

# MODULI SPACES OF RIEMANN SURFACES

ZHAOSHEN ZHAI

HAOYANG GUO

April 9, 2023

*Directed Reading Program – Winter 2023*

*Graduate mentor: Kaleb Ruscitti*

## ABSTRACT

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Aliquam nulla facilisi cras fermentum. At urna condimentum mattis pellentesque. Cursus risus at ultrices mi tempus imperdiet nulla malesuada pellentesque. Quis hendrerit dolor magna eget est lorem. Vulputate odio ut enim blandit volutpat maecenas volutpat. Mattis aliquam faucibus purus in massa tempor nec feugiat. Malesuada fames ac turpis egestas sed tempus. Ornare arcu odio ut sem nulla pharetra. Urna condimentum mattis pellentesque id nibh tortor. Volutpat diam ut venenatis tellus in. Congue nisi vitae suscipit tellus mauris a. Nulla at volutpat diam ut venenatis tellus in metus. Nulla at volutpat diam ut venenatis tellus. Neque vitae tempus quam pellentesque nec nam aliquam. Id leo in vitae turpis massa sed. Nulla aliquet porttitor lacus luctus. Lorem dolor sed viverra ipsum nunc aliquet. Tellus molestie nunc non blandit massa enim nec. Erat nam at lectus urna.

## CONTENTS

<b>1</b>	<b>Riemann Surfaces</b>	<b>1</b>
1.1	Charts and Atlases	1
1.1.1	The Riemann Sphere $\hat{\mathbb{C}}$	1
1.1.2	Complex Tori	2
1.2	Maps on Riemann Surfaces	3
1.2.1	Holomorphic Functions and Maps	3
1.2.2	Singularities of Functions	4
1.2.3	Meromorphic Functions on $\hat{\mathbb{C}}$	5
1.2.4	Local Normal Form	5
<b>2</b>	<b>Covering Spaces and Analytic Continuation</b>	<b>7</b>
2.1	Covering Maps and the Degree	7
2.1.1	Ramification and Critical Points	7
2.1.2	Proper and Covering Maps	7
2.1.3	Liftings of Curves	8
2.1.4	Degrees and Multiplicities	9
2.2	Sheaves and Function Germs	10
2.2.1	Presheaves and Sheaves	10
2.2.2	Stalks and the Étale Space	11
2.3	Analytic Continuation	12
2.3.1	Analytic Continuation of Germs along Curves	12
2.3.2	Existence of Analytic Continuations	13
<b>3</b>	<b>Moduli Spaces</b>	<b>14</b>
3.1	Case for $g = 0$ and $g = 1$	14
3.1.1	Moduli Space of $S^2$	14
3.1.2	Moduli Space of $T^2$	14
3.2	Uniformization and Classification	16

# Chapter 1

## Riemann Surfaces

### 1.1 Charts and Atlases

We assume that the reader is familiar with the basic notions of real manifolds. The case for complex manifolds is similar, so our exposition will be brief.

**Definition 1.1.** Let  $X$  be a second-countable Hausdorff space. A  $d$ -dimensional complex chart on  $X$  is a pair  $(U, \varphi)$  where  $\varphi : U \rightarrow V$  is a homeomorphism from an open subset  $U \subseteq X$  onto an open subset  $V \subseteq \mathbb{C}^d$  for some  $d$ . Two  $d$ -dimensional charts  $(U_1, \varphi_1)$  and  $(U_2, \varphi_2)$  are said to be holomorphically compatible if either  $U_1 \cap U_2 = \emptyset$ , or the map

$$\varphi_2 \circ \varphi_1^{-1} : \varphi_1(U_1 \cap U_2) \rightarrow \varphi_2(U_1 \cap U_2)$$

is biholomorphic. A  $d$ -dimensional complex atlas on  $X$  is a collection  $\mathfrak{A} := \{(U_i, \varphi_i)\}_{i \in I}$  of  $d$ -dimensional complex charts such that every two charts  $(U_i, \varphi_i)$  and  $(U_j, \varphi_j)$  are holomorphically compatible and  $X = \bigcup_{i \in I} U_i$ .

**Remark.** Two atlases  $\mathfrak{A}$  and  $\mathfrak{B}$  on a manifold  $X$  are said to be analytically equivalent if every chart in  $\mathfrak{A}$  is compatible with every chart in  $\mathfrak{B}$ . By Zorn's Lemma, every atlas  $\mathfrak{A}$  of a manifold  $X$  is contained in a unique maximal atlas on  $X$ . Moreover, two atlases are equivalent iff they are contained in the same maximal atlas, which justifies the following definition. ♦

**Definition 1.2.** Let  $X$  be a second-countable Hausdorff space. A  $d$ -dimensional complex structure on  $X$  is a  $d$ -dimensional maximal atlas  $\mathfrak{A}$  on  $X$ , or, equivalently, an equivalence class of  $d$ -dimensional complex atlases on  $X$ . The pair  $(X, \mathfrak{A})$  is then called a  $d$ -dimensional complex manifold.

**Definition 1.3.** A Riemann surface is a connected 1-dimensional complex manifold.

**Example 1.4.** Some elementary examples of Riemann surfaces.

- The complex plane  $\mathbb{C}$ , equipped with its standard topology, can be given a complex structure  $\mathfrak{A}$  by choosing the atlas containing a single chart  $(\mathbb{C}, \text{id}_{\mathbb{C}})$ . We may, however, also give  $\mathbb{C}$  a different complex structure  $\mathfrak{A}'$  by choosing the chart map  $\varphi : z \mapsto \bar{z}$  instead. Indeed,  $\mathfrak{A} \neq \mathfrak{A}'$  since the map  $\varphi \circ \text{id}_{\mathbb{C}}^{-1} = \varphi$  is not holomorphic and hence the atlases  $\{(\mathbb{C}, \text{id}_{\mathbb{C}})\}$  and  $\{(\mathbb{C}, \varphi)\}$  are not equivalent. This example generalizes to any domain  $D \subseteq \mathbb{C}$ .
- Let  $D \subseteq \mathbb{C}$  be a domain and consider any holomorphic function  $f : D \rightarrow \mathbb{C}$ . Then the graph  $\Gamma_f := \{(z, f(z)) \mid z \in D\}$ , equipped with the subspace topology inherited from  $\mathbb{C}^2$ , can be given a complex structure by choosing the chart map  $\pi : \Gamma_f \rightarrow D : (z, f(z)) \mapsto z$ . ♦

#### 1.1.1 The Riemann Sphere $\hat{\mathbb{C}}$

A particularly important Riemann surface is the Riemann sphere  $\hat{\mathbb{C}}$ , which admits several constructions. Here, we give three; see Example 1.14 for a proof that they are all biholomorphic (in the sense of Definition 1.13).

**Example 1.5** (One-point Compactification of  $\mathbb{C}$ ). Let  $\infty$  be a symbol not belonging to  $\mathbb{C}$  and set  $\mathbb{C}_{\infty} := \mathbb{C} \cup \{\infty\}$ . We declare a set  $U \subseteq \mathbb{C}_{\infty}$  to be open if either  $U \subseteq \mathbb{C}$  is open or  $U = K^c \cup \{\infty\}$  where  $K \subseteq \mathbb{C}$  is compact. We employ two charts

$$\begin{aligned} U_1 &:= \mathbb{C}_{\infty} \setminus \{\infty\} = \mathbb{C} & \varphi_1 : U_1 \rightarrow \mathbb{C} : z &\mapsto z & (\varphi_1 &:= \text{id}_{\mathbb{C}}) \\ U_2 &:= \mathbb{C}_{\infty} \setminus \{0\} = \mathbb{C}^* \cup \{\infty\} & \varphi_2 : U_2 \rightarrow \mathbb{C} : z &\mapsto \begin{cases} 1/z & \text{if } z \in \mathbb{C}^* \\ 0 & \text{else.} \end{cases} \end{aligned}$$

Clearly  $\varphi_1$  is a homeomorphism. Since  $\varphi_2$  is invertible with  $\varphi_2^{-1}(z) := 1/z$  for all  $z \in \mathbb{C}^*$  and  $\varphi_2^{-1}(0) := \infty$ , and

$$\lim_{z \rightarrow \infty} \varphi_2(z) = 0 = \varphi_2(\infty) \quad \text{and} \quad \lim_{z \rightarrow 0} \varphi_2^{-1}(z) = \infty = \varphi_2^{-1}(0),$$

we see that  $\varphi_2$  is a homeomorphism too. Furthermore,

$$\varphi_2 \circ \varphi_1^{-1} : \mathbb{C}^* \rightarrow \mathbb{C}^* : z \mapsto \frac{1}{z}$$

is holomorphic, so the atlas  $\{(U_1, \varphi_1), (U_2, \varphi_2)\}$  defines a complex structure on  $\mathbb{C}_{\infty}$ . ♦

Charts provide us a way of making  $X$  ‘look like’ an open set in  $\mathbb{C}^d$ . Indeed, they provide local coordinates for every point in  $X$  in such a way that the ‘change of coordinates’ map  $\varphi_2 \circ \varphi_1^{-1}$  ensures that local notions of functions in  $\mathbb{C}^d$  are well-defined on  $X$  too.

$$\begin{array}{ccc} & U_1 \cap U_2 & \\ \varphi_1 \swarrow & & \searrow \varphi_2 \\ \varphi_1(U_1 \cap U_2) & \xrightarrow{\varphi_2 \circ \varphi_1^{-1}} & \varphi_2(U_1 \cap U_2) \end{array}$$

It is clear that one only needs  $\varphi_2 \circ \varphi_1^{-1}$  to be holomorphic for it to be biholomorphic.

To give a complex structure  $\mathfrak{A}$  to  $X$ , it suffices to give  $X$  a complex atlas since it extends to a unique complex structure.

Every Riemann surface can be regarded as a (connected) 2-dimensional real manifold by ‘forgetting’ its complex structure; indeed all holomorphic maps are real  $\mathcal{C}^{\infty}$  functions.

Showing that *every* Riemann surface that is topologically a sphere is biholomorphic to  $\hat{\mathbb{C}}$  is a highly non-trivial task, and it will be the main goal of this paper to establish this fact.

This makes  $\mathbb{C}_{\infty}$ , equipped with the collection  $\mathcal{T}$  of all such open sets, a second-countable Hausdorff space. Indeed, the fact that  $\mathcal{T}$  is a topology on  $\mathbb{C}_{\infty}$  follows from De Morgan's Laws and the Heine-Borel Theorem. It is trivially Hausdorff, and it is second-countable since we may append, to any countable basis for the standard topology of  $\mathbb{C}$ , the countable collection  $\{B_r(0)^c \cup \{\infty\}\}_{r \in \mathbb{Q}^+}$ .

**Example 1.6** (Stereographic Projection). Consider the unit sphere  $S^2 \subseteq \mathbb{R}^3$  as a topological subspace of  $\mathbb{R}^3$ , which makes it a second-countable Hausdorff space. Identifying the plane  $w = 0$  as  $\mathbb{C}$ , we employ the charts

$$\begin{aligned} U_1 &:= S^2 \setminus \{(0, 0, 1)\} & \varphi_1 : U_1 \rightarrow \mathbb{C} : (x, y, w) &\mapsto \frac{x + iy}{1 - w} \\ U_2 &:= S^2 \setminus \{(0, 0, -1)\} & \varphi_2 : U_2 \rightarrow \mathbb{C} : (x, y, w) &\mapsto \frac{x - iy}{1 + w}. \end{aligned}$$

Clearly  $\varphi_1$  and  $\varphi_2$  are continuous, and it can be verified that they are invertible with continuous inverses

$$\varphi_1^{-1}(z) := \left( \frac{2 \operatorname{Re} z}{|z|^2 + 1}, \frac{2 \operatorname{Im} z}{|z|^2 + 1}, \frac{|z|^2 - 1}{|z|^2 + 1} \right) \quad \text{and} \quad \varphi_2^{-1}(z) := \left( \frac{2 \operatorname{Re} z}{|z|^2 + 1}, \frac{-2 \operatorname{Im} z}{|z|^2 + 1}, \frac{1 - |z|^2}{|z|^2 + 1} \right).$$

Observe that  $U_1 \cap U_2 = S^2 \setminus \{(0, 0, \pm 1)\}$  and  $\varphi_2 \circ \varphi_1^{-1} : \mathbb{C}^* \rightarrow \mathbb{C}^* : z \mapsto 1/z$ , which is holomorphic, so the atlas  $\{(U_1, \varphi_1), (U_2, \varphi_2)\}$  defines a complex structure on  $\mathbb{C}$ .  $\blacklozenge$

**Example 1.7** (Complex Projective Line). Consider the equivalence relation  $\sim$  on  $\mathbb{C}^2 \setminus \{(0, 0)\}$  defined by  $(z_1, w_1) \sim (z_2, w_2)$  iff  $(z_1, w_1) = \lambda(z_2, w_2)$  for some  $\lambda \in \mathbb{C}^*$ . Set  $\mathbb{P}^1 := (\mathbb{C}^2 \setminus \{(0, 0)\}) / \sim$  and equip it with the quotient topology. Since  $\sim$  is an open equivalence relation whose graph is closed in  $(\mathbb{C}^2 \setminus \{(0, 0)\})^2$ , we see that  $\mathbb{P}^1$  is a second-countable Hausdorff space. Denoting the equivalence class of  $(z, w)$  by  $[z : w]$ , we employ the charts

$$\begin{aligned} U_1 &:= \mathbb{P}^1 \setminus \{[0 : w] \mid w \in \mathbb{C}\} & \varphi_1 : U_1 \rightarrow \mathbb{C} : [z : w] &\mapsto w/z \\ U_2 &:= \mathbb{P}^1 \setminus \{[z : 0] \mid z \in \mathbb{C}\} & \varphi_2 : U_2 \rightarrow \mathbb{C} : [z : w] &\mapsto z/w. \end{aligned}$$

Clearly  $\varphi_1$  and  $\varphi_2$  are continuous, and it is easily verified that they are invertible with continuous inverses

$$\varphi_1^{-1}(z) := [1 : z] \quad \text{and} \quad \varphi_2^{-1}(z) := [z : 1].$$

Furthermore,  $\varphi_2 \circ \varphi_1^{-1} : \mathbb{C}^* \rightarrow \mathbb{C}^* : 1 \mapsto 1/z$  is holomorphic, so the atlas  $\{(U_1, \varphi_1), (U_2, \varphi_2)\}$  defines a complex structure on  $\mathbb{P}^1$ .  $\blacklozenge$

See [Tu10, section 7.5].

## 1.1.2 Complex Tori

Recall that a torus is any manifold homeomorphic to  $T^2 := S^1 \times S^1$ , which admits a representation as a quotient  $\mathbb{C}/\Gamma$  by the lattice  $\Gamma := \mathbb{Z} \oplus \mathbb{Z}$ . Thus (by definition) there is only one torus up to homeomorphism, but it turns out that we can equip it with many different complex structures.

**Example 1.8** (Complex Tori). Let  $\omega_1, \omega_2 \in \mathbb{C}$  be linearly independent over  $\mathbb{R}$  and consider the lattice  $\Gamma := \mathbb{Z}\omega_1 \oplus \mathbb{Z}\omega_2$ . Then the quotient  $\mathbb{C}/\Gamma$  is a torus in the topological sense since the map

$$\varphi : \mathbb{C}/\Gamma \rightarrow T^2 \quad \text{mapping} \quad [z] \mapsto (e^{2\pi i \lambda_1}, e^{2\pi i \lambda_2}),$$

where  $z = \lambda_1 \omega_1 + \lambda_2 \omega_2$  for unique  $\lambda_1, \lambda_2 \in \mathbb{R}$ , is a homeomorphism. Indeed,  $\varphi$  is well-defined since for any  $\lambda_1 \omega_1 + \lambda_2 \omega_2 \sim \mu_1 \omega_1 + \mu_2 \omega_2$  in  $\mathbb{C}$ , we have  $(\lambda_1 - \mu_1)\omega_1 + (\lambda_2 - \mu_2)\omega_2 \in \Gamma$  and so  $\lambda_i - \mu_i \in \mathbb{Z}$  for  $i = 1, 2$ . The fact that it is a homeomorphism is clear. This makes  $\mathbb{C}/\Gamma$  a second-countable Hausdorff space, which we now endow with the following complex structure.

