Complex Dynamics of The Hyperbolic Tangent of The Logarithm Of One Minus The Square of The Hardy Z Function

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1 Introduction

In Poetry of the Universe[11, Ch.IV], Robert Osserman points out that one recurring them in the history of mathematics is how a new concept gradually evolves from its initial rejection as being too abstract, to eventually recognizing its suitability(despite its initially unnatural appearance), to its eventual eleveation to the status of a rudimentary and indespensible implement in the repertoire of the mathematician who wishes to understand how nature accomplishes so many purposes.

1.1 The Riemann ζ And Related Function

There are many functions such as the Hardy $Z(t)$ function, Riemann $\xi(t)$ function, and the Dirichlet $\eta(t)$ function which are equivalent to the Riemann zeta $\zeta(t)$ function in the sense that they have a set of roots which coincides with those of $\zeta(t)$ up to an affine transform. [17, …] Another function which has some intriguing properties and shares the same roots can be defined by $X(t) = S(Z(t)) = C_Z(S)$ where $C_g(f) = f(g(t))$ is the Koopman composition operator[7] and $S(t) = \tanh(\ln(1 - t^2)) = \frac{(1-t^2)^2 - 1}{(1-t^2)^2 + 1}$ is a ratioanl quartic function

TODO: depict ζ ξ η Z and X and S by itself in another figure

Figure 1.

Figure 2. TODO: insert arb4j generated figures here showing the traces of the real and imaginary zero loci of each of the mentioned functions

1.1.1 Roots of $X(t)$

All roots of Z are roots of X but the converse is not true because the $S(t)$ function has additional roots which become roots of the composite function and therefore $X(t)$ has strictly more roots than just those of the $Z(t)$ function.

The curves $\mathrm{Re}(X(t))=0$ and $\mathrm{Im}(X(t))=0$ are orthogonal when they intersect at 1 point at the root on the real axis for a total of 5 intersection points. This means that for every root of $Z(t)$ there are 5 roots of $X(t)$ where the 4 roots consist of a pair of points and their mirror conjugates; that is, if $\rho=x+iy$ is a root $X(\rho)=0$ then so is the complement which is the complex conjugate $X(\bar{\rho})=0$ where $\bar{\rho}=x-iy$.

1.2 The Schröder Equation

Definition 1

Schröder's equation is functional eigenvalue equation for the (Koopman) composition operator

$$C_h f(x)\colon f(x)\to f(h(x)) \tag{1}$$

in one independent variable; where a function, $h(x)$, is given and a function, $\Psi(x)$, is sought which satisifes

$$\Psi(h(x))=s\Psi(x) \tag{2}$$

where $s=\dot{h}(0)$ is the eigenvalue.

1.2.1 Koenig's Linearization Theorem

Let $f_{t_0}(t)=f(t_0+t)$ be a function< such that the fixed-point of interest corresponds to the origin such that $f_{t_0}(0)=0$ and $f(t_0)=0$.

Definition 2

A holomorphic function $f(t)$ that is one-to-one is said to be injective in a domain $t\in B\subset\mathbb{C}$ such that $f(z_1)\neq f(z_2)$ when $z_1\neq z_2$ and is also said to be univalent or conformal. The inverse function $z=f^{-1}(w)$ is then also necessarily conformal in the same domain B.

Theorem 3

*(**Koenigs Linearization Theorem**) If the magnitude (absolute value) of the multiplier $\lambda=|\dot{f}(0)|$ of a holomorphic map f is not strictly equal to 0 or 1, that is $\lambda\not\subset\{0,1\}$, then a local holomorphic change of coordinates $w=\phi(z)$, called the Koenig's function, unique up to a scalar multiplication by nonzero constant, exists, having a fixed-point at the origin $\phi(0)=0$ such that Schröder's equation is true*

$$\phi\circ f\circ\phi^{-1}=\lambda w\forall w\in\varepsilon_0 \tag{3}$$

for some neighborhood ε_0 of the origin 0. [10, Theorem 8.2][15, 2. Koenig's Theorem, Part I.][1, 1.7]

