Chapter 1

Hurwitz existence problem

1.1   Branched coverings of surfaces

According to standard terminology, a *surface* is simply a topological 2-manifold. We will, however, only be concerned with compact, connected surfaces without boundary. For the sake of conciseness, unless otherwise stated, we will always implicitly assume that the surfaces we mention have these properties.

There is a structure theorem which completely classifies orientable and non-orientable surfaces.

- An orientable surface is (homeomorphic to) a connected sum of $g \geq 0$ tori. We call such a connected sum a *surface of genus g*, and we denote it by Σ_g. By definition, we say that Σ_0 is the 2-sphere S^2; this is consistent with the formula $\chi(\Sigma_g) = 2 - 2g$ for the Euler characteristic.

- A non-orientable surface is (homeomorphic to) a connected sum of $g \geq 1$ real projective planes. We denote such a connected sum by N_g. The Euler characteristic for a non-orientable surfaces is given by $\chi(N_g) = 2 - g$.

Loosely speaking, given two surfaces Σ, $\widetilde{\Sigma}$, a *covering map* between them is a continuous function $f \colon \widetilde{\Sigma} \to \Sigma$ which is locally modeled on the identity function $\mathbb{R}^2 \to \mathbb{R}^2$. Sometimes, however, the notion of covering map can be too restrictive. Consider, for instance, the sphere S^2: being simply connected, it does not admit any non-trivial coverings. However, every (non-constant) homolorphic function $S^2 \to S^2$ is *almost* a covering map, in the sense that it is locally modeled on the identity $\mathbb{C} \to \mathbb{C}$, except for a finite number of *branching points*, where it looks like the map

$$F_k \colon \mathbb{C} \longrightarrow \mathbb{C}$$
$$z \longmapsto z^k$$

for some $k \geq 2$. In fact, it turns out that every (non-constant) holomorphic function between two complex 1-manifolds (which, topologically, are just oriented surfaces), has this remarkable property. This motivates the following definition.

Definition 1.1. Let $\Sigma, \widetilde{\Sigma}$ be two surfaces. A continuous function $f \colon \widetilde{\Sigma} \to \Sigma$ is a *branched covering map* (or simply a *branched covering*) if the following property holds: for every $x \in \Sigma$, $\widetilde{x} \in f^{-1}(x)$ there exist a positive integer k, open neighborhoods $U, \widetilde{U}$ of $x, \widetilde{x}$ respectively, and homeomorphisms $\varphi \colon U \to \mathbb{C}$, $\widetilde{\varphi} \colon \widetilde{U} \to \mathbb{C}$ such that $\varphi(x) = 0$, $\widetilde{\varphi}(\widetilde{x}) = 0$, $f(\widetilde{U}) = U$ and the

diagram

$$
\begin{array}{ccc}
\widetilde{U} & \xrightarrow{\ f\ } & U \\
\Big\downarrow{\scriptstyle\widetilde{\varphi}} & & \Big\downarrow{\scriptstyle\varphi} \\
\mathbb{C} & \xrightarrow{\ F_k\ } & \mathbb{C}
\end{array}
$$

commutes (F_k is the map defined above). We say that $\widetilde{U}$ is a *trivializing neighborhood* of $\widetilde{x}$.

More informally, we can say that a branched covering is a continuous function between surfaces which is locally modeled on the complex map $z \mapsto z^k$, where $k \geq 1$ depends on the point. Note that, for each point $\widetilde{x} \in \widetilde{\Sigma}$, the integer k is well-defined, independently of the charts φ and $\widetilde{\varphi}$: using the notation from the definition, we have that k is equal to the cardinality of $f^{-1}(y) \cap \widetilde{U}$, where y is any point in $U \smallsetminus \{x\}$. We call this integer the *local degree* of $\widetilde{x}$; to emphasize the dependence on $\widetilde{x}$, we will denote it by $k(\widetilde{x})$.

A point $\widetilde{x} \in \widetilde{\Sigma}$ is called a *branching point* if $k(\widetilde{x}) > 1$; in other words, if f is *not* a local homeomorphism in a neighborhood of $\widetilde{x}$. We also say that a point $x \in \Sigma$ is a *branching point* if $f^{-1}(x)$ contains at least one branching point; usually, no ambiguity will arise as to which kind of branching point we are referring to.

It is not hard to see that branching points are quite rare. If $\widetilde{x} \in \widetilde{\Sigma}$ is a branching point, then (using again the notation from the definition) every other point in $\widetilde{U}$ is not a branching point; by compactness, it follows that the set of branching points in $\widetilde{\Sigma}$ is finite. As a consequence, the set of branching points in Σ is finite as well.

Given a branched covering $f \colon \widetilde{\Sigma} \to \Sigma$, we denote by $\Sigma^{\bullet}$ the subspace of Σ containing all the non-branching points; since the set of branching points is finite, $\Sigma^{\bullet}$ is a non-compact connected surface with finitely many punctures. We also set $\widetilde{\Sigma}^{\bullet} = f^{-1}(\Sigma^{\bullet})$, and we denote by $f^{\bullet}$ the restriction of f to $\widetilde{\Sigma}^{\bullet}$. By construction, $f^{\bullet} \colon \widetilde{\Sigma}^{\bullet} \to \Sigma^{\bullet}$ is a covering map and, as such, has a well-defined degree d (the number of preimages of an arbitrary point); we call this integer the *degree* of the branched covering f. The following proposition shows that the notion of degree extends nicely to branching points.

Proposition 1.1. *Let $f \colon \widetilde{\Sigma} \to \Sigma$ be a branched covering of degree d. Then for every point $x \in \Sigma$ we have that the set $f^{-1}(x)$ is finite and*

$$
\sum_{\widetilde{x} \in f^{-1}(x)} k(\widetilde{x}) = d.
$$

Proof. If x is not a branching point, the conclusion follows immediately, since x has exactly d preimages, all of which have local degree k equal to 1. Assume now that x is a branching point; it is clear from the definition that the set $f^{-1}(x) \subseteq \widetilde{\Sigma}$ is discrete and, hence, finite. Let $f^{-1}(x) = \{\widetilde{x}_1, \ldots, \widetilde{x}_r\}$. Fix disjoint trivializing neighborhoods $\widetilde{U}_1, \ldots, \widetilde{U}_r$ of $\widetilde{x}_1, \ldots, \widetilde{x}_r$ respectively; a routine compactness argument shows that there exists an open neighborhood U of x such that $f^{-1}(U) \subseteq \widetilde{U}_1 \cup \ldots \cup \widetilde{U}_r$. Fix a point $y \in U \smallsetminus \{x\}$: it follows from the discussion above that y is not a branching point and that $|f^{-1}(y) \cup \widetilde{U}_i| = k(\widetilde{x}_i)$ for every $1 \leq i \leq r$. Since $|f^{-1}(y)| = d$, we immediately conclude that

$$
\sum_{i=1}^{r} k(\widetilde{x}_i) = \sum_{i=1}^{r} |f^{-1}(y) \cap \widetilde{U}_i| = |f^{-1}(y)| = d. \qquad \square
$$

1.2 Branching data

Let $f\colon \widetilde{\Sigma} \to \Sigma$ be a branched covering. For each point $x \in \Sigma$, as we have just seen in proposition 1.1, the sum $k(\widetilde{x}_1) + \ldots k(\widetilde{x}_r)$ of the local degrees of its preimages is equal to the degree d of the branched covering. Since there is no natural ordering on the set $f^{-1}(x)$, the appropriate combinatorial object for representing the collection $k(\widetilde{x}_1), \ldots, k(\widetilde{x}_r)$ is a *partition*.

Definition 1.2. Let d be a positive integer. A *partition* of d is an unordered finite multiset $\pi = [k_1, \ldots, k_r]$, where $k_i > 0$ is an integer for every $1 \le i \le r$ and $k_1 + \ldots + k_r = d$.

Given a positive integer d, we denote the set of all partitions of d by $\Pi(d)$. If $\pi = [k_1, \ldots, k_r]$ is a partition of d, we call the integer r the *length* (or *size*, or *cardinality*) of π, and we denote it by $\ell(\pi)$. We also say that the *sum* of π, denoted by $\sum \pi$, is $k_1 + \ldots + k_r$ or, in other words, d. Finally, we introduce a new quantity, the *branching number* $v(\pi) = d - \ell(\pi)$, whose purpose will soon become apparent.

For every point $x \in \Sigma$, if $f^{-1}(x) = \{\widetilde{x}_1, \ldots, \widetilde{x}_r\}$, we can define the *associated partition* $\pi(x) = [k(\widetilde{x}_1), \ldots, k(\widetilde{x}_r)] \in \Pi(d)$. For all non-branching points, the associated partition will simply be $[1, \ldots, 1]$. On the contrary, if x is a branching point, then $\pi(x) \ne [1, \ldots, 1]$ (or, equivalently, $v(\pi(x)) > 0$).

Definition 1.3. Let $f\colon \widetilde{\Sigma} \to \Sigma$ be a branched covering of degree d. Let $x_1, \ldots, x_n \in \Sigma$ be the branching points of f. The *branching datum* of f is the tuple

$$\mathcal{D}(f) = (\widetilde{\Sigma}, \Sigma; d; \pi(x_1), \ldots, \pi(x_n)),$$

well-defined up to a permutation of the branching points $x_1, \ldots, x_n$.

Branching data are a way to extract some combinatorial information from branched coverings. Even though the exact location of the branching points (both in Σ and in $\widetilde{\Sigma}$) is not encoded in the branching datum, this piece of information is completely irrelevant, since surfaces are *homogeneous*[1]. However, the reader should not be induced to believe that the combinatorial information provided by the branching datum is enough to fully reconstruct the topology of f. In fact, it turns out that this is not the case. More on this later (?).

This entire thesis is devoted to the problem of determining what values can actually be attained by $\mathcal{D}(f)$ as f ranges over all the possible branched covering maps. We start with a very general definition.

Definition 1.4. A *combinatorial datum* is a tuple

$$\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n),$$

where $\Sigma, \widetilde{\Sigma}$ are surfaces, d and n are positive integers, and $\pi_1, \ldots, \pi_n$ are partitions of d different from $[1, \ldots, 1]$.

Again, a combinatorial datum is defined up to a permutation of the partitions $\pi_1, \ldots, \pi_n$. In other words, we will consider two combinatorial data equal if they have the same partitions, irrespective of the ordering.

Technically, we could also allow combinatorial data to have $n = 0$ partitions. However, data of this kind would correspond to standard covering maps, without any branching points. Since covering maps between surfaces are completely understood from a topological point of view, we

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[1]By *homogeneous*, we mean that, for each $n \ge 1$, the group of homeomorphisms of a surface Σ acts transitively on the set of n-uples of pairwise distinct points $(y_1, \ldots, y_n)$.

will always assume that $n \geq 1$. For the same reason, when we say "branched covering", we will be implicitly excluding the trivial cases of standard covering maps.

We say that a combinatorial datum $\mathcal{D}$ is *realizable* if $\mathcal{D} = \mathcal{D}(f)$ for some branched covering $f \colon \widetilde{\Sigma} \to \Sigma$, *exceptional* otherwise. A first, naive guess could be that every combinatorial datum can be realized. However, it turns out that there are a few easy and general necessary conditions for a combinatorial datum to be associated to a branched covering. The first one, and arguably the most important, is known as the *Riemann-Hurwitz formula*; we state it in the next proposition.

Proposition 1.2. *Let $f \colon \widetilde{\Sigma} \to \Sigma$ be a branched covering, and let $\mathcal{D}(f) = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$ be its branching datum. Then we have the equality*

$$d\chi(\Sigma) - \chi(\widetilde{\Sigma}) = v(\pi_1) + \ldots + v(\pi_n).$$

Proof. Using the same notation as above, consider the covering map $f^\bullet \colon \widetilde{\Sigma}^\bullet \to \Sigma^\bullet$. Since $f^\bullet$ has degree d, the Euler characteristics of $\Sigma^\bullet$ and $\widetilde{\Sigma}^\bullet$ are related by the formula $d\chi(\Sigma^\bullet) = \chi(\widetilde{\Sigma}^\bullet)$. Note that there are n branching points in Σ, and the number of points in $\widetilde{\Sigma} \smallsetminus \widetilde{\Sigma}^\bullet$ is $\ell(\pi_1) + \ldots + \ell(\pi_n)$; therefore

$$\chi(\Sigma^\bullet) = \chi(\Sigma) - n, \qquad\qquad \chi(\widetilde{\Sigma}^\bullet) = \chi(\widetilde{\Sigma}) - \ell(\pi_1) - \ldots - \ell(\pi_n).$$

As a consequence, we have that

$$d\chi(\Sigma) - \chi(\widetilde{\Sigma}) = d\chi(\Sigma^\bullet) + dn - \chi(\widetilde{\Sigma}^\bullet) - \ell(\pi_1) - \ldots - \ell(\pi_n) = v(\pi_1) + \ldots + v(\pi_n). \qquad \square$$

There are three more conditions that every branching datum must satisfy: two of them concern the orientability of Σ and/or $\widetilde{\Sigma}$, and the other one provides an additional constraint for the *total branching number* $v(\pi_1) + \ldots + v(\pi_n)$; we group these four requirements in the following definition.

Definition 1.5. A combinatorial datum $\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$ is a *candidate datum* if it satisfies the following conditions:

(i) $d\chi(\Sigma) - \chi(\widetilde{\Sigma}) = v(\pi_1) + \ldots + v(\pi_n)$;

(ii) $v(\pi_1) + \ldots + v(\pi_n)$ is even;

(iii) if Σ is orientable, then $\widetilde{\Sigma}$ is orientable as well;

(iv) if Σ is non-orientable and $\widetilde{\Sigma}$ is orientable, then d is even, and each π_i can be written as $\pi_i' \cup \pi_i''$, where π_i' and π_i'' are partitions of $d/2$.

Remark 1.1. In proposition 1.10, we will show that conditions (i)–(iv) are necessary for a combinatorial datum to be realizable (actually, the first condition was already proved in proposition 1.2). For now, let us focus on condition (iii), which is perhaps the most obvious one. If Σ is orientable, then so is $\Sigma^\bullet$, since removing a finite number of points does not affect orientability. The non-compact surface $\widetilde{\Sigma}^\bullet$, being a covering space of an orientable manifold, is itself orientable. Finally, this implies that $\widetilde{\Sigma}$ is orientable as well.

