Lecture Notes to Fuchsian Groups
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Chapter 1

Preliminaries

1.1 The Hyperbolic Plane

1.1.1 The Riemann Sphere

Definition 1.1.1 (The Riemann Sphere). The *Riemann sphere* is a one-dimensional complex manifold, denoted $\hat{\mathbb{C}} = \mathbb{C} \cup \{\infty\}$, the charts of which are the following.

$$\begin{aligned} U_1 &= (\mathbb{C}, f_1) \\ U_2 &= \left(\hat{\mathbb{C}} \setminus \{0\}, f_2\right) \end{aligned}$$

where

$$\begin{aligned} f_1 \colon \mathbb{C} &\to \mathbb{C} \\ z &\mapsto z \end{aligned}$$

and

$$\begin{aligned} f_2 \colon \mathbb{C} &\to \hat{\mathbb{C}} \setminus \{0\} \\ z &\mapsto \frac{1}{z}. \end{aligned}$$

Definition 1.1.2 (Möbius Transformation). A map $T \colon \hat{\mathbb{C}} \to \hat{\mathbb{C}}$ of the form

$$z \mapsto \frac{az+b}{cz+d}$$

where $ad - bc \neq 0$ is called a *Möbius transformation*.

Notation 1.1.3. 1. We denote the image of $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{GL}_2(\mathbb{C})$ in $\mathrm{PGL}_2(\mathbb{C})$ by $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$.

2. For every $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \mathrm{PGL}_2(\mathbb{C})$, we denote by T_g the Möbius transformation $z \mapsto \frac{az+b}{cz+d}$.

Lemma 1.1.4. *The set of Möbius transformations is a group under composition, and the map $g \mapsto T_g$ is an isomorphism between $\mathrm{PGL}_2(\mathbb{C})$ and the group of Möbius transformation.*

Proof. It holds that

$$\begin{aligned} T_{g_1} \circ T_{g_2}(z) &= \frac{a_1\left(\frac{a_2 z + b_2}{c_2 z + d_2}\right) + 1}{c_1\left(\frac{a_2 z + b_2}{c_2 z + d_2}\right) + d_1} \\ &= \frac{(a_1 a_2 + b_1 c_2) z + (a_1 b_2 + b_1 d_2)}{(c_1 a_2 + d_1 c_2) z + (c_1 b_2 + d_1 d_2)} \\ &= T_{g_1 g_2}(z). \end{aligned}$$

In particular, $T_{g^{-1}}$ is the inverse of T_g.

The rest of the proof is clear. ∎

Definition 1.1.5 (Generalised Circle). A generalised circle in $\mathbb{C}$ is either an Euclidean circle or an Euclidean straight line.

Lemma 1.1.6. *Let $T\colon \hat{\mathbb{C}} \to \hat{\mathbb{C}}$ be a Möbius transformation. Then*

1. *T is an endomorphism of $\hat{\mathbb{C}}$.*
2. *T is conformal.*
3. *T sends generalised circles to generalised circles.*

1.1.2 Models of the Hyperbolic Plane

Definition 1.1.7 (The Upper Half Plane Model for the Hyperbolic Plane). 1.
As a set, define $\mathbb{H} := \{z \in \mathbb{C} \mid \Im(z) > 0\}$.

2. Let $\gamma\colon [0,1] \to \mathbb{H}$ be a piecewise continuously differentiable path given by $\gamma(t) = x(t) + iy(t)$ for real functions $x(t), y(t)$. The *hyperbolic length* of γ is given by

$$h(\gamma) := \int_0^1 \frac{\sqrt{\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2}}{y(t)}\,\mathrm{d}t = \int_0^1 \frac{\left|\frac{\mathrm{d}\gamma}{\mathrm{d}t}\right|}{y(t)}\,\mathrm{d}t.$$

3. The *hyperbolic distance* $\rho(z,w)$ between two points $z, w \in \mathbb{H}$ is defined as $\inf_\gamma h(\gamma)$ where the infimum is taken over all piecewise continuously differentiable paths γ from z to w.

Remark 1.1.8. $\mathbb{H}$ is a Riemann surface where for every $z \in \mathbb{H}$, the inner product of $T_z H$ is given by

$$((x_1, y_1), (x_2, y_2)) = \frac{x_1 x_2 + y_1 y_2}{(\Im z)^2}.$$

In particular, Euclidean angles are equal to hyperbolic angles.

Definition 1.1.9 (The Disc Model for the Hyperbolic Plane).

1. As a set, define $\mathbb{U} \coloneqq \{z \in \mathbb{C} \mid |z| < 1\}$.

2. Let $\gamma \colon [0,1] \to \mathbb{U}$ be a piecewise continuously differentiable path. The *hyperbolic length* of γ is given by

$$h_u(\gamma) \coloneqq \int_0^1 \frac{2\left|\frac{\mathrm{d}\gamma}{\mathrm{d}t}\right|}{1 - |\gamma(t)|^2}\,\mathrm{d}t.$$

3. The *hyperbolic distance* $\rho_u(z, w)$ between $z, w \in \mathbb{U}$ is defined to be $\inf_\gamma h(\gamma)$ where the infimum is taken over all piecewise continuously differentiable paths from z to w.

Remark 1.1.10. It is clear that hyperbolic circles around 0 are exactly Euclidean circles around it (with a generally different radius).

Remark 1.1.11. Rotations around 0 are isometries in the disc model.

