition is similar to that contained in Chapter 2.

Let $T : X \to X$ be a continuous map of a compact metric space (X, ρ) and let μ be a Borel probability measure on X. Given $\varepsilon > 0$ and $0 \leq \delta \leq 1$ a set $E \subset X$ is said to be $\mu - (n, \varepsilon, \delta)$-spanning if

$$\mu\bigg(\bigcup_{x \in E} B_n(x, \varepsilon)\bigg) \geq 1 - \delta.$$

Let $\phi : X \to \mathbb{R}$ be a continuous function. We define

$$Q_\mu(T, \phi, n, \varepsilon, \delta) = \inf_E\bigg\{\sum_{x \in E} \exp S_n \phi(x)\bigg\}$$

where the infimum is taken over all $\mu - (n, \varepsilon, \delta)$-spanning sets E. The main result of this section is the following.

Theorem 10.5.1. *For every $0 < \delta < 1$ and every ergodic measure μ*

$$\mathrm{h}_\mu(T) + \int \phi \, d\mu = \lim_{\varepsilon \to 0} \liminf_{n \to \infty} \frac{1}{n} \log Q_\mu(T, \phi, n, \varepsilon, \delta)$$

$$= \lim_{\varepsilon \to 0} \limsup_{n \to \infty} \frac{1}{n} \log Q_\mu(T, \phi, n, \varepsilon, \delta)$$

Proof. Denote the the number following the first equality sign by $\underline{\mathrm{P}}_\mu(T, \phi, \delta)$ and the number following the second equality sign by $\overline{\mathrm{P}}_\mu(T, \phi, \delta)$. First, following essentially the proof of the Part I of Theorem 2.4.1, we shall show that

$$\underline{\mathrm{P}}_\mu(T, \phi, \delta) \geq \mathrm{h}_\mu(T) + \int \phi \, d\mu \qquad (10.5.1)$$

Indeed, similarly as in that proof consider a finite partition $\mathcal{U} = \{A_1, \ldots, A_s\}$ of X into Borel sets and compact sets $B_i \subset A_i$, $i = 1, 2, \ldots, A_s\}$, such that for the partition $\mathcal{V} = \{B_1, \ldots, B_s, X \setminus (B_1 \cup \ldots \cup B_s)\}$ we have $H_\mu(\mathcal{U}|\mathcal{V}) \leq 1$. For every $\theta > 0$ and $q \geq 1$, set

$$X_q = \left\{ x \in X : -\frac{1}{n} \log \mu\big(\mathcal{V}^n(x)\big) \geq \mathrm{h}_\mu(T, \mathcal{V}) - \theta \ \text{ for all } \ n \geq q \right.$$

$$\left. \frac{1}{n} S_n \phi(x) \geq \int \phi \, d\mu - \theta \ \text{ for all } \ n \geq q \right\}$$

Fix now $0 \leq \delta < 1$. It follows from Shannon-McMillan-Breiman theorem and Birkhoff's ergodic theorem that for q large enough $\mu(X_q) > \delta$. Take $0 < \varepsilon < \frac{1}{2} \min\{\rho(B_i, B_j) : 1 \leq i < j \leq s\} > 0$ so small that

$$|\phi(x) - \phi(y)| < \theta$$

if $\rho(x, y) \leq \varepsilon$. Since for every $x \in X$ the set $B_n(x, \varepsilon) \cap X_q$ can be covered by at most 2^n elements of $\mathcal{V}^n$,

$$\mu(B_n(x, \varepsilon) \cap X_q) \leq \exp\big(n(\log 2 - \mathrm{h}_\mu(T, \mathcal{V}) + \theta)\big).$$

Now let E be a $\mu - (n, \varepsilon, \delta)$-spanning set for $n \geq q$, and consider the set $E' = \{x \in E : B_n(x, \varepsilon) \cap X_q \neq \emptyset\}$. Take any point $y(x) \in B_n(x, \varepsilon) \cap X_q$. Then by

the choice of ε, $S_n\phi(x) - S_n\phi(y) > -n\theta$. Therefore we have

$$\sum_{x \in E} \exp S_n\phi(x) \exp\left(-n\left(\mathrm{h}_\mu(T,\mathcal{V}) + \int \phi \, d\mu - 3\theta - \log 2\right)\right) \geq$$

$$\geq \sum_{x \in E'} \exp S_n\phi(x) \exp\left(-n\left(\mathrm{h}_\mu(T,\mathcal{V}) + \int \phi \, d\mu - 3\theta - \log 2\right)\right)$$

$$= \sum_{x \in E'} \exp\left(S_n\phi(x) - n\int \phi \, d\mu\right) \exp\left(-n(\mathrm{h}_\mu(T,\mathcal{V}) - 3\theta - \log 2)\right)$$

$$= \sum_{x \in E'} \exp\left(S_n\phi(x) - S_n\phi(y) + S_n\phi(y) - n\int \phi \, d\mu\right) \exp\left(-n\left(\mathrm{h}_\mu(T,\mathcal{V}) - 3\theta - \log 2\right)\right)$$

$$\geq \sum_{x \in E'} \exp(-n\theta) \exp(-n\theta) \exp(2n\theta) \exp\left(-n(\mathrm{h}_\mu(T,\mathcal{V}) - \theta - \log 2)\right)$$

$$= \sum_{x \in E'} \exp\left(n(\log 2 - \mathrm{h}_\mu(T,\mathcal{V}) + \theta)\right)$$

$$\geq \sum_{x \in E'} \mu(B_n(x,\varepsilon) \cap X_q) \geq \mu(X_q) - \delta > 0$$

which implies that

$$Q_\mu(T,\phi,n,\varepsilon,\delta) \geq \mathrm{h}_\mu(T,\mathcal{V}) + \int \phi \, d\mu - 3\theta - \log 2.$$

Since $\theta > 0$ is an arbitrary number and since $\mathrm{h}_\mu(T,\mathcal{U}) \leq \mathrm{h}_\mu(T,\mathcal{V}) + H_\mu(\mathcal{U}|\mathcal{V}) \leq \mathrm{h}_\mu(T,\mathcal{V}) + 1$, letting $\varepsilon \to 0$, we get

$$\underline{\mathrm{P}}_\mu(T,\phi,\delta) \geq \mathrm{h}_\mu(T,\mathcal{U}) - 1 + \int \phi \, d\mu - \log 2$$

Therefore, by the definition of entropy of an automorphism, $\underline{\mathrm{P}}_\mu(T,\phi,\delta) \geq \mathrm{h}_\mu(T) + \int \phi \, d\mu - \log 2 - 1$. Using now the standard trick, actually always applied in the setting we are whose point is to replace T by its arbitrary iterates T^k and ϕ by $S_k\phi$, we obtain $k\underline{\mathrm{P}}_\mu(T,\phi,\delta) \geq k\,\mathrm{h}_\mu(T) + k\int \phi \, d\mu - \log 2 - 1$. So, dividing this inequality by k, and letting $k \to \infty$, we finally obtain

$$\underline{\mathrm{P}}_\mu(T,\phi,\delta) \geq \mathrm{h}_\mu(T) + \int \phi \, d\mu$$

Now let us prove that

$$\overline{\mathrm{P}}_\mu(T,\phi,\delta) \leq \mathrm{h}_\mu(T) + \int \phi \, d\mu \qquad (10.5.2)$$

where $\overline{\mathrm{P}}_\mu(T,\phi,\delta)$ denotes limsup appearing in the statement of Theorem 10.5.1. Indeed, fix $0 < \delta < 1$, then $\varepsilon > 0$ and $\theta > 0$. Let $\mathcal{P}$ be a finite partition of X of

diameter $\leq \varepsilon$. By Shannon-McMillan-Breiman theorem and Birkhoff's ergodic theorem there exists a Borel set $Z \subset X$ such that $\mu(Z) > 1 - \delta$ and

$$\frac{1}{n} S_n \phi(x) \leq \int \phi \, d\mu + \theta \quad -\frac{1}{n} \log \mu(\mathcal{P}^n(x)) \leq \mathrm{h}_\mu(T) + \theta \qquad (10.5.3)$$

for every n large enough and all $x \in Z$. From each element of $\mathcal{P}^n$ having non-empty intersection with Z choose one point obtaining, say, a set $\{x_1, x_2, \ldots, x_q\}$. Then $B_n(x_j, \varepsilon) \supset \mathcal{P}^n(x_j)$ for every $j = 1, 2, \ldots, q$ and therefore the set $\{x_1, x_2, \ldots, x_q\}$ is $\mu-(n, \varepsilon, \delta)$-spanning. By the second part of (9.5.3) we have $q \leq \exp(n(\mathrm{h}_\mu(T) + \theta))$. Using also the first part of (9.5.3), we get

$$\sum_{j=1}^{q} \exp S_n \phi(x_j) \leq \exp(n(\mathrm{h}_\mu(T) + \theta + \int \phi \, d\mu + \theta))$$

Therefore $Q_\mu(T, \phi, n, \varepsilon, \delta) \leq \exp(n(\mathrm{h}_\mu(T) + \theta + \int \phi \, d\mu + \theta))$ and letting consequtively $n \to \infty$ and $\varepsilon \to 0$, we obtain $\overline{\mathrm{P}}_\mu(T, \phi, \delta) \leq \mathrm{h}_\mu(T) + \int \phi \, d\mu + 2\theta$. Since θ is an arbitrary positive number, (10.5.2) is proved. This and (10.5.1) complete the proof of Theorem 10.5.1. ♣

10.6   Katok's theory—hyperbolic sets, periodic points, and pressure

In this section we again come back to the setting of Section 9.1. So, let X be a compact subset of the closed complex plane $\overline{\mathbb{C}}$ and let $f : X \to X$ be a continuous map that can be analytically extended to an open neighbourhood $U(f)$ of X.

Let μ be an f-invariant ergodic measure on X with positive Lyapunov exponent. $\mathrm{h}_\mu(f)$ and let $\phi : X \to \mathbb{R}$ be a real continuous function. Our first aim is to show that the number $\mathrm{h}_\mu(f) + \int \phi \, d\mu$ can be approximated by the topological pressures of ϕ on hyperbolic subsets of X and then as a straightforward consequence we will obtain the same approximation for the topological pressure $\mathrm{P}(f, \phi)$.

Theorem 10.6.1. *If μ is an f-invariant ergodic measure on X with positive Lyapunov expenent χ_μ and if $\phi : X \to \mathbb{R}$ is a real-valued continuous function, then there exists a sequence X_k, $k = 1, 2, \ldots$, of compact f- invariant subsets of U such that for every k the restriction $f|_{X_k}$ is a conformal expanding repeller,*

$$\liminf_{k \to \infty} \mathrm{P}(f|_{X_k}, \phi) \geq \mathrm{h}_\mu(f) + \int \phi \, d\mu \qquad (10.6.1)$$

and if μ_k is any ergodic f-invariant measure on X_k, then the sequence μ_k, $k = 1, 2, \ldots$, converges to μ in the weak-*-topology on a closed neighbourhood of X. Moreover $\chi_{\mu_k}(f|_{X_k}) = \int \log |f'| \, d\mu_k \to \int \log |f'| \, d\mu = \chi_\mu(f)$. In particular μ_k can be supported by individual periodic orbits in X_k.

Proof. Since $\mathrm{P}(f|_{X_k}, \phi + c) = \mathrm{P}(f|_{X_k}, \phi) + c$ and since $\mathrm{h}_\mu(f) + \int(\phi + c)\,d\mu = \mathrm{h}_\mu(f) + \int \phi\,d\mu + c$, adding a constant if necessary, we can assume that ϕ is positive, that is that $\inf \phi > 0$. As in Section 9.2 we work in the natural extension $(\tilde{X}, \tilde{f}, \tilde{\mu})$. Given $\delta > 0$ let $\tilde{X}(\delta)$ and $r(\delta)$ be produced by Corollary 10.2.4. The set $\pi(\tilde{X}(\delta))$ is assumed to be compact. This corollary implies the existence of a constant $\chi' > 0$ (possibly with a smaller radius $r(\delta)$) such that

$$\mathrm{diam}\big(f_{x_n}^{-n}(B(\pi(\tilde{x}), r(\delta)))\big) \leq e^{-n\chi'} \tag{10.6.2}$$

for all $\tilde{x} \in \tilde{X}(\delta)$ and $n \geq 0$. Fix a countable basis $\{\psi_j\}_{j=1}^\infty$ of the Banach space $C(X)$ of all continuous real-valued functions $C(X)$. Fix $\theta > 0$ and an integer $s \geq 1$. In view of Theorem 10.5.1 and continuity of functions ϕ and ψ_i there exists $\varepsilon > 0$ so small that

$$\liminf_{n\to\infty} \frac{1}{n} \log Q_\mu(T, \phi, n, \varepsilon, \delta) - (\mathrm{h}_\mu(f) + \int \phi\,d\mu) > -\theta, \tag{10.6.3}$$

if $|x - y| < \varepsilon$, then

$$|\phi(x) - \phi(y)| < \theta \tag{10.6.4}$$

and

$$|\psi_i(x) - \psi_i(y)| < \frac{1}{2}\theta \tag{10.6.5}$$

for all $i = 1, 2, \ldots, s$.

