# Dynamical zeta functions and the distribution of orbits

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#### Abstract

In this survey we will consider various counting and equidistribution results associated to orbits of dynamical systems, particularly geodesic and Anosov flows. Key tools in this analysis are appropriate complex functions, such as the zeta functions of Selberg and Ruelle, and Poincaré series. To help place these definitions and results into a broader context, we first describe the more familiar Riemann zeta function in number theory, the Ihara zeta function for graphs and the Artin-Mazur zeta function for diffeomorphisms.

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*Key words*: Dynamical zeta function, closed orbits, Selberg zeta function, Ihara zeta function *MSC*: 37C30, 37C27, 11M36

Acknowledgements: I am grateful to the organisers and participants of the Summer school "Number Theory and Dynamics" in Grenoble for their questions and comments and, in particular, to Mike Boyle for his detailed comments on the draft version of these notes. I am particularly grateful to Athanase Papadopoulos for his help with the final version.

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# 1 Introduction

### 1.1 Zeta functions as complex functions

We will want to define zeta functions which, in different settings, are functions of a single complex variable defined in terms of a countable collection of suitable real numbers. One might think of them as being a device to keep track of these values, but more often they are a useful tool for extracting information about these values.

There are two basic questions which apply equally well to all zeta functions (or, more generally, any complex function).

**Question 1.1.** Where are these functions defined? How far can we extend them as analytic or meromorphics functions?

Once this is established one can next ask:

**Question 1.2.** Where are the zeros and poles of these functions? What values do they take at specific points in their domains?

These questions are particularly important for complex functions arising both in number theory, geometry and ergodic theory.

### **1.2** Different types of zeta functions

In general terms we will discuss four different types of zeta functions in four different settings:

- 1. Number Theory and the Riemann zeta function;
- 2. Graph Theory and the Ihara zeta function;
- 3. Geometry and the Selberg zeta function;
- 4. Dynamical Systems and the Ruelle zeta function.

What they all have in common is that they are complex functions defined in terms of a countable collection on numbers (which in theses four examples are: prime numbers, lengths of closed paths, lengths of closed geodesics, periods of closed orbits).

# 2 Zeta functions in Number Theory

The most famous setting for zeta functions is in number theory, and we begin with the most famous such zeta function.

### 2.1 Riemann zeta function

We recall the well known definition:

**Definition 2.1.** The Riemann zeta function is defined for Re(s) > 1 by

$$\zeta(s) = \prod_{p=prime} (1 - p^{-s})^{-1}.$$

Of course, by multiplying out the terms in the definition one gets an even better known definition:

Lemma 2.2. We can also write

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$$

for Re(s) > 1.



Figure 1: Riemann (1826-1866) and Euler (1707-1783)

The Riemann zeta function was actually studied earlier in 1737 by Euler (at least when *s* was real). However, in 1859 Riemann was elected member of the Berlin Academy of Sciences and had to report on his research, and in a departure from his previous (or subsequent) research he sent in a report "On the number of primes less than a given magnitude". In particular, he established the following basic properties of his zeta function:

**Theorem 2.3** (Riemann, 1859). The zeta function  $\zeta(s)$  converges to a non-zero analytic function for Re(s) > 1. Moreover,

- 1.  $\zeta(s)$  has a single (simple) pole at s = 1;
- 2.  $\zeta(s)$  extends to all complex numbers  $s \in \mathbb{C}$  as a meromorphic function; and
- 3. There is a functional equation relating  $\zeta(s)$  and  $\zeta(1-s)$ .<sup>1</sup>

<sup>1</sup>More precisely,  $\Lambda(s) := \pi^{-s/2} \Gamma(s/2) \zeta(s)$  satisfies the functional equation  $\Lambda(s) = \Lambda(1-s)$ .

One of the main subsequent applications of the zeta function was as a means to prove the prime number theorem (which was eventually proved by Hadamard and de la Vallée Poussin in 1896)<sup>2</sup> and says:

Theorem 2.4 (Prime Number Theorem).

$$\#\{primes \ p \le x\} \sim \frac{x}{\log x} \text{ as } x \to +\infty.$$



Meinen Dank für die Auszeichnung, welche mir die Akademie durch die Aufnahme unter ihre Correspondenten hat zu Theil werden lassen, glaube ich am besten dadurch zu erkennen zu geben, dass ich von der hierdurch erhaltenen Erlaubniss baldigst Gebrauch mache durch Mittheilung einer Untersuchung über die Häufigkeit der Primzahlen; ein Gegenstand, welcher durch das Interesse, welches Gauss und Dirichlet demselben längere Zeit geschenkt haben, einer solchen Mittheilung vielleicht nicht ganz unwerth erscheint.

Bei dieser Untersuchung diente mir als Ausgangspunkt die von Euler gemachte Bemerkung, dass das Product

$$\prod \frac{1}{1-\frac{1}{p^s}} = \Sigma \frac{1}{n^s},$$

wenn für p alle Primzahlen, für n alle ganzen Zahlen gesetzt werden. Die Function der complexen Veränderlichen s, welche durch diese beiden Ausdrücke, so lange sie convergiren, dargestellt wird, bezeichne ich durch  $\xi(s)$ . Beide convergiren nur, so lange der reelle Theil von s grösser als 1 ist; es lässt sich indess leicht ein immer gältig bleibender Ausdruck der Function finden. Durch Anwendung der Gleichung

$$\int_{0}^{\infty} e^{-nx} \ x^{s-1} \ dx = \frac{\Pi(s-1)}{n^s}$$
erhält man zunächst

П

$$f(s-1) \xi(s) = \int_{-\infty}^{\infty} \frac{x^{s-1} dx}{x^{s-1}} dx$$

# On the Number of Prime Numbers less than a Given Quantity

Monatsberichte der Berliner Akademie, November 1859.

I believe that I can best convey my thanks for the honour which the Academy has to some degree conferred on me, through my admission as one of its correspondents, if I speedily make use of the permission thereby received to communicate an investigation into the accumulation of the prime numbers; a topic which perhaps seems not wholly unworthy of such a communication, given the interest which Gauss and Dirichlet have themselves shown in it over a lengthy period. For this investigation my point of departure is provided by the observation of Euler that the product

$$\prod \frac{1}{1-\frac{1}{p^s}} = \sum \frac{1}{n^s}$$

if one substitutes for p all prime numbers, and for n all whole numbers. The function of the complex variable s which is represented by these two expressions, wherever they converge, I denote by  $\zeta(s)$ . Both expressions converge only when the real part of s is greater than 1; at the same time an expression for the function can easily be found which always remains valid. On making use of the equation

$$\int_0^\infty e^{-snx} x^{s-1} dx = \frac{\Pi(s-1)}{n^s}$$

one first sees that

$$\Pi(s-1)\zeta(s) = \int_0^\infty \frac{x^{s-1}dx}{e^x - 1}.$$

Figure 2: The first page of Riemann's 1859 memoir and an English translation.

However, there remain a number of interesting problems on the Riemann zeta function which have important applications to counting primes. There are always trivial zeros at the negative even integers (the trivial zeros). The still unproved Riemann hypothesis says the following:

<sup>&</sup>lt;sup>2</sup>The proof required additionally showing that  $\zeta(s)$  has no zeros on the line Re(s) = 1.



Figure 3: Hadamard (1863-1963); de la Vallée Poussin (1869-1962); Hardy (1877-1947)

**Conjecture 2.5** (Riemann Hypothesis). The non-trivial zeros of  $\zeta(s)$  are on the line  $Re(s) = \frac{1}{2}$ .

This was formulated by Riemann in 1859 and was restated as Hilbert's 8th problem and one of the Clay Institute million dollar problems. If it were valid then it would lead to significant improvements in the Prime Number Theorem.

**Corollary 2.6** (Of Riemann Hypothesis). If the Riemann Hypothesis holds then for any  $\epsilon > 0$  we have

$$\#\{primes \ p \le x\} = \int_2^x \frac{du}{\log u} + O(x^{\frac{1}{2}+\epsilon}) \ as \ x \to +\infty.$$

The principal term on the right hand side of the above expression is often called the *logarithmic* integral and is asymptotic to  $x/\log x$  as  $x \to +\infty$ , as required by Theorem 2.4.

It has been experimentally verified for a very large number of zeros. An early result was the following result of Hardy.  $^{\rm 3}$ 

**Theorem 2.7** (Hardy, 1914). There are infinitely many zeros on the line  $Re(s) = \frac{1}{2}$ .

In 1941, Selberg improved this to show that at least a (small) positive proportion of zeros lie on the line.

*Remark* 2.8. Hilbert and Polya proposed the idea of trying to understand the location of the zeros of the Riemann zeta function in terms of eigenvalues of some (as of yet) undiscovered

 $^{3}$ In fact, the Riemann Conjecture topped Hardy's famous wish list from the 1920s:

- 1. Prove the Riemann Hypothesis.
- 2. Make 211 not out in the fourth innings of the last test match at the Oval.
- 3. Find an argument for the nonexistence of God which shall convince the general public.
- 4. Be the first man at the top of Mount Everest.
- 5. Be proclaimed the first president of the U.S.S.R., Great Britain and Germany.
- 6. Murder Mussolini.

self-adjoint operator whose necessarily real eigenvalues are related to the zeros. This idea has yet to reach fruition for the Riemann zeta function but the approach works particularly well for the Selberg Zeta function. Interestingly, Selberg showed that the Riemann zeta function wasn't needed in counting primes.

Remark 2.9. Recently it has been noticed that (assuming the Riemann Hypothesis) the spacings of the imaginary parts of the non-trivial zeros of  $\zeta(s)$  behave like the eigenvalues of random Hermitian matrices. Katz and Sarnak call this the Montgomery-Odlyzko law (another name is GUE for Gaussian Unitary Ensemble) although the law does not appear to have found a proof.

### 2.2 Other types of complex functions in Number Theory

#### 2.2.1 *L*-functions

One generalisation of the Riemann zeta function is the *L*-function associated to a character  $\chi: \mathbb{Z} \to \mathbb{C}$  of the form  $\chi(n) = e^{2\pi i n m}$ , say. In particular, we can define

$$L(s,\chi) = \prod_{p} (1 - \chi(n)p^{-s})^{-1}$$

which converges for Re(s) > 1. When  $\chi$  is trivial then this reduces to the Riemann zeta function.

The study of L-functions in place of the Riemann zeta function leads to a generalisation of the Prime Number Theorem due to Dirichlet (who was also the brother-in-law of the composer Mendelssohn):

**Theorem 2.10** (Dirichlet). Let  $1 \le m \le n$  be coprime to n, then

#{primes 
$$p \le x$$
 and  $m = p \pmod{n}$ }  $\sim \frac{1}{\phi(m)} \frac{x}{\log x}$  as  $x \to +\infty$ 

where  $\phi(m) = \#\{1 \le a \le m : (a, m) = 1\}.$ 

**Example 2.11.** For example, if we let m = 3 then  $\phi(3) = 2$ . Thus "half the primes lie in  $3\mathbb{N} + 1$  and half the primes lie in  $3\mathbb{N} + 2$ ".

#### 2.2.2 Dedekind Zeta functions

In number theory, the Dedekind zeta function is associated to an algebraic number field K, such as  $\mathbb{Q}(\sqrt{2})$ , for example. This zeta function is an infinite product over prime ideals p in  $O_K$ , the ring of algebraic integers of K. The terms in the product are  $\zeta_K(s) = \prod_{P \subset O_K} (1 - (N_{K/\mathbb{Q}}^{-s}))^{-1}$ , where  $N(p) = \#(O_K/p)$  for each prime ideal p. The results on the Riemann zeta function can be extended to this case and can be used to prove the analogous Prime Ideal Theorem. When  $K = \mathbb{Q}$  this reduces to the Riemann zeta function.

