Monodromy, $\ell$-adic Representations

&

the Regular Inverse Galois Problem

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Abstract. Since Abel and Galois, modular curves have always joined algebra and complex analysis. Since 1960, strongly in two considerations: Serre’s Open Image Theorem (OIT); and the Shimura-Taniyama-Weil Conjecture that postulated a formula by which an elliptic curve over \( \mathbb{Q} \) (of given conductor) might be uniformized by a modular curve whose upper half plane quotient was defined by a specific congruence subgroup of \( SL_2(\mathbb{Z}) \). There were some small accidents with modular curves producing new groups as Galois groups over \( \mathbb{Q} \), but not regularly. So, there was no general relation between \( \ell \)-adic representations, say as in generalizing Serre’s OIT, and the Regular version of the Inverse Galois Problem that came together over generalizing modular curves.

Ch. 1 and Ch. 2 tie up threads that came just before Modular Towers (MTs). They show how Hurwitz spaces encode versions of the Inverse Galois Problem. Also, by geometrically connecting with classical problems, why the Inverse Galois Problem has been so difficult. We modernize our approach to investigating moduli (definition) fields of Hurwitz space components vis-a-vis lift invariants with examples.

Ch. 3 joins the first third and last third of the book in a new approach to the lift invariant and Hurwitz space components based on the universal Frattini cover of a finite group, the main ingredient behind MTs.

Ch. 4 explains MTs – started in 1995 – as a program giving such a relationship. We use that to interpret the OIT in a generality not indicated by Serre’s approach. Ch. 5 uses one example, close to modular curves, that is clearly not of modular curves. This explains why our approach to (families of) covers of the projective line can handle a barrier noted by Grothendieck to generalizing the OIT.

Primary 11F32, 11G18, 11R58; Secondary 20B05, 20C25, 20D25, 20E18, 20F34

Moduli of covers, \( j \)-line covers, braid group and Hurwitz monodromy group, action on cohomology, Frattini and Spin covers, Lift invariants
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1. Traversing $\bar{\Gamma}_i$, $z_i$ and $z_{i+1}$ change places without meeting \hspace{1cm} 63
This book naturally divides into two parts of two chapters each, flanked by two chapters of a bridge nature. Part I: Hurwitz spaces and the Inverse Galois Problem, comprising Ch. 1 and Ch. 2. Both include much exposition and observations/examples we didn’t have time for in the original papers.

Then, Part II: Hurwitz Monodromy on \(\ell\)-adic representations and Modular Towers comprising Ch. 4 and Ch. 5. Most of Part II is new, but we will publish separately many of the proofs. Between these two parts lies the first bridge, Ch. 3, based on using Frattini covers of groups. It completes Part I, sliding it into the main issues in Part II, expanding territory untreated since the publication of \[FrV92\].

Ch. 1 and Ch. 2 show how Hurwitz spaces interpret problems that require understanding solutions to equations that relate two complex variables. The foremost relation is given by a compact Riemann surface \(W\) mapping to the Riemann sphere \(\mathbb{P}^1_z\) in a variable \(z: \varphi_W: W \rightarrow \mathbb{P}^1_z\). The foremost problem is the Regular Inverse Galois Problem, RIGP.

Interpreting diophantine problems assiduously uses the Galois closure, and its monodromy group, of such a cover. There have been papers with examples, where the two halves of the title

\[\text{[\ell\text{-adic representations]} \text{ and [the RIGP]}}\]

could be said to relate. Yet, we use generalizing Serre’s Open Image Theorem (OIT), a result about points on modular curves, to show that relation has not previously aimed at a fitting conclusion. The group theory of this extension depends on the universal \(\ell\)-Frattini cover of the finite group \(G\). The exposition on this topic is not found anywhere else. This device gives Modular Towers (MTs) whose tower levels generalize classical modular curve levels.

The definition of MT first appears in Ch. 3 Def. 3.3 as a tower of absolutely irreducible components of a sequence of Hurwitz spaces for which the base Hurwitz space is defined by group \(G\), a prime \(\ell\) dividing \(|G|\), and \(\ell'\) conjugacy classes \(C\) of \(G\). The main ingredient in forming the tower is a sequence of \(\ell\)-Frattini extensions of \(G\). Modulo testable conditions, the data \((G, C, \ell)\) produces a canonical, nonempty, tower of Hurwitz spaces.

The group for the data of each level is a cover \(\tilde{k}\tilde{\psi}: \tilde{k}G \rightarrow G\) with:

\[
\ker(\tilde{k}\tilde{\psi}) = (\mathbb{Z}/\ell^k)^\nu \text{ a } \mathbb{Z}/\ell^k[G] \text{ module; and } \\
\nu > 0 \text{ independent of } k, k \geq 0.
\]

(0.1)

For given \((G, \ell)\), Ch. 6 Prop. 1.7 describes a maximal (finite) \(\nu \overset{\text{def}}{=} \nu(G, \ell)_{\text{max}}\).

We state the the rubric for the typical case that \(G\) is \(\ell\)-perfect (has no \(\mathbb{Z}/\ell\) quotient) although circumstances and comparison with classical results sometimes require modification to include this case. The main point is that without excluding nontrivial nilpotent quotients of \(\tilde{k}G\), there won’t be a canonical construction.
For $\nu = \nu(G, \ell)_{\max}$, $(\mathbb{Z}/\ell^k)^{\nu}$ has these properties:

- It is an indecomposable $\mathbb{Z}/\ell^k[G]$ module;
- $k \psi$ is universal for covers of $G$ with abelian exponent $\ell^k$ kernel; and
- $\nu(G, \ell)_{\max} > 1$ except when $G$ is a slight generalization of dihedral.

(0.2b) The (Hurwitz) monodromy action arises on the $\mathbb{Z}_\ell[G]$ module kernels, $L_{G, \ell}$, of $\lim_{\kappa \to k} \ell^k G \to G$.

(0.2c) The action of (0.2b) identifies with an action on flags in $H_1(X_0, \mathbb{Z}_\ell)$ with $X_0$ a curve in the family.

Throughout the book we use the abbreviation RIGP for the sl Regular Inverse Galois Problem, and OIT for some version of the Open Image Theorem. Often, $\nu(G, \ell)_{\max}$ is the only possible value of $\nu$ ($>0$) in (0.1). Each possible value of $\nu$ presents its own challenges to the RIGP and the OIT. When $G$ is close to a dihedral or alternating group, points on tower levels include classical problems for both the RIGP and OIT. It is, though, the relation between them that is most interesting.

For a version of the OIT like Serre’s – including all modular curves – for us there are two collections of related groups,

$$\{D_\ell\}_{\text{primes } \ell} \text{ and } \{(\mathbb{Z}/\ell)^2 \times \mathbb{Z}/2\}_{\text{primes } \ell}.$$ 

For each group in each series, the conjugacy classes naturally extend from four repetitions of the non-trivial class in $\mathbb{Z}/2$.

To show how generalizing the OIT works, we use one example (in the sense that all modular curves are one example). Our example exhibits the features of Serre’s example, though our MT levels are not modular curves. A striking difference is the appearance of the lift invariant) among the levels of our MTs. At all times we note comparisons (cusps included) with modular curves. This approach circumvents a difficulty noted by Grothendieck – stemming from the many correspondences on Jacobians – for generalizing the full force of Serre’s OIT, Ch. 6 5.3. A reader can see this in following the Hurwitz monodromy approach to computing the monodromy action (Ch. 4) on the $\ell$-adic representations.

Before getting to the RIGP or OIT, we develop the basics of how Hurwitz spaces work. The first basic is to describe equivalence classes of covers associated to a group $G$ and conjugacy classes $C$ – whose elements generate $G$; we suppress these in this exposition – from which we produce a Hurwitz space $\mathcal{H}(G, C)$. The second basic is conditions that guarantee that any point on the Hurwitz spaces will produce a curve cover that solves the arithmetic problem for which we aim.

This comes together in the description of the moduli field $\mathbb{Q}_{G, C}$ of the Hurwitz space $\mathcal{H}(G, C)$. This depends on the equivalence class of covers representing those points, which in turn is fashioned toward the desired arithmetic problem. For a point
\( p \) on a Hurwitz space component \( \mathcal{H} \) to corresponds to a cover in the equivalence class represented by \( p \), its coordinates must generate over \( \mathbb{Q} \), \( \mathbb{Q}(p) \), a field containing the moduli field \( \mathbb{Q}_H \) of the Hurwitz space. Further, \( \mathcal{H} \) having \textit{fine moduli} then guarantees such a representing cover over \( \mathbb{Q}(p) \). The moduli field appears from the appropriate version of the \textit{Branch Cycle Lemma (BCL)}, Ch. 2 Lem. 4.1.\(^1\)

When, however, \( \mathcal{H} \) has more than one component, any given component, say \( \mathcal{H}' \), has its own moduli field \( \mathbb{Q}_{H'} \) containing \( \mathbb{Q}_{G,C} \). Further, often a treatment of it is similar to the \textbf{BCL} using a \textit{lift invariant}, a major topic in this book.

Ch. 6, has its own overview of the book. Material serves as appendices that enhance our examples. Note Ch. 6 §1.1.1: For permutation groups we usually use right actions, though occasionally concede to linear algebra matrix left action.

\(^1\)Called the Branch Cycle Argument on [Fr77, p. 62].
CHAPTER 1

Covers and monodromy groups

The key inputs for a cover of the Riemann sphere, \( \mathbb{P}^1 \), uniformized by a fixed complex variable \( z \), are a finite group \( G \) and a choice of its (unordered) conjugacy classes, \( \mathcal{C} = \{ C_1, \ldots, C_r \} \). We start slowly with the case \( W = \mathbb{P}^1_w \), as a reminder examples of such appeared in High School math classes.

From \((G, C)\) we form a Nielsen class, \( \text{Ni}(G, C) \); an equivalence on Nielsen class elements; and an action of the braid group (actually its quotient, the Hurwitz monodromy group, \( H_r \)) on \( r \)-strings (§2 and §3).

We can understand algebra and (complex) geometry coming together with one of the beginning formulas that connects the spaces of covers to the absolute Galois group of \( \mathbb{Q} \) through the Branch Cycle Lemma (BCL). Among its applications it gives the minimal definition (a precise cyclotomic field) of these spaces. That gives us the tools to introduce MTs, Ch. 4, and the \( \ell \)-adic representations they support.

Fundamental properties of the spaces come from braid group action on Nielsen classes. The first use is that Hurwitz space components correspond to the orbits of the action. While the Nielsen class of a cover is a strong invariant, when there is more than one component to a Hurwitz space – one cover will not deform into all other covers in the Nielsen class – there are often good explanations. The long history of applications to easily stated problems using the components of these spaces (and their definition fields) is not well known. We give many examples.

1. The Regular inverse Galois Problem

Assume \( K \subset \bar{\mathbb{Q}} \), the algebraic numbers, with \( G_K \) its absolute Galois group. §1.1 differentiates the Inverse Galois Problem from the RIGP. We cannot escape using some specific group theory for results, and for enriched examples. Our introduction to this is §1.2 which is sufficient to do many examples of split and none split extensions of groups we use to illustrate our main theorems. Then, §1.3 introduces the extreme extensions we call Frattini covers.

Our intention is to avoid interrupting our telling the relation between two stories – \( \ell \)-adic representations and the RIGP – that is the reason d’etre of this book. Therefore, some basics on Frattini covers continue in §1 along with other structural finite group theory.
1.1. The IGP vs the RIGP. A group $G$ is a Galois group over $K$, if $G$ is a quotient of $\mathcal{G}_K$: There exists an exact sequence $\psi: \mathcal{G}_K \to G \to 1$. We say, $K$ satisfies the IGP if this holds for all finite groups $G$. This isn’t known for any finite extension $K$ – a number field – of $\mathbb{Q}$. One aspect of Ch. 2 is to show you just how far from known it is, and how much that is related to many renown problems that don’t at first seem to have much to do with it.

Similarly, $G$ is a regular Galois group over $K$ if for each $G$,

there exists $\psi: \mathcal{G}_{K(x)} \to G \to 1$, with $(\text{the fixed field of } \ker(\psi)) \cap \bar{K} = K$.

The major success on the IGP has come through the RIGP for which the basic tools are versions of Riemann’s existence theorem followed by specialization (Hilbert’s irreducibility theorem). That is, an RIGP realization gives $\infty$-ly many independent realizations of $G$ as a quotient of $\mathcal{G}_\mathbb{Q}$. Constructing just one out of thin air doesn’t seem to work well, except for groups regarded as obvious in the history of group theory: abelian groups, $S_n$s and groups close to dihedral groups.

Mysteries for Rational functions?: Even for dihedral groups, there is a simple mystery connected to famous problems about modular curves (§5.1.3), whose description we can give naturally using rational functions in one variable. Applying serious Galois theory is wholly different than quoting the technical equivalences around its fundamental theorem. We illustrate with many examples.

Here $z$ indicates the complex variable from a 1st year graduate course. Changing from the High School $x$ to $w$ or $z$ just indicates we intend to plug in complex values. Each Hurwitz space is seeded by a finite group $G$ and $r \geq 3$ conjugacy classes $C$ of $G$. These indicate our concentration on the type of ramification of covers of the projective line $\mathbb{P}_z^1$. For the cycle type of an element $g \in S_n$, the symmetric group of degree $n$, a reasonable notation would be $(u_1)(u_2)\cdots(u_t)$, indicating that $g$ is a product of disjoint cycles of respective lengths $u_1,\ldots,u_t$.

For example, in $S_5$, $(5)$ indicates a disjoint cycle of length 5. This stipulates $g$ as a representative of the unique conjugacy class of 5-cycles in $S_5$. Yet, we can also regard a 5-cycle as an element of $A_5$, which has two (conjugacy) classes of 5-cycles, represented by $(1\ 2\ 3\ 4\ 5)$ and $(1\ 2\ 3\ 5\ 4)$.

For an example of a cover of compact Riemann surfaces, consider

$$f : \mathbb{P}_w^1 \to \mathbb{P}_z^1 \text{ by } f : w \mapsto \frac{w^3-1}{w^2+w+1} = \frac{f_2(w)}{f_1(w)},$$

with $f_1, f_2 \in \mathbb{C}[w]$. This might have appeared in a high school SAT exam, with this question: what is $f$ in lowest terms?

We would expect a student to see that the numerator and denominator have a common factor, and $f = w - 1$. The degree, $\deg(f)$, then is $\max(f_1, f_2)$, if they are in lowest terms. The correct value of $\deg(f)$ is 1.
The Hurwitz spaces $\mathcal{H}(G, C)$ appeared in [Fr77] along with the first applications of the BCL giving their precise moduli fields. We concentrate on how they are moduli spaces of equivalence classes of covers. For given $(G, C)$ there are several Hurwitz spaces, depending on our choice of equivalence between covers.

Yet, all equivalences (denote such here by †) have direct interpretation on the Nielsen class, $\text{Ni}(G, C)†$. Then the permutation representation of $H_r$ on $\text{Ni}(G, C)†$ produces $\mathcal{H}(G, C)†$ as a cover of $U_r$, projective $r$-space, $\mathbb{P}^r$, minus its discriminant locus. We use dihedral groups and alternating groups as running examples throughout the book.

Our example(s), §4.2 and §1.1, are handy in following this. The former is an exemplar continuing in several places, that starts with §2.7. That presents the absolute version as a space of rational function covers. Like in high school; as above, though not the ones you had in high school; those behind the scenes you had if you studied modular curves as in §4.2.

**A context for statements on the RIGP:** One should be suspicious, 120+ years after Hilbert’s formulation, that some magic – without considerable additional insight – might suddenly produce all groups as Galois groups over $\mathbb{Q}$. Generally, nilpotent $G$ (product of its $\ell$-Sylows) have been realized through the IGP, but mostly not at all through the RIGP. 

**Definition 1.1.** If a variable $\ell$, say, clearly indicates a prime, then the phrase $\ell'$, applied to any collection related to groups means that the collection consists of elements whose orders are prime to $\ell$.

**Definition 1.2 ($\ell$-perfect $G$).** Complementary to nilpotent is $\ell$-perfect:

$$\ell || G$$

but $\mathbb{Z}/\ell$ is not a quotient of $G$.

Then, $\ell'$ elements generate $G$. It is elementary that $\ell$-perfect for all $\ell || G$, is equivalent to $G$ is its own commutator subgroup $[G, G]$ (again, take its closure for the profinite case): $G$ is perfect.