It would be natural to ask whether the necessary conditions we have enumerated are also sufficient for a candidate datum to be realizable. We will see in the following chapters that the answer is negative, and that, in general, determining the full list of exceptional data is remarkably difficult; we call this the *Hurwitz existence problem*[2], and we state it in the following deliberately vague fashion.

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[2]The question originally posed by Hurwitz was actually even harder: the task was counting *how many* branched coverings (up to a suitable notion of isomorphism) realize a given candidate datum. We will, however, mostly ignore this point of view, considering that the existence problem is hard enough as it is. The interested reader may. . .

Hurwitz existence problem. Determine necessary and sufficient conditions for a candidate datum $(\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$ to be realizable.

In the remainder of this thesis, we will try to address some instances of this problem. We will present a variety of techniques, which will provide us with a full solution for some classes of candidate data.

1.3 Symmetric group and partitions

The first approach we will describe is based on the monodromy action. Before describing this action and how it relates to branched coverings, we will recall a few elementary facts about permutations and partitions.

Given a set X, we denote by $\mathfrak{S}(X)$ the set of bijective functions $X \to X$. The set $\mathfrak{S}(X)$ is naturally endowed with a group structure, where the product is given by the composition operator $(\circ)$; we call this group the *symmetric group* of X. Elements of $\mathfrak{S}(X)$ are also called *permutations*.

We will sometimes need to work in a setting where the product in $\mathfrak{S}(X)$ is reversed. Given a group G with product $(*)$, we define the *opposite group* G^{op}, which has the same underlying set as G, but the product $(*^{\mathrm{op}})$ is defined as $g_1 *^{\mathrm{op}} g_2 = g_2 * g_1$.

If d is a positive integer, we will employ the notation $\mathfrak{S}_d$ as a shorthand for $\mathfrak{S}(\{1, \ldots, d\})$. Whenever X is a finite (non-empty) set, we have an isomorphism $\mathfrak{S}(X) \simeq \mathfrak{S}_d$, where d is the cardinality of X. We will therefore restrict out attentions to the groups $\mathfrak{S}_d$, keeping in mind that everything we say also holds for symmetric groups of arbitrary finite sets.

Recall that every permutation $\alpha \in \mathfrak{S}_d$ has a *cycle decomposition* (that is, it can be written as a product of disjoint, possibly trivial cycles):

$$\alpha = (x_{1,1}, \ldots, x_{1,k_1})(x_{2,1}, \ldots, x_{2,k_2}) \cdots (x_{r,1}, \ldots, x_{r,k_r}).$$

The natural action of (the subgroup generated by) α on the set $A = \{1, \ldots, d\}$ induces a decomposition $A = A_1 \sqcup \ldots \sqcup A_r$ into orbits, where $A_i = \{x_{i,1}, \ldots, x_{i,k_i}\}$. This decomposition, in turn, gives rise to a partition $\pi = [|A_1|, \ldots, |A_r|] \in \Pi(d)$. We say that α *matches* the partition π, and we use the notation $[\alpha]$ to refer to the (unique) partition matched by α. We also define the *branching number* $v(\alpha)$ as the branching number of $[\alpha]$; note that $v(\alpha) = 0$ if and only if $\alpha = \mathrm{id} \in \mathfrak{S}_d$ is the trivial permutation.

It is well known that two permutations are conjugate if and only if they match the same partition. In other words, there is a natural bijection between conjugacy classes of $\mathfrak{S}_d$ and the set of partitions $\Pi(d)$.

We conclude this section with a very simple result relating the branching number of two permutations to the branching number of their product. Recall that every permutation has a well-defined *sign*: *even* permutations can only be written as a product of an even number of transpositions (2-cycles), while *odd* permutations can only be written as a product of an odd number of transpositions. The *alternating group* of order d is the index-2 subgroup $\mathfrak{A}_d \leq \mathfrak{S}_d$ containing all the even permutations.

Proposition 1.3. *Let $\alpha, \beta \in \mathfrak{S}_d$ be permutations. Then $v(\alpha\beta) \equiv v(\alpha) + v(\beta) \pmod{2}$.*

Proof. We show that $v(\alpha)$ is even if and only if α is even; the conclusion will then follow trivially. Fix a cycle decomposition

$$\alpha = (x_{1,1}, \ldots, x_{1,k_1})(x_{2,1}, \ldots, x_{2,k_2}) \cdots (x_{r,1}, \ldots, x_{r,k_r}).$$

Since a k-cycle can be written as a product of $k-1$ transpositions, we have that α is the product of $d - r = v(\alpha)$ transpositions. This shows that $v(\alpha)$ is even if and only if $\alpha \in \mathfrak{A}_d$, which concludes the proof. $\square$

1.4   Branched covering action of the fundamental group

We now introduce the monodromy action in the general setting of topological spaces; we will assume that all the spaces we mention are locally path-connected and locally simply-connected.

Let $f: \widetilde{X} \to X$ be a covering map between topological spaces, with X path-connected. Fix a base-point $x_0 \in X$, and let $\widetilde{x}_0 \in \widetilde{X}$ be a point in $f^{-1}(x_0)$. Given a path $\gamma: [0,1] \to X$ with $\gamma(0) = x_0$, denote by $\mathrm{lift}(\gamma, \widetilde{x}_0): [0,1] \to \widetilde{X}$ the unique lift of γ such that $\mathrm{lift}(\gamma, \widetilde{x}_0)(0) = \widetilde{x}_0$. There is a very natural right action of the fundamental group $\pi_1(X, x_0)$ on the fiber $f^{-1}(x_0)$, defined by[3]

$$\widetilde{x} \bullet \gamma = \mathrm{lift}(\gamma, \widetilde{x})(1) \qquad\qquad \text{for } \widetilde{x} \in f^{-1}(x_0),\, \gamma \in \pi_1(X, x_0).$$

We call this the *monodromy action* of the covering map. It is easy to see that $\widetilde{X}$ is path-connected if and only if the monodromy action on $f^{-1}(x_0)$ is transitive.

There is a relation between monodromy and the fundamental group of $\widetilde{X}$. Fix a base-point $\widetilde{x}_0 \in f^{-1}(x_0) \subseteq \widetilde{X}$. By elementary properties of covering spaces, we have that

$$\begin{aligned}
f_*(\pi_1(\widetilde{X}, \widetilde{x}_0)) &= \{\gamma \in \pi_1(X, x_0) : \mathrm{lift}(\gamma, \widetilde{x}_0) = \widetilde{x}_0\} \\
&= \{\gamma \in \pi_1(X, x_0) : \widetilde{x}_0 \bullet \gamma = \widetilde{x}_0\} \\
&= \mathrm{Stab}_{\pi_1(X, x_0)}(\widetilde{x}_0).
\end{aligned}$$

The monodromy action induces a group homomorphism $\mathfrak{m}: \pi_1(X, x_0) \to \mathfrak{S}(f^{-1}(x_0))^{\mathrm{op}}$. If the covering map has a finite degree d, we will sometimes implicitly fix a bijection between $f^{-1}(x_0)$ and $\{1, \ldots, d\}$, and consider the homomorphism $\mathfrak{m}: \pi_1(X, x_0) \to \mathfrak{S}_d^{\mathrm{op}}$ instead; of course, this map is well-defined up to a conjugation in $\mathfrak{S}_d^{\mathrm{op}}$. The following existence theorem shows that every group homomorphism of this kind is induced by the monodromy action of some covering space.

Theorem 1.4. *Let X be a path-connected topological space, $x_0 \in X$ a point. Let d be a positive integer, and let $\psi: \pi_1(X, x_0) \to \mathfrak{S}_d^{\mathrm{op}}$ be a group homomorphism. Then there exists a covering map $f: \widetilde{X} \to X$ with $\mathfrak{m} = \psi$ (up to conjugation).*

After introducing monodromy for general topological spaces, we turn our attention to the case of branched coverings of surfaces. Let $f: \widetilde{\Sigma} \to \Sigma$ be a branched covering. As we have seen, by removing the branching points from Σ, we get an associated covering map $f^{\bullet}: \widetilde{\Sigma}^{\bullet} \to \Sigma^{\bullet}$. Fix a base-point $x_0 \in \Sigma^{\bullet}$, and let $x \in \Sigma$ be any point. There is a path $\gamma \in \pi_1(\Sigma^{\bullet}, x_0)$ which "goes around x once"; to be more precise, we can construct it as follows. Pick a small neighborhood $U \subseteq \Sigma$ of x which is homeomorphic to $\mathbb{R}^2$ and does not contain any other branching points; here we can define a loop $\beta: [0,1] \to U \smallsetminus \{x\}$ that goes around x once (we do not care about the orientation). Finally, pick a path $\alpha: [0,1] \to \Sigma^{\bullet}$ connecting x_0 to $\beta(0) = \beta(1)$, and define $\gamma = \alpha * \beta * \iota(\alpha)$, where $(*)$ is the concatenation of paths and $\iota(\alpha)$ denotes the inverse path $\iota(\alpha)(t) = \alpha(1 - t)$. Of course, the homotopy class of $\gamma \in \pi_1(\Sigma^{\bullet}, x_0)$ depends on α and even β (we could have chosen $\iota(\beta)$ instead); we will say that any path constructed with the procedure we have described is a *loop around x* (based at x_0).

We are finally ready to prove the connection between branched coverings and the monodromy of the associated covering map.

Proposition 1.5. *Let $f: \widetilde{\Sigma} \to \Sigma$ be a branched covering of degree d, and let $f^{\bullet}: \widetilde{\Sigma}^{\bullet} \to \Sigma^{\bullet}$ be the associated covering map. Fix a base-point $x_0 \in \Sigma^{\bullet}$ and a point $y \in \Sigma$. Let γ be a loop around y.*

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[3]Since the lifting operation is, in some sense, invariant up to homotopy, we will often use the same symbol (γ, in this case) to interchangeably represent a class in the fundamental group $\pi_1(X, x_0)$ and a representative of that class.

Consider the monodromy homomorphism $\mathfrak{m}\colon \pi_1(\Sigma^\bullet, x_0) \to \mathfrak{S}(f^{-1}(x_0))^{\mathrm{op}}$. *Then the permutation* $\mathfrak{m}(\gamma)$ *matches* $\pi(y)$.

Proof. Let the preimages $\widetilde{y}_1, \ldots, \widetilde{y}_r$ of y have local degrees $k_1, \ldots, k_r$. Fix disjoint trivializing neighborhoods $\widetilde{U}_1, \ldots, \widetilde{U}_r$ of $\widetilde{y}_1, \ldots, \widetilde{y}_r$ respectively. Let $U \subseteq \Sigma$ be an open neighborhood of x which is homeomorphic to $\mathbb{R}^2$ and such that $f^{-1}(U) \subseteq \widetilde{U}_1 \cup \ldots \cup \widetilde{U}_r$. Since γ is a loop around y, we can write $\gamma = \alpha * \beta * \iota(\alpha)$ as described above. Up to homotopy, we can assume that $\beta(t) \in U$ for every $t \in [0,1]$. Let $z = \alpha(1) = \beta(0) = \beta(1) \in U$; note that every preimage of z lies exactly in one $\widetilde{U}_l$. Finally, let $\widetilde{x}_1, \ldots, \widetilde{x}_d$ be the preimages of x_0. We will show that $\widetilde{x}_i$ and $\widetilde{x}_j$ belong to the same orbit of $\mathfrak{m}(\gamma)$ if and only if $\mathrm{lift}(\alpha, \widetilde{x}_i)(1)$ and $\mathrm{lift}(\alpha, \widetilde{x}_j)(1)$ lie in the same $\widetilde{U}_l$. Since $f^{-1}(z) \cap \widetilde{U}_l$ has cardinality k_l and $\pi(y) = [k_1, \ldots, k_r]$, this would complete the proof.

Let $\widetilde{x}_i \in f^{-1}(x_0)$, $\widetilde{z}_1 = \mathrm{lift}(\alpha, \widetilde{x}_i)(1)$. Let l be the unique index such that $\widetilde{z}_1 \in \widetilde{U}_l$. For each $m \geq 1$, inductively define $\widetilde{z}_{m+1} = \mathrm{lift}(\beta, \widetilde{z}_m)(1)$. Since the support of β lies entirely in U, we have that the support of $\mathrm{lift}(\beta, \widetilde{z}_m)$ lies entirely in $\widetilde{U}_l$ and, therefore, $\widetilde{z}_{m+1} \in \widetilde{U}_l$ as well. Since $\widetilde{U}_l$ is a trivializing neighborhood of $\widetilde{y}_l$, which has local degree k_l, it is easy to see that the sequence $\widetilde{z}_1, \widetilde{z}_2, \ldots$ is periodic of period k_l, and that $f^{-1}(z) \cap \widetilde{U}_l = \{\widetilde{z}_1, \ldots \widetilde{z}_{k_l}\}$. It is also clear that

$$\mathfrak{m}(\gamma)(\widetilde{x}_i) = \mathrm{lift}(\iota(\alpha), \widetilde{z}_2)(1)$$

and, by induction, that

$$\mathfrak{m}(\gamma)^s(\widetilde{x}_i) = \mathrm{lift}(\iota(\alpha), \widetilde{z}_{s+1})(1) \qquad\qquad \text{for every } s \geq 1.$$

This shows that, if $\widetilde{x}_j = \mathfrak{m}(\gamma)^s(\widetilde{x}_i)$, then $\mathrm{lift}(\alpha, \widetilde{x}_j)(1) = \widetilde{z}_{s+1} \in \widetilde{U}_l$.

Conversely, assume that $\mathrm{lift}(\alpha, \widetilde{x}_j)(1) \in \widetilde{U}_l$. This implies that $\mathrm{lift}(\alpha, \widetilde{x}_j)(1) = \widetilde{z}_s$ for some $s \geq 1$. But then

$$\widetilde{x}_j = \mathrm{lift}(\iota(\alpha), \widetilde{z}_s)(1) = \mathfrak{m}(\gamma)^{s-1}(\widetilde{x}_i),$$

so $\widetilde{x}_i$ and $\widetilde{x}_j$ belong to the same orbit of $\mathfrak{m}(\gamma)$. $\qquad\qquad\square$

1.5 Monodromy and realizability

From Proposition 1.5 we can derive a group-theoretic criterion for the realizability of a given combinatorial datum.