Set $\beta = r(\delta)/2$ and fix a finite $\beta/2$-spanning set of $\pi(\tilde{X}(\delta))$, say $\{x_1, \ldots, x_t\}$. That is $B(x_1, \beta/2) \cup \ldots \cup B(x_t, \beta/2) \supset \pi(\tilde{X}(\delta/2))$. Let $\mathcal{U}$ be a finite partition of X with diameter $< \beta/2$ and let n_1 be sufficiently large that

$$\exp(-n_1\chi') < \min\{\beta/3, K^{-1}\}. \tag{10.6.6}$$

Given $n \geq 1$ define

$$\tilde{X}_{n,s} = \{\tilde{x} \in \tilde{X}(\delta) : \tilde{f}^q(\tilde{x}) \in \tilde{X}(\delta) \ \ \pi(\tilde{f}^q(\tilde{x})) \in \mathcal{U}(\pi(\tilde{x}))$$
$$\text{for some} \ \ q \in [n+1, (1+\theta)n]$$
$$\left| \frac{1}{k} S_k(\psi_i)(\pi(\tilde{x})) - \int \psi_i\,d\mu \right| < \frac{1}{2}\theta$$
$$\text{for every} \ k \geq n \ \text{ and all } \ i = 1, 2, \ldots, s\}.$$

By Birkhoff's ergodic theorem $\lim_{n\to\infty} \mu(\tilde{X}_{n,s}) = \mu(\tilde{X}(\delta)) > 1 - \delta$. Therefore there exists $n \geq n_1$ so large that $\mu(\tilde{X}_{n,s}) > 1 - \delta$. Let $X_{n,s} = \pi((\tilde{X}_{n,s}))$. Then $\mu(X_{n,s}) > 1 - \delta$ and let $E_n \subset X_{n,s}$ be a maximal (n, ε)-separated subset of $X_{n,s}$. Then E_n is a spanning set of $X_{n,s}$ and therefore it follows from (10.6.3) that for all n large enough

$$\frac{1}{n} \log \sum_{x \in E_n} \exp S_n\phi(x) - (\mathrm{h}_\mu(f) + \int \phi\,d\mu) > -\theta.$$

Equivalently

$$\sum_{x \in E_n} \exp(S_n \phi(x)) > \exp(n(\mathrm{h}_\mu(f) + \int \phi \, d\mu - \theta)).$$

For every $q \in [n+1, (1+\theta)n]$ let

$$V_q = \{x \in E_n : f^q(x) \in \mathcal{U}(x)\}$$

and let $m = m(n)$ be a value of q that maximizes $\sum_{x \in V_q} \exp(S_n \phi(x))$. Since $\bigcup_{q=n+1}^{(1+\theta)n} V_q = E_n$, we thus obtain

$$\sum_{x \in V_m} \exp S_n \phi(x) \geq (n\theta)^{-1} \sum_{q=n+1}^{(1+\theta)n} \sum_{x \in V_q} \exp S_n \phi(x)$$

$$\geq (n\theta)^{-1} \sum_{x \in E_n} \exp(S_n \phi(x)) \geq \exp(n(\mathrm{h}_\mu(f) + \int \phi \, d\mu - 2\theta)).$$

Consider now the sets $V_m \cap B(x_j, \beta/2)$, $1 \leq j \leq t$ and choose the value $i = i(m)$ of j that maximizes $\sum_{x \in V_m \cap B(x_j, \beta/2)} \exp(S_n \phi(x))$. Thus, writing D_m for $V_m \cap B(x_{i(m)}, \beta/2)$ we have $V_m = \bigcup_{j=1}^{t} V_m \cap B(x_i, \beta/2)$ and

$$\sum_{x \in D_m} \exp S_n \phi(x) \geq \frac{1}{t} \exp(n(\mathrm{h}_\mu(f) + \int \phi \, d\mu - 2\theta)).$$

Since ϕ is positive, this implies that

$$\sum_{x \in D_m} \exp S_m \phi(x) \geq \frac{1}{t} \exp(n(\mathrm{h}_\mu(f) + \int \phi \, d\mu - 2\theta)). \tag{10.6.7}$$

Now, if $x \in D_m$, then $|f^m(x) - x_i| \leq |f^m(x) - x| + |x - x_i| < \beta/2 + \beta/2 = \beta$ and therefore

$$f^m(x) \in B(x_i, \beta) \subset B(f^m(x), 2\beta).$$

Thus, by (10.6.2) and as $m \geq n \geq n_1$, we have $\mathrm{diam}\big(f_{\tilde{x}}-m(B(f^m(x), 2\beta)\big) \leq \exp(-m\chi') < \beta/3$, where $\tilde{x} \in \pi^{-1}(x) \cap \tilde{X}_{n,s}$. Therefore

$$f_{\tilde{x}}^{-m}(B(x_i, \beta)) \subset B\left(x_i, \frac{\beta}{2} + \frac{\beta}{3}\right) = B\left(x_i, \frac{5}{6}\beta\right)$$

In particular

$$\overline{f_{\tilde{x}}^{-m}(B(x_i, \beta))} \subset B(x_i, \beta) \tag{10.6.8}$$

Consider now two distinct points $y_1, y_2 \in D_m$. Then $f_{y_2}^{-m}(B(x_i, \beta)) \cap f_{y_1}^{-m}(B(x_i, \beta)) = \emptyset$ and decreasing β a little bit, if necessary, we may assume that

$$f_{y_2}^{-m}\big(\overline{B(x_i, \beta)}\big) \cap f_{y_1}^{-m}\big(\overline{B(x_i, \beta)}\big) = \emptyset.$$

Let

$$\xi = \min \left\{ \beta, \min \left\{ \operatorname{dist}\left(f_{y_2}^{-m}(\overline{B(x_i,\beta)}), f_{y_1}^{-m}(\overline{B(x_i,\beta)}) \right) : y_1, y_2 \in D_m, y_1 \neq y_2 \right\} \right\}.$$

Define now inductively the sequence of sets $\{X^{(j)}\}_{j=0}^{\infty}$ contained in $U(f)$ by setting

$$X^{(0)} = \overline{(B(x_i,\beta))} \text{ and } X^{(j+1)} = \bigcup_{x \in D_m} f_x^{-m}(X^{(j)})$$

By (10.6.8), $\{X^{(j)}\}_{j=0}^{\infty}$, is a descending sequence of non-empty compact sets, and therefore the intersection

$$X^* = X^*(\theta, s) = \bigcap_{j=0}^{\infty} X^{(j)}$$

is also a non-empty compact set. Moreover, by the construction $f^m(X^*) = X^*$, $f^m|_{X^*}$ is topologically conjugate to the full one-sided shift generated by an alphabet consisting of $\#D_m$ elements and it immediately follows from Corollary 10.2.4 that $f^m|_{X^*}$ is an expanding map. Since $f^m|_{X^*}$ is an open map, by Lemma 5.1.2 the triple (f^m, X^*, U_m) is a conformal expanding repeller with a sufficiently small neighborhood U_m of X^*. Thus $(f, X(\theta, s), W_s)$, is a conformal expanding set, where

$$X(\theta, s) = \bigcup_{l=0}^{m-1} f^l(X^*) \text{ and } W_s = \bigcup_{l=0}^{m-1} f^l(U_m).$$

It can be extended to a conformal expanding repeller $\hat{X}(\theta, s)$ in W_s, by Proposition 3.5.6.

Fix now an integer $j \geq 1$. For any j-tuple $(z_0, z_1, \ldots, z_{j-1})$, $z_l \in D_m$ choose exactly one point y from the set $f_{z_{j-1}}^{-m} \circ f_{z_{j-2}}^{-m} \circ \ldots \circ f_{z_0}^{-m}(X^*)$ and denote the made up set by A_j. Since by (10.6.4) and (10.6.6) $S_{jm}\phi(y) \geq \sum_{l=0}^{j-1} S_m\phi(z_l) - jm\theta$ we see that

$$\sum_{y \in A_j} \exp S_{jm}\phi(y) \geq \Big(\sum_{x \in D_m} \exp S_m\phi(x) \Big)^j \exp(-jm\theta)$$

and

$$\frac{1}{j} \log \sum_{y \in A_j} \exp S_{jm}\phi(y) \geq \log \sum_{x \in D_m} \exp S_m\phi(x) - m\theta$$

In view of the definition of ξ, the set A_j is (j, ξ)-separated for f^m and ξ is an expansive constant for f^m. Hence, letting $j \to \infty$ we obtain

$$\mathrm{P}(f^m|_{X^*}, S_m\phi) \geq \log \sum_{x \in D_m} \exp S_m\phi(x) - m\theta$$

$$\geq n\Big(\mathrm{h}_\mu(f) + \int \phi \, d\mu - 2\theta \Big) - \log t - m\theta$$

where the last inequality was written in view of (10.6.7). Since $n + 1 \leq m \leq n(1 + \theta)$ and since $\inf \phi > 0$ (and consequently $h_\mu(f) + \int \phi \, d\mu > 0$), we get

$$P(f|_{\hat{X}(\theta,s)}, \phi) \geq P(f|_{X(\theta,s)}, \phi) = \frac{1}{m} P(f^m|_{X(\theta,s)}, S_m\phi) \geq \frac{1}{m} P(f^m|_{X^*}, S_m\phi)$$

$$\geq \frac{1}{1+\theta}\left(h_\mu(f) + \int \phi \, d\mu - 2\theta\right) - \frac{\log t}{m} - \theta$$

Supposing now that n (and consequently also m) was chosen sufficiently large we get

$$P(f|_{X(\theta,s)}, \phi) \geq \frac{1}{1+\theta}(h_\mu(f) + \int \phi \, d\mu) - 4\theta.$$

If now ν is any ergodic f-invariant measure on $\hat{X}(\theta, s)$, then it follows from the definition of the set $\tilde{X}_{n,s}$, the construction of the set $X(\theta, s)$ and since $\hat{X}(\theta, s)$ is arbitrarily close to it, and else by the Birkhoff ergodic theorem, that $|\int \psi_i \, d\nu - \int \psi_i \, d\mu| < \theta$ for every $i = 1, 2, \ldots, s$. A similar estimate for $\log|f'|$ follows from the definition of $\tilde{X}(\delta)$ and Corollary 10.2.4. Therefore putting for example $X_k = \hat{X}(1/k, k)$, completes the proof of Theorem 10.6.1.   ♣

Remark 10.6.2. In fact the sets X_k in Theorem 10.6.1 can be found independent of ϕ.

Indeed. Set just $\phi \equiv 0$. Find X_k for this function. We get $\limsup_{k\to\infty} h_\top(f|X_k) \geq h_\mu(f)$. Let μ_k be a measure of maximal entropy on X_k, for $k = 1, 2, \ldots$, i.e. $h_{\mu_k}(f) = h_{\text{top}}(f|_{X_k})$. Consider an arbitrary continuous function $\phi : X \to \mathbb{R}$. Then $\mu_k \to \mu$ weakly* yields $\int \phi \, d\mu_k \to \int \phi \, d\mu$, hence with the use of the Variational Principle

$$\liminf_{k\to\infty} P(f|_{X_k}, \phi) \geq \liminf_{k\to\infty} h_{\mu_k}(f) + \int \phi \, d\mu_k \geq h_\mu(f) + \int \phi \, d\mu.$$

Remark 10.6.3. One can find X_k above so that each f_{X_k} is topologically transitive.

This follows from the general Theorem 3.3.8 on the existence of Spectral Decomposition. It implies that for each k there exists $\Omega_k \subset X_k$ such that $f|_{\Omega_k}$ is open, see Lemma 3.3.10, topologically transitive and satisfying $h_{\text{top}}(f|_{\Omega_k}) = h_{\text{top}}(f|_{X_k})$, see Exercise 3.5. Hence, using μ_k measures of maximal entropy on Ω_k, we obtain (10.6.1) as in Remark 10.6.2.

(Another way to proceed is to use Markov partition, in the related directed graph to find an appropriate transitive subgraph, and finally consider as X_k the related limit set.)

Remark 10.6.4. If the set X is repelling, that is if $\bigcap_{n\geq 0} f^{-n}(U) = X$, then the sets X_k constructed in the proof of Theorem 10.6.1 are all contained in X. In particular we get the following.