Lemma 4

*(**`The Simplicity Lemma`**) The Koenig's function ϕ is the only solution to the eigenvalue equation as all of the other solutions are constant multiples of powers of σ*

1.3 Eigenfunctions of Compact Composition Operators

Compactness of a composition operator can be determined by understanding how it maps the unit disc, and somehow the action of the operator is conjugate to a dilation of a Mobius transform acting on this "Koenig domain" $S(U)$ where U is the unit disc. [16, Ch.6 Compactness and Eigenfunctions]

$$\int_{-\pi}^{\pi}|S(e^{i\theta})|^2\mathrm{d}\theta=\frac{14\pi}{5}=2.8\pi \tag{4}$$

1.3.1 The Frobenius-Perron Transfer Operator

Definition 5

The (Frobenius-Perron) `transfer operator` *[17, Ch9], also known as the* `Koopman operator` *[7]is defined as normalized sum over the inverse branches of an iteration function $f \in C^1$*

$$\mathcal{K} f(x) = \sum_{y \in f^{-1}(x)} \frac{f(y)}{|\dot{f}(y)|} \tag{5}$$

which is a linear operator that determines how densities evolve under the action of $f(x)$; There exists an invariant measure φ of the transfer operator which is unchanged by the action of f and satisifies

$$\mathcal{K} \varphi(x) = \varphi(x) \tag{6}$$

1.3.2 Spectra of the Newton Map of the S Transform and Composition Operators

The transfer operator of the Newton map

$$N_S(t) = t - \frac{S(t)}{\dot{S}(t)} \tag{7}$$

of the S transform[1] is given by

$$\begin{aligned} \mathcal{K} N_S(t) &= \sum_{s \in N_S^{-1}(t)} \frac{N_S(s)}{|\dot{N}_S(s)|} \\ &= \sum_{s \in N_S^{-1}(t)} \frac{s - \frac{S(s)}{\dot{S}(s)}}{|\dot{N}_S(s)|} \\ &= \ldots \end{aligned} \tag{8}$$

which should be related to the transfer operator of the composition operator of the Newton map of X

$$\begin{aligned} \mathcal{K} N_X(t) &= \mathcal{K} N_{C_{Z(S)}}(t) \\ &= \sum_{s \in N_X^{-1}(t)} \frac{N_X(s)}{|\dot{N}_X(s)|} \end{aligned} \tag{9}$$

Spectra stuff here: [2]

1.4 Physical Interpretations of the Cauchy-Riemann Equations

The physical interpretation[8, 14.2.2 III] of the Cauchy–Riemann equations

$$\frac{\partial \mathrm{Re}}{\partial x} = \frac{\partial \mathrm{Im}}{\partial y} \tag{10}$$

$$\frac{\partial \mathrm{Re}}{\partial y} = -\frac{\partial \mathrm{Im}}{\partial x} \tag{11}$$

going back to Riemann's work on function theory [6] is that the real part $\mathrm{Re}(f)$ of an analytic function f is the **velocity potential** of an *incompressible fluid flow* in a plane and its imaginary part $\mathrm{Im}(f)$ is the corresponding **stream function**.

When the pair of twice continuously differentiable functions $\{\mathrm{Re}(f(x+iy)), \mathrm{Im}(f(x+iy))\}$ of f satisfies the Cauchy–Riemann equations then $\mathrm{Re}(f)$ is its **velocity potential** and the gradient of the real part $\nabla \mathrm{Re}$ is its **velocity vector** defined by

$$\nabla \mathrm{Re} = \frac{\partial \mathrm{Re}(f(x+iy))}{\partial x} + i \frac{\partial \mathrm{Re}(f(x+iy))}{\partial y} \tag{12}$$