Proposition 1.6. *Let Σ be a surface, $d \geq 1$ an integer, $\pi_1, \ldots, \pi_n \in \Pi(d)$ partitions of d. Let $x_1, \ldots x_n \in \Sigma$ be distinct points; define $\Sigma^\bullet = \Sigma \setminus \{x_1, \ldots, x_n\}$. Fix a base-point $x_0 \in \Sigma^\bullet$ and loops $\gamma_1, \ldots, \gamma_n \in \pi_1(\Sigma^\bullet, x_0)$ around $x_1, \ldots, x_n$ respectively. Then the following are equivalent.*

 (i) *There exist a surface $\widetilde{\Sigma}$ and a branched covering $f\colon \widetilde{\Sigma} \to \Sigma$ with branching datum $\mathcal{D}(f) = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$.*

 (ii) *There exists a group homomorphism $\psi\colon \pi_1(\Sigma^\bullet, x_0) \to \mathfrak{S}_d^{\mathrm{op}}$ such that $\psi(\pi_1(\Sigma^\bullet, x_0)) \leq \mathfrak{S}_d^{\mathrm{op}}$ acts transitively on $\{1, \ldots, d\}$ and $[\psi(\gamma_i)] = \pi_i$ for every $1 \leq i \leq n$.*

Proof. Assume we are given a branched covering $f\colon \widetilde{\Sigma} \to \Sigma$ with $\mathcal{D}(f) = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$. Since surfaces are homogeneous, we can assume that the branching points are exactly $x_1, \ldots, x_n$, with associated partitions $\pi_1, \ldots, \pi_n$ respectively. Let $f^\bullet\colon \widetilde{\Sigma}^\bullet \to \Sigma^\bullet$ be the induced covering map, and let $\mathfrak{m}\colon \pi_1(\Sigma^\bullet, x_0) \to \mathfrak{S}_d^{\mathrm{op}}$ be the monodromy homomorphism. By proposition 1.5 we have $[\mathfrak{m}(\gamma_i)] = \pi_i$ for every $1 \leq i \leq n$, and the action of $\mathfrak{m}(\pi_1(\Sigma^\bullet, x_0))$ on $\{1, \ldots, d\}$ is transitive since $\Sigma^\bullet$ is connected. Therefore setting $\psi = \mathfrak{m}$ gives the desired homomorphism.

Assume conversely that we are given a group homomorphism $\psi\colon \pi_1(\Sigma^{\bullet}, x_0) \to \mathfrak{S}_d^{\mathrm{op}}$. Theorem 1.4 gives a covering map $f^{\bullet}\colon \widetilde{\Sigma}^{\bullet} \to \Sigma^{\bullet}$ of degree d with monodromy $\mathfrak{m} = \psi$. The non-compact surface $\widetilde{\Sigma}^{\bullet}$ is connected by the transitivity hypothesis. We can "fill the holes" in $\Sigma^{\bullet}$ and $\widetilde{\Sigma}^{\bullet}$ to get a branched covering between compact surfaces; here are the details. Consider one of the points x_i, and fix an open neighborhood $U \subseteq \Sigma$ of x_i homeomorphic to $\mathbb{R}^2$. Now $(f^{\bullet})^{-1}(U \smallsetminus \{x_i\})$ is a covering space of $U \smallsetminus \{x_i\} \simeq \mathbb{R}^2 \smallsetminus \{0\}$. By the classification of covering spaces, we get that $(f^{\bullet})^{-1}(U \smallsetminus \{x_i\})$ is a disjoint union of punctured disks $\widetilde{V}_1 \sqcup \ldots \sqcup \widetilde{V}_r$; moreover, for each $1 \leq j \leq r$ we have charts $\varphi_j\colon U \smallsetminus \{x_i\} \to \mathbb{C} \smallsetminus \{0\}$, $\widetilde{\varphi}_j\colon \widetilde{V}_j \to \mathbb{C} \smallsetminus \{0\}$ and a positive integer k_j such that the diagram

$$
\begin{array}{ccc}
\widetilde{V}_j & \xrightarrow{\ f^{\bullet}\ } & U \smallsetminus \{x_i\} \\
\downarrow{\scriptstyle \widetilde{\varphi}_j} & & \downarrow{\scriptstyle \varphi_j} \\
\mathbb{C} \smallsetminus \{0\} & \xrightarrow{\ F_{k_j}\ } & \mathbb{C} \smallsetminus \{0\}
\end{array}
$$

commutes, where $F_{k_j}(z) = z^{k_j}$. We can "fill the hole" in $\widetilde{V}_j$ by considering the surface $\widetilde{\Sigma}_1^{\bullet} = \widetilde{\Sigma}^{\bullet} \sqcup \mathbb{C}/\sim$, where $y \sim \widetilde{\varphi}_j(y)$ for each $y \in \widetilde{V}_j$. It is clear that $f^{\bullet}$ extends to a continuous function $\widetilde{\Sigma}_1^{\bullet} \to \Sigma$ by sending $0 \in \mathbb{C}$ to x_i; this map is locally modeled on $z \mapsto z^{k_j}$ near 0. If we "fill the hole" in $\widetilde{V}_j$ for $1 \leq j \leq r$, and then repeat the process for each x_i, we end up with a surface $\widetilde{\Sigma}$ and a map $f\colon \widetilde{\Sigma} \to \Sigma$. It is easy to see from the construction that $\widetilde{\Sigma}$ is compact and connected, and that f is a branched covering. Since the associated covering map is exactly $f^{\bullet}\colon \widetilde{\Sigma}^{\bullet} \to \Sigma^{\bullet}$, proposition 1.5 implies that $\pi(x_i)$ matches $\mathfrak{m}(\gamma_i) = \psi(\gamma_i)$, so $\pi(x_i) = \pi_i$. $\qquad\square$

By combining proposition 1.6 with the classification of surfaces, we obtain the following criteria for realizability.

Corollary 1.7. *Let Σ_g be the connected sum of $g \geq 0$ tori, $d \geq 1$ an integer, $\pi_1, \ldots, \pi_n \in \Pi(d)$ partitions of d. Then there exists a realizable combinatorial datum $\mathcal{D} = (\widetilde{\Sigma}, \Sigma_g; d; \pi_1, \ldots, \pi_n)$ if and only if there exist permutations $\alpha_1, \ldots, \alpha_n, \beta_1, \ldots, \beta_g, \gamma_1, \ldots, \gamma_g \in \mathfrak{S}_d$ such that:*

(i) $[\alpha_i] = \pi_i$ *for each* $1 \leq i \leq n$;

(ii) $[\beta_1, \gamma_1] \cdots [\beta_g, \gamma_g] \cdot \alpha_1 \cdots \alpha_n = 1$;

(iii) the subgroup $\langle \alpha_1, \ldots, \alpha_n, \beta_1, \ldots, \beta_g, \gamma_1, \ldots, \gamma_g \rangle \leq \mathfrak{S}_d$ *acts transitively on* $\{1, \ldots, d\}$.

In this case, $\widetilde{\Sigma}$ is necessarily orientable.

Proof. Let $\Sigma_g^{\bullet}$ be the non-compact surface obtained by removing n points $x_1, \ldots, x_n$ from Σ_g. Fix a base-point $x_0 \in \Sigma_g^{\bullet}$. Once we observe that $\pi_1(\Sigma_g^{\bullet}, x_0)$ has a presentation

$$
\pi_1(\Sigma_g^{\bullet}, x_0) = \langle a_1, \ldots, a_n, b_1, \ldots, b_g, c_1, \ldots, c_g \mid [b_1, c_1] \cdots [b_g, c_g] \cdot a_1 \cdots a_n \rangle,
$$

where a_i is a loop around x_i, the criterion follows immediately from proposition 1.6. The orientability of $\widetilde{\Sigma}$ was already addressed in remark 1.1. $\qquad\square$

Remark 1.2. Given Σ_g, d and $\pi_1, \ldots, \pi_n$, there is at most one surface $\widetilde{\Sigma}$ such that $\mathcal{D} = (\widetilde{\Sigma}, \Sigma_g; d; \pi_1, \ldots, \pi_n)$ is a candidate datum. In fact, the Riemann-Hurwitz formula gives

$$
\chi(\widetilde{\Sigma}) = d\chi(\Sigma_g) - v(\pi_1) - \ldots - v(\pi_n)
$$

which, in turn, uniquely determines the orientable surface $\widetilde{\Sigma}$. As an application, assume that we have a candidate datum $\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$, and we find permutations in $\mathfrak{S}_d$ satisfying conditions (i)–(iii): this immediately implies that $\mathcal{D}$ is realizable.

Before stating the monodromy criterion for non-orientable surfaces, we recall a few basic facts about covering maps and orientability.

Given a non-orientable topological manifold M, let $\omega\colon \widehat{M} \to M$ be its orientable double covering. Fix a base-point $x_0 \in M$, and consider the monodromy homomorphism

$$w\colon \pi_1(M, x_0) \longrightarrow \mathfrak{S}(\omega^{-1}(x_0)) \simeq \mathbb{Z}/2.$$

We denote the kernel of w (which is a subgroup of $\pi_1(M, x_0)$ of index 2) by $W(M, x_0)$. Note that $W = \omega_*(\pi_1(\widehat{M}, \widehat{x}_0))$ for every base-point $\widehat{x}_0 \in \omega^{-1}(x_0)$, where $\omega_*\colon \pi_1(\widehat{M}, \widehat{x}_0 \to \pi_1(M, x_0)$ denotes the map induced by ω on the fundamental groups. Given a connected topological manifold N and a covering map $f\colon N \to M$, elementary properties of covering spaces imply that the following are equivalent:

(i) N is orientable;

(ii) $f_*(\pi_1(N, y_0)) \le W(M, x_0)$ for every base-point $y_0 \in f^{-1}(x_0)$;

(iii) there exists a covering map $\widehat{f}\colon N \to \widehat{M}$ such that f factors as $f = \omega \circ \widehat{f}$.

Corollary 1.8. *Let N_g be the connected sum of $g \ge 1$ projective planes, $d \ge 1$ an integer, $\pi_1, \ldots, \pi_n \in \Pi(d)$ partitions of d. Then there exists a realizable combinatorial datum $\mathcal{D} = (\widetilde{\Sigma}, N_g; d; \pi_1, \ldots, \pi_n)$ if and only if there exist permutations $\alpha_1, \ldots, \alpha_n, \beta_1, \ldots, \beta_g \in \mathfrak{S}_d$ such that:*

(i) $[\alpha_i] = \pi_i$ for each $1 \le i \le n$;

(ii) $\beta_1^2 \cdots \beta_g^2 \cdot \alpha_1 \cdots \alpha_n = 1$;

(iii) the subgroup $\langle \alpha_1, \ldots, \alpha_n, \beta_1, \ldots, \beta_g \rangle \le \mathfrak{S}_d$ acts transitively on $\{1, \ldots, d\}$.

In this case, $\widetilde{\Sigma}$ is non-orientable if and only if there exists a permutation $\gamma \in \mathfrak{S}_d$ which has a fixed point and can be written as the product of an odd number of β_j and any number of α_i.

Proof. The proof of the criterion is identical to that of corollary 1.7: simply let $N_g^\bullet = N_g \smallsetminus \{x_1, \ldots, x_n\}$ and observe that there is a presentation

$$\pi_1(N_g^\bullet, x_0) = \left\langle a_1, \ldots, a_n, b_1, \ldots, b_g \mid b_1^2 \cdots b_g^2 \cdot a_1 \cdots a_n \right\rangle,$$

where a_i is a loop around x_i. As far as the orientability of $\widetilde{\Sigma}$ is concerned, note that $w(a_1) = \ldots = w(a_n) = 0$, while $w(b_1) = \ldots = w(b_g) = 1$. Let $f^\bullet\colon \widetilde{\Sigma}^\bullet \to N_g^\bullet$ be the covering map associated to the branched covering, and let $\mathfrak{m}\colon \pi_1(N_g^\bullet, x_0) \to \mathfrak{S}_d$ be the monodromy homomorphism. Fix a base-point $\widetilde{x}_0 \in f^{-1}(x_0)$; we have that $\widetilde{\Sigma}^\bullet$ is orientable if and only if $f_*(\pi_1(\widetilde{\Sigma}^\bullet, \widetilde{x}_0)) \le W(N_g^\bullet, x_0)$. Since $f_*(\pi_1(\widetilde{\Sigma}^\bullet, \widetilde{x}_0)) = \mathrm{Stab}_{\pi_1(N_g^\bullet, x_0)}(\widetilde{x}_0)$, it follows that $\widetilde{\Sigma}^\bullet$ is non-orientable if and only if there exists a loop $c \in \pi_1(N_g^\bullet, x_0)$ such that $w(c) = 1$ and $\widetilde{x}_0 \bullet c = \widetilde{x}_0$. By applying $\mathfrak{m}$, we see that this is equivalent to the existence of a permutation $\gamma \in \mathfrak{S}_d$ which has a fixed point and can be written as the product of an odd number of β_j and an arbitrary number of α_i; note that the exact fixed point does not matter, since the subgroup generated by the α_i and β_j acts transitively on $\{1, \ldots, d\}$. Finally, observe that $\widetilde{\Sigma}^\bullet$ is orientable if and only if $\widetilde{\Sigma}$ is. $\square$

Remark 1.3. Given N_g, d and $\pi_1, \ldots, \pi_n$, there are at most two surfaces $\widetilde{\Sigma}$, one orientable and one non-orientable, such that $\mathcal{D} = (\widetilde{\Sigma}, N_g; d; \pi_1, \ldots, \pi_n)$ is a candidate datum: like in remark 1.2, the Riemann-Hurwitz formula fixes $\chi(\widetilde{\Sigma})$ which, together with orientability, uniquely determines the surface $\widetilde{\Sigma}$.

Moreover, we can show that realizability in the case where Σ is non-orientable and $\widetilde{\Sigma}$ is orientable can be reduced to a situation where both surfaces are orientable.

Proposition 1.9. *Let $\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots \pi_n)$ be a combinatorial datum, with Σ non-orientable and $\widetilde{\Sigma}$ orientable. Then $\mathcal{D}$ is realizable if and only if d is even and there exist partitions $\pi'_1, \ldots, \pi'_n, \pi''_1, \ldots, \pi''_n \in \Pi(d/2)$ with $\pi_i = \pi'_i \cup \pi''_i$ for each $1 \le i \le n$, such that the combinatorial datum*

$$\mathcal{D}' = (\widetilde{\Sigma}, \widehat{\Sigma}; d/2; \pi'_1, \ldots, \pi'_n, \pi''_i, \ldots, \pi''_n)$$

is realizable, where $\widehat{\Sigma}$ is the orientable double covering of Σ.