Any nilpotent group $G$ for which $\ell || G$ has both a nontrivial $\ell$ center and a nontrivial $\mathbb{Z}/\ell$ quotient. While nilpotent groups naturally generalize abelian groups, because of their nontrivial centers, they don’t amend themselves to the Hurwitz space approach. Therefore, if we consider Hurwitz spaces based on them, a $\mathbb{Q}$ point on such a space doesn’t automatically give a regular realization.

This is as in Ch. 2 Thm. 1.7 whose proof uses the idea that for any $G$, we may form a cover $H \to G$ where $H$ has no center. Yet, $H$ will fail being $\ell$-perfect if $G$ fails to capture how we display and control the relation between the RIGP and $\ell$-adic representations. Key words for that put nilpotent groups on one side, and $\ell$-perfect – referencing a prime $\ell$ dividing the order of the group – on the other (§1.3).
is not $\ell$-perfect. Still, we may substitute $H$ for $G$ to assume $G$ has no center. Any regular realization of this new $G$ makes moot one for the old $G$.

One problem: Most finite groups require a different approach than anything akin to the finite group classification. For example, let us start from any group $G$, that is, say, $\ell$-perfect and centerless. Then, there exists $v(G) > 0$ (outside a slight generalization of dihedral groups, $>1$) giving the universal exponent $\ell^{k+1}$-Frattini extensions

$$((\mathbb{Z}/\ell^k)^{v(G)}) \rightarrow G$$

Even for $G = A_5$, and $\ell = 2$ where $v(G) = 5$ ($\S1.4$) for no $k > 0$ has any of these been realized over $\mathbb{Q}$, regularly or not.

**Problem 1.3 (Basic RIGP problem).** For a given centerless finite group $G$, and field $K$, what are the conjugacy classes $C$ for which there is a solution to the RIGP for $(G, C)$?

**Definition 1.4.** A standout case in Cor. 4.7 has

$$Q(G, C) = Q : C^n = C, \text{ for all } n \in (\mathbb{Z}/N_C)^* \text{ (2.42).}$$

We say $C$ is a rational union of conjugacy classes; it is necessary for an RIGP solution for $(G, C)$ to exist over $\mathbb{Q}$, with or without fine moduli.

If we take $K = \mathbb{Q}$, then we would be satisfied with an answer like this.

Consider distinct conjugacy classes $C'$ in $G$ that form a rational union (Def. 1.4). Assume $C$ runs over rational unions of conjugacy classes with support in $C'$.\(^2\) Must there be infinitely many such $C$ with a solution to the RIGP for $(G, C)$?

For a first engagement with this problem, consider this result with the hypotheses for $C'$ and $C$ above. There is a solution to the RIGP for $(G, C)$ for every PAC subfield of $\bar{\mathbb{Q}}$ precisely for those $C$ for which $\mathcal{H}(G, C)^{lin}$ has an absolutely irreducible $\mathbb{Q}$ component as a moduli space. This holds for all but finitely many $C$ satisfying this additional hypothesis:

(1.1) Each element of $C'$ appears in $C$ sufficiently often.

\(^2\)If $C$ is a rational union of classes, then the union of the distinct classes in $C$ is automatically a rational union since the definition applies to the underlying sets of elements.
Chevalley groups of arbitrary high rank, including \[ \text{Th90}, \text{Vo92}, \text{Vo94} \]. These all used versions of the braid group monodromy method producing explicit Hurwitz spaces with rational points from the technique behind Ch. 2 Thm. 1.7.

The A(bsolute)IGP: More often we seek regular extensions \( L/K(z) \) with Galois closure \( \hat{L}/K(z) \) where, with \( \hat{K} \) the constant field of \( \hat{L} \), \( G(\hat{L}/\hat{K}(z)) \) is \( G \). Then, \( G \) is the geometric monodromy group (of \( L/K(z) \)), a normal subgroup of the arithmetic monodromy \( \hat{G} = G(\hat{L}/\hat{K}(z)) \) (also, \( \leq S_n \)).

This is a \((G, \hat{G})\) realization. Finding such for some \( \hat{G} \) is the A(bsolute)IGP (we often care which \( \hat{G} \)s are achieved). For example, consider rational functions \( f \) over a number field \( K \) that have the Schur cover property of Prob. 1.5. Denote the residue class field of \( K \) at a prime \( p \) by \( F_p \).

**Problem 1.5.** Find pairs \((f, K)\) for which \( f : P^1_w(F_{pp}) \to P^1_z(F_{pp}) \) as a map is one-one for infinitely many primes \( p \) of \( K \).

We described the solution of this problem in [Fr17, §2.3.2] (based on [Fr78, §2] and [GuMS03]) as leading to the relation between absolute and inner Hurwitz spaces (Thm. 3.5). That gave a general tool, for which one corollary was the first presentation of \( GQ \) (Ch. 3 Prop. 4.9). Many practical problems that engage the properties of functions have a strong connection to the A(bsolute)IGP.

### 1.2. Groups through matrix multiplication.

Behind all our geometric objects lies an interplay between non-nilpotent finite groups and actions of a quotient of the braid group. Except for the phrase "Frattini cover" (Def. 1.13) all our example finite groups appear in a first graduate algebra course.

We introduce the notation for semidirect products. As we will see, the same notation gives a memorable device for understanding some of the cohomology statements on extensions that we often use. While many readers likely have seen a treatment of this at some time, these reminders will come in handy. [Br82, p. 87–90] is an alternative consultation point, even if our notation differs, since we use that text and [Nor62], often later.

Start with an action of any group \( G \) on an abelian group \( A \), using the notation \( g * a, g \in G, a \in A \) for that action. Consider a short exact sequence

\[
0 \to A \to E \xrightarrow{\psi} G \to 1, \quad \text{with } G \text{ acting by a fixed action on } A.
\]

#### 1.2.1. Splittings.

Start with \( \psi \) splittings. This is a homorphism \( G \xrightarrow{s} E \) for which \( \psi \circ c_{sp} = \text{Id}_G \) – the identity map on \( G \) – for which the following hold:

- \( s(G) \cap A = \{1_G\} \); \( s(G) \cdot A = E \), \( \cdot \) indicating set theoretic product; and the conjugation action of \( s(G) \) on \( A \) is the original action of \( G \) on \( A \).
DEFINITION 1.6. If $\psi$ has a splitting, this identifies $E$ set theoretically with $G \times A$. Denote that identification by $A \times^s G$, or $A_\psi \times^s G$ if we must indicate $G$ acting on $A$ through $g \ast a \overset{\text{def}}{=} eae^{-1}$ for any lift $e$ of $g$ to $E$.

By explicitly denoting $s(g) \in G \times A$ as $(g, c_{sp}(g) \overset{\text{def}}{=} a_g)$ we recapture that $s$ is a homomorphism through $2 \times 2$ matrix multiplication.

$$( \begin{array}{cc} g_1 & a_{g_1} \\ 0 & 1 \end{array} ) ( \begin{array}{cc} g_2 & a_{g_2} \\ 0 & 1 \end{array} ) = ( \begin{array}{cc} g_1 g_2 & g_1 a_{g_2} + a_{g_1} \\ 0 & 1 \end{array} ), \text{ or } c_{sp}(g_1 g_2) = g_1 \ast c_{sp}(g_2) + c_{sp}(g_1).$$

Once you have determined what $s$ does, embedding of $A$ by $a \mapsto (\begin{array}{cc} 1 & a \\ 0 & 1 \end{array})$ determines the rest of the multiplication through

$$( \begin{array}{cc} 1 & a \\ 0 & 1 \end{array} ) ( \begin{array}{cc} g & a_g \\ 0 & 1 \end{array} ) = ( \begin{array}{cc} g & a + a_g \\ 0 & 1 \end{array} ).$$

The 1-cocycle $c_{sp}$ is called a derivation. [Br82, p. 88] suggests the name looks more reasonable by regarding $G$ as acting on the right of $A$ with the trivial action. That is, $a_{g_1} = a_{g_1} \ast g_2$. Maybe!

We often identify the splitting $s$ with another, say $s'$, that differs by conjugation by an element of $A$. That is, if the latter were given by $g \mapsto \psi'_{s}(g)$ with

$$( \begin{array}{cc} g & a_g' \\ 0 & 1 \end{array} ) = ( \begin{array}{cc} 1 & a \\ 0 & 1 \end{array} ) ( \begin{array}{cc} g & a_g \\ 0 & 1 \end{array} ) ( \begin{array}{cc} 1 & -a \\ 0 & 1 \end{array} ), \text{ a } \in A \text{ independent of } g.$$ Multiplying the matrices gives $\psi'(g) - \psi(g) = a - g \ast a$, a bounding 1-cycle.

DEFINITION 1.7 ($H^1(G, A)$). The quotient, splitting 1-cycles mod bounding 1-cycles, are the elements of the first cohomology, $H^1(G, A)$, of $G$ with coefficients in $A$. Given one splitting of a semidirect product, $A \times^s G$, all others are a homogenous space whose elements correspond to $H^1(G, A)$.

1.2.2. Extensions. Use notation for $G$ acting on $A$ above. Consider an extension $E$ of $G$ with $\ker(\psi)$ in (1.2). Refer to another extension $E'$ of $G$ replacing $E$ as equivalent to (1.2) if an isomorphism $E \to E'$ induces the identity on $G$ and on $A$. Even if $\psi$ doesn’t split, we may still consider a section $s : G \to E$ for $\psi$, though now we don’t assume $s$ is a homomorphism.

To put a group structure on $G \times A$ compatible with $s$, write $s(g) = (g, a_g)$ as above. We can simplify by adjusting the section so that $s(1_G) = (1_G, 0_A)$. Indeed, here we expect our choice of section only to modify the multiplication in a standard way, so to simplify our first attempt take $a_g = 0, g \in G$. Similar to the previous, any

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3We will take advantage of familiarity with matrix multiplication, but for permutation actions to act on the “integers” of the representation on the right.

4For $G$ action on the right (as in §1.1.1): $(\begin{array}{cc} g_1 & a_1 \\ 0 & 1 \end{array}) (\begin{array}{cc} g_2 & 0 \\ a_2 & 1 \end{array}) = (\begin{array}{cc} a_1 + g_1 g_2 & a_2 \\ 1 & 1 \end{array})$. Or when we want to include $A$ not abelian replace $a_1 \ast g_2 + a_2$ by $a_1 \ast g_2 \cdot a_2$, as in, say, Ch. 6 §3.3.2.
“multiplication” on \( G \times A \) forces a matrix product from a function, \( c_e : G \times G \to A \):

\[
\begin{pmatrix} g_1 & a_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} g_2 & a_2 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} g_1 g_2 & g_1 a_2 + a_1 + c_e(g_1, g_2) \\ 0 & 1 \end{pmatrix}.
\]

The forced multiplication by \( A \) gives a group law (and so an extension \( E \)) if and only if it has an identity, is associative and elements have inverses.

We have just stipulated an identity. The group multiplication is associative if and only if multiplying the matrices for \((s(g_1)s(g_2))s(g_3)\) and \(s(g_1)(s(g_2)s(g_3))\) have the same upper-right entry. This is equivalent to

\[
(1.3) \quad c_e(g_1, g_2) + c_e(g_1 g_2, g_3) = g_1 * c_e(g_2, g_3) + c_e(g_1, g_2 g_3).
\]

As for the inverse, solving for \( a' \) in

\[
\begin{pmatrix} g & a \\ 0 & 1 \end{pmatrix} \begin{pmatrix} g^{-1} & a' \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]

gives \( a' = -g^{-1} * (c_e(g, g^{-1}) + a) \).

With the multiplication in the other direction, the unique solution for \( a' \) is \(-g^{-1} * a - c_e(g^{-1}, g)\). Apply (1.3) with \( g_1 = g^{-1}, g_2 = g, g_3 = g^{-1} \) to see the inverses are the same.\(^5\)

Finally, suppose you take another choice \( s' \) of \( s \), with \( s(1) = (1_G, 0_A) \). Then, \( s-s' \) is given by any function \( c_h : G \to A \) – an \( A \)-modification of the splitting – taking \( 1_G \) to \( 0_A \). To compute \( c_e' \) associated to \( s' \) calculate the term that belongs in the slot labeled \{??\}:

\[
\begin{pmatrix} g_1 & a_1 + c_h(g_1) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} g_2 & a_2 + c_h(g_2) \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} g_1 g_2 & g_1 (a_2 + c_h(g_1, g_2)) + a_1 + c_h(g_1) \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} g_1 g_2 & \{??\} + c_h(g_1, g_2) \\ 0 & 1 \end{pmatrix}.
\]

The difference \( c_e(g_1, g_2) - c_e'(g_1, g_2) \) is

\[
(1.4) \quad g_1 * c_h(g_2) - c_h(g_1, g_2) + c_h(g_1).
\]

**Definition 1.8** \((H^2(G, A))\). Denote equivalence classes of extensions (1.2) with the given \( G \) action on \( A \), modulo the \( A \)-modifications, by \( H^2(G, A) \). The identity element of this abelian group is the split extension.

Why \( H^2(G, A) \) is \( H^2(G, A) \)? We now say why this “definition” actually is what the literature calls \( H^2(G, A) \). Our goal is to place the extensions of Def. 1.13) among all extensions, rather than developing cohomology theory. Still, cohomology will give us tools (as in Prop. 1.7) for actually displaying extensions in the main objects of our study.

The elements of \( \text{Hom}_G(\mathbb{Z}[G]^n, A) \) are given by functions from \( G^n \to A \) (then extend linearly). In this case \( c_e \in C^2(G, A) \) is a function – called a factor set in the literature – \( G^2 \to A \). Then, \( \partial(c_e)(g_1, g_2, g_3) \) is just what you get from subtracting the term of (1.3) on the right, from the left side.

\(^5\)Matrix multiplication is useful for working out particular cases, as we will, though it is equivalent to [Br82, p. 92], which only lists the inverse, and includes a peculiar typo.
This piece of the projective resolution of $\mathbf{1}_G$, with this coboundary operator, is the degree 2 part of the bar resolution of $\mathbb{Z}$ as a $\mathbb{Z}[G]$ module, with the cohomology defined by the quotient of the kernel of $\partial$ by the image of $\partial$ from $\text{Hom}_G(\mathbb{Z}[G], A)$. That is, by applying $\partial$ to functions $c_b : G \to A$ to get (1.4). Between these two examples, it should now be clear what $\partial$ does for general $n$.

**Remark 1.9.** When $G$ acts trivially on $A$, a 1-cocycle (derivation) is just a homomorphism $G \to A$, or $H^1(G, A) = \text{Hom}(G, A)$.

**Remark 1.10 (Schur-Zassenhaus).** We don’t intend to limit discussing extensions, split and otherwise, to only those statements we prove. Rather to have, when we need it, appropriate reminders. For example, the following results from composing the restriction and corestriction maps on cohomology/homology (as in (6.20)).

**Proposition 1.11.** For $[G : H] < \infty$, $A$ a $G$ module, if $H^n(H, A) = 0$, then multiplication by $[G : H]$ annihilates $H^n(G, A)$. [Br82, III. Prop. 10.1]

Thus, [Br82, IV. Cor. 3.13]) gives Schur-Zassenhaus: If $(|A|, |G|) = 1$, there is a unique, so split, extension of $G$ when $A$ is abelian, an essential case – the one we use. Once you know Feit-Thompson, odd order groups are solvable, it is true even if $A$ is not abelian.

**1.3. Extreme extensions.** Groups theorists tend to love classifications.

We emphasize: That is not the topic of this book. Indeed, our group theory is structural rather than description explicit. The extreme extensions we refer to are Frattini covers. They are essential to our constructions in both halves of the book. So, we will give explicit examples.

A homomorphism $\psi : H \to G$ is a cover if it is surjective. A cover automatically produces an extension, but the kernel (as in (1.2)) is not necessarily abelian. Even so, the extensions we are about to construct, which are extreme in that they are the opposite of split, can mostly be understood from extensions with abelian kernel.

**Definition 1.12.** Given two covers $\psi_i : H_i \to G$, $i = 1, 2$, their fiber product

$$H_1 \times_G H_2 = \{(h_1, h_2) \mid \psi_1(h_1) = \psi_2(h_2)\}$$

is a universal target for covers $\psi : H \to G$ factoring through $\psi_i$, $i = 1, 2$.

That is, given $\psi = \psi_1 \circ \psi_1' = \psi_2 \circ \psi_2'$ with $\psi_i' : H \to H_i$, there is a natural homomorphism $(\psi_1', \psi_2') : H \to H_1 \times_G H_2$. This doesn’t mean $\psi$ factors as a cover of the fiber product. Compare Lem. 1.15 with Lem. 2.4.