#### 2.2.3 Finite Field Zeta functions

In 1949, André Weil proposed some fundamental conjectures related to the number of solutions to a system of polynomial equations over finite fields. Consider  $y^2 = x^3 - 1 \pmod{7}$ , say. There are 4 solutions in  $\mathbb{F}_7$ ; 47 solutions in  $\mathbb{F}_{7^2}$ ; 364 solutions in  $\mathbb{F}_{7^3}$ ; etc. More generally, we can consider  $q = p^r$  where there are also zeta functions for projective algebraic varieties X over a finite field  $F_q$  defined by

$$\zeta(s) = \exp\left(\sum_{m=1}^{\infty} \frac{N_m}{m} q^{-sm}\right)$$

where  $N_m$  is the number of points of X defined over the degree *m*-extension  $F_{q^m}$  of  $F_q$ . This is a rational function of  $q^{-s}$ , as was proved by Dwork in 1960. Deligne proved the analogue of the Riemann Hypothesis in 1974.

# 3 Zeta functions for graphs

We can consider two types of finite graphs: directed graphs and undirected graphs. If the graphs were road maps of a town then the directed graph would be where all of the streets are one way, and the undirected graph would be where traffic could go either way down each street.



Figure 4: (i) A directed graph; and (ii) an undirected graph

We treat first the zeta functions of finite directed graphs and then the case of undirected graphs.

### 3.1 Directed graphs: Bowen-Lanford zeta functions

#### 3.1.1 The zeta function for directed graphs

We denote a directed graph by  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ , where  $\mathcal{V}$  denotes the set of vertices and  $\mathcal{E}$  denotes the set of directed edges. Given an edge  $e \in \mathcal{E}$  we will assume that it has a specific orientation.

We will assume for simplicity that there is at most one edge e between any two pairs of vertices v, v', say. In particular, this allows the following simplification:

• We can uniquely identify pairs of neighbouring vertices (v, v') with a unique directed edge  $e \in \mathcal{E}$  joining them;

• Given a directed edge  $e \in \mathcal{E}$  we can associate the vertices v = e(0) and v' = e(1) in  $\mathcal{V}$  (i.e., the starting and finishing vertices of the edge e).

We are interested in *closed paths* in G which follow the orientation of the edges. In particular, under the above simplifying assumption we can represent this as either:

- 1. a sequence of edges  $(e_1, \dots, e_n)$  with  $e_k(1) = e_{k+1}(0) \in \mathcal{V}$ , for  $k = 1, \dots, n-1$ , and  $e_n(1) = e_1(0) \in \mathcal{V}$  or, equivalently,
- 2. a sequence of vertices  $(v_1, \dots, v_n)$  with  $(v_k, v_{k+1}) \in \mathcal{E}$ , for  $k = 1, \dots, n-1$ , and  $(v_n, v_1) \in \mathcal{E}$ .

A cyclic permutation of such words will represent the same closed path  $\mathcal{G}$ . We let n denote the length of the closed path. We will let  $\tau$  denote a *prime* closed path<sup>4</sup> and we denote the length of the path by  $n = |\tau|$ .

**Definition 3.1.** We can then define the Bowen-Lanford zeta function by

$$\zeta(z) = \prod_{\tau} (1 - z^{|\tau|})^{-1}$$

which converges provided |z| is sufficiently small. <sup>5</sup>

We can also multiply out the terms in this zeta function  $\zeta(z)$  in much the same way as we did for the Riemann zeta function (cf. Lemma 2.1)

**Lemma 3.2.** Let N(n) denote the number of all possible strings  $(v_1, \dots, v_n)$  representing a closed path in  $\mathcal{G}$  of length n.<sup>6</sup> Then

$$\zeta(z) = \exp\left(\sum_{n=1}^{\infty} \frac{z^n}{n} N(n)\right).$$

*Proof.* This is just a simple expansion of  $\log(1 - x) = \sum_{k=1}^{\infty} \frac{x^k}{k}$ :

$$\log \zeta(z) = \sum_{\tau} \log(1 - z^{|\tau|}) = \sum_{\tau} \left( \sum_{k=1}^{\infty} \frac{z^{k|\tau|}}{k} \right)$$
$$= \sum_{k=1}^{\infty} \left( \sum_{\tau} |\tau| \left( \frac{z^{k|\tau|}}{k|\tau|} \right) \right) = \sum_{n=1}^{\infty} \frac{z^n}{n} N(n)$$

provided |z| is sufficiently small to give convergence.

We would like to show that  $\zeta(z)$  has a meromorphic extension in  $\mathbb{C}$  to the entire complex plane. The most convenient way to do this is to introduce a matrix:

<sup>&</sup>lt;sup>4</sup>A prime closed path is simply one that is not merely a shorter path traversed more than once.

<sup>&</sup>lt;sup>5</sup>It would suffice that  $|z| < \frac{1}{|\mathcal{E}|}$ , say.

<sup>&</sup>lt;sup>6</sup>In particular, they need not be prime, not are they necessarily cyclically reduced.

**Definition 3.3.** We can associate to the graph  $\mathcal{G}$  a  $|\mathcal{V}| \times |\mathcal{V}|$  transition matrix A with

$$A(v, v') = f \begin{cases} 1 & \text{if } e = (v, v') \in \mathcal{E} \\ 0 & \text{if } e = (v, v') \notin \mathcal{E} \end{cases}$$

In particular, we immediately have the following simple identity (which is equally easy to prove).

**Lemma 3.4.** For each  $n \ge 1$ ,  $N(n) = trace(A^n)$ .

It is convenient to further assume that the graph  $\mathcal{G}$  has the property that the transition matrix is aperiodic, (i.e., there exists N > 0 such that  $A^N > 0$ ).<sup>7</sup>

Moreover, having introduced a (non-negative) matrix and having assumed it is aperiodic it is convenient to use the classical Perron-Frobenius theorem for aperiodic matrices which describes their eigenvalues.

**Lemma 3.5** (Perron-Frobenius Theorem, 1908). Assume that the matrix A is aperiodic then:

- 1. A has a simple positive eigenvalue  $\lambda_1 > 0$ ;
- 2. all the other eigenvalues  $\lambda_i$   $(i = 2, \dots, k)$  satisfy  $\max_{2 \le i \le k} |\lambda_i| < \lambda_1$ .





Figure 5: Perron (1880-1975) and Frobenius (1849 - 1917)

Since A has natural number entries and is aperiodic it is easy to see that  $\lambda_1 > 0$ . Lemma 3.5 leads easily to the following basic result on zeta functions for directed graphs.

**Theorem 3.6** (Bowen-Lanford, 1968). The zeta function  $\zeta(z)$  is non-zero and analytic for  $|z| < 1/\lambda_1$ . Moreover,

- 1. The zeta function  $\zeta(z)$  has a simple pole at  $z = 1/\lambda_1$ ;
- 2. The zeta function  $\zeta(z)$  has a meromorphic extension to  $\mathbb{C}$  of the form

$$\zeta(z) = 1/\det(I - zA).$$

In particular, it is the reciprocal of a polynomial.



Figure 6: Bowen (1947-1978) and Lanford (1940 -2013)

Proof. By Lemmas 3.4 and 3.5 we see that the power series

$$\sum_{n=1}^{\infty} \frac{z^n}{n} N(n) = \sum_{n=1}^{\infty} \frac{z^n}{n} \operatorname{trace}(A^n) = O\left(\sum_{n=1}^{\infty} \frac{|z|^n}{n} \lambda_1^n\right)$$

converges for  $|z| < 1/\lambda_1$  and thus  $\zeta(z)$  is non-zero and analytic on this domain. Moreover, since

$$N(n) = \operatorname{trace}(A^n) = \lambda_1^n + \sum_{i=1}^k \lambda_i^n$$

we can write

$$\begin{aligned} \zeta(z) &= \exp\left(\sum_{n=1}^{\infty} \frac{z^n}{n} \left(\lambda_1^n + \sum_{i=1}^k \lambda_i^n\right)\right) \\ &= \exp(-\log(1-\lambda_1 z)) \prod_{i=1}^k \exp(-\log(1-\lambda_i z)) \\ &= (1-\lambda_1 z)^{-1} \prod_{i=1}^k (1-z\lambda_i)^{-1} = 1/\det(I-zA), \end{aligned}$$

providing |z| is sufficiently small, from which part (3) follows. Finally, part (2) follows from this explicit expression.

#### 3.1.2 The prime graph theorem (for directed graphs)

We can use the Bowen-Lanford zeta function to prove a simple analogue of the Prime Number Theorem for paths in the directed graph. Fortunately, the proof is even easier than for prime numbers.<sup>8</sup>

<sup>&</sup>lt;sup>7</sup>This is equivalent to saying that one can get from any vertex to any other vertex along a path of precisely length N.

<sup>&</sup>lt;sup>8</sup>And although we implicitly use the zeta function we don't need it explicitly.

Theorem 3.7 (Prime Graph Theorem for directed graphs).

$$\operatorname{Card}\{\tau \, : \, |\tau|=n\}\sim rac{\lambda_1^n}{n} \, \operatorname{as} \, n \to +\infty$$

*Proof.* In fact it suffices to show that  $N(n) \sim \lambda_1^n$  as  $n \to +\infty$  since we can write

$$\operatorname{Card}\{\tau : |\tau| = n\} = \frac{N(n)}{n} + O\left(\lambda^{n/2}\right)$$

since:

- 1. we need to divide by n to allow for cyclic permutations to get from sequences of vertices to closed paths  $\tau$ ; and
- 2. we need to throw away non-prime orbits, which number at most  $N\left(\frac{n}{2}\right) + N\left(\frac{n}{3}\right) + \cdots = O\left(\lambda_1^{n/2}\right)$

However, using Lemma 3.4 again we see that

$$N(n) = \frac{\operatorname{trace}(A^n)}{n} = \frac{\lambda_1^n}{n} + \sum_{i=2}^k \frac{\lambda_i^n}{n} = \frac{\lambda_1^n}{n} + O(\lambda_1^n)$$

3.1.3 A dynamical viewpoint

In these notes it will later prove convenient to take a more dynamical viewpoint. To preview this idea, let us denote by  $X_A$  the space of all infinite paths in the graph  $\mathcal{G}$ . These can be labelled by the sequence of vertices they pass throughand so can be identified with:

$$X_A = \{ (v_n)_{n \in \mathbb{Z}} \in \prod_{n \in \mathbb{Z}} \mathcal{V} : A(v_n, v_{n+1}) = 1, n \in \mathbb{Z} \}.$$

This is a compact metrizable space (with the Tychonoff product topology). We can then associate a homeomorphism  $\sigma : X_A \to X_A$  by  $\sigma(v_n) = (v_{n+1})$  by shifting paths by one place.<sup>9</sup> We then see that there is a natural bijection between closed paths and the set of periodic points  $\sigma^n(v_k) = (v_{k+1})$  for the map  $\sigma$ .<sup>10</sup>

We now move onto the slightly more geometric notion of an undirected graph.

<sup>&</sup>lt;sup>9</sup>This is simply a subshift of finite type.

<sup>&</sup>lt;sup>10</sup>In light of this dynamical interpretation, we see that the Bowen-Lanford zeta function is actually an example of the Artin-Mazur zeta function defined in terms of periodic points for transformations.

### 3.2 Undirected graphs: Ihara zeta function

#### 3.2.1 The zeta function for undirected graphs

Now let  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$  be a finite connected non-trivial *non-directed* graph (i.e., the "usual" type of graph where we don't associate orientations to the edges).<sup>11</sup>

In the same spirit as before, we want to consider *prime* closed paths  $\tau$  in  $\mathcal{G}$  and associate to these an appropriate zeta function. However, if we consider closed paths in the context of undirected graphs then it is natural to make an additional assumption.

We adopt the convention that there is no backtracking (i.e., we don't allow paths to take the same edge in one direction and then immediately afterwards take the same edge back).

In this context we again let  $\tau$  denote a closed path which passes through  $|\tau|$  edges.