Proof. Assume that $\mathcal{D}$ is realized by a branched covering $f \colon \widetilde{\Sigma} \to \Sigma$. Let $f^\bullet \colon \widetilde{\Sigma}^\bullet \to \Sigma^\bullet$ be the associated covering map, and let $\omega \colon \widehat{\Sigma} \to \Sigma$ be the orientable double covering. Define $\widehat{\Sigma}^\bullet = \omega^{-1}(\Sigma^\bullet)$, and denote by $\omega^\bullet$ the restriction of ω to $\widetilde{\Sigma}^\bullet$; clearly, $\omega^\bullet \colon \widehat{\Sigma}^\bullet \to \Sigma^\bullet$ is the orientable double covering of $\Sigma^\bullet$. Since $\widetilde{\Sigma}^\bullet$ is orientable while $\Sigma^\bullet$ is not, $f^\bullet$ factors as $f^\bullet = \widehat{f}^\bullet \circ \omega^\bullet$ for some covering map $\widehat{f}^\bullet \colon \widetilde{\Sigma}^\bullet \to \widehat{\Sigma}^\bullet$; in particular, d is even and $\widehat{f}^\bullet$ has degree $d/2$. The conclusion follows from a routine topological argument; for the sake of completeness, we will now report the details. Fix a branching point $x \in \Sigma \setminus \Sigma^\bullet$; let $f^{-1}(x) = \{\widetilde{x}_1, \ldots, \widetilde{x}_r\}$ and $\omega^{-1}(x) = \{\widehat{x}_1, \widehat{x}_2\}$. There exists a small open neighborhood $U \subseteq \Sigma$ of x homeomorphic to $\mathbb{R}^2$ such that:

- $f^{-1}(U) = \widetilde{U}_1 \sqcup \ldots \sqcup \widetilde{U}_r$, where $\widetilde{U}_i$ is a trivializing neighborhood of $\widetilde{x}_i$;

- $\omega^{-1}(U) = \widehat{U}_1 \sqcup \widehat{U}_2$, where $\widehat{U}_i$ is a trivializing neighborhood of $\widehat{x}_i$.

It is now clear that $\widehat{f}^\bullet \colon \widetilde{\Sigma}^\bullet \to \widehat{\Sigma}^\bullet$ extends to a branched covering $\widehat{f} \colon \widetilde{\Sigma} \to \widehat{\Sigma}$: for each $1 \le i \le r$, we simply set $\widehat{f}(\widetilde{x}_i) = \widehat{x}_1$ if $\widehat{f}^\bullet(\widetilde{U}_i \setminus \{\widetilde{x}_i\}) = \widehat{U}_1 \setminus \{\widehat{x}_1\}$, and $\widehat{f}(\widetilde{x}_i) = \widehat{x}_2$ otherwise; obviously, we must repeat this process for every branching point x. The branched covering $\widehat{f}$ has degree $d/2$; moreover, it is easy to see from the construction that $\pi_f(x) = \pi_{\widehat{f}}(\widehat{x}_1) \cup \pi_{\widehat{f}}(\widehat{x}_2)$ (we use the subscript in order to clarify which branched covering we are referring to). Therefore the realizable combinatorial datum $\mathcal{D}(\widehat{f})$ has the required form.

Conversely, assume that d is even and we are given a branched covering $\widehat{f} \colon \widetilde{\Sigma} \to \widehat{\Sigma}$ with branching datum

$$\mathcal{D}(\widehat{f}) = (\widetilde{\Sigma}, \widehat{\Sigma}; d/2; \pi'_1, \ldots, \pi'_n, \pi''_1, \ldots, \pi''_n),$$

where $\pi_i = \pi'_i \cup \pi''_i$ for every $1 \le i \le n$. Let $x'_1, \ldots, x'_n, x''_1, \ldots, x''_n \in \widehat{\Sigma}$ be the branching points corresponding to the similarly named partitions of $\mathcal{D}(\widehat{f})$. Since surfaces are homogeneous, we can assume that $\omega(x'_i) = \omega(x''_i)$ for each $1 \le i \le n$, where $\omega \colon \widehat{\Sigma} \to \Sigma$ is the covering map. It is now easy to see that

$$\mathcal{D}(\omega \circ \widehat{f}) = (\widetilde{\Sigma}, \Sigma; d; \pi'_1 \cup \pi''_1, \ldots, \pi'_n \cup \pi''_n). \qquad \square$$

We conclude this introductory chapter by showing that the four conditions described in definition 1.5 are actually necessary for a combinatorial datum to be realizable.

Proposition 1.10. *Let $f \colon \widetilde{\Sigma} \to \Sigma$ be a branched covering. Then its branching datum $\mathcal{D}(f)$ is a candidate datum.*

Proof. Conditions (i) and (iii) of definition 1.5 were already addressed, respectively, in proposition 1.2 and remark 1.1. Condition (iv) follows immediately from proposition 1.9, so we only have to show that the total branching number $v(\pi_1) + \ldots + v(\pi_n)$ is even. Using the notations of corollaries 1.7 and 1.8, by proposition 1.3 we have that

$$v(\alpha_1 \cdots \alpha_n) \equiv \begin{cases} v([\beta_1, \gamma_1] \cdots [\beta_g, \gamma_g]) & \text{if } \Sigma \text{ is orientable,} \\ v(\beta_1^2 \cdots \beta_g^2) & \text{if } \Sigma \text{ is non-orientable} \end{cases} \pmod 2.$$

However, not every splitting leads to a realizable datum.

But commutators and squares are even permutations, therefore

$$v(\pi_1) + \ldots + v(\pi_n) = v(\alpha_1) + \ldots v(\alpha_n) \equiv v(\alpha_1 \cdots \alpha_n) \equiv 0 \pmod{2}. \qquad \square$$

Chapter 2

Realizablility by monodromy

2.1 Non-positive Euler characteristic

The monodromy approach developed in the previous chapter will allow us to completely solve the Hurwitz existence problem for a large class of candidate data. With the following elementary result about symmetric groups, we will already be able to fully address the cases where $\chi(\Sigma) \leq 0$.

Lemma 2.1. *Let $\alpha \in \mathfrak{S}_d$ be a permutation. Set $r = d - v(\alpha)$, and let $t \geq 0$ be an integer such that $2t \leq v(\alpha)$. Then α can be written as the product of a $(r + 2t)$-cycle and a d-cycle.*

Proof. Without loss of generality, assume that

$$\alpha = (1, \ldots, d_1)(d_1 + 1, \ldots, d_2) \cdots (d_{r-1} + 1, \ldots, d_r),$$

where $d_r = d$. Fix

$$\beta_0 = (1, b_1, b_2, \ldots, b_{2t}), \qquad \beta_1 = (1, d_1 + 1, d_2 + 1, \ldots, d_{r-1} + 1),$$

where $b_1 < b_2 < \ldots < b_{2t}$ are elements of $\{1, \ldots, d\} \smallsetminus \{d_1 + 1, \ldots, d_{r-1} + 1\}$. Set

$$\beta = \beta_0 \beta_1 = (1, d_1 + 1, d_2 + 1, \ldots, d_{r-1} + 1, b_1, b_2, \ldots, b_{2t}).$$

An easy computation shows that

$$
\begin{aligned}
\beta\alpha &= \beta_0\beta_1\alpha \\
&= (1, b_1, b_2, \ldots, b_{2t})(1, 2, \ldots, d) \\
&= (1, \ldots, b_1 - 1, b_2, \ldots, b_3 - 1, b_4, \ldots, b_{2t-1} - 1, b_{2t}, \ldots, d, b_1, \ldots, b_2 - 1, b_3, \ldots, b_{2t} - 1).
\end{aligned}
$$

Writing $\alpha = \beta^{-1}(\beta\alpha)$ gives the desired decomposition. $\qquad\square$

Corollary 2.2. *Let $\alpha \in \mathfrak{A}_d$ be an even permutation. Then α can be written as:*

  (i) a commutator $[\beta, \gamma]$, where γ is a d-cycle;

  (ii) a product of two squares $\delta^2 \epsilon^2$, where $\delta\epsilon$ is a d-cycle.

Proof. Since α is an even permutation, its branching number $v(\alpha)$ is even. By lemma 2.1, there exist two d-cycles $\tau, \sigma \in \mathfrak{S}_d$ such that $\alpha = \tau\sigma$.

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(i) Since τ and σ^{-1} are conjugated, there exists a permutation $\beta \in \mathfrak{S}_d$ such that $\tau = \beta\sigma^{-1}\beta^{-1}$. Setting $\gamma = \sigma^{-1}$, we immediately get that

$$\alpha = \tau\sigma = \beta\sigma^{-1}\beta^{-1}\sigma = \beta\gamma\beta^{-1}\gamma^{-1} = [\beta, \gamma].$$

(ii) Since τ and σ are conjugated, there exists a permutation $\delta \in \mathfrak{S}_d$ such that $\tau = \delta\sigma\delta^{-1}$. Setting $\epsilon = \delta^{-1}\sigma$, we have that

$$\alpha = \tau\sigma = \delta\sigma\delta^{-1}\sigma = \delta^2(\delta^{-1}\sigma)^2 = \delta^2\epsilon^2. \qquad \square$$

Theorem 2.3. *Let $\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$ be a candidate datum. If $\chi(\Sigma) \leq 0$, then $\mathcal{D}$ is realizable.*

Proof. Let us first assume that Σ is orientable; this means that $\Sigma = \Sigma_g$ is the connected sum of $g \geq 1$ tori, and that $\widetilde{\Sigma}$ is orientable as well. Choose permutations $\alpha_1, \ldots, \alpha_n \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$ for each $1 \leq i \leq n$. Let $\alpha = \alpha_1 \cdots \alpha_n$. Since $\mathcal{D}$ is a candidate datum, we have that

$$v(\alpha) \equiv v(\alpha_1) + \ldots + v(\alpha_n) \equiv 0 \pmod 2.$$

By corollary 2.2, we can find permutations $\beta_1, \gamma_1 \in \mathfrak{S}_d$ such that $\alpha = [\gamma_1, \beta_1]$ and β_1 is a d-cycle. Set $\beta_2 = \ldots = \beta_g = \gamma_2 = \ldots = \gamma_g = \mathrm{id} \in \mathfrak{S}_d$. All the conditions of corollary 1.7 are satisfied; since $\widetilde{\Sigma}$ is orientable, this implies that $\mathcal{D}$ is realizable (see remark 1.2).

Assume now that Σ and $\widetilde{\Sigma}$ are both non-orientable; this means that $\Sigma = N_g$ is the connected sum of $g \geq 2$ projective planes. Choose permutations $\alpha_1, \ldots, \alpha_n \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$ for each $1 \leq i \leq n$. Let $\alpha = \alpha_1 \cdots \alpha_n$. Similarly to what we did for the previous case, we can find $\beta_1, \beta_2 \in \mathfrak{S}_d$ such that $\alpha = \beta_2^{-2}\beta_1^{-2}$ and $\beta_1\beta_2$ is a d-cycle. Note that, since $\beta_1\beta_2$ is a d-cycle, there exists an integer $m \geq 0$ such that $\beta_1(\beta_1\beta_2)^m$ has a fixed point. By setting $\beta_3 = \ldots = \beta_g = \mathrm{id} \in \mathfrak{S}_d$, corollary 1.8 (together with remark 1.3) implies the realizability of $\mathcal{D}$.

Finally, consider the case where Σ is non-orientable and $\widetilde{\Sigma}$ is orientable. Since $\mathcal{D}$ is a candidate datum, d is even and there exist partitions $\pi_1', \ldots, \pi_n', \pi_1'', \ldots, \pi_n'' \in \Pi(d/2)$ with $\pi_i = \pi_i' \cup \pi_i''$ for each $1 \leq i \leq n$. Let $\widehat{\Sigma}$ be the double orientable covering of Σ; by the first case we analyzed, the candidate datum

$$\mathcal{D}' = (\widetilde{\Sigma}, \widehat{\Sigma}; d/2; \pi_1', \ldots, \pi_n', \pi_1'', \ldots, \pi_n'')$$

is realizable. By proposition 1.9, $\mathcal{D}$ is realizable as well. $\qquad \square$

2.2   Products in symmetric groups

The monodromy approach can prove to be quite fruitful also in the cases where $\chi(\Sigma) > 0$ (namely, when Σ is either the sphere S^2 or the projective plane $\mathbb{RP}^2$). In order to deal with this instances of the Hurwitz existence problem, however, we will need a few more technical results about products of permutations.

Lemma 2.4. *Let X, Y be finite sets; denote by h the cardinality of Y, and by k the cardinality of $X \cap Y$. Let $\alpha \in \mathfrak{S}(X)$, $\beta \in \mathfrak{S}(Y)$, $\gamma \in \mathfrak{S}(X \cap Y)$. Assume that $\beta = (b_1, \ldots, b_h)$ is a h-cycle, and that γ is a k-cycle of the form $\gamma = (b_{i_1}, \ldots, b_{i_k})$ with $1 \leq i_1 \leq \ldots \leq i_k \leq h$. Then $\alpha \in \mathfrak{S}(X)$ and $\alpha\gamma^{-1}\beta \in \mathfrak{S}(X \cup Y)$ have the same number of cycles.*

Proof. Write $\gamma = (u_1, \ldots, u_k)$, where $u_j = b_{i_j}$. Without loss of generality, assume that $i_1 = 1$. Then we can write

$$\beta = (u_1, \ldots, w_1, u_2, \ldots, w_2, u_3, \ldots, w_{k-1}, u_k, \ldots, w_k),$$

possibly with $u_j = w_j$ for some values of j. We immediately get that

$$\gamma^{-1}\beta = (u_1, \ldots, w_1)(u_2, \ldots, w_2)\cdots(u_k, \ldots, w_k).$$

If we denote by $A_1, \ldots, A_r \subseteq X$ the orbits of α, it is then easy to see that the orbits of $\alpha\gamma^{-1}\beta$ are $A'_1, \ldots, A'_r \subseteq X \cup Y$, where

$$A'_j = A_j \cup \bigcup_{u_l \in A_j} \{u_l, \ldots, w_l\}. \qquad \square$$

Proposition 2.5. *Let $\pi, \rho \in \Pi(d)$ be partitions of d. Assume that $v(\pi) + v(\rho) \le d - 1$. Then there exist permutations $\alpha, \beta \in \mathfrak{S}_d$ with $[\alpha] = \pi$ and $[\beta] = \rho$ such that $v(\alpha\beta) = v(\alpha) + v(\beta)$.*