**Frattini covers and kernels:** For $\ell$ a prime, a pro-$\ell$ group is a profinite group for which all its finite quotients are $\ell$-groups. A projective profinite group, $P$, has the
property that for any cover $\psi : P \to G$, if $\psi' : H \to G$ is a cover, then there is a homomorphism (not necessarily a cover) $\psi'' : P \to H$ for which $\psi' \circ \psi'' = \psi$.

**Definition 1.13.** We say $\psi$ is Frattini if it is a group cover, and if $H^* \leq H$ maps by restriction of $\psi$ as a cover of $G$, then $H^* = H$.

Lem. 1.14 in some form is due to Frattini. It is akin to [FrJ86, Lem. 20.2] or [FrJ86, Lem. 22.1.2]. While both its statements are valuable, we primarily use the former. Denote the Frattini subgroup of any (pro-)finite group $G$ by $\Phi(G)$.

**Lemma 1.14.** For Frattini covers $\psi : H \to G$, $\ker(\psi)$ is nilpotent (Ch. 6 §1.1.2). Further, given $G, G \to G/\Phi(G)$ is the maximal Frattini cover by $G$.

**Proof.** For the first statement, consider any $g \in G$, and choose a lift $h_g \in H$ of $g$ to $H$. Then, $h_gPh_g^{-1}$ is another $\ell$-Sylow of $H$. Apply the Sylow theorems: all $\ell$-Sylows in $P$ are conjugate in $\ker(\psi)$. Thus, $h_gPh_g^{-1} = u_gPu_g^{-1}$ for some $u_g \in \ker(\psi)$. That is, $h_gu_g^{-1}$ is in the normalizer, $N_H(P)$, of $P$ in $G$.

Now consider the subgroup $N' = \langle h_gu_g^{-1} \mid g \in G \rangle$. It is in $N_H(P)$ and it covers $G$. Since $\psi$ is a Frattini cover, $N' = N_H(P) = H$. Therefore $P$ is a normal subgroup of $\ker(\psi)$ and $\ker(\psi)$ is nilpotent.

Now consider any profinite $G$. Suppose $M < G$ maps surjectively to $G/\varphi(G)$. With no loss, take $M$ maximal. Since it contains $\Phi(G)$, $M/\Phi(G)$ is a proper subgroup of $G/\Phi(G)$, contrary to assumption. $\square$

Recall the rank, $\text{rk}(G)$, of a profinite group is the minimal number of elements generating a subgroup whose closure is $G$. We easily extend the notion of Frattini cover to profinite groups. Immediately, if $H \to G$ is a Frattini cover of profinite groups, then the lift of any generators of $G$ to $H$ gives a subgroup whose closure maps onto $G$. Therefore $\text{rk}(H) = \text{rk}(G)$. See Rem. 1.17.

**Lemma 1.15.** Assume $\psi_i : H_i \to G$, $i = 1, 2$, are Frattini covers. Then, any $H \leq H_1 \times_G H_2$ that covers $G$ automatically covers $H_i$, $i = 1, 2$.

A minimal (not necessarily unique) subgroup of $H_1 \times_G H_2$ is a Frattini cover of $G$. From Def. 1.13, a Frattini cover $\psi : H \to G$, $\text{rk}(H) = \text{rk}(G)$. Also, Frattini covers of perfect groups are perfect.

**Proof.** Suppose $H \leq H_1 \times_G H_2$ covers $G$ by restriction of $(\psi_1, \psi_2)$. Then, the image of $H$ in $H_i$ by projection is a subgroup of $H_i$ that is a cover of $G$. Since $\psi_i$ is a Frattini cover, the image must be all of $H_i$, $i = 1, 2$. If $H$ is minimal as a cover of $G$, then, by definition, it must be a Frattini cover.

Now suppose $G$ is a perfect group, and $\psi : H \to G$ is a Frattini cover. Consider the commutator subgroup $[H, H]$ of $H$. (If the groups are profinite, consider the
closed subgroup generated by \([H,H]\). It maps onto \([G,G] = G\) by \(\psi\), and so it covers \(G\). Since \(\psi\) is a Frattini cover, \([H,H] = H\). This concludes the proof. \(\square\)

**Definition 1.16.** Since Frattini covers of \(G\) form a projective system, they produce a profinite cover, the Universal Frattini cover, \(\tilde{\psi}_G : \tilde{G} \to G\) that factors surjectively through any Frattini cover of \(G\).

**Remark 1.17.** [FrJ86, Chap. 22] is more encyclopedic than we will be. In particular, our Frattini covers will usually have finite (or at worst, countable) rank. Larger cardinality can require more careful proof.

*Constructing \(\tilde{\psi} : \tilde{G} \to G\):* A Frattini cover \(\psi : H \to G\) is a structural idea. We apply it only to profinite groups – where subgroup means closed subgroup – and especially to finite groups. Suppose \(G\) has rank \(t\). Denote the profinite completion of the free group \(F_t\) on \(t\) generators with respect to all subgroups of finite index by \(\tilde{F}_t\). Consider any fixed map \(\tilde{\psi}_t : \tilde{F}_t \to G\), by mapping generators of \(\tilde{F}_t\) to \(g \in \{g_1, \ldots, g_t\}\), generators of \(G\).

**Lemma 1.18.** The group \(\tilde{G}\) is a closed subgroup of \(\tilde{F}_t\). Therefore, the cover \(\tilde{\psi}\) is projective in the category of profinite groups.

**Proof.** Here is a way to produce \(\tilde{G}\). Take the lift to \(\tilde{G}\) of any collection, \(\tilde{g}\) of \(t\) elements that lift to \(\tilde{F}_t\), a set of generators of \(G\). Let \(\tilde{H}_{\tilde{g}}\) be the closure of the group generated by \(\tilde{g}\) in \(\tilde{F}_t\). There is no way to assure that the natural map \(\tilde{\psi} : \tilde{H}_{\tilde{g}} \to G\) is a Frattini cover.

Still, the axiom of choice lets us form a maximal chain (by containment) of such covers, with an indexing \(\{\tilde{H}_{\tilde{g}_\alpha}\}_{\alpha \in I}\). By the Tychonoff Theorem the intersection, \(\tilde{H}_\infty\), of all of the \(\tilde{H}_{\tilde{g}_\alpha}\) is closed in \(\tilde{F}_t\). We easily show it is a subgroup having a limit set \(\tilde{g}_\infty\) that maps onto \(g\) by restriction of \(\tilde{\psi}\). Since the chain was maximal, \(\tilde{H}_\infty \to G\) must be a Frattini cover.

Should \(\mu : \tilde{H}_\infty \to V\) and \(\nu : V' \to V\) be covers of groups, then we can extend the map \(\mu\) to \(\tilde{F}_t\). Then extend \(\mu\) to \(\mu' : \tilde{F}_t \to V'\) and restrict \(\mu'\) to give \(\tilde{H}_\infty \to V'\) extending \(\nu\). This says that \(\tilde{H}_\infty\) is projective. \(\square\)

**Remark 1.19.** If we relied on the unconstructive Lem. 1.18, we would know little of the necessary information we will need about characteristic quotients of \(\tilde{G}\), as in §1.4. These provide information on the levels of the towers of the moduli spaces at the heart of this book.

**Remark 1.20.** The end argument of the proof in Lem. 1.18 is a special case of a general result that closed objects of a free object are projective.
Universal $\ell$-Frattini covers: Reminder: a profinite group is nilpotent (or pronilpotent in the profinite case) if it is a product of its (pro-$\ell$) $\ell$-Sylows. For each prime $\ell$, dividing the order of a nilpotent group $N$, there is a cover $N \to \mathbb{Z}/\ell$.

For $\psi : H \to G$ a Frattini cover, write $\ker(\psi) = \prod_{\ell \mid |G|, i = 1, \ldots, t} \ker(\psi_{\ell_i})$ (Def. 1.13) indicating the product is over its $\ell$-Sylows. For each $\ell_i$, quotient out by all the $\ell_j$-Sylows, $j \neq i$, in $\ker(\psi)$ to form $\psi_{\ell_i} : H_{\ell_i} \to G$.

The fiber product of the $H_{\ell_i}$s over $G$ equals $H$. Many structural statements on $\tilde{\psi} : \tilde{G} \to G$ appear in [FrJ86, Chap. 22]. We have picked some that are essential to understanding $\tilde{\psi}$ and its quotient groups. Especially as they apply to detecting components of Hurwitz spaces and constructing $\text{M}(\text{odular})\text{T}(\text{owers})$.

Now decompose $\ker(\tilde{\psi}_G)$ as a product of its $\ell$-Sylows.

Here are some valuable conceptual statements on pro-$\ell$ groups.

(1.5a) Tate: A closed subgroup of a pro-free pro-$\ell$ group is a pro-free (pro-$\ell$) group, and a pro-$\ell$ group is projective if and only if it is pro-free, [FrJ86, Cor. 22.7.6 and Cor. 22.7.7]$_2$.

(1.5b) Schreier: For $\tilde{F}_t$, pro-free on $t$ generators, a constructive procedure finds $1+n(t-1)$ independent pro-free generators of a finite index subgroup $U \leq \tilde{F}_t$ with $(\tilde{F}_t : U) = n$ [FrJ86, §17.5]$_2$.

(1.5c) The expression $1+n(t-1)$ from (1.5b) is a bound on the rank of any subgroup of index $n$ in a group of rank $t$.

**Problem 1.21.** Use Lem. 1.23 as a characterization of a pro-$\ell$ group to show (1.5a). Use (1.5b) to show that the projective cover $\tilde{\psi}_G : \tilde{G} \to G$ cannot be a pro-free group if at least two primes divide $|G|$. Hint: A profree group cannot be the product of 2 or more $\ell$-Sylows.

**Definition 1.22.** For each prime $\ell||G|$, there is a profinite Frattini cover $\ell\tilde{\psi}_G : \ell\tilde{G} \to G$ with $\ker(\ell\tilde{\psi}_G)$ profree, pro-$\ell$, of finite rank, $\text{rk}(\ell\tilde{G})$.

Especially, consider these points running over all such $\ell$.

(1.6a) $\tilde{G}$ is projective, and equal to the fiber product over $G$ of the $\ell\tilde{G}$s ($\S 1.3$).

(1.6b) $\tilde{\psi}$ is the minimal (profinite) cover of $G$ with all its $\ell$-Sylows projective, and so pro-free pro-$\ell$ finitely generated groups (Prop. 1.29).

**1.4. Characteristic quotients of $\tilde{\psi}_G$.** We will see that Frattini covers are determined – albeit in complicated ways – by statements about $\ell$-Sylows. Although extensions given by Frattini covers do not necessarily have abelian kernels, this is compatible with similar statements about $H^n(G, A)$ being determined by statements about the $\ell$-Sylows of $G$ (see Rem. 1.24).
Lemma 1.23. For any pro-$\ell$ group, $P$, of finite rank, its Frattini subgroup is $\langle [P,P], P^\ell \rangle \overset{\text{def}}{=} \frattini P$. That is, 

$$P/\frattini P = (\mathbb{Z}/\ell)^{rk(P)}$$

is the smallest quotient of $P$ presenting $P$ as a Frattini cover [FrJ86, Lem. 22.7.4].

Proof. Again, the Sylow theorems: Maximal subgroups of pro-$\ell$ groups are normal subgroups of index $\ell$. Now use that a composition of Frattini covers is Frattini. Therefore, the Frattini quotient $P/\Phi(P)$ must be $(\mathbb{Z}/\ell)^m$, since it will be an $\ell$ group and the minimal Frattini cover.

The quotient is abelian. So, that puts the commutator subgroup and all $\ell$ powers in $\Phi(P)$. As $P \to P/\Phi(P)$ is a Frattini cover, the two groups have the same rank. □

Remark 1.24. [Br82, Thm. III. 10.3] notably relates the cohomology of $G$ and restrictions of the cohomology to the $\ell$-Sylows of $G$. For $P$ an $\ell$-Sylow of finite group $G$, restriction to $P$ maps the $\ell$-primary part of $H^n(G,A)$ isomorphically to the $G$ invariant elements of $H^n(P,A)$. The rub is that saying the conjugation action of $G$ is invariant is tricky as the chains for $H^n(P,A)$ are defined by functions in $\text{Hom}_{\mathbb{Z}[H]}$, not $\text{Hom}_{\mathbb{Z}[G]}$ (see §1.1.1).

1.4.1. Characteristic quotient notation. As usual, $\frattini P$ is the closed subgroup of $P$ generated by $\ell$ powers and commutators of $P$. Recover a cofinal family of finite quotients of $\frattini G$ through the Frattini kernel of the natural map

$$1 \to \ker 0 \to \frattini G \to G \to 1.$$ 

This produces the characteristic sequences of $\frattini G$:

(1.7) Kernels: $\frattini K_G : \ker 0 \overset{\ell}{\to} \ker 0 \overset{\text{def}}{=} \ker 1 \geq \cdots \geq \ker k \overset{\text{def}}{=} \ker k \cdots$

Frattini Covers: $\{\frattini G : \frattini G \overset{\text{def}}{=} \frattini G/\ker k \to G\}_{k \geq 0}$.

Generally we use the $\overset{\text{def}}{=} \text{def}$ to indicate a Frattini tail is present. The projective limit of the $\frattini k$'s is $\frattini G$. Sometimes we denote $\ker k/\ker k'$ by $\frattini M_{k,k'}$ or $M_{k,k'}$ for $k' \geq k$.

There is a natural $\mathbb{Z}/\ell^{\frattini k} G$ structure on $\frattini M_{k,k+1}$. Lift $g \in \frattini kG$ to

(1.8) $\tilde{g} \in \frattini k+1G$ and act by conjugation $m \mapsto \tilde{g}^{-1}m\tilde{g}$ for $m \in \frattini M_{k,k+1}$.

Especially, $\frattini M_{0,1} \overset{\text{def}}{=} \frattini M_{0,1}$ is the characteristic $\mathbb{Z}/\ell[G]$ module.

As $\frattini M_{k,k+1}$ is an (abelian) module, the (1.8) action of $\tilde{g}$ is independent of its lift.

Example 1.25 (Prelude to a normal $\ell$-Sylow). The easiest cases of (1.7) with an $\ell$-perfect $G$ are slight generalizations of $D_{\ell^n}$: the dihedral group of order $2 \cdot \ell^n$ with $\ell$ odd. The quotient $\frattini G/\ker k$ is $D_{\ell^{k+1}}$, and the commutators $[\ker k, \ker k]$ are trivial. They won’t be in general.

The obvious generalization is $G = 0G = \mathbb{Z}/\ell^n \times^s H$, with $H$ an $\ell'$ group acting faithfully through $(\mathbb{Z}/\ell^n)^*: \ell$-Sylow of $G$ is normal and cyclic. Then, $\frattini kG$ is $\mathbb{Z}/\ell^{n+k} \times^s H$ with the $H$ action extending to $\mathbb{Z}/\ell^{n+k}$.

\[\triangle\]
1. THE REGULAR INVERSE GALOIS PROBLEM

Terms of \( \ell K_G = \{ \ker_k \}_{k=0}^\infty \) should reference \( G \) unless it is understood. For example, they may not be characteristic subgroups of \( \ell \hat{G} \), as in the example for \( P = \ell \hat{F} \) (1.5b). Lem. 1.5 characterizes when they are.

**Abelianized quotients:** We add the abelianizations of the Frattini tails:

\[
\ell \hat{G}_{ab,(0)} \overset{\text{def}}{=} \ell \hat{G}/[\ker_0, \ker_0], \text{ abelianization from level 0.}
\]

\[
\ell \hat{G}_{ab,(k_0)} \overset{\text{def}}{=} \ell \hat{G}/[\ker_{k_0}, \ker_{k_0}], \text{ abelianization from level } k_0.
\]

So long as there can be no confusion, we will denote \( \ell \hat{G}_{ab,(0)} \) as \( \ell \hat{G}_{ab} \).