Corollary 10.6.5. *If the set X is repelling and if $\mathrm{P}(f,\phi) > \sup\phi$, then there exists a sequence X_k, $k = 1, 2, \ldots$, of compact f-invariant subsets of X such that for every k, $f|_{X_k}$ is a conformal expanding repeller,*

$$\lim_{k \to \infty} \mathrm{P}(f|_{X_k}, \phi) = \mathrm{P}(f, \phi)$$

and if μ_k is any ergodic f-invariant measure on X_k, then the sequence μ_k, $k = 1, 2, \ldots$, converges to μ in the weak-*-topology on X.

Remark 10.6.6. Of course in Corollary 10.6.5 it was sufficient to assume that $\mathrm{P}(f,\phi) = \sup\{\mathrm{h}_\mu(f) + \int\phi\,d\mu\}$ where the supremum is taken over all ergodic invariant measures of positive entropy, which is assured for example by the inequality $\mathrm{P}(f,\phi) > \sup\phi$. Besides, if the function ϕ has an equilibrium state of positive entropy, then the sequence μ_k can be chosen to converge to this equilibrium state.

Our last immediate conclusion concerns periodic points.

Corollary 10.6.7. *If $f : X \to X$ is repelling and $\mathrm{h}_{\mathrm{top}}(f) > 0$, then f has infinitely many periodic points. Moreover the number of periodic points of period n grows exponentially fast with n.*

Exercises

10.1. Prove the following general version of Theorem 10.1.1: Let X be a compact f-invariant subset of a smooth Riemannian manifold for a C^1 mapping $f : U \to M$, defined on a neighbourhood U of X. Let μ be an f-invariant Borel probability measure X. Then

$$h_\mu(f) \le \int_X \max\{0, \chi_\mu^+(x)\}\,d\mu(x),$$

where $\chi_\mu^+(x) = \lim_{n\to\infty} \frac{1}{n}\log\|(Df^n)^\wedge\|$. Here Df^n is the differential and $(Df^n)^\wedge$ is the exterior power, the linear operator between the exterior algebras generated by the tangent spaces at x and $f^n(x)$. The norm is induced by the Riemann metric. Saying directly $\|(Df^n)^\wedge\|$ is supremum of the volumes of Df^n-images of unit cubes in k-dimensional subspaces of $T_x M$ with $k = 0, 1, \ldots, \dim M$.

Bibliographical notes

Theorem 10.1.1 and the Exercise following it rely on [Ruelle 1978a].

The content of Sections 10.2, 10.5 and 10.6 corresponds to facts from Pesin's and Katok's theories for diffeomorphisms [Katok & Hasselblatt 1995] Supplement 5. For Theorem 10.2.3 see for example [Przytycki, Urbański & Zdunik 1989].

Mañé's partition for diffeomorphisms was discussed in [Mañé 1987]. References to volume lemma are for example [Mañé 1988], [Przytycki 1985], [Ledrappier 1984].

The problem of constructing $X_k \subset X$ in the case (X, f) is not a repeller, in Theorem 10.6.1, was recently dealt with in [Przytycki 2005]

Chapter 11

Conformal measures

11.1 General notion of conformal measures

Let $T : X \to X$ be a continuous map of a compact metric space (X, ρ) and let $g : X \to \mathbb{R}$ be a non–negative measurable function. A Borel probability measure m on X is said to be g–conformal for $T : X \to X$ if

$$m(T(A)) = \int_A g \, dm \qquad (11.1.1)$$

for any Borel set $A \subset X$ such that $T|_A$ is injective and $T(A)$ is Borel measurable. Sets with this property will be called *special sets*.

If $g > 0$, then T is backward quasi-invariant (non-singular) with respect to the g-conformal measure m, see Chapter 4, Section 4.2.

Consider now an arbitrary Borel probability measure m on X, backward quasi-invariant for T. Assume that T is uniformly bounded–to–one, or countable–to–one, i.e. $X = \bigcup X_j$, where X_j are measurable, pairwise disjoint, and for each j the map $T|_{X_j} \to T(X_j)$ is a measurable isomorphism, as in Section 4.2. Denote $\hat{g} := d(m \circ (T|_{X_j})^{-1})/dm$.

Consider, as in Section 4.2, the operator $\mathcal{L}_m : L^1(m) \to L^1_m$ defined in the present notation and the notation of (4.2.8) by

$$\mathcal{L}_m(u)(x) = \mathcal{L}_{\log \hat{g}}(x) = \sum_{T(y)=x} u(y)\hat{g}(y),$$

So, for all $u \in L^1(m)$,

$$\int \mathcal{L}_m^*(\mathbb{1})u \, dm = \int \mathbb{1}\mathcal{L}_m(u) \, dm = \int u \, dm,$$

see (4.2.4). We conclude that, by Proposition 4.2.1, if m is a g-conformal measure and $g > 0$ then $\hat{g} = 1/g$ and

$$\mathcal{L}_{-\log g}^*(\mathbb{1}) = \mathcal{L}_m^*(\mathbb{1}) = \mathbb{1}. \qquad (11.1.2)$$

Conversely, if m is backward quasi-invariant, $\hat{g} > 0$ and (11.1.2) holds, then for $g = 1/\hat{g}$ the measure m is g-conformal.

Notice that even if T is continuous, $\mathcal{L}_m$ need not map $C(X)$ into $C(X)$, unlike for T open, continuous. However, if we assume $\mathcal{L}_m : C(X) \to C(X)$ and T being uniformly bounded–to–one, then $\mathcal{L}_m^* : C^*(X) \to C^*(X)$. Then, under the above constrains concerning positivity, we conclude with

Proposition 11.1.1. *A probability measure m is g-conformal if and only if*

$$\mathcal{L}_{-\log g}^*(m) = m.$$

Now, since we can have troubles with the operator $\mathcal{L}^*$ for T not open, we shall provide another general method of constructing conformal measures, called Patterson-Sullivan method. The construction will make use of the following simple fact. For a sequence $\{a_n : n \geq 1\}$ of reals the number

$$c = \limsup_{n \to \infty} \frac{a_n}{n} \tag{11.1.3}$$

will be called the *transition parameter* of $\{a_n : n \geq 1\}$. It is uniquely determined by the property that

$$\sum_{n \geq 1} \exp(a_n - ns)$$

converges for $s > c$ and diverges for $s < c$. For $s = c$ the sum may converge or diverge. By a simple argument one obtains the following.

Lemma 11.1.2. *There exits a sequence $\{b_n : n \geq 1\}$ of positive reals such that*

$$\sum_{n=1}^{\infty} b_n \exp(a_n - ns) \begin{cases} < \infty & s > c \\ = \infty & s \leq c \end{cases}$$

and $\lim_{n \to \infty} \frac{b_n}{b_{n+1}} = 1$.

Proof. If $\sum \exp(a_n - nc) = \infty$, put $b_n = 1$ for every $n \geq 1$. If $\sum \exp(a_n - nc) < \infty$, choose a sequence $\{n_k : k \geq 1\}$ of positive integers such that $\lim_{k \to \infty} n_k n_{k+1}^{-1} = 0$ and $\varepsilon_k := a_{n_k} n_k^{-1} - c \to 0$. Setting

$$b_n = \exp\left(n\left(\frac{n_k - n}{n_k - n_{k-1}}\varepsilon_{k-1} + \frac{n - n_{k-1}}{n_k - n_{k-1}}\varepsilon_k\right)\right) \quad \text{for } n_{k-1} \leq n < n_k,$$

it is easy to check that the lemma follows.   ♣

Getting back to dynamics let $\{E_n\}_{n=1}^{\infty}$ be a sequence of finite subsets of X such that

$$T^{-1}(E_n) \subset E_{n+1} \qquad \text{for every} \quad n \geq 1 \tag{11.1.4}$$

Let $\phi : X\mathbb{R}$ be an arbitrary measurable function of bounded absolute value.

Functions of the form $-\phi + \text{Const}$ will play the role of "potential" functions; $\exp(-\phi + \text{Const})$ corresponds to the Jacobian g discussed above.

Let

$$a_n = \log\Big(\sum_{x \in E_n} \exp(S_n \phi(x))\Big)$$

where $S_n \phi = \sum_{0 \le k < n} \phi \circ T^k$. Denote by c the transition parameter of this sequence. Choose a sequence $\{b_n : n \ge 1\}$ of positive reals as in lemma 10.1.2 for the sequence $\{a_n : n \ge 1\}$. For $s > c$ define

$$M_s = \sum_{n=1}^{\infty} b_n \exp(a_n - ns) \tag{11.1.5}$$

and the normalized measure

$$m_s = \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in E_n} b_n \exp(S_n \phi(x) - ns) \delta_x, \tag{11.1.6}$$

where δ_x denotes the unit mass at the point $x \in X$. Let A be a special set. Using (11.1.4) and (11.1.6) it follows that

$$m_s(T(A)) = \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in E_n \cap T(A)} b_n \exp(S_n \phi(x) - ns)$$

$$= \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in A \cap T^{-1} E_n} b_n \exp(S_n \phi(T(x)) - ns)$$

$$= \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in A \cap E_{n+1}} b_n \exp[S_{n+1} \phi(x) - (n+1)s] \exp(s - \phi(x))$$

$$- \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in A \cap (E_{n+1} \setminus T^{-1} E_n)} b_n \exp(S_n \phi(T(x)) - ns). \tag{11.1.7}$$

Set

$$\Delta_A(s) = \left| \frac{1}{M_s} \sum_{n=1}^{\infty} \sum_{x \in A \cap E_{n+1}} b_n \exp[S_{n+1} \phi(x) - (n+1)s] \exp(s - \phi(x)) - \int_A \exp(c - \phi) \, dm_s \right|$$

and observe that

$$\Delta_A(s) = \frac{1}{M_s}\Bigg|\sum_{n=1}^{\infty}\sum_{x\in A\cap E_{n+1}}\exp[S_{n+1}\phi(x) - (n+1)s]\exp(-\phi(x))\big[b_n e^s - b_{n+1}e^c\big]$$

$$- b_1\sum_{x\in A\cap E_1} e^{c-s}\Bigg|$$

$$\leq \frac{1}{M_s}\sum_{n=1}^{\infty}\sum_{x\in A\cap E_{n+1}}\left|\frac{b_n}{b_{n+1}} - e^{c-s}\right|b_{n+1}\exp(s-\phi(x))\exp[S_{n+1}\phi(x) - (n+1)s]$$

$$+ \frac{1}{M_s}b_1\exp(c-s)\,\sharp(A\cap E_1)$$

$$\leq \frac{1}{M_s}\sum_{n=1}^{\infty}\sum_{x\in E_{n+1}}\left|\frac{b_n}{b_{n+1}} - e^{c-s}\right|b_{n+1}\exp(s-\phi(x))\exp[S_{n+1}\phi(x) - (n+1)s]$$

$$+ \frac{1}{M_s}b_1\exp(c-s)\,\sharp E_1.$$

By lemma 10.1.2 we have $\lim_{n\to\infty}b_{n+1}/b_n = 1$ and $\lim_{s\downarrow c}M_s = \infty$. Therefore

$$\lim_{s\downarrow c}\Delta_A(s) = 0 \qquad\qquad (11.1.8)$$

uniformly for all special sets A.

Any weak accumulation point, when $s\searrow c$, of the measures $\{m_s : s > c\}$ defined by (11.1.6) will be called a limit measure (associated to the function ϕ and the sequence $\{E_n : n \geq 1\}$).

In order to find conformal measures among the limit measures, it is necessary to examine (11.1.7) in greater detail. To begin with, for a Borel set $D \subset X$, consider the following condition

$$\lim_{s\downarrow c}\frac{1}{M_s}\sum_{n=1}^{\infty}\sum_{x\in D\cap(E_{n+1}\setminus T^{-1}E_n)} b_n\exp[S_n\phi(T(x)) - ns] = 0. \qquad (11.1.9)$$

We will need the following definitions.

A point $x \in X$ is said to be singular for T if at least one of the following two conditions is satisfied:

There is no open neighbourhood U of x such that $T|_U$ is injective.
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (11.1.10)$$
$\forall_{\varepsilon>0}\exists_{0<r<\varepsilon}$ such that $T(B(x,r))$ is not an open subset of X.   (11.1.11)

The set of all singular points is denoted by $\mathrm{Sing}(T)$, the set of all points satisfying condition (11.1.10) is denoted by $\mathrm{Crit}(T)$ and the set of all points satisfying condition (11.1.11) is denoted by $X_0(T)$.

It is easy to give examples where $X_0 \cap \mathrm{Crit}(T) \neq \emptyset$. If $T : X \to X$ is an open map, no point satisfies condition (11.1.11) that is $X_0(T) = \emptyset$.