By analogy with the definition of the Bowen-Lanford zeta function (cf. Definition 3.1) we define a zeta function in the present context as follows:

**Definition 3.8.** We define the Ihara zeta function  $\zeta(z)$  for undirected graphs by

$$\zeta(z) = \prod_{\tau} (1 - z^{|\tau|})^{-1}.$$

We want to understand the properties of  $\zeta(z)$ . Let us assume for the simplicity of subsequent statements that:

- 1. the graph  $\mathcal{G}$  has valency q + 1 with  $q \ge 2$  (i.e., every vertex has q + 1 edges attached);
- 2. there is at most one edge between any two vertices;
- 3. there are no edges starting and finishing at the same vertex.

We can associate a type of adjacency matrix B to this undirected graph as follows:

**Definition 3.9.** More generally, without the simplifying assumptions 2 and 3 the same statements will hold providing we associate instead the  $|\mathcal{V}| \times |\mathcal{V}|$  matrix B defined by

$$B(v,v') = \begin{cases} 1 & \text{if an edge joins } v \text{ and } v' \\ 0 & \text{otherwise.} \end{cases}$$

The usefulness of the matrix B in this case <sup>12</sup> is shown by the following classic result:

**Theorem 3.10** (Ihara). Let  $\mathcal{G}$  be a finite connected graph of valency q + 1 then

$$\zeta(z)^{-1} = (1 - z^2)^{r-1} \det(I - zB + qz^2I)$$

where  $r = |\mathcal{E}| - |\mathcal{V}| + 1$ .

We outline later a short proof of this result (due to Bass) which morally depends on the Bowen-Lanford zeta function.

<sup>11</sup>Perhaps foolishly, I will still use the same notation  $\mathcal{E}$  for the now undirected edge set.

<sup>12</sup>Or, more generally,  $B(v, v') = \begin{cases} \text{Number of edges from } v \text{ to } v' & \text{if } v \neq v' \\ 2 \times \text{ number of loops at } v & \text{if } v = v'. \end{cases}$ 





Figure 7: Ihara (1938 - ) and Bass (1932 - )

**Example 3.11.** Consider the tetrahedron graph  $K_4$ , with four vertices and six edges. The zeta function

$$1/\zeta(z) = (1-z^2)^2(1-z)(1-2z)(1+z+2z^2)^3$$

has poles at  $-1, \frac{1}{2}, 1, (-1 \pm \sqrt{-7})/4$ .

Some useful consequences of the location of poles of the lhara zeta function of an undirected graph with valency q + 1 are the following:

**Corollary 3.12.** The zeta function  $\zeta(z)$  is non-zero and analytic for  $|z| < \frac{1}{q}$ . Moreover,

- 1.  $\zeta(z)$  has a simple pole at  $z = \frac{1}{q}$ ; and
- 2. the poles of the zeta function  $\zeta(z)$  lie on the union of the circle  $\{z \in \mathbb{C} : |z| = 1/\sqrt{q}\}$ and the intervals  $[1/q, 1] \cup [-1, -1/q]$ .



Figure 8: The poles of the Ihara zeta function  $\zeta(z)$  are restricted to the region illustrated

There is an interesting extension of this to the case of zeta functions for which the valency is not constant. Assume that all the vertices have degree at most  $q_1 + 1$  and at least  $q_2 + 1$ .

Theorem 3.13 (Kotani-Sunada). Under the above hypotheses:

1. Every pole of  $\zeta(z)$  lies in the annulus  $\frac{1}{q_1} \leq |z| \leq 1$ ; and

2. every pole on the real line satisfies  $\frac{1}{\sqrt{q_1}} \leq |u| \leq \frac{1}{\sqrt{q_2}}$ .

*Remark* 3.14. An important class of graphs we don't have time to discuss are Ramanujan graphs, for which the eigenvalues either have modulus q + 1 or modulus at most  $2\sqrt{q}$ . This might perhaps be viewed as the analogue of the Riemann Hypothesis were we looking for one at present.

#### 3.2.2 The prime graph theorem (for undirected graphs)

We can use the Ihara zeta function to prove a simple analogue of the Prime Number Theorem for paths in the undirected graph.

To simplify the statement, let us further assume that the lengths of closed orbits have greatest common divisor 1 (i.e., they are not all natural number multiples of some  $a \ge 2$ ).

Theorem 3.15 (Prime Graph Theorem for undirected graphs).

$$Card\{\tau : |\tau| = n\} \sim \frac{\lambda_1^n}{n} \text{ as } n \to +\infty$$

*Proof.* As in Lemma 3.2, let N(n) denote the number of all possible strings  $(v_1, \dots, v_n)$  representing a path in the now undirected graph  $\mathcal{G}$  of length n.<sup>13</sup> By analogy with Lemma 3.2 we can write the Ihara zeta function in the form:

$$\zeta(z) = \exp\left(\sum_{n=1}^{\infty} \frac{z^n}{n} N(n)\right).$$

Let us now consider the logarithmic derivative

$$\frac{d}{dz}\log\zeta(z) = \sum_{n=1}^{\infty} N(n)z^{n-1}.$$

The properties that we need to extract from Theorem 3.10 are that  $\zeta(z)$  has a simple pole at 1/q and there are no other poles (or zeros) in a disk  $|z| < (1 + \epsilon)/q$ .<sup>14</sup> Writing  $\zeta(z) = (z - 1/q)\phi(z)$ , where  $\phi(z)$  is analytic and non-zero in the disk  $|z| < (1 + \epsilon)/q$ , then we can write

$$\frac{d}{dz}\log\zeta(z) = \frac{1}{z - 1/q} + \psi(z)$$

where  $\psi(z) = \frac{\phi'(z)}{\phi(z)}$  is analytic in the disk  $|z| < (1+\epsilon)/q$ . Expanding  $\frac{1}{z-1/q} = \sum_{n=0}^{\infty} q^{n+1} z^n$  and comparing coefficients in the power series for the two expressions for  $\frac{d}{dz} \log \zeta(z)$  shows that  $N(n) = q^n (1 + O(((1+\epsilon)^{-n})))$ . Finally, arguing as in the proof of Theorem 5.4 for directed graphs this is equivalent to the asymptotic in the statement.

 $<sup>^{13}</sup>$ We are recycling the notation in the hope that it isn't too confusing, although we are now labelling undirected graphs.

<sup>&</sup>lt;sup>14</sup>This uses the simplifying assumption to eliminate the possibility that  $z = -\frac{1}{q}$  is a pole.

### 3.3 The laplacian for undirected graphs

### 3.3.1 The laplacian

Instead of the adjacency matrix B we could also consider the laplacian on graphs. In particular, if we consider functions in  $l^2(\mathcal{V})$  on the vertex set  $\mathcal{V}$ , then we can define the Laplacian to be the linear operator  $\Delta : l^2(\mathcal{V}) \rightarrow l^2(\mathcal{V})$  defined by

$$\Delta w(v) = w(v) - \frac{1}{(q+1)} \sum_{(v,v') \in \mathcal{E}} w(v').$$

Of course, since the space is finite dimensional this linear operator can also be represented by a matrix. In this case, it takes the form  $I - \frac{1}{(q+1)}B$ , where B is the associated adjacency matrix. The operator is self adjoint and thus the spectrum lies in the the interval [-1,1]. As for any self-adjoint operator, one can write  $\Delta = \int_{-1}^{1} \lambda dE(\lambda)$ , where E is a spectral measure taking values in projections on  $l^2(\mathcal{V})$ . We can consider the spectral measure

$$\mu = \frac{1}{|\operatorname{spec}(\Delta)|} \sum_{\lambda \in \operatorname{spec}(\Delta)} \delta_{\lambda}$$

supported on the finite set of eigenvalues in the spectrum of  $\Delta$ . We can then write

$$\log \zeta_{\mathcal{G}}(z) = -\left(\frac{d-2}{2}\right) \log(1-z^2) - \int_{-1}^{1} \log(1-zdx + (d-1)z^2) d\mu(x)$$

where  $\mu$  is the spectral measure associated to  $\mathcal{G}$ .

#### 3.3.2 Zeta functions for infinite graphs

As an application, we can consider zeta functions of infinite graphs following, for example, Grigorchuk and Zuk and thinking of them as taking limits of finite graphs.

Let  $\mathcal{G}_n$  be a finite family of graphs and let  $\mu_n$  be the associated measures. In this context, there are two natural ways to approach this, which can be shown to be equivalent using the following result.

**Lemma 3.16** (Serre). The convergence of  $\mu_n \to \mu_\infty$  in the weak star topology is equivalent to the formal power series

$$\log \zeta_{\mathcal{G}_n}(z) = -\sum_{k=1}^{\infty} \frac{c_k^{(n)} z^k}{k}$$

converging termwise to a limit, i.e.,  $c_k = \lim_{n \to +\infty} c_k^{(n)}$  exists for each  $k \ge 1$ .

When convergence in either of these equivalent senses holds then we can define the zeta function for the limiting graph  $\mathcal{G}$  by:

$$\log \zeta_{\mathcal{G}}(z) := \lim_{n \to +\infty} \frac{1}{|\mathcal{V}_n|} \log \zeta_{\mathcal{G}_n}(z).$$

The uniqueness of the definition in the connected component  $V_0$  of  $\mathbb{C} - X$  follows from the uniqueness of the analytic extension. Furthermore, given the explicit form of the lhara zeta function for finite graphs we have the following:

**Theorem 3.17** (Grigorchuk-Zuk). When the limit of  $\log \zeta_{\mathcal{G}_n}(z)$  exists it takes the form

$$\log \zeta_{\mathcal{G}_{\infty}}(z) := -\frac{d-2}{2}\log(1-z^2) - \int_{-1}^{1}\log(1-zdx + (d-1)z^2)d\mu_{\infty}(x)$$

where  $\mu_{\infty}$  is the weak star limit of the associated spectral measures  $\mu_n$ .

In particular, the expression for  $\log \zeta_{\mathcal{G}_{\infty}}(z)$  converges to an analytic function on  $|z| < \frac{1}{d-1}$  and has an analytic extension to  $V_0$ . More generally, for the Cayley graph associated to an infinite group we can associate the logarithm of the zeta function  $\log \zeta(z)$  by using the definition where  $\mu_{\infty}$  is taken to be the Kesten spectral measure for the random walk.

# 4 Zeta functions for Diffeomorphisms

We next want to introduce the first of our dynamical zeta functions (not withstanding the dynamical interpretation of the Bowen-Lanford zeta function).

Let  $f: M \to M$  be a  $C^{\infty}$  diffeomorphism of a compact manifold. Let us denote

$$\mathsf{Fix}(f^n) = \{x : f^n x = x\}$$

and assume that for every  $n \ge 1$  we have  $Card(Fix(f^n)) < +\infty$ . This gives us some hope of making the following definition.

**Definition 4.1.** We formally define the Artin-Mazur zeta function by

$$\zeta(z) = \exp\left(\sum_{n=1}^{\infty} \frac{z^n}{n} \operatorname{Fix}(f^n)\right).$$





Figure 9: Artin (1934-) and Mazur (1937-)

We begin with a class of diffeomorphisms about which we can say most, and for which the zeta functions have properties closest to those for the graphs.

### 4.1 Anosov diffeomorphisms

Let  $f: M \to M$  be a  $C^{\infty}$  diffeomorphism of a compact manifold M.

**Definition 4.2.** We say that f is Anosov if:

- 1. there is a continuous splitting  $TM = E^s \oplus E^u$  and there exist C > 0,  $0 < \lambda < 1$  such that:
  - (a)  $||Df^n|E^s|| \leq C\lambda^n$  for  $n \geq 0$ , and
  - (b)  $||Df^{-n}|E^u|| \leq C\lambda^n$  for  $n \geq 0$ ; and
- 2.  $f: M \to M$  is transitive (i.e., there exists a dense orbit).

The following result is well known for Anosov diffeomorphisms.

**Lemma 4.3.** The number N(n) of periodic points grows exponentially fast, i.e.,

$$h(f) = \lim_{n \to +\infty} \frac{1}{n} \log N(n) > 0.$$

This leads naturally to the following definition.