Proof. First of all, note that the conclusion is trivial whenever $v(\pi) = 0$ or $v(\rho) = 0$. This already solves the cases $d = 1$ and $d = 2$. We now proceed by induction on $d \ge 3$, assuming that $v(\pi) > 0$ and $v(\rho) > 0$. Write $\pi = [a_1, \ldots, a_r]$, $\rho = [b_1, \ldots, b_s]$; without loss of generality, assume that $b_1 > 1$. Fix

$$\beta = (1, \ldots, d_1)(d_1 + 1, \ldots, d_2)\cdots(d_{s-1} + 1, \ldots, d_s),$$

where $b_1 = d_1 \ge 2$, $b_i = d_i - d_{i-1}$ for $2 \le i \le s$ (in particular, $d_s = d$). Note that

$$d - 1 \ge v(\pi) + v(\rho) = (a_1 - 1) + \ldots + (a_r - 1) + d - s \ge a_1 - 1 + d - s,$$

hence $a_1 \le s$. Fix $\alpha_1 = (1, d_1 + 1, \ldots, d_{a_1-1} + 1)$, and let $A = \{1, d_1 + 1, \ldots, d_{a_1-1} + 1\}$ be the support of α_1. Define $Q = \{1, \ldots, d_{a_1}\} \smallsetminus A$; note that Q_1 is non-empty, since $d_1 + 1 \ge 3$ implies that $2 \in Q_1$. Consider the partitions

$$\pi' = [a_2, a_3, \ldots, a_r], \qquad\qquad \rho' = [|Q|, b_{a_1+1}, \ldots, b_s].$$

We have that

$$\sum \pi' = \sum \rho' = d - a_1, \qquad v(\pi') = v(\pi) - a_1 + 1, \qquad v(\rho') = v(\rho) - 1.$$

Since $d - a_1 < d$ and $v(\pi') + v(\rho') = v(\pi) + v(\rho) - a_1 < d - a_1$, by induction we find $\alpha', \beta' \in \mathfrak{S}(\{1, \ldots, d\} \smallsetminus A)$ with $[\alpha'] = \pi'$ and $[\beta'] = \rho'$ such that $v(\alpha'\beta') = v(\alpha') + v(\beta')$. Up to conjugation, we may assume that

$$\beta' = \beta_1(d_{a_1} + 1, \ldots, d_{a_1+1})(d_{a_1+1} + 1, \ldots, d_{a_1+2})\cdots(d_{s-1} + 1, \ldots, d_s),$$

where β_1 is the $|Q|$-cycle whose entries are the elements of Q in increasing order. An easy computation shows that

$$\alpha_1\beta = (1, \ldots, d_{a_1})(d_{a_1} + 1, \ldots, d_{a_1+1})\cdots(d_{s-1} + 1, \ldots, d_s).$$

Therefore, setting $\alpha = \alpha'\alpha_1$, we have that

$$\begin{aligned}
\alpha\beta &= \alpha_1\alpha'\beta \\
&= \alpha'(1, \ldots, d_{a_1})(d_{a_1} + 1, \ldots, d_{a_1+1})\cdots(d_{s-1} + 1, \ldots, d_s) \\
&= \alpha'\beta'\beta_1^{-1}(1, \ldots, d_{a_1})
\end{aligned}$$

By lemma 2.4, this implies that $\alpha\beta$ has the same number of cycles as $\alpha'\beta'$, so that

$$\begin{aligned}
v(\alpha\beta) &= a_1 + v(\alpha'\beta') \\
&= a_1 + v(\alpha') + v(\beta') \\
&= a_1 + (v(\pi) - a_1 + 1) + (v(\rho) - 1) \\
&= v(\pi) + v(\rho).
\end{aligned}$$

Since $[\alpha] = \pi$ and $[\beta] = \rho$, the conclusion follows. $\qquad \square$

Proposition 2.6. *Let $\pi, \rho \in \Pi(d)$ be partitions of d. Assume that $v(\pi) + v(\rho) \geq d - 1$ and $v(\pi) + v(\rho) \equiv d - 1 \pmod 2$. Then there exist permutations $\alpha, \beta \in \mathfrak{S}_d$ with $[\alpha] = \pi$ and $[\beta] = \rho$ such that $\alpha\beta$ is a d-cycle.*

Proof. If $v(\pi) + v(\rho) = d - 1$, the conclusion follows immediately from proposition 2.5. Therefore, we can assume that $v(\pi) + v(\rho) \geq d$.

Write $\pi = [a_1, \ldots, a_r]$. Since $v(\rho) \leq d - 1$ and $v(\pi) + v(\rho) \geq d$, there exists a largest integer $0 \leq i \leq r$ such that $(a_1 - 1) + \ldots (a_i - 1) + v(\rho) \leq d - 1$. Define

$$z = d - v(\rho) - (a_1 - 1) - \ldots - (a_i - 1).$$

Consider the partition $\pi' = [a_1, \ldots, a_i, z, 1, \ldots, 1] \in \Pi(d)$. Since by construction $v(\pi') + v(\rho) = d - 1$, thanks to proposition 2.5 we can find permutations $\alpha', \beta \in \mathfrak{S}_d$ with $[\alpha'] = \pi'$ and $[\beta] = \rho$ such that $v(\alpha'\beta) = d - 1$; in other words, $\alpha'\beta$ is a d-cycle. Consider now the partition $\pi'' = [a_{i+1} - z + 1, a_{i+2}, \ldots, a_r]$, whose branching number is $v(\pi'') = v(\pi) + v(\rho) - d + 1$. Let $n = \sum \pi''$; fix an element u_1 of the z-cycle of α', and let $u_2, \ldots, u_n$ be the fixed points of α' corresponding to the last ones of π' (it is easy to see that there are exactly $n - 1$ such ones). Since $v(\pi'')$ is even, lemma 2.1 gives permutations $\alpha'', \gamma \in \mathfrak{S}(\{u_1, \ldots, u_n\})$ such that $[\alpha''] = \pi''$ and γ and $\alpha''\gamma$ are n-cycles. Up to conjugation, we can assume that $\gamma = (u_1, \ldots, u_n)$. Moreover, it is not restrictive to assume that $u_1, \ldots, u_n$ appear in this order in the d-cycle $\alpha'\beta$. Therefore, setting $\alpha = \alpha''\alpha'$, we have that

$$\alpha\beta = (\alpha''\gamma)\gamma^{-1}(\alpha'\beta);$$

by lemma 2.4, this implies that $\alpha\beta$ has the same number of cycles as $\alpha''\gamma \in \mathfrak{S}(\{u_1, \ldots, u_n\})$, that is $v(\alpha\beta) = d - (k+1)$. Since $[\alpha] = \pi$ and $[\beta] = \rho$, the proof is complete. $\qquad\square$

Remark 2.1. Write $\pi = [a_1, \ldots, a_r]$, $\rho = [b_1, \ldots, b_s]$; assume that $b_1 \geq 2$. By directly examining the proof of proposition 2.6. As a consequence, its statement can be enhanced by adding the following line: *α and β can be chosen in such a way that 1 belongs to the a_1-cycle of α and to the b_1-cycle of β, provided that $b_1 \geq 2$.* We will need this improvement for the upcoming proof.

Proposition 2.7. *Let $\pi, \rho \in \Pi(d)$ be partitions of d. Assume that $v(\pi) + v(\rho) \geq d$ and $v(\pi) + v(\rho) \equiv d \pmod 2$. Then there exist permutations $\alpha, \beta \in \mathfrak{S}_d$ with $[\alpha] = \pi$ and $[\beta] = \rho$ such that $\langle \alpha, \beta \rangle$ acts transitively on $\{1, \ldots, d\}$ and*

$$[\alpha\beta] = \begin{cases} [d/2, d/2] & \text{if } \pi = \rho = [2, \ldots, 2], \\ [1, d-1] & \text{otherwise.} \end{cases}$$

Proof. Assume first that $\pi = \rho = [2, \ldots, d]$. We can choose

$$\alpha = (2,3)(4,5)\cdots(d,1), \qquad\qquad \beta = (1,2)(3,4)\cdots(d-1,d).$$

The action of $\langle \alpha, \beta \rangle$ is obviously transitive, and

$$\alpha\beta = (1, 3, \ldots, d-1)(2, 4, \ldots, 2).$$

Otherwise, since $v(\pi) + v(\rho) \geq d$, at least one of π and ρ has an entry which is greater than 2; without loss of generality, we can assume it is ρ. Write $\pi = [a_1, \ldots, a_r]$, $\rho = [b_1, \ldots, b_s]$ with $a_1 \geq 2$ (since $v(\pi) \geq 1$) and $b_1 \geq 3$. Fix

$$\beta = (1, \ldots, d_1)(d_1 + 1, \ldots, d_2)\cdots(d_{s-1} + 1, \ldots, d_s),$$

where $b_1 = d_1 \geq 3$, $b_i = d_i - d_{i-1}$ for $2 \leq i \leq s$ (in particular, $d_s = d$). Consider the partitions

$$\pi' = [a_1 - 1, \ldots, a_r], \qquad\qquad \rho' = [b_1 - 1, \ldots, b_s].$$

Since $\sum \pi' = \sum \rho' = d - 1$ and $v(\pi') + v(\rho') = v(\pi) + v(\rho) - 2$, by proposition 2.6 we can find permutations $\alpha', \beta' \in \mathfrak{S}(\{2, \ldots, d\})$ with $[\alpha'] = \pi'$ and $[\beta'] = \rho'$ such that $\alpha'\beta'$ is a $(d-1)$-cycle. Up to conjugation, we can assume that

$$\beta' = (2, \ldots, d_1)(d_1 + 1, \ldots, d_2) \cdots (d_{s-1} + 1, \ldots, d_s)$$

or, in other words, $\beta = (1,2)\beta'$; moreover, as explained in remark 2.1, we can choose α' in such a way that its $(a_1 - 1)$-cycle contains 2. By setting $\alpha = \alpha'(1,2)$, we immediately get that $\alpha\beta = \alpha'\beta'$ is a $(d-1)$-cycle fixing 1. Finally, the action of $\langle \alpha, \beta \rangle$ is transitive since α does not fix 1. $\qquad\square$

The following result sums up the statements of propositions 2.6 and 2.7, at the cost of some generality. However, for many of the upcoming applications, it will be more than enough.

Corollary 2.8. *Let $\pi, \rho \in \Pi(d)$ be partitions of d. Assume that $v(\pi) + v(\rho) \geq d - 1$. Then there exist permutations $\alpha, \beta \in \mathfrak{S}_d$ with $[\alpha] = \pi$ and $[\beta] = \rho$ such that $\langle \alpha, \beta \rangle$ acts transitively on $\{1, \ldots, d\}$ and*

$$[\alpha\beta] \in \{[d], [1, d-1], [d/2, d/2]\}.$$

Proof. The conclusion follows immediately from proposition 2.6 or proposition 2.7 depending on the parity of $v(\pi) + v(\rho) + d$. $\qquad\square$

2.3 Projective plane

As a first application of the results established in the previous section, we fully solve the Hurwitz existence problem in the cases where $\Sigma = \mathbb{RP}^2$ and $\widetilde{\Sigma}$ is non-orientable.

Theorem 2.9. *Let $\mathcal{D} = (\widetilde{\Sigma}, \mathbb{RP}^2; d; \pi_1, \ldots, \pi_n)$ be a candidate datum. If $\widetilde{\Sigma}$ is non-orientable, then $\mathcal{D}$ is realizable.*

Proof. First of all, since $\mathcal{D}$ is a candidate datum, the Riemann-Hurwitz formula implies that

$$v(\pi_1) + \ldots + v(\pi_n) = d\chi(\mathbb{RP}^2) - \chi(\widetilde{\Sigma}) \geq d - 1$$

(recall that $\widetilde{\Sigma}$ is non-orientable, so $\chi(\widetilde{\Sigma}) \leq 1$). Moreover, the total branching $v(\pi_1) + \ldots + v(\pi_n)$ is even. In order to apply corollary 1.8, we will now inductively define permutations $\alpha_i \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$, satisfying the following invariant: for every $0 \leq i \leq n$, either

$$v(\alpha_1 \cdots \alpha_i) = v(\pi_1) + \ldots + v(\pi_i)$$

or

$$[\alpha_1 \cdots \alpha_i] \in \{[d], [1, d-1], [d/2, d/2]\} \text{ and } \langle \alpha_1, \ldots, \alpha_i \rangle \text{ acts transitively.}$$

Assume we have already defined $\alpha_1, \ldots, \alpha_{i-1}$; we want to suitably choose α_i. Let $\alpha = \alpha_1 \cdots \alpha_{i-1}$; there are two cases.

- ♦ If $v(\alpha) + v(\pi_i) < d$, by proposition 2.5 we can find $\alpha_i \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$ such that $v(\alpha\alpha_i) = v(\alpha) + v(\alpha_i)$. The invariant is still satisfied: if $v(\alpha) = v(\pi_1) + \ldots + v(\pi_{i-1})$ then obviously $v(\alpha\alpha_i) = v(\pi_1) + \ldots + v(\pi_i)$. If instead $[\alpha] \in \{[d], [1, d-1], [d/2, d/2]\}$, then either α_i is the identity, or $\alpha\alpha_i$ is a d-cycle; either way, $[\alpha\alpha_i] \in \{[d], [1, d-1], [d/2, d/2]\}$. Note that if the action of $\langle \alpha_1, \ldots, \alpha_{i-1} \rangle$ is transitive, then the action of $\langle \alpha_1, \ldots, \alpha_i \rangle$ is transitive as well.

- If $v(\alpha) + v(\alpha_i) \geq d$, corollary 2.8 gives a permutation $\alpha_i \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$ such that $[\alpha\alpha_i] \in \{[d], [1, d-1], [d/2, d/2]\}$ and the action of $\langle \alpha, \alpha_i \rangle$ is transitive. The invariant is obviously satisfied.

By induction, we can find $\alpha_1, \ldots, \alpha_n \in \mathfrak{S}_d$ with $[\alpha_i] = \pi_i$ such that

$$[\alpha_1 \cdots \alpha_n] \in \{[d], [1, d-1], [d/2, d/2]\}$$

and $\langle \alpha_1, \ldots, \alpha_n \rangle$ acts transitively on $\{1, \ldots, d\}$ (note that $v(\alpha_1 \cdots \alpha_n) = v(\alpha_1) + \ldots + v(\alpha_n)$ also implies that $[\alpha_1 \cdots \alpha_n] = [d]$). By proposition 1.3 we have that

$$v(\alpha_1 \cdots \alpha_n) \equiv v(\alpha_1) + \ldots + v(\alpha_n) \equiv 0 \pmod 2.$$

We now prove that $\alpha = \alpha_1 \cdots \alpha_n$ is a square.