Lemma 11.1.3. *Let m be a Borel probability measure on X and let Γ be a compact set containing $\mathrm{Sing}(T)$. If (11.1.1) for g integrable holds for every special set A whose closure is disjoint from Γ and such that $m(\partial A) = m(\partial T(A)) = 0$, then (11.1.1) continues to hold for every special set A disjoint from Γ.*

Proof. Let A be a special set disjoint from Γ. Fix $\varepsilon > 0$. Since on the complement of Γ the map T is open, for each point $x \in A$ there exists an open neighbourhood $U(x)$ of x such that $T|_{U(x)}$ is a homeomorphism, $m(\partial U(x)) = m(\partial T(U(x))) = 0$, $\overline{U(x)} \cap \Gamma = \emptyset$ and such that

$$\int_{\cup U(x) \setminus A} g \, dm < \varepsilon$$

Choose a countable family $\{U_k\}$ from $\{U(x)\}$ which covers A and define recursively $A_1 = U_1$ and $A_n = U_n \setminus \bigcup_{k<n} U_k$. By the assumption of the lemma, each set A_k satisfies (10.1.1) and hence

$$m(T(A)) = m\left(\bigcup_{k=1}^{\infty} T(A \cap A_k) \right) \leq \sum_{k=1}^{\infty} m(T(A_k))$$

$$= \sum_{k=1}^{\infty} \int_{A_k} g \, dm = \int_A g \, dm + \sum_{k=1}^{\infty} \int_{A_k \setminus A} g \, dm$$

$$\leq \int_A g \, dm + \varepsilon.$$

If $\varepsilon \to 0$, it follows that

$$m(T(B)) \leq \int_B g \, dm$$

for any special set B disjoint from Γ. Using this fact, the lower bound for $m(T(A))$ is obtained from the following estimate, if $\varepsilon \to 0$:

$$m(T(A)) = m\left(\bigcup_{k=1}^{\infty} T(A \cap A_k) \right) = \sum_{k=1}^{\infty} m(T(A \cap A_k))$$

$$= \sum_{k=1}^{\infty} \left(m(T(A_k)) - m(T(A_k \setminus A)) \right) \geq \sum_{k=1}^{\infty} \int_{A_k} g \, dm - \int_{A_k \setminus A} g \, dm$$

$$= \int_{\cup_{k \geq 1} A_k} g \, dm - \int_{\cup_{k \geq 1} A_k \setminus A} g \, dm \geq \int_A g \, dm - \varepsilon.$$

This proves the lemma. ♣

Lemma 11.1.4. *Let $\phi : X \to \mathbb{R}$ be a function of bounded absolute value and m be a limit measure as above, and let Γ be a compact set containing $\mathrm{Sing}(T)$. Assume that every special set $D \subset X$ with $m(\partial D) = m(\partial T(D)) = 0$ and $\bar{D} \cap \Gamma = \emptyset$ satisfies condition (11.1.9). Then $m(T(A)) = \int_A \exp(c - \phi) \, dm$ for every special set A disjoint from Γ.*

Proof. Let $D \subset X$ be a special set such that $\bar{D} \cap \Gamma = \emptyset$ and $m(\partial D) = m(\partial T(D)) = 0$. It follows immediately from (11.1.7)–(11.1.9) that $m(T(D)) = \int_D \exp(c - \phi) \, dm$. Applying now Lemma 11.1.3 completes the proof.   ♣

Lemma 11.1.5. *Let m be a limit measure. If condition (11.1.9) is satisfied for $D = X$, then $m(T(A)) \geq \int_A \exp(c - f) \, dm$ for every special set A disjoint from $\mathrm{Crit}(T)$.*

Proof. Suppose first that A is compact and $m(\partial A) = 0$. From (10.1.7), (11.1.8) and the assumption one obtains

$$\lim_{s \in J} |m_s(T(A)) - \int_A \exp(c - \phi) \, dm_s| = 0$$

where J denotes the subsequence along which m_s converges to m. Since $T(A)$ is compact, this implies

$$m(T(A)) \geq \liminf_{s \in J} m_s(T(A)) = \lim_{s \in J} \int_A \exp(c - \phi) \, dm_s = \int_A \exp(c - \phi) \, dm$$

Now, drop the assumption $m(\partial A) = 0$ but keep A compact and assume additionally that for some $\varepsilon > 0$ the ball $B(A, \varepsilon)$ is also special. Choose a descending sequence A_n of compact subsets of $B(A, \varepsilon)$ whose intersection equals A and $m(\partial A_n) = 0$ for every $n \geq 0$. By what has been already proved

$$m(T(A)) = \lim_{n \to \infty} m(T(A_n)) \geq \int_{A_n} \exp(c - \phi) \, dm = \int_A \exp(c - \phi) \, dml$$

The next step is to prove the lemma for A, an arbitrary open special set disjoint from $\mathrm{Crit}(T)$ by partitioning it by countably many compact sets. Then one approximates from above special sets of sufficiently small diameters by special open sets and the last step is to partition an arbitrary special set disjoint from $\mathrm{Crit}(T)$ by sets of so small diameters that the lemma holds.   ♣

Lemma 11.1.6. *Let Γ be a compact subset of X containing $\mathrm{Sing}(T)$. Suppose that for every integer $n \geq 1$ there are a continuous function $g_n : X \to X$ and a measure m_n on X satisfying (11.1.1) for $g = g_n$ and for every special set $A \subset X$ with*

$$\overline{A} \cap \Gamma = \emptyset \tag{a}$$

and satisfying

$$m_n(B) \geq \int_B g_n \, dm_n$$

for any special set $B \subset X$ such that $B \cap \mathrm{Crit}(T) = \emptyset$. Suppose, moreover, that the sequence $\{g_n\}_{n=1}^\infty$ converges uniformly to a continuous function $g : X \to \mathbb{R}$. Then for any weak accumulation point m of the sequence $\{m_n\}_{n=1}^\infty$ we have

$$m(T(A)) = \int_A g \, dm \tag{b}$$

for all special sets $A \subset X$ such that $A \cap \Gamma = \emptyset$ and

$$m(T(B)) \geq \int_B g \, dm \tag{c}$$

for all special sets $B \subset X$ such that $B \cap \mathrm{Crit}(T) = \emptyset$.
    Moreover, if (a) is replaced by

$$\overline{A} \cap (\Gamma \setminus (\mathrm{Crit}(T) \setminus X_0(T))) = \emptyset, \tag{a'}$$

then for any $x \in \mathrm{Crit}(T) \setminus X_0(T)$

$$m(\{T(x)\}) \leq g(x)m(\{x\}) \leq q(x)m(\{T(x)\}) \tag{d}$$

where $q(x)$ denotes the maximal number of preimages of single points under the transformation T restricted to a sufficiently small neighbourhood of x.

The proof of property (b) is a simplification of the proof of Lemma 11.1.4 and the proof of property (c) is a simplification of the proof of Lemma 11.1.5. The proof of (d) uses the same technics and is left for the reader.

11.2 Sullivan's conformal measures and dynamical dimension, I

Let, as in Chapter 10, X denote a compact subset of the extended complex plane $\overline{\mathbb{C}}$ and let $f \in \mathcal{A}(X)$ which means that $f : X \to X$ is a continuous map that can be analytically extended to an open neighbourhood $U(f)$ of X.
    Let $t \geq 0$. Any $|f'|^t$–conformal measure for $f : X \to X$ is called a t–conformal Sullivan's measure or even shorter a t–conformal measure. Rewriting the definition (11.1.1) it means that

$$m(f(A)) = \int_A |f'|^t \, dm \tag{11.2.1}$$

for every special set $A \subset X$. An obvious but important property of conformal measures is formulated in the following

Lemma 11.2.1. *If $f : X \to X$ is topologically exact, then every Sullivan's conformal measure is positive on nonempty open sets of X.*

In particular it follows from this lemma that if f is topologically exact, then for every $r > 0$
$$M(r) = \inf\{m(B(x, r)) : x \in X\} > 0 \tag{11.2.2}$$

Denote by $\delta(f)$ the infinium over all exponents $t \geq 0$ for which a t–conformal measure for $f : X \to X$ exists.
    Our aim in the two subsequent sections is to show the existence of conformal measures and moreover to establish more explicit dynamical characterization of the number $\delta(f)$. As a matter of fact we are going to prove that under some

additional assumptions $\delta(f)$ coincides with the dynamical dimension $\mathrm{DD}(X)$ of X and the hyperbolic dimension $\mathrm{HyD}(X)$ of X which are defined as follows.

$$\mathrm{DD}(X) = \sup\{\mathrm{HD}(\mu) : \mu \in M_e^+(f)\}$$
$$\mathrm{HyD}(X) = \sup\{\mathrm{HD}(Y) : f|_Y \text{ is a conformal expanding repeller}\}$$

In HyD one can even restrict to Y being topological Cantor sets.

In this section we shall prove the following two results.

Lemma 11.2.2. *If $f : X \to X$ is topologically exact, then $\mathrm{DD}(X) \le \delta(f)$.*

Proof. Our main idea "to get to a large scale" is the same as in [Denker & Urbański 1991b]. However to carry it out we use Pesin theory described in Sec. 9.2 instead of Mañé's partition, applied in [Denker & Urbański 1991b]. So, let $\mu \in M_e^+(f)$ and let m be a t–conformal measure. We again work in the natural extension $(\tilde{X}, \tilde{f}, \tilde{\mu})$. Fix $\varepsilon > 0$ and let $\tilde{X}(\varepsilon)$ and $r(\varepsilon)$ be given by Corollary 10.2.4. In view of the Birkhoff ergodic theorem there exist a measurable set $\tilde{F}(\varepsilon) \subset \tilde{X}(\varepsilon)$ such that $\tilde{\mu}(\tilde{F}(\varepsilon)) = \tilde{\mu}(\tilde{X}(\varepsilon))$ and an increasing sequence $\{n_k = n_k(\tilde{x}) : k \ge 1\}$ such that $\tilde{f}^{n_k}(\tilde{x}) \in \tilde{X}(\varepsilon)$ for every $k \ge 1$. Let $F(\varepsilon) = \pi(\tilde{F}(\varepsilon))$. Then $\mu(F(\varepsilon)) = \tilde{\mu}(\pi^{-1}(F(\varepsilon)) \ge \tilde{\mu}(\tilde{F}(\varepsilon)) \ge 1 - 2\varepsilon$. Consider now $x \in F(\varepsilon)$ and take $\tilde{x} \in \tilde{F}(\varepsilon)$ such that $x = \pi(\tilde{x})$. Since $\tilde{f}^{n_k}(\tilde{x}) \in \tilde{X}(\varepsilon)$ and since $\pi(\tilde{f}^{n_k}(\tilde{x}) = f^{n_k}(x)$, Corollary 10.2.4 produces a holomorphic inverse branch $f_x^{-n_k} : B(f^{n_k}(x), r(\varepsilon)) \to \overline{\mathbb{C}}$ of f^{n_k} such that $f_x^{-n_k} f^{n_k}(x) = x$ and

$$f_x^{-n_k}\big(B(f^{n_k}(x), r(\varepsilon))\big) \subset B\big(x, K|(f^{n_k})'(x)|^{-1}r(\varepsilon)\big)$$

Set $r_k(x) = K|(f^{n_k})'(x)|^{-1}r(\varepsilon)$. Then by Corollary 10.2.4 and $t-$ conformality of m

$$m(B(x, r_k(x))) \ge K^{-t}|(f^{n_k})'(x)|^{-t}m\big(B(f^{n_k}(x), r(\varepsilon))\big)$$
$$\ge M(r(\varepsilon))^{-1}K^{-2t}r(\varepsilon)^{-t}r_k(x)^t$$

Therefore, it follows from Theorem 7.5.1 (Besicovitch covering theorem) that $\Lambda_t(F(\varepsilon)) \le M(r(\varepsilon))K^{2t}r(\varepsilon)^t b(2) < \infty$. Hence $\mathrm{HD}(F(\varepsilon)) \le t$. Since $\mu\big(\bigcup_{n=1}^\infty F(1/n)\big) = 1$, it implies that $\mathrm{HD}(\mu) \le t$. This finishes the proof. ♣

Theorem 11.2.3. *If $f : X \to X$ is topologically exact and X is a repelling set for f, then $\mathrm{HyD}(X) = \mathrm{DD}(X)$.*

Proof. In order to see that $\mathrm{HyD}(X) \le \mathrm{DD}(X)$ notice only that in view of Theorems 4.3.2, 8.1.6 and Corollary 8.1.7 there exists $\mu \in M_e^+(f|_Y) \subset M_e^+(f)$ such that $\mathrm{HD}(\mu) = \mathrm{HD}(Y)$. In order to prove that $\mathrm{DD}(X) \le \mathrm{HyD}(X)$ we will use Katok's theory from Section 10.6 applied to μ, an arbitrary ergodic invariant measure of positive entropy. First, for every integer $n \ge 0$ define on X a new continuous function

$$\phi_n = \max\{-n, \log|f'|\}.$$

Then $\phi_n \ge \log|f'|$ and $\phi_n \searrow \log|f'|$ pointwise on X. Since in addition $\phi_n \le \log\|f'\|_\infty$, it follows from the Lebesgue monotone convergence theorem that