**Definition 4.4.** The value h(f) is called the topological entropy of the Anosov diffeomorphism.

In particular, this bound on the rate of growth of the numbers N(n) shows that the zeta function converges for  $|z| < e^{-h(f)}$ . The classical result on the extension of the Artin-Mazur zeta function for Anosov diffeomorphisms is the following:

**Theorem 4.5** (Williams, Guckenheimer, Manning, 1971). The Artin Mazur zeta function for Anosov diffeomorphisms has a meromorphic extension to  $\mathbb{C}$ . Moreover, it is a rational function, i.e., a quotient P(z)/Q(z) of two polynomials  $P, Q \in \mathbb{C}[z]$ .



Figure 10: Anosov (1936-2014), Manning (1946-) and the CAT map

The proof, which we omit, is based on modelling the diffeomorphism using the maps  $\sigma$ :  $X_A \rightarrow X_A$  associated to directed graphs which arise from Markov partitions constructed for Anosov diffeomorphisms. However, for some simple examples of Anosov diffeomorphisms it is possible to compute the Artin-Mazer zeta functions directly.

**Example 4.6** (The Arnol'd CAT map). Let  $f : \mathbb{T}^d \to \mathbb{T}^d$  be a hyperbolic linear toral automorphism associated to  $A \in SL(d, \mathbb{Z})$  with no eigenvalues of modulus 1, i.e.,  $f(x + \mathbb{Z}^d) = Ax + \mathbb{Z}^d$ . For definiteness, we can take d = 2 and consider  $A = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$ . The zeta function in this case is  $\zeta(z) = \frac{(1-z)^2}{z^2 - 3z + 1}$ .

Remark 4.7. In this particular case, where  $f: \mathbb{T}^d \to \mathbb{T}^d$  preserves orientation, one can apply a useful trick and write

$$N(n) = \sum_{k=0}^{d} (-1)^k \operatorname{trace} \left( f_{k*}^n : H_k(\mathbb{T}^d, \mathbb{R}) \to H_k(\mathbb{T}^d, \mathbb{R}) \right)$$

where  $f_{k*}$  is a matrix corresponding to the induced action on the *k*th homology group. This uses the Lefschetz fixed point theorem (where, in greater generality, one sums the Lefschetz index ±1 over fixed points, but in this case it always takes the value 1). Moreover,  $f_{k*}$  is represented by a matrix and we can deduce that  $\zeta(z) = \prod_{k=0}^{d} \det(I - zf_{k*})^{(-1)^{k}}$ .

### 4.2 Generic diffeomorphisms

The Artin-Mazur zeta function was originally introduced to deal with more general diffeomorphisms. Whereas there is a very simple result for all Anosov diffeomorphisms, they form a relatively small class amongst all diffeomorphisms. In the opposite direction, the original application of the Artin-Mazur zeta function was to show that "generically" for diffeomorphisms one expects rationality.

Given a diffeomorphism  $f: M \to M$ , let  $N_f(n)$  denote the number of isolated fixed points for  $f^n: M \to M$ , for  $n \ge 1$ .

**Theorem 4.8** (Artin-Mazur). Let M be a compact manifold. For  $k \ge 1$ , there is a  $C^k$  dense subset  $\mathcal{F}_k \subset C^k(M)$  such that for each  $f \in \mathcal{F}_k$  we have  $N_f(n) < +\infty$ , for each  $n \ge 1$  and, furthermore,

$$\limsup_{n \to +\infty} \frac{1}{n} \log N_f(n) < +\infty.$$

In particular, we have the following.

**Corollary 4.9.** If  $f \in \mathcal{F}$  then the associated zeta function  $\zeta(z)$  converges on a sufficiently small disk around the origin.

The proof of Theorem 4.8 used results of Nash on approximation of manifolds and diffeomorphisms. There is also a generalisation by Kaloshin to the effect that for each  $k \ge 1$ , there is a  $C^k$  dense subset  $\mathcal{H}_k \subset C^k(M)$  such that  $f \in \mathcal{H}_k$  has only hyperbolic periodic points.

### 4.3 Ruelle zeta function for Anosov diffeomorphisms

In the context of differomorphisms it is natural not only to count periodic points, but also to introduce weightings for the orbits that might, for example, reflect where the periodic points are on the manifold.

Let  $g:M\to\mathbb{R}$  be a  $C^\infty$  function. We can consider the following generalisation of the Artin-Mazur zeta function.

**Definition 4.10.** We can formally define the Ruelle zeta function for an Anosov diffeomorphism by

$$\zeta_g(z) = \exp\left(\sum_{n=1}^{\infty} \frac{z^n}{n} \sum_{T^n x = x} \exp\left(\sum_{k=0}^{n-1} g(T^i x)\right)\right).$$

In particular, this weights the periodic points  $\{x, fx, \dots, f^{n-1}x\}$ , where  $f^n x = x$ , by

$$\exp\left(\sum_{k=0}^{n-1} g(T^i x)\right).$$

Of course, in the particular case that g = 0 this weight reduces to 1 and the zeta function reduces to the classical Artin-Mazur zeta function defined earlier. Whereas for Anosov diffeomorphisms  $f: M \to M$  the Artin-Mazur zeta function  $\zeta(z)$  converges to an analytic function on a disk of radius  $e^{-h(f)}$ , where h(f) denotes the topological entropy. The corresponding region for the Ruelle zeta function depends on the following:

**Definition 4.11.** We can denote by

$$P(g) = \limsup_{n \to +\infty} \frac{1}{n} \log \left( \sum_{T^n x = x} \exp \left( \sum_{i=0}^{n-1} g(T^i x) \right) \right)$$

the pressure of the function  $g: M \to \mathbb{R}$ .

In particular, it follows from Definition 4.10 that the zeta function  $\zeta_g(z)$  converges to a nonzero analytic function for  $|z| < e^{-P(g)}$ . Furthermore, it is relatively easy to show that  $e^{-P(g)}$  is a simple pole for  $\zeta_g(z)$ .

Unfortunately, the meromorphic extension for this zeta function is harder to establish than in the case of the Artin-Mazur zeta function. Moreover, we can no longer expect the zeta function to be a simple rational function. However, it was proved relatively recently that:

**Theorem 4.12** (Liverani-Tsujii, Baladi). If  $f : M \to M$  is a  $C^{\infty}$  Anosov diffeomorphism then  $\zeta_q(z)$  has a meromorphic extension to  $\mathbb{C}$ .



Figure 11: Liverani (1957-), Tsujii (1964-) and Baladi (1963-)

The basic method of proof is to introduce a linear operator called a Ruelle transfer operator, which heuristically plays the role of the matrix A in the case of the simpler Bowen-Lanford zeta

function for directed graphs. The difficulty is in identifying an appropriate Banach space relative to which this operator has good spectral properties, and then deriving from these the meromorphic extension.

However, the situation for Anosov flows is even more complicated. Therefore, we first want to consider the classical special case of geodesic flows on negatively curved surfaces.

# 5 Selberg Zeta function

Perhaps one of the easier routes into understanding dynamical zeta functions for flows is via the more geometric example of a geodesic flow on negatively curved manifolds.

### 5.1 Hyperbolic geometry and closed geodesics

A particularly important zeta function in both analysis and geometry is the Selberg zeta function. A comprehensive account appears in the book of Hejhal. A lighter account appears in the work of [11].

Assume that V is a compact surface with constant curvature  $\kappa = -1$ . The covering space is the Poincaré disc  $\mathbb{D}^2 = \{z = x + iy : |z| < 1\}$  with the Poincaré metric

$$ds^{2} = 4\frac{dx^{2} + dy^{2}}{(1 - |z|^{2})^{2}}$$

(which again has constant curvature  $\kappa = -1$ ). In particular, compared with the usual Euclidean distance, the distance in the Poincaré metric tends to infinity as |z| tends to 1, to the extent that geodesics never actually reach the boundary.

We begin with an elementary result.

Lemma 5.1. There are a countable infinity of closed geodesics.

*Proof.* There is a one-one correspondence between closed geodesics and conjugacy classes in the fundamental group  $\pi_1(V)$ . The group  $\pi_1(V)$  is finitely generated and countable, as are its conjugacy classes.

We can denote by  $\gamma$  one of the countably many closed geodesics on V. We can then write  $l(\gamma)$  for the length of  $\gamma$ .

### 5.2 The definition of the Selberg zeta function

We now come to the definition of the Selberg zeta function for closed geodesics on the compact surface  $V.^{15}$ 

<sup>&</sup>lt;sup>15</sup>The fact that we have a zero at s = 1, rather than pole, is simply an artefact of the way the Selberg zeta function is defined. Rather than defy convention, we prefer to use this definition. However, when we (eventually) define the Ruelle zeta function for flows we will use a convention closer to that of the Riemann zeta function.



Figure 12: The Poincaré disk with some geodesics, and Selberg (1917–2007)

**Definition 5.2.** The Selberg zeta function is a function of  $s \in \mathbb{C}$  defined by

$$Z(s) = \prod_{n=0}^{\infty} \prod_{\gamma} \left( 1 - e^{-(s+n)l(\gamma)} \right),$$

which converges for Re(s) > 1.

One explanation for the extra product over n is that it simplifies the statement on the location of the zeros for Z(s). The main result on the Selberg zeta function is the following:

**Theorem 5.3** (Selberg, 1956). The zeta function Z(s) converges to a non-zero analytic function for Re(s) > 1. Moreover,

- 1. Z(s) has a simple zero at s = 1;
- 2. Z(s) has no further zeros on Re(s) = 1;
- 3. Z(s) has an analytic extension to  $\mathbb{C}$ .

The original proof used the Selberg trace formulae, which we will briefly describe later.

As an immediate application of Theorem 5.3 (in particular parts 1 and 2) one could proceed by complete analogy with the proof of the Prime Number Theorem to deduce the following:

Theorem 5.4 (Prime geodesic theorem).

$$\operatorname{Card}\{\gamma \, : \, l(\gamma) \leq T\} \sim \frac{e^T}{T} \text{ as } T \to +\infty$$

Here the lengths appear in the exponent, which is why the principal term takes the form  $e^T/T$ , compared with  $x/\log T$  for the Prime Number Theorem (Theorem 2.4). Moreover, that the exponent is 1 is a consequence of the choice of the curvature being -1. More generally, if the curvature were  $-|\kappa| < 0$  then the asymptotic would be of the form  $e^{\sqrt{|\kappa|}T}/(\sqrt{|\kappa|}T)$ .

### 5.3 The Laplacian and the "Riemann Hypothesis"

The Selberg zeta function Z(s) has a distinct advantage over the Riemann zeta function  $\zeta(s)$  in that one can show a version of the Riemann Hypothesis for Z(s), and consequently get stronger versions of the Prime geodesic theorem. This stems from a characterisation of the zeros of Z(s) in terms of the spectrum of the Laplacian.

**Definition 5.5.** Let  $\Delta : L^2(V) \to L^2(V)$  be the Laplacian (the operator is actually defined on the  $C^{\infty}(M)$  functions and extends to the square integrable functions in which they are dense).

The Laplacian is defined locally, so we can more consider the Poincaré Disc (i.e., its universal cover with the associated lifted metric) where the corresponding Laplacian takes the explicit form

$$\Delta_{\mathbb{D}^2} = \frac{1}{4} (1 - |z|^2) \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)$$

where  $z = x + iy \in \mathbb{D}^2$ . The following result is standard:

**Lemma 5.6.** The laplacian is a self-adjoint operator. In particular, its spectrum lies on the real line.

We are interested in the solutions  $^{16}$ 

$$0 = \lambda_0 < \lambda_1 \le \lambda_2 \le \cdots$$

for the eigenvalue equation  $\Delta \phi_n + \lambda_n \phi_n$ . The location of the zeros  $s_n$  for Z(s) are described in terms of the eigenvalues  $\lambda_n$  for the Laplacian:

**Theorem 5.7** (Selberg). The zeros of the Selberg zeta function Z(s) can be described by:

- 1. s = 1 is a simple zero;
- 2.  $s_n = \frac{1}{2} \pm i \sqrt{\frac{1}{4} \lambda_n}$ , for  $n \ge 1$ , are "spectral zeros"; and
- 3. s = -m, for  $m = 0, 1, 2, \cdots$ , are "trivial zeros".