The Universal abelianized \( \ell \)-Frattini cover of \( G \):

\[
V_{G,\ell} \overset{\text{def}}{=} (\mathbb{Z} \ell)^{\nu(G,\ell)} \to \ell \hat{G}_{ab} \to G, \nu(G,\ell) = \dim_{\mathbb{Z}/\ell}(\ell M_{0,1}).
\]

It is universal for covers of \( G \) with abelian \( \ell \)-group as kernel. Akin to (1.7), consider the sequence

\[
\ell_{ab} G_G : \{ \ell \hat{G}_{ab}/\ell^k V_{G,\ell} \overset{\text{def}}{=} k \ell \hat{G}_{ab} \to G \}_{k \geq 0}.
\]

Sometimes, when \( G \) is a semidirect product \( P \rtimes H \), with \( P \) an abelian \( \ell \)-Sylow, we require abelianization right from the top, as in \( \tilde{P}/[\tilde{P}, \tilde{P}] \times s H \) (notation as in Prop. 1.29). Then we use the notation \( \ell \hat{G}_{ab(-1)} \). In rare cases, \( P \) may only be a subgroup of the \( \ell \)-Sylow:

\[
\ell \parallel H \text{ as in the case } \ell = 2 \text{ in §3.2.}
\]

That \( G \) module \( \ell M_{0,1} \) in (1.9) replicates as

\[
\text{the kernel of } \ell^{k+1} \hat{G}_{ab} \to \ell \hat{G}_{ab}.
\]

Exchanging \( \mathbb{Z}/\ell[G] \) modules for \( \mathbb{Z}[G] \) modules changes some crucial details about the modules. Ch. 6 §1.4 gives guidelines in going mod \( \ell \) (modular representations) including that the theory of projective modules in characteristic \( \ell \) is different.

**Remark 1.26 (\( \ell \hat{G} \neq \ell \hat{G}_{ab} \)).** Unless the rank of \( \ker(\ell \hat{G} \to G) \) is \( t = 1 \), the only case where the pro-free group of rank \( t \) is abelian, \( \ell \hat{G} \) can never equal \( \ell \hat{G}_{ab} \).

This follows from (1.5a) because the \( \ell \)-Sylow of \( \ell \hat{G} \) is a pro-free pro-\( \ell \) group. From (1.5b), its finite index subgroup is also.

1.4.2. \( \ell \hat{G} \) vs \( \ell \hat{G}_{ab} \) and non-perfect primes. In application to the RIGP, accomplishing such regular realizations over certain fields is clearly stronger using the whole Frattini cover \( \ell \hat{G} \to G \), as in §5.2. Yet, an important theme in the book is the pure diophantine difficulty of finding solutions to the RIGP as optimized by the Main Conj. 3.1 of MTs, and the cases where that conjecture has been proven.

\[\text{Here, with } \nu(G,\ell,k_0) = \dim_{\mathbb{Z}/\ell}(\ell M_{k_0,k_0+1}), \text{ is a variant for abelianization from } k_0:\]

\[
\ell_{ab}(k_0) G_G : \{ \ell \hat{G}_{ab,(k_0)}/\ell^{k-k_0} (\mathbb{Z})^\nu(G,\ell,k_0) \overset{\text{def}}{=} k \ell \hat{G}_{ab,(k_0)} \to G \}_{k \geq k_0}.
\]
Here then, understanding the difficulty – as a generalization of results on modular curves – is strengthened using formulations with the cover $\tilde{\mathcal{G}}_{ab} \rightarrow G$.\footnote{There are, Ch. 6 §1.5, maximal nilpotent and solvable quotients of $G$.} Also, using $\tilde{\mathcal{G}}_{ab}$ is the right level to make positive comparisons of the OIT generalization with Serre’s result.

Denote by $G_{abq}$ the maximal abelian quotient, $G/[G,G]$ of $G$. The primes $\ell$ dividing $|G_{abq}|$ are exactly those for which $G$ is not $\ell$-perfect (as in Def. 1.2). Usually, when using $\tilde{\mathcal{G}}$, we assume $G$ is $\ell$-perfect. Alas, we have these opposing considerations on including $\ell||G_{abq}|$.

(1.11a) Including such $\ell$ without modification won’t give a canonical tower of Hurwitz spaces from $(G, C, \ell)$.

(1.11b) Excluding all the $\ell$-Frattini extensions associated with $(G, C, \ell)$ leaves out towers and RIGP possibilities with classical consequence.

The point of (1.11a) appears in the proof of Prop. 3.4. Examples of (1.11b) are almost immediate in our intention to extend Serre’s OIT, for example as explained in Ch. 6 §3.3.3.

While we may not yet have the best solution to this dilemma, it suffices to make inroads and it does rightfully exclude towers that come from pure $\ell$-Frattini covers of $G$ obtained by pullback of the universal $\ell$-Frattini cover of $G_{abq}$. So, we cannot, quite, dismiss non-perfect primes, though pure nilpotent groups don’t lend themselves to the moduli space approach.

1.4.3. Preliminary grasp of $\ell M_G$. This section is a guide to where we will concentrate on using the universal Frattini cover. Prop. 1.29 gives the first constructive aspects on describing $\tilde{\mathcal{G}} \rightarrow G$, the case where the $\ell$-Sylow of $G$ is normal. These continue as “$\ell$ pieces Parts 3 and 4” (resp. Ch. 3 Prop. 2.18 and Ch. 6 Prop. 1.7), to describe, more deeply, the universal $\ell$-Frattini extensions of an $\ell$-perfect $G$.

Monodromy action on various objects, including $\ell$-adic representations, comes from a braid group action on Nielsen classes, starting in §3.1.3. Ultimately, the $\ell$-adic representations of the book’s title stem from,

the Universal abelianized $\ell$-Frattini cover of $G$.

Definition 1.27 (Universal elementary $\ell$-extension). To understand either the abelianized Universal $\ell$-Frattini, or the general $\ell \tilde{\mathcal{G}} \rightarrow G$, we start with

$$\ell M_{0,1} = \ell M_G = \ker(\ell \tilde{\psi}_{ab})/\ell \ker(\ell \tilde{\psi}_{ab})$$

as in (1.8).

Proposition 1.28 (\ell pieces: Part 1). Fiber products of $\ell \tilde{\psi}_{ab}$, running over $\ell||G||$, give $\tilde{\psi}_{ab} : \tilde{\mathcal{G}}/\ker(\tilde{\psi}), \ker(\tilde{\psi}) \rightarrow G$.

Using conjugation, as in (1.8), $\ker(\ell \tilde{\psi}_{ab})$ is naturally a free $\mathbb{Z}/\ell|G|$ module extending the $\mathbb{Z}/\ell|G|$ module structure on $\ell M_{0,1}$.
If $H \leq G$ is an $\ell'$ group, by applying Schur-Zassenhaus to lift embed $H$ in $\hat{\ell}G$ (up to conjugacy) then each of the $\hat{\ell}G$'s inherits a compatible system of coset representations (meaningfully designated by a single symbol $T_H$).

Prop. 1.29 gives our first structural statements on $\hat{G}$.

**Proposition 1.29 (\ell pieces: Part 2).** Any automorphism of $G$ extends to $\hat{G}$, and for $K$ a characteristic subgroup of $\hat{G}$, to $\hat{G}/K$. Denote an $\ell$-Sylow of $G$ by $P_\ell$.

(1.12a) If $P_\ell$ is normal, then with $H = G/P_\ell$, $\hat{\ell}G = \hat{P}_\ell \times^s H$, $\hat{P}_\ell = \ell \hat{F}_{\text{rk}(P)}$: $\times^s$ indicating $H \leq \text{Aut}(G)$ extends to $\text{Aut}(\hat{G})$.

(1.12b) All such extensions of $H$ to $\hat{\ell}G$ differ by a conjugation from $\hat{\ell}G$.

Characterize $\hat{\ell}G$ (resp. $\hat{G}$) as the minimal profinite cover $\hat{G}^* \to G$ for which the (resp. all) $\ell$-Sylow(s) of $\hat{G}^*$ is (resp. are) $\ell$-free.

**Construction Comments.** Consider the first statement with $\alpha : G \to G$ an automorphism. Then, $\alpha \circ \hat{\psi}_G : \hat{G} \to G$ is a Frattini cover of $G$

giving a morphism $\hat{\alpha} : \hat{G} \to \hat{G}$ for which $\hat{\psi}_G \circ \hat{\alpha} = \alpha \circ \hat{\psi}_G$.

The image of $\hat{\alpha}$ is a subgroup of the Frattini cover $\hat{G} \to G$ that maps surjectively to $G$. Therefore $\hat{\alpha}$ maps surjectively to $\hat{G}$. Since $\hat{G}$ is finitely generated, $\hat{\alpha}$ is an isomorphism [FrJ86, Prop. 15.3]$.^8$ Then, if $K$ is a characteristic normal subgroup of $\hat{G}$, by definition the automorphism will preserve it, producing an automorphism of the quotient of $\hat{G}/K$.

Now consider (1.12a). Under the hypothesis, if we can extend the action of $H = G/P$ to $\hat{P}$, then we have a Frattini cover with a pro-free pro-$\ell$ Sylow. So it must be the $\ell$-Frattini cover of $G$. Let $t = \text{rk}(P)$.

From the above, each $h \in H$ extends to an automorphism, $\hat{h}$, of $\hat{P} = \ell \hat{F}_t$, a rank $t$ cover of $P$. From Lem. 1.5, the group $\hat{H}$ generated by $\{\hat{h} \mid h \in H\}$ is profinite. Now apply the profinite Schur-Zassenhaus [FrJ86, Lem. 22.10.1]$_2$; extending from finite to profinite is an exercise.

Albeit, we can profitably consider that extension’s nature, as in Ex. 1.8, where $P = (\mathbb{Z}/\ell)^t$ in (1.12a). The last paragraph of the proposition generalizes a cohomological statement that a $\mathbb{Z}[G]$ module $M$ is projective if and only if it passes the homological criteria that it is $\ell$-projective for each prime $\ell || G$. Or use [FrJ86, §22.4]$_2$ to interpret that directly using elementary abelian $\ell$-groups for $M$. □

**Guidance on mod \ell representations:** In the remainder of this chapter we go to the heart of the book, the moduli spaces which we produce by applying the Frattini

---

$^8$This would be obvious if $G$ is finite. It becomes so for finitely generated profinite groups because the intersection of all subgroups of finite index, say $n$, both of finite index and characteristic.
constructions. While the book will gives examples, as guidance, we thankfully don’t need a general classification of the representations of $G$ that appear in (1.9). Besides, group theorists and computer scientists consider that – in detail as one understood collection – this is essentially impossible.

Yet, in our applications, we always need to know nontrivial structural data on $\mathbb{Z}/\ell[G]$ quotients of $\ell M_G$. Here we point preliminarily to appropriate results. The classification of representations of finite groups is a starting model for these modular representations. In characteristic 0, a module not a direct sum of two proper submodules (is indecomposable) has no proper submodules at all.

That is no longer true for $\mathbb{Z}/\ell[G]$ modules. Indeed, a simple first definition is the maximal quotient $M/\text{Rad}(M)$ of $M$ which is a completely reducible: A direct sum of irreducible $\mathbb{Z}/\ell[G]$ modules. See Ch. 6 (6.3a) for the names attached to the Loewy series resulting from this definition. Also, it is standard (and often necessary), for applying classification theorems of modules, to tensor with an algebraic closure, $\bar{F}$, of the quotient field $F$ of the base ring.

Ch. 3 Lem. 2.15 and Prop. 2.16 give precise homological characterizations of $\ell M_G$. Ch. 3 Prop. 2.18 says, if $G$ is $\ell$-perfect and centerless, then the same is true of all the characteristic $\ell$-Frattini quotients $\ell^k G$, $k \geq 0$. This is crucial to their use on MT levels, giving all those levels fine moduli space properties.

Quotients, of say ker($\ell G \to G$), on which $G$ acts trivially, give central $\ell$-Frattini extensions. This is a dominant theme in Ch. 3, the book’s center, for detecting components of Hurwitz spaces. Also for properties of those spaces on their boundary (cusps). Frattini central extensions have two types, Ext and Comm in §2.1 which describes both cohomologically. This is in the service of the general lift invariant.

Since the Comm type central extensions are so mysterious, explicating them in important cases is an additional reason for investigating the kernel of, say, $\ell G \to G$; Prop. 1.29 is a first result in that direction.

2. Nonsingular sphere covers and Galois closure

The author, here, as in his papers, acts by permutations on the right of the symbols of the permutation representation. Most of this section and the next applies to any cover of compact Riemann surfaces. When, however, we start to compute how covers work, we deal primarily with sphere covers: $\varphi : W \to \mathbb{P}^1_{\mathbb{C}}$. These ramify if deg($\varphi$) > 1, since the sphere is simply connected.

2.1. Algebraist’s Galois closure. One of the techniques that appears in considering sphere covers, especially, when they are used in (Hurwitz) families is to start with covers that aren’t Galois. Then go to their Galois closures. We give a general construction for the Galois closure of a cover $\varphi : W \to Z$ of normal,
quasi-projective (locally closed subspaces of some projective space) varieties, with $W$ irreducible, over a field $K$. T

There is no reason to assume $\varphi$, with $\deg(\varphi) = n$, is étale. Let us, however, say that it is finite, flat and separable, and indicate the degree (well-defined from flatness) by $n = n_\varphi$. This is what Grothendieck called a (not necessarily étale) cover. §2.1.1 constructs the Galois closure group, $G_\varphi$, and natural permutation representation, $T_\varphi$, attached to $\varphi$, a slight abstraction of [BFr02, §3.1.3].

2.1.1. Fiber product construction. Take the set theoretic fiber product of the cover $\varphi$, $n$ times:

$$W^{(n)}_\varphi = \{(w_1, \ldots, w_n) \in W^n \mid \varphi(w_1) = \cdots = \varphi(w_n)\}.$$  

There are components we don’t want: Those where the whole component has $n$-tuples with two entries (or more) that are equal. That collection, denoted $\Delta_n$, is called the fat diagonal.

Now remove $\Delta_n$, referring to the result as $W^0_\varphi$. Then, $S_n$ still acts on it by permuting coordinates. Normalization of a projective variety, $X$, in a finite extension, $F$, of its field of functions $K(X)$, is a topic found in [Mu66, p. 396-397]. We have used it often, say, as in [Fr77, p. 36] akin to as in the Comments of Prop. 3.5, to generalize what is below to form families of Galois closures of covers.

For a complex analytic space, $X$, the main category in this book, there is a natural local definition of normalization. At each $p \in X$, there is ring (integral domain), $R_p$, of local holomorphic functions (precisely the meaning of an analytic space) about $p$. That right has a quotient field $K_p$, and normal means that at each point the integral closure of $R_p$ in $K_p$ is just $R_p$. With this we can also discuss normalization of $X$.

Assuming $X$ has a single component, we must consider that its (function) field of meromorphic function may actually have no nonconstant meromorphic functions. By contrast, projective algebraic varieties have a function field which determines them up to birational morphism. Here are some other points.

(1.14a) There is a natural algebraic map from the normalization, $\tilde{X}_F$ of $X$ in $F$ to $X$ (defined on geometric points): $\tilde{\psi}_F : \tilde{X}_F \to X$.

(1.14b) We call $X$ normal if $\tilde{\psi}_{K(X)}$ is an isomorphism.

(1.14c) If $X$ is normal and projective, then so is $\tilde{X}_F$.

(1.14d) If $X$ is normal, it is nonsingular in codimension 1.

We start off Ch. 2 explaining precisely why we need normalization and projective varieties, rather than just complex analytic spaces.

Back to $W^0_\varphi$, (1.13) with the fat diagonal removed.

---

9Actually, in either [H77] or [Mu66], fields of definition are almost always algebraically closed, compatible with the interests of those authors.
(1.15a) Normalize the result, $W^0_\varphi$, in the function field of each component. You don’t have to do this if $\varphi$ is étale.

(1.15b) Denote any irreducible $K$-component of $W^0_\varphi$, by $\hat{\varphi} : \hat{W} \to Z$ (as a cover). From normalization, (1.14d), all components are disjoint.

See §1.1.1 for the notation we will use for permutation representations. Then, $\hat{\varphi}$ is a Galois closure of $\varphi$. (See §1.2.1 for a little categorical glitch if it should turn out that $\hat{W}$ is singular.) §3.2 illustrates Lem. 2.1 in detail in our running example on dihedral groups. For $H' \leq H$, denote the normalizer of $H'$ in $H$ by $N_H(H')$.

2.1.2. The canonical permutation representation. Classical problems didn’t feature the Galois closure of a cover. Simple versions of the Inverse Galois problem emphasized it only. The connection between the two is the canonical permutation representation.

**Lemma 2.1.** The group, $G_\varphi \leq S_n$, of $\hat{\varphi}$, appears as the elements of $S_n$ that leave $\hat{W}$ fixed. It is a Galois cover because $G_\varphi$ acts transitively on each fiber over $Z$. By restriction $\hat{W}$ has a projection onto each copy of $W$ in the fiber product. Say, project on the 1st.