They manifest by quotienting  $\mathbb{C}$  by different lattices, and we shall derive a criterion on  $\Gamma_1 := \mathbb{Z}\omega_1 \oplus \mathbb{Z}\omega_2$  and  $\Gamma_2 := \mathbb{Z}\eta_1 \oplus \mathbb{Z}\eta_2$  for the tori  $\mathbb{C}/\Gamma_1$  and  $\mathbb{C}/\Gamma_2$  to be biholomorphic.

Since  $\Gamma$  is discrete, there exists some  $\varepsilon > 0$  such that  $\varepsilon < |\omega|/2$  for every non-zero  $\omega \in \Gamma$ . Fix any such  $\varepsilon$ , which ensures that no two points in any open ball with radius  $\varepsilon$  can be equivalent. Indeed, take any  $z \in \mathbb{C}$  and  $w_1, w_2 \in B(z, \varepsilon) =: V_z$ . For  $w_1 \sim w_2$ , we need some  $n, m \in \mathbb{Z}$  such that  $w_1 - w_2 = n\omega_1 + m\omega_2$ . But

$$|w_1 - w_2| \leq |z - w_1| + |z - w_2| < 2\varepsilon < |n\omega_1 + m\omega_2|$$

for any  $n, m \in \mathbb{Z}$ , so this is impossible. Fixing any such  $\varepsilon$ , this gives us a family  $\{V_z\}_{z \in \mathbb{C}}$  of open sets in  $\mathbb{C}$  for which the projections  $\pi|_{V_z} : V_z \rightarrow \pi(V_z)$  are homeomorphisms. Letting  $U_z := \pi(V_z)$  and  $\varphi_z : U_z \rightarrow V_z$  be the inverse of  $\pi|_{V_z}$ , we obtain complex charts  $(U_z, \varphi_z)$  for all  $z \in \mathbb{C}$ . We claim that the collection  $\mathfrak{A} := \{(U_z, \varphi_z)\}_{z \in \mathbb{C}}$  form an atlas, for which it suffices to take  $(U_1, \varphi_1), (U_2, \varphi_2) \in \mathfrak{A}$  and show that the transition map  $T := \varphi_2 \circ \varphi_1^{-1} : \varphi_1(U) \rightarrow \varphi_2(U)$ , where  $U := U_1 \cap U_2$ , is holomorphic. Observe that the diagram

$$\begin{array}{ccc} & \pi|_{V_1} & \\ & \swarrow & \searrow \\ & U & \\ & \swarrow \varphi_1 & \searrow \varphi_2 \\ V_1 = \varphi_1(U) & \xrightarrow{T} & \varphi_2(U) = V_2 \end{array}$$

commutes, so  $\pi|_{V_2} \circ T = \pi|_{V_1}$  on  $\varphi_1(U)$ . Then  $\pi(T(z)) = \pi(z)$  for every  $z \in \varphi_1(U)$ , so  $T(z) \sim z$  and hence  $\ell(z) := T(z) - z \in \Gamma$ . This holds for all  $z \in \varphi_1(U)$ , so we obtain a continuous function  $\ell : \varphi_1(U) \rightarrow \Gamma : z \mapsto T(z) - z$ . Note that  $\Gamma \subseteq \mathbb{C}$  is equipped with the subspace topology, but since it is discrete, every  $L \subseteq \Gamma$  is open. In particular, fix  $z_0 \in \varphi_1(U)$  and set  $\omega_0 := T(z_0) - z_0$ . With  $L := \{\omega_0\}$ , continuity of  $\ell$  shows that  $\ell^{-1}(L)$  is open. Thus  $\ell(B(z_0, \delta_1)) \subseteq \{\omega_0\}$  for some  $\delta_1 > 0$ , so  $\ell(w) = \omega_0$  for all  $w \in B(z_0, \delta_1)$ . But then  $\ell(B(\omega_0, \delta_2)) \subseteq \{\omega_0\}$  for some  $\delta_2 > 0$  too, so we may repeat this process to show that  $\ell$  is constant on every connected component of  $\varphi_1(U)$ . Thus  $T(z) = z + \omega_0$  for all  $z \in \varphi_1(U)$  in a local neighborhood around  $z_0$ , so  $T$  is locally holomorphic. But this holds for all  $z_0 \in \varphi_1(U)$ , so  $T$  is holomorphic on  $\varphi_1(U)$ .  $\blacklozenge$

This exposition follows [Mir95, Section I.2].

The choice of  $\varepsilon$  ensures that no two points in  $V_z$  are equivalent, which make all such projections injective.

Since  $U = \pi(V_1) \cap \pi(V_2)$ , it may not be connected. Hence  $\varphi_1(U)$  may not be connected, so  $\ell$  may take on multiple values. What matters, however, is that they coincide within every connected component of  $\varphi_1(U)$ .

## 1.2 Maps on Riemann Surfaces

### 1.2.1 Holomorphic Functions and Maps

**Definition 1.9.** Let  $X$  be a Riemann surface and let  $W \subseteq X$  be open. For a fixed  $p \in W$ , a function  $f : W \rightarrow \mathbb{C}$  is said to be holomorphic at  $p$  if there exists a chart  $(U, \varphi)$  of  $X$  containing  $p$  such that  $f \circ \varphi^{-1} : \varphi(U) \rightarrow \mathbb{C}$  is holomorphic at  $\varphi(p)$ . If  $f$  is holomorphic at every point of  $W$ , then  $f$  is said to be holomorphic on  $W$ .

**Remark.** It must be checked that ‘being holomorphic’ does not depend on the choice of chart. This is indeed the case, for if  $(V, \psi)$  is another chart containing  $p$ , then, since

$$f \circ \psi^{-1} = f \circ (\varphi^{-1} \circ \varphi) \circ \psi^{-1} = (f \circ \varphi^{-1}) \circ (\varphi \circ \psi^{-1}) : \psi(U \cap V) \rightarrow \mathbb{C} \quad (1.1)$$

on the intersection  $U \cap V$ , we see that  $f \circ \psi^{-1} : \psi(U \cap V) \rightarrow \mathbb{C}$  is also holomorphic at  $p$ .  $\blacklozenge$

**Example 1.10.** Some elementary examples of holomorphic functions.

- Any holomorphic function  $f : W \rightarrow \mathbb{C}$  from an open set  $W \subseteq \mathbb{C}$ , considering  $\mathbb{C}$  as a Riemann surface with the standard chart  $(\mathbb{C}, \text{id}_{\mathbb{C}})$ , is holomorphic in the classical sense.
- Any chart map  $\varphi : U \rightarrow \mathbb{C}$  of a Riemann surface is (tautologically) holomorphic in the above sense.
- If  $f, g : W \rightarrow \mathbb{C}$  are both holomorphic at some  $p \in W$ , then so are  $f \pm g$  and  $f \cdot g$ . If  $g(p) \neq 0$ , then so is  $f/g$ .  $\blacklozenge$

**Definition 1.11.** Let  $X$  and  $Y$  be Riemann surfaces and let  $W \subseteq X$  be open. For a fixed  $p \in W$ , a mapping  $F : W \rightarrow Y$  is said to be holomorphic at  $p$  if there exists a chart  $(U, \varphi)$  of  $X$  containing  $p$  and a chart  $(V, \psi)$  of  $Y$  containing  $F(p)$  such that  $\psi \circ F \circ \varphi^{-1} : \varphi(U) \rightarrow \psi(V)$  is holomorphic at  $\varphi(p)$ . If  $F$  is holomorphic at every point of  $W$ , then  $F$  is holomorphic on  $W$ .

**Example 1.12.** It is easy to show that the identity map  $\text{id}_X$  on a Riemann surface  $X$  is a holomorphic map. Furthermore, for all Riemann surfaces  $X, Y$  and  $Z$  and holomorphic maps  $F : X \rightarrow Y$  and  $G : Y \rightarrow Z$ , their composite  $G \circ F : X \rightarrow Z$  is also a holomorphic map. This shows that the collection of all Riemann surfaces is a *category*.  $\blacklozenge$

**Definition 1.13.** Let  $X$  and  $Y$  be Riemann surfaces. A biholomorphism between  $X$  and  $Y$  is an invertible holomorphic map  $F : X \rightarrow Y$  whose inverse  $F^{-1} : Y \rightarrow X$  is also holomorphic. Two Riemann surfaces  $X$  and  $Y$  are said to be biholomorphic if there exists a biholomorphism  $F : X \rightarrow Y$ .

**Example 1.14** (Biholomorphisms between Riemann spheres). Let  $\mathbb{C}_{\infty}$ ,  $S^2$ , and  $\mathbb{P}^1$  denote the three constructions for the Riemann sphere  $\hat{\mathbb{C}}$  presented in Examples 1.5, 1.6, and 1.7, respectively. We claim that the maps

$$F : S^2 \rightarrow \mathbb{P}^1 : (x, y, w) \mapsto [1 - w : x + iy] \quad \text{and} \quad G : S^2 \rightarrow \mathbb{C}_{\infty} : (x, y, w) \mapsto \frac{x + iy}{1 - w}$$

are biholomorphisms, which shows that all three constructions are biholomorphic. Indeed  $F$  is holomorphic since with the charts

$$\begin{aligned} U &:= S^2 \setminus \{(0, 0, 1)\} & \varphi : U \rightarrow \mathbb{C} : (x, y, w) &\mapsto \frac{x + iy}{1 - w} \\ V &:= \mathbb{P}^1 \setminus \{[0 : w] \mid w \in \mathbb{C}\} & \psi : V \rightarrow \mathbb{C} : [z : w] &\mapsto \frac{w}{z}, \end{aligned}$$

we see that

$$\begin{aligned} (\psi \circ F \circ \varphi^{-1})(z) &= \psi \left( F \left( \frac{2 \operatorname{Re} z}{|z|^2 + 1}, \frac{2 \operatorname{Im} z}{|z|^2 + 1}, \frac{|z|^2 - 1}{|z|^2 + 1} \right) \right) \\ &= \psi \left( \left[ 1 - \frac{|z|^2 - 1}{|z|^2 + 1} : \frac{2z}{|z|^2 + 1} \right] \right) \\ &= \psi([1 : z]) \\ &= z \end{aligned}$$

for all  $z \in \varphi(U) = \mathbb{C}$ , which is clearly holomorphic. Furthermore, it can be checked that  $F$  is invertible with inverse

$$F^{-1}([z : w]) := \frac{(2 \operatorname{Re}(z\bar{w}), 2 \operatorname{Im}(z\bar{w}), |z|^2 - |w|^2)}{|z|^2 + |w|^2},$$

which is well-defined, and since  $(\psi \circ F \circ \varphi^{-1})^{-1} = \varphi \circ F^{-1} \circ \psi^{-1}$ , we see that  $F^{-1}$  is holomorphic too.  $\blacklozenge$

Defining some property  $P$  of  $f$  using charts by transporting  $f$  to a function  $f \circ \varphi^{-1}$  on a subset of  $\mathbb{C}$ , and borrowing  $P$  from  $f \circ \varphi^{-1}$ , will be a common theme. However, one must check that  $P$  is *independent of charts*; that is, if  $f \circ \varphi^{-1}$  satisfies  $P$ , then so does  $f \circ \psi^{-1}$  for any other chart  $(V, \psi)$ .



This makes the set  $\mathcal{O}(W)$  of all holomorphic functions  $f : W \rightarrow \mathbb{C}$  into a  $\mathbb{C}$ -algebra.

For  $Y := \mathbb{C}$  regarded as a Riemann surface, this definition agrees with the above. Again, we must check that ‘being holomorphic’ is well-defined, but it follows from the commutativity of the diagram below.



Take  $G(0, 0, 1) := \infty$ .

Since the collection of Riemann surfaces form a category, the ‘is isomorphic to’ relation is an equivalence relation. Thus we are justified to call all three constructions ‘the’ Riemann sphere, and, henceforth, we shall denote all three by  $\hat{\mathbb{C}}$ .

A similar calculation shows that  $G$  is biholomorphic. Indeed, we choose the same chart  $(U, \varphi)$ , and choose  $V := \mathbb{C}_{\infty} \setminus \{\infty\} = \mathbb{C}$  with  $\psi := \text{id}_{\mathbb{C}}$ . Then  $(\psi \circ G \circ \varphi^{-1})(z) = z$  for all  $z \in \varphi(U) = \mathbb{C}$ , and  $G$  is invertible with inverse

$$G^{-1}(z) := \begin{cases} \varphi^{-1}(z) & \text{if } z \in \mathbb{C} \\ (0, 0, 1) & \text{else.} \end{cases}$$

**Proposition 1.15.** Any holomorphic function  $f : X \rightarrow \mathbb{C}$  on a compact Riemann surface  $X$  is constant.

*Proof.* Since  $f$  is holomorphic, the function  $|f| : X \rightarrow \mathbb{R}$  defined by  $|f|(x) := |f(x)|$  is continuous on  $X$ . But  $X$  is compact, so  $|f|$  achieves its maximum at some point  $p \in X$ . Choosing a connected chart  $(U, \varphi)$  centered at  $p$ , we see that  $f \circ \varphi : U \rightarrow \mathbb{C}$  is holomorphic. Then  $|f \circ \varphi| : U \rightarrow \mathbb{R}$  has a local maximum at 0, so, since  $U$  is connected,  $f \circ \varphi$  is constant by the Maximum Principle. Then  $f$  is locally constant around  $p$ , so, since  $X$  is connected,  $f$  is constant on  $X$ . ■

## 1.2.2 Singularities of Functions

Throughout this section, let  $X$  be a Riemann surface, let  $p \in X$ , and let  $f : W \rightarrow \mathbb{C}$  be defined and holomorphic on a punctured neighborhood  $W$  of  $p$ . As above, we can transport the behaviour of  $f$  at  $p$  from its chart representation  $f \circ \varphi^{-1}$ .

**Definition 1.16.** Let  $f : W \rightarrow \mathbb{C}$  be a holomorphic function in a punctured neighborhood of  $p$ . We say that  $f$  has a removable singularity (resp. pole, essential singularity) at  $p$  if there exists a chart  $(U, \varphi)$  of  $X$  containing  $p$  such that  $f \circ \varphi^{-1} : \varphi(U) \rightarrow \mathbb{C}$  has a removable singularity (resp. pole, essential singularity) at  $\varphi(p)$ .

*Proof.* (Well-definition): Equation (1.1) shows that those notions are chart independent; the composition of  $f \circ \varphi^{-1}$  having a singularity at  $p$  with a transition map that is holomorphic at  $p$  yields a function with the same type of singularity at  $p$ . ■

**Remark.** Functions having an essential singularity at  $p$  are very ill-behaved. Indeed, this occurs iff  $|f(x)|$  has a non-zero oscillation near  $p$ . Other singularities behave much better:

- A removable singularity occurs iff  $|f(x)|$  is bounded in a neighborhood of  $p$ , and can be ‘filled in’ by defining  $\tilde{f}(p) := \lim_{x \rightarrow p} f(x)$ . This makes  $\tilde{f} : \tilde{W} \rightarrow \mathbb{C}$  into a holomorphic function.
- A pole occurs iff  $|f(x)| \rightarrow \infty$  as  $x \rightarrow p$ , which can also be ‘filled in’ by defining the map

$$F : W \rightarrow \hat{\mathbb{C}} \quad \text{mapping} \quad x \mapsto \begin{cases} \infty & \text{if } x = p \\ f(x) & \text{else} \end{cases}$$

that extends the codomain of  $f$  to the Riemann sphere  $\hat{\mathbb{C}}$ ; it is clear that  $F$  is holomorphic.