In particular, we have a variant of the "Riemann Hypothesis" for Z(s).

**Corollary 5.8.** Z(s) has only finitely many zeros in the half-plane  $Re(s) > \frac{1}{2}$  (which lie on the real axis).

Thus we have the corresponding improvement to Prime Geodesic Theorem 5.4.

**Corollary 5.9.** There exists  $\epsilon > 0$  such that

$$\operatorname{Card}\{\gamma : l(\gamma) \le T\} = \int_{2}^{e^{T}} \frac{du}{\log u} + O\left(e^{(1-\epsilon)T}\right) \text{ as } T \to +\infty.$$

<sup>&</sup>lt;sup>16</sup>Which tend to infinity at a rate given by Weyl's law.



Figure 13: Zeros of the Selberg zeta function Z(s)

### 5.4 Pairs of pants: an example of analytic extension for Z(s)

Having extolled the (very real) virtues of the spectral approach for compact surfaces of constant negative curvature, we will now consider the case of a non-compact infinite area surface for it is more appropriate to use a dynamical, rather than a spectral approach.

A pair of pants V (or three funnelled surface) is a classical example of a surface of constant curvature  $\kappa = -1$ , but unlike the previous setting has three infinite area funnels. Equivalently, we can consider this as a sphere with three geodesic boundary components by choosing the closed geodesics around each of the funnels.



Figure 14: A pair of pants: A surface of constant curvature, but with three geodesic boundary components

In this context we have the following result:

**Theorem 5.10.** There exists  $0 < \delta < 1$  such that Z(s) converges to a non-zero analytic function for  $Re(s) > \delta$ . Moreover,

- 1. Z(s) has a simple zero at  $s = \delta$ ; and
- 2. Z(s) has an analytic extension to  $\mathbb{C}$ .

Unlike the case of compact surfaces, the location of the other zeros in  $Re(s) < \delta$  is very mysterious, and we will return to this problem later.

We can give a sketch of a proof of Theorem 5.10 (particularly of the second part) which uses a transfer operator approach. This can vaguely be thought of as using Ruelle transfer operators as a natural generalisation of the matrix in the case of graph zeta functions.

#### 5.4.1 Maps on the boundary

We begin by associating to the surface an expanding map on four arcs on the unit circle.



Figure 15: The Möbius maps associated to a Pair of Pants

- 1. Möbius maps: We can associate to the pair of pants two Möbius maps  $a, b : \mathbb{D}^2 \to \mathbb{D}^2$ which generate the covering transformations for V and preserve the unit disk  $\mathbb{D}^2$  (and are isometric with respect to the Poincaré metric) and extend to the boundary  $S^1 = \partial \mathbb{D}^2$ . In particular, we can write  $V = \mathbb{D}^2/\Gamma$ . We can then associate to each element of  $\Gamma_0 =$  $\{a, b, a^{-1}, b^{-1}\}$  their isometric circles (i.e., for any such Möbius map  $g \in \Gamma_0$  we write  $C(g) = \{z \in \overline{\mathbb{D}^2} : |g'(z)| = 1\}$ ).
- 2. Isometric circles: The four arcs  $C(a), C(b), C(a^{-1}), C(b^{-1}) \subset \overline{\mathbb{D}^2}$  are disjoint and each meets the boundary  $\partial \mathbb{D}^2$  orthogonally. Moreover, observe that if  $g \in \Gamma_0$  then  $gC(g) = C(g^{-1})$  since  $(g^{-1}g)'(z) = (g^{-1})'(gz)g'(z) = 1$  and thus if |g'(z)| = 1 then  $|(g^{-1})'(gz)| = 1$ . In particular, we have <sup>17</sup>

$$aC(a) = C(a^{-1})$$
  

$$bC(b) = C(b^{-1})$$
  

$$a^{-1}C(a^{-1}) = C(a)$$
  

$$b^{-1}C(b^{-1}) = C(b).$$

3. The transformations: For each  $g \in \Gamma_0$ , we denote by I(g) the natural arc of  $\partial D$  which has the two endpoints  $\partial \mathbb{D}^2 \cap C(g)$ . The arcs  $I(a), I(b), I(a^{-1}), I(b^{-1})$  are disjoint. We

<sup>&</sup>lt;sup>17</sup>This construction is described on pages 337-338 of [10].

then have well defined maps

$$\begin{split} T_a: I(a^{-1}) \cup I(b) \cup I(b^{-1}) &\to I(a^{-1}) \text{ defined by } T_a(z) = az \\ T_b: I(a) \cup I(a^{-1}) \cup I(b^{-1}) &\to I(b^{-1}) \text{ defined by } T_b(z) = bz \\ T_{a^{-1}}: I(a) \cup I(b) \cup I(b^{-1}) &\to I(a) \text{ defined by } T_{a^{-1}}(z) = a^{-1}z \\ T_{b^{-1}}: I(a) \cup I(b^{-1}) \cup I(a^{-1}) &\to I(b^{-1}) \text{ defined by } T_{b^{-1}}(z) = b^{-1}z \end{split}$$

These maps can be assumed to be contracting.

The first advantage of the above coding is that we can write the lengths of closed geodesics in terms of the derivatives of compositions of the maps at their unique fixed points. More precisely, given any cyclically reduced string of generators  $g = g_1 \cdots g_n \in \langle a, b \rangle$  we can associate a contracting map

$$T_g := T_{g_1} \circ \cdots \circ T_{g_n} : I(g_1^{-1}) \to I(g_1^{-1}).$$

Let x(g) be the unique fixed point then we can see by a simple calculation<sup>18</sup> that:

**Lemma 5.11.** The length of the corresponding closed geodesic is  $-\log |T'_q(x(g))|$ .

### 5.4.2 The Ruelle transfer operator

We next want to introduce a classical Ruelle transfer operator. Let  $\mathcal{B}$  be the Banach space of bounded analytic functions functions on a small complex neighbourhood U, say, the union of the four arcs.

**Definition 5.12.** We want to define a family of operators  $\mathcal{L}_s : B \to B$ , where  $s \in \mathbb{C}$ , by

$$\mathcal{L}_s w(z) = \sum_{g \neq g_0} e^{-s \log |T'_g(z)|} w(T_g z) \text{ for } z \in I(g_0)$$

where the sum is over three of the four elements  $g \in \Gamma_0$  where we exclude the one  $g_0$  for which z lies in the arc  $I(g_0)$ . This makes the operator well defined.

The operator is well defined providing the neighbourhood U is sufficiently small. The key features of these operators on this Banach space are the following strong spectral properties.

**Lemma 5.13** (Grothendieck, 1955). The operator  $\mathcal{L}_s$ , (and its powers  $\mathcal{L}_s^n$ ,  $n \ge 1$ ) are trace class (i.e., there are only countably many non-zero eigenvalues and their sum is well defined).

Perhaps one might think of the operators  $\mathcal{L}_s$  as somehow replacing the matrices we had before for graphs. We can easily check by explicit calculations the following:

 $<sup>^{18}\</sup>mbox{For example},$  by considering the axis of the hyperbolic translation corresponding to the geodesic.

<sup>&</sup>lt;sup>19</sup>A very nice reference for this in the simpler case of continued fractions is [6].

Lemma 5.14 (Ruelle, 1976). We have

$$trace(\mathcal{L}_s^n) = \sum_{g=g_1\cdots g_n} \frac{e^{-s(\log |T'_g(x(g)|))}}{1 - T'_g(x(g))}$$

and then we can write

$$Z(s) = \exp\left(-\sum_{n=1}^{\infty} \frac{1}{n} \operatorname{trace}(\mathcal{L}_{s}^{n})\right).$$

This provides the analytic extension. The other results follow from the properties of the eigenvalues of  $\mathcal{L}_s$ .

Remark 5.15. If one thinks of trace class operators as being natural generalisations of matrices A (i.e., finite dimensional operators) then the equation for Z(s) above is rather reminiscent of the easy matrix identity

$$\frac{1}{\det(I-A)} = \exp\left(-\sum_{n=1}^{\infty} \frac{1}{n} \operatorname{trace}(A^n)\right).$$

#### **5.4.3** The zeros for Z(s) for a pair of pants.

In contrast to the case of compact surfaces (where the spectral theory of the Laplacian is available) much less is known about the location of the zeros of Z(s) in this case. Indeed experimental evidence shows that the situation is very different.





There are a small number of interesting results on the locations of the zeros.

1. For any  $\sigma < \delta$ , we have

Card{zeros  $z : T \leq |Im(z)| \leq T + 1, \sigma \leq Re(z) \leq \delta$ } =  $O(T^{\delta})$ 

(Guillopé-Lin-Zworski).

2. There is a zero free region  $\{s \in \mathbb{C} : Re(s) > \delta - \epsilon\} - \{\delta\}$ , for some  $\epsilon > 0$  (Naud)

Moreover, it is conjectured that there are only finitely many zeros in any half-plane  $\frac{\delta}{2} + \epsilon < Re(s)$ .

Related estimates appear in work of Bourgain-Gamburd-Sarnak and Bourgain-Kontorovich.

*Remark* 5.16. This application of transfer operators to Z(s) is illustrative of how useful they can be in situations where they can be applied to get accurate numerical estimates of values. Similar methods have been applied to computing the Hausdorff Dimension of hyperbolic Julia sets and the limit sets of Schottky groups.

### 5.5 The definition of the *L*-function

Let us return to the case of compact surfaces V of constant negative curvature  $\kappa = -1$ . We can modify the definition of the Selberg zeta function by associating to closed geodesics a weight given by a unitary representation  $R : \pi_1(V) \to U(N)$ , where the unitary group U(N) consists of  $N \times N$  matrices A for which  $A^*A$  is a non-zero multiple of the identity matrix I.

If  $\gamma$  is a closed geodesic then we denote by  $[\gamma]$  the associated free homotopy class (i.e., conjugacy class in  $\pi_1(V)$ ) and the value  $R([\gamma]) \in U(N)$ .

**Definition 5.17.** The Selberg L-function associated to a unitary representation  $R : \pi_1(V) \to U(N)$  is a function of  $s \in \mathbb{C}$  defined by

$$L(s,R) = \prod_{n=0}^{\infty} \prod_{\gamma} \det \left( I - e^{-(s+n)l(\gamma)} R([\gamma]) \right),$$

which converges for Re(s) > 1.

The main result on the Selberg L-function is the following generalization of Theorem 5.3:

**Theorem 5.18** (Selberg, 1956). The L-function L(s, R) converges to a non-zero analytic function for Re(s) > 1. Moreover,

- 1. Z(s) has a simple zero at s = 1 if and only if R is the trivial representation;
- 2. Z(s) has no further zeros on Re(s) = 1;
- 3. Z(s) has an analytic extension to  $\mathbb{C}$ .

The original role of the L-function in number theory was to describe the distribution of primes in different congruency classes (Theorem 2.10). In the context of geodesics  $\gamma$  on V there is another form of equidistribution result. More precisely, let us assume that  $\hat{V}$  is a finite cover for V and let G be the finite covering group. Each closed geodesic  $\gamma$  on V can be lifted to a closed geodesic  $\hat{\gamma}$  on  $\hat{V}$ . However, the lifted geodesic  $\hat{\gamma}$  need not necessarily have the same length as  $\gamma$ . Therefore if  $\gamma$  has length  $l(\gamma)$  then we can choose any point  $x \in \gamma$  and consider its lift to  $\hat{x} \in \hat{\gamma}$ . The corresponding point on  $\hat{V}$  which is at a distance  $l(\gamma)$  along the geodesic from  $\hat{x}$  is again a lift of x. It can therefore be written as  $g\hat{x}$  where  $g = g(\gamma) \in G$  (which is defined up to conjugacy, depending on the initial choice of  $\hat{x}$ ).