By differentiating the Cauchy–Riemann equations a second time, it is shown that real part solves Laplace's equation:

$$\frac{\partial^2 \mathrm{Re}(f(x+iy))}{\partial x^2} + \frac{\partial^2 \mathrm{Re}(f(x+iy))}{\partial y^2} = 0 \tag{13}$$

That is, the real part of an analytic function is harmonic which means that it is incompressible since the divergence of its gradient vanishes and can therefore go no lower. The imaginary part also satisfies the Laplace equation, by a similar analysis. The Cauchy–Riemann equations also imply that the dot product of the gradients of the real and imaginary parts vanishes

$$\nabla \mathrm{Re} \cdot \nabla \mathrm{Im} = 0 \tag{14}$$

which indicates that the gradient of the real part must point along the streamlines of the flow where the stream function is constant $\mathrm{Im} = \mathrm{const}$ and therefore the curves of constant real part $\mathrm{Re} = \mathrm{const}$ are the corresponding orthogonal **equipotential curves**.

Definition 6

A line along which stream function (ψ) is constant is known as streamline*. Equipotential line: A line along which velocity potential function (φ) is constant is known as the equipotential line. They are orthogonal to each line other.*

1. From hereon S will be referred to as a (linear) operator or a transform when it is being applied to functions or other functionals and as just a regular meromorphic rational quartic function when its argument is real or complex variable.

2 The Operator $S_f^a(t) = \tanh\left(\ln\left(1 - \left(\frac{f(t)}{a}\right)^2\right)\right)$

Definition 7

Let the operator which takes a complex analytic function from $\bar{\mathbb{C}} \to \bar{\mathbb{C}}$ and returns the hyperbolic tangent of the logarithm of one minus the square of that function, divided by a scaling factor a, be defined by

$$S_f^a(t) = S^a(f(t)) = \tanh\left(\ln\left(1 - \left(\frac{f(t)}{a}\right)^2\right)\right) = \frac{\left(1 - \left(\frac{f(t)}{a}\right)^2\right)^2 - 1}{\left(1 - \left(\frac{f(t)}{a}\right)^2\right)^2 + 1} \tag{15}$$

where $f(t) \in \bar{\mathbb{C}} \forall t \in \bar{\mathbb{C}}$ is an analytic function of a single complex variable whose domain is the extended complex plane. If a is not specified then it is assumed to be equal to 1, e.g, $S_f(t) = S_f^a(t)$. When the function $f(t)$ is the identity function $f: t \to t$ then we have

$$\begin{aligned} S^a(t) &= S_{t\to t}^a(t) \\ &= \frac{(1 - (\frac{t}{a})^2)^2 - 1}{(1 - (\frac{t}{a})^2)^2 + 1} \\ &= 1 - \frac{2}{1 + (1 - (\frac{t}{a})^2)^2} \end{aligned} \tag{16}$$

which is a quartic, a rational (meromorphic) function of degree 4 from $\bar{\mathbb{C}} \to \bar{\mathbb{C}}$ with a double-root at the origin.

Theorem 8

The function $S_{t\to t}(t)$ is in the Hardy class H^2

Proof *Recall that a function is in the Hardy class H^p if*

$$\sup_{0 \leqslant r < 1} \left(\frac{\int_0^{2\pi} |f(re^{ia})|^p \mathrm{d}a}{2\pi} \right)^{\frac{1}{p}} < \infty$$

then let $p = 2$ and note that

$$\sqrt{\frac{1}{2\pi} \int |S(re^{ia})|^2 \mathrm{d}x} = \sqrt{\frac{1}{2\pi} \frac{2\pi^4(r^8 - 2r^4 + 8)}{(r^4 - 2)(r^8 + 4)}} \tag{17}$$

is bounded $\forall 0 \leqslant r < 1$ □

2.1 The Curve $\mathrm{Re}(S(t)) = 0$ is a Bernoullian Lemniscate

Theorem 9

The zero set $\{t : \mathrm{Re}(S(t)) = 0\}$ of the real part $\mathrm{Re}(S(t))$ of $S(t)$ where $t = x + iy$ is a horizontally oriented lemniscate of Bernoulli, also known as a hyperbolic lemniscate[9, 5.3 p.121], at the origin with parameter 2. That is,

$$\{(x, y) : \mathrm{Re}(S(x + iy)) = 0\} = \{(x, y) : (x^2 + y^2)^2 = 2(x^2 - y^2)\} \tag{18}$$