Lemma 1.1.12. *Let π be the Möbius transformation defined by*

$$\pi(z) = \frac{iz + 1}{z + i}.$$

Then

1. *π is a bijection from $\mathbb{H}$ to $\mathbb{U}$.*

2. *For every piecewise continuously differentiable path $\gamma \colon [0,1] \to \mathbb{H}$,it holds that $h_u(\pi(\gamma)) = h(\gamma)$. In particular, π is an isometry.*

Proof.

1. It holds that

$$\begin{aligned} \pi(-1) &= -1 \\ \pi(0) &= -i \\ \pi(1) &= 1. \end{aligned}$$

Since Möbius transformations send generalised circles to generalised circles we get that π sends $\mathbb{R}$ to the unit circle. Since $\pi(i) = 0$ and π is a homeomorphism of the Riemann sphere, we get the result.

2. Let $\gamma\colon [0,1] \to \mathbb{H}$ be a piecewise continuously differentiable path. Denote $\psi = \pi^{-1}$ and $\delta = \pi(\gamma)$. Then

$$\psi(z) = \frac{iz-1}{-z+i} = \frac{(iz-1)-\bar{z}-i}{(-z+i)-\bar{z}-i} = \frac{(z+\bar{z})+i\left(1-|z|^2\right)}{|-z+i|^2}.$$

So,

$$\Im(\psi(z)) = \frac{1-|z|^2}{|-z+i|^2}.$$

Since

$$\frac{\mathrm{d}\psi}{\mathrm{d}z} = \frac{-2}{(-z+i)^2},$$

we get that

$$\begin{aligned} h(\gamma) &= \int_0^1 \frac{\left|\frac{\mathrm{d}\gamma}{\mathrm{d}t}\right|}{\Im(\gamma(t))}\,\mathrm{d}t \\ &= \int_0^1 \frac{\left|\frac{\mathrm{d}\psi(\delta)}{\mathrm{d}t}\right|}{\Im(\psi(\delta(t)))}\,\mathrm{d}t \\ &= \int_0^1 \frac{\left|\frac{\mathrm{d}\psi}{\mathrm{d}z}(\delta(t))\,\frac{\mathrm{d}\delta}{\mathrm{d}t}\right|}{\Im(\psi(\delta(t)))} \\ &= \int_0^1 \frac{2\left|\frac{\mathrm{d}\delta}{\mathrm{d}t}\right|}{1-|\delta(t)|^2}\,\mathrm{d}t \\ &= h_u(\delta). \end{aligned}$$

■

1.1.3 Isometries of the Hyperbolic Plane

Lemma 1.1.13. *For every* $g \in \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \mathrm{PSL}_2(\mathbb{R})$ *it holds that*

$$T_g(\mathbb{H}) \subseteq \mathbb{H}.$$

Proof. It's enough to show the inclusion $T_g(\mathbb{H}) \subseteq \mathbb{H}$ since then

$$T_{g^{-1}}(\mathbb{H}) = (T_g)^{-1}(\mathbb{H}) \subseteq \mathbb{H}$$

which implies $T_g(\mathbb{H}) \supseteq \mathbb{H}$ by applying T_g.

Now, we have

$$\begin{aligned} T_g(z) &= \frac{az+b}{cz+d} \\ &= \frac{(az+b)(c\bar{z}+d)}{|cz+d|^2} \\ &= \frac{ac|z|^2+adz+bc\bar{z}+bg}{|cz+d|^2}. \end{aligned}$$

Thus,

$$\begin{aligned}\Im\left(T_g\left(z\right)\right) &= \frac{T_g\left(z\right)-\overline{T_g\left(z\right)}}{2i}\\ &= \frac{\left(ad-bc\right)z-\left(ad-bc\right)\bar{z}}{2i\left|cz+d\right|^2}\\ &\underset{ad-bc=1}{=} \frac{\Im\left(z\right)}{\left|cz+d\right|^2}.\end{aligned}$$

■

This lemma allows us to identify $\mathrm{PSL}_2\left(\mathbb{R}\right)$ as a subgroup of $\mathrm{Sym}\left(\mathbb{H}\right)$. The next lemma shows that even more is true.

Lemma 1.1.14. $\mathrm{PSL}_2\left(\mathbb{R}\right)\subseteq\mathrm{Isom}\left(\mathbb{H}\right)$.

Proof. It's enough to show that for every $g\in\mathrm{PSL}_2\left(\mathbb{R}\right)$ and every piecewise continuously differentiable path γ it holds that $h\left(\gamma\right)=h\left(T_g\left(\gamma\right)\right)$. Denote $T=T_g$ and $\delta=T\left(\gamma\right)$. Then

$$\begin{aligned}h\left(\delta\right) &= \int_0^1\frac{\left|\frac{\mathrm{d}\delta}{\mathrm{d}t}\right|}{\Im\left(\delta\left(t\right)\right)}\,\mathrm{d}t\\ &= \int_0^1\frac{\left|\frac{\mathrm{d}T}{\mathrm{d}z}\left(\gamma\left(t\right)\right)\frac{\mathrm{d}\gamma}{\mathrm{d}t}\right|}{\Im\left(\delta\left(t\right)\right)}\,\mathrm{d}t\\ &\underset{\star}{=} \int_0^1\frac{\left|\frac{\mathrm{d}\gamma}{\mathrm{d}t}\right|}{\gamma\left(t\right)}\,\mathrm{d}t\\ &= h\left(\gamma\right)\end{aligned}$$

where $\star$ follows from

$$\begin{aligned}\Im\left(T_g\left(z\right)\right) = \frac{\Im\left(z\right)}{\left|cz+d\right|^2} \oplus \frac{\mathrm{d}T}{\mathrm{d}z} &= \frac{a\left(cz+d\right)-c\left(az+b\right)}{\left(cz+d\right)^2}\\ &= \frac{1}{\left(cz+d\right)^2}.\end{aligned}$$

■

Corollary 1.1.15. $\mathrm{Isom}\left(\mathbb{H}\right)$ *acts transitively on* $\mathbb{H}$.