We will assume that  $\widehat{V}$  is a Galois covering for V, i.e., for any two points in  $\widehat{V}$  which project to the same point in V then one can be mapped to the other by some element of G. The generalisation of Theorem 5.4 takes the following form.

**Theorem 5.19** (Dirichlet geodesic theorem). Let C be a conjugacy class in G.

Card{
$$\gamma : l(\gamma) \leq T \text{ and } g(\gamma) \in C$$
}  $\sim \frac{|C|}{|G|} \frac{e^T}{T}$  as  $T \to +\infty$ 

where |C| and |G| are numbers of elements in C and G, respectively.

#### 5.6 Poincaré series and orbital counting

There is natural parallel between zeta functions and Poincaré series, another complex function associated to a surface V with constant curvature  $\kappa = -1$ .

#### 5.6.1 The case of compact surfaces

Let us initially return to the original hypothesis that V is a compact surface. If we fix a point  $x_0 \in V$  then there is a correspondence between elements of the fundamental group  $\pi_1(V, x_0)$  and geodesic arcs beginning and ending at  $x_0$ .

Let  $\tilde{x}_0 \in \mathbb{D}^2$  be a lift to the Poincaré disk, which is the covering space for V. The group of covering transformations  $\Gamma < \text{Isom}(\mathbb{D}^2)$  is isomorphic to the Fundamental group, i.e.,  $\Gamma \cong \pi_1(V, x_0)$ . We can therefore consider the orbit  $g\tilde{x}_0$ ,  $g \in \Gamma$ , and associate the distances  $d(g) := d(g\tilde{x}_0, \tilde{x}_0)$ .

**Definition 5.20.** The Poincaré series is a function of  $s \in \mathbb{C}$  defined by

$$\eta(s) = \sum_{g \in \Gamma - \{e\}} e^{-sd(g)}$$

which converges for Re(s) > 1.

The main result on the Poincaré series is the following:

**Theorem 5.21** (Selberg, 1956). The zeta function  $\eta(s)$  converges to a non-zero analytic function for Re(s) > 1. Moreover,

- 1.  $\eta(s)$  has a simple zero at s = 1;
- 2.  $\eta(s)$  has no further zeros on Re(s) = 1; and
- 3.  $\eta(s)$  has an analytic extension to  $\mathbb{C}$ .

The statement and proof are very similar to those for Theorem 5.3. Similarly, by analogy with Theorem 5.4, we have the following application.

**Theorem 5.22** (Orbital Counting). There exists C > 0 such that

$$Card\{g \in \Gamma : d(g) \le T\} \sim Ce^T \text{ as } T \to +\infty.$$

This is often called a "hyperbolic circle problem" by analogy with the classical problem of counting lattice points from  $\mathbb{Z}^2$  in a disk of Euclidean radius T (where, of course, the counting function is simply asymptotic to  $\pi T^2$ ).

In the context of counting points in the orbit  $\Gamma \tilde{x}_0 = \{g\tilde{x}_0 : g \in \Gamma\}$  a natural refinement is to count those  $g \in \Gamma$  which lie in a sector with vertex at  $\tilde{x}_0$ . More precisely, let us consider two geodesics in  $\mathbb{D}^2$  starting from  $\tilde{x}_0$  and separated by an angle  $0 < \theta \leq \pi$ . This describes a sector in  $\mathbb{D}^2$  which we can denote by  $S(\tilde{x}_0, \theta)$ . The following gives a nice refinement of Theorem 5.22 above.

**Theorem 5.23** (Sector Theorem). There exists C > 0 such that

Card{
$$g \in \Gamma : g\widetilde{x}_0 \in S(\widetilde{x}_0, \theta) \text{ and } d(g) \leq T$$
} ~  $C\theta e^T$  as  $T \to +\infty$ .

The analogy between the Poincaré series  $\eta(s)$  and the Selberg zeta function Z(s) extends to their entire domain. In particular, the zeros of  $\eta(s)$  are closely related to those of Z(s) through a common interpretation in terms of the spectrum of the Laplacian  $\Delta : L^2(V) \to L^2(V)$ . In particular, we again have that there exists  $\epsilon > 0$  such that the only zero for  $\eta(s)$  in the half-plane  $Re(s) > 1 - \epsilon$  occurs at s = 1.

Thus we have the corresponding improvement to the Orbital Counting Theorem 5.22.

**Theorem 5.24.** There exists C > 0 and  $\epsilon > 0$  such that

$$Card\{g \in \Gamma : d(g) \le T\} = Ce^T + O(e^{(1-\epsilon)T}) \text{ as } T \to +\infty.$$

#### 5.6.2 The case of a pair of pants

Let us now consider the case that V is an infinite area surface and, for definiteness, that it is a pair of pants. If we fix a point  $x_0 \in V$  then there is again a correspondence between elements of the fundamental group  $\pi_1(V, x_0)$  and geodesic arcs beginning and ending at  $x_0$ . We can again associate the distances  $d(g) := d(g\tilde{x}_0, \tilde{x}_0)$  and the Poincaré series

$$\eta(s) = \sum_{g \in \Gamma} e^{-sd(g)}$$

which converges for  $Re(s) > \delta$ .

The main result on the Poincaré series is the following analogue of Theorem 5.21.

**Theorem 5.25.** The Poincaré series  $\eta(s)$  converges to a non-zero analytic function for  $Re(s) > \delta$ . Moreover,

- 1.  $\eta(s)$  has a simple zero at  $s = \delta$ ;
- 2.  $\eta(s)$  has no further zeros on  $Re(s) = \delta$ ; and
- 3.  $\eta(s)$  has an analytic extension to  $\mathbb{C}$ .

The statement is very similar to the first two parts of Theorem 5.21. However, the method of proof is somewhat different, requiring a dynamical viewpoint rather than that of the classical proof of Theorem 5.21 using trace formulae. However, by analogy with Theorem 5.22, we still have the following application.

**Theorem 5.26** (Orbital Counting). There exists C > 0 such that

Card
$$\{g \in \Gamma : d(g) \leq T\} \sim Ce^{\delta T} \text{ as } T \to +\infty.$$

There is also an analogue of the sector theorem.

**Theorem 5.27** (Sector Theorem). There exists C > 0 such that

Card{ $g \in \Gamma : g\widetilde{x}_0 \in S(\widetilde{x}_0, \theta) \text{ and } d(g) \leq T$ } ~  $C\theta e^{\delta T}$  as  $T \to +\infty$ .

### 6 Ruelle zeta function for Anosov flows

We now come to the more general setting of the Ruelle zeta function for Anosov flows. This includes, as a special case, the zeta function for geodesic flows on manifolds with negative sectional curvatures.

### 6.1 Definitions

We recall the definition of an Anosov flow on a compact manifold M.

**Definition 6.1.** We say that a  $C^{\infty}$  flow  $\phi_t : M \to M$  is Anosov if the following hold.

- 1. There is a  $D\phi_t$ -invariant splitting  $TM = E^0 \oplus E^s \oplus E^u$  such that
  - (a)  $E^0$  is one dimensional and tangent to the flow direction;
  - (b)  $\exists C, \lambda > 0$  such that  $\|D\phi_t|E^s\| \leq Ce^{-\lambda t}$  and  $\|D\phi_{-t}|E^u\| \leq Ce^{-\lambda t}$  for t > 0.
- 2. The flow is transitive (i.e., there exists a dense orbit).



Figure 17: The hyperbolicity transverse to the orbit of an Anosov flow

The main example is the geodesic flow on a surface of (variable) negative curvature.

**Example 6.2** (Geodesic flow). Let V be a compact surface with curvature  $\kappa(x) < 0$ , for  $x \in V$ . Let  $M = SV = \{(x, v) \in TV : ||v||_x = 1\}$  denote the unit tangent bundle then we let  $\phi_t : M \to M$  denote the geodesic flow, i.e.,  $\phi_t(v) = \dot{\gamma}(t)$  where  $\gamma : \mathbb{R} \to V$  is the unit speed geodesic with  $\dot{\gamma}(0) = (x, v)$ . Moreover, the closed orbits for the geodesic flow correspond to closed geodesics on V.



Figure 18: The geodesic flow on a negatively curved surface is an example of an Anosov flow

In particular, the study of Anosov flows therefore includes the extension of geodesic flows from constant to variable negative curvature.

**Definition 6.3.** We say that  $\tau$  is a closed orbit of least period  $\lambda(\tau)$  if there exists  $x \in \tau$  with  $\phi_{\lambda(\tau)}x = x$ , with  $\lambda(\tau) > 0$  the least such value.

We can denote by  $N(T) = \text{Card}\{\tau : \lambda(\tau) \leq T\}$  the number of periodic orbits  $\tau$  of (prime) period  $\lambda(\tau) \leq T$ . The following result is the continuous analogue of Lemma 4.3.

**Lemma 6.4** (Sinai, 1966). The number N(T) grows exponentially fast, i.e.,

$$h(\phi) = \lim_{T \to +\infty} \frac{1}{T} \log N(T) > 0.$$

This leads naturally to the following definition.

**Definition 6.5.** The value  $h(\phi)$  is called the topological entropy of the Anosov flow.

By analogy with the product form of the zeta function for diffeomorphisms we define the zeta function for an Anosov flow as follows:

Definition 6.6. The Ruelle zeta function for an Anosov flow is the function

$$\zeta(s) = \prod_{\tau} \left( 1 - e^{-s\lambda(\tau)} \right)^{-1}$$

It is easy to see from Lemma 6.4 that the zeta function  $\zeta(s)$  converges on the half-plane  $Re(s) > h(\phi)$ .

Remark 6.7. Definition 6.6 can be viewed as the natural analogue of Definition 2.1 of the Riemann zeta function. In that definition we can replace the primes by closed orbits  $\tau$  and the value p by  $e^{\lambda(\tau)}$  and then this formally gives the expression for the zeta function of Ruelle. Remark 6.8. The "extra" product over n in the definition of the Selberg zeta function is essentially a convenience in presenting results which are specific to that setting. However, it can easily be to related to the definition of the Ruelle zeta function. Formally, we can write

$$\zeta(s) = \frac{Z(s+1)}{Z(s)}$$
 and  $Z(s) = \prod_{n=0}^{\infty} \zeta(s+n)^{-1}$ .

### 6.2 Basic properties of the Ruelle zeta function

There are old results which are analogues of the first properties of the Riemann zeta function.<sup>20</sup>

Figure 19: Ruelle (1935-) and Parry (1934-2006)

**Theorem 6.9** (Ruelle, 1978; Parry-Pollicott, 1983). The Ruelle zeta function is non-zero and analytic on  $Re(s) > h(\phi)$ . Moreover,

- 1.  $\zeta(s)$  has a simple pole at  $s = h(\phi)$ ; and
- 2.  $\zeta(s)$  has an analytic extension to a neighbourhood of  $\{s \in \mathbb{C} : Re(s) = h(\phi)\} \{h(\phi)\}$ (when the flow is weak-mixing, e.g., geodesic flows).

However, as in the case of the derivation of the Prime Geodesic Theorem (Corollary 5.4) and the proof of the Prime number theorem we have a corresponding Prime Orbit Theorem. For convenience we make the following assumption: The periods of closed orbits are not all natural number multiples of a single constant, i.e., there is no a > 0 such that  $\{\lambda(\tau)\} \subset a\mathbb{N}$ . This is a generic condition called topological weak mixing and holds, for example, for any geodesic flow on a negatively curved manifold.

Theorem 6.10 (Prime orbit theorem). For any topologically weak mixing Anosov flow

$$Card\{\tau : \lambda(\tau) \le T\} \sim \frac{e^{h(\phi)T}}{h(\phi)T} \text{ as } T \to +\infty.$$

One can develop a little more the approach used to prove Theorem 6.9 in order to get the following slightly stronger result:

**Theorem 6.11** (Pollicott, 1986). There exists  $\epsilon > 0$  such that the zeta function  $\zeta(s)$  has a meromorphic extension to a slightly large half-plane  $Re(s) > 1 - \epsilon$ .