Proof

The parametric equations[3] for the lemniscate of Bernoulli with scale parameter 2 are given by

$$\begin{aligned} x(t) &= 2\frac{\cos(t)}{1 + \sin^2(t)} \\ y(t) &= 2\frac{\sin(t)\cos(t)}{1 + \sin^2(t)} = x(t)\sin(t) \end{aligned} \tag{19}$$

Let us combine the coordinate functions $(x(t), y(t)) \in \mathbb{R}^2$ into an equivalent function $z(t) \in \bar{\mathbb{C}}$

$$\begin{aligned} z(t) &= x(t) + iy(t) \\ &= \frac{2\cos(t)}{1 - i\sin(t)} \end{aligned} \tag{20}$$

where it can be shown that

$$\begin{aligned} S(z(t)) &= S_z(t) \\ &= S\left(\frac{S\cos(t)}{1 - i\sin(t)}\right) \\ &= i\frac{32\cos(t)^2\sin(t)}{20\cos(2t) + \cos(4t) - 13} \end{aligned} \tag{21}$$

so that

$$\mathrm{Re}(S_z(t)) = 0 \forall t \in \mathbb{R} \tag{22}$$

and thus $z(t)$ is a geodesic of the real part of S □

2.2 The Curve $\mathrm{Im}(S(t)) = 0$ is a Conjugate Pair of Rectangular Hyperbolas

Theorem 10

The zero set $\{t: \mathrm{Im}(S(t)) = 0\}$ *of the imaginary part* $\mathrm{Im}(S(t))$ *of* $S(t)$ *where* $t = x + iy$ *is a conjugate pair of rectangular hyperbolas.*

$$\{(x, y): \mathrm{Im}(S(x + iy)) = \{(x, y): x^2 - y^2 = 1\}\} \tag{23}$$

Proof

The parametric equations[3] for the equilateral (rectangular) hyperbola with unit parameter are given by

$$\begin{aligned} x(t) &= \sec(t) \\ y(t) &= \tan(t) \end{aligned} \tag{24}$$

which are combined into a complex-valued function

$$\begin{aligned} z(t) &= x(t) + i y(t) \\ &= \sec(t) + i \tan(t) \end{aligned} \tag{25}$$

where it can be shown that

$$\begin{aligned} S(z(t)) &= S(\sec(t) + i \tan(t)) \\ &= -\frac{2(\cos(2t) - 3)^2}{20\cos(2t) + \cos(4t) - 13} \end{aligned} \tag{26}$$

so that

$$\mathrm{Im}(S(z(t))) = 0 \forall t \in \mathbb{R} \tag{27}$$

and thus $z(t)$ *is a geodesic of the imaginary part of* S

□

2.3 Newton Maps and Flows of $S_f(t)$

Definition 11

Let $N_f(t)$ *denote the* `Newton map` *of* $f(t)$

$$N_f(t) = t - \frac{f(t)}{\dot{f}(t)} \tag{28}$$

Definition 12

The Newton map $N_{S_f}(t)$ *of the composition* $S_f(t) = S(f(t))$ *is a rational meromorphic function of* $f(t)$ *given by*

$$\begin{aligned} N_{S_f}(t) &= t - \frac{S_f(t)}{\dot{S}_f(t)} \\ &= t - \frac{\frac{(1 - f(t)^2)^2 - 1}{(1 - f(t)^2)^2 + 1}}{\frac{8\dot{f}(t) f(t)(f(t)^2 - 1)}{((f(t) - 1)^2 (f(t) + 1)^2 + 1)^2}} \\ &= t - \frac{1}{8} \frac{((f(t) - 1)^2 (1 + f(t)^2)^2 + 1)^2 ((1 - f(t)^2)^2 - 1)}{f(t) \dot{f}(t)(f(t)^2 - 1)(1 + (1 - f(t)^2)^2)} \end{aligned} \tag{29}$$