Proof. It's enough to show that for every $z\in\mathbb{H}$ there's $g\in\mathrm{PSL}_2\left(\mathbb{R}\right)$ such that $T_g\left(z\right)=i$.

If $z=x+yi$, take $g=\begin{pmatrix}\frac{1}{\sqrt{y}} & -\frac{x}{\sqrt{y}}\\ 0 & \frac{1}{\sqrt{y}}\end{pmatrix}$, then

$$T_g\left(z\right)=\frac{1}{y}\left(x+yi\right)-\frac{x}{y}=i.$$

■

Lemma 1.1.16. *Let $\pi\colon \mathbb{H} \to \mathbb{U}$ be the isometry $z \mapsto \frac{iz+1}{z+i}$ which we defined previously. Then*

$$\left\{\pi T_g \pi^{-1} \;\middle|\; g \in \mathrm{PSL}_2(\mathbb{R})\right\} = \left\{ \begin{pmatrix} r & s \\ \bar{r} & \bar{s} \end{pmatrix} \;\middle|\; {\scriptstyle r,s\in\mathbb{C} \atop |r|^2-|s|^2=1} \right\}.$$

In particular, by taking $r = e^{i\theta}$ and $s = 0$ we see that the action of $\mathrm{PSL}_2(\mathbb{R})$ on $\mathbb{U}$ contains all the rotations around 0.

Proof. It holds that

$$\begin{pmatrix} i & 1 \\ 1 & i \end{pmatrix}\begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} i & -1 \\ -1 & i \end{pmatrix} = \frac{1}{2}\begin{pmatrix} (a+d)+i(b-c) & b+c+i(a-d) \\ (b+c)-i(a+d) & (a+d)-i(b-c) \end{pmatrix}.$$

Now, $(a+d, a-d, b+c, b-c)$ can be any 4-tuple. Specifically, for every $r, s \in \mathbb{C}$ we have $a, b, c, d \in \mathbb{R}$ such that $\pi T_g \pi^{-1} = \begin{pmatrix} r & s \\ \bar{s} & \bar{r} \end{pmatrix}$, and by the equality from the determinants we get that $\begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \mathrm{PSL}_2(\mathbb{R})$. ■

Corollary 1.1.17. *Let $z_1, z_2, w_1, w_2 \in \mathbb{H}$ be such that $\rho(z_1, w_1) = \rho(z_2, w_2)$, then there exists $g \in \mathrm{PSL}_2(\mathbb{R})$ such that $T_g(z_1) = z_2$ and $T_g(w_1) = w_2$.*

Proof. Since $\mathrm{PSL}_2(\mathbb{R})$ acts transitively on $\mathbb{H}$ we can assume that $z_1 = z_2$ and show that $\mathrm{Stab}(z_1)$ acts transitively on $\{w \in \mathbb{H} \mid \rho(z_1, w) = \rho(z_1, w_1)\}$. We already showed this in the disc model, in the case $z_1 = i$. ■

Definition 1.1.18. Let (X, d) be a metric space.

1. Let $x, y \in X$. A path $\gamma\colon [a, b] \to X$ which joins x and y is called a *geodesic segment* if for every $a \leq t_1 \leq t_2 \leq b$ it holds that $|t_2 - t_1| = d(\gamma(t_1), \gamma(t_2))$.

2. A path $\gamma\colon \mathbb{R} \to X$ is called a *geodesic line* if for every $a < b$ it holds that $\gamma|_{[a,b]}$ is a geodesic segment.

Remark 1.1.19. Let γ be a geodesic segment or line. Then γ is determined by the image of γ up to a composition with an isometry of R. Thus, we can identify geodesic segments and lines with their image up to orientation.

Lemma 1.1.20. *Let $b > a > 0$ be real numbers. Then $\{iy \mid a \leq y \leq b\}$ is the unique geodesic segment between ia and ib and $\{iy \mid y > 0\}$ is the unique geodesic line through ia and ib.*

Proof. We begin with the first part of the lemma. Let $\gamma\colon [0, 1] \to \mathbb{H}$ be a piecewise continuously differentiable path joining ia and ib. For $t \in [0, 1]$ denote

$\gamma(t) = x(t) + iy(t)$ where $x(t), y(t) \in \mathbb{R}$. Then

$$\begin{aligned} h(\gamma) &= \int_0^1 \frac{\sqrt{\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2}}{y(t)} \mathrm{d}t \\ &\underset{\star}{\geq} \int_0^1 \frac{\left|\frac{\mathrm{d}y}{\mathrm{d}t}\right|}{y(t)} \mathrm{d}t \\ &\geq \int_0^1 \frac{\frac{\mathrm{d}y}{\mathrm{d}t}}{y(t)} \mathrm{d}t \\ &= \ln\left(\frac{b}{a}\right). \end{aligned}$$

Thus, $\rho(ia, ib) \geq \ln\left(\frac{b}{a}\right)$. If $y(t) = i((b-a)t + a)$, the above inequalities are equalities so $\rho(ia, ib) = \ln\left(\frac{b}{a}\right)$. The inequality $\star$ is an equality if and only if $x(t) = 0$ for all $t \in [a, b]$. It follows that the unique geodesic segment between a and b is $\{iy \mid a \leq y \leq b\}$.