However, this is as far as this classical method of "symbolic dynamics" could get us and therefore a new idea was needed.  $^{21}$ 

<sup>&</sup>lt;sup>20</sup>Ruelle's result was that  $h(\phi)$  is a simple pole, a result that appears as an exercise in his book Thermodynamic Formalism which Parry and I couldn't solve. The following recollection appears in David Ruelle's article [9] "Having obtained the above nontrivial but apparently useless result, I put it as Exercise 7(c) on page 101 in my book Thermodynamic Formalism. A few years later (December 29, 1982) Bill Parry of Warwick wrote to me about very interesting results on Axiom A flows he had obtained with his student Mark Pollicott. These results used Exercise 7(c), which unfortunately he had been unable to do. Could I help? By the time I had (painfully) managed to reconstruct the solution of the exercise I received another letter: 13 Jan 83

Dear David, We've finally managed to do your exercise! So ignore my last letter. Sincerely, Bill Parry."

What Ruelle didn't know is that our solution to the exercise was incorrect, and so we used his answer after all.

<sup>&</sup>lt;sup>21</sup>The basic steps were the following:

<sup>1.</sup> Choose codimension-one Markov sections transverse to the flow (with associated flow boxes);

### 6.3 Further extensions

Using more modern techniques one can get a full extension to all of  $\mathbb{C}.^{22}$ 

**Theorem 6.12** (Giulietti-Liverani-Pollicott, 2013; Dyatlov-Zworski, 2013). Let  $\phi_t : M \to M$ be a  $C^{\infty}$  Anosov flow. The zeta function  $\zeta(s)$  has a meromorphic extension to  $\mathbb{C}$ .

Similar results were previously known under stronger hypotheses:

- 1. If the Anosov flow  $\phi_t : M \to M$  is  $C^{\omega}$  and has stable and unstable foliations which are  $C^{\omega}$  then  $\zeta(s)$  has a meromorphic extension to  $\mathbb{C}$  (Ruelle, 1976); and stronger still;
- 2. If the Anosov flow  $\phi_t : M \to M$  is  $C^{\omega}$  then  $\zeta(s)$  has a meromorphic extension to  $\mathbb{C}$  (Rugh, Fried 1996).

Thus our main result is really to go from  $C^{\omega}$  to  $C^{\infty}$ .

We briefly recall the strategy of the poof of Theorem 6.12.

Step 1. Motivated by work of Gouëzel-Liverani (and Baladi-Tsujii) for Anosov diffeomorphisms: We define simple operators on complicated Banach spaces. Consider the one-parameter family of operators  $\mathcal{L}_t : C^0(M) \to C^0(M)$  defined by

$$\mathcal{L}_t w(x) = w(\phi_t x)$$
 for  $t > 0$ .

Step 2. To eliminate the effect of the flow direction we want to "integrate away" the flow direction: For each  $s \in \mathbb{C}$  let  $R(s) : C^0(M) \to C^0(M)$ , be defined by

$$R(s)w(x) = \int_0^\infty e^{-st} \mathcal{L}_t w(x) dt \text{ where } w \in C^0(M)$$

for Re(S) > 0, say. (This corresponds to the resolvent of the generator for the Anosov flow).

Step 3. We need to replace  $C^0(M)$  by "better spaces"  $\mathbb{B}$  of special distributions, i.e., one for which there is less spectrum (i.e., *complicated* Banach spaces).

**Theorem 6.13.** For each  $k \ge 1$  we can choose  $\mathbb{B}_k$  appropriately so that that  $R(s) : \mathcal{B}_k \to \mathcal{B}_k$  has only isolated eigenvalues for Re(s) > -k.

- 2. The flow boxes are foliated by stable/contracting manifolds;
- 3. The flow boxes can be collapsed along the stable/contracting directions; and finally
- 4. The Poincaré map reduces to an expanding map.

The advantage of the expanding map is that there are many preimages, which can be used to approximate the periodic orbits; and the dual (transfer) operator to the expanding map has good spectral properties (e.g., a spectral gap). However, the regularity of the stable foliations determines the regularity of the function space, and thus the size of the essential spectrum of the operator.

 $^{22}$ The paper of Giulietti-Liverani-Pollicott was written between 2007-2012. The paper of Dyatlov-Zworski appeared as a preprint 5 days before the lectures which were the origin of the notes were given in 2013, and uses semi-classical analysis to construct the anisotropic spaces used in both proofs.

**Step 4.** We want to use the operator  $\mathcal{L}_t$  to extend  $\zeta(s)$ . We need to make sense of

$$\texttt{``det}(I - R(s)) = \exp\left(\sum_{n=1}^{\infty} \frac{1}{n} \mathsf{tr}\left(R(s)^n\right)\right)''$$

for operators R(s) which are not trace class (using suitable approximations).

Step 5. Finally, we need to relate  $\zeta(s)$  to "det(I - R(s))", which in fact involves having to repeat the previous steps all over again for spaces of differential forms in place of functions, in order to fix up the identities.

In fact the proof also works well when the flow is only finitely differentiable. If we consider a  $C^k$  Anosov flow  $\phi_t : M \to M$  ( $1 \le k < +\infty$ ) then we get the following extension.

**Theorem 6.14** (Giulietti-Liverani-Pollicott). Let  $\lambda > 0$  be the value in the definition of the Anosov flow. Then  $\zeta(s)$  has a meromorphic extension to  $Re(s) > h(\phi) - \lambda[\frac{k}{2}]$ .

In particular, a consequence of the main theorem is the following generalization of Selberg's theorem (originally proved using the Selberg trace formula approach).

**Corollary 6.15** (of the Main Theorem). For compact manifolds having variable negative sectional curvature,  $\zeta(s)$  extends meromorphically to the entire complex plane  $\mathbb{C}$ .

Consider the special case of a compact surface of *constant negative curvature*  $\kappa = -1$ . We then recover the following:

**Corollary 6.16** (Selberg, 1956; Ruelle, 1976). For surfaces of constant negative curvature,  $\zeta(s)$  extends meromorphically to the entire complex plane  $\mathbb{C}$ .

### 6.4 The Riemann hypothesis for the Ruelle zeta function

#### 6.4.1 The case for surfaces

We recall the "Riemann hypothesis" for geodesic flows on negatively curved surfaces.

**Theorem 6.17** (Dolgopyat, 1998). Let V be a compact negatively curved surface V. There exists  $\epsilon > 0$  such that  $\zeta(s)$  has an analytic zero-free extension to  $Re(s) > h(\phi) - \epsilon$ , except for a simple pole at s = h.

This has the following consequences for the number N(T) of closed orbits  $\tau$  for the geodesic flow with  $\lambda(\tau) \leq T$ .

**Corollary 6.18.** Under the above hypotheses we have the estimate

$$N(T) = \int_{2}^{e^{h(\phi)T}} \frac{1}{\log u} du + O(e^{(h(\phi) - \epsilon)T})$$

### 6.4.2 The case for higher-dimensional manifolds

Thieorem 6.17 has the following partial generalization to higher-dimensional manifolds V.

**Theorem 6.19** (Giulietti, Liverani and Pollicott, 2013). Let V be a compact manifold for which the (negative) sectional curvatures are  $\frac{1}{9}$ -pinched. There exists  $\epsilon > 0$  such that  $\zeta(s)$  has an analytic zero-free extension to  $Re(s) > h - \epsilon$ , except for a simple pole at s = h.

The result also holds at the level of contact Anosov flows which are  $\frac{1}{3}$ -bunched.

By analogy with what we have seen before several times, Theorem 6.19 has immediate consequences for improving the Prime Orbit Theorem:

**Corollary 6.20.** Under the above hypotheses we can estimate that the number N(T) of closed orbits  $\tau$  for the geodesic flow with  $\lambda(\tau) \leq T$  by

$$N(T) = \int_2^{e^{hT}} \frac{1}{\log u} du + O(e^{(h-\epsilon)T}).$$

This can be viewed as a generalisation of previous results:

- 1. This generalizes the theorem of Selberg and Huber from 1956-1959 (from the geodesic flow on manifolds V of *constant* negative curvature(s) to that of variable negative curvature(s)); and
- 2. This partly generalizes the theorem of Margulis from 1969 (for the geodesic flow on manifolds V of variable negative curvature(s), but with no error estimate).

We do not know if Corollary 6.20 remains for true for geodesic flows without the pinching condition (or even for any weak-mixing Anosov flows).

### 6.5 *L*-functions for closed geodesics

#### 6.5.1 Closed geodesics null in homology

Following Katsuda and Sunada, we can associate to a closed geodesic  $\gamma$  on a compact manifold with negative sectional curvatures its homology class  $[\gamma] \in H_1(V, \mathbb{Z})$ . Let  $\chi : H_1(V, \mathbb{Z}) \to \mathbb{C}$  be a character. We define an *L*-function by

$$L(s,\chi) = \prod_{\tau} \left( 1 - \chi\left( [\tau] \right) e^{-s\lambda(\tau)} \right)^{-1}.$$

The analysis of this L-function allows one to get analogues of Dirichlet's theorem for homology classes. Let N(T) denote the number of closed orbits  $\tau$  for the geodesic flow on a negatively curved manifold for which the least period satisfies  $\lambda(\tau) \leq T$  and which are null in homology. Let b be the first Betti number.

**Theorem 6.21** (Katsuda-Sunada). There exists C > 0 such that

$$N(T) \sim C \frac{e^{h(\phi)T}}{T^{b/2+1}}.$$

*Remark* 6.22. It would be natural to expect that  $L(s, \chi)$  has a meromorphic extension to  $\mathbb{C}$  and that  $L(0, \chi)$  is related to the torsion.

### 6.5.2 Closed orbits and Knots

Finally, we mention a recent application of McMullen of equidistribution results for homology. We can consider a sequence  $K_1, K_2, \cdots$  of smooth knots on a compact manifold M. Let  $L_n = \bigcup_{i=1}^n K_i$  and let G be a finite group. A surjective homeomorphism  $\rho : \pi_1(M - L_n) \to G$  determines a covering  $\widetilde{M} \to M$  with Galois group G. The remaining knots give a sequence of conjugacy classes  $[K_i] \subset G$ .

Following Mazur, we say that that  $(K_i)$  obey a *Chebotarov law* if for any conjugacy class  $C \subset G$  we have

$$\lim_{N \to +\infty} \frac{|\{n \le i \le N : [K_i] = C\}|}{N} = \frac{|C|}{|G|}.$$

McMullen showed the following [7]:

**Theorem 6.23** (McMullen). Let X be a closed surface of constant curvature and let  $K_1, K_2, \dots \subset M = T_1 X$  be the closed orbits of the geodesic flow ordered by length. Then  $(K_i)$  obeys a Chebotarov law.

**Theorem 6.24** (McMullen). Let  $K_1, K_2, \dots \subset M$  be the closed orbits of any topologically mixing pseudo-Anosov flow on a closed 3-manifold. Then  $(K_i)$  obeys a Chebotarov law.

# 7 Appendices

### 7.1 Proof of Theorem 3.10

We now recall the simple proof of Bass of the theorem of Ihara.<sup>23</sup> Given an undirected graph with adjacency matrix A we can use the edge presentation of the closed paths to write

$$\zeta(z) = \prod_\tau (1-z^{|\tau|})$$

where  $\tau$  is a closed non-back tracking curve which we can identify with a sequence of edge lengths. We can associate an (oriented edge) adjacency matrix W by taking each unoriented edge e and associating to it two oriented edges denoted by  $e, \overline{e}$ , say. We can then write  $\zeta(z) = \det(I-zW)^{-1}$ . We can next define a new  $2|\mathcal{E}| \times 2|\mathcal{E}|$  matrix C by

$$C(e,e') = \begin{cases} 0 & \text{ if } e'(1) \neq e(0) \\ 1 & \text{ if } e'(1) = e(0) \text{ and } e' \neq \overline{e}. \end{cases}$$

By analogy with the proof for the Bowen-Lanford zeta function we see that  $\zeta(z) = 1/\det(I-C)$ .