Thus we see that every such function  $f : W \rightarrow \mathbb{C}$  having pole at  $p$  can be holomorphically extended to a map  $F : W \rightarrow \hat{\mathbb{C}}$ . Conversely, every holomorphic map  $F : W \rightarrow \hat{\mathbb{C}}$  (that is not identically zero) can be regarded as a function  $f : W \setminus F^{-1}(\infty) \rightarrow \mathbb{C}$  that is holomorphic everywhere except where  $F(x) = \infty$ , in which case it either has a pole. This motivates the following definition. ♦

**Definition 1.17.** A function  $f : W \rightarrow \mathbb{C}$  is said to be meromorphic at  $p$  if it does not have an essential singularity at  $p$ ; that is, if it is either holomorphic, has a removable singularity, or has a pole at  $p$ . If  $f$  is meromorphic at every point of  $W$ , then  $f$  is meromorphic on  $W$ .

**Remark.** The previous remark can now be rephrased by saying that the set of all meromorphic functions  $f : W \rightarrow \mathbb{C}$  are in one-to-one correspondence with the set of all holomorphic maps  $F : W \rightarrow \hat{\mathbb{C}}$  (which are not identically zero). That is, meromorphic functions are the holomorphic maps to the Riemann sphere. ♦

**Definition 1.18.** Let  $f : W \rightarrow \mathbb{C}$  be meromorphic at  $p$  and consider its Laurent series  $f_\varphi(z) := (f \circ \varphi^{-1})(z) = \sum_i c_i (z - z_0)^i$  under a chart  $(U, \varphi)$  of  $X$  with  $z_0 := \varphi(p)$ . The order of  $f$  at  $p$  is

$$\text{ord}_p(f) := \min \{n \in \mathbb{Z} \mid 0 \neq (z - z_0)^n f_\varphi(z) \in \mathcal{O}(W)\}.$$

*Proof.* (Well-definition). Let  $z$  be the local coordinates given by  $(U, \varphi)$  and suppose that  $(V, \psi)$  is another chart with  $w_0 := \psi(p)$  giving another local coordinate  $w$ . Then the transition function  $T : \varphi \circ \psi^{-1}$  is holomorphic, so it admits a power series representation

$$z = T(w) = \sum_{n \geq 0} a_n (w - w_0)^n = z_0 + \sum_{n \geq 1} a_n (w - w_0)^n.$$

Since  $T'(w_0) \neq 0$ , we see that  $a_1 \neq 0$ . Suppose now that the Laurent series of  $f$  at  $p$  in the coordinate  $z$  is  $c_{-n_0} (z - z_0)^{-n_0} + \text{higher order terms}$ , so that the order of  $f$  at  $p$  computed by employing  $z$  is  $n_0$ . Then the Laurent series of  $f$  at  $p$  in the coordinate  $w$  is

$$c_{-n_0} \left( \sum_{n \geq 1} a_n (w - w_0)^n \right)^{-n_0} + \text{higher order terms},$$

whose lowest order term is  $c_{-n_0} a_1^{-n_0} (w - w_0)^{-n_0}$ . Observe that  $b_{-n_0} := c_{-n_0} a_1^{-n_0} \neq 0$ , so the order of  $f$  at  $p$  computed via  $w$  is also  $n_0$ . ■

Such a connected  $U$  can always be found since we may let  $V$  be a chart around  $p$  and choose  $\varepsilon > 0$  small enough so that  $U := B(p, \varepsilon) \subseteq V$ .

That is, let  $f$  be defined and holomorphic on  $B(p, \varepsilon) \setminus \{p\}$  for some  $\varepsilon > 0$ .

We recall those notions from complex analysis. Let  $f : W \subseteq \mathbb{C} \rightarrow \mathbb{C}$  be a holomorphic function (in the regular sense) in a punctured neighborhood of  $p$ . Suppose that  $f$  is not holomorphic at  $p$ .

- If  $\lim_{z \rightarrow p} f(z)$  exists, then  $f$  has a removable singularity at  $p$ .
- If  $\lim_{z \rightarrow p} f(z) = \pm\infty$ , then  $f$  has a pole at  $p$ . This is equivalent to the existence of some  $n > 0$  such that the limit  $\lim_{z \rightarrow p} (z - p)^n f(z)$  exists. See Definition 1.18.
- Otherwise,  $f$  has an essential singularity at  $p$ .

$\tilde{W} := W \cup \{p\}$ .

Here, we consider  $\hat{\mathbb{C}} = \mathbb{C}_\infty$ .

As in Example 1.10, if  $f, g : W \rightarrow \mathbb{C}$  are both meromorphic at  $p$ , then so are  $f \pm g$  and  $f \cdot g$ . If  $g$  is not identically 0, then so is  $f/g$ . This makes the set  $\mathcal{M}(W)$  of all meromorphic functions  $f : W \rightarrow \mathbb{C}$  into a  $\mathbb{C}$ -algebra.

Note that  $f$ , being meromorphic, ensures that its Laurent series has finitely-many negative terms. Thus the set  $\{n \in \mathbb{Z} \mid c_n \neq 0\}$  achieves its minimum, so the definition makes sense. If  $f$  is not meromorphic, we take  $\text{ord}_p(f) := \infty$ .

The arithmetic of  $\text{ord}_p$  is straightforward. Indeed, if  $f, g : W \rightarrow \mathbb{C}$  are meromorphic at  $p$ , then

- $\text{ord}_p(fg) = \text{ord}_p(f) + \text{ord}_p(g)$ .
- $\text{ord}_p(f/g) = \text{ord}_p(f) - \text{ord}_p(g)$ , if  $g \neq 0$ .
- $\text{ord}_p(1/f) = -\text{ord}_p(f)$ , if  $f \neq 0$ .
- $\text{ord}_p(f \pm g) \geq \min \{\text{ord}_p(f), \text{ord}_p(g)\}$ .

**Remark.** The order  $\text{ord}_p(f)$  can be used to classify the behaviour of  $f$  at  $p$ . Indeed, it is readily verified that  $f$  is holomorphic at  $p$  iff  $\text{ord}_p(f) \leq 0$ , in which case  $f(p) = 0$  iff  $\text{ord}_p(f) < 0$ . Similarly,  $f$  has a pole at  $p$  iff  $\text{ord}_p(f) > 0$ , so  $f$  has neither a zero nor a pole at  $p$  iff  $\text{ord}_p(f) = 0$ . This motivates the following definition.  $\blacklozenge$

**Definition 1.19.** Let  $f : W \rightarrow \mathbb{C}$  be meromorphic at  $p$ . We say that  $f$  has a zero (resp. pole) of order  $n$  at  $p$  if  $\text{ord}_p(f) = n < 0$  (resp.  $n > 0$ ).

### 1.2.3 Meromorphic Functions on $\hat{\mathbb{C}}$

**Example 1.20.** Let  $f : W \subseteq \hat{\mathbb{C}} \rightarrow \mathbb{C}$  be a non-zero rational function  $f(z) := p(z)/q(z)$ . Then  $f$  is holomorphic at all points  $z \in \mathbb{C}$  such that  $q(z) \neq 0$ , and has a pole otherwise. Also,  $f(\infty) \in \mathbb{C}$  if  $\deg p = \deg q$ , vanishes if  $\deg p < \deg q$ , and has a pole otherwise. In any case,  $f$  is meromorphic on  $\hat{\mathbb{C}}$ . To compute  $\text{ord}_z(f)$  at all  $z \in \mathbb{C}$ , we split  $p$  and  $q$  into linear factors to write  $f$  uniquely as

$$f(z) = c \prod (z - \lambda_i)^{\alpha_i}$$

where  $c \neq 0$  and each  $\lambda_i$  is distinct. Fix  $i$ . Setting  $g_j(z) := (z - \lambda_j)^{\alpha_j}$  for all  $j$ , we see that  $\text{ord}_{\lambda_i}(g_i) = -\alpha_i$  and  $\text{ord}_{\lambda_j}(g_i) = 0$  for all  $i \neq j$ . Thus

$$\text{ord}_{\lambda_i}(f) = \sum_j \text{ord}_{\lambda_i}(g_j) = -\alpha_i.$$

Moreover, if  $\alpha_i > 0$  (resp.  $\alpha_i < 0$ ), then  $g_i$  has a pole (resp. zero) of order  $|\alpha_i|$  at  $\infty$ . It follows then that  $\text{ord}_{\infty}(g_i) = \alpha_i$ , so

$$\text{ord}_{\infty}(f) = \sum_i \text{ord}_{\infty}(g_i) = \sum_i \alpha_i.$$

Lastly, it is clear that  $\text{ord}_z(f) = 0$  for all  $z \neq \lambda_i, \infty$ .  $\blacklozenge$

**Proposition 1.21.** Any meromorphic function on  $\hat{\mathbb{C}}$  is a rational function.

*Proof.* Let  $f : \hat{\mathbb{C}} \rightarrow \mathbb{C}$  be meromorphic. Since  $\hat{\mathbb{C}}$  is compact, it has finitely-many poles. W.l.o.g., assume that  $\infty$  is not a pole of  $f$  (since we may consider  $1/f$  instead). Now, for each pole  $\lambda_i \in \mathbb{C}$  of  $f$ , consider its principle part

$$h_i(z) = \sum_{j=-m_i}^{-1} c_{ij} (z - \lambda_i)^j$$

for some  $m_i > 1$ . Then the function  $g := f - \sum_i h_i$  is holomorphic function on  $\hat{\mathbb{C}}$ , and since  $\hat{\mathbb{C}}$  is compact, it is constant by Proposition 1.15. Thus  $f = g + \sum_i h_i$ , which is a rational function.  $\blacksquare$

**Remark.** Together with the above computation, this shows that if  $f$  is a meromorphic function on  $\hat{\mathbb{C}}$ , then  $\sum_{z \in \hat{\mathbb{C}}} \text{ord}_z(f) = 0$ . As we shall see, this is a general fact for all compact Riemann surfaces.  $\blacklozenge$

### 1.2.4 Local Normal Form

**Theorem 1.22 (Local Normal Form).** Let  $X$  and  $Y$  be Riemann surfaces and let  $F : X \rightarrow Y$  be a non-constant holomorphic map. Then, for every  $p \in X$ , there exists a unique  $m \geq 1$  such that for any chart  $(U_2, \varphi_2)$  of  $Y$  centered at  $F(p)$ , there exists a chart  $(U_1, \varphi_1)$  of  $X$  centered at  $p$  such that  $\varphi_2 \circ F \circ \varphi_1^{-1} : z \mapsto z^m$  for all  $z \in \varphi_1(U_1)$ .

*Proof.* Let  $(U_2, \varphi_2)$  be a chart of  $Y$  centered at  $F(p)$  and consider any chart  $(V, \psi)$  of  $X$  centered at  $p$ . Then the function  $h := \varphi_2 \circ F \circ \psi^{-1}$  is holomorphic, so it admits a power series representation  $h(w) = \sum_{i=0}^{\infty} c_i w^i$  for all  $w \in \psi(V)$ . Note that  $h(0) = \varphi_2(F(p)) = 0$ , so  $c_0 = 0$ . Let  $m \geq 1$  be the smallest integer such that  $c_m \neq 0$ , so

$$h(w) = \sum_{i \geq m} c_i w^i = w^m \sum_{i \geq 0} c_{i-m} w^i =: w^m g(w).$$

Then  $g$  is holomorphic at 0 with  $g(0) = c_m \neq 0$ , so there is a function  $r$  holomorphic on some neighborhood  $W$  of 0 such that  $(r(w))^m = g(w)$  for all  $w \in W$ . Thus  $h(w) = (wr(w))^m$ , so set  $\eta(w) := wr(w)$  for all  $w \in W$ . Note that  $\eta'(0) = r(0) \neq 0$ , so  $\eta$  is invertible on some neighborhood  $W' \subseteq W$  of 0. Set  $U_1 := \psi^{-1}(W')$  and  $\varphi_1 := \eta \circ \psi$ . Then  $(U_1, \varphi_1)$  is a chart of  $X$  centered at  $p$  such that

$$(\varphi_2 \circ F \circ \varphi_1^{-1})(z) = (\varphi_2 \circ F \circ \psi^{-1} \circ \eta^{-1})(z) = h(\eta^{-1}(z)) = [\eta(\eta^{-1}(z))]^m = z^m$$

for all  $z \in \varphi_1(U_1)$ . To show uniqueness, it suffices to show that such an  $m$  is chart-independent. But this is clear, for if a different chart  $U'_2$  is chosen such that  $F$  acts as  $z \mapsto z^n$  for some neighborhood  $U'_1$  of  $p$ , then  $z^n = z^m$  on  $\varphi_1(U_1) \cap \varphi'_1(U'_1)$  forces  $n = m$ .  $\blacksquare$

In fact, any meromorphic function on the Riemann sphere is a rational function; see Proposition 1.21.

Otherwise, the set of poles would have a limit point, contradicting the discreteness of poles.

This theorem also give easy proofs of some elementary properties of holomorphic maps, which we collect here; see [For81, Section 1.2] for details. Throughout,  $F : X \rightarrow Y$  is a non-constant holomorphic map between Riemann surfaces  $X$  and  $Y$ .

- $F$  is an open map.
- If  $F$  is injective, then it is biholomorphic onto its image.
- If  $Y = \mathbb{C}$ , then  $|F|$  does not attain its maximum.
- If  $X$  is compact, then  $F$  is surjective and  $Y$  is compact.

Together, the last two claims give an alternative proof for Proposition 1.15.

**Definition 1.23.** With the above notation, the unique  $m \geq 1$  such that there are local coordinates around  $p$  and  $F(p)$  where  $F$  acts like  $z \mapsto z^m$  is called the multiplicity of  $F$  at  $p$ , denoted  $\text{mult}_p(F)$ .

**Remark.** We give a simple way of computing  $\text{mult}_p(F)$  that does not involve casting  $F$  into Local Normal Form, or even having to find local coordinates centered at  $p$  and  $F(p)$ . Indeed, let  $(U_1, \varphi_1)$  and  $(U_2, \varphi_2)$  be charts around  $p$  and  $F(p)$ , say with  $z_0 := \varphi_1(p)$  and  $w_0 := \varphi_2(F(p))$ . Letting  $f := \varphi_2 \circ F \circ \varphi_1^{-1}$ , we see that  $f(z_0) = w_0$  and hence its power series representation has the form

$$f(z) = f(z_0) + \sum_{i \geq m} c_i (z - z_0)^i$$

for some  $m \geq 1$  with  $c_m \neq 0$ . Then, since  $z - z_0$  and  $w - w_0 = f(z) - f(z_0)$  are local coordinates centered at  $p$  and  $F(p)$ , respectively, we see from the above proof that  $\text{mult}_p(F) = m$ . Thus to compute  $\text{mult}_p(F)$ , it suffices to cast  $F$  into local coordinates  $(U_1, \varphi_1)$  around  $p$  and  $(U_2, \varphi_2)$  around  $F(p)$  and find the lowest non-zero power of the Taylor series of  $f := \varphi_2 \circ F \circ \varphi_1^{-1}$ . ♦

**Proposition 1.24.** Let  $f$  be a meromorphic function on a Riemann surface  $X$  and let  $F : X \rightarrow \hat{\mathbb{C}}$  be its associated holomorphic map. Fix  $p \in X$ .