Now, it is clear that $\{iy \mid y > 0\}$ is a geodesic line which passes through ia and ib. We want to show it's unique.

Assume towards a contradiction that there exists a geodesic line ℓ between ia and ib which isn't the positive part of the y-axis. Then there's $z = x + iy \in \ell$ for which $x \neq 0$ and $\rho(z, ia) > \rho(z, ib)$. By the previous lemma, there exists $g \in \mathrm{PSL}_2(\mathbb{R})$ such that $T_g(ia) = ia$ and $T_g(z) \in i\mathbb{R}$. Since T_g sends generalised circles to generalised circles, $T_g(ib) \notin i\mathbb{R}$. Indeed, otherwise the image of the segment between ia and ib would belong to $i\mathbb{R}$, and since T_g sends generalised circles to generalised circles, it would send $i\mathbb{R}$ to itself.

We get that there exists a geodesic between ia and $T_g(z) = ic$ which is not contained in $i\mathbb{R}$, and this is impossible. ∎

Theorem 1.1.21. *1. Every distinct points $z, w \in \mathbb{H}$ are contained in a unique geodesic segment and a unique geodesic line.*

2. The geodesics in $\mathbb{H}$ are semicircles and lines orthogonal to the real axis.

Proof. 1. For every $g \in \mathrm{PSL}_2(\mathbb{R})$ it holds that $T_g(\mathbb{R} \cup \{\infty\}) = \mathbb{R} \cup \{\infty\}$. If $z, w \in \mathbb{H}$, by a previous lemma there exists $g \in \mathrm{PSL}_2(\mathbb{R})$ such that $T_g(z) = ia$ and $T_g(w) = ib$ for some $a, b \in \mathbb{R}_+$. Thus, $T_g^{-1}([ia, ib])$ is the unique geodesic segment between z and w.

2. This follows from the fact that Möbius circles are conformal, send generalised circles to generalised circles, and sends $\mathbb{R} \cup \{\infty\}$ to itself. ∎

Corollary 1.1.22. *The geodesic segment in $\mathbb{U}$ are segments of straight lines through zero or arcs of circles which are orthogonal to the unit circles.*

Theorem 1.1.23. *Let $z, w \in \mathbb{H}$. Then*

$$\sinh\left(\frac{1}{2}\rho(z,w)\right) = \frac{|z-w|}{2\left(\Im(z)\Im(w)\right)^{\frac{1}{2}}}.$$

Proof. Since $\mathrm{PSL}_2(\mathbb{R}) \subseteq \mathrm{Isom}(\mathbb{H})$, the left side of the equation is invariant under the action of $\mathrm{PSL}_2(\mathbb{R})$. We first show that the right side is also invariant.

It's clear that the right side is invariant under maps of the form $z \mapsto az+b$ for $a, b \in \mathbb{R}$. Since $\mathrm{PSL}_2(\mathbb{R})$ (viewed as a group of Möbius transformations) is generated by maps of the forms

$$\begin{aligned} &z \mapsto az+b,\ a,b \in \mathbb{R} \\ &z \mapsto -\frac{1}{z} \end{aligned}$$

it's enough to show that the right side is invariant under these maps.

The right side is indeed invariant under $\frac{1}{z}$ since

$$\begin{aligned} \frac{\left|\frac{1}{z}-\frac{1}{w}\right|}{2\left(\Im\left(\frac{1}{z}\right)\Im\left(\frac{1}{w}\right)\right)^{\frac{1}{2}}} &= \frac{\left|\frac{z-w}{zw}\right|}{2\left(\Im\left(\frac{z}{|z|^2}\right)\Im\left(\frac{w}{|w|^2}\right)\right)^{\frac{1}{2}}} \\ &= \frac{|z-w|}{2\left(\Im(z)\Im(w)\right)^{\frac{1}{2}}}. \end{aligned}$$

Since both sides of the equation are invariant under the action of $\mathrm{PSL}_2(\mathbb{R})$, it's enough to prove the equality for $z = i$ and $w = ir$ for some $r \in \mathbb{R}_+$. Indeed,

$$\begin{aligned} \sinh\left(\frac{1}{2}\rho(i,ir)\right) &= \sinh\left(\frac{1}{2}|\ln r|\right) \\ &= \frac{\left|\sqrt{r}-\frac{1}{\sqrt{r}}\right|}{2} \\ &= \frac{|r-1|}{2\sqrt{r}} \\ &= \frac{|i-ir|}{2\left(\Im(i)\Im(ir)\right)^{\frac{1}{2}}}. \end{aligned}$$

■

Corollary 1.1.24.

1. *The hyperbolic topology is equal to the Euclidean topology.*
2. *$\mathbb{H}$ is a complete metric space.*

Proof.