where $\dot{S}_f(t)$ *is the derivative of the composite function* $S(f(t))$ *given by*

$$\dot{S}_f(t) = \frac{\mathrm{d}}{\mathrm{d}t} S(f(t)) = \dot{S}(f(t)) \dot{f}(t) = \frac{8\dot{f}(t) f(t)(f(t)^2 - 1)}{((f(t) - 1)^2 (f(t) + 1)^2 + 1)^2} \tag{30}$$

which is just the usual derivative of S *multiplied by the derivate of* f *which can be found with an application of the usual chain rule of calculus and simplifying the algebra by combining like terms, factoring and rearranging terms.*

Theorem 13

The Newton map of S_f *transforms superattractive* $(\lambda = 0)$ *fixed-points of* $N_f(t)$ *to geometrically attractive fixed-points of* $N_{S_f}(t)$

Proof

There is geometrically attractive fixed-point at $t = 0$ *with multiplier equal to*

$$\lambda_{N_{S_f}(0)} = \left| 1 - \frac{1 + \lambda_{N_f}(0)}{2} \right| \tag{31}$$

TODO: prove this.. apply S *to some other functions and see how it transforms the multipliers of the fixed-points*

□

2.3.1 Factoring Out The Double-Root at the Origin of $N_{S_f}(t)$

If $m = m_f(\alpha)$ is the multiplicity of the root of f at the point α then f factorizes as

$$f(x) = (x - \alpha)^m g(x) \tag{32}$$

where $g(\alpha) = 0$.

2.3.2 The Newton Flow

Definition 14

The `Newton flow` $\mathcal{N}_S(f)$ *of* $S_f(t)$ *is defined by the differential equation*

$$\dot{z}(t) = \frac{\mathrm{d}}{\mathrm{d}t} z(t) = -\frac{S_f(z(t))}{\dot{S}_f(z(t))} \tag{33}$$

which is approximated by the relaxed Newton method where the limit of the step size is taken towards zero , it is defined by

$$\begin{aligned}\mathcal{N}_S^h(f) &= t - h\frac{S_f(t)}{\dot{S}_f(t)} \\ &= t - \frac{h\frac{(1 - f(t)^2)^2 - 1}{(1 - f(t)^2)^2 + 1}}{\frac{8\dot{f}(t)f(t)(f(t)^2 - 1)}{((f(t) - 1)^2 (f(t) + 1)^2 + 1)^2}} \\ &= t - \frac{h}{8}\frac{((f(t) - 1)^2 (1 + f(t)^2)^2 + 1)^2 ((1 - f(t)^2)^2 - 1)}{f(t)\dot{f}(t)(f(t)^2 - 1)(1 + (1 - f(t)^2)^2)}\end{aligned} \tag{34}$$

where h *is taken to be a small number which is used to approximate the flow* $\dot{z}(t)$

The Newton flow $\mathcal{N}(f)$ has the drawback that it is undefined at the critical points of f. To remedy this situation there exists the desingularized Newton flow for entire functions.

2.3.3 The Desingularized Newton Flow For Entire Functions

Definition 15

If f *is an entire function then an equivalent* `desingularized Newton flow` *which is devoid of singularities at the critical points is given by*

$$\dot{z}(t) = -\overline{\dot{f}(z(t))}\, f(z(t)) \tag{35}$$

[5]

The function of interest here, S_f, is meromorphic and therefore will be divergent at the poles of S_f. To rectify this situation we can apply the continuous Newton method for mermorphic functions which defines an equivalent real holomorphic vector field devoid of any singularities.