- If $[\alpha] = [d]$, then d is odd, so α is the square of $\alpha^{(d+1)/2}$.

- If $[\alpha] = [1, d-1]$, then d is even, so α is the square of $\alpha^{d/2}$.

- If $[\alpha] = [d/2, d/2]$, then d is even, and it is easy to see that α is the square of a d-cycle.

In any case, we obtain a permutations $\beta_1 \in \mathfrak{S}_d$ such that $\alpha = \beta_1^{-2}$ By corollary 1.8, this implies that there exists a realizable candidate datum $\mathcal{D}' = (\widetilde{\Sigma}', \mathbb{RP}^2; d; \pi_1, \ldots, \pi_n)$. To see that $\widetilde{\Sigma}'$ is non-orientable (and, therefore, equal to $\widetilde{\Sigma}$, as shown in remark 1.3), simply note that there exists a permutation $\gamma \in \langle \alpha_1, \ldots, \alpha_n \rangle$ such that $\gamma\beta_1$ has a fixed point, since $\langle \alpha_1, \ldots, \alpha_n \rangle$ acts transitively on $\{1, \ldots, d\}$. $\square$

2.4   Combinatorial moves

With theorems 2.3 and 2.9, we have shown that every candidate datum $\mathcal{D} = (\widetilde{\Sigma}, \Sigma; d; \pi_1, \ldots, \pi_n)$ is realizable whenever

- $\chi(\Sigma) \leq 0$, or

- $\Sigma = \mathbb{RP}^2$ and $\widetilde{\Sigma}$ is non-orientable.

Moreover, proposition 1.9 shows that the cases where $\Sigma = \mathbb{RP}^2$ and $\widetilde{\Sigma}$ is orientable can be reduced to the analysis of realizable candidate data on the sphere. As a consequence, it stands to reason that, from now on, we will only be concerned with candidate data where $\Sigma = S^2$; in fact, a classification of the realizable data of this kind would lead to a full solution of the Hurwitz existence problem. However, we will soon find out that realizability on the sphere can be a very delicate matter: there are several seemingly unrelated families of exceptional data, and even to this day we are still far from a complete understanding of the problem.

Since, from now on, we will only deal with branched coverings on the sphere, we adopt the following convention: whenever we have a combinatorial datum $\mathcal{D} = (\Sigma_g, S^2; d; \pi_1, \ldots \pi_n)$, we can omit the S^2 and simply write $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots \pi_n)$.

For convenience, we will now briefly discuss once and for all the cases where $n \leq 2$.

- If $n = 1$, corollary 1.7 immediately implies that every candidate datum $\mathcal{D} = (\Sigma_g; d; \pi_1)$ is not realizable (recall that we are always assuming $\pi_1 \neq [1, \ldots, 1]$).

- If $n = 2$, the only realizable candidate data are of the form $\mathcal{D} = (S^2; d; [d], [d])$, again by corollary 1.7.

be fair, even after
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$= \mathbb{RP}^2$ and $\widetilde{\Sigma}$ ori-
table could still be
n-trivial.

Finally, we turn to the topic promised by the title of this section. *Combinatorial moves* are conceptually trivial things, but they offer a convenient framework for presenting proofs based on a reduction technique. The definition is extremely simple.

Really?

Definition 2.1. Let $\mathcal{D}, \mathcal{D}'$ be combinatorial data. We say that there is a *combinatorial move* between them, and we write $\mathcal{D} \rightsquigarrow \mathcal{D}'$, if the realizability of $\mathcal{D}'$ implies that $\mathcal{D}$ is realizable as well.

In this thesis we will encounter two kinds of combinatorial moves. The first one, which we introduce in this section, focuses on reducing the number of partitions of a combinatorial datum by means of products in the symmetric group. In **??**, we will describe another kind of combinatorial moves, which relies instead on topological constructions to reduce the genus of the surface $\widetilde{\Sigma}$.

Combinatorial move A.1. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, \ldots, \pi_n)$ be a candidate datum. Assume that $v(\pi_1) + v(\pi_2) \leq d - 1$. Then there exists a partition $\pi_1' \in \Pi(d)$ such that $v(\pi_1') = v(\pi_1) + v(\pi_2)$, $\mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, \ldots, \pi_n)$ is a candidate datum and $\mathcal{D} \rightsquigarrow \mathcal{D}'$.*

Proof. By proposition 2.5, we can find permutations $\alpha_1, \alpha_2 \in \mathfrak{S}_d$ with $[\alpha_1] = \pi_1$ and $[\alpha_2] = \pi_2$ such that $v(\alpha_1 \alpha_2) = v(\pi_1) + v(\pi_2)$. Let $\pi_1' = [\alpha_1 \alpha_2]$; it is easy to check that $\mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, \ldots, \pi_n)$ is a candidate datum. Assume that $\mathcal{D}'$ is realizable; by corollary 1.7, this implies the existence of permutations $\alpha_1', \alpha_3, \ldots, \alpha_n \in \mathfrak{S}_d$ matching $\pi_1', \pi_3, \ldots, \pi_n$ respectively, such that $\alpha_1' \alpha_3 \cdots \alpha_n = 1$ and $\langle \alpha_1', \alpha_3, \ldots, \alpha_n \rangle$ acts transitively on $\{1, \ldots, d\}$. Since $[\alpha_1'] = [\alpha_1 \alpha_2]$, up to conjugation we may assume that $\alpha_1' = \alpha_1 \alpha_2$. It is clear that the permutations $\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_n$ imply the realizability of $\mathcal{D}$, again by corollary 1.7 (see also remark 1.2). $\square$

Combinatorial move A.2. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, \ldots, \pi_n)$ be a candidate datum. Assume that:*

- $v(\pi_1) + v(\pi_2) \geq d - 1$;

- $v(\pi_3) + \ldots + v(\pi_n) \geq d - 1$.

Then there exist an orientable surface $\Sigma_{g'}$ and a partition $\pi_1' \in \Pi(d)$ such that $\mathcal{D}' = (\Sigma_{g'}; d; \pi_1', \pi_3, \ldots, \pi_n)$ is a candidate datum and $\mathcal{D} \rightsquigarrow \mathcal{D}'$. Moreover, if $\pi_1 = \pi_2 = [2, \ldots, 2]$ then π_1' can be chosen equal to $[d/2, d/2]$, otherwise it can be chosen in such a way that $\pi_1' \in \{[d], [1, d - 1]\}$.

Proof. By proposition 2.6 or proposition 2.7, depending on the parity of $v(\pi_1) + v(\pi_2) + d$, we can find permutations $\alpha_1, \alpha_2 \in \mathfrak{S}_d$ with $[\alpha_1] = \pi_1$ and $[\alpha_2] = \pi_2$ such that $[\alpha_1 \alpha_2] \in \{[d], [1, d-1], [d/2, d/2]\}$. More specifically, if $\pi_1 = \pi_2 = [2, \ldots, 2]$ we can assume that $[\alpha_1 \alpha_2] = [d/2, d/2]$, otherwise we can choose $[\alpha_1 \alpha_2] \in \{[d], [1, d-1]\}$. Let $\pi_1' = [\alpha_1 \alpha_2]$; if we want $\mathcal{D}' = (\Sigma_{g'}; d; \pi_1', \pi_3, \ldots, \pi_n)$ to be a candidate datum, the Riemann-Hurwitz formula requires that

$$g' = \frac{1}{2}(v(\pi_1') + v(\pi_3) + \ldots + v(\pi_n)) - d + 1.$$

But $v(\pi_1') \geq d - 2$ and $v(\pi_3) + \ldots + v(\pi_n) \geq d - 1$, so

$$v(\pi_1') + v(\pi_3) + \ldots + v(\pi_n) \geq 2d - 3.$$

Moreover, $v(\pi_1')$ and $v(\pi_1) + v(\pi_2)$ have the same parity, so $v(\pi_1') + v(\pi_3) + \ldots + v(\pi_n)$ is even and actually

$$v(\pi_1') + v(\pi_3) + \ldots + v(\pi_n) \geq 2d - 2.$$

Therefore g' is a non-negative integer, and $\mathcal{D}'$ is a candidate datum. The very same argument used in the proof of combinatorial move A.1 shows that $\mathcal{D} \rightsquigarrow \mathcal{D}'$. $\square$

2.5   Some results on the sphere

In this section, we will make extensive use of the combinatorial moves we have just described to solve the Hurwitz existence problem for some specific families of candidate data. As we have already discussed the realizability of candidate data with $n \leq 2$, from now on we will always assume that $n \geq 3$. We start by addressing the cases where one partition (without loss of generality, the last one) has length 1.

Proposition 2.10. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_{n-1}, [d])$ be a candidate datum. Then $\mathcal{D}$ is realizable.*

Proof. We proceed by induction on n, starting with the base case $n = 3$. If $\mathcal{D} = (\Sigma_g, S^2; d; \pi_1, \pi_2, [d])$ is a candidate datum, by the Riemann-Hurwitz formula we have that

$$v(\pi_1) + v(\pi_2) = 2d - 2 + 2g - (d - 1) \geq d - 1.$$

Moreover, the total branching number $v(\pi_1) + v(\pi_2) + d - 1$ is even. Proposition 2.6 then gives permutations $\alpha_1, \alpha_2 \in \mathfrak{S}_d$ with $[\alpha_1] = \pi_1$ and $[\alpha_2] = \pi_2$ such that $[\alpha_1 \alpha_2] = [d]$. By corollary 1.7, $\mathcal{D}$ is realizable (see remark 1.2).

We now turn to the case $n \geq 4$. Fix a candidate datum $\mathcal{D} = (\Sigma_g, S^2; d; \pi_1, \ldots, \pi_{n-1}, [d])$; there are two cases.

- Assume that $v(\pi_1) + v(\pi_2) \leq d - 1$. Combinatorial move A.1 gives

$$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, \ldots, \pi_{n-1}, [d])$$

  for a suitable candidate datum $\mathcal{D}'$. By induction, $\mathcal{D}'$ is realizable, therefore the same holds for $\mathcal{D}$.

- Otherwise, we have that $v(\pi_1) + v(\pi_2) \geq d$. Note that $v([d]) = d - 1$, so combinatorial move A.2 gives

$$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, \ldots, \pi_{n-1}, [d])$$

  for a suitable candidate datum $\mathcal{D}'$. Similarly to the previous case, this implies that $\mathcal{D}$ is realizable. $\square$

We now turn to candidate data containing the partition $[1, d-1]$. This is the first step towards the goal of this thesis, which will be further developed in **??**: the full classification of exceptional data containing a partition of length 2.

Proposition 2.11. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_{n-1}, [1, d - 1])$ be a candidate datum. Then $\mathcal{D}$ is non-realizable if and only if it satisfies one of the following.*

(1) $\mathcal{D} = (\Sigma_{n-3}; 4; [2, 2], \ldots, [2, 2], [1, 3])$.

(2) $\mathcal{D} = (S^2; 2k; [2, \ldots, 2], [2, \ldots, 2], [1, 2k - 1])$ with $k \geq 2$.

Proof. We proceed by induction on n, starting from the base case $n = 3$. Let

$$\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, [1, d - 1]) \neq (S^2; d; [2, \ldots, 2], [2, \ldots, 2], [1, d - 1])$$

be a candidate datum. The Riemann-Hurwitz formula implies that

$$v(\pi_1) + v(\pi_2) = 2d - 2 + 2g - (d - 2) \geq d.$$

Moreover, the total branching number $v(\pi_1) + v(\pi_2) + d - 2$ is even. Proposition 2.7 then gives permutations $\alpha_1, \alpha_2 \in \mathfrak{S}_d$ with $[\alpha_1] = \pi_1$ and $[\alpha_2] = \pi_2$ such that $[\alpha_1 \alpha_2] = [1, d-1]$ and the action of $\langle \alpha_1, \alpha_2 \rangle$ is transitive. As usual, corollary 1.7 implies that $\mathcal{D}$ is realizable.

We now turn to the case $n \geq 4$; we will employ a reduction technique, similar to the proof of proposition 2.10. Fix a candidate datum

$$\mathcal{D} = (\Sigma_{n-3}; d; \pi_1, \ldots, \pi_{n-1}, [1, d-1]) \neq (\Sigma_{n-3}; 4; [2, 2], \ldots, [2, 2], [1, 3]).$$

There are two cases.

- Assume that the inequality $v(\pi_i) + v(\pi_j) \leq d - 1$ holds for a pair of indices $1 \leq i < j \leq n-1$; up to reindexing, we can assume that $i = 1$ and $j = 2$. Combinatorial move A.1 gives

$$\mathcal{D} \rightsquigarrow\blacktriangleright \mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, \ldots, \pi_{n-1}, [1, d-1])$$

  for a suitable candidate datum $\mathcal{D}'$, where $v(\pi_1') = v(\pi_1) + v(\pi_2)$. By induction, $\mathcal{D}'$ is realizable unless one of the following happens.

  - $\mathcal{D}' = (S^2; 2k; [2, \ldots, 2], [2, \ldots, 2], [1, 2k-1])$ with $2k = d$. If this is the case, then $n = 4$, $g = 0$ and $v(\pi_1') = v(\pi_3) = k$. This implies that

  $$k < 1 + k \leq v(\pi_1) + v(\pi_3) < 2k = d.$$

  Repeating the construction with $i = 1$ and $j = 3$ will yield a realizable $\mathcal{D}'$.

  - $\mathcal{D}' = (\Sigma_{n-3}; 4; [2, 2], \ldots, [2, 2], [1, 3])$. This implies that $\pi_1 = \pi_2 = [1, 1, 2]$ and $\pi_3 = \ldots = \pi_{n-1} = [2, 2]$. Repeating the construction with $i = 1$ and $j = 3$ will yield a realizable $\mathcal{D}'$.

  Therefore we can assume that $\mathcal{D}'$ is realizable. Since $\mathcal{D} \rightsquigarrow\blacktriangleright \mathcal{D}'$, we have that $\mathcal{D}$ is realizable as well.