1. Let $z \in \mathbb{H}$. If $|\Im(z) - \Im(w)| < \frac{1}{2}\Im(z)$ then

$$\frac{|z-w|}{\sqrt{6}\Im(z)} \leq \sinh\left(\frac{1}{2}\rho(z,w)\right) \leq \frac{|z-w|}{\sqrt{2}\Im(z)}.$$

2. We show that $\mathbb{U}$ is a complete metric space, which implies the result since there's an isometry between $\mathbb{U}$ and $\mathbb{H}$. Let $z, w \in \mathbb{U}$, we have

$$\sinh^2\left(\frac{1}{2}\rho\left(z,w\right)\right) = \frac{\left|z-w\right|^2}{\left(1-\left|z\right|^2\right)\left(z-\left|w\right|^2\right)}. \qquad \blacksquare$$

Let $\left(z_n\right)_{n\in\mathbb{N}}$ be a hyperbolic Cauchy sequence. Then it's bounded in the hyperbolic metric, and (2) implies that it does not have a limit point on the unit circle and so is contained in a compact subset of the unit circle.

The result follows since (2) implies that on such a subset the hyperbolic and Euclidean metric are Lipschitz equivalent.

Exercise 1. Prove that if $z, w \in \mathbb{U}$ then

$$\sinh^2\left(\frac{1}{2}\rho\left(z,w\right)\right) = \frac{\left|z-w\right|^2}{\left(1-\left|z\right|^2\right)\left(1-\left|w\right|^2\right)}.$$

Theorem 1.1.25. *Let* $\tau\colon \mathbb{H} \to \mathbb{H}$ *be* $\tau\left(z\right) = -\bar{z}$. *Then* $\operatorname{Isom}\left(\mathbb{H}\right) = \mathrm{PSL}_2\left(\mathbb{R}\right) \rtimes \langle\tau\rangle$. *In particular,* $\mathrm{PSL}_2\left(\mathbb{R}\right)$ *is a normal index two subgroup of* $\operatorname{Isom}\left(\mathbb{H}\right)$.

Proof. Clearly, τ is of order two. Since every index two subgroup is normal, it is enough to prove that for every hyperbolic isometry $s \in \operatorname{Isom}\left(\mathbb{H}\right)$ there exists $g \in \mathrm{PSL}_2\left(\mathbb{R}\right)$ such that sT_g is either the identity or τ.

There's $g \in \mathrm{PSL}_2\left(\mathbb{R}\right)$ such that $T_g\left(i\right) = s^{-1}\left(i\right)$ and $T_g\left(2i\right) = s^{-2}\left(2i\right)$ (since $\mathrm{PSL}_2\left(\mathbb{R}\right)$ is 2-transitive). Then $sT_g\left(i\right) = i$ and $sT_g\left(2i\right) = 2i$. Since isometries send geodesics to geodesics, for every $t > 0$ it holds that $sT_g\left(ti\right) = ti$.

Denote

$$\begin{aligned} U_+ &\coloneqq \left\{z \in \mathbb{H} \mid \Re\left(z\right) > 0\right\} \\ U_- &\coloneqq \left\{z \in \mathbb{H} \mid \Re\left(z\right) < 0\right\}. \end{aligned}$$

Since sT_g is continuous it follows that $sT_g\left(U_+\right) \subseteq U_+$ or $sT_g\left(U_+\right) \subseteq U_-$. In the first case denote $R \coloneqq sT_g$, and in the second case denote $R \coloneqq \tau sT_g$. In either case, $R\left(U_+\right) \subseteq U_+$.

In order to finish the proof, we want to show that $R = \mathrm{id}$. For every $t > 0$ we have

$$\begin{aligned} \frac{\left|it-w\right|}{2\left(t\Im\left(w\right)\right)^{\frac{1}{2}}} &= \sinh\left(\frac{1}{2}\rho\left(it,w\right)\right) \\ &= \sinh\left(\frac{1}{2}\rho\left(R\left(it\right),R\left(w\right)\right)\right) \\ &= \sinh\left(\frac{1}{2}\rho\left(it,R\left(w\right)\right)\right) \\ &= \frac{\left|it-R\left(w\right)\right|}{2\left(t\Im\left(R\left(w\right)\right)\right)^{\frac{1}{2}}}. \end{aligned}$$

So,

$$|it - w|^2 \Im(R(w)) = |it - R(w)|^2 \Im(w).$$

This holds for every t, which implies together with

$$\Im(R(w)) = \lim_{t\to\infty} \frac{|it - w|^2 \Im(R(w))}{t^2}$$

that

$$\Im(R(w)) = \lim_{t\to\infty} \frac{|it - R(w)|^2 \cdot \Im(w)}{t^2} = \Im(w).$$

Now, for every $t > 0$ we get

$$|it - w| = |it - R(w)|$$

which implies $w = R(w)$ or $w = -\overline{R(w)}$. The latter case is impossible since $R(U_+) \subseteq U_+$. ∎

Corollary 1.1.26. *Every element of* $\operatorname{Isom}(\mathbb{H})$ *is either conformal or anti-conformal.*

An element of $\operatorname{Isom}(\mathbb{H})$ *is conformal if and only if it belongs to* $\mathrm{PSL}_2(\mathbb{R})$*.*

Definition 1.1.27. Let $\hat{\mathbb{C}}$ be the Riemann sphere. The cross ratio of distinct points $z_1, z_2, z_3, z_4 \in \hat{\mathbb{C}}$ is

$$(z_1, z_2 : z_3, z_3) \coloneqq \frac{(z_1 - z_2)\, z_3 - z_4}{(z_2 - z_3)(z_4 - z_1)}.$$

Lemma 1.1.28. *Möbius transformations preserve the cross ratio.*

Proof. We prove this when $z_1, z_2, z_3, z_4 \in \mathbb{C} \setminus \{0\}$. The other cases are left as exercise.