That cover is also Galois, with group $G(T_\varphi,1)$. Then, $T_\varphi$ is the permutation representation of $G_\varphi$ on the cosets of $G(T_\varphi,1)$, where we can take 1 to correspond to the coset of the group element 1.

The collection of components of $W^0_\varphi$ with the exact same $G_\varphi \leq S_n$ correspond to the elements of the quotient $N_{S_n}(G_\varphi)/G$.

**Proof.** Since $S_n$ is transitive on the fibers of $W^0_\varphi \to Z$, so too will be $G_\varphi$ as the elements leaving $\hat{W}$ fixed, showing the $\hat{\varphi}$ is Galois. The rest of the first two paragraphs is already explained from this.

Now suppose $\hat{W}'$ is another component of $W^0_\varphi$, and the elements in $S_n$ that leave it fixed form the group $G'_\varphi$. From transitivity of $S_n$ on the components, there is $g \in S_n$ that maps $\hat{W}_\varphi \to \hat{W}'_\varphi$. Then, $gG'_\varphi g^{-1}$ also consists of elements in $S_n$ that leave $\hat{W}_\varphi$ fixed (note: we are acting as we mostly do on the right). If we assume that $G'_\varphi = G_\varphi$, then this implies $g \in N_{S_n}(G_\varphi)$. This is reversible and gives the last paragraph of the lemma. \(\square\)

The attached permutation representation: The significance of the following lemma is that it ties together the fundamental condition called *fine moduli* (see §3) for covers where equivalence is called *absolute* to that for covers where equivalence is called *inner*. 


DEFINITION 2.2. For a pair \((G, T)\) where \(T\) is transitive and faithful, consider the normalizer, \(N_G(G(T, 1))\), of \(G(T, 1)\) in \(G\).

Call \((G, T)\) self-normalizing if \(N_G(G(T, 1)) = G(T, 1)\).

Consider \(\text{Cen}_T(G) = \{h \in S_n \mid hgh^{-1}, \forall g \in G\}\).

LEMMA 2.3. Then, \(\text{Cen}_T(G) = N_G(G(T, 1))/G(T, 1)\) is isomorphic to the automorphisms of \(W\) that commute with \(\varphi\). If \(G\) is self-normalizing, then \(\varphi\) has no automorphisms (analytic isomorphisms that commute with \(\varphi\)). Further, \(G\) is centerless. That the representation is faithful means \(\cap_{i=1}^n G(T, i)\) is trivial.

A decomposition of \(\varphi : W \to Z\) into a chain of (normal) covers

\[\varphi_1 : W \to W_2, \varphi_2 : Z\]

corresponds to a subgroup \(G(T, 1) \leq H \leq G\), with the degrees of \(\varphi_i\), \(i = 1, 2\), respectively equal to \((G : H)\) and \((H : G(T, 1))\).

PROOF. The interpretation of the automorphisms of \(\varphi\) as \(N_{G(T, 1)}(G)/G(T, 1)\) is [Fr77, Lem. 2.1]. Then, [Fr77, Lem. 2.2] identifies this group with the complete centralizer of \(G\) in \(S_n\). Since we make use of it often, here is the argument that says self-normalizing implies \(G\) is centerless.

Suppose \(g \in G\) is in the center. Then, \(gG(T, 1)g^{-1} = G(T, 1)\) and so \(g \in G(T, 1)\).

Since \(T\) is transitive, for each \(i \in \{1, \ldots, n\}\), there exists an \(h \in G\), for which \((1)T(h) = i\). Then, \(h^{-1}gh = g\) takes \(i\) to \(i\). Since this holds for all \(i\), and \(T\) is faithful, \(g\) is trivial.

The correspondence between covers between \(W\) and \(Z\) with subgroups between \(G(T_1, 1)\) and \(G\) is a special case of the Galois correspondence. \(\square\)

Reasonably we ask: What is the pair \((G, T, \varphi)\) given \(\varphi\)? A good answer requires significant labels for such pairs. Considering our limited understanding of finite groups, we must separate such pairs using other concepts. See Ch. 6 §1.1, especially compare the cases when \(\varphi\) does not or does decompose, as \(\varphi_2 \circ \varphi_1\) with \(\deg(\varphi_i) > 1\).

2.1.3. Group of an equation a la Galois. Suppose \(f(y)\) is a degree \(n\), separable and irreducible, polynomial over a field \(K\). For simplicity on a critical point, we will assume – somehow – you have managed to find these roots as particular complex numbers in \(\mathbb{C}\). We list them as \(\{\alpha_1, \ldots, \alpha_n\}\). Then, the sought for Galois group appears as the group of permutations of \(\{\alpha_i\}_{i=1}^n\) given as field automorphisms of the extension \(\bar{K}_f = K(\alpha_1, \ldots, \alpha_n)/K\). That, however, leaves a mystery: like, how do you detect field automorphisms?

The vector space \(V_k = \{\sum_{j=k}^{n-1} m_j \alpha_j^k\}\) equals the field \(K(\alpha_k)\). Further, the substitution map \(s_{k,k'} : \alpha_k \mapsto \alpha_{k'}\) gives a natural field isomorphism \(V_k \to V_{k'}\).
Alas, since $V_{k'}$ is not necessarily equal to $V_k$, this may not be an automorphism, and $V_k$ is not $K_f$.\footnote{Indeed, for $k \neq k'$, $V_k \cap V_{k'} = K$, except for some rare exceptions.}

Our comments below are basic Galois theory. Yet, like a foreign language learned after childhood, they are easily forgotten. Here are reminders.

Apply to $\text{Spec}(K[y]/(f(y))) \to \text{Spec}(K)$ the $n$-fold fiber product construction of §2.1.1. At the level of taking the tensor product of rings, associate a direct summand of the ring tensor product, to the Galois closure. Since, however, that’s not the way it is done in algebra courses, consider one classical construction, of a polynomial $f$, for which any one of its roots gives $K_f$.\footnote{Perhaps due to van der Waerden, but compatible with Galois.} It goes, over $K$, like this.

Form any linear combination $L_a \overset{\text{def}}{=} L_a(\alpha) \overset{\text{def}}{=} \sum_{i=1}^{n} a_i\alpha_i$ of the roots of $f(y)$, $a_i \in K$. For $\tau \in S_n$ use the notation $L_a((\alpha)\tau) \overset{\text{def}}{=} \sum_{i=1}^{n} a_i\alpha_{(i)\tau}$.

(1.16a) Choose $a$ so that the $L_a((\alpha)\tau)$, for $\tau \in S_n$, are distinct.

(1.16b) Choose $\hat{f}$ to be an irreducible factor (over $K$) of $\prod_{\tau \in S_n} (y - L_a((\alpha)\tau))$.

Comments on (1.16a): Having $f$ an irreducible polynomial $K$ implies their quotient rings are fields. Since we don’t know $\{\alpha_1, \ldots, \alpha_n\}$, we cannot a priori pick those coefficients $a = a_1, \ldots, a_n$, though their existence is assured by avoiding values $a \in K^n$ that lie on the union of the hyperplanes

$$\left\{ (x_1, \ldots, x_n) \overset{\text{def}}{=} \mathbf{x} \in \mathbb{C}^n \mid L_{x}((\alpha)\tau) - L_{x}((\alpha)\tau'), \tau, \tau' \in S_n, \tau \neq \tau' \right\}.$$

Alas, it is hard to detect when a particular permutation is a field automorphism. So, it is hard to compute $G_P$. A more positive approach uses the case above:

(1.17) replacing $\alpha_1$ by $L_a$, a single field generator of $K(\alpha_1, \ldots, \alpha_n)$.

The effect of an automorphism $\tau$ on $K(\alpha_1, \ldots, \alpha_n)$, is determined by $L_a \mapsto L_{a}\tau$, one of the conjugates of $L_a$: zeros of the irreducible polynomial for $L_a$ over $K$—whose degree we take to be $N$.

Also, each $\alpha_k$ equals $A_k(L_a), k = 1, \ldots, n$, with $A_k \in K[y]$, a polynomial of degree $\leq N - 1$. The effect of any $L_a \mapsto L_{a}\tau$ is given by this substitution in the $A_k$s. Thus, the elements in $G_P \leq S_n$ correspond to these substitutions: $G_P$ consists of $\{\tau_1, \ldots, \tau_N\}$.

Comments on (1.16b): You can avoid making any choices for $a$ by using the variables $\mathbf{x}$ above, and forming the product

$$f_{\mathbf{x}}(y) = \prod_{\tau \in S_n} (y - \sum_{i=1}^{n} \alpha_{(i)\tau}x_i) \in K[\mathbf{x}].$$

Then, find an irreducible factor, $\hat{f}_{\mathbf{x}}(y)$, of it in $K[\mathbf{x}]$.

The group $G_f$ of $f$ is $\{\tau \in S_n \mid \hat{f}(\mathbf{x})\tau(y) \text{ identically equals } \hat{f}(\mathbf{x})y\}$. 
Any of these definitions work. The geometric one of the previous section – with only one significant choice; picking a connected component or irreducible factor – works especially well for understanding using components of Hurwitz spaces as moduli for variants on the RIGP.

**Remark 2.4.** In a tasteful, rather nice book, after noting that Galois introduced the word and full concept of (finite) group (quoting \[\text{Gal31}\]), \[\text{St10}, \text{p. 391}\] says:

Galois produced \([\text{the group, } G_E, \text{ of an equation called } E]\) as the permutation of roots that leave rational functions of the coefficients unaltered . . . .

A typo or a misunderstanding, by me or by him? Later, \[\text{St10, p. 413}\] says

We may be fairly sure that whatever Galois did was later superceded by Riemann.

Like many I am totally in the thrall of Riemann – as in \[\text{Fr02b}\]. Yet, you won’t find in Riemann Galois’s intuition about finite groups. Yes, Galois made mistakes, but his insight was specific and tasteful in his selection of problems.

Yet, I found Stillwell’s interpretation of Galois’ death, especially and thoughtfully included Galois despondency over “the suicide of his father, and Galois’s own self-destructive tendencies.” I have commented similarly on \[\text{Rig96}\], for example in \[\text{Fr90b, Ch. 2, §10.3}\], though regarding it as a moment of despondency during the Republican time in France that would have severely depressed many.

**2.2. \(\mathbb{P}^1\) covers and Nielsen classes.** We return to \(\varphi : W \to \mathbb{P}^1\), sphere covers. Call the images, \(z'\), of points of \(\varphi\) that ramify branch points. Such \(z'\) are places on the \(z\)-sphere where there are \(< n = \deg(\varphi) = n_\varphi\) distinct \(z'\)’s in \(\varphi^{-1}(z')\).

There are just finitely many such (distinct) points, \(\{z'_1, \ldots, z'_r\} = z'\). We often use \(r = 4\), the first value of \(r\) significantly using braids (§3.1.1).

2.2.1. *Using a fundamental group.* Denote the fundamental group of

\[\mathbb{P}^1_z \setminus z' \overset{\text{def}}{=} U_{z'}, \text{ based at } z_0 \in U_{z'}, \text{ by } \pi(U_{z'}, z_0).\]

As always, a (connected) cover, say, the restriction of \(\varphi\) to the points of \(W\) over \(U_z\) of degree \(n\) is given by a (transitive) permutation representation – homomorphism of \(\pi(U_{z'}, z_0) \to S_n\) by acting on the fiber, \(\mathbf{w'} = \{w'_1, \ldots, w'_r\}\), over \(z_0\) using the unique path-lifting property.

Here, though, we are more explicit and careful about choices. As a preliminary we can profitably use the definition of a \(z'_i\)-loop: That would be a path based at \(z_0\), that is homotopic to \(\delta_i \circ \tilde{\gamma}_i \circ \delta_i^{-1}\) on \(U_{z'}\) with \(\delta_i\) a simple path from \(z_0\) to a tiny disk neighborhood \(D_i\) of \(z'_i\) (on \(U_{z'}\)) ending at \(b_i\), and \(\tilde{\gamma}_i\) a (clockwise) circle around \(D_i\) starting and ending at \(b_i\). Fig. 1 compares two loops around \(z'_i\).
1. Covers and Monodromy Groups

Figure 1. Comparing two loops around $z'_{(i)}$

**Lemma 2.5 (Conjugate loops).** The loop $\delta_{i,j} \circ \gamma_{i,j} \circ \delta_{i,j}^{-1}$, $j = 1, 2$, are conjugate in the fundamental group $\pi_1(U_{z'}, z_0)$.

**Proof.** With no loss, up to the homotopy classes of the paths in question, we may assume the disks that $\gamma_{i,j}$, $j = 1, 2$ surround lie one inside the other, with an annulus between them. As in the figure on the right, we have drawn a (simple) path, $\rho$ within that annulus between $b_{i,1}$ and $b_{i,2}$, so that the path $\delta'_i$ is $\delta_{i,1} \circ \rho$.

If we conjugate $\delta_{i,1} \circ \gamma_{i,1} \circ \delta_{i,1}^{-1}$ by $\delta_{i,1} \circ \rho \circ \delta_{i,2}^{-1}$ the result is

$$\delta_{i,2} \circ \rho \circ \delta_{i,1}^{-1} \circ \delta_{i,1} \circ \gamma_{i,1} \circ \delta_{i,1}^{-1} \circ \delta_{i,1} \circ \rho^{-1} \circ \delta_{i,2}^{-1}$$

which is easily seen to be homotopic to $\delta_{i,2} \circ \gamma_{i,2} \circ \delta_{i,2}^{-1}$. That proves the lemma. \qed

Then Classical generators for the fundamental group of $\mathbb{P}^1 \setminus z'$ def $U_{z'}$ based at $z_0$ appear in many places. In words: They are (piecewise simplicial) closed paths, \{P_1, \ldots, P_r\} = \mathcal{P}$, representing, respectively,

$z'_i$ - loops, $i = 1, \ldots, r$, in $\pi_1(U_{z'}, z_0)$.

Further, other than at $z_0$ we may assume they pairwise intersect nowhere else. Given $\mathcal{P}$, there is one significant ordering: That these paths emanate from $z_0$ in going clockwise around a suitably small circle about $z_0$.

**Nielsen classes:** For convenience in listing properties of covers with branch points $z'$ relative to these paths, we assume the order of emanation of the $z'_i$-loops is given by their subscripts $1, \ldots, r$. For a cover $\phi : W \to \mathbb{P}^1_z$ with $z_0$ and $z'$ as above, label the points on $W$ above $z_0$ as $w' = \{w'_1, \ldots, w'_n\}$.

---

\[12\] For those who learned about tame ramification groups of Dedekind domain extensions, it may come as a surprise that Lem. 2.5 picks out a conjugacy class, rather than just a generator. That comes from our choice of a clockwise orientation in our loops.

\[13\] (1.18) is done in great detail in [Fr90b, Ch. 4] starting from [Ahl79, §1.1–1.3]. [Vo96] use idealized classical generators, leaving out a crucial point: The braid group is transitive on all possible classical generators, as used in the conclusions of (1.24).
2. NONSINGULAR SPHERE COVERS AND GALOIS CLOSURE

(1.18a) Homotopy classes of $\mathcal{P}$ generate $\pi_1(U_{z'}, z_0)$ freely with one relation: $P_1 \cdots P_r$ is homotopic to 1 (order given above).

(1.18b) Unique path lifting: $P_i \mapsto g_i \in S_n$ by the rule, running over $w'_j$, the unique lift of $P_i$ starting at $w'_j$ ends at $w'_k = w'_{(j)g_i}$, $i = 1, \ldots, r$.

(1.18c) branch cycles $(g_1, \ldots, g_r) = g$ satisfy Nielsen Class properties:

- **Generation**: the group $\langle g_1, \ldots, g_r \rangle = G_\varphi$ is the geometric monodromy (Galois closure) group of $\varphi$.
- **Product-one**: $g_1 \cdots g_r = 1$.
- **Conjugacy classes**: Independent of $P$, $\{g_i | i = 1, \ldots, r\}$ define conjugacy classes $C = \{C_1, \ldots, C_r\}$ in $G_\varphi$.

The path notation of Fig. 2 is compatible with that of Fig. 1.

**Figure 2.** Example classical generators based at $z_0$

**Problem 2.6.** Use Ch. 2 Prob. 2.3 to create classical generators from any base point $z_0$ for any given distinct points $z' \in \mathbb{P}^1_z$.