Let  $n = |\mathcal{V}|$  be the number of vertices and let  $m = |\mathcal{E}|$  be the number of unoriented edges. We now have some simple linear algebra:

1. We can define

$$J = \begin{pmatrix} 0 & I_m \\ I_m & 0 \end{pmatrix}$$

where  $I_m$  is the  $m \times m$  identity matrix;

 $<sup>^{23}</sup>$ Following the account in the work of Terras [11].

2. let S be a  $n\times 2m$  matrix with

$$S(v,e) = \begin{cases} 1 & \text{ if } e(0) = v \\ 0 & \text{ otherwise} \end{cases}; \text{ and }$$

3. let T be a  $n\times 2m$  matrix with

$$T(v,e) = \begin{cases} 1 & \text{ if } e(1) = v \\ 0 & \text{ otherwise} \end{cases}$$

It is a routine calculation to check that:

- 1. SJ = T and TJ = S;
- 2.  $A = ST^T$  and  $(q+1)I_n = SS^T = TT^T$ ; and
- 3.  $W + J = T^T S$ .

In particular, we can now check the matrix identity:

$$\begin{pmatrix} I_n & 0\\ T^T & I_{2m} \end{pmatrix} \begin{pmatrix} I_n(1-z^2) & Sz\\ 0 & I_{2m}-Wu \end{pmatrix} = \begin{pmatrix} I_n - Az + qIz^2 & Sz\\ 0 & I_{2m}+Jz \end{pmatrix} \begin{pmatrix} I_n & 0\\ T^T - S^Tz & I_{2m} \end{pmatrix}.$$

We next take determinants and write

$$(1-z^2)^n \det(I-zW) = \det(I_n - Az + qIz^2) \det(I_{2m} + Jz).$$

Finally, we we only need to observe that since

$$I_{2m} + Jz = \begin{pmatrix} I_m & I_m z \\ I_m z & I_m \end{pmatrix}$$

we have that

$$\begin{pmatrix} I_m & 0\\ -I_m z & I_m \end{pmatrix} (I + Jz) = \begin{pmatrix} I_m & I_m z\\ 0 & I_m (1 - z^2) \end{pmatrix}$$

and taking determinants gives  $det(I_{2m} + Jz) = (1 - z^2)^m$ . Furthermore, r - 1 = m - n and the result follows.

### 7.2 Selberg trace formulae

#### 7.2.1 The Heat kernel

We define the Heat Kernel on V by

$$K(x, y, t) = \sum_{n} \phi_n(x)\phi_n(y)e^{-\lambda_n t}.$$

(This has a nice interpretation as the probability of a Brownian Motion path going from x to y in time t > 0.) In particular we can define the trace:

$$\operatorname{tr}(K(\cdot,\cdot,t)) := \int_M K(x,x,t) d\nu(x) = \sum_n e^{-\lambda_n t} d\mu(x) = \sum_n$$

#### 7.2.2 Homogeneity and the trace

Let us now choose the covering space to be the upper half plane  $\mathbb{H}^2 = \{z = x + iy : y > 0\}$  with the Poincaré metric

$$\frac{dx^2 + dy^2}{y^2}.$$

We can consider the Poincaré distance between  $\overline{x}, \overline{y} \in \mathbb{H}^2$  given by

$$d(\overline{x},\overline{y}) = \cosh^{-1}\left(1 + \frac{|\overline{x} - \overline{y}|^2}{2Im(\overline{x}).Im(\overline{y})}\right).$$

The heat kernel is homogeneous, i.e., the heat kernel  $\widetilde{K}(\cdot, \cdot, t)$  on  $\mathbb{H}^2$  depends only on the relative distance  $d(\overline{x}, \overline{y})$  apart of  $\overline{x}, \overline{y} \in \mathbb{H}^2$ . Let us now fix lifts  $\overline{x}$  and  $\overline{y}$  of x and y, respectively, in some fundamental domain F. We can then write

$$K(x, y.t) = \sum_{\gamma \in \Gamma} \widetilde{K}(\overline{x}, \gamma \overline{y}, t) = \sum_{\gamma \in \Gamma} \widetilde{K}(d(\overline{x}, \gamma \overline{y}), t)$$

and evaluate the trace

$$\operatorname{tr}(K(\cdot,\cdot,t)) := \int_F K(x,x,t) d\nu(x) = \int_F \widetilde{K}(d(\overline{x},\overline{x}),t) d\nu(x) + \sum_{\gamma \in \Gamma - \{e\}} \int_F \widetilde{K}(d(\overline{x},\gamma\overline{x}),t) d\nu(x).$$

**Lemma 7.1.** There is a correspondence between  $\Gamma$  and  $\{kp^nk^{-1} : n \in \mathbb{Z}, p, k \in \Gamma/\Gamma_p\}$  where p runs through the non-conjugate primitive elements of  $\Gamma$  and  $g \in \Gamma$ .

Since  $\nu$  is preserved by translation by elements of the group, we can write

$$\sum_{\gamma\in\Gamma-\{e\}}\int_{F}\widetilde{K}(d(\overline{x},\gamma\overline{x}),t)d\nu(x) = \sum_{n=1}^{\infty}\sum_{p}\underbrace{\left(\sum_{k\in\Gamma/\Gamma_{p}}\int_{F}\widetilde{K}(d(k^{-1}\overline{x},p^{n}k^{-1}\overline{x}),t)d\nu(x)\right)}_{=\int_{F_{p}}\widetilde{K}(d(\overline{x},p^{n}\overline{x}),t)d\nu(x)}.$$
 (1)

where  $F_p$  is a fundamental domain for  $\Gamma_p$ . Without loss of generality, we can take the fundamental domain z = x + iy where  $1 \le y \le m^2$  (where  $l(g) = 2 \log m$ ) and the integral can be explicitly evaluated

$$\frac{l(p)}{\sqrt{\cosh(l(p^n)) - 1}} \int_{\cosh l(p^n)}^{\infty} \frac{\tilde{K}(s)ds}{\sqrt{s - \cosh l(p^n)}}.$$
(2)

#### 7.2.3 Explicit formulae and Trace formula

The heat kernel  $\widetilde{K}(\overline{x}, \overline{y}, t)$  on  $\mathbb{H}^2$  has the following standard explicit form, which we state without proof.

Lemma 7.2. One can write

$$\widetilde{K}(\overline{x},\overline{y},t) = \widetilde{K}(d(\overline{x},\overline{y}),t) = \frac{\sqrt{2}}{(4\pi t)^{3/2}} e^{-t/4} \int_{d(\overline{x},\overline{y})}^{\infty} \frac{u e^{-u^2/4t}}{\sqrt{\cosh(u) - \cosh(d(\overline{x},\overline{y}))}} du$$

and, in particular,

$$\widetilde{K}(0,t) = \frac{1}{(4\pi)^{3/2}} \int_0^\infty \frac{u e^{-u^2/4t}}{\sinh(u/2)} du.$$

We start with the first term in (1):

$$\int_M \widetilde{K}(0,t) d\nu(x) = \frac{\nu(M)e^{-t/4}}{(4\pi t)^{3/2}} \int_0^\infty \frac{se^{-s^2/4t}}{\sinh(s/2)} ds.$$

The connection with the orginal problem comes via the standard result: The length of a closed geodesic in the conjugacy class of g is given by  $l(g) = \inf_{x \in H} d(xg, x)$ . Moreover,  $l(g^n) = |n|l(g)$ .

**Lemma 7.3.** There is a bijection between nontrivial conjugacy classes and closed geodesics on the surface. Moreover,  $tr(g) = 2\cosh(l(\gamma))$ .

Furthermore, we can write

$$\sum_{\gamma \in \Gamma - \{e\}} \int_M \widetilde{K}(d(\overline{x}, \gamma \overline{x}), t) d\nu(x) = \sum_{[\gamma]} \int_M \widetilde{K}(d(\overline{x}, \gamma \overline{x}), t) d\nu(x)$$

which allows us to write the rest of the trace explicitly:

Lemma 7.4 (McKean). The trace takes the form

$$\frac{\nu(M)e^{-t/4}}{(4\pi t)^{3/2}} \int_0^\infty \frac{se^{-s^2/4t}}{\sinh(s/2)} ds + \frac{e^{-t/4}}{(16\pi t)^{1/2}} \sum_{n=1}^\infty \sum_{\gamma} \frac{l(\gamma)}{\sinh(nl(\gamma)/2)} e^{(nl(\gamma))^2/4t}$$
(3)

where the sum is over conjugacy classes of  $\gamma \in \Gamma$ .

This is an explicit computation. Using Lemma 7.2 and (2) we have that

$$\int_{\cosh l(p^n)}^{\infty} \frac{\widetilde{K}(s)ds}{\sqrt{s - \cosh l(p^n)}} = \frac{\sqrt{2}e^{-t/4}}{(4\pi t)^{3/2}} \int_{\cosh l(p^n)}^{\infty} \int_{s}^{\infty} \frac{se^{-s^2/4t}}{\sqrt{\cosh(u) - \cosh(s)}} duds$$

which we can immediately evaluate as  $\frac{e^{-t/4}}{\sqrt{8\pi t}}e^{-l(p^n)^2/4t}$  , and we are done.

#### 7.2.4 Generalizations and the Selberg zeta function

If we consider the logarithmic derivative of the Selberg Zeta function then it takes the form:

$$\frac{1}{s-\frac{1}{2}}\frac{Z'(s)}{Z(s)} = 2\sum_{\gamma}\sum_{k=0}^{\infty}\frac{l(\gamma)}{\sinh(kl(\gamma)/2)}g_s(kl(\gamma))$$
(4)

where

$$g_s(u) = \frac{1}{2s-1} \exp\left(-\left(s-\frac{1}{2}\right)|u|\right).$$

The double summation is similar to that in (3). To make these terms identical, we can consider more general choices of kernel  $\widetilde{K}_s(\cdot, \cdot)$  which we can then write in the form  $\widetilde{K}_s(x, y)) = \sum_n h_s(\lambda_n)\phi_n(x)\overline{\phi}_n(y)$ , for suitable  $h_s(\cdot)$ . Moreover, we can write

$$\sum_{n} h_s \left( \sqrt{\lambda_n - \frac{1}{4}} \right) = \frac{\nu(M)}{2\pi} \int_{-\infty}^{\infty} r \tanh(\pi r) h(r) dr + \sum_{\gamma} \sum_{k=1}^{\infty} \frac{l(\gamma)}{\sinh(kl(\gamma))} g_s(l(\gamma))$$
(5)

where  $g_s(u) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-ru} h_s(r) dr$ . In particular, choosing  $h_s(r) = (r^2 + (s - \frac{1}{2})^2)^{-1}$  results in  $g_s(u)$  having the correct form<sup>24</sup> to give the infinite summation in (4). In particular, (5) tells us that the poles for Z'(s)/Z(s) (i.e., the zeros for Z(s)) come from the eigenvalues.

### 8 Further reading

- 1. One of my favourite references for prime numbers and the Riemann zeta function is [3]. Another remarkably nice small (and cheap) book on prime numbers is [12].
- 2. An extremely readable reference for zeta functions and graphs is [11].
- 3. For basic background on geodesics flows and their dynamics a good references is [1].
- There is a comprehensive book on the Selberg trace formula and the Selberg Zeta function [5] and a more concise account in [13],
- 5. There are not many pedagogical references for the use of Ruelle operators. The main ideas from Ruelle's approach are very nicely illustrated in a particular case in [6]. The interesting experimental results on the zeros of Z(s) for a pair of pants can be found find in [2].
- 6. The older approach to Anosov flows using symbolic dynamics is described in [8]. There are not (yet) many surveys on the newer approach to Anosov flows due to Liverani et al; nor the exciting recent work of Tsujii, Faure, Zworski, Nonnemacher. However, these authors write well and their recent articles and lecture notes are very interesting to read. One good starting point might be [4]. Many other interesting results can be found in these original articles.

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 $<sup>^{24}</sup>$ Actually a slight modification is still needed to make the integrals converge, etc.

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