2.3.4 The Continuous Desingularized Newton Flow for Meromorphic Functions

Lemma 16

(Desingularization Lemma) The flow defined by

$$\bar{\mathcal{N}}(f) = -\frac{\bar{\dot{f}}(z) f(z)}{(1 + |f(z)|^4)} \tag{36}$$

is a `real analytic vector field` *[12] defined on the whole complex plane* $\mathbb{C}$ *with the properties that*

i. Trajectories of $\mathcal{N}$ *are also trajectories of* $\bar{\mathcal{N}}(f)$

ii. A critical point of f *is an equilibrium state for* $\bar{\mathcal{N}}(f)$

iii. $\bar{\mathcal{N}}(f) = -\bar{\mathcal{N}}\left(\frac{1}{f}\right)$

2.3.5 The Continuous Newton Flow $\bar{\mathcal{N}}(S_f)$ and Its Approximation $\bar{\mathcal{N}}^h(S_f)$

Apply Lemma 16 to define a real analytic vector field on $\mathbb{C}$

$$\bar{\mathcal{N}}(S_f) = -\frac{\bar{\dot{S}}_f(z) S_f(z)}{(1 + |S_f(z)|^4)} \tag{37}$$

which is approximated by a similiarly modified relaxed Newton's method

$$\mathcal{N}^h(S_f) = t - h\frac{\bar{\dot{S}}_f(t) S_f(t)}{(1 + |S_f(z)|^4)} \tag{38}$$

where h is accuracy of the solution. TODO: insert some figures

3 The Riemann Zeta ζ Function

Definition 17

The Riemann zeta function is defined by

$$\begin{aligned}\zeta(s) &= \sum_{n=1}^{\infty} \frac{1}{n^s} \forall \mathrm{Re}(s) > 1 \\ &= \frac{1}{1-2^{1-s}} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^s} \forall \mathrm{Re}(s) > 0\end{aligned} \tag{39}$$

and its argument has a representation as

$$S(t) = \frac{1}{\pi} \arg\left(\zeta\left(\frac{1}{2} + it\right)\right) = \frac{1}{\pi} \int_{\frac{1}{2}}^{\infty} \mathrm{Im}\left(\frac{\dot{\zeta}(\sigma+it)}{\zeta(\sigma+it)}\right) \mathrm{d}\sigma \forall t \in \mathbb{R} \backslash \{0\} \tag{40}$$

3.1 The Riemann Hypothesis

Conjecture 18

(The Riemann Hypothesis)

Bernhard Riemann conjectured [13] that,

$$\left\{\mathrm{Re}(t) = \frac{1}{2} \colon \zeta(t) = 0 \forall t \neq -2n \forall t \in \bar{\mathbb{C}}, n \in \mathbb{N}^+\right\}$$

,all of the roots that are not negative even integers where $\zeta(-2n) = 0$ all lie on the `critical line` $\mathrm{Re}\left(\frac{1}{2}\right)$ *in the complex plane such that $\zeta(\sigma + is) = 0$ only when $\sigma = \frac{1}{2}$ where $\mathbb{R}^+ \ni s > 0$.*

3.1.1 Lines of Constant Phase and the Riemann Hypothesis

The following theorem is the main result of [14].

Theorem 19

1. *If all lines of constant phase $\arg(\zeta(t)) = kn$ of ζ where $k \in \mathbb{N}$ merge with the critical line*

   OR

2. *all points where $\dot{\zeta}(t)$ vanishes are located on the critical line and the phases of ζ at consecutive zeros of $\dot{\zeta}$ differs by π*

then the Riemann Hypothesis (18) is true.

3.2 The Hardy Z Function

Definition 20

(The Gamma and Log Gamma functions)

Let

$$\Gamma(t) = (t-1)! = \int_0^{\infty} x^{t-1} e^{-x} \mathrm{d}x \forall \mathrm{Re}(t) > 0 \tag{41}$$

be the gamma function and

$$\ln\Gamma(t) = \ln(\Gamma(t)) \tag{42}$$

be the principle branch of the logarithm of the Γ function.