2.2.2. **First Nielsen class example.** Excluding stipulating the equivalence † we intend to use on covers – several appear – $\text{Ni}(G, C)^\dagger$ is just a listing of the covers of the sphere satisfying the conditions of (1.18c) with attached $(G, C, T)$ branched precisely at $z'$. Of course, $T$ depends on how we label points in $w'$. In §3 our † will be more explicit about that dependence. RET (Riemann’s Existence Theorem) says that giving covers with data attached to $(G, C, T, z')$ is the same as giving $r$-tuples $g$ as in (1.18c). That is, the sets are the same, though the associations between them depend on the choice of classical generators.

Comments on Prop. 3.5 say more on RET and identifying $\langle g_1, \ldots, g_r \rangle$ with the group of the Galois closure of $\varphi : W \to \mathbb{P}^1$. We have just shown that the identification requires recognizing that $W$ has a function field.
A cover doesn’t include an ordering its branch points. Adding such an ordering would destroy the applications to the RIGP. This makes sense of saying a cover is in the Nielsen class \(\text{Ni}(G, C, T)\) (or \(\text{Ni}(G, C)\)).

In some ways the dihedral group, \(D_{\ell^{k+1}} = \mathbb{Z} / \ell^{k+1} \times \{\pm 1\}\), of order \(2 \cdot \ell^{k+1}\) with \(\ell\) (for now) an odd prime, is an easy group. Still, it will be an extremely important running example for which we consider its elements, and those of related groups, as \(2 \times 2\) matrices. We have the choice, as in Def. 1.6, to consider \(\langle \pm 1 \rangle\) as acting on the left (resp. right). For example, with \(C_2\) the conjugacy class of \(
\begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}
\)
, we would regard \(C_2\) as the collection

- **Left action:** \[
\left\{ \begin{pmatrix}
-1 & a \\
0 & 1
\end{pmatrix} \mid a \in \mathbb{Z} / \ell^{k+1} \right\}
\]

- **Right action:** \[
\left\{ \begin{pmatrix}
-1 & 0 \\
a & 1
\end{pmatrix} \mid a \in \mathbb{Z} / \ell^{k+1} \right\}.
\]

Then, for the standard permutation representation \(T : D_{\ell^{k+1}} \to S_{\ell^{k+1}}\), with letters \(b \in \mathbb{Z} / \ell^{k+1}\), we would respectively have \(g \in D_{\ell^{k+1}}\) act by

- **Left action:** \[
g = \begin{pmatrix}
-1 & a \\
0 & 1
\end{pmatrix} : (b 1) \mapsto (a-b 1)
\]

- **Right action:** \[
g = \begin{pmatrix}
-1 & 0 \\
a & 1
\end{pmatrix} : (b 1) \mapsto (a-b 1),
\]

as expected by extending matrix multiplication to vectors.

**Example 2.7 (An “Elementary” example).** As above, using the left action, let \(N_k\) be the normalizer in \(S_{\ell^{k+1}}\) of \(D_{\ell^{k+1}}\) and consider absolute Nielsen classes \(\text{Ni}(D_{\ell^{k+1}}, C_2, T)^{\text{abs}} = \text{Ni}_k^{\text{abs}}\). Associate

\[
\left( \begin{pmatrix}
-1 & a_1 \\
0 & 1
\end{pmatrix}, \begin{pmatrix}
-1 & a_2 \\
0 & 1
\end{pmatrix}, \begin{pmatrix}
-1 & a_3 \\
0 & 1
\end{pmatrix}, \begin{pmatrix}
-1 & a_4 \\
0 & 1
\end{pmatrix} \right)
\]

to \((a_1, a_2, a_3, a_4) \in \left(\mathbb{Z} / \ell^{k+1}\right)^4\) modulo \(N_k\).

Count these using representatives with these properties:

- (1.19a) \(a_1 = 0, a_2-a_3+a_4 = 0;\) and
- (1.19b) \(a_2 = 1\) or \(\ell \mid a_2\) and \(a_3 = 1\).

Then: \(|\text{Ni}_k^{\text{abs}}| = \ell^{k+1} + \ell^k\). Modding out only by \(D_{\ell^{k+1}}\) — instead of \(N_k\) — gives \(|\text{Ni}_k^{\text{in}}| = (\ell^{k+1} + \ell^k)\varphi(\ell^{k+1})/2\) with \(\varphi\) the Euler \(\varphi\)-function.

Renormalize: Use \(a_2-a_3 = a'\ell^u\) with \((a', \ell) = 1\) in place of \(a_2 = 1\); conjugate by \(
\begin{pmatrix}
a' & 0 \\
0 & 1
\end{pmatrix}
\)
to take \(a' = 1\). This allows further conjugation with \(a \equiv 1 \mod \ell^{k+1-i}\).

This example continues in Ch. 2 §3.2. Ch. 6 §3.2 identifies spaces of covers (§3) in dihedral Nielsen classes, when \(C = C_2^4\), with modular curves. △

### 2.3. Classical visions of RET.
Since Riemann died in 1866, there has been a long history of accustoming to RET, much of it evidence of different generations learning it anew, since there is no obvious place in the (especially undergraduate) curriculum where it belongs. In the short subsections §2.3.1 – field theoretic – and
§2.3.2 - picture centric - I engage that history. We would never get anywhere if we only concentrated on the elementary questions they raise, though at least the first of these sections deserves more treatment.

2.3.1. Field version of RET. Suppose \( L/C(z) \) is a finite extension, given by an irreducible polynomial \( F_L(z, w) \), of degree \( n \) in \( w \). For each \( z' \) (branch point or not), we may find \( n \) zeros of \( F_L \) in the field of Puiseux expansions \( \cup_{k=1}^{\infty} C(((z - z')^{1/k})) \).

That is, we have an embedding \( \psi_{z'} : \hat{L} \to \text{Pu}_{z'} \) of the Galois closure, \( \hat{L} \), of \( L/C(z) \) in \( \text{Pu}_{z'} \). Such a \( \psi_{z'} \) is defined up to composing with elements of \( G(\hat{L}/C(z)) \).

Elementary statement of RET: Further, there is a canonical automorphism of \( \text{Pu}_{z'} \) (fixed on the Laurent series, \( C((z - z')) \)) in \( z - z' \) given by

\[
\sigma_{z'} : (z - z')^{1/k} \mapsto e^{\frac{2\pi i}{k}} (z - z')^{1/k} \text{ for all } k \geq 1.
\]

Only for \( z' \) among the branch points \( z_L \) will the restriction to \( \hat{L} \) be nontrivial. For each branch point, \( z_i \), that restriction gives an element \( g_{z_i} \) in \( G(\hat{L}/C(z)) \), thereby, as previously, defining a conjugacy class \( C_i \) in this group.

**Proposition 2.8.** The Nielsen class conditions imply for some choices of \( \psi_{z_i} \), \( 1, \ldots, r \), the \( g = \{g_1, \ldots, g_r\} \) satisfy product-one and generation.

Further, they imply the inverse problem. Assume any distinct \( z \) and elements \( g \) that satisfy product-one that generate a (finite) group \( G \), with a transitive permutation representation of degree \( n \). Then there is \( L/C(z) \) as above producing \( g \).

As \( g \) defines the genus of the unique Riemann surface associated to \( L \) from the RH formula (1.32). So, there is a natural collection of appropriate questions that go under the following heading.

**Question 2.9.** Is any of this easy, or doable explicitly, or without using the fundamental group of the \( r \)-punctured sphere (a la Fig. 2)?

**Fiber products of genus 0 covers:** For example, consider these questions.

(1.20a) Can we answer Quest. 2.9 affirmatively for genus 0 (given by a rational function in \( w \)) extensions?

(1.20b) if the answer is yes, to (1.20a) can we use fiber products of genus 0 extensions to answer yes to all extensions.

Even Riemann relied on fiber products of genus 0 covers – the description of hyperelliptic curves, and finding nondegenerate odd half-canonical classes (§1.3 – to conclude one of his most famous theorems. In that he gave a formula for finding all functions on any Riemann surface of genus \( g \) as a ratio of translates of a particular \( \theta \) function formed from that half-canonical class. This generalized Abel’s analogous
theorem on elliptic curves, the only genus where half-canonical classes could be confused with 2-division points, and where there is a unique odd half-canonical class. This Abel Theorem, not discussed in great detail in [Fr02b], though it is the concentration point of most treatises that do mention Abel’s Theorems.\footnote{It is in the subjects of [Fr90b, §7.2] and [Fr10, §6] in a style related to that of Riemann.}

**Proposition 2.10.** Even if the answer to (1.20a) is affirmative, the answer to (1.20b) is no.\footnote{See the proof for the meaning of this.}

**Proof.** Suppose a cover \( \varphi : W \to \mathbb{P}_z^1 \) has monodromy group one of the simple groups that does not appear as a composition factor of a genus 0 cover of \( \mathbb{P}_z^1 \). Answering (1.20b) affirmatively means that the Galois closure of a given cover, say \( \varphi \), appears as a quotient of the fiber products of the Galois closures of genus zero covers. In that case, however, the group \( G_\varphi \) would have each composition factor appear as a composition factor of the Galois closure of one of those genus 0 covers.

From, however, the genus 0 problem [Fr05b, §7.2.1], only finitely many simple groups – outside of cyclic and alternating groups – appear as composition factors of monodromy of genus 0 covers.\footnote{This is the result on the genus 0 problem as originally formulated by the author and J. Thompson, but R. Guralnicks stronger conjectures on the specific monodromy of primitive genus 0 covers, and also general genus, have been proven.} Yet, every group appears as the monodromy of \( \mathbb{P}_z^1 \) cover from RET, including those simple groups that can’t be realized from the genus 0 problem. \( \square \)

**Remark 2.11.** There is a simplification in trying to construct rational function covers, for – by Luroth’s Theorem – they are pure transcendental over some coefficient field. In particular cases, they have been so described as covers of \( \mathbb{P}_z^1 \) following their appearance in families of Hurwitz spaces. For example, as in [CoCa99], which constructs the polynomial covers – called Davenport pairs – using a computer program. Still, the group theory and RET as in [Fr80] lie behind their solution.

Another example – for regularly realizing \( \text{Spin}_n \) – is those covers in the Nielsen classes denoted \( \text{Ni}(A_n, C_{3n-1}) \), \( n \geq 5 \) and odd in Ch. 3 Ex. 2.9. Here – [Me90], with an exposition in [Se92, §9.3], and an earlier attempt for \( n \equiv 1 \mod 8 \) in [Vi85] – the construction is only explicit for \( \varphi : X \to \mathbb{P}_z^1 \) in the Nielsen class when there is \( z' \in \mathbb{P}_z^1(\mathbb{Q}) \) with \( \varphi^{-1}(z') \) consisting of \( \mathbb{Q} \) geometric points.

2.3.2. **Cuts and impossible pictures.** There has been a tradition for drawing “3D pictures” – in \( \mathbb{R}^3 \) – of covers of the sphere, by functions even easier than those given by in Ex. 2.7, for covers with just 3 branch points (or even 2, rather than 3). I have asked two questions:

(1.21a) Are the pictures meaningful, usefully conveying properties of the covers?
(1.21b) Do they turn out to work in more serious examples?

**Projecting from $\mathbb{C}^2$ to $\mathbb{R}^3$:** Consider the problem of representing covers by pictures in $\mathbb{R}^3$, with an attempt to give a description of the ramified cover $f : U_{w,0,\infty} \to U_{z,0,\infty}$ by $w \mapsto w^n$ in Fig. 3. Points of $U_{w,0,\infty}$ over $z \in U_{z,0,\infty}$ correspond on the graph of $f$ to $\mathbb{C} \times \mathbb{C}$ points on the line with constant second coordinate $z$.

You can’t draw pictures in $\mathbb{C} \times \mathbb{C} = \mathbb{R}^4$. So first year complex variables texts try to represent $U_{w,0,\infty}$ and $U_{z,0,\infty}$ as subsets of $\mathbb{R}^3$. In Fig. 3, a traditional picture representing the $n$th power map as if it were the projection on a real coordinate. Let $(x_1, x_2, x_3)$ be coordinates for $\mathbb{R}^3$, and let $x_3 = 0$ represent $U_{z,0,\infty}$ sitting in $\mathbb{R}^3 \setminus \{(0,0,0)\}$. Pictures try to represent an annulus around the origin in $U_{w,0,\infty}$ as a set $M$ in $\mathbb{R}^3$ over an annulus $D_0$ in $U_{z,0,\infty}$. Then, points of $M$ over $(x_1, x_2, 0) \in D_0$ are on the line in $\mathbb{R}^3$ whose points have first coordinates $x_1$ and $x_2$. That is, $f$ appears as a coordinate projection.

A lift of $\gamma$ (a clockwise circle, compatible with choices for classical generators) is $\tilde{\gamma}$ going $\frac{1}{n}$ of the way around a clockwise circle. The associated permutation is an $n$-cycle of $S_n$ representing that $\tilde{\gamma}$ goes from the lift $y' = 2^{1/n}$ of $\gamma(0) = 2$ to $y'' = 2^{1/n} e^{-2\pi i}$, the point on $\tilde{\gamma}$ lying $\frac{1}{n}$ of the way around from $y'$.

**Figure 3.** An $n$-cycle of path liftings

There is, however, no topological subspace $M$ of $\mathbb{R}^3$ that can work! If there were, then a cylinder perpendicular to the plane $x_3 = 0$, with $(0,0,0)$ on its axis, would intersect $M$ in a simple closed path winding $n$ times around the cylinder. Represent such a path by $\gamma : [0,1] \to \mathbb{R}^3$ where $t \in [0,1]$ maps to

$$\gamma(t) = (\cos(2\pi nt), \sin(2\pi nt), x_3(2\pi nt)) \text{ and } x_3(2\pi n) = x_3(0).$$

Conclude: $w(t) = x_3(2\pi nt) - x_3(2\pi nt + 2\pi)$ is 0 for some value of $t$ between 0 and $(n - 1)/n$. So, the path isn’t simple. The author has never seen such a picture attempt in the literature for any noncyclic cover, much less for more demanding nonsolvable groups.
A word on “cuts”: Even the case when the degree \( n \) is 2, and we are considering \( \varphi : W \to \mathbb{P}^1_z \), where \( W \) has a presentation as a sphere with \( g \) handles in \( \mathbb{R}^3 \), presenting the map \( \varphi \) by a picture in \( \mathbb{R}^3 \) can be confusing. Still, something akin to that appears in many books – for example, [Con78, p. 243] – and it is analyzed in [Fr90b, Ch. 2, § 2.4.1]. That picture includes all the usual elements, especially the cuts. The discussion there, concentrates on the Fig. 7, there: two discs snipped along cuts along their negative real axes, with the left cut on one jointed to the right cut on the other, etc. Then, paths around an origin in the picture jump from one cut disk to the other, in a way that represents continuity symbolically.

From [Ne81], we learn that Gauss introduced Riemann to cuts. Their value is that they suggest how a combination of symbols and pictures can justify the topology. This establishes the idea behind the cuts is that “similar” covers – meaning they are in the same Nielsen class – have a locally constant structure. Yet, that symbolic case is a hyperelliptic curve covering \( \mathbb{P}^1_z \).

While we don’t develop those cuts here in detail, §3.1.1 – under the rubric of “dragging a cover by its branch points” – shows where they get used precisely in the description of the Hurwitz monodromy group, \( H_r \). §3 takes the approach that a Nielsen class representing a space of covers, that deform through changing their branch points, can leap us over an entanglement with impossibly complicated paths on particular Riemann surface covers.

There are so many problems that demand going beyond hyperelliptic covers. One standout, Prob. 3.8 however, dominates the applications in this book.

3. Hurwitz spaces parametrize covers in \( \text{Ni}(G, C) \)

We now discuss the space of all covers in a given Nielsen class. Ch. 5 §3 will explicitly illustrate each of Prop. 3.1, 3.2 and 3.5 on the main example of this paper. That is, we illustrate computing with braids, and Nielsen class elements. That does not mean we will write out equations for the spaces and covers.

3.1. Parameters for covers. A (Hurwitz) space whose points parametrize covers in a particular Nielsen class of \( r \) classes appears as a cover of a configuration space. This is \( r \) unordered branch points minus the locus where two come together:

\[
U_r = \text{projective } r\text{-space } \mathbb{P}^r, \text{ minus its discriminant locus, } D_r.
\]

Take \( z_0 \) to be a basepoint of \( U_r \), and
denote \( \pi_1(U_r, z_0) \), the Hurwitz monodromy group, by \( H_r \).