It is clear that maps of the form $z \mapsto az + b$, with $a \neq 0$, preserve the cross-ratio. Thus it's enough to prove that the map $z \mapsto -\frac{1}{z}$ preserves the cross-ratio. Indeed,

$$\begin{aligned}
(z_1, z_2; z_3, z_4) &= \frac{(z_1 - z_2)\, z_3 - z_4}{(z_2 - z_3)(z_4 - z_1)} \\
&= \frac{\left(\frac{z_1 - z_2}{z_1 z_2}\right) \frac{z_3 - z_4}{z_3 z_4}}{\left(\frac{z_2 - z_3}{z_2 z_3}\right)\left(\frac{z_4 - z_1}{z_1 z_4}\right)} \\
&= \frac{\left(\frac{1}{z_1} - \frac{1}{z_2}\right)\left(\frac{1}{z_3} - \frac{1}{z_4}\right)}{\left(\frac{1}{z_2} - \frac{1}{z_3}\right)\left(\frac{1}{z_4} - \frac{1}{z_1}\right)} \\
&= \left(\frac{1}{z_1}, \frac{1}{z_2}; \frac{1}{z_3}, \frac{1}{z_4}\right).
\end{aligned}$$

∎

Theorem 1.1.29. *Let $z, w \in \mathbb{H}$ and let the geodesic joining z, w have have end points z^* and w^* in $\mathbb{R} \cup \{\infty\}$, chosen in a way that z lies between z^* and w. Then*

$$\rho(z, w) = \ln((w, z^*; z, w^*)).$$

Proof. Since both sides are invariant to the action of $\mathrm{PSL}_2(\mathbb{R})$ we can assume that $z = i$ and $w = ri$ with $r > 1$. Then $z^* = 0$ and $w^* = \infty$, so $r = (w, z^*, z, w^*)$ and $\rho(i, ir) = \ln(r)$. ■

1.2 The Gauss-Bonnet Formula

Definition 1.2.1 (Hyperbolic Measure). We define a measure μ on subsets of $\mathbb{H}$ by

$$\mu(A) = \int_A \frac{\mathrm{d}x\,\mathrm{d}y}{y^2}$$

for which this exists.

Theorem 1.2.2. *The hyperbolic area is invariant under* $\mathrm{PSL}_2(\mathbb{R})$.

Proof. Let $f\colon \mathbb{C} \to \mathbb{C}$ given by

$$f(x + iy) = u(x, y) + iv(x, y)$$

where $u, v\colon \mathbb{C} \to \mathbb{R}$.

By Cauchy-Riemann

$$\begin{aligned}\frac{\partial(u, v)}{\partial(x, y)} &= \frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x} \\ &= \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 \\ &= \dots\end{aligned}$$

Let $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \mathrm{PSL}_2(\mathbb{R})$. Recall that

$$\begin{aligned}\left|\frac{\mathrm{d}T_g}{\mathrm{d}z}\right| &= \frac{1}{|cz + d|^2} \\ \Im(T_g(z)) &= \frac{\Im(z)}{|cz + d|^2}.\end{aligned}$$

Then

$$T_g(x + iy) = u(x, y) + iv(x, y)$$

so

$$\begin{aligned}
\mu\left(T_g\left(A\right)\right) &= \int_{T_g(A)} \frac{\mathrm{d}u\,\mathrm{d}v}{v^2} \\
&= \int_A \frac{\partial\left(u,v\right)}{\partial\left(x,y\right)} \frac{\mathrm{d}x\,\mathrm{d}y}{v^2} \\
&= \int_A \frac{1}{\left|cz+d\right|^4} \cdot \frac{\left|cz+d\right|^4}{y\,\mathrm{d}x\,\mathrm{d}y} \\
&= \mu\left(A\right).
\end{aligned}$$

■

Definition 1.2.3 ($\tilde{\mathbb{H}}$). 1. Define $\tilde{\mathbb{H}} = \mathbb{H} \cup \mathbb{R} \cup \{\infty\}$.

2. A hyperbolic n-sided polygon is a closed subset of $\tilde{\mathbb{H}}$ bounded by the closure of n hyperbolic geodesic segments or rays.

3. A side of a polygon is the closure of a geodesic segment or ray which bounds to polygon.

4. A point $z \in \tilde{\mathbb{H}}$ is called a vertex if it is the intersection of two distinct sides.

Example 1.2.4. There rare four types of hyperbolic triangles, which depend on the number of vertices on the boundary.

Theorem 1.2.5 (Gauss-Bonnet). *Let Δ be a hyperbolic triangle with angles α, β, γ. Then*

$$\mu\left(\Gamma\right) = \pi - \alpha - \beta - \gamma.$$

Proof. First assume that Δ has a vertex on the boundary. Since $\mathrm{PSL}_2\left(\mathbb{R}\right)$ preserves area, we may assume that this vertex is ∞. Thus, two sides are given by equations $x = a$ and $x = b$ (and assume $a < b$). By applying a transformation of the form

$$z \mapsto \lambda z + k$$

where $\lambda > 0$ and $k \in \mathbb{R}$, we can assume that the third side of Γ is an arc on the geodesic $\left|z\right|^2 = 1$.