- If  $p$  is not a pole of  $f$ , then  $\text{mult}_p(F) = -\text{ord}_p(f - f(p))$ .
- If  $p$  is a pole of  $f$ , then  $\text{mult}_p(F) = \text{ord}_p(f)$ .

*Proof.* Suppose that  $p$  is not a pole of  $f$ , so  $f(p) = F(p) \in \mathbb{C}$ . Since the set of all poles of a meromorphic function forms a discrete set, let  $p \in U \subseteq X$  be small enough so that  $f|_U$  is holomorphic. Let  $(U, \varphi)$  be a chart of  $X$  and consider the chart  $(\mathbb{C}, \psi)$  of  $\hat{\mathbb{C}}$  around  $F(p)$  defined by  $\psi(z) := z - F(p)$ . Then  $f - f(p) = \psi \circ F$  on  $U$ , so

$$(f - f(p))_\varphi := (f - f(p)) \circ \varphi^{-1} = \psi \circ F \circ \varphi^{-1}$$

on  $\varphi(U)$ . Expanding in power series around  $z_0 := \varphi(p) \in \varphi(U)$ , we see that

$$(\psi \circ F \circ \varphi^{-1})(z) = (f - f(p))_\varphi(z) = \sum_{i \geq m} c_i (z - z_0)^i$$

for some  $m \in \mathbb{N}$  with  $c_m \neq 0$ . Note that  $(f - f(p))_\varphi(z_0) = (f - f(p))(p) = 0$ , so  $m > 0$  and hence  $\text{mult}_p(F) = m$ . But  $m$  is also the smallest integer such that

$$0 \neq (z - z_0)^{-m} (f - f(p))_\varphi(z) \in \mathcal{O}(U),$$

so  $\text{ord}_p(f - f(p)) = -m$ . Suppose now that  $p$  is a pole of  $f$ , so  $F(p) = \infty$ . Since  $\lim_{z \rightarrow p} 1/f(z) = 0$ , we may let  $p \in U \subseteq X$  be small enough so that the function  $\tilde{f} : U \rightarrow \mathbb{C}$  defined by

$$\tilde{f}(x) := \begin{cases} 0 & \text{if } x = p \\ 1/f(x) & \text{else} \end{cases}$$

is holomorphic. Let  $(U, \varphi)$  be a chart of  $X$  and consider the chart  $(\hat{\mathbb{C}} \setminus \{0\}, \psi)$  of  $\hat{\mathbb{C}}$  defined by  $\psi(z) := 1/z$ . Then  $\tilde{f} = \psi \circ F$  on  $U$ , so  $\tilde{f}_\varphi := \tilde{f} \circ \varphi^{-1} = \psi \circ F \circ \varphi^{-1}$  on  $\varphi(U)$ . By the same argument as above, we see that  $\text{mult}_p(F) = -\text{ord}_p(\tilde{f})$ . Now  $\text{ord}_p(f) = -\text{ord}_p(\tilde{f})$ , so the result follows. ■

Consider the power function  $f(z) := z^m$  where  $m := \text{mult}_p(F)$ . Then, for all  $z \in \mathbb{C}^*$ , we see that  $f^{-1}(z)$  has exactly  $m$  elements given by the  $m$  distinct  $m^{\text{th}}$  roots of  $z^m$ . Thus the map  $f$  causes  $\mathbb{C}$  to ‘cover itself  $m$  times’, and those coverings meet at the fixed point 0. But  $f^{-1}(0) = \{0\}$  has only 1 element, which prevents  $f$  to be a  $n$ -sheeted covering of  $\mathbb{C}$ . To remedy this, we count 0 with multiplicity  $m$ ; see Chapter 2 for a more formal discussion. Since  $F$  is locally represented by  $f$ , and  $(U_1, \varphi_1)$  is centered at  $p$ , we see that  $m$  counts the multiplicity at which neighbors of  $p$  are mapped to  $F(p)$ .

## Chapter 2

# Covering Spaces and Analytic Continuation

This chapter assumes that the reader is familiar with the basic notions of liftings and homotopy of curves from algebraic topology, for which we refer the reader to [Hat02, Chapter 1].

### 2.1 Covering Maps and the Degree

We devote this section to develop the tools necessary to define the *degree* of a proper holomorphic map, which, intuitively, is the *number of sheets* in which it covers its image. However, there are points in the image which are not covered ‘correctly’, and they must be taken care of separately.

Using the theory of degrees, we prove a criterion for a compact Riemann surface  $X$  to be bi-holomorphic to the Riemann sphere  $\hat{\mathbb{C}}$ , which will be used in Section 3.1.1 to calculate the moduli space of  $\hat{\mathbb{C}}$ .

#### 2.1.1 Ramification and Critical Points

**Definition 2.1.** Let  $X$  and  $Y$  be Riemann surfaces and let  $F : X \rightarrow Y$  be a non-constant holomorphic map. A point  $p \in X$  is said to be a ramification point of  $F$  if  $F|_U$  is not injective for any neighborhood  $U$  of  $p$ , in which case  $F(p) \in Y$  is said to be a critical value of  $F$ . If  $F$  has no ramification points, then  $F$  is said to be an unbranched holomorphic map.

**Proposition 2.2.** Let  $X$  and  $Y$  be Riemann surfaces and fix  $p \in X$ . A non-constant holomorphic map  $F : X \rightarrow Y$  has a ramification point at  $p$  iff  $\text{mult}_p(F) \geq 2$ .

*Proof.* By Theorem 1.22, there exist charts  $(U, \varphi)$  centered at  $p$  and  $(V, \psi)$  centered at  $F(p)$  such that  $f := \psi \circ F \circ \varphi^{-1}$  is the power map  $z \mapsto z^m$  where  $m := \text{mult}_p(F)$ . Since  $\varphi$  and  $\psi$  are, in particular, injections, we see that  $F$  is locally injective at  $p$  iff  $f$  is locally injective at 0. But this occurs precisely when  $m = \text{mult}_p(F) < 2$ , so the result follows. ■

**Example 2.3.** For any lattice  $\Gamma \subseteq \mathbb{C}$  the projection  $\pi : \mathbb{C} \rightarrow \mathbb{C}/\Gamma$  is an unbranched holomorphic map. This follows from our construction of complex tori in Example 1.8 where for every  $z \in \mathbb{C}$  a small enough neighborhood  $U$  was found so that  $\pi|_U$  is injective. ♦

**Proposition 2.4.** Let  $X$ ,  $Y$  and  $Z$  be Riemann surfaces and let  $F : X \rightarrow Y$  be a holomorphic map. Then any lifting  $\tilde{F} : X \rightarrow Z$  of  $F$  w.r.t. an unbranched holomorphic map  $\pi : Z \rightarrow Y$  is a holomorphic map.

*Proof.* Take  $p \in X$  and set  $r := \tilde{F}(p)$  and  $q := \pi(r) = F(p)$ . Since  $\pi$  is unbranched, there exists a neighborhood  $W$  of  $r$  such that  $\pi|_W : W \rightarrow Y$  is holomorphic, so it is biholomorphic onto its image  $V := \pi(W)$ . Let  $\chi := \pi|_W^{-1} : V \rightarrow W$ . Since  $\tilde{F}$  is continuous, its inverse image  $U := \tilde{F}^{-1}(V)$  is open. Observe that

$$F|_U = (\pi \circ \tilde{F})|_U = \pi|_W \circ \tilde{F}|_U,$$

so  $\tilde{F}|_U = \chi \circ F|_U$ . Then  $p \in U$  and  $\tilde{F}|_U$  is a composition of two holomorphic maps, so  $\tilde{F}$  is holomorphic at  $p$ . ■

#### 2.1.2 Proper and Covering Maps

In this section, we gather some basic results on the theory of covering maps from topology. Throughout this section and the next,  $E$  and  $X$  are locally-compact topological spaces.

**Definition 2.5.** A map  $\pi : E \rightarrow X$  is said to be proper if the preimage of every compact set is compact.

**Proposition 2.6.** Let  $\pi : E \rightarrow X$  be a proper map. Then for every  $p \in X$  and every neighborhood  $V$  of  $\pi^{-1}(p)$ , there exists a neighborhood  $U$  of  $p$  such that  $\pi^{-1}(U) \subseteq V$ .

*Proof.* Since  $V$  is open, the set  $E \setminus V$  is closed. Since  $\pi$  is proper, it is closed and hence  $\pi(E \setminus V)$  is closed too. Clearly  $p \notin \pi(E \setminus V) =: W$ , so  $U := E \setminus W$  is a neighborhood of  $p$ ; we claim that  $\pi^{-1}(U) \subseteq V$ . Indeed, for all  $\pi(e) \in U$ , we see that  $\pi(e) \notin \pi(E \setminus V)$  and so  $e \notin E \setminus V$ . ■

It is immediate that  $F$  is unbranched iff it is a local homeomorphism. Indeed, if  $F$  is unbranched, then for every  $p \in X$  there exists a neighborhood  $U$  of  $p$  such that  $F|_U$  is injective. By the Open Mapping Theorem,  $F$  is open and hence  $F|_U$  maps  $U$  homeomorphically to the open set  $F(U)$ . Conversely, if  $F$  is a local homeomorphism, then for every  $p \in X$  there exists a neighborhood  $U$  of  $p$  that is mapped homeomorphically onto an open set in  $Y$ . In particular,  $F|_U$  is injective, so  $F$  is unbranched at  $p$ .

Recall that a continuous map  $\tilde{F}$  is a lifting of  $F$  w.r.t.  $\pi$  if the diagram

$$\begin{array}{ccc} & & Z \\ & \nearrow \tilde{F} & \downarrow \pi \\ X & \xrightarrow{F} & Y \end{array}$$

commutes.

The assumption that  $E$  and  $X$  are locally compact ensures that all proper maps are closed; that is, then send closed sets to closed sets.



**Definition 2.7.** A map  $\pi : E \rightarrow X$  is said to be a covering map if every point  $p \in X$  has a neighborhood  $U$  such that  $\pi^{-1}(U) = \bigcup_{j \in J} V_j$  where  $V_j$  are disjoint open sets in  $E$ , each homeomorphic to  $U$  via  $\pi|_{V_j}$ .

**Example 2.8.** Let  $m \geq 2$  be a natural number and consider the power map  $f : \mathbb{C}^* \rightarrow \mathbb{C}^*$  mapping  $z \mapsto z^m$ . We claim that  $f$  is a covering map, so take  $b \in \mathbb{C}^*$  and let  $a \in \mathbb{C}^*$  be any one of its  $m^{\text{th}}$  roots. Since  $f$  is unbranched, there exist neighborhoods  $V_0$  of  $a$  and  $U$  of  $b$  such that  $f|_{V_0} : V_0 \rightarrow U$  is a homeomorphism. It is clear then that

$$f^{-1}(U) = \bigcup_{j=0}^{m-1} \omega^j V_0,$$

where  $\omega$  is an  $m^{\text{th}}$  root of unity, and since  $f^{-1}(b)$  is discrete, the sets  $V_j := \omega^j V_0$  can be made small enough so that they are pairwise disjoint. Then each  $f|_{V_j} : V_j \rightarrow U$  is a homeomorphism, as desired.  $\blacklozenge$

**Example 2.9.** For any lattice  $\Gamma \subseteq \mathbb{C}$ , the projection  $\pi : \mathbb{C} \rightarrow \mathbb{C}/\Gamma$  is a covering map. Indeed, take  $z + \Gamma \in \mathbb{C}/\Gamma$  and let  $w \in \mathbb{C}$  be such that  $\pi(w) = z + \Gamma$ . Since  $\pi$  is unbranched, there exist neighborhoods  $V$  of  $w$  and  $U$  of  $z + \Gamma$  such that  $\pi|_V : V \rightarrow U$  is a homeomorphism. Then clearly

$$\pi^{-1}(U) = \bigcup_{\lambda \in \Gamma} (\lambda + V)$$

where the sets  $V_\lambda := \lambda + V$  are all disjoint and each  $\pi|_{V_\lambda} : V_\lambda \rightarrow U$  is a homeomorphism.  $\blacklozenge$

**Proposition 2.10.** Any proper local homeomorphism is a covering map.

*Proof.* Let  $\pi : E \rightarrow X$  be a proper local homeomorphism and take  $p \in X$ . We claim that  $\pi^{-1}(p)$  is finite.

- For each  $e \in \pi^{-1}(p)$ , there exist neighborhoods  $W_e$  of  $e$  and  $U$  of  $p$  such that  $\pi|_{W_e} : W_e \rightarrow U$  is a homeomorphism. Then the sets  $W_e$  must be disjoint, for if  $e' \in W_e$  for some  $e' \neq e$ , then  $\pi|_{W_e}(e) = p = \pi|_{W_e}(e')$ , contradicting that  $\pi|_{W_e}$  is a homeomorphism. Thus  $\pi^{-1}(p)$  must be finite, lest the cover  $\{W_e\}$  admits no finite subcover.

Thus  $\pi^{-1}(p) = \{e_1, \dots, e_n\}$  for some  $e_j \in E$ . Letting  $W_j := W_{e_j}$  as above, we see that  $\bigcup_{j=1}^n W_j$  is a neighborhood of  $\pi^{-1}(p)$ . By Proposition 2.6, there is a neighborhood  $U$  of  $p$  such that  $\pi^{-1}(U) \subseteq \bigcup_{j=1}^n W_j$ , so  $\pi^{-1}(U) = \bigcup_{j=1}^n V_j$  where the sets  $V_j := W_j \cap \pi^{-1}(U)$  are all disjoint and each  $\pi|_{V_j} : V_j \rightarrow U$  is a homeomorphism.  $\blacksquare$

### 2.1.3 Liftings of Curves

This section develops some technical tools to define the *number of sheets* of a covering, which in turn is used to define the *degree* of a proper holomorphic map.

**Definition 2.11.** A function  $\pi : E \rightarrow X$  is said to have the curve lifting property if for every curve  $\alpha : [0, 1] \rightarrow X$  and every point  $e_0 \in E$  with  $\pi(e_0) = \alpha(0)$ , there exists a lifting  $\tilde{\alpha} : [0, 1] \rightarrow E$  w.r.t.  $\pi$  such that  $\tilde{\alpha}(0) = e_0$ .

**Proposition 2.12.** Every covering map  $\pi : E \rightarrow X$  has the curve lifting property.

*Proof.* Let  $\alpha : [0, 1] \rightarrow X$  be a curve and let  $e_0 \in E$  be a point such that  $\pi(e_0) = \alpha(0)$ . Consider any open cover  $\{U_i\}$  of  $\alpha([0, 1])$  where each  $U_i$  is a connected open set in  $X$ . Thus  $\{\alpha^{-1}(U_i)\}$  is an open cover of  $[0, 1]$ , so it admits a finite subcover  $\{(t_i, t_{i+1})\}_{i=1}^n := \{\alpha^{-1}(U_i)\}_{i=1}^n$ . Reindexing if necessary, we obtain a partition

$$0 = t_0 < t_1 < \dots < t_n = 1$$

of  $[0, 1]$  such that  $\alpha([t_{i-1}, t_i]) \subseteq U_i$  for all  $1 \leq i \leq n$ . Now, since  $\pi$  is a covering map, there exist disjoint open sets  $V_{ij}$  in  $E$ , each homeomorphic to  $U_i$  via  $\pi|_{V_{ij}}$ , such that  $\pi^{-1}(U_i) = \bigcup_{j \in J_i} V_{ij}$ . We now construct a lifting  $\tilde{\alpha}|_{[0, t_k]} : [0, t_k] \rightarrow E$  by induction on  $k \in \mathbb{N}$ .