3.1.1. Dragging a cover. Here is how to think of forming Hurwitz spaces, a process we refer to as dragging a cover by its branch points.
Start with $\varphi_0 : W_0 \to \mathbb{P}^1_z$, a cover with branch points $z_0$, classical generators $\mathcal{P}_0$ and (branch cycles) $g_0 \in \text{Ni}(G, C)$. Drag the branch points along any path $B$ in $U_r$, starting at $z_0$ and ending at $z_1$. Then, deform the classical generators along that path to $\mathcal{P}_1$. With no further choices, we may canonically form a cover $\varphi_t : W_t \to \mathbb{P}^1_z$ with respect to the same $g_0$ along the path indicated by the parameter.

**Classical generators $\to$ identifying branch cycles:** This produces a collection of $\mathbb{P}^1_z$ covers of cardinality $|\text{Ni}(G, C)|$ over every point of $U_r$, forcing upon us a decision. Should $B$ be a closed path, representing an element of $\pi(U_r, z_0)$, how do we identify branch cycles $g_1$ for the cover $\varphi_1 : W_1 \to \mathbb{P}^1_z$ lying at the end of the path, relative to the original classical generators $\mathcal{P}_0$?

(1.23) That is, what will we choose for $\dagger$?

Here are key points going back to [Fr77, §4].

(1.24a) **Endpoint of the Drag:** A cover at the end of $B$ is still in $\text{Ni}(G, C)$. It depends only on the homotopy class of $B$ with its ends fixed.

(1.24b) **Branch cycle finale:** For $B$ closed, a braid, $q_B \in H_r$ (§2) applied to $g_0$ gives $g_1 = (g_0)q_B$.

(1.24c) **Minimal equivalence:** For each $g \in G$, some braid $q_g$ conjugates entries by $g$; see Ch. 2 Prob. 2.2: $(g_0)q = g(g_0)g^{-1}$.

(1.24d) **$H_r$ orbits:** (Irreducible) components of spaces of covers in $\text{Ni}(G, C)$ correspond to $H_r$ orbits.

Ch. 2 §2.1.2 gives explicit paths on $U_r$, and their effect as braids. Whatever the problem application, we must be able to identify the Galois closure of the cover. The key ambiguity is in labeling $w' = \{w'_1, \ldots, w'_n\}$, points lying over $z_0$. Changing that labeling changes $T : G \to S_n$. A slightly subtler change comes from changing $z'_0$. There is a distinction between them.

Changing $z'_0$ to $z^*_0$ is affected by rewriting the $z_i$-loops as

\[
\lambda^* \circ \lambda \circ \rho \circ \lambda^{-1} \circ (\lambda^*)^{-1}, \text{ with } \lambda^* \text{ a path from } z^*_0 \text{ to } z_0.
\]

3.1.2. Absolute vs Inner equivalence. Assume $\varphi_0 : W_0 \to \mathbb{P}^1_z$ is a cover, branched at $z_0$, with assigned branch cycles using a classical set of generators as above. Applications dictate under what circumstances we will identify covers $\varphi_i : W_i \to \mathbb{P}^1_z$, $i = 0, 1$, branched at $z_0$, obtained from dragging a given cover $\varphi : W \to \mathbb{P}^1_z$ around two (different) closed paths in $U_r$ using the dragging-branch-points principle.

Prop. 3.1 is a first statement on equivalences of covers corresponding to elements in a Nielsen class. Denote the subgroup of the normalizer, $N_{S_n}(G)$, of $G$ in $S_n$ that permutes a given collection, $C$, of conjugacy classes, by $N_{S_n}(G, C)$.
Proposition 3.1 (Spaces I). As above, suppose \( \mu : W_0 \to W_1 \) is a continuous isomorphism with \( \mu \circ \varphi_1 = \varphi_0 \) (commuting with the projections to \( \mathbb{P}^1_z \)). Then, \( \mu \) is automatically analytic. It permutes elements of \( \mathbb{w}' \) according to \( h \in N_{S_n}(G, C) \), inducing \( \mu^*_h : g \in G \mapsto hgh^{-1} \); and conversely.

There are two extremes for the equivalences we allow for such \( \mu \) s:

(1.26a) Inner: The effect of running over all \( g(\lambda^i) \) s is to change the permutation representation \( T \) by conjugating by an element of \( G \).

(1.26b) Absolute: Changes of permutation given by conjugating \( T \) by any \( g \in S_n \) maps \( \langle g_1, \ldots, g_r \rangle = G \) into itself.

That is, inner equivalence is minimal to account for not indicating a choice of basepoint, and absolute is maximal (equivalencing the most covers).

Comments. There is a point to be made on (1.25) To keep the loops pairwise non-intersecting except at \( z_0^* \) requires only using a fan of \( \lambda^i \) s, one for each \( i \), just slightly varied from each other. It is a minor point (see [Fr77, Lem. 1]).

When \( \lambda^i \) is a closed path, using the path lifting property produces a permutation \( g(\lambda^i) \in G \) on \( \mathbb{w}' \), the points lying over \( z_0 \). This is the source of why inner equivalence is the minimal equivalence to assure that using a base point in the construction of the Hurwitz spaces does not appear in their final description in §3.1.3. \( \Box \)

3.1.3. Representations of \( H_r \) produce spaces. Now we show how braids acting on (equivalence classes of) elements in Nielsen classes produce the Hurwitz spaces. Each equivalence class corresponds to an equivalence class of Nielsen classes. Again, we distinguish between the two most used equivalences: absolute and inner. Then, assuming the hypothesis of Lem. 2.3, Prop. 3.5 constructs total spaces of covers from the main theorem on fundamental groups applied to the space \( U_r \). We also relate the respective spaces for those two equivalences.

Fundamental group representations give covers: Recall: unramified covers of a space, \( Z \), arise from permutation representations \( T : \pi_1(Z, z_0) \to S_n \) of the fundamental group of \( Z \). We now apply this to \( \pi_1(U_r, z_0) = H_r \).

(1.27) The cover is connected if and only if \( T \) is transitive:

For each \( i \in \{1, \ldots, n\} \), \( \exists h \in \pi_1(Z, z_0) \mid (1)T(h) = i \).

Proposition 3.2 (Spaces II). Applied to (1.24b), equivalences interpret when the final cover, \( \varphi_1 \), after dragging \( \varphi_0 \) along \( q_B \) is isomorphic to \( \varphi_0 \). Whatever the equivalence \( \dagger \), this defines a parameter space of covers denoted by \( \mathcal{H}(G, C)^\dagger \).

Mapping a cover of \( \mathbb{P}^1_z \) to its (unordered) branch points presents \( \mathcal{H}(G, C)^\dagger \) as an unramified cover \( \Phi^\dagger_k : \mathcal{H}(G, C)^\dagger \to U_r \) of \( U_r \).

Here: \( \mathcal{H}(G, C)^\dagger \) arises from a representation of \( \pi_1(U_r, z_0) \) acting on \( \text{Ni}(G, C)^\dagger \) (made explicit using the rules of §2) [Fr77, §4].
(1.28a) If \( \dagger = \text{abs (absolute)} \), then \( \text{Ni}(G, C)\dagger \) is
\[
\text{Ni}(G, C)\dagger^{\text{abs}} = \text{Ni}(G, C)^{\text{absT}} = \text{Ni}(G, C)/\text{NS}_n(G, C),
\]
where we drop the representation \( T \) if we know it from context.

(1.28b) If \( \dagger = \text{in (inner)} \) then \( \text{Ni}(G, C)\dagger = \text{Ni}(G, C)^{\text{in}} = \text{Ni}(G, C)/G \).

**Comments.** We make use of the following comments later. Inner equivalence is understood to be \( \text{Ni}(G, C, T)^{\text{in}} = \text{Ni}(G, C)/G \) where \( T \) is the regular representation of \( G \), and each (Galois) cover \( \hat{W} \rightarrow \mathbb{P}^1 \) in the Nielsen class includes an isomorphism \( \psi : \text{Aut}(\hat{W}/\mathbb{P}^1) \rightarrow G \), defined up to an inner isomorphism of \( G \).

For each \( h \in G \), and \( g \in \text{Ni}(G, C)\dagger \), there exists \( q_B \in H_r \) such that
\[
(g)q_B = hg^{-1}, \quad \text{with } q_B \text{ dependent on both } h \text{ and } g.
\]
With the operators \( q_i \) in §2, the idea comes from
\[
(g)q_1 \cdot q_2 \cdots q_{r-1} \cdot q_{r-1} \cdots q_2 \cdot q_1 = g_1g^{-1}.
\]
This concludes showing that the braid action automatically equivalences Nielsen classes if they are inner conjugate.

Dragging a cover around by its branch points defines an orbit of \( H_r \) on a Nielsen class \( \text{Ni}(G, C)\dagger \). Therefore an irreducible cover of \( U_r \) (Prop. 3.2). Doing this for each \( H_r \) orbit assigns an equivalence class of covers to each point on the cover \( \mathcal{H}(G, C)\dagger \) or even a space of covers in any simply connected neighborhood of any point of \( \mathcal{H}(G, C)\dagger \). The next proposition relates absolute and inner equivalence.

The spaces of Prop. 3.2 are generalizations of the *moduli space of curves of a fixed genus*. That is, all covers \( \varphi : W \rightarrow \mathbb{P}^1 \) in a fixed Nielsen class \( \text{Ni}(G, C)\dagger \) have the same genus, \( g_W \overset{\text{def}}{=} g_{G, C} \). We compute it easily using the notation of the index,
\[
\text{ind}(g) = \text{deg}(T) - k,
\]
of any \( g \) in a class \( C \) which has precisely \( k \) orbits under \( T \). This defines \( \text{ind}(C) \), and
\[
\text{Riemann-Hurwitz: } 2(\text{deg}(T) + g_{G, C} - 1) = \sum_{i=1}^{r} \text{ind}(C_i).
\]

**Remark 3.3.** See Def. 3.7 on braiding inner vs outer automorphisms. This topic is significant for many of our applications.

**Remark 3.4 (Comments on equivalences).** Branch cycles give permutation representations of \( \Pi_1(U_2, z_0) \). We’re not done with our basic equivalences yet, as we also have reduced equivalence Ch. 2 §2.1.3. There are others, too, that have been used in applications such as [DFr90b]. Further, there is a natural notation for considering when one permutation representation extends another, on the same group or a covering group, and thereby consider chains of covers and the maps induced on Hurwitz spaces from these.
Further, more generally we could add equivalences on permutation representations of $\Pi_1(U_z, z_0)$. That would be appropriate for relating the Hurwitz spaces themselves. We haven’t considered these systematically as the applications are a different nature than those considered in this book.

3.2. Relating inner and absolute spaces. Given a faithful (transitive) permutation representation $T : G \to S_n$, and a Nielsen class $\Ni(G, C)$, there is automatically a relation between $\mathcal{H}(G, C)\text{in}$ and $\mathcal{H}(G, C)\text{abs}$.

Prop. 3.5 shows the result on the spaces $\mathcal{H}(G, C)\text{abs}$ of the fine moduli condition on the group $G$.

**Proposition 3.5 (Spaces III).** Assume $(G, T)$ is self-normalizing as in Lem. 2.3. Then, there is a unique total family, or fine moduli structure,

$$\Phi^{\text{abs}}_T : T^{\text{abs}} \to \mathcal{H}(G, C)^{\text{abs}} \times \mathbb{P}^1_z$$

on $\mathcal{H}(G, C)^{\text{abs}}$, so that the pullback over $p \times \mathbb{P}^1_z$ represents the equivalence class of the covers associated to $p \in \mathcal{H}(G, C)^{\text{abs}}$.

The Galois closure construction of (1.15) produces a unique total family,

$$\Phi^{\text{in}}_T : T^{\text{in}} \to \mathcal{H}(G, C)^{\text{in}} \times \mathbb{P}^1$$

on $\mathcal{H}(G, C)^{\text{in}}$ with $\tilde{p} \in \mathcal{H}(G, C)^{\text{in}}$ over $p$ representing an inner (Galois) cover mapping to an absolute cover. Further, all these spaces are quasi-projective varieties.

For any irreducible component $\mathcal{H}''$ of $\mathcal{H}(G, C)^{\text{in}}$, the natural map to its image, $\mathcal{H}'$, in $\mathcal{H}(G, C)^{\text{abs}}$

(1.33)

is Galois with group a subgroup of $N_{S_n}(G, C)/G$.

The remainder of this subsection consists of background and comments on Prop. 3.5. §3.2.1 emphasizes the main condition on a moduli space that appears in applications: fine moduli. It also introduces the idea that RET meshes seamlessly with describing the moduli spaces that put covers in natural families.

Braid orbits on absolute (resp. inner) Nielsen classes give the absolutely irreducible components of absolute (resp. inner) Hurwitz spaces. At the heart of §3.2.2 is how to enumerate the components of the inner Hurwitz space that go to a a single component of the absolute space. A major part of identifying components appears in the topic of braiding outer automorphisms.

3.2.1. Fine moduli and expanding RET. In relating the construction of $\mathcal{H}^{\text{in}}$ to that of $\mathcal{H}^{\text{abs}}$ as a Galois closure construction based on (1.15) we are elaborating on [BFr02, §3.1.3]. We give the original argument in [Fr77, §4], based on Riemann’s work on compact Riemann surfaces and [GRe57] as below.

From Lem. 2.3, the self-normalizing condition translates to say covers in the Nielsen class $\Ni(G, C)^{\text{abs}}$ have no automorphisms. Thus, a unique map patches
any family of such covers on two overlapping open (simply-connected) sets on $\mathcal{H}(G, C)^\text{abs}$. A well-known co-cycle patching puts a total family over the space, giving $\Phi^\text{abs}$. We regard the association of elements of Nielsen classes to covers with branch cycles in a Nielsen class, as in (1.18), as part of RET.

Many refer to RET as if its only aspect is that any (compact Riemann surface) cover $\varphi : W \to \mathbb{P}^1_z$ has a function field determining it. Or its equivalent, it embeds in a closed subspace of some projective space.

Ch. 2 applications require the generalization of this to which we refer below in these comments. Some need only moduli fields of the components (definition fields as moduli spaces; Def. 4.8). Others require finding points on those same spaces over some specific field (like $\mathbb{Q}$).

Now you can apply the Galois closure construction to $\Phi_T^\text{abs}$, remove the appropriate version of the fat diagonal and refer to the result as

$$\Phi' : T' \to \mathcal{H}(G, C)^\text{abs} \times \mathbb{P}^1_z.$$  

The construction then is to take the $n$-fold fiber product of $\Phi^\text{abs}$, remove the appropriate version of the fat diagonal and refer to the result as

$$(1.34) \quad \Phi' : T' \to \mathcal{H}(G, C)^\text{abs} \times \mathbb{P}^1_z.$$  

The Galois closure of the individual covers appears along the fibers over each $p \times \mathbb{P}^1_z$, for $p \in \mathcal{H}(G, C)^\text{abs}$, but usually more times than even in the application of the construction for each individual cover. Now, however, we must figure how to normalize and what we are getting from taking a component. From the start, we need to know that irreducible components of $\mathcal{H}(G, C)^\text{abs}$ are quasi-projective normal varieties. Initially, we form them analytically, not algebraically.

[Fr77] applies a deep theorem – that of Grauert-Remmert [GRe57] – to assert that normalization in a function field makes sense. [H77, p. 442] references [GRe58], which is a more complete writeup of the three short Comptes Rendu papers. This, by itself is an extension of part of Riemann’s existence theorem.

It says that if $W$ is an irreducible analytic space, covering a Zariski open quasi-projective normal variety $Z$, then $W$ itself is dominated by a unique quasi-projective normal variety $\hat{W}$. The major point is that $\hat{W}$ has a field of functions, obtained by extending the functions of $Z$ by one more function that separates points and tangent directions in general fibers of $W \to Z$.

(1.35a) For the case of $\mathcal{H}(G, C)^\text{abs}$, the quasi-projective normal variety $Z$ is the $U_r, (1.22)$ which is nonsingular, so normal.

(1.35b) Even the case $\varphi : W \to \mathbb{P}^1_z$ in §2 required this.$^{17}$

(1.35c) With self-normalizing for $(G, T): W = T^\text{abs}$ and $Z = U_r \times \mathbb{P}^1_z$.