$\lim_{n\to\infty} \int \phi_n \, d\mu = \chi_\mu(f) = \int \log |f'| \, d\mu > 0$. Fix $\varepsilon > 0$. Then for all n sufficiently large, say $n \geq n_0$, $\int \phi_n d\mu \leq \chi_\mu/(1-\varepsilon)$ which implies that

$$h_\mu(f) = HD(\mu)\chi_\mu \geq (1-\varepsilon) HD(\mu) \int \phi_n \, d\mu. \qquad (11.2.3)$$

Fix such $n \geq n_0$. Let $X_k \subset X$, $k \geq 0$, be the sequence of conformal expanding repellers produced in Theorem 10.6.1 for the measure μ and the function $-HD(\mu)\phi_n$ and let μ_k be an equilibrium state of the map $f|_{X_k}$ and the potential $-HD(\mu)\phi_n$ restricted to X_k. It follows from the second part of Theorem 10.6.1 that $\lim_{k\to\infty} \int \phi_n \, d\mu_k = \int \phi_n \, d\mu > 0$. Thus by Theorem 10.6.1 and (11.2.3)

$$\liminf_{k\to\infty} \left(h_{\mu_k} - HD(\mu) \int \phi_n \, d\mu_k \right) = \liminf_{k\to\infty} P\left(f|_{X_k}, -HD(\mu)\phi_n \right)$$

$$\geq h_\mu(f) - HD(\mu) \int \phi_n \, d\mu$$

$$\geq -\varepsilon \, HD(\mu) \int \phi_n \, d\mu$$

Hence, for all k large enough

$$h_{\mu_k} \geq HD(\mu) \int \phi_n \, d\mu_k - 2\varepsilon \, HD(\mu) \int \phi_n \, d\mu$$

$$\geq HD(\mu) \int \phi_n \, d\mu_k - 3\varepsilon \, HD(\mu) \int \phi_n \, d\mu_k$$

$$= (1-3\varepsilon) HD(\mu) \int \phi_n \, d\mu_k \geq (1-3\varepsilon) HD(\mu) \int \log |f'| \, d\mu_k.$$

Thus

$$HD(X_k) \geq HD(\mu_k) = \frac{h_{\mu_k}(f)}{\chi_{\mu_k}} \geq (1-3\varepsilon) HD(\mu).$$

So, letting $\varepsilon \to 0$ finishes the proof. ♣

11.3 Sullivan's conformal measures and dynamical dimension, II

In this section $f : \overline{\mathbb{C}} \to \overline{\mathbb{C}}$ is assumed to be a rational map of degree ≥ 2 and X is its Julia set $J(f)$. Neverthless it is worth to mention that some results proved here continue to hold under weaker assumption that $f|_X$ is open or X is a perfect locally maximal set for f. By $Crit(f)$ we denote the set of all critical points contained in the Julia set $J(f)$.

Lemma 11.3.1. *If $z \in J(f)$ and $\overline{\{f^n(z) : n \geq 0\}} \cap Crit(f) = \emptyset$, then the series $\sum_{n=1}^\infty |(f^n)'(z)|^{\frac{1}{3}}$ diverges.*

Proof. By the assumption there exists $\varepsilon > 0$ such that for every $n \geq 0$ the map f restricted to the ball $B(f^n(z), \varepsilon)$ is injective. Since f is uniformly continuous there exists $0 < \alpha < 1$ such that for every $x \in \overline{\mathbb{C}}$

$$f(B(x, \alpha\varepsilon)) \subset B(f(x), \varepsilon). \tag{11.3.1}$$

Suppose that the series $\sum_{n=1}^{\infty} |(f^n)'(z)|^{\frac{1}{3}}$ converges. Then there exists $n_0 \geq 1$ such that $\sup_{n \geq n_0}(2|(f^n)'(z)|)^{\frac{1}{3}} < 1$. Choose $0 < \varepsilon_1 = \varepsilon_2 = \ldots = \varepsilon_{n_o} < \alpha\varepsilon$ so small that for every $n = 1, 2, \ldots, n_0$

$$f^n \text{ restricted to the ball } B(z, \varepsilon_n) \text{ is injective.} \tag{11.3.2}$$

and

$$f^n(B(z, \varepsilon_n)) \subset B(f^n(z), \varepsilon) \tag{11.3.3}$$

For every $n \geq n_0$ define ε_{n+1} inductively by

$$\varepsilon_{n+1} = (1 - (2|(f^n)'(z)|)^{\frac{1}{3}})\varepsilon_n. \tag{11.3.4}$$

Then $0 < \varepsilon_n < \alpha\varepsilon$ for every $n \geq 1$. Assume that (11.3.2) and (11.3.3) are satisfied for some $n \geq n_0$. Then by the Koebe Distortion Lemma 5.2.4 and (11.3.4) the set $f^n(B(z, \varepsilon_{n+1}))$ is contained in the ball centered at $f^n(z)$ and of radius

$$\varepsilon_{n+1}|(f^n)'(z)| \frac{2}{(1 - \varepsilon_{n+1}/\varepsilon_n)^3} = \frac{2\varepsilon_{n+1}|(f^n)'(z)|}{2|(f^n)'(z)|} = \varepsilon_{n+1} < \alpha\varepsilon.$$

Therefore, since f is injective on $B(f^n(z), \varepsilon)$, formula (11.3.2) is satisfied for $n + 1$ and using also (11.3.1) we get

$$f^{n+1}(B(z, \varepsilon_{n+1})) = f\big(f^n(B(z, \varepsilon_{n+1}))\big) \subset f(B(f^n(z), \alpha\varepsilon)) \subset B(f^{n+1}(z), \varepsilon).$$

Thus (11.3.3) is satisfied for $n + 1$.

Let $\varepsilon_n \searrow \varepsilon_0$. Since the series $\sum_{n=1}^{\infty} |(f^n)'(z)|^{\frac{1}{3}}$ converges, it follows from (10.3.4) that $\varepsilon_0 > 0$. Clearly (11.3.2) and (11.3.3) remain true with ε_n replaced by ε_0. It follows that the family $\{f^n|_{B(z,\frac{1}{2}\varepsilon_0)}\}_{n=1}^{\infty}$ is normal and consequently $z \notin J(f)$. This contradiction finishes the proof. ♣

As an immediate consequence of this lemma and of Birkhoff's Ergodic Theorem we get the following.

Corollary 11.3.2. *If μ be an ergodic f–invariant measure for which there exists a compact set $Y \subset J(f)$ such that $\mu(Y) = 1$ and $Y \cap Crit(f) = \emptyset$, then $\chi_\mu \geq 0$.*

In fact the assumption $Y \cap Crit(f) = \emptyset$ is not needed, see [Przytycki 1993]. Compare Theorem 11.3.10.

Let now Ω be a finite subset of $\overline{\bigcup_{n=1}^{\infty} f^n(\mathrm{Crit}(f))}$ such that

$$\Omega \cap \overline{\{f^n(c) : n = 1, 2 \ldots\}} \neq \emptyset \qquad \text{for every } c \in \mathrm{Crit}(f) \tag{11.3.5}$$

and
$$\Omega \cap \mathrm{Crit}(f) = \emptyset. \tag{11.3.6}$$

Sets satisfying these conditions exist since no critical point of f lying in $J(f)$ can be periodic. Now let $V \subset J(f)$ be an open neighbourhood of Ω and define $K(V)$ to be the set of those points of $J(f)$ whose forward trajectory avoids V. Equivalently this means that

$$K(V) = \{z \in J(f) : f^n(z) \notin V \text{ for every } n \geq 0\} = \bigcap_{n=0}^{\infty} f^{-n}(J(f) \setminus V)$$

Hence $K(V)$ is a compact subset of $J(f)$ and $f(K(V)) \subset K(V)$. Consequently we can consider dynamical system $f|_{K(V)} : K(V) \to K(V)$. Note that $f(K(V)) = K(V)$ does not hold for all sets V and that usually $f^{-1}(K(V)) \not\subset K(V)$. Simple considerations based on (10.3.5) and the definition of sets $K(V)$ give the following.

Lemma 11.3.3. $\mathrm{Crit}(f|_{K(V)}) \subset \mathrm{Crit}(f) \cap K(V) = \emptyset$, $K(V)_0(f) = \mathrm{Sing}(f) \subset \partial V$, and $-t \log|f'|$ is a well–defined continuous function on $K(V)$.

Fix now $z \in K(V)$ and set $E_n = f|_{K(V)}^{-n}(z)$, $n \geq 0$. Then $E_{n+1} = f|_{K(V)}^{-1}(E_n)$ and therefore the sequence $\{E_n\}$ satisfies (10.1.9) with $D = K(V)$. Take $t \geq 0$ and let $c(t, V)$ be the transition parameter associated to this sequence and the function $-t \log|f'|$. Put $\mathrm{P}(t, V) = \mathrm{P}(f|_{K(V)}, -t \log|f'|)$. We shall prove the following.

Lemma 11.3.4. $c(t, V) \leq \mathrm{P}(t, V)$.

Proof. Since $K(V)$ is a compact set disjoint from $\mathrm{Crit}(f)$, the map $f|_{K(V)}$ is locally 1-to-1 which means that there exists $\delta > 0$ such that $f|_{K(V)}$ restricted to any set with diameter $\leq \delta$ is 1-to-1. Consequently, all the sets E_n are (n, ε)-separated for $\varepsilon < \delta$. Hence, the required inequality $c(t, V) \leq \mathrm{P}(t, V)$ follows immediately from Theorem 2.3.2. ♣

The standard straightforward arguments showing continuity of topological pressure prove also the following.

Lemma 11.3.5. *The function* $t \mapsto c(t, V)$ *is continuous.*

Set
$$s(V) = \inf\{t \geq 0 : c(t, V) \leq 0\} < +\infty$$

We shall prove the following.

Lemma 11.3.6. $s(V) \leq \mathrm{DD}(J(f))$.

Proof. Suppose that $\mathrm{DD}(J(f)) < s(V)$ and take $0 \leq \mathrm{DD}(J(f)) < t < s(V)$. From this choice and by Lemma 11.3.4 we have $0 < c(t, V) \leq \mathrm{P}(t, V)$ and by the Variational Principle, Theorem 2.4.1, there exists $\mu \in M_e(f_{K(V)}) \subset M_e(f)$ such that $\mathrm{P}(t, V) \leq \mathrm{h}_\mu(f) - t\chi_\mu(f) + c(t, V)/2$. Therefore, by Corollary 11.3.2 and Lemma 11.3.3 we get $\mathrm{h}_\mu(f) \geq c(t, V)/2 > 0$ and applying additionally

Theorem 10.1.1 (Ruelle's inequality), $\chi_\mu(f) > 0$. Hence, it follows from Theorem 10.4.1 that

$$t \leq \mathrm{HD}(\mu) - \frac{1}{2}\frac{c(t,V)}{\chi_\mu} < \mathrm{HD}(\mu) \leq \mathrm{DD}(J(f))$$

This contradiction finishes the proof.   ♣

Let m be a limit measure on $K(V)$ associated to the sequence E_n and the function $-s(V)\log|f'|$. Since $c(0,V) \geq 0$ and $s(V) < \infty$, it follows from Lemma 11.3.5 that $c(s(V),V) = 0$. Therefore, applying Lemma 11.1.4 and Lemma 11.1.5 with $\Gamma = \partial V$ we see that $m(f(A)) \geq \int_A |f'|^{s(V)}\,dm$ for any special set $A \subset K(V)$ and $m(f(A)) = \int_A |f'|^{s(V)}\,dm$ for any special set $A \subset K(V)$ such that $A \cap \partial V = \emptyset$. Treating now m as a measure on $J(T)$ and using straightforward measure–theoretic arguments we deduce from this that

$$m(f(A)) \geq \int_A |f'|^{s(V)}\,dm \qquad\qquad (11.3.7)$$

for any special set $A \subset J(f)$ and

$$m(f(A)) = \int_A |f'|^{s(V)}\,dm \qquad\qquad (11.3.8)$$

for any special set $A \subset J(f)$ such that $A \cap \bar{V} = \emptyset$. Now we are in position to prove the following.

Lemma 11.3.7. *For every Ω there exist $0 \leq s(\Omega) \leq \mathrm{DD}(J(f))$ and a Borel probability measure m on $J(f)$ such that*

$$m(f(A)) \geq \int_A |f'|^{s(\Omega)}\,dm$$

for any special set $A \subset J(f)$ and

$$m(f(A)) = \int_A |f'|^{s(\Omega)}\,dm$$

for any special set $A \subset J(f)$ disjoint from Ω.