Pass segments from 0 to the vertices of the triangle and call the angles between these and the real axis α and β. Then

$$\begin{aligned}
\mu\left(\Delta\right) &= \int_\Delta \frac{\mathrm{d}x\,\mathrm{d}y}{y^2} \\
&= \int_a^b \mathrm{d}x \int_{\sqrt{1-x^2}}^\infty \frac{\mathrm{d}y}{y^2} \\
&= \int_a^b \frac{\mathrm{d}x}{\sqrt{1-x^2}} \\
&\underset{x=\cos\theta}{=} \int_{\pi-\alpha}^\beta -\frac{\sin\theta}{\sin\theta}\,\mathrm{d}\theta = \pi - \alpha - \beta - \cancelto{0}{\gamma}.
\end{aligned}$$

In the other case, consider a triangle $\Delta = \mathrm{ABC}$ with respective angles α, β, γ. Continue the geodesic segment AB to get an intersection D with the boundary. Let $\Delta' = \mathrm{CBD}$ and $\Delta'' = \mathrm{ABD}$.

Now, Δ' and Δ'' have a vertex at infinity, so

$$\begin{aligned}\mu(\Delta) &= \mu(\Delta'') - \mu(\Delta') \\ &= \pi - (\alpha + \gamma + \theta) - (\pi - \theta - (\pi - \beta)) \\ &= \pi - \alpha - \beta - \gamma.\end{aligned}$$

■

1.3 Hyperbolic Geometry

Theorem 1.3.1. *Let Δ be a hyperbolic triangle with sides of hyperbolic lengths a, b, c and opposite angles α, β, γ. Assume that $\alpha, \beta, \gamma > 0$ (so there is no vertex at the boundary).*

The following holds.

The Sine Rule:

$$\frac{\sinh(a)}{\sin\alpha} = \frac{\sinh(b)}{\sin\beta} = \frac{\sinh(c)}{\sin\gamma}$$

The First Cosine Rule:

$$\cosh(c) = \cosh(a)\cosh(b) - \cos\gamma\sinh(a)\sinh(b)$$

The Second Cosine Rule:

$$\cosh(c) = \frac{\cos\alpha\cos\beta + \cos\gamma}{\sin\alpha\sin\beta}.$$

Proof. **The First Cosine Rule:** We use the disc model to prove the rule. Let Δ be a triangle in $\mathbb{U}$ with sides a, b, c and let v_a, v_b, v_c be the vertices opposite to the respective sides.

We can assume $v_c = 0$ and $v_a = r \in (0,1)$, and denote $v_b = z \in \mathbb{U}$. We have

$$\sinh^2\left(\frac{1}{2}\rho_u(z,w)\right) = \frac{|z-w|}{\left(1-|z|^2\right)\left(1-|w|^2\right)},$$

but

$$\sinh^2(\alpha) = \frac{1}{2}\cosh(2\alpha) - \frac{1}{2}\alpha$$

because

$$\begin{aligned}\left(\frac{e^{\alpha} - e^{-\alpha}}{2}\right)^{\alpha} &= \frac{e^{2\alpha} - 2 + e^{-2\alpha}}{4} \\ &= \frac{1}{2}\cdot\frac{e^{2\alpha} + e^{-2\alpha}}{2} - \frac{1}{2}.\end{aligned}$$

Hence

$$\cosh\left(\rho_u\left(z,w\right)\right)=\frac{2\left|z-w\right|}{\left(1-\left|z\right|^2\right)\left(1-\left|w\right|^2\right)}+1.$$

Then

$$\begin{aligned}\cosh\left(a\right)&=\frac{1+\left|z\right|^2}{1-\left|z\right|^2}\\ \cosh\left(b\right)&=\frac{1+r^2}{1-r^2}\\ \cosh\left(c\right)&=\frac{2\left|z-r\right|^2}{\left(1-\left|z\right|^2\right)\left(1-r^2\right)}+1.\end{aligned}$$

Using

$$\begin{aligned}\sinh\left(a\right)&=\sqrt{\cosh^2\left(\left|z\right|\right)-1}=\frac{2\left|z\right|}{1-\left|z\right|^2}\\ \sinh\left(b\right)&=\sqrt{\cosh^2\left(r\right)-1}=\frac{2r}{1-r^2}\end{aligned}$$

and the Euclidean cosine rule

$$\cos\gamma=\frac{r^2+\left|z\right|^2-\left|2-r\right|^2}{2r\left|z\right|}$$

we get

$$\begin{aligned}\cosh\left(a\right)\cosh\left(b\right)-\sinh\left(a\right)\sinh\left(b\right)\cos\left(\gamma\right)&=\left(\frac{1+\left|z\right|^2}{1-\left|z\right|^2}\right)\left(\frac{1+r^2}{1-r^2}\right)-\frac{4r\left|z\right|}{\left(1-r^2\right)\left(1-\left|z\right|^2\right)}\cdot\frac{r^2+\left|z\right|^2}{2r}\\ &=\frac{\left(1+r^2\right)\left(1+\left|z\right|^2\right)-2r^2-2\left|z\right|^2+2\left|z-r\right|^2}{\left(1-r^2\right)\left(1-\left|z\right|^2\right)}\\ &=1+\frac{2\left|z-r\right|^2}{\left(1-r\right)^2\left(1-\left|z\right|^2\right)}\\ &=\cosh\left(c\right).\end{aligned}$$