- The base case for when  $k = 0$  is trivial by defining  $\tilde{\alpha}(0) := e_0$ .

Suppose now that the lifting  $\tilde{\alpha}|_{[0, t_{k-1}]} : [0, t_{k-1}] \rightarrow E$  has been constructed for some  $k \geq 1$ . Then  $\alpha(t_{k-1}) = \pi(\tilde{\alpha}(t_{k-1})) \in U_k$ , so there exists some  $j \in J_k$  such that  $\tilde{\alpha}(t_{k-1}) \in V_{kj}$ . Letting  $\chi \rightarrow V_{kj}$  be the inverse of  $\pi|_{V_{kj}} : V_{kj} \rightarrow U_k$ , we set

$$\tilde{\alpha}|_{[t_{k-1}, t_k]} := \chi \circ \alpha|_{[t_{k-1}, t_k]}.$$

Clearly,  $\tilde{\alpha}(t_{k-1})$  agrees with our existing lifting, which makes the piecewise-defined map  $\alpha|_{[0, t_k]}$  a lifting of  $\alpha|_{[0, t_k]}$  w.r.t.  $\pi$ .  $\blacksquare$

Indeed, for all  $c \in f^{-1}(U)$ ,  $f(c) \in U$  and so there exists some  $a' \in V_0$  such that  $f(a') = f(c)$ . Then  $c = \omega^j a'$  for some  $0 \leq j \leq m-1$ , so  $c \in \omega^j V_0$ . Conversely, if  $c \in \omega^j V_0$  for some  $0 \leq j \leq m-1$ , then  $c = \omega^j a'$  for some  $a' \in V_0$  and hence  $f(c) = f(\omega^j a') = f(a') \in U$ .

Similarly, for all  $z \in \pi^{-1}(U)$ ,  $\pi(z) \in U$  and so there exists some  $w' \in V$  such that  $\pi(z) = \pi(w')$ . Then  $z + \Gamma = w' + \Gamma$ , so  $z = w' + \lambda$  for some  $\lambda \in \Gamma$ . Conversely, if  $z \in \lambda + V$  for some  $\lambda \in \Gamma$ , then  $z = w' + \lambda$  for some  $w' \in V$  and hence  $\pi(z) = \pi(w' + \lambda) = \pi(w') \in U$ .

The idea of this proof is to split  $\alpha([0, 1])$  into (overlapping) paths  $\alpha([t_{k-1}, t_k])$ , each of which is an open set, and construct the lifting  $\tilde{\alpha}$  inductively: Given a lifting  $\tilde{\alpha}$  defined up to some boundary  $t_{k-1}$ , we define it on the next interval  $[t_{k-1}, t_k]$  by lifting  $\alpha$  (restricted to  $[t_{k-1}, t_k]$ ) via  $\chi$ . This gives us a ‘chain’ of paths, which when joined together gives us a global lifting of  $\alpha$ .

The base case of this induction simply sets  $\tilde{\alpha}(0) := e_0$  in order to start-off this process.

$$\begin{array}{ccc} & & E \\ & \nearrow \tilde{\alpha} & \downarrow \pi \\ [0, 1] & \xrightarrow{\alpha} & X \end{array}$$

$\tilde{\alpha}(t_{k-1}) = \chi(\alpha(t_{k-1})) = \chi(\pi(\tilde{\alpha}(t_{k-1})))$  on the appropriate restrictions.

**Corollary 2.12.1.** *Suppose that  $X$  is path-connected and let  $\pi : E \rightarrow X$  be a covering map. Then, for any  $p_1, p_2 \in X$ , the sets  $\pi^{-1}(p_1)$  and  $\pi^{-1}(p_2)$  are equinumerous.*

*Proof.* Since  $X$  is path-connected, there exists a curve  $\alpha : [0, 1] \rightarrow X$  from  $p_1$  to  $p_2$ . We define a map  $\varphi : \pi^{-1}(p_1) \rightarrow \pi^{-1}(p_2)$  as follows. Every  $e \in \pi^{-1}(p_1)$  induces a unique lifting  $\tilde{\alpha} : [0, 1] \rightarrow E$  such that  $\tilde{\alpha}(0) = e$ , and since  $\pi(\tilde{\alpha}(1)) = \alpha(1) = p_2$ , we have  $\tilde{\alpha}(1) \in \pi^{-1}(p_2)$ . Hence we define  $\varphi(e) := \tilde{\alpha}(1)$ . The uniqueness of liftings ensures that  $\varphi$  is well-defined and bijective, so  $\pi^{-1}(p_1)$  and  $\pi^{-1}(p_2)$  are equinumerous. ■

## 2.1.4 Degrees and Multiplicities

Throughout this section,  $X$  and  $Y$  are Riemann surfaces and  $F : X \rightarrow Y$  is a non-constant proper holomorphic map.

**Definition 2.13.** *The degree of  $F$ , denoted  $\deg F$ , is the cardinality of the fiber  $F^{-1}(q)$  of any non-critical point  $q \in Y$ .*

*Proof.* (Well-definition): Since  $F$  is a proper map, the fiber  $F^{-1}(q)$  is compact and is hence finite by Discreteness of Preimages. Being unramified, we see that  $F$  is a local homeomorphism, so it is a covering map by Proposition 2.10. Finally, Corollary 2.12.1 shows that  $\deg F$  is well-defined. ■

**Remark.** Let  $n := \deg F$ . Then  $n$  is referred to as the number of sheets of  $F$  and  $F$  is said to be an  $n$ -sheeted holomorphic covering map. ♦

**Theorem 2.14.** *Fix an arbitrary  $q \in Y$ . Then  $\deg F$  is the sum of the multiplicities at each  $p \in F^{-1}(q)$  of  $F$ . That is,*

$$\deg F = \sum_{p \in F^{-1}(q)} \text{mult}_p(F).$$

*Proof.* If  $q$  is not a critical point, then Proposition 2.2 shows that  $\text{mult}_p(F) = 1$  for any  $p \in F^{-1}(q)$ . Then  $\deg F = |F^{-1}(q)|$ , which agrees with our definition.

Otherwise,  $q$  is a critical point of  $F$ . Since  $F^{-1}(q)$  is compact, we see that  $F^{-1}(q) = \{p_1, \dots, p_n\}$  for some  $p_i \in X$ . Fix  $1 \leq j \leq n$  and set  $m_j := \text{mult}_{p_j}(F)$ . We claim that there exist neighborhoods  $U_j$  of  $p_j$  and  $V_j$  of  $q$  such that  $|F^{-1}(r) \cap U_j| = m_j$  for all  $r \in V_j \setminus \{q\}$ .

- By Theorem 1.22, there exist charts  $(U_j, \varphi_j)$  of  $X$  centered at  $p_j$  and  $(V_j, \psi_j)$  of  $Y$  centered at  $q$  such that  $F$  acts as the power function  $f(z) := z^{m_j}$  on  $\varphi_j(U_j)$ . Take  $r \in V_j \setminus \{q\}$  and set  $w := \psi_j(r) \neq 0$ . Then  $|f^{-1}(w)| = m_j$ , so we have

$$|F^{-1}(r) \cap U_j| = |\varphi_j(F^{-1}(r))| = \left| \varphi_j \left( F^{-1} \left( \psi_j^{-1}(w) \right) \right) \right| = |f^{-1}(w)| = m_j.$$

Since  $U_j$  is a neighborhood of  $p_j$ , we see that  $F^{-1}(V_j) \subseteq U_j$  by restricting  $V_j$  in accordance with Proposition 2.6, if necessary. Then, with  $V := \bigcap_{i=1}^n V_i$ , we see that  $F^{-1}(V) \subseteq \bigcup_{i=1}^n U_i$  where the sets  $U_i$  are all disjoint. Take any  $r \in V \setminus \{q\}$ . Then  $r \in V_i \setminus \{q\}$  for all  $1 \leq i \leq n$ , so

$$|F^{-1}(r)| = \left| F^{-1}(r) \cap \bigcup_{i=1}^n U_i \right| = \left| \bigcup_{i=1}^n (F^{-1}(r) \cap U_i) \right| = \sum_{i=1}^n |F^{-1}(r) \cap U_i| = \sum_{i=1}^n m_i.$$

But  $r$  is not a critical point of  $F$ , so the result follows. ■

**Corollary 2.14.1.** *If  $X$  is compact, then a holomorphic map  $F : X \rightarrow Y$  is a biholomorphism iff  $\deg F = 1$ .*

*Proof.* Since  $X$  is compact, we see that  $F$  is proper surjection. Observe that  $F$  is an injection iff it has no critical points, and by Proposition 2.2, this occurs iff  $\text{mult}_p(F) = 1$  for all  $p \in X$ .

- ( $\Rightarrow$ ) If  $F$  is an injection, then  $|f^{-1}(p)| = 1$  for all  $p \in X$ . Thus  $\deg F = 1$ .
- ( $\Leftarrow$ ): Since  $\text{mult}_p(F) \geq 1$  for all  $p \in X$ , the above theorem forces  $\text{mult}_p(F) = 1$ . ■

**Corollary 2.14.2.** *If  $X$  is compact and there exists a meromorphic function  $f : X \rightarrow \mathbb{C}$  with a single simple pole, then  $X \cong \hat{\mathbb{C}}$ .*

*Proof.* Let  $f : X \rightarrow \mathbb{C}$  be a meromorphic function with only a simple pole at  $p$  and consider its associated holomorphic map  $F : X \rightarrow \hat{\mathbb{C}}$ . By Proposition 1.24, we see that  $\text{mult}_p(F) = \text{ord}_p(f) = 1$  and hence  $p$  is unramified. Since  $p$  is the only pole of  $f$ , we see that  $\deg F = |F^{-1}(\infty)| = 1$ . ■

Instead of simply counting the elements in the fiber, we need count them *with multiplicities*.

Although  $q$  is a critical point of  $F$ , every point in a small enough neighborhood around it is not a critical point.

Note that  $V_j$  can be taken small enough so that  $r$  is *not* a critical value of  $F$ .

## 2.2 Sheaves and Function Germs

Unless otherwise stated, in this section,  $X$  denotes a topological space with  $\mathcal{T}$  its system of open sets. Our exposition on sheaves roughly follows [For81, Section 6] and [Mir95, Chapter IX].

### 2.2.1 Presheaves and Sheaves

**Definition 2.15.** A *presheaf of Abelian groups on  $X$*  is a pair  $(\mathcal{F}, \rho)$  consisting of

- a family  $\mathcal{F} := \{\mathcal{F}(U)\}$  of Abelian groups  $\mathcal{F}(U)$  for every  $U \in \mathcal{T}$ ,
- a family  $\rho := \{\rho_V^U\}$  of group homomorphisms  $\rho_V^U : \mathcal{F}(U) \rightarrow \mathcal{F}(V)$  for every  $U, V \in \mathcal{T}$  with  $V \subseteq U$ ,

such that the following two properties hold:

- For every  $U \in \mathcal{T}$ , we have  $\rho_U^U = \text{id}_{\mathcal{F}(U)}$ .
- For every  $U, V, W \in \mathcal{T}$  with  $W \subseteq V \subseteq U$ , we have  $\rho_W^V \circ \rho_V^U = \rho_W^U$ .

**Remark.** Presheaves give us a way of tracking data associated with open sets of a topological space in such a way that makes restricting to a smaller open set  $V \subseteq U$  well-behaved. Consider, for instance, a Riemann surface  $X$  and the presheaf of all holomorphic functions  $\mathcal{O}$  on  $X$ .

- To every open set  $U \subseteq X$  we consider the  $\mathbb{C}$ -algebra  $\mathcal{O}(U)$  of all holomorphic functions  $f : U \rightarrow \mathbb{C}$ . For any open  $V \subseteq U$ , we define  $\rho_V^U(f) := f|_V$ . The two properties are then trivial, which respectively states that restricting to the domain does nothing, and that restricting once to  $V$  and then to  $W \subseteq V$  yields the same function as restricting to  $W$  directly.

Similarly, we have the presheaf of all meromorphic functions  $\mathcal{M}$  on  $X$ . However, those two examples are much more than presheaves since global information about elements in  $\mathcal{F}(X)$  can be obtained locally by ‘restricting’ to  $U$ . The notion of a sheaf makes this precise. ♦

**Definition 2.16.** A presheaf  $\mathcal{F}$  on  $X$  is said to be a *sheaf* if for every open set  $U \subseteq X$  and every family  $\{U_i\}_{i \in I}$  of open subsets that cover  $U$ , the following two properties hold:

- (Identity): For every  $f, g \in \mathcal{F}(U)$ , if  $\rho_{U_i}^U(f) = \rho_{U_i}^U(g)$  for every  $i \in I$ , then  $f = g$ .
- (Gluing): For every family  $\{f_i\}_{i \in I}$  with  $f_i \in \mathcal{F}(U_i)$ , if  $\rho_{U_i \cap U_j}^{U_i}(f_i) = \rho_{U_i \cap U_j}^{U_j}(f_j)$  for all  $i, j \in I$ , then there is a function  $f \in \mathcal{F}(U)$  such that  $\rho_{U_i}^U(f) = f_i$  for every  $i \in I$ .

**Example 2.17.** We give an example of a presheaf that is *not* a sheaf. Let  $X$  be a normed vector space. For all  $U \subseteq X$ , let  $\mathcal{B}(U)$  be the vector space of all bounded functions  $f : U \rightarrow \mathbb{R}$ .

- It is clear from our remarks above that  $\mathcal{B}$  is a presheaf. In fact, since  $\mathcal{B}(U)$  contains functions, we see that if  $f, g \in \mathcal{B}(U)$  agree on all restrictions, then they agree on  $U$ .

The problem arises when we consider glueing. For instance, let  $U_i := \{p \in X \mid \|p\| < i\}$  and observe that  $\{U_i\}_{i \in \mathbb{R}^+}$  covers  $X$ . Consider the family  $\{f_i\}$  where each  $f_i := \text{id}_{U_i}$ , which clearly agree on their pairwise intersections. But no function  $f : X \rightarrow \mathbb{R}$  such that  $f|_{U_i} = f_i$  for all  $i \in \mathbb{R}^+$  can be bounded, so  $\mathcal{B}$  is not a sheaf. ♦

**Example 2.18.** We give two examples of sheaves relating to *divisors* on a Riemann surface  $X$ ; that is, a function  $D : X \rightarrow \mathbb{Z}$  whose support  $\{p \in X \mid D(p) \neq 0\}$  is a discrete subset of  $X$ .

- Let  $D$  be a divisor on  $X$ . For every  $U \in \mathcal{T}$ , let  $\mathcal{O}[D](U)$  denote the set of all meromorphic functions  $f : X \rightarrow \mathbb{C}$  such that  $\text{ord}_p(f) \leq D(p)$  for all  $p \in X$ . The usual restriction homomorphisms make  $\mathcal{O}[D]$  a sheaf of Abelian groups, for if  $\{f_i\}$  is a family of meromorphic functions having poles bounded by  $D$ , then the meromorphic function  $f : X \rightarrow \mathbb{C}$  that glues them together also has poles bounded by  $D$ .
- For every  $U \in \mathcal{T}$ , let  $\mathcal{D}(U)$  denote the group of all discretely-supported functions from  $U$  to  $\mathbb{Z}$  (which is exactly a divisor on  $U$ ). This makes  $\mathcal{D}$  into a sheaf since for every family  $\{D_i\}$ , the function  $D : X \rightarrow \mathbb{Z}$  that glues them together is also discretely-supported. ♦

**Definition 2.19.** Let  $(\mathcal{F}, \rho)$  and  $(\mathcal{G}, \sigma)$  be two sheaves of Abelian groups on  $X$ . A *morphism of sheaves*  $\eta : \mathcal{F} \rightarrow \mathcal{G}$  is a family  $\{\eta_U\}_{U \in \mathcal{T}}$  of group homomorphisms  $\eta_U : \mathcal{F}(U) \rightarrow \mathcal{G}(U)$  such that for every  $U \in \mathcal{T}$  and every open set  $V \subseteq U$ , the following diagram commutes.