Proof. For every $n \geq 1$ let $V_n = B(\Omega, \frac{1}{n})$ and let m_n be the measure on $J(f)$ satisfying (11.3.7) and (11.3.8) for the neighbourhood V_n. Using Lemma 11.1.6 we shall show that any weak–* limit m of the sequence of measures $\{m_n\}_{n=1}^\infty$ satisfies the requirements of Lemma 11.3.7. Indeed, first observe that the sequence $\{s(V_n)\}_{n=1}^\infty$ is nondecreasing and denote its limit by $s(\Omega)$. Therefore the sequence of continuous functions $g_n = |f'|^{s(V_n)}$, $n = 1, 2, \ldots$, defined on $J(f)$ converges uniformly to the continuous function $g = |f'|^{s(\Omega)}$. Let A be a special subset of $J(f)$ such that

$$\overline{A} \cap (\mathrm{Sing}(f) \cup \Omega) = \emptyset. \qquad\qquad (11.3.9)$$

Then one can find a compact set $\Gamma \subset J(f)$ disjoint from $\overline{A}$ and such that $\text{Int}(\Gamma) \supset \text{Sing}(f) \cup \Omega$. So, using also Lemma 11.3.3, we see that for any n sufficiently large, say $n \geq q$,

$$\overline{V_n} \subset \Gamma \qquad \text{and} \qquad \overline{V_n} \cap \text{Crit}(f) = \emptyset. \tag{11.3.10}$$

Therefore, by (11.3.7) and (11.3.8), we conclude that Lemma 11.1.6 applies to the sequence of measures $\{m_n\}_{n=q}^\infty$ and the sequence of functions $\{g_n\}_{n=q}^\infty$. Hence, the first property required in our lemma is satisfied for any special subset of $J(f)$ disjoint from $\text{Crit}(f)$ and since $A \cap \Gamma = \emptyset$, the second property is satisfied for the set A. So, since any special subset of $J(f)$ disjoint from $\text{Sing}(f) \cup \Omega$ can be expressed as a disjoint union of special sets satisfying (11.3.9), an easy computation shows that the second property is satisfied for all special sets disjoint from $\text{Sing}(f) \cup \Omega$. Therefore, in order to finish the proof, it is enough to show that the second requirement of the lemma is satisfied for every point of the set $\text{Sing}(f)$. First note that by (11.3.10) and (11.3.8), formula (a') in Lemma 11.1.6 is satisfied for every $n \geq q$ and every $x \in \text{Crit}(f) \setminus J(f)_0(f)$. As $f : J(f) \to J(f)$ is an open map, the set $J(f)_0(f)$ is empty and $\text{Sing}(f) = \text{Crit}(f)$. Consequently formula (d) of Lemma 10.1.6 is satisfied for any critical point $c \in J(f)$ of f. Since $g(c) = |f'(c)|^{s(\Omega)} = 0$, this formula implies that $m(f()) \leq 0$. Thus $m(\{f(c)\}) = 0 = |f'(c)|^{s(\Omega)} m(\{c\})$. The proof is finished. ♣

Lemma 11.3.8. *Let m be a the me the measure constructed in Lemma 11.3.7. If for some $z \in J(f)$ the series $S(t, z) = \sum_{n=1}^\infty |(f^n)'(z)|^t$ diverges then $m(\{z\}) = 0$ or a positive iteration of z is a parabolic point of f. Moreover, if z itself is periodic then $m(\{f(z)\}) = |f'(z)|^t m(\{z\})$.*

Proof. Suppose that $m(\{z\}) > 0$. Assume first that the point z is not eventually periodic. Then by the definition of a conformal measure on the complement of some finite set we get $1 \geq m(\{f^n(z) : n \geq 1\}) \geq m(\{z\}) \sum_{n=1}^\infty |(f^n)'(z)|^t = \infty$, which is a contradiction. Hence z is eventually periodic and therefore there exist positive integers k and q such that $f^k(f^q(z)) = f^q(z)$. Since $f^q(z) \in J(f)$ and since the family of of all iterates of f on a sufficiently small neighbourhood of an attractive periodic point is normal, this implies that $|(f^k)'(f^q(z))| \geq 1$. If $|(f^k)'(f^q(z))| = \lambda > 1$ then, again by the definition of a conformal measure on the complement of some finite set, $m(\{f^q(z)\}) > 0$ and $m(\{f^{kn}(f^q(z))\}) \geq \lambda^{nt} m(\{f^q(z)\})$. Thus $m(\{f^{kn}(f^q(z))\})$ converges to ∞, which is a contradiction. Therefore $|(f^k)'(f^q(z))| = 1$ which finishes the proof of the first assertion of the lemma. In order to prove the second assertion assume that $q = 1$. Then, using the definition of conformal measures on the complement of some finite set again, we get $m(\{f(z)\}) \geq m(\{z\})|f'(z)|^t$ and on the other hand

$$m(\{z\}) = m(\{f^{k-1}(f(z))\}) \geq m(\{f(z)\})|(f^{k-1})'(f(z))|^t = m(\{f(z)\})|f'(z)|^{-t}.$$

Therefore $m(\{f(z)\}) = m(\{z\})|f'(z)|^t$. The proof is finished. ♣

Corollary 11.3.9. *If for every $x \in \text{Crit}(f)$ one can find $y(x) \in \overline{\{f^n(x) : n \geq 0\}}$ such that the series $S(t, y(x))$ diverges for every $0 \leq t \leq \text{DD}(J(f))$, then there exists an s-conformal measure for $f : J(f) \to J(f)$ with $0 \leq s \leq \text{DD}(J(f))$.*

Proof. Let m be a the me the measure constructed in Lemma 11.3.7. Since $S(t, y(x))$ diverges for every $0 \leq t \leq \mathrm{DD}(J(f))$, we see that $y(x) \notin \mathrm{Crit}(f)$. If for some $x \in \mathrm{Crit}(f)$, $y(x)$ is a non-periodic point eventually falling into a parabolic point, then let $z(x)$ be this parabolic point; otherwise put $z(x) = y(x)$. The set $\Omega = \{z(x) : x \in \mathrm{Crit}(f)\}$ meets the conditions (11.3.5), (11.3.6) and is contained in $\bigcup_{n=1}^{\infty} f^n(\mathrm{Crit}(f))$. Since for every $t \geq 0$ and $z \in J(f)$ the divergence of the series $S(t, z)$ implies the divergence of the series $S(t, f(z))$, it follows immediately from Lemma 11.3.7 and Lemma 11.3.8 that the measure m is s-conformal.   ♣

Fortunately the assumptions on the existence of $y(x)$ with the divergence of $(t, y(x))$ hold. They follow from the following fact, for which we refer the reader to [Przytycki 1993] and omit the proof here.

Theorem 11.3.10. *For every f-invariant probability measure μ on $J(f)$, $\int \log |f'| \, d\mu \geq 0$, in particular $\log |f'|$ is μ-integrable. For μ ergodic this reads that the Lyapunov characteristic exponent is non-negative, $\chi_\mu(f) \geq 0$. For μ a.e. y*

$$\limsup_{n \to \infty} |(f^n)'(y)| \geq 1.$$

Now we are in position to finish the proof the following main result of this section.

Theorem 11.3.11. $\mathrm{HyD}(J(f)) = \mathrm{DD}(J(f)) = \delta(f)$ *and there exists a $\delta(f)$-conformal measure for $f : J(f) \to J(f)$.*

Proof. For every $x \in \mathrm{Crit}(f)$ the set $\overline{\{f^n(x) : n \geq 0\}}$ is closed and forward invariant under f. Therefore, in view of Theorem 2.1.8 (Bogolubov-Krylov theorem) there exists $\mu \in M_e(f)$ supported on $\overline{\{f^n(x) : n \geq 0\}}$. By Theorem 11.3.10 there exists at least one point $y(x) \in \overline{\{f^n(x) : n \geq 0\}}$ such that $\limsup_{n \to \infty} |(f^n)'(y(x))| \geq 1$ and consequently the series $S(t, y(x))$ diverges for every $t \geq 0$. So, in view of Corollary 11.3.9 there exists an s-conformal measure for $f : J(f) \to J(f)$ with $0 \leq s \leq \mathrm{DD}(J(f))$. Combining this with Lemma 11.2.2 and Theorem 11.2.3 complete the proof.   ♣

11.4   Pesin's formula

follows.

Theorem 11.4.1 (Pesin's formula)**.** *Assume that X is a compact subset of the closed complex plane $\overline{\mathbb{C}}$ and that $f \in \mathcal{A}(X)$. If m is a t- conformal measure for f and $\mu \in M_e^+(f)$ is absolutely continuous with respect to m, then $\mathrm{HD}(\mu) = t = \delta(f)$.*

Proof. In view of Lemma 11.2.2 we only need to prove that $t \leq \mathrm{HD}(\mu)$ and in order to do this we essentially combine the arguments from the proof of Lemma 11.2.2 and from the proof of formula (10.4.1). So, we work in the

natural extension $(\tilde{X}, \tilde{f}, \tilde{\mu})$. Fix $0 < \varepsilon < \chi_\mu/3$ and let $\tilde{X}(\varepsilon)$ and $r(\varepsilon)$ be given by Corollary 10.2.4. In view of the Birkhoff ergodic theorem there exists a measurable set $\tilde{F}(\varepsilon) \subset \tilde{X}(\varepsilon)$ such that $\tilde{\mu}(\tilde{F}(\varepsilon)) \geq 1 - 2\varepsilon$ and

$$\lim_{n \to \infty} \frac{1}{n} \sum_{j=1}^{n-1} \chi_{\tilde{X}(\varepsilon)} \circ \tilde{f}^n(\tilde{x}) = \tilde{\mu}(\tilde{X}(\varepsilon))$$

for every $\tilde{x} \in \tilde{F}(\varepsilon)$. Let $F(\varepsilon) = \pi(\tilde{F}(\varepsilon))$. Then $\mu(F(\varepsilon)) = \tilde{\mu}(\pi^{-1}(F(\varepsilon)) \geq \tilde{\mu}(\tilde{F}(\varepsilon)) \geq 1 - 2\varepsilon$. Consider now $x \in F(\varepsilon) \cap X_o$ and take $\tilde{x} \in \tilde{F}(\varepsilon)$ such that $x = \pi(\tilde{x})$. Then by the above there exists an increasing sequence $\{n_k = n_k(x) : k \geq 1\}$ such that $\tilde{f}^{n_k}(\tilde{x}) \in \tilde{X}(\varepsilon)$ and

$$\frac{n_{k+1} - n_k}{n_k} \leq \varepsilon \tag{11.4.1}$$

for every $k \geq 1$. Moreover Corollary 10.2.4 produces holomorphic inverse branches $f_x^{-n_k} : B(f^{n_k}(x), r(\varepsilon)) \to \overline{\mathbb{C}}$ of f^{n_k} such that $f_x^{-n_k} f^{n_k}(x) = x$ and

$$f_x^{-n_k}\big(B(f^{n_k}(x), r(\varepsilon))\big) \subset B\big(x, K|(f^{n_k})'(x)|^{-1} r(\varepsilon)\big)$$

Set $r_k = r_k(x) = K^{-1}|(f^{n_k})'(x)|^{-1} r(\varepsilon)$. By Corollary 10.2.4 $r_k \leq K^{-2} \exp\big(-(\chi_\mu - \varepsilon)n_k\big) r(\varepsilon)$. So, using Corollary 10.2.4 again and (11.4.1) we can estimate

$$r_k = r_{k+1} |(f^{n_{k+1}-n_k})'(f^{n_k}(x))| \leq r_{k+1} K \exp\big(\chi_\mu + \varepsilon)(n_{k+1} - n_k)\big)$$
$$\leq r_{k+1} K \exp\big(\chi_\mu + \varepsilon)n_{k+1}\varepsilon\big) \leq K r_{k+1} \exp\big(\chi_\mu - \varepsilon)2n_{k+1}\varepsilon\big)$$
$$\leq r_{k+1} K (K^{-2} r(\varepsilon) r_{k+1}^{-1})^{2\varepsilon} = K^{1-4\varepsilon} r(\varepsilon)^{2\varepsilon} r_{k+1}^{1-2\varepsilon}$$

Take now any $0 < r \leq r_1$ and find $k \geq 1$ such that $r_{k+1} < r \leq r_k$. Then using this estimate, t-conformality of m, and invoking Corollary 10.2.4 once more we get

$$m(B(x,r)) \leq m(B(x, r_k)) \leq K^t |(f^{n_k})'(x)|^{-t} m(B(x, r(\varepsilon)))$$
$$\leq K^{2t} r(\varepsilon)^{-t} r_k^t$$
$$\leq K^{(3-4\varepsilon)t} r(\varepsilon)^{2\varepsilon t} r^{(1-2\varepsilon)t}$$

So, by Theorem 7.5.1 (Besicovitch covering theorem) $\Lambda_{(1-2\varepsilon)t}(X) \geq \Lambda_{(1-2\varepsilon)t}(F(\varepsilon)) > 0$, whence $\mathrm{HD}(X) \geq (1 - 2\varepsilon)t$. Letting $\varepsilon \to 0$ completes the proof. ♣

Remark 11.4.2. For m being the Riemann measure on $\overline{\mathbb{C}}$, which is 2-conformal by definition, $\mathrm{HD}(m) = 2$ is obvious, even without assuming the existence of μ.