The Sine Rule: It holds by the first cosine rule that that

$$\begin{aligned}\left(\frac{\sinh c}{\sin\gamma}\right)^2&=\frac{\sinh^2 c}{1-\left(\frac{\cosh a\cosh b-\cosh c}{\sinh(a)\sinh(b)}\right)^2}\\ &=\left(\cosh^2\left(a\right)-1\right)\left(\cosh^2\left(b\right)-1\right)-\left(\cosh\left(a\right)\cosh\left(b\right)-\cosh\left(c\right)\right)^2\\ &=1+2\cosh\left(a\right)\cosh\left(b\right)\cosh\left(c\right)-\cosh^2\left(a\right)-\cosh^2\left(b\right)-\cosh^2\left(c\right)\end{aligned}$$

where the last term is symmetric in a,b,c. ■

Chapter 2

Fuchsian Groups

2.1 Fuchsian Groups

2.1.1 Definitions

Definition 2.1.1 ($\mathbf{SL_2}(\mathbb{R})$). Let $\mathrm{SL}_2(\mathbb{R})$ be the group of 2×2 real matrices with determinant 1, with the topology from $\mathbb{R}^4$ via $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \mapsto \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix}$.

Throughout the course, we endow $\mathrm{PSL}_2(\mathbb{R})$ with the quotient topology from $\mathrm{GL}_2(\mathbb{R})$.

We endow $\mathrm{Isom}(\mathbb{H})$ with the following topology. Let $\tau \in \mathrm{Isom}(\mathbb{H}) \setminus \mathrm{PSL}_2(\mathbb{R})$ and. $U \subseteq \mathrm{Isom}(\mathbb{H})$ is open if and only if $U \cap \mathrm{PSL}_2(\mathbb{R})$ and $\tau U \cap \mathrm{PSL}_2(\mathbb{R})$ are open.

Exercise 2. 1. $\mathrm{SL}_2(\mathbb{R}), \mathrm{PSL}_2(\mathbb{R}), \mathrm{Isom}(\mathbb{H})$ are topological groups.

2. The actions of $\mathrm{PSL}_2(\mathbb{R})$ on $\mathbb{H}$ and $\mathbb{R} \cup \{\infty\}$ are continuous.

Definition 2.1.2. Let

$$S\mathbb{H} \coloneqq \{(z, \alpha) \mid z \in \mathbb{H}, \alpha \in \mathbb{C}, |\alpha| = \Im(z)\}$$

be the unit tangent bundle of $\mathbb{H}$, which is homeomorphic to $\mathbb{H} \times S^1$.

Definition 2.1.3. For every $g \in \mathrm{PSL}_2(\mathbb{R})$ and $(W, \alpha) \in S\mathbb{H}$, denote $T_g \cdot (w, \alpha) = (T_g(w), D(T_g)(w))$.

Definition 2.1.4 (Sharply Transitive Action). A group action is called *sharply transitive* if its transitive and the stabiliser of every element is trivial.

Lemma 2.1.5. *1. The map* $\mathrm{PSL}_2(\mathbb{R}) \times S\mathbb{H} \to S\mathbb{H}$ *is a group action.*

2. $\mathrm{PSL}_2(\mathbb{R})$ *acts sharply transitive on* $S\mathbb{H}$.

3. The map $g \mapsto T_g((i,i))$ *is a homeomorphism of* $\mathrm{PSL}_2(\mathbb{R})$ *and* $S\mathbb{H}$.

Proof. 1. Let $(w,\alpha) \in S\mathbb{H}$ and $g,h \in \mathrm{PSL}_2(\mathbb{R})$. We first show that $g\cdot(w,\alpha) \in S\mathbb{H}$. It holds that

$$\Im(T_g(w)) = \left|\frac{\mathrm{d}T_g}{\mathrm{d}z}(w)\right| \cdot \Im(w),$$

so

$$\left| DT_g|_{w(\alpha)} \right| = |\Im(T_g(w))|.$$

We now have to check that this is an action. It holds that

$$\begin{aligned}(gh)\cdot(w,\alpha) &= (T_{gh}(\alpha), DT_{gh}(w)\alpha)\\ &= (T_g(T_h(w)), DT_g(T_h(w))\alpha)\\ &= g\cdot(h\cdot(w,\alpha)).\end{aligned}$$

2. Let $(w,\alpha) \in S\mathbb{H}$. It is enough to show that there exists a unique $g \in \mathrm{PSL}_2(\mathbb{R})$ such that $g\cdot(i,i) = (w,\alpha)$. Recall that geodesic lines in $\mathbb{H}$ are oriented generalised semicircles orthogonal to the real axis. Hence there exists a unique geodesic $\ell\colon \mathbb{R} \to \mathbb{H}$ which passes through w and whose derivative at w is α. Let $\gamma\colon \mathbb{R} \to \mathbb{H}$ be the geodesic given by $\gamma(t) = ie^t$. Since T_g sends geodesics to geodesics, it must send i to w, send γ to ℓ, and respect the orientation of γ and ℓ. There exists a unique such g.

3. Prove this as an exercise. ■