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\eta_U} & \mathcal{G}(U) \\ \rho_V^U \downarrow & & \downarrow \sigma_V^U \\ \mathcal{F}(V) & \xrightarrow{\eta_V} & \mathcal{G}(V) \end{array}$$

Analogously, we define the presheaf of sets, rings, vector spaces, algebras, etc, on a topological space  $X$ .

For those with some category theory background, fix any category  $\mathbf{C}$ . A  $\mathbf{C}$ -valued presheaf on  $X$  is simply a contravariant functor  $\mathcal{F} : \mathcal{T} \rightarrow \mathbf{C}$  where  $\mathcal{T}$  is the preorder category induced by  $(\mathcal{T}, \subseteq)$ .

Similarly, consider the (multiplicative) group  $\mathcal{O}^*(U)$  of all holomorphic functions  $f : U \rightarrow \mathbb{C}^*$ , which defines a presheaf  $\mathcal{O}^*$  of Abelian groups. We define  $\mathcal{M}^*(U)$  similarly, but instead restrict to all meromorphic functions  $f : U \rightarrow \mathbb{C}$  that do not vanish identically on any connected-component of  $U$ .

It is immediate that  $\mathcal{O}$ ,  $\mathcal{O}^*$ ,  $\mathcal{M}$ , and  $\mathcal{M}^*$  are all sheaves on  $X$ . Indeed, if we have a family  $\{f_i\}$  that agree on all pairwise common domains, then there exists a globally defined function  $f$  whose restrictions are  $f_i$ ’s. We only need to show that this globally defined function is of the ‘right type’, but this can be checked easily.

In other words, boundedness is a local behaviour.

For compact Riemann surfaces, we see that a function  $D : X \rightarrow \mathbb{Z}$  is a divisor iff it has finite support, so its set of divisors is the free Abelian group of the points of  $X$ .

This construction generalizes both  $\mathcal{O}$  and  $\mathcal{M}$ . Intuitively, the use of divisors here allow us to ‘bound’ the orders of the poles of  $f$  at specific points  $p$ , thereby restricting how badly-behaved it can be.

Phrased categorically, a morphism of sheaves is simply a natural transformation  $\eta : \mathcal{F} \Rightarrow \mathcal{G}$ . This makes the collection of all sheaves on  $X$  into a category.

**Example 2.20.** Some examples relating to divisors of a Riemann surface  $X$ .

- For divisors  $D_1$  and  $D_2$  of a Riemann surface  $X$ , we write  $D_1 \leq D_2$  if  $D_1(p) \leq D_2(p)$  for all  $p \in X$ . This induces an *inclusion morphism*  $\iota : \mathcal{O}[D_1] \hookrightarrow \mathcal{O}[D_2]$  defined by  $\iota_U(f) := f$  for all  $U \in \mathcal{T}$  and  $f \in \mathcal{O}[D_1](U)$ , which makes sense since if  $D_1 \leq D_2$  and the poles of  $f$  are bounded by  $D_1$ , then they are also clearly bounded by  $D_2$ . This inclusion also respects restrictions, so it is indeed a morphism of sheaves.
- For all  $U \in \mathcal{T}$ , we associate to each  $f \in \mathcal{M}^*(U)$  the divisor  $\text{div } f : U \rightarrow \mathbb{Z} : p \mapsto \text{ord}_p(f)$ . This induces a morphism of sheaves  $\text{div} : \mathcal{M}^* \rightarrow \mathcal{D}$  since for all  $U \in \mathcal{T}$  and all open sets  $V \subseteq U$ , the restriction of the divisor of any  $f \in \mathcal{M}^*(U)$  coincides with the divisor of the restriction  $f|_V$ .  $\blacklozenge$

In particular, we have the inclusion  $\mathcal{O} \hookrightarrow \mathcal{M}$ .

Such a function  $\text{div } f$  is a divisor by discreteness of zeros and poles.

## 2.2.2 Stalks and the Étale Space

Throughout this section,  $p \in X$  is a fixed point in a topological space  $X$ .

**Definition 2.21.** Let  $\mathcal{F}$  be a presheaf of Abelian groups on  $X$ . The *stalk of  $\mathcal{F}$  at  $p$*  is the Abelian group

$$\mathcal{F}_p := \left( \bigsqcup_{U \ni p} \mathcal{F}(U) \right) / \sim_p$$

where  $\sim_p$  is the equivalence relation on the disjoint union, defined, for all  $f \in \mathcal{F}(U)$  and  $g \in \mathcal{F}(V)$ , by  $f \sim_p g$  iff there exists an open set  $W \in \mathcal{T}$  with  $p \in W \subseteq U \cap V$  such that  $\rho_W^U(f) = \rho_W^V(g)$ . For any  $f \in \mathcal{F}(U)$ , its equivalence class  $[f]_p$  is called the *germ of  $f$  at  $p$* .

This construction is analogous to that of the *tangent space*  $T_p M$  of a (real) manifold  $M$  at some point  $p$ .

**Example 2.22.** Let  $D$  be a divisor on a Riemann surface  $X$  and consider the stalk  $\mathcal{O}_p[D]$ . Fix a chart centered at  $p$ . Since any meromorphic function  $f$  admits a Laurent series, we see that the function germ  $[f]_p$  is represented by a Laurent series  $\sum_{i=i_0}^{\infty} c_i z^i$  for some  $i_0 \geq -D(p)$  and  $c_i \in \mathbb{C}$ . Conversely, the germ of any Laurent series  $\sum_{i=i_0}^{\infty} c_i z^i$  with  $i_0 \geq -D(p)$  and  $c_i \in \mathbb{C}$  lifts to a meromorphic function germ  $[f]_p$ , so this defines a bijection between  $\mathcal{O}_p[D]$  and the set of all such Laurent series.  $\blacklozenge$

This equivalence relation allows us to ‘evaluate’ a function germ  $\eta \in \mathcal{O}_p[D]$  as  $\eta(p) := f(p)$  where  $U \ni p$  is any open set and  $f \in \mathcal{O}[D](U)$  is any function such that  $\eta = [f]_p$ .

This isomorphism depends on the chosen chart map, so it is not canonical.

**Remark.** The sheaf axioms guarantee that if  $\mathcal{F}$  is a sheaf of Abelian groups on  $X$  and  $U \in \mathcal{T}$ , then an element  $f \in \mathcal{F}(U)$  is zero iff all germs  $[f]_p$ , for  $p \in U$  vanish. Indeed, let  $0 \in \mathcal{F}(U)$  denote the zero element, so  $f \sim_p 0$  for all  $p \in U$  furnishes a family  $\{W_p\}$  of open sets  $W_p \subseteq U$  containing  $p$  such that  $\rho_{W_p}^U(f) = \rho_{W_p}^U(0)$ . This family covers  $U$ , so  $f = 0$  by the first sheaf axiom.  $\blacklozenge$

The forward direction is tautological.

**Proposition 2.23.** Let  $\mathcal{F}$  be a presheaf of Abelian groups on  $X$ . Let  $|\mathcal{F}| := \bigsqcup_{p \in X} \mathcal{F}_p$  and consider the projection  $\pi : |\mathcal{F}| \rightarrow X$  mapping each  $\eta \in \mathcal{F}_p$  to  $p$ . Then the system  $\mathcal{B}$  of all sets

$$[U, f] := \{[f]_p \mid p \in U\} \subseteq |\mathcal{F}|$$

for  $U \in \mathcal{T}$  and  $f \in \mathcal{F}(U)$  is a basis for a topology on  $|\mathcal{F}|$  and  $\pi$  is a local homeomorphism.

*Proof.* We first verify that  $\mathcal{B}$  is a basis.

- Take  $\eta \in |\mathcal{F}|$ , so there exists an open set  $U \in \mathcal{T}$  such that  $\eta = [f]_p$  for some  $f \in \mathcal{F}(U)$  and  $p \in U$ . Observe that  $\eta \in [U, f]$ .
- Take  $[U, f], [V, g] \in \mathcal{B}$  and  $\eta \in [U, f] \cap [V, g]$ . Then there exists a point  $p \in X$  such that  $\eta = [f]_p = [g]_p$ , which furnishes an open set  $W \in \mathcal{T}$  with  $p \in W \subseteq U \cap V$  such that  $\rho_W^U(f) = \rho_W^V(g) =: h$ . Then  $\eta = [h]_p$  with  $h \in W$ , so  $\eta \in [W, h] \subseteq [U, f] \cap [V, g]$ .

To show that  $\pi$  is a local homeomorphism, fix  $\eta \in |\mathcal{F}|$ , say with  $p := \pi(\eta)$ . By (a), there exists some  $[U, f] \in \mathcal{B}$  containing  $\eta$ ; we claim that  $\pi|_{[U, f]} : [U, f] \rightarrow U$  is a homeomorphism.

- For injectivity, take  $\psi_1, \psi_2 \in [U, f]$  such that  $\pi(\psi_1) = \pi(\psi_2)$ . Then  $\psi_1 = [f]_p$  and  $\psi_2 = [f]_q$  for some  $p, q \in X$ , but since  $p = q$ , they coincide.
- For continuity, it suffices to show that  $\pi|_{[U, f]}$  is an open map. Indeed, if  $[V, g] \subseteq [U, f]$  is open, then  $\pi|_{[U, f]}([V, g]) = V$  is open too.  $\blacksquare$

**Definition 2.24.** The *Étalé space* of a presheaf  $\mathcal{F}$  of Abelian groups on  $X$  is the topological space  $|\mathcal{F}|$  equipped the projection  $\pi : |\mathcal{F}| \rightarrow X$ .

**Definition 2.25.** A presheaf  $\mathcal{F}$  of Abelian groups on  $X$  is said to satisfy the *Identity Theorem* if for all  $U \in \mathcal{T}$  and all  $f, g \in \mathcal{F}(U)$ , if there is some  $p \in U$  such that  $[f]_p = [g]_p$ , then  $f = g$  (on  $U$ ).

In particular, this holds for all  $\mathcal{O}[D]$ .

**Proposition 2.26.** *If  $X$  is a locally-connected Hausdorff space and  $\mathcal{F}$  is a presheaf of Abelian groups on  $X$  that satisfy the Identity Theorem, then  $|\mathcal{F}|$  is Hausdorff.*

*Proof.* Take distinct  $\eta_1, \eta_2 \in |\mathcal{F}|$ . Two cases occur.

- If  $p := \pi(\eta_1) \neq \pi(\eta_2) =: q$ , then, since  $X$  is Hausdorff, there exist disjoint neighborhoods  $U$  of  $p$  and  $V$  of  $q$ . On those neighborhoods,  $\pi$  is invertible and the sets  $\pi^{-1}(U)$  and  $\pi^{-1}(V)$  are disjoint neighborhoods of  $\eta_1$  and  $\eta_2$ , respectively.

Otherwise, set  $p := \pi(\eta_1) = \pi(\eta_2)$  and suppose that each  $\eta_i$  is represented by some  $f_i \in \mathcal{F}(U_i)$ . Since  $X$  is locally-connected, there exists a connected neighborhood  $U \subseteq U_1 \cap U_2$  of  $p$ . Restricting both  $f_i$  to  $g_i := \rho_U^{U_i}(f_i)$ , the sets  $[U, g_i]$  are neighborhoods of  $\eta_i$ . Suppose, for sake of contradiction, that there exists some  $\psi \in [U, g_1] \cap [U, g_2]$ . Setting  $q := \pi(\psi)$ , we see that  $\psi = [g_1]_q = [g_2]_q$ , from which the Identity Theorem shows that  $g_1 = g_2$ . Note that  $f_i \sim_p g_i$ , so  $\eta_1 = \eta_2$ , a contradiction. Hence the neighborhoods  $[U, g_1]$  and  $[U, g_2]$  are disjoint, as desired. ■

## 2.3 Analytic Continuation

We now restrict to when  $X$  is a Riemann surface with a fixed point  $p \in X$ . For convenience, we write  $\mathcal{O}[p] := \mathcal{O}[D]$  where  $D$  is the divisor on  $X$  defined by  $D(p) := 1$  and zero everywhere else. Throughout,  $\alpha : [0, 1] \rightarrow X$  is a curve with  $p = \alpha(0)$  and  $q := \alpha(1) \neq p$ , and  $\eta_0 \in \mathcal{O}_p[p]$  is a fixed germ.

Thus if  $U \subseteq X$  is an open set containing  $p$ , then any  $f \in \mathcal{O}_p[p](U)$  has at most a single simple pole. Otherwise, if  $p \notin U$ , then  $f$  is holomorphic.

### 2.3.1 Analytic Continuation of Germs along Curves

**Definition 2.27.** *A germ  $\hat{\eta} \in \mathcal{O}_q$  is said to be the analytic continuation of  $\eta_0$  along  $\alpha$  if there exist a family  $\eta_t \in \mathcal{O}_{\alpha(t)}[p]$  of germs for all  $t \in [0, 1]$  with  $\hat{\eta} = \eta_1$  such that for all  $\tau \in [0, 1]$ , there exists a neighborhood  $T \subseteq [0, 1]$  of  $\tau$ , an open set  $U \subseteq X$  with  $\alpha(T) \subseteq U$ , and a function  $f \in \mathcal{O}[p](U)$  such that  $[f]_{\alpha(t)} = \eta_t$  for all  $t \in T$ .*

**Proposition 2.28.** *A germ  $\hat{\eta} \in \mathcal{O}_q$  is an analytic continuation of  $\eta_0$  along  $\alpha$  iff there exists a lifting  $\tilde{\alpha} : [0, 1] \rightarrow |\mathcal{O}[p]|$  such that  $\tilde{\alpha}(0) = \eta_0$  and  $\tilde{\alpha}(1) = \hat{\eta}$ .*

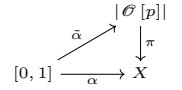
*Proof.* If  $\hat{\eta} \in \mathcal{O}_q$  is an analytic continuation of  $\eta_0$  along  $\alpha$ , let  $\{\eta_t\}$  be a family of germs as defined above. We claim that the curve  $\tilde{\alpha} : [0, 1] \rightarrow |\mathcal{O}[p]|$  mapping  $t \mapsto \eta_t$  is a lifting of  $\alpha$ .

- First, note that  $\eta_t \in \mathcal{O}_{\alpha(t)}[p]$  for all  $t \in [0, 1]$ , so  $(\pi \circ \tilde{\alpha})(t) = \pi(\tilde{\alpha}(t)) = \pi(\eta_t) = \alpha(t)$ . It remains to show that  $\tilde{\alpha}$  is continuous, so fix a basis element  $[U, f] \subseteq |\mathcal{O}[p]|$  and take  $\tau \in \tilde{\alpha}^{-1}([U, f])$ . Then  $\tau \in [0, 1]$ , so there exists a neighborhood  $T \subseteq [0, 1]$  of  $\tau$  such that  $[f]_{\alpha(t)} = \eta_t$  for all  $t \in T$ . Observe that  $\tilde{\alpha}(T) \subseteq [U, f]$  since for all  $\eta_t \in \tilde{\alpha}(T)$ , we have  $\alpha(t) \in U$  and hence  $\eta_t = [f]_{\alpha(t)} \in [U, f]$ .