Of course there exist 2-conformal measures for which no $\mu \in M_e^+(f)$ with $\mu \ll m$ exists. Take for example $f(z) = z^2 + 1/4$. It has a parabolic fixed point $z = 1/2$, as $f'(1/2) = 1$. Put $m(1/2) = 1$ and for each $n \geq 0$ and $w \in f^{-n}(1/2)$ put $m(w) = |(f^n)'(w)|^{-t}$. For $t \geq 2$ the series $\Sigma := \sum_{n,w} |(f^n)'(w)|^{-t}$ converges (Exercise, use Koebe Distortion Theorem). Normalize m by dividing by Σ. Check that there is no $\mu \in M_e^+$ with $\mu \ll m$. In this example, for $t = \delta(f)$, the measure μ exists. However it is also not always the case. Consider

$f(z) = z^2 - 3/4$ and m built as above starting from the fixed point $-1/2$. See [Aaronson, Denker & Urbański 1993]

Other, very nice examples can be found in [Avila & Lyubich 2008].

For an arbitrary 2-conformal m the equality $h_\mu(f)/\chi_\mu(f) = \mathrm{HD}(\mu) = 2$, i.e. $h_\mu(f) = 2\chi_\mu(f)$ is nontrivial. For m Riemann measure, the first equality is nontrivial. In higher dimension its analog is usually called Pesin formula, see [Mañé 1987]. It corresponds to Rohlin's equality in Theorem 1.9.7.

The following theorem converse to Theorem 11.4.1, holds. We formulate it for f a rational function on $\overline{\mathbb{C}}$ and X its Julia set. We shall not prove it here. We refer to [Ledrappier 1984] and recent [Dobbs 2008].

Theorem 11.4.3. *If m is a t-conformal measure supported on $J(f)$ for $f : \overline{\mathbb{C}} \to \overline{\mathbb{C}}$ a rational function of degree at least 2 on the Riemann sphere, and μ is an f-invariant ergodic probability measure on $J(f)$ of positive Lyapunov exponent such that $\mathrm{HD}(\mu) \geq t$, then $\mu \ll m$. Moreover the density $d\mu/dm$ is bounded away from 0. In particular μ is unique satisfying these properties.*

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11.5 More about geometric pressure and dimensions

Here we provide a simple proof of $\mathrm{HyD}(J(f)) = \delta(f)$, see Theorem 11.3.11 omitting the construction via the sets $K(V)$ and omitting Pesin's theory.

Let $f : \overline{\mathbb{C}} \to \overline{\mathbb{C}}$ be a rational mapping of degree $d \geq 2$ on the Riemann sphere $\overline{\mathbb{C}}$. Here we denote by $\mathrm{Crit} = \mathrm{Crit}(f)$ the set of all critical points in $\overline{\mathbb{C}}$, that is $f'(x) = 0$ for $x \in \mathrm{Crit}(f)$. The symbol $J = J(f)$ stands as before for the Julia set of f. Absolute values of derivatives and distances are considered with respect to the standard Riemann sphere metric. We consider pressures below for all $t > 0$. All the pressures will occur to coincide giving rise to a generalization of the geometric pressure $\mathrm{P}(t)$ introduced in Section 8.1 in the uniformly expanding case.

Definition 11.5.1 (Tree pressure). For every $z \in \overline{\mathbb{C}}$ define

$$\mathrm{P}_{\mathrm{tree}}(z, t) := \limsup_{n \to \infty} \frac{1}{n} \log \sum_{f^n(x) = z} |(f^n)'(x)|^{-t}.$$

Definition 11.5.2 (Hyperbolic pressure).

$$\mathrm{P}_{\mathrm{hyp}}(t) := \sup_X \mathrm{P}(f|_X, -t \log |f'|),$$

where the supremum is taken over all compact f-invariant (that is $f(X) \subset X$) Cantor repelling hyperbolic (expanding) subsets of J.

$P(f|_X, -t \log |f'|)$ denotes the standard topological pressure for the continuous mapping $f|_X : X \to X$ and continuous real-valued potential function $-t \log |f'|$ on X, as in the previous sections.

Note that these definitions imply that $P_{hyp}(t)$ is a continuous monotone decreasing function of t.

One can restrict in the definition of the hyperbolic pressure the supremum to be over Cantor repelling hyperbolic sets X such that $f|_X$ is topologically transitive, see Remark 10.6.3.

Definition 11.5.3 (Conformal pressure). Set $P_{Conf}(t) := \log \lambda(t)$, where

$$\lambda(t) = \inf\{\lambda > 0 : \exists \mu, \ \text{a } \lambda|f'|^t - \text{conformal probability measure on } J(f)\}.$$

We know that the set of λ's above is non-empty from Section 11.3. However we want this section to be independent. So the existence of $\lambda(t)$ will be proved later on again, more directly.

In the sequel we shall call any $\lambda|f'|^t$-conformal probability measure on $J(f)$ a (λ, t)-conformal measure and a $(1, t)$-conformal measure by a t-conformal measure.

Proposition 11.5.4. *For each $t > 0$ the number $P_{Conf}(t)$ is attained, that is there exists a (λ, t)-conformal measure with $\lambda = P_{Conf}(t)$.*

This Proposition follows from the following (compare the proof of Lemma 11.3.7).

Lemma 11.5.5. *If μ_n is a sequence of (λ_n, t)-conformal measures of J for an arbitrary $t > 0$, weakly* convergent to a measure μ and $\lambda_n \to \lambda$ then μ is a (λ, t)-conformal measure.*

Proof. Let $E \subset J$ on which f is injective. E can be decomposed into a countable union of critical points and sets E_i pairwise disjoint and such that f is injective on a neighbourhood V of $\operatorname{cl} E_i$. For every ε there exist compact set K and open U such that $K \subset E_i \subset U \subset V$ and $\mu(U) - \mu(K) < \varepsilon$ and $\mu(f(U)) - \mu(f(K)) < \varepsilon$. Consider an arbitrary continuous function $\chi : J \to [0, 1]$ so that χ is 1 on K and 0 on $J \setminus U$. Then there exists $s : 0 < s < 1$ such that for $A = \chi^{-1}([s, 1])$, $\mu(\partial f(A)) = 0$. Then the weak* convergence of μ_n implies $\mu_n(f(A)) \to \mu(f(A))$, as $n \to \infty$, see Theorem 2.1.4. Moreover this weak* convergence and $\lambda_n \to \lambda$ imply $\int \chi \lambda_n |f'|^t d\mu_n \to \int \chi \lambda |f'| d\mu$. Therefore from $\mu_n(f(A)) = \int_A \lambda_n |f'|^t d\mu_n$, letting $\varepsilon \to 0$, we obtain $\mu(f(E_i)) = \int_{E_i} |f'|^t d\mu$.

If $E = \{c\}$ where $c \in \operatorname{Crit}(f) \cap J(f)$ then for every $r > 0$ small enough and for all n, we have $\mu_n(f(B(c, r)) \le 2(\sup_k \lambda_k)(2r)^t$ and since the bound is independent of n we get $\mu(f(c)) = 0$, hence $\mu(f(c)) = \int_c |f'|^t d\mu$, as $f'(c) = 0$. ♣

Remark 11.5.6. For a continuous map $T : X \to X$ of a compact metric space X and an integrable function $g : X \to \mathbb{R}$, for an arbitrary $\varepsilon \ge 0$, a probability

measure m on X is said to be ε-g-*conformal* if for every special set $A \subset X$ we have

$$|m(T(A)) - \int_A g\, dm| \leq \varepsilon.$$

Compare (11.1.1). Then, in Lemma 11.5.5, it is sufficient to assume that μ_n is a sequence of ε_n-$\lambda_n|f'|^t$-conformal measures, with $\varepsilon_n \to 0$.

Definition 11.5.7. We call $z \in \overline{\mathbb{C}}$ *safe* if

(1) $z \notin \bigcup_{j=1}^{\infty} f^j(\mathrm{Crit}(f)$ and

(2) $\liminf_{n \to \infty} \frac{1}{n} \log \mathrm{dist}(z, f^n(\mathrm{Crit}(f))) = 0$.

Remark 11.5.8. For every safe $z \in \overline{\mathbb{C}}$ and every $t > 0$ the pressure $\mathrm{P}_{\mathrm{tree}}(z, t)$ is finite. Indeed, if $z \notin B(f^n(\mathrm{Crit}), \varepsilon\lambda{-n}$ for all $n = 1, 2, ...$ and some $\varepsilon > 0$ and $\lambda > 1$, then for each $x \in f^{-n}(z)$ the mapping f^n is univalent on $\mathrm{Comp}_x f^{-n}B(f^n(\mathrm{Crit}), \frac{\varepsilon}{2}\lambda{-n}$ with distortion bounded by a constant $C > 0$, see Koebe Distortion Lemma 5.2.3. Recall that Comp_x denotes the component containing x. Hence

$$|(f^n)'(x)| \geq C^{-1} \frac{\frac{\varepsilon}{2}\lambda^{-n}}{\mathrm{diam}\,\mathrm{Comp}_x f^{-n}B(z, \frac{\varepsilon}{2}\lambda{-n}} \geq C^{-1}\frac{\varepsilon}{2}\lambda^{-n}.$$

Summing up over x and letting $\lambda \to 1$ and $n \to \infty$ we obtain

$$\mathrm{P}_{\mathrm{tree}}(z, t) \leq \log \deg f. \tag{11.5.1}$$

Definition 11.5.9. We call $z \in \overline{\mathbb{C}}$ *repelling* if there exist Δ and $\lambda = \lambda_z > 1$ such that for all n large enough f^n is univalent on $\mathrm{Comp}_z f^{-n}(B(f^n(z), \Delta))$ and $|(f^n)'(z)| \geq \lambda^n$.

Proposition 11.5.10. *The set S of repelling safe points in J is nonempty. Moreover* $\mathrm{HD}(S) \geq \mathrm{HyD}(J)$.

Proof. The set NS of non-safe points is of zero Hausdorff dimension. This follows from $NS \subset \bigcup_{j=1}^{\infty} f^j(\mathrm{Crit}(f)) \cup \bigcup_{\xi < 1} \bigcap_{n=1}^{\infty} \bigcup_{j=n}^{\infty} B(f^j(\mathrm{Crit}(f)), \xi^j)$, finiteness of $\mathrm{Crit}(f)$ and from $\sum_n (\xi^n)^t < \infty$ for every $0 < \xi < 1$ and $t > 0$. Therefore the existence of safe repelling points in J follows from the existence of hyperbolic sets $X \subset J$ with $\mathrm{HD}(X) > 0$. Note that every point in a hyperbolic set X is repelling.   ♣

Theorem 11.5.11. *For all $t > 0$, all repelling safe $z \in J$ and all $w \in \overline{\mathbb{C}}$*

$$\mathrm{P}_{\mathrm{tree}}(z, t) \leq \mathrm{P}_{\mathrm{hyp}}(t) \leq \mathrm{P}_{\mathrm{Conf}}(t) \leq \mathrm{P}_{\mathrm{tree}}(w, t).$$

We will provide a proof later on. Now let us state corollaries.

Corollary 11.5.12. $P_{hyp}(t) = P_{Conf}(t)$ *and* $HyD(J) = \delta(f)$

Proof. The first equality follows from Theorem 11.5.11 and existence of repelling safe points in J. The second from the fact that both quantities are first zeros of $P_{hyp}(t)$ and $P_{Conf}(t)$. We shall prove the latter, including the existence of a finite zero.