- Otherwise, the inequality $v(\pi_1) + v(\pi_j) \geq d$ holds for every $1 \leq i < j \leq n-1$. In particular, $v(\pi_1) + v(\pi_2) \geq d$ and $v(\pi_3) + v([1, d-1]) \geq d - 1$. Combinatorial move A.2 gives

$$\mathcal{D} \rightsquigarrow\blacktriangleright \mathcal{D}' = (\Sigma_{g'}; d; \pi_1', \pi_3, \ldots, \pi_{n-1}, [1, d-1])$$

  for a suitable candidate datum $\mathcal{D}'$, where $v(\pi_1') \geq d - 2$. Note that, if $d = 4$, we can assume that $\pi_1 \neq [2, 2]$; as remarked in the statement of combinatorial move A.2, this allows us to choose $\pi_1' \neq [2, 2]$. It is then easy to see that $\mathcal{D}'$ is realizable by induction: the case $d = 4$ was addressed just now, while $\mathcal{D}' = (S^2; d; [2, \ldots, 2], [2, \ldots, 2], [1, d-1])$ is impossible for $d \geq 6$ since

$$v(\pi_1') \geq d - 2 > \frac{d}{2} = v([2, \ldots, 2]).$$

  Since $\mathcal{D} \rightsquigarrow\blacktriangleright \mathcal{D}'$, this implies that $\mathcal{D}$ is realizable as well. $\qquad \square$

The next result we are going to prove does not have immediate applications to the study of candidate data with a short partition, but the theoretical consequences it provides are definitely interesting.

Proposition 2.12. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_n)$ be a candidate datum. Assume that $d \neq 4$ and that $2g \geq d - 1$. Then $\mathcal{D}$ is realizable.*

Proof. Note that the the condition $2g \geq d - 1$ is equivalent to

$$v(\pi_1) + \ldots + v(\pi_n) \geq 3d - 3$$

by the Riemann-Hurwitz formula. Moreover, the cases where $d = 2$ are trivial because of proposition 2.10; therefore, assume that $d \geq 3$.

We proceed by induction, starting from the base case $n = 3$. If $n = 3$, the inequality $v(\pi_1) + v(\pi_2) + v(\pi_3) \geq 3d - 3$ implies that $\pi_1 = \pi_2 = \pi_3 = [d]$; by proposition 2.10, $\mathcal{D}$ is then realizable.

We now turn to the case $n \geq 4$; we will once again employ a reduction technique. Fix a candidate datum $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_n)$. We can assume that $\pi_i \neq [d]$ for every $1 \leq i \leq n$, otherwise $\mathcal{D}$ is immediately realizable by proposition 2.10. There are two cases.

- Assume that the inequality $v(\pi_i) + v(\pi_j) \leq d - 1$ holds for a pair of indices $1 \leq i < j \leq n$. It is now routine to employ combinatorial move A.1 to show that $\mathcal{D}$ is realizable by induction.

- Otherwise, we have $v(\pi_i) + v(\pi_j) \geq d$ for every $1 \leq i < j \leq n$. We consider two sub-cases.

  - Assume first that there is a partition, say π_1, which is different from $[2, \ldots, 2]$. Combinatorial move A.1 gives

    $$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_{g'}; d; \pi_1', \pi_3, \ldots, \pi_n)$$

    for a suitable candidate datum $\mathcal{D}'$, where $\pi_1' \in \{[d], [1, d-1]\}$. By propositions 2.10 and 2.11, $\mathcal{D}'$ is realizable unless $\mathcal{D}' = (S^2; d; [2, \ldots, 2], [2, \ldots, 2], [1, d-1])$. If this were the case, we would have $n = 4$ and

    $$v(\pi_1) + v(\pi_2) + v(\pi_3) + v(\pi_4) \leq d - 2 + d - 2 + \frac{d}{2} + \frac{d}{2} = 3d - 4,$$

    which contradicts the hypothesis. Therefore $\mathcal{D}'$ is realizable, and the same holds for $\mathcal{D}$.

  - Finally, consider the case where $\pi_1 = \ldots = \pi_n = [2, \ldots, 2]$. In this situation $d = 2k \geq 6$ and
    $$v(\pi_1) + \ldots + v(\pi_n) = nk > 6k - 3$$

    (the inequality is strict since the total branching number is even, while $6k - 3$ is odd). Since $k \geq 3$, this immediately implies that $n \geq 6$. We have that $v(\pi_1) + v(\pi_2) = 2k$ and $v(\pi_3) + \ldots + v(\pi_n) = (n-2)k > 2k$, so we can apply combinatorial move A.2 to get
    $$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_{g'}; 2k; [k, k], \pi_3, \ldots, \pi_n)$$

    for a suitable candidate datum $\mathcal{D}'$. Now, $v([k, k]) + v(\pi_3) = 2k - 2 + k \geq 2k$ and $v(\pi_4) + \ldots + v(\pi_n) = (n-3)k > 2k$, so we can apply combinatorial move A.2 once again and find that

    $$\mathcal{D}' \rightsquigarrow \mathcal{D}'' = (\Sigma_{g''}; 2k; \pi_1'', \pi_4, \ldots, \pi_n)$$

    for a suitable candidate datum $\mathcal{D}''$, where $\pi_1'' \in \{[2k], [1, 2k-1]\}$. Since $n - 2 \geq 4$ and $2k \geq 6$, propositions 2.10 and 2.11 imply that $\mathcal{D}''$ is realizable. As a consequence, $\mathcal{D}$ is realizable as well. □

Corollary 2.13. *Let d be a positive integer with $d \neq 4$. Then there exist at most finitely many exceptional candidate data of the form $(\Sigma_g; d; \pi_1, \ldots, \pi_n)$.*

Proof. By proposition 2.12, every candidate datum with $n \geq 3d - 3$ is realizable, and there are a finite number of candidate data with $n < 3d - 3$. □

Instead, there exist infinitely many exceptional candidate data of degree 4.

Proposition 2.14. *Let $\mathcal{D} = (\Sigma_g; 4; \pi_1, \ldots, \pi_n)$ be a candidate datum. Then $\mathcal{D}$ is realizable if and only if*

$$\mathcal{D} \neq (\Sigma_{n-3}; 4; [2,2], \ldots, [2,2], [1,3]).$$

Proof. We proceed by induction, starting from the base case $n = 3$. Note that if any of the partitions is either $[4]$ or $[1,3]$, we immediately conclude by propositions 2.10 and 2.11. By the Riemann-Hurwitz formula, we have the inequality $v(\pi_1) + v(\pi_2) + v(\pi_3) \geq 6$; therefore, the only candidate datum left to consider is $(S^2; 4; [2,2], [2,2], [2,2])$. This datum is realizable, for instance, by choosing

$$\alpha_1 = (1,2)(3,4), \qquad \alpha_2 = (1,3)(2,4), \qquad \alpha_3 = (1,4)(2,3).$$

We now turn to the case $n \geq 4$; once again, we can assume that all the partitions are either $[1,1,2]$ or $[2,2]$. There are three cases.

- ♦ If all the partitions are equal to $[2,2]$, then we can apply combinatorial move A.2 to combine two partitions into a single $[2,2]$, and conclude by a reduction argument.

- ♦ If all the partitions are equal to $[1,1,2]$, then by the Riemann-Hurwitz formula we have $n \geq 6$. We can apply combinatorial move A.1 twice to combine three partitions into a single $[4]$, and conclude by reduction.

- ♦ Otherwise, there is at least one $[2,2]$ and one $[1,1,2]$; using combinatorial move A.1, we can combine them into a single $[4]$ and conclude by reduction. □

> Non-realizability will be addressed at some point.

2.6 Prime-degree conjecture

This section is devoted to a fascinating and surprising conjecture related to the Hurwitz existence problem. After studying many examples of exceptional data, a very unexpected pattern begins to emerge: it looks like no such datum can be found when the degree is a prime number. In other words, one comes to suspect the following.

Prime-degree conjecture. *Let p be a prime number. Then every candidate datum $(\Sigma_g; p; \pi_1, \ldots, \pi_n)$ with $n \geq 3$ is realizable.*

It is not immediately clear why prime numbers should be even remotely related to the realizability of candidate data. In fact, to the best of the author's knowledge, there is no number-theoretic argument in favor (or against) this conjecture; all the evidence gathered so far supporting the prime-degree conjecture is "experimental".

- ♦ As shown in **??**, for every composite number $d \geq 4$ there is an exceptional candidate datum of degree d.

- ♦ In general, all the exceptional data found so far have a composite degree; for all the families of candidate data whose realizability is completely understood (including those presented in the previous section), the prime-degree conjecture holds.

- The first efficient algorithmic approach to the Hurwitz existence problem was presented in [?]. Every candidate datum with $n = 3$ and $d \leq 20$ was analyzed by a computer, and no exceptional data with prime degree were found; therefore, the prime-degree conjecture was verified for degrees numbers up to 19 (see proposition 2.15 below). In **??**, with a much heavier computational effort, we extend this result to prime numbers up to 29.

Or $d \leq 22$, ac
some sources

The following proposition is an essential tool for the computational approach to the existence problem, since it reduces the verification of the prime-degree conjecture to the case of $n = 3$ partitions.

Proposition 2.15. *Let d be a positive integer. Assume that every candidate datum $(\Sigma_g; d; \pi_1, \pi_2, \pi_3)$ is realizable. Then every candidate datum $(\Sigma_g; d; \pi_1, \ldots, \pi_n)$ with $n \geq 3$ is realizable.*

Proof. We proceed by induction on $n \geq 4$, using the standard reduction technique. Fix a candidate datum $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_n)$; there are two cases.

- If there are two indices $1 \leq i < j \leq n$ such that $v(\pi_i) + v(\pi_j) \leq d - 1$, then a routine application of combinatorial move A.1 shows that $\mathcal{D}$ is realizable.

- Otherwise, $v(\pi_i) + v(\pi_j) \geq d$ for every $1 \leq i < j \leq n$. In particular, $v(\pi_1) + v(\pi_2) \geq d$ and $v(\pi_3) + \ldots + v(\pi_n) \geq d$. By applying combinatorial move A.2, it is easy to see that $\mathcal{D}$ is realizable. $\square$

Chapter 3

Dessins d'enfant

3.1 Child's drawings on surfaces

In section 2.4, we discussed how the Hurwitz existence problem can be reduced to the analysis of candidate data on the sphere. Moreover, thanks to combinatorial moves A.1 and A.2, we have devised a relatively reliable technique to decrease the number n of partitions; this technique was successfully employed in **??** to show the realizability of a wide variety of candidate data by induction on n, starting from the base case $n = 3$. Ignoring the cases where $n \leq 2$, which were fully analyzed in section 2.4, it should come as no surprise that candidate data with $n = 3$ play a very important role in the study of the existence problem.

Up to this point, we have only approached the Hurwitz existence problem from a group-theoretic point of view, showing realizability by looking for elements of $\mathfrak{S}_d$ with certain properties. In this section, we will present a totally different tool, of a more topological and combinatorial nature, for attacking the same problem. The concept of dessins d'enfant[1] was introduced by Grothendieck in [**?**], in a setting related to, but different from, the Hurwitz existence problem. *Dessins d'enfant* provide a strikingly elementary tool for showing the realizability of candidate data with $n = 3$ partitions, although they generalize quite nicely to the case $n \geq 4$. However, we will not deal with said generalization, since the reduction technique will prove to be sufficient for our purposes; we refer the interested reader to [**?**].

We start by introducing some basic terminology about graphs. Given a surface Σ, a *graph* embedded in Σ (or, simply, a graph on Σ) is a closed subspace $\Gamma \subseteq \Sigma$ consisting of:

- Ꙭ a finite number of points $x_1, \ldots, x_r \in \Sigma$, called *vertices*;

- Ꙭ a finite number of segments (subspaces homeomorphic to $[0, 1]$) $e_1, \ldots, e_d \subseteq \Sigma$, called *edges*; we require that each edge connects two (not necessarily distinct) vertices, and that the interiors of two edges are disjoint; in other words, two edges may intersect at most at their endpoints; moreover, a vertex cannot lie on the interior of an edge.

The *degree* of a vertex x is the number of edges having x as an endpoint; edges connecting x to itself are counted twice; we denote the degree of x by $k(x)$. In order to avoid unpleasant corner cases, we will always require that there are no *isolated vertices* or, in other words, that $k(x) \geq 1$ for every vertex x.

A *bipartite graph* is a graph whose vertices are colored either black or white, and each edge connects a black vertex and a white one. If we denote the black vertices by $x_1, \ldots, x_r$ and the

---

[1] *"Dessin d'enfant"* is French for "child's drawing", hence the title of this section.

white vertices by $y_1, \ldots, y_s$, an easy counting argument shows that

$$k(x_1) + \ldots + k(x_r) = k(y_1) + \ldots + k(y_s) = d,$$

where d is the number of edges.

Given a graph Γ on a surface Σ, the space $\Sigma \smallsetminus \Gamma$ is a disjoint union of a finite number of non-compact surfaces $S_1 \sqcup \ldots \sqcup S_h$. Fix one of these *complementary regions*, say S_i. By traveling along its boundary, always keeping S_i to the left, we get a cyclic sequence of edges of Γ, which we call *combinatorial boundary* of S_i, and denote by ∂S_i. Note that the same edge can be traveled along twice, once for each direction; in this case, it will appear twice in ∂S_i. The number of edges (with multiplicity) of ∂S_i is the *perimeter* of S_i, denoted by $|\partial S_i|$. Again, an easy counting argument shows that

$$|\partial S_1| + \ldots + |\partial S_h| = 2d.$$

We are finally ready to give the definition of the much anticipated *dessins d'enfant*.

Definition 3.1. Let Σ be a surface. A dessin d'enfant on Σ is a bipartite graph $\Gamma \subseteq \Sigma$ whose complementary regions are topological disks.

If Γ is a *dessin d'enfant* on Σ (or, actually, any bipartite graph), it is easy to see that the perimeters of its complementary regions are even: in fact, when traveling along the boundary of a region, we alternately encounter black and white vertices, so an even number of edges is required to get back to the starting color.

Definition 3.2. Let Γ be a *dessin d'enfant* on a surface Σ; let d be the number of edges. Let $x_1, \ldots, x_r$ be the black vertices, $y_1, \ldots, y_s$ the white ones. Denote by $D_1, \ldots, D_h$ be the complementary regions of Γ. The *branching datum* of Γ is the tuple

$$\mathcal{D}(\Gamma) = (\Sigma, S^2; d; [k(x_1), \ldots, k(x_r)], [k(y_1), \ldots, k(y_s)], [|\partial D_1|/2, \ldots, |\partial D_h|/2]).$$

From the discussion above, we immediately see that $\mathcal{D}(\Gamma)$ is a combinatorial datum, since

$$k(x_1) + \ldots + k(x_r) = k(y_1) + \ldots + k(y_s) = |\partial D_1|/2 + \ldots + |\partial D_h|/2 = d.$$

Actually, if Σ is orientable, $\mathcal{D}(\Gamma)$ is a candidate datum: by the Euler formula,

$$\chi(\Sigma) = r + s - d + h = 2d - v(\pi_1) - v(\pi_2) - v(\pi_3),$$

where $\pi_1 = [k(x_1), \ldots, k(x_r)]$, $\pi_2 = [k(y_1), \ldots, k(y_s)]$ and $\pi_3 = [|\partial D_1|/2, \ldots, |\partial D_h|/2]$. This is no coincidence, just like the name "branching datum of Γ" was not picked at random: the following result establishes a strong connection between *dessins d'enfant* and realizable combinatorial data.