Conversely, suppose that there is a lifting  $\tilde{\alpha} : [0, 1] \rightarrow |\mathcal{O}[p]|$  of  $\alpha$  with  $\tilde{\alpha}(0) = \eta_0$  and  $\tilde{\alpha}(1) = \hat{\eta}$ . For all  $t \in [0, 1]$ , we define  $\eta_t := \tilde{\alpha}(t)$ , so  $\eta_1 = \hat{\eta}$ . Fix  $\tau \in [0, 1]$ , so there exists a basis neighborhood  $[U, f] \subseteq |\mathcal{O}[p]|$  of  $\tilde{\alpha}(\tau)$ . But  $\tilde{\alpha}$  is continuous, so there exists a neighborhood  $T \subseteq [0, 1]$  of  $\tau$  such that  $\tilde{\alpha}(T) \subseteq [U, f]$ . Projecting, we see that  $\alpha(T) \subseteq \pi([U, f]) = U$ . Finally, the commutativity of the diagram gives  $[f]_{\alpha(t)} = \eta_t$  for all  $t \in T$ , so  $\hat{\eta}$  is an analytic continuation of  $\eta_0$  along  $\alpha$ . ■

In particular, the uniqueness of liftings shows that if an analytic continuation of  $\eta_0$  along  $\alpha$  exists, then it is unique.

Clearly  $\tilde{\alpha}(0) = \eta_0$  and  $\tilde{\alpha}(1) = \hat{\eta}$ .



**Corollary 2.28.1** (Monodromy Theorem). *Let  $\alpha_0, \alpha_1 : [0, 1] \rightarrow X$  be homotopic curves from  $p$  to  $q$ . If the germ  $\eta_0 \in \mathcal{O}_p[p]$  admits an analytic continuation along every deformation of  $\alpha_0$  to  $\alpha_1$ , then the analytic continuations of  $\eta_0$  along  $\alpha_0$  and  $\alpha_1$  coincide.*

*Proof.* By Propositions 2.23 and 2.26,  $|\mathcal{O}[p]|$  is Hausdorff whose projection  $\pi : |\mathcal{O}[p]| \rightarrow X$  is a local homeomorphism. Since each deformation admits a lifting starting at  $\eta_0$ , the liftings  $\tilde{\alpha}_0$  and  $\tilde{\alpha}_1$  have the same endpoints; that is, the analytic continuations along  $\alpha_0$  and  $\alpha_1$  coincide. ■

This is a standard result in algebraic topology. For a proof, see [For81, Proposition 4.10].

**Corollary 2.28.2.** *Suppose  $X$  is simply-connected. If the germ  $\eta_0 \in \mathcal{O}_p[p]$  admits an analytic continuation along every curve starting at  $p$ , then there exists a unique (globally-defined) function  $f \in \mathcal{O}[p](X)$  with  $[f]_p = \eta_0$ .*

*Proof.* Uniqueness follows from the Identity Theorem. For existence, we define  $f(q) := \hat{\eta}_q(q)$  where  $\hat{\eta}_q \in \mathcal{O}_q[p]$  is the analytic continuation along any curve from  $p$  to  $q$ . Since  $X$  is simply-connected, the Monodromy Theorem ensures that  $\hat{\eta}_q$  is well-defined. Clearly  $f(p) = \eta_0(p)$ , so  $[f]_p = \eta_0$ . Finally, since  $[f]_q = \hat{\eta}_q \in \mathcal{O}_q[p]$  for all  $q \in X$ , we see that  $f \in \mathcal{O}[p](X)$ . ■

**Remark.** Let  $U \subseteq X$  be any open set containing  $p$  and consider any function  $f_0 \in \mathcal{O}[p](U)$ . We have reduced the problem of analytically continuing  $f_0$  to a global function  $f \in \mathcal{O}[p](X)$  with  $f|_U = f_0$  into finding analytic continuations of  $[f_0]_p$  along every curve starting at  $p$ . We shall establish this fact under relatively tame conditions in the next section. ♦

### 2.3.2 Existence of Analytic Continuations

**Theorem 2.29.** *Let  $\eta_0 \in \mathcal{O}_p[p]$  be a germ whose Laurent series representation in some chart has finitely-many terms with positive powers. Then, for any  $q \in X$  and any curve  $\alpha : [0, 1] \rightarrow X$  with  $\alpha(0) = p$  and  $\alpha(1) = q$ , there exists an analytic continuation  $\hat{\eta} \in \mathcal{O}_q[p]$  of  $\eta_0$  along  $\alpha$ .*

*Proof.* Let  $E \subseteq |\mathcal{O}[p]|$  be the connected component of the Étale space of  $\mathcal{O}[p]$  containing  $\eta_0$ , and, abusing notation, we write  $\pi : E \rightarrow X$  as the restricted projection map. Define a complex structure  $\mathfrak{A}$  on  $E$ , that makes  $\pi : E \rightarrow X$  locally biholomorphic, as follows.

- For any  $\zeta \in E$ , let  $(U_0, \varphi)$  be a chart of  $X$  around  $\pi(\zeta)$ . Since  $\pi$  is a local homeomorphism, there exist neighborhoods  $V \subseteq E$  of  $\zeta$  and  $U \subseteq U_0$  of  $\pi(\zeta)$  such that  $\pi|_V : V \rightarrow U$  is a homeomorphism. Set  $\psi := \varphi \circ \pi|_V$ , so  $(V, \psi)$  is a chart on  $E$  around  $\zeta$ . Let  $\mathfrak{A}$  be the collection of all such charts, which defines an atlas on  $E$  since for any pair of charts  $(V_1, \psi_1), (V_2, \psi_2) \in \mathfrak{A}$  with  $V_1 \cap V_2 \neq \emptyset$ , there exist charts  $(U_1, \varphi_1)$  and  $(U_2, \varphi_2)$  of  $X$  such that

$$\psi_2 \circ \psi_1^{-1} = (\varphi_2 \circ \pi|_{V_2}) \circ (\varphi_1 \circ \pi|_{V_1})^{-1} = \varphi_2 \circ (\pi|_{V_2} \circ \pi|_{V_1}^{-1}) \circ \varphi_1^{-1},$$

when restricted to  $\psi_1(V_1 \cap V_2)$ , reduces to  $\varphi_2 \circ \varphi_1^{-1}$ . This shows that the charts  $(V_1, \psi_1)$  and  $(V_2, \psi_2)$  are holomorphically compatible, as desired. Furthermore, we claim that  $\pi : E \rightarrow X$  is locally biholomorphic w.r.t.  $\mathfrak{A}$ . Indeed, for any  $\zeta \in E$ , there exist charts  $(V, \psi)$  of  $E$  around  $\zeta$  and  $(U_0, \varphi)$  of  $X$  around  $\pi(\zeta)$  such that  $\psi = \varphi \circ \pi|_V$ . Then  $\varphi \circ \pi|_V \circ \psi^{-1} = \text{id}_V$ , which is holomorphic, so  $\pi$  is locally biholomorphic.

We now define a family  $\eta_t \in \mathcal{O}_{\alpha(t)}[p]$  for  $t \in [0, 1]$  as follows. For all  $t \in [0, 1]$ , let  $\zeta_t \in E$  be such that  $\pi(\zeta_t) = \alpha(t)$ . Then there exist neighborhoods  $V_t$  around  $\zeta_t$  and  $U_t$  around  $\alpha(t)$  such that  $\pi|_{V_t} : V_t \rightarrow U_t$  is a biholomorphism. Let  $\chi_t := \pi|_{V_t}^{-1}$  and define  $\eta_t := (\chi_t \circ \alpha)(t) \in \mathcal{O}_{\alpha(t)}[p]$ . Observe that  $\hat{\eta} := \eta_1 \in \mathcal{O}_q[p]$ , which we claim is the analytic continuation of  $\eta_0$  along  $\alpha$ .

Such a  $\zeta_t$ , if it exists, need not be unique. Here, we let  $\zeta_t$  be *any* such germ. Thus an analytic continuation of  $\eta_0$  along  $\alpha$ , if it exists at all, need not be unique in general.

$$\begin{array}{ccccc} E & \xleftarrow{\quad} & V_t & \xrightarrow{\ell|_{V_t}} & \mathbb{C} \\ \pi \downarrow & & \chi_t \updownarrow & \nearrow \pi|_{V_t} & \nearrow f_t \\ X & \xleftarrow{\quad} & U_t & \xleftarrow{\alpha} & [0, 1] \end{array}$$

- We first construct a function  $\ell : E \rightarrow \mathbb{C}$  as follows. For  $\zeta \in E$ , consider any chart  $(U_0, \varphi)$  of  $X$  around  $\pi(\zeta)$  and any function  $g \in \mathcal{O}[p](U_0)$  such that  $\zeta = [g]_{\pi(\zeta)}$ . Set  $\ell(\zeta) := g(\pi(\zeta))$ . We claim that  $\ell$  has at most a single simple pole at  $\eta_0$ . Indeed, for any  $\zeta \in E$ , the chart  $(V, \psi)$  as defined above that makes  $\pi|_V : V \rightarrow U$  a homeomorphism ensures that

$$\ell \circ \psi^{-1} = (\ell \circ \pi|_V^{-1}) \circ \varphi^{-1} = g \circ \varphi^{-1},$$

which is meromorphic with at most a single simple pole at  $\varphi(p)$ ; observe that  $\ell(\eta_0) = g(p)$ .

Take  $\tau \in [0, 1]$  and consider  $\chi_\tau : U_\tau \rightarrow V_\tau$  as defined above. Since  $U_\tau$  is open, the continuity of  $\alpha$  furnishes a neighborhood  $T_\tau \subseteq [0, 1]$  of  $\tau$  such that  $\alpha(T_\tau) \subseteq U_\tau$ . Set  $f_\tau := \ell|_{V_\tau} \circ \chi_\tau$ , which is in  $\mathcal{O}[p](U_\tau)$  since  $\chi_\tau$  is holomorphic and  $\ell$  is meromorphic with at most a single simple pole at  $\eta_0$ . It remains to show that  $[f_t]_{\alpha(t)} = \eta_t$  for all  $t \in T$ . But this is clear since  $\pi([f_t]_{\alpha(t)}) = \alpha(t) \in U_t$  and  $\pi|_{V_t} : V_t \rightarrow U_t$  is invertible, so

$$[f_t]_{\alpha(t)} = (\pi|_{V_t}^{-1} \circ \alpha)(t) = (\chi_t \circ \alpha)(t) = \eta_t. \quad \blacksquare$$

This is well-defined.

## Chapter 3

# Moduli Spaces

For any genus  $g$ , we let  $\mathcal{M}_g$  denote the *moduli space* of Riemann surfaces of genus  $g$ ; that is, the set of all Riemann surfaces of genus  $g$  up to biholomorphism. Using the language and machinery developed in Chapters 1 and 2, we compute  $\mathcal{M}_0$  and  $\mathcal{M}_1$ , which are the moduli spaces of the sphere  $S^2$  and the torus  $T^2$ , respectively.

We conclude with a brief discussion of the *Uniformization Theorem* and the *Classification of Riemann Surfaces*.

### 3.1 Case for $g = 0$ and $g = 1$

#### 3.1.1 Moduli Space of $S^2$

We show that the moduli space of the sphere  $S^2$  is a point. That is, there is a *unique* complex structure on the sphere.

It turns out that this is an easy corollary of the Riemann-Roch Theorem, but its proof is beyond the scope of this paper. Here, we present a more elementary proof.

**Theorem 3.1.** *Every simply-connected compact Riemann surface  $X$  is biholomorphic to the Riemann sphere  $\hat{\mathbb{C}}$ .*

*Proof.* Fix an arbitrary point  $p \in X$  and let  $(U, \varphi)$  be any chart of  $X$  centered at  $p$ . Consider the function  $f_0 \in \mathcal{O}[p](U)$  defined by  $f_0(q) := 1/\varphi(q)$  for all  $q \in U \setminus \{p\}$ . Applying Theorem 2.29 to  $\eta_0 := [f_0]_p$  and using Corollary 2.28.2, we obtain a function  $f \in \mathcal{O}[p](X)$  such that  $f|_U = f_0$ . Since  $\text{ord}_p(f_0) = 1$ , we see that  $f$  is meromorphic on  $X$  with a single simple pole, so  $X \cong \hat{\mathbb{C}}$  by Corollary 2.14.2. ■

**Remark.** This is part of the *Uniformization Theorem*, which states that every simply-connected Riemann surface is biholomorphic to either the Riemann sphere  $\hat{\mathbb{C}}$ , the complex plane  $\mathbb{C}$ , or the upper-half plane  $\mathbb{H}$  of  $\mathbb{C}$ . A brief discussion and proof sketch is given in Section 3.2. ♦

#### 3.1.2 Moduli Space of $T^2$

We show that the moduli space of the torus  $T^2$  is  $\mathbb{H}/\text{PSL}_2(\mathbb{Z})$  where  $\mathbb{H}$  is the upper-half plane of  $\mathbb{C}$  and  $\text{PSL}_2(\mathbb{Z})$  is the *modular group* consisting of all functions  $\gamma : \mathbb{H} \rightarrow \mathbb{H}$  mapping

$$\tau \mapsto \frac{a\tau + b}{c\tau + d}$$

for some  $a, b, c, d \in \mathbb{Z}$  with  $ad - bc = 1$ .

**Lemma 3.2.** *Let  $\Gamma, \Gamma' \subseteq \mathbb{C}$  be two lattices and suppose  $\alpha\Gamma \subseteq \Gamma'$  for some  $\alpha \in \mathbb{C}^*$ . Then  $z \mapsto \alpha z$  descends to a holomorphic map  $\varphi : \mathbb{C}/\Gamma \rightarrow \mathbb{C}/\Gamma'$ , which is biholomorphic iff  $\alpha\Gamma \subseteq \Gamma'$ .*

This gives a simple criterion for when two tori are biholomorphic.

*Proof.* Let  $\Gamma := \mathbb{Z}\omega_1 \oplus \mathbb{Z}\omega_2$  and  $\Gamma' := \mathbb{Z}\omega'_1 \oplus \mathbb{Z}\omega'_2$ . Define  $\varphi(z + \Gamma) := \alpha z + \Gamma'$  for all  $z \in \mathbb{C}$ , which is clearly holomorphic if it is well-defined in the first place. To verify, take  $z_1, z_2 \in \mathbb{C}$  such that  $z_1 + \Gamma = z_2 + \Gamma$ . Then  $z_1 - z_2 \in \Gamma$ , so  $z_1 - z_2 = m\omega_1 + n\omega_2$  for some  $n, m \in \mathbb{Z}$ . Observe that

$$\alpha z_1 - \alpha z_2 = \alpha(z_1 - z_2) = m(\alpha\omega_1) + n(\alpha\omega_2) \in \alpha\Gamma \subseteq \Gamma',$$

so  $\alpha z_1 + \Gamma' = \alpha z_2 + \Gamma'$ . This shows that  $\varphi$  is well-defined. Furthermore, it is invertible with holomorphic inverse

$$\varphi^{-1}(z + \Gamma') := z/\alpha + \Gamma$$

iff  $\varphi^{-1}$  is well-defined, in which case  $\varphi$  is a biholomorphism. We claim that this occurs iff  $\alpha\Gamma \subseteq \Gamma'$ .

- ( $\Rightarrow$ ): It suffices to show that  $\Gamma' \subseteq \alpha\Gamma$ , so take  $m\omega'_1 + n\omega'_2 \in \Gamma'$ . Then

$$\varphi^{-1}(m\omega'_1 + n\omega'_2 + \Gamma') = (m\omega'_1 + n\omega'_2)/\alpha + \Gamma,$$

but since  $m\omega'_1 + n\omega'_2 + \Gamma' = 0 + \Gamma'$  and  $\varphi^{-1}(0 + \Gamma') = 0 + \Gamma$ , we see that  $(m\omega'_1 + n\omega'_2)/\alpha \in \Gamma$ .