First notice the monotone decreasing of $P_{hyp}(t)$, which follows immediately from the monotone decreasing of $P(X,t) := P(f|_X, -t\log|f'|)$ for every hyperbolic X, see for example the discussion after Theorem 8.1.4 and Definition 11.5.2. Continuity follows from the equicontinuity of the family $P(X,t)$ following, using the definition of pressure, from its uniform Lipschitz continuity with the Lipschitz constant $\sup|f'|$. (In fact by Variational Principle the Lipschitz constant of all $P(X,t)$ is bounded by $\sup_\mu \chi_\mu(f)$, the supremum over all probability f-invariant measures on J.) If t_0 is the first zero of $P_{hyp}(t)$ (we have not excluded yet the case $P_{hyp}(t) > 0$ for all t; in such a case write $t_0 = \infty$) and $t_0(X)$ is zero of $P(X,t)$, then $P(X,t) \to P_{hyp(t)}$ for all t implies $t_0(X) \to t_0$. Since $t_0(X) \le HD(X) \le 2$, see Corollary 8.1.7, t_0 is finite.

Observe finally that $\delta(f)$ is also the first zero t_0 of $P_{Conf}(t)$ (which we know already to be equal to $P_{hyp}(t)$). It cannot be larger, because there exists a t_0-conformal measure, due to Proposition 11.5.4. It cannot be smaller since $P_{Conf}(t) > 0$ for $t < t_0$. ♣

We obtain also a simple proof of the following

Corollary 11.5.13. $P_{tree}(z,t)$ *does not depend on z for $z \in J$ repelling safe.*

Proof of Theorem 11.5.11. 1. We prove first that $P_{tree}(z,t) \le P_{hyp}(t)$. Fix repelling safe $z = z_0 \in J$ and $\lambda = \lambda_{z_0} > 1$ according to Definition 11.5.9. Since z_0 is repelling, we have for $\delta = \Delta/2$, $l = 2\alpha n$ and all n large enough

$$W := \mathrm{Comp}_{z_0} f^{-l} B(f^l(z_0), 2\delta) \subset B(z, \varepsilon\lambda^{-\alpha n}),$$

and f^l is univalent on W. Since z_0 is safe we have

$$B(z_0, \lambda^{-\alpha n}) \cap \bigcup_{j=1}^{2n} f^j(\mathrm{Crit}(f)) = \emptyset$$

for arbitrary constants $\varepsilon, \alpha > 0$.

By the Koebe Distortion Lemma for ε small enough, for every $1 \le j \le 2n$ and $z_j \in f^{-j}(z_0)$ we have

$$\mathrm{Comp}_{z_j} f^{-j} B(z_0, \varepsilon\lambda^{-\alpha n}) \subset B(z_j, \delta).$$

Let $m = m(\delta)$ be be such that $f^m(B(y, \delta/2)) \supset J$ for every $y \in J$. Then, putting $y = f^l(z_0)$, for every $z_n \in f^{-n}(z_0)$ we find $z'_n \in f^{-m}(z_n) \cap f^m(B(y, \delta/2))$. Hence the component W_{z_n} of $f^{-m}(\mathrm{Comp}_{z_n} f^{-n}(B(z_0, \varepsilon\lambda^{-\alpha n})))$ containing z'_n is contained in $\subset B(y, \frac{3}{2}\delta))$ and f^{m+n} is univalent on W_{z_n} (provided $m \le n$).

Therefore f^{m+n+l} is univalent from $W'_{z_n} := \mathrm{Comp}(f^{-(m+n+l)}(B(y, 2\delta)) \subset W_{z_n}$ onto $B(y, 2\delta)$. The mapping

$$F = f^{m+n+l} : \bigcup_{z_n \in f^{-n}(z_0)} W'_{z_n} \to B(y, 2\delta)$$

has no critical points, hence $Z := \bigcap_{k=0}^{\infty} F^{-k}(B(y, 2\delta))$ is a repelling expanding F-invariant Cantor subset of J.

We obtain for a constant $C > 0$ resulting from distortion and $L = \sup |f'|$,

$$\mathrm{P}(F|_Z, -t \log |F'|) \geq \log\Big(C \sum_{z_n \in f^{-n}(z_0)} |(f^{m+n+l})'(z'_n)|^{-t} \Big)$$

$$\geq \log\Big(C \sum_{z_n \in f^{-n}(z_0)} |(f^n)'(z_n)|^{-t} L^{-t(m+l)} \Big). \tag{11.5.2}$$

Hence on the expanding f-invariant set $Z' := \bigcup_{j=0}^{m+n+l-1} f^j(Z)$ we obtain

$$P(f|_{Z'}, -t \log |f'|) \geq \frac{1}{m+n+l} P(F, -t \log |F'|)$$

$$\geq \frac{1}{m+n+l}\Big(\log C - t(m+l) \log L + \log \sum_{z_n \in f^{-n}(z_0)} |(f^n)'(z_n)|^{-t} \Big).$$

Passing with n to ∞ and next letting $\alpha \searrow 0$ we obtain

$$P(f|_{Z'}, -t \log |f'|) \geq P_{\mathrm{tree}}(z_0, t).$$

Finally one can find an f-invariant repelling expanding Cantor set Z'' containing Z', contained in J as in the Proof of Theorem 10.6.1, relying on Proposition 3.5.6. The latter inequality for Z'' in place of Z' is of course satisfied.

Notice that we proved by the way that $P(z_0, t) < \infty$ for z_0 safe and repelling. This is however weaker than (11.5.1), proved for all z safe.

2. $\mathrm{P}_{\mathrm{hyp}}(t) \leq \mathrm{P}_{\mathrm{Conf}}(t)$ is immediate. Let μ be an arbitrary (λ, t)-conformal measure on J. From the *topological exactness* of f on J, see [Carleson & Gamelin 1993], we get $\int_U \lambda^N |(f^N)'|^t d\mu \geq 1$. Hence $\mu(U) > 0$ (compare Lemma 11.2.1).

Let X be an arbitrary f-invariant non-empty isolated hyperbolic subset of J. Then, for U small enough, $(\exists C)(\forall x_0 \in X)(\forall n \geq 0)(\forall x \in X \cap f^{-n}(x_0))$ f^n maps $U_x = \mathrm{Comp}_x f^{-n}(U)$ onto U univalently with distortion bounded by C. So, for every n,

$$\mu(U) \cdot \sum_{x \in f^{-n}(x_0) \cap X} \lambda^{-n} |(f^n)'(x)|^{-t} \leq C \sum_{x \in f^{-n}(x_0) \cap X} \mu(U_x) \leq C.$$

Hence

$$P(f|_X, -\log \lambda - t \log |f'|) \leq 0 \ \text{ hence } \ P(f|_X, -t \log |f'|) \leq \log \lambda.$$

3. Now we prove $\mathrm{P}_{\mathrm{Conf}}(t) \leq \mathrm{P}_{\mathrm{tree}}(w,t)$ and in particular that the definition of $\mathrm{P}_{\mathrm{Conf}}(t)$ makes sense. The proof is via Patterson-Sullivan construction, as started in Section 10.5.1, but it is much simpler and direct, omitting approximation via $K(V)$'s in the following sections. We can assume that $\mathrm{P}_{\mathrm{tree}}(w,t) < \infty$, otherwise there is nothing to prove.

Let us assume first that w is such that for any sequence $w_n \in f^{-n}(w)$ we have $w_n \to J$. This means that w is neither in an attracting periodic orbit, nor in a Siegel disc, nor in a Herman ring, see [Carleson & Gamelin 1993]. Assume also that w is not periodic. Let $\mathrm{P}_{\mathrm{tree}}(w,t) = \lambda$. Then for all $\lambda' > \lambda$

$$\sum_{x \in f^{-n}(w)} (\lambda')^{-n} |(f^n)'(x)|^{-t} \to 0$$

exponentially fast, as $n \to \infty$. We find a sequence of numbers $\phi_n > 0$ such that $\lim_{n \to \infty} \phi_n / \phi_{n+1} \to 1$ and for $A_n := \sum_{x \in f^{-n}(w)} \lambda^{-n} |(f^n)'(x)|^{-t}$ the series $\sum_n \phi_n A_n$ is divergent, compare Lemma 11.1.2. For every $\lambda' > \lambda$ consider the measure

$$\mu_{\lambda'} = \sum_{n=0}^{\infty} \sum_{x \in f^{-n}(w)} D_x \cdot \phi_n \cdot (\lambda')^{-n} |(f^n)'(x)|^{-t} / \Sigma_{\lambda'},$$

where D_x is the Dirac delta measure at x and $\Sigma_{\lambda'}$ is the sum over all x of the weights at D_x, so that $\mu_{\lambda'}(J) = 1$. Notice that m'_λ is $1/\Sigma_{\lambda'}$-$\lambda'|f'|^t$-conformal.

Indeed, the only point where this purely atomic measure is not conformal, is w. But $f(w)$ does not belong to $\bigcup_{n \geq 0} f^{-n}(\{w\})$ since w is not periodic, hence $\mu_{\lambda'}(\{f(w)\}) = 0$.

Finally we find a (λ, t)-conformal measure μ as a weak* limit of a convergent subsequence of $\mu_{\lambda'}$ as $\lambda' \searrow \lambda$, see Lemma 11.5.5 and Remark 11.5.6.

If w is in an attracting periodic orbit which is one of at most two exceptional fixed points (∞ for polynomials, 0 or ∞ for $z \mapsto z^k$, in adequate coordinates) then it is a critical value, so $\mathrm{P}_{\mathrm{tree}}(w,t) = \infty$. If w is in a non-exceptional periodic orbit or in a Siegel disc or Herman ring S, take $w' \in f^{-1}(w)$ not in the periodic orbit of w, neither in the periodic orbit of S in the latter cases. Then for w' we have the first case, hence $\mathrm{P}_{\mathrm{Conf}}(f) \leq \mathrm{P}_{\mathrm{tree}}(w',t) \leq \mathrm{P}_{\mathrm{tree}}(w,t)$. The latter inequality follows from

$$\mathrm{P}_{\mathrm{tree}}(w',t) = \limsup_{n \to \infty} \frac{1}{n-1} \sum_{x \in f^{-(n-1)}(w')} |(f^{-(n-1)})'(x)|^{-t} \leq$$

$$\leq \limsup_{n \to \infty} \frac{1}{n} \sum_{x \in f^{-(n-1)}(w')} |(f^n)'(x)|^{-t} \sup_{z \in \overline{\mathbb{C}}} |f'|^t \leq \mathrm{P}_{\mathrm{tree}}(w,t).$$

♣

Remark 11.5.14. There is a direct simple proof of $\mathrm{P}_{\mathrm{tree}}(z,t) \leq \mathrm{P}_{\mathrm{Conf}}(t)$ for μ-a.e. z, using Borel-Cantelli Lemma, see [Przytycki 1999, Theorem 2.4].

Remark 11.5.15. In [Przytycki 1999, Th.3.4] a stronger fact than Corollary 2 has been proved, also by elementary means, namely that $P_{\text{tree}}(z, t)$ does not depend on $z \in \overline{\mathbb{C}}$ except zero Hausdorff dimension set of z's.

To complete this section it is worthy to mention one more definition of pressure, see [Przytycki 1999] and [Przytycki, Rivera-Letelier & Smirnov 2004].

Definition 11.5.16.

$$P_{\text{varhyp}}(t) = \sup h_\mu(f) - t\chi_\mu(f),$$

the supremum taken over all f-invariant probability ergodic measures on J with positive Lyapunov exponent.

The inequalities $P_{\text{hyp}}(t) \geq P_{\text{varhyp}}(t) \geq P_{\text{hyp}}(t)$ hold by Theorem 10.6.1 and the Variational Principle, Theorem 2.4.1, respectively.

Remark 11.5.17. In conclusion we can denote all the pressures above by $P(t)$ as anticipated at the beginning of this section and call it *geometric pressure*.

A remarkable dichotomy holds for rational maps: Either $P(t)$ is strictly decreasing to $-\infty$ as $t \nearrow \infty$, or $P(t) \equiv 0$ for all $t \geq t_0 = HyD(J)$. The first happens precisely for so-called Topological Collet-Eckmann maps, abbr. TCE-maps . Here is one of characterization of this class, which explains another name: *non-uniformly hyperbolic* A rational map $f\overline{\mathbb{C}} \to \overline{\mathbb{C}}$ is TCE if and only if

$$\inf_\mu \chi_\mu(f) > 0,$$

the infimum taken over all probability f-invariant measures on J. For details of this theory see [Przytycki, Rivera-Letelier & Smirnov 2003].

Bibliographical notes

Section 11.1 roughly follows [Denker & Urbański 1991a]. However here the set Sing need not be finite; this is the version introduced and used in [Denker & Urbański 1991b]. Sections 11.2 and 11.3 follow [Denker & Urbański 1991b], with some simplifications. For example the proof of Lemma 11.2.2 is much simpler.

The construction of conformal measures was first sketched in [Sullivan 1983] and followed an analogous notion and construction by S.J. Patterson on the limit sets of a Kleinian group.

The content of Section 11.5 has been extracted from [Przytycki, Rivera-Letelier & Smirnov 2004], see [Przytycki 2005K].

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