3.2.1 The Phase of ζ

The $\mathrm{Riemann} - \mathrm{Siegel}$ theta function $\vartheta(t)$ corresponds to the smooth part of the phase of the zeta function which has a jump discontinuity when t is equal to the imaginary part of a Riemann zero on the critical line.

Definition 21

(The Riemann-Siegel vartheta function)

Let

$$\vartheta(t) = -\frac{i}{2}\left(\ln\Gamma\left(\frac{1}{4} + \frac{it}{2}\right) - \ln\Gamma\left(\frac{1}{4} - \frac{it}{2}\right)\right) - \frac{\ln(\pi)\, t}{2} \tag{43}$$

be the the Riemann-Siegel (var)theta function.

Definition 22

(The Hardy Z function)

Let

$$Z(t) = e^{i\vartheta(t)}\zeta\left(\frac{1}{2}+it\right) \tag{44}$$

be the Hardy Z function which has the property that $Z(t)$ is real when t is real, that is, $Z(t) \in \mathbb{R} \forall t \in \mathbb{R}$ independently of the Riemann hypothesis.

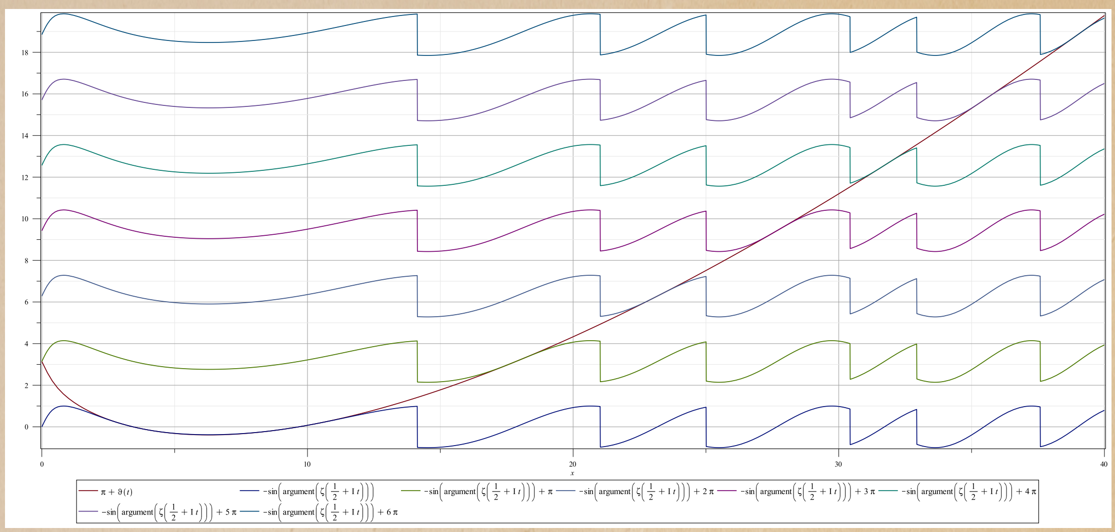

Figure 3. Illustration of the relationship between vartheta ϑ and the argument of zeta ζ on the critical line

3.3 The Function $X(t) = (S \circ Z)(t)$

Definition 23

(The X function)

Let $X(t)$ be defined as the composition of the S function with the Hardy Z function

$$X(t) = C_Z(S)(t) = (S \circ Z)(t) = S(Z(t)) = \frac{(1 - Z(t)^2)^2 - 1}{(1 - Z(t)^2)^2 + 1} \tag{45}$$

3.3.1 Integration Along a Curve: A Newton Iteration for the Angle

In order to find an explicit expression for the angle $\theta_m(h)$ in the implicit formula Formula (?) we can use a modified Newton's method that converges to the angle in which to step given a basepoint t, a direction a, and a magnitude h to minimize the real part of a function f.