- ( $\Leftarrow$ ): Take  $z_1, z_2 \in \mathbb{C}$  such that  $z_1 + \Gamma' = z_2 + \Gamma'$ , so  $z_1 - z_2 \in \Gamma' \subseteq \alpha\Gamma$  and hence

$$z_1/\alpha - z_2/\alpha = (z_1 - z_2)/\alpha \in \Gamma.$$

Then  $z_1/\alpha + \Gamma = z_2/\alpha + \Gamma$ , so  $\varphi^{-1}$  is well-defined. ■

**Lemma 3.3.** Any torus  $\mathbb{C}/\Gamma$  is biholomorphic to  $X_\tau := \mathbb{C}/(\mathbb{Z} + \tau\mathbb{Z})$  for some  $\tau \in \mathbb{H}$ .

*Proof.* Let  $\Gamma := \mathbb{Z}\omega_1 \oplus \mathbb{Z}\omega_2$  and set  $\alpha := 1/\omega_1$  and  $\tau := \omega_2/\omega_1$ . Then  $\text{Im } \tau \neq 0$ , lest  $\omega_1, \omega_2$  be linearly dependent over  $\mathbb{R}$ . Without loss of generality, suppose that  $\text{Im } \tau > 0$ ; if not, take  $\tau := \bar{\omega}_2/\omega_1$ . Then, since

$$\alpha(m\omega_1 + n\omega_2) = \alpha\omega_1(m + n\omega_2/\omega_1) = m + n\tau$$

for all  $m, n \in \mathbb{Z}$ , we see that  $\alpha\Gamma = \mathbb{Z} \oplus \mathbb{Z}\tau$ . By Lemma 3.2, we see that the map  $z \mapsto \alpha z$  descends to a biholomorphism  $\varphi : \mathbb{C}/\Gamma \rightarrow \mathbb{C}/(\mathbb{Z} \oplus \mathbb{Z}\tau) = X_\tau$ , so  $\mathbb{C}/\Gamma \cong X_\tau$ . ■

**Theorem 3.4.** For any  $\tau, \tau' \in \mathbb{H}$ , the tori  $X_\tau$  and  $X_{\tau'}$  are biholomorphic iff there exists some  $\gamma \in \text{PSL}_2(\mathbb{Z})$  such that  $\tau' = \gamma(\tau)$ .

**Corollary 3.4.1.** The moduli space of  $T^2$  is  $\mathbb{H}/\text{PSL}_2(\mathbb{Z})$ .

*Proof.* The backwards direction is relatively straightforward. Indeed, note that

$$\tau' = \frac{a\tau + b}{c\tau + d} \quad \Rightarrow \quad \tau = \frac{b - d\tau'}{c\tau' - a}$$

for any  $a, b, c, d \in \mathbb{Z}$  with  $ad - bc = 1$ , so let  $\alpha := c\tau' - a$ . Then, with  $\Gamma := \mathbb{Z} \oplus \mathbb{Z}\tau$  and  $\Gamma' := \mathbb{Z} \oplus \mathbb{Z}\tau'$ , we proceed by proving that  $\alpha\Gamma = \Gamma'$ , from which the result follows from Lemma 3.2.

- ( $\subseteq$ ): For any  $m, n \in \mathbb{Z}$ , our choice of  $\alpha$  shows that

$$m\alpha + n\alpha\tau = m(c\tau' - a) + n(b - d\tau') = (nb - ma) + (mc - nd)\tau' \in \mathbb{Z} \oplus \mathbb{Z}\tau',$$

so  $\alpha(\mathbb{Z} \oplus \mathbb{Z}\tau) \subseteq \mathbb{Z} \oplus \mathbb{Z}\tau'$ .

- ( $\supseteq$ ): For any  $m, n \in \mathbb{Z}$ , the condition that  $ad - bc = 1$  shows that

$$(m + n\tau')/\alpha = \frac{(na - mc)\tau + (nb - md)}{a(c\tau + d) - c(a\tau + b)} = (nb - md) + (na - mc)\tau \in \mathbb{Z} \oplus \mathbb{Z}\tau,$$

so  $\mathbb{Z} \oplus \mathbb{Z}\tau' \subseteq \alpha(\mathbb{Z} \oplus \mathbb{Z}\tau)$ .

For the forward direction, let  $\varphi : X_\tau \rightarrow X_{\tau'}$  be a biholomorphism, which lifts to a biholomorphic mapping  $\tilde{\varphi} : \mathbb{C} \rightarrow \mathbb{C}$  such that

$$\begin{array}{ccc} \mathbb{C} & \xrightarrow{\tilde{\varphi}} & \mathbb{C} \\ \pi \downarrow & & \downarrow \pi' \\ \mathbb{C}/\Gamma & \xrightarrow{\varphi} & \mathbb{C}/\Gamma' \end{array}$$

commutes. Fix  $\lambda \in \Gamma$  and consider the map  $f_\lambda(z) := \tilde{\varphi}(z + \lambda) - \tilde{\varphi}(z)$ . Then, since  $z + \lambda + \Gamma = z + \Gamma$ , we see that  $\varphi(z + \lambda + \Gamma) = \varphi(z + \Gamma)$  and hence the commutativity of the diagram forces  $\tilde{\varphi}(z + \lambda) + \Gamma' = \tilde{\varphi}(z) + \Gamma'$ . Thus  $f_\lambda(z) \in \Gamma'$  for all  $z \in \mathbb{C}$ , so, since  $f_\lambda$  is a continuous map into a discrete set, it must be constant. Differentiating gives us  $f'_\lambda(z) = \tilde{\varphi}'(z + \lambda) - \tilde{\varphi}'(z) = 0$ , so  $\tilde{\varphi}'(z + \lambda) = \tilde{\varphi}'(z)$  for all  $z \in \mathbb{C}$ . But  $\lambda \in \Gamma$  is arbitrary, so  $\tilde{\varphi}'$  is  $\Gamma$ -periodic. Thus  $\tilde{\varphi}'$  is a bounded entire function and hence is constant by Liouville's Theorem. This shows that  $\tilde{\varphi}(z) = \alpha z + \beta$  for some  $\alpha, \beta \in \mathbb{C}$  with  $\alpha \neq 0$ . Without loss of generality, assume that  $\beta = 0$ . We now claim that  $\alpha\Gamma = \Gamma'$ .

- Indeed, for all  $z \in \alpha\Gamma$ , we have  $z/\alpha \in \Gamma$  and so  $z/\alpha + \Gamma = 0 + \Gamma$ . Applying  $\varphi$  to both sides and comparing gives

$$0 + \Gamma' = \varphi(0 + \Gamma) = \varphi(z/\alpha + \Gamma) = \tilde{\varphi}(z/\alpha) + \Gamma' = z + \Gamma',$$

so  $z \in \Gamma'$ . The converse is similar.

Observe then that  $\tilde{\varphi}(\tau) = \alpha\tau = b - d\tau'$  and  $\tilde{\varphi}(1) = \alpha = c\tau' - a$  for some  $a, b, c, d \in \mathbb{Z}$ , so

$$\tau = \frac{b - d\tau'}{c\tau' - a} \quad \text{and hence} \quad \tau' = \frac{a\tau + b}{c\tau + d}.$$

A computation now shows that  $\alpha = -(ad - bc)/(c\tau + d)$ , so  $ad - bc \neq 0$ . Then, since

$$\begin{bmatrix} \alpha\tau \\ \alpha \end{bmatrix} = \begin{bmatrix} b & -d \\ -a & c \end{bmatrix} \begin{bmatrix} 1 \\ \tau' \end{bmatrix},$$

we solve for  $\tau'$  to obtain

$$\tau' = -\frac{b\alpha + a\alpha\tau}{ad - bc} = \left(\frac{-b}{ad - bc}\right)\alpha + \left(\frac{-a}{ad - bc}\right)\alpha\tau$$

But  $\tau' \in \alpha\Gamma$ , which forces  $ad - bc = \pm 1$ . A little algebra now shows that

$$\text{Im } \tau' = \frac{ad - bc}{|c\tau + d|^2} (\text{Im } \tau) > 0,$$

so  $ad - bc = 1$ . ■

This reduces the analysis to just tori of the form  $X_\tau$ , which is considerably more simpler.

This proof follows [Shu05, Proposition 1.3.2]. For an alternative proof, see [Tan91, Lemma 2.8]

Let  $\tau := e + fi$  and  $\tau' := g + hi$  and expand.



### 3.2 Uniformization and Classification

Results in this section will only be discussed briefly and all proofs presented are sketches.

**Theorem 3.5** (Uniformization). *Every simply-connected Riemann surface  $X$  is biholomorphic to either the Riemann sphere  $\hat{\mathbb{C}}$ , the complex plane  $\mathbb{C}$ , or the upper-half plane  $\mathbb{H}$ .*

*Proof sketch.* As in Theorem 3.1, fix  $p \in X$  and let  $f \in \mathcal{O}[p](X)$  be meromorphic with a single simple pole. Let  $F : X \rightarrow \hat{\mathbb{C}}$  be its associated holomorphic map, so  $F(p) = \infty$ . Since  $\deg F = 1$ , we see that  $\text{mult}_p(F) = 1$  and so  $F|_U : U \rightarrow V$  is a biholomorphism for some neighborhoods  $U \subseteq X$  of  $p$  and  $V \subseteq \hat{\mathbb{C}}$  of  $\infty$ . We outline the rest of the proof.

- First, it can be shown that  $\text{Im } F(x) \rightarrow 0$  as  $x \rightarrow \infty$  in  $X$ . That is, for every  $\varepsilon > 0$ , there is a large enough compact subset  $K$  of  $X$  such that  $\text{Im } F(x) < \varepsilon$  for all  $x \in K \setminus X$ .
- It can also be shown that  $\text{im } F$  is open, contains the ‘top and bottom halves’ of  $\hat{\mathbb{C}}$ , and is a biholomorphism onto its image.

Thus  $\text{Im } F \cong \hat{\mathbb{C}} \setminus I$  for some  $I \subseteq \mathbb{R}$ . By simply-connected to  $X$ , we see that  $I$  is connected and hence we have three possibilities.

- If  $I = \emptyset$ , then  $F : X \rightarrow \hat{\mathbb{C}}$  is a biholomorphism, which reduces to Theorem 3.1.
- If  $I$  is a singleton, then  $\hat{\mathbb{C}} \setminus I \cong \mathbb{C}$ , so  $X \cong \mathbb{C}$ .
- If  $I$  is an interval  $[a, b]$ , we may w.l.o.g. take  $a = 0$  and  $b = \infty$ . Then the (usual branch of the) square root function sends  $\hat{\mathbb{C}} \setminus [0, \infty]$  to  $\mathbb{H}$ . ■

**Remark.** It turns out that one can construct a simply-connected Riemann surface  $\tilde{X}$  from any Riemann surface  $X$ . Since  $\tilde{X}$  is exactly one of three types, this leads to a classification of Riemann surfaces. ♦

**Definition 3.6.** Let  $X$  and  $E$  be connected topological spaces. A covering map  $\pi : E \rightarrow X$  is said to be the *universal covering of  $X$*  if for every covering  $\pi' : E' \rightarrow X$  on a connected topological space  $E'$  and every  $e \in E$  and  $e' \in E'$  such that  $\pi(e) = \pi'(e')$ , there exists a unique continuous map  $\sigma : E \rightarrow E'$  with  $\sigma(e) = e'$  making the below diagram commute.

$$\begin{array}{ccc} E & \xrightarrow{\sigma} & E' \\ \pi \searrow & & \swarrow \pi' \\ & X & \end{array}$$

**Remark.** Note that  $\sigma$  is the lifting of  $\pi$  along  $\pi'$ . Recall that if  $E$  is simply-connected, such a lifting exists and is unique, so in this case *any* covering map is the universal covering of  $X$ . We quote the following theorem that guarantees the existence of such a simply-connected space. ♦

**Theorem 3.7** ([For81, Theorem 5.3]). *Suppose  $X$  is a connected manifold. Then there exists a connected, simply-connected manifold  $\tilde{X}$  and a covering map  $\pi : \tilde{X} \rightarrow X$ .*

**Example 3.8.** Recall from Example 2.3 that for any lattice  $\Gamma \subseteq \mathbb{C}$ , the projection  $\pi : \mathbb{C} \rightarrow \mathbb{C}/\Gamma$  is a covering map. Since  $\mathbb{C}$  is simply-connected, we see that  $\pi$  is the universal covering of  $\mathbb{C}/\Gamma$ . ♦

**Remark.** For any Riemann surface  $X$ , let  $\tilde{X}$  be its simply-connected universal covering. If  $\tilde{X} \cong \hat{\mathbb{C}}$  (resp.  $\mathbb{C}$ ,  $\mathbb{H}$ ), then  $X$  is said to be *elliptic* (resp. *parabolic*, *hyperbolic*).

- Since  $\hat{\mathbb{C}}$  is simply-connected, it is the universal covering of itself and hence  $\hat{\mathbb{C}}$  is elliptic.
- Since  $\mathbb{C}$  is the universal covering of any torus  $\mathbb{C}/\Gamma$ , we see that  $\mathbb{C}/\Gamma$  is parabolic.

It turns out that the universal covering for any compact Riemann surfaces with  $g > 1$  is  $\mathbb{H}$ , so they are all hyperbolic. A more robust study of universal coverings is required for  $g > 1$ . ♦

This sketch follows [Kro19].

These claims are highly-nontrivial and is beyond the scope of this paper.

That is,  $\{x \in X \mid \text{Im } \varphi(z) \neq 0\} \subseteq \text{im } F$ .

As with all ‘universal properties’, the universal covering of  $X$  is unique up to isomorphism.

In fact, every Riemann surface admits a Riemannian metric of constant curvature, either of 1, 0, or  $-1$ . We wish to study the connection between the conformal and metric structures on Riemann surfaces in the future.

# Bibliography

- [1] Otto Forster. Lectures on Riemann Surfaces. Graduate Texts in Mathematics. Springer New York, NY, 1981. ISBN: 978-0-387-90617-1. DOI: <https://doi.org/10.1007/978-1-4612-5961-9>.
- [2] Allen Hatcher. Algebraic Topology. Cambridge University Press, 2002. ISBN: 978-0-521-79540-1.
- [3] Peter Kronheimer. “Riemann Surfaces”. In: (2019). URL: [https://people.math.harvard.edu/~jeffs/Complex\\_Analysis\\_Class\\_Notes.pdf](https://people.math.harvard.edu/~jeffs/Complex_Analysis_Class_Notes.pdf).
- [4] Rick Miranda. Algebraic Curves and Riemann Surfaces. Graduate Studies in Mathematics. American Mathematical Society; UK ed. edition, 1995. ISBN: 978-0-821-80268-7.
- [5] Fred Diamond & Jerry Shurman. A First Course in Modular Forms. Graduate Texts in Mathematics. Springer New York, NY, 2005. ISBN: 978-0-387-23229-4. DOI: <https://doi.org/10.1007/978-0-387-27226-9>.
- [6] Yoichi Iwayoshi & Masahiko Taniguchi. An Introduction to Teichmüller Spaces. Springer Tokyo, 1991. ISBN: 978-4-431-68176-2. DOI: <https://doi.org/10.1007/978-4-431-68174-8>.
- [7] Loring W. Tu. An Introduction to Manifolds. Universitext. Springer New York, NY, 2010. ISBN: 978-1-441-97399-3. DOI: <https://doi.org/10.1007/978-1-4419-7400-6>.