Proposition 3.1. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, \pi_3)$ be a combinatorial datum. Then $\mathcal{D}$ is realizable if and only if there exists a* dessin d'enfant *$\Gamma \subseteq \Sigma_g$ with $\mathcal{D}(\Gamma) = \mathcal{D}$.*

Proof. Assume that $\mathcal{D}$ is realized by a branched covering $f \colon \Sigma_g \to S^2$. Let $\{\widetilde{x}_1, \ldots, \widetilde{x}_r\} = f^{-1}(x)$, $\{\widetilde{y}_1, \ldots, \widetilde{y}_s\} = f^{-1}(y)$, $\{\widetilde{z}_1, \ldots, \widetilde{z}_h\} = f^{-1}(z)$. Fix a segment $e \subseteq S^2$ connecting x and y; we claim that $\Gamma = f^{-1}(e)$ is the desired *dessin d'enfant*. Let $\mathring{e}$ be the interior of e (that is, $\mathring{e} = e \smallsetminus \{x, y\}$). First of all, note that $f^{-1}(\mathring{e})$ is the disjoint union of d open segments $\mathring{e}_1, \ldots, \mathring{e}_d$, since the restriction of f to $S^2 \smallsetminus \{x, y, z\}$ is a covering map of degree d. Moreover, it is easy to see that the closure of each $\mathring{e}_i$ is a closed segment e_i connecting one point in $f^{-1}(x)$ and one point of $f^{-1}(y)$; it follows that Γ is a bipartite graph on Σ_g, with black vertices $\widetilde{x}_1, \ldots, \widetilde{x}_r$ and white vertices $\widetilde{y}_1, \ldots, \widetilde{y}_s$. Consider a vertex $\widetilde{x}_i$; recall that f is locally modeled on the complex map $\xi \mapsto \xi^k$,

where $k = k(\widetilde{x}_i)$ is the local degree of $\widetilde{x}_i$. As a consequence, we immediately see that there are exactly $k(\widetilde{x}_i)$ edges of Γ with $\widetilde{x}_i$ as an endpoint; of course, the same holds for every $\widetilde{y}_j$. Finally, we turn to the complementary regions of Γ. Let $D = S^2 \smallsetminus e \simeq \mathbb{R}^2$, $D^\bullet = D \smallsetminus \{z\} \simeq \mathbb{R}^2 \smallsetminus \{0\}$. The restriction of f to $f^{-1}(D^\bullet) = \Sigma_g \smallsetminus (\Gamma \cup \{\widetilde{z}_1, \ldots, \widetilde{z}_h\})$ is a covering map of the punctured disk $D^\bullet$. It is then easy to see that the complementary regions of Γ are discs $\widetilde{D}_1, \ldots, \widetilde{D}_h$, with $\widetilde{z}_i \in \widetilde{D}_i$ for each $1 \leq i \leq h$, and that the restriction $f \colon \widetilde{D}_i \to D$ is modeled the complex map $\xi \mapsto \xi^{k(\widetilde{z}_i)}$. Since the perimeter of D is 2, we have that $|\partial \widetilde{D}_i| = 2k(\widetilde{z}_i)$; this concludes the proof of the equality $\mathcal{D}(f) = \mathcal{D}(\Gamma)$.

Conversely, assume that we are given a *dessin d'enfant* $\Gamma \subseteq \Sigma_g$ with $\mathcal{D}(\Gamma) = \mathcal{D}$. Fix three arbitrary points $x, y, z \in S^2$, and let $e \subseteq S^2$ be a segment connecting x and y. First of all, we define f on Γ, sending black vertices to x and white vertices to y, and mapping edges homeomorphically to e. Extending f to all of Σ_g is a relatively easy task: here are the details. Consider the standard closed disk $K = \{a \in \mathbb{R}^2 : \|a\| \leq 1\}$, and take a complementary region $\widetilde{D} \subseteq \Sigma_g$; let $\varphi \colon K \to \Sigma_g$ be a continuous map which restricts to a homeomorphism $\varphi \colon \mathring{K} \to \widetilde{D}$, where $\mathring{K}$ denotes the interior of K. There exists a map $\psi \colon K \to S^2$ such that $\psi(0) = z$, the diagram

> Picture much needed.

$$
\begin{array}{ccc}
\partial K & & \\
\Big\downarrow{\scriptstyle \varphi} & \overset{\psi}{\searrow} & \\
\Gamma & \xrightarrow{\ f\ } & e
\end{array}
$$

commutes, ψ is a local homeomorphism in $\mathring{K} \smallsetminus \{0\}$ and it is modeled on $\xi \mapsto \xi^k$ in a neighborhood of $0 \in K$; in particular k will necessarily be equal to half the perimeter of $\widetilde{D}$. We can now extend f to $\widetilde{D}$ by setting $f(\widetilde{x}) = \psi(\varphi^{-1}(\widetilde{x}))$ for every $\widetilde{x} \in \widetilde{D}$. After repeating the process for all the complementary regions, it is not hard to verify that the map $f \colon \widetilde{\Sigma} \to S^2$ we have obtained is a branched covering with branching points $x, y, z \in S^2$. Since $\Gamma = f^{-1}(e)$, the first part of the proof implies that $\mathcal{D}(\Gamma) = \mathcal{D}(f)$. $\qquad\square$

> Namely, $\Rightarrow$.

Chapter 4

Exceptional data with a short partition

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4.1 Realizability on the sphere

Theorem 4.1. *Let* $\mathcal{D} = (S^2; d; \pi_1, \pi_2, [s, d-s])$ *be a candidate datum. Then* $\mathcal{D}$ *is realizable unless it satisfies one of the following.*

(1) $\mathcal{D} = (S^2; 12; [2, 2, 2, 2, 2, 2], [1, 1, 1, 3, 3, 3], [6, 6])$.

(2) $\mathcal{D} = (S^2; 2k; [2, \ldots, 2], [2, \ldots, 2], [s, 2k - s])$ *with* $k \geq 2$, $s \neq k$.

(3) $\mathcal{D} = (S^2; 2k; [2, \ldots, 2], [1, 2, \ldots, 2, 3], [k, k])$ *with* $k \geq 2$.

(4) $\mathcal{D} = (S^2; 4k + 2; [2, \ldots, 2], [1, \ldots, 1, k + 1, k + 2], [2k + 1, 2k + 1])$ *with* $k \geq 1$.

(5) $\mathcal{D} = (S^2; 4k; [2, \ldots, 2], [1, \ldots, 1, k + 1, k + 1], [2k - 1, 2k + 1])$ *with* $k \geq 2$.

(6) $\mathcal{D} = (S^2; kh; [h, \ldots, h], [1, \ldots, 1, k + 1], [lk, (h - l)k])$ *with* $h \geq 2$, $k \geq 2$, $1 \leq l \leq h - 1$.

Theorem 4.2. *Let* $\mathcal{D} = (S^2; d; \pi_1, \ldots, \pi_{n-1}, [s, d - s])$ *be a candidate datum with* $n \geq 4$. *Then* $\mathcal{D}$ *is realizable.*

4.2 Realizability on the torus for $n = 3$

Theorem 4.3. *Let* $\mathcal{D} = (\Sigma_1; d; \pi_1, \pi_2, [s, d - s])$ *be a candidate datum. Then* $\mathcal{D}$ *is realizable unless it satisfies one of the following.*

(1) $\mathcal{D} = (\Sigma_1; 6; [3, 3], [3, 3], [2, 4])$.

(2) $\mathcal{D} = (\Sigma_1; 8; [2, 2, 2, 2], [4, 4], [3, 5])$.

(3) $\mathcal{D} = (\Sigma_1; 12; [2, 2, 2, 2, 2, 2], [3, 3, 3, 3], [5, 7])$.

(4) $\mathcal{D} = (\Sigma_1; 16; [2, 2, 2, 2, 2, 2, 2, 2], [1, 3, 3, 3, 3, 3], [8, 8])$.

(5) $\mathcal{D} = (\Sigma_1; 2k; [2, \ldots, 2], [2, \ldots, 2, 3, 5], [k, k])$ *with* $k \geq 5$.

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4.3   Realizability on higher genus surfaces for $n = 3$

Theorem 4.4. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, [s, d - s])$ be a candidate datum with $g \geq 2$. Then $\mathcal{D}$ is realizable.*

4.4   Realizability for $n \geq 4$

Theorem 4.5. *Let $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_{n-1}, [s, d - s])$ be a candidate datum with $n \geq 4$. Then $\mathcal{D}$ is realizable unless it satisfies one of the following.*

(1) $\mathcal{D} = (\Sigma_{n-3}; 4; [2, 2], \ldots, [2, 2], [1, 3])$.

(2) $\mathcal{D} = (\Sigma_2; 8; [2, 2, 2, 2], [2, 2, 2, 2], [2, 2, 2, 2], [3, 5])$.

Proof. We will proceed by induction on n. We start with the base case $n = 4$, which requires the heaviest casework. Fix a candidate datum $\mathcal{D} = (\Sigma_g; d; \pi_1, \pi_2, \pi_3, [s, d - s])$.

- The only exceptional data are:

    (1) $\mathcal{D} = (\Sigma_1; 4; [2, 2], [2, 2], [2, 2], [1, 3])$;

    (2) $\mathcal{D} = (\Sigma_2; 8; [2, 2, 2, 2], [2, 2, 2, 2], [2, 2, 2, 2], [3, 5])$.

- If $g = 0$, then $\mathcal{D}$ is realizable by theorem 4.2.

- Assume that the inequality $v(\pi_i) + v(\pi_j) < d$ holds for a pair of indices $1 \leq i < j \leq 3$; up to reindexing, we can assume that $v(\pi_1) + v(\pi_2) < d$. Combinatorial move A.1 gives

$$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_g; d; \pi_1', \pi_3, [s, d - s])$$

for a suitable candidate datum $\mathcal{D}'$, where $v(\pi_1') = v(\pi_1) + v(\pi_2)$. If $g \geq 2$, then $\mathcal{D}'$ is realizable by theorem 4.4. If instead $g = 1$, then $\mathcal{D}'$ is realizable by theorem 4.3 unless

$$\mathcal{D}' = (\Sigma_1; 2k; [2, \ldots, 2], [2, \ldots, 2, 3, 5], [k, k]) \text{ with } 2k = d.$$

If this is the case, then $s = k$ and $\{\pi_1', \pi_3\} = \{[2, \ldots, 2], [2, \ldots, 2, 3, 5]\}$. Some more casework is required to show that $\mathcal{D}'$ can actually be chosen to be realizable; since $\mathcal{D} \rightsquigarrow \mathcal{D}'$, this will imply that $\mathcal{D}$ is realizable as well.

  - If $\pi_1' = [2, \ldots, 2]$, then $v(\pi_1') = k$ and $v(\pi_3) = k + 2$. Assume without loss of generality that $v(\pi_1) \leq k/2$. We have that

$$k + 2 < 1 + k + 2 \leq v(\pi_1) + v(\pi_3) \leq \frac{k}{2} + k + 2 < d.$$

  Repeating the construction with $i = 1$ and $j = 3$ will yield a realizable $\mathcal{D}'$.

  - If $\pi_3 = [2, \ldots, 2]$ and $v(\pi_1) \notin \{2, k, k + 1\}$ then $v(\pi_1) + v(\pi_3) < d$ and $v(\pi_1) + v(\pi_3) \notin \{k, k + 2\}$. Therefore, repeating the construction with $i = 1$ and $j = 3$ will yield a realizable $\mathcal{D}'$.

  - If $\pi_3 = [2, \ldots, 2]$, $v(\pi_1) = 2$ and $\pi_2 \neq [2, \ldots, 2]$, then repeating the construction with $i = 1$ and $j = 3$ will yield a realizable $\mathcal{D}'$.

♦ If $\pi_2 = \pi_3 = [2, \ldots, 2]$, we follow a different approach. By applying combinatorial move A.2 to the partitions π_2 and π_3 we get

$$\mathcal{D} \rightsquigarrow \mathcal{D}'' = (S^2; d; \pi_1, [k,k], [k,k]).$$

But $\mathcal{D}''$ is realizable by theorem 4.1, so $\mathcal{D}$ is realizable as well.

Up to swapping π_1 and π_2, this analysis covers all the possible cases.

♦ Otherwise, the inequality $v(\pi_i) + v(\pi_j) \geq d$ holds for every $1 \leq i < j \leq 3$. In particular, up to reindexing, we can assume that $v(\pi_3) \geq d/2$. Note that $v(\pi_1) + v(\pi_2) \geq d$ and $v(\pi_3) + v([s, d-s]) \geq 1 + d - 2 = d - 1$, so combinatorial move A.2 gives

$$\mathcal{D} \rightsquigarrow \mathcal{D}' = (\Sigma_{g'}; d; \pi_1', \pi_3, [s, d-s])$$

for a suitable candidate datum $\mathcal{D}'$, where $v(\pi_1') \geq d - 2$. We can actually compute

$$g' = \frac{1}{2}(v(\pi_1') + v(\pi_3) + v([s, d-s]) - d + 1 \geq \frac{1}{2}\left(d - 2 + \frac{d}{2} + d - 2\right) - d + 1 = \frac{d}{4} - 1 \geq 2.$$

Therefore $\mathcal{D}'$ is realizable by theorem 4.4, and $\mathcal{D}$ is realizable as well.

We now turn to the case $n \geq 5$; we show by induction that every candidate datum $\mathcal{D} = (\Sigma_g; d; \pi_1, \ldots, \pi_{n-1}, [s, d-s])$ different from $(\Sigma_{n-3}; 4; [2,2], \ldots, [2,2], [1,3])$ is realizable. The case $d = 4$ is addressed by proposition 2.14. If $n = 5$ and $d = 8$, a computer-aided search shows that $\mathcal{D}$ is realizable. Otherwise, the routine reduction argument relying on combinatorial moves A.1 and A.2 shows that $\mathcal{D}$ is realizable. □