Definition 24

Let the Newton map for the roots of the real part of

$$X(t + h e^{ia}) \tag{46}$$

be defined by

$$\begin{aligned} N_{\theta_m}(a_{m,k}; t, h) &= \mathrm{frac}\left(a_{m,k-1} + \tanh\left(\frac{\mathrm{Re}(X(t+he^{ia}))}{\mathrm{Re}\left(\frac{\mathrm{d}}{\mathrm{d}a}X(t+he^{ia})\right)}\right)_{a=a_{m,k-1}}\right) \\ &= \mathrm{frac}\left(a_{m,k-1} + \tanh\left(\frac{\mathrm{Re}(X(t+he^{ia}))}{\pi\,\mathrm{Im}(\dot{X}(t+he^{ia})\,he^{ia})}\right)_{a=a_{m,k-1}}\right) \end{aligned}$$

TODO: this takes a special form, see

where the initial $(k=0)$ angle of the first$(m=0)$ step of length h is $a_{m,0} = \frac{\theta_{m-1}}{\pi}$ where we normalize by π since the variable has domain $[-1, 1]$ (the angle at the previous point) or $a_{0,0} = \frac{3}{4}$ which is -45° for the initial element of the sequence wheen $m = 0$, that is, the (initial)boundary conditions are

$$a_{m,0} = \begin{cases} \frac{3}{4} & m = 0 \\ \frac{\theta_{m-1}}{\pi} & m \geqslant 1 \end{cases} \tag{47}$$

and the corresponding curve is traversed in a positive clockwise direction moving initially into the upper-left quadrant . Let the angle at the m-th step (of length h) be defined as the limit

$$\begin{aligned}\theta_m &= \theta_m(t,h) \in [-\pi, +\pi] \\ &= \pi \lim_{k\to\infty} N_{\theta_m}(a_{m,k}; t, h)\end{aligned} \tag{48}$$

which is dependent on the basepoint t and radius h, but the when the dependence is not written as $\theta_m(t,h)$ it is still implied unless otherwise noted. The notation $\dot{Y}(t) = \frac{\mathrm{d}}{\mathrm{d}t} Y(t)$ is the more concise notation for first-deriative.

3.3.2 Roots of $X(t)$ on the Real Line

The critical line of the zeta function $\mathrm{Re}(s) = \frac{1}{2}$ corresponds to the real line $\mathrm{Im}(s) = 0$ of the Z and X functions

4 Linearizing

Definition 25

Let the Newton map of the shifted X function

$$X_n(t) = X(z_n + t) \tag{49}$$

where z_n is the n-th root of the Hardy Z function on the real line, starting with

$$\begin{aligned} z_1 &\cong \texttt{14.1347251...} \\ z_2 &= \texttt{21.0220396...} \\ \ldots & \ldots \end{aligned}$$

, be denoted

$$N_{X_{z_n}}(t) = t - \frac{X_{z_n}(t)}{\dot{X}_{z_n}(t)} \tag{50}$$

TODO: this has nice symmetric factorized form, see (29)

5 Appendix

5.1 The Spectral Theorem

Theorem 26

The Spectral Theorem

Let $U : \mathcal{S}(\mathbb{R}^n) \to \mathcal{S}(\mathbb{R}^n)$ be unitary then U extends uniquely to a unitary operator on all of $L^2(\mathbb{R}^n)$ and all generalized eigenvalues λ lie on the unit circle $|\lambda| = 1$. The space $L^2(\mathbb{R}^n)$ can be expressed as a direct integral

$$\int_{|\lambda|=1} \mathcal{H}(\lambda) d\mu(\lambda) \tag{51}$$

of Hilbert spaces $\mathcal{H}(\lambda) \subseteq E_\lambda$ so that U sends the function $h \in L^2(\mathbb{R}^n)$ to the function Uh with λ-component

$$(Uh) = \lambda h_\lambda \in \mathcal{H}(\lambda) \tag{52}$$

and its set of generized eigenvectors forms a complete basis. [4, Theorem 1.3.2]

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