$^{17}$Riemann-Roch is stronger, saying for any compact Riemann Surface, it has a field of functions. This is nontrivial even when applied to a genus 0 Riemann surface. There is no general version like that for analytic spaces.
1. COVERS AND MONODROMY GROUPS

(1.35d) The proof of [FrV91, Thm 1] reduces the special cases (1.35a) and (1.35c) to the 1-dimensional case (1.35b).

(1.35e) Besides having a coherent modern treatment, [Gr71] has the foundations of ℓ-adic modules from cohomology.

3.2.2. Identifying fibers of $\mathcal{H}^{\text{in}}$ over a point of $\mathcal{H}^{\text{abs}}$. Consider a component $\mathcal{H}'$ of $\mathcal{H}(G, C)^{\text{abs}}$. For each cover, $W_p \to p \times \mathbb{P}^1_z$, appearing in in a fiber of $\Phi^{\text{abs}}_T$ we get a correct count of covers, over this given cover, along each fiber of $\Phi'$ from the quotient of the cardinalities of the respective Nielsen classes: $|N_{S_n, C}(G)/G|$.

Continue (1.34) and take a connected component, $\mathcal{T}^{\text{in}}$, of $\mathcal{T}$. Normalize $\mathcal{H}'$ in the function field of $\mathcal{T}^{\text{in}}$ to get $\mathcal{H}'$. A subgroup, $G_{\mathcal{H}'/\mathcal{H}'} \leq N_{S_n}(G, C)/G$ is transitive on the covers in the fiber of $\mathcal{T}^{\text{in}}$ lying over $W_p \to p \times \mathbb{P}^1_z$, for all $p \in \mathcal{H}'$. Thus, $\mathcal{H}'' \to \mathcal{H}'$ is Galois with group $G_{\mathcal{H}'/\mathcal{H}'}$. This completes (1.33).

This shows that connected covers $W''_p \to p \times \mathbb{P}^1_z$ over $W_p \to p \times \mathbb{P}^1_z$ in $\mathcal{T}^{\text{in}}$ correspond to composing the identification of their automorphism groups with $G$ (up to conjugation by $G$) with conjugation by elements of $N_{S_n}(G, C)$. As previously (with $S_n$ action on (1.13)), we get transitivity on those connected covers from explicit elements of $N_{S_n}(G, C)$. See Def. 3.7 for why these may not all lie in one connected component.

Remark 3.6. Applications, however, even without the adjective, fine, use that $\mathcal{H}(G, C)^\dagger$ has moduli space meaning, with the relation between the equivalence classes inner and absolute (see Rem. 3.10). Ch. 6 §4.3.2 expediently surveys what is now called the stack structure for one approach.

**Braiding automorphisms:** Consider a braid orbit $O$ in $\text{Ni}(G, C)$ and an automorphism $\alpha$ of $G$ that preserves $C$ (with proper multiplicity).

**Definition 3.7** (Braiding automorphisms). If for $g \in O$ and $q \in H_r$,

$$\langle g \rangle q = (g)\alpha,$$

we say $q$ braids $\alpha$.

Since the $\alpha$ action commutes with any braid $q' \in H_r$ acting, the test for braiding an automorphism is independent of the representative $g \in O$.

More generally, the dominant problem in this book is the following.

**Problem 3.8.** For a given Nielsen class $\text{Ni}(G, C)^\dagger$, find conditions that identify Hurwitz space components (braid orbits) and their moduli fields.

Our techniques for doing this – especially the $\text{sh}$-incidence matrix, and the lift invariant – often either reveal a geometric way to separate the distinct orbits, or show them to be conjugate under the action of the absolute Galois group $G_{\mathbb{Q}}$. 
A preliminary example on the Nielsen class \( \mathrm{Ni}(A_4, C_{\pm}) \) illustrates both techniques. Ch. 2 §3.3.2 for \( \text{sh} \)-incidence and Ch. 2 §3.3.3 for the lift invariant, where precise cusp types, called there \( \text{HM} \) and \( \text{DI} \) separate the components. Then, (1.36) gives geometric interpretation we can recognize as more classical, whereas cuts might not give much of a clue. Label the respective inner Hurwitz space components as \( \mathcal{H}_{\text{HM}} \) and \( \mathcal{H}_{\text{DI}} \).

(1.36a) Only for \( \hat{\varphi} : \hat{W} \to \mathbb{P}^1_z \) in \( \mathcal{H}_{\text{HM}} \) does there exists a degree 2 unramified cover \( \varphi' : Y \to W \) for which \( \hat{\varphi} \circ \varphi' \) is Galois with group \( \hat{A}_4 \).

(1.36b) Only for \( \hat{\varphi} : \hat{W} \to \mathbb{P}^1_z \) in \( \mathcal{H}_{\text{HM}} \) can we identify a cover on the boundary of the compactification of \( \mathcal{H}_{\text{HM}} \) with a totally degenerate cover.

These separations are recognized by \( G_{\mathbb{Q}} \), and therefore both \( \mathcal{H}_{\text{HM}} \) and \( \mathcal{H}_{\text{DI}} \) have moduli field \( \mathbb{Q} \). This is an example that uses “cuts,” as a theoretical background behind braid orbits, though indirectly an answer for what the questions (1.21) seek.

**Remark 3.9.** Expression (1.31) says you can always braid inner automorphisms: conjugations of \( g \) by some \( g \in G \). This may not apply to \( h \in N_{S_n}(G, C) \) or to an outer automorphism not represented by some \( g \in S_n \), even if it permutes the conjugacy classes in \( C \). Explaining when you can, or cannot, braid outer automorphisms appears in most applications (say, Thm. 1.7 or in Ch. 5).

**Remark 3.10.** We always have the regular representation \( T \) for considering \( \mathrm{Ni}(G, C)^{\text{abs}} \): the representation of \( G \) on the cosets of \( \{1_G\} \). Unless, however, \( G \) is trivial, that won’t satisfy fine moduli.
This section starts using what we introduced in Ch. 1. In (1.35), especially in comments to Prop. 3.5, we allude to two oft present extras on families of covers:

(2.1a) quasi-projective coordinates; and
(2.1b) a fine moduli structure.

§1 explains how (2.1) allows us to reliably correspond $K$ points (say, a number field), on certain Hurwitz spaces to encapsulate diophantine problems like the RIGP.

Two tools immediately allow serious computing: Braid action and the Branch Cycle Lemma (BCL). §2 starts the former topic, and an equivalence – reduced, along with their corresponding Hurwitz spaces – on covers. Then it focuses on the Braid action when the Nielsen classes are of $r = 4$ conjugacy classes.

This case is important as it expands greatly on modular curves in a territory still modular curve-like making our examples accessible. When $r = 4$, reduced spaces are upper half-pane quotient coverings of the $j$-line. Their cusps on the compactification over $j = \infty \in \mathbb{P}_j^1$ explicitly identify with orbits of a subgroup of the Hurwitz monodromy group $H_4$. That produces an efficient formula for the genus of the reduced Hurwitz spaces.

§3 introduces the first computational tool for identifying Hurwitz space components: the $\text{sh}$-incidence matrix. It applies for all values of $r$. We show it off on two examples directed at the ultimate goals of the book applying to the OIT.

Then, §4 introduces the BCL. A corollary gives the moduli field of absolute or inner Hurwitz spaces, the first ingredient for an application, say, to the RIGP.

While this can sometimes be sufficient for results, it is subtler to find the precise moduli field of the components of Hurwitz spaces. The main theme of Ch. 3 is an approach to generalizing the BCL that often does suffice, based on the second fundamental idea for identifying Hurwitz space components, the lift-invariant.

1. Polarizations and fine moduli

Embedding an algebraic variety, $V$, over a field $K$ in projective space requires having a divisor $D$, for which the linear system $L(D) \overset{\text{def}}{=} \{f \in K(V)|(f) + D \geq 0\}$ contains sufficiently many functions that their values separate points and tangent directions at those points. A polarization starts with having a divisor $D'$, for which
some multiple $D = mD'$ gives such an embedding in projective $N$-space, $\mathbb{P}^N$:

$$v \in V(\overline{\mathbb{Q}}) \mapsto (f_0(v), \ldots, f_N(v)),$$

using some basis $\{f_0, \ldots, f_N\}$ of $L(D)$.

The author learned it indirectly from the cocycle condition – as applied to abstract varieties – of Andre Weil [We56] through [ShT61] during his post-doctoral at the Institute for Advanced Studies 1967–69. In each case, though, it depends on how the divisor class relates to the moduli problem. §1.1 comments on the cases that arise with Hurwitz spaces where we see the polarization arising from the natural polarization on the configuration space $U_r$.

Since our Hurwitz spaces are mainly families of curve covers of $\mathbb{P}^1_\mathbb{Z}$, the canonical divisor class is always at hand. §1.3 adds comments on canonical classes as these appear in several different applications.

1.1. Hurwitz space moduli definition field. The Hurwitz space structures we produce are analytic, as in Prop. 3.1.3. Those include the Hurwitz space (unramified) cover $\Phi^1_H : H^1 \to U_r$, of manifolds (so normal analytic varieties) for $\dagger$ either absolute or inner equivalence.

1.1.1. Applying Grauert-Remmert. If, say, fine absolute moduli holds, that gives a unique analytic total space (ramified) cover $\Phi^\text{abs}_T : T^\text{abs} \to H^\text{abs} \times \mathbb{P}^1_\mathbb{Z}$, of manifolds compatible with the projection maps to $U_r$. Then, in the construction of §3.2, a similar cover $\Phi^\text{abs}_P$ appears, for which fine inner moduli holds (Lem. 2.3) from it holding in the absolute case.

Then, the Grauert-Remmert Theorem (Comments of Ch. 1 Prop. 3.5) produces a function field (for each component) for $H^\text{abs}$. Normalization of $U_r$ in that function field gives a unique normal project algebraic variety. Putting the components together this gives $H^\text{abs}$ over $U_r$. A general remark suffices to show that an (unramified) cover of $U_r$ is equivalent to a cover with definition field in $\overline{\mathbb{Q}}$ (Rem. 1.2).

Similarly, using that $H^\text{abs} \times \mathbb{P}^1_\mathbb{Z}$ is quasi-projective (from the Segre embedding), we get a unique normal project variety for $\Phi^\text{abs}_T$. The construction of $\Phi^\text{abs}_P$ is done without Grauert-Remmert, and the projective structure is another application of the Segre embedding applied to the fiber product construction of §2.1.1.

1.1.2. The moduli field, $\mathbb{Q}_H$. The goal for a particular Hurwitz space, $H$, is an explicit (number) field $\mathbb{Q}_H$ for which a $K$ point $p \in H$ containing $\mathbb{Q}_H$ assures that a representative of the equivalence class will have definition field $K = \mathbb{Q}(p)$. The moduli field is well-defined (below). Yet, the conclusion in general – without fine moduli – is only this.

$$K \supset \mathbb{Q}_H.$$
said here. Without fine moduli, $\mathbb{Q}_H$ still has meaning, though such a $K$ point leads to a weaker conclusion (Rem. 4.9).

Each Hurwitz space, absolute, inner, and reduced versions of each, is defined by an equivalence on a Nielsen class. For each there is a precise criterion for fine moduli, based on that Nielsen class equivalence, $\text{Ni}(G, \mathbb{C})^1$. The ingredients appear in the following two lists that address the relation between a given cover $\varphi : X \to \mathbb{P}^1_z$ (2.3) describing how to detect the Nielsen class of the cover.

First: Compatible actions of $\sigma \in G_Q$ on a cover, its branch points and Puiseux expansions above branch points.

(2.3a) Given a cover $\varphi : X \to \mathbb{P}^1_z$ in a Nielsen class, defined over $\bar{\mathbb{Q}}$, $\sigma \in G_Q$ acts on the cover to give $\varphi^\sigma : X^\sigma \to \mathbb{P}^1_z$.

(2.3b) In all cases, $\sigma$ acts on the branch points $z$ of $\varphi$, sending them to collectively to branch points of $\varphi^\sigma$.

(2.3c) (2.3b) induces a compatible action on the Puiseux expansions of functions locally uniformizing $\varphi$ over those branch points.

Second: Compatible actions of $\sigma \in G_Q$ on the point representing a cover and the moduli space data.

(2.4a) Inner equivalence adds the action of $\sigma$ on the automorphims of $\varphi$.

(2.4b) Adding reduced equivalence won’t change the moduli definition field, though fine moduli may no longer hold.

(2.4c) $\sigma$ acts on $\varphi$ compatibly with acting on $T \to \mathcal{H} \times \mathbb{P}^1_z \to U_r$.

The definition fields in each case come from the oft-appearing Branch Cycle Lemma (BCL, §4). Even with fine moduli, an absolutely irreducible component $\mathcal{H}'$ of $\mathcal{H}$ (corresponding to a braid orbit on a Nielsen class; we give many examples) may have a nontrivial extension, say $\mathbb{Q}_{\mathcal{H}'}$, of $\mathbb{Q}_{\mathcal{H}}$ as its moduli definition. For that component, $\mathbb{Q}_{\mathcal{H}'}$ is analogous as above for a representative of a point in $\mathcal{H}'$.

The Hurwitz space and its attached moduli structure need – at least – a scheme structure for their $K$ points to have any meaning. We must assure that if someone else has done the same with the same spaces, their $K$ points and ours will be the same. This requires that structure arise from an embedding in projective space, based on the linear system of an equivalence class of divisors compatible with the moduli structure.

Polarization data does exactly that. Usually we expect a natural divisor class, say giving a polarization, to arise from a relation between a space and some convenient projective space. §3.2.1 has already used such on $\mathcal{H}$, its total space $T \to \mathcal{H} \times \mathbb{P}^1_z$ and the diagram including the map to the configuration space $U_r$. We track all of these to the projective space $\mathbb{P}^r$ containing $U_r$. 
1.2. Covers over \( \mathbb{Q} \). Assume the normal quasi-projective variety \( V \) (a locally closed subset of projective, normal \( \bar{V} \)), is defined over a subfield \( K \leq \mathbb{C} \). We mean that \( \bar{V} \setminus V \) is also defined over \( K \). We only require a little of the topology of quasi-projective algebraic varieties, because the moduli spaces which we define use fundamental groups detailed explicitly in [Fr90b]. Nevertheless Rem. 1.2 has references to a relatively modern book, which includes that the (discrete) fundamental group \( \pi_1(V,v_0) \) of such a variety can be gleaned from its structure as a CW complex using a generic curve on \( V \). In particular, a finite unramified cover \( \varphi_H : \bar{W}_H \to \bar{V} \) is defined by a subgroup, \( H \leq \pi_1(V,v_0) \) of finite index.

**Lemma 1.1.** Then \( W_H \) is a equivalent to a cover of \( V \) defined over a finite extension of \( K \).

**Proof.** From [GRe58] as used in Ch. 1 §3.2.1, \( W_H \) is quasi-projective, a locally closed subset in \( \mathbb{P}^d \) with its closure \( \bar{W}_H \) a normal variety (defined over \( \mathbb{C} \)). It is therefore defined over a finitely generated extension \( L \) of \( K \) (contained in \( \mathbb{C} \)) gleaned from the coefficients of the equations for \( \bar{W}_H \). We show it is equivalent to a cover defined over a finite extension of \( K \). Three points establish the Lemma.

(2.5a) \( L \) defines a variety \( U_L \overset{\text{def}}{=} U \) with function field \( L \), for which \( u \in U(\bar{K}) \) gives a specialization \( W_H, u \) with equations having coefficients in \( K(u) \).

(2.5b) The discriminant of the cover, as a function of \( u \) is defined over \( K \). Conclude over a Zariski open subset of \( U \), the discriminant is constant, and each \( W_{H,u} \) is a cover of \( \bar{V} \), unramified over \( V \).

(2.5c) In a Zariski neighborhood of \( u_* \), all covers \( W_{H,u} \to V \) are topologically (and therefore analytically) equivalent.

The conclusion of the lemma then follows, since in any neighborhood of \( u_* \) there will be points, algebraic over \( K \), on \( U \), say, by Hilbert’s nullstellensatz.

**Proof of (2.5a):** Since \( L \) is finitely generated, it has finite transcendence dimension. Therefore it has a description as a chain of extensions \( L/K(y)/K \): with \( y \) a transcendence basis for \( L \), a maximal set of elements algebraically independent over \( K \); and \( L/K(y) \) a finite extension [La71, p. 254]. Define \( U_L \) as the normalization in \( L \) of the affine variety defined by the coordinates \( y \).

We can use the coefficients of \( W_H \), generating \( L \), as a generic point, \( u_* \) of \( U_L \).

Then, \( U_L \) is quasi-projective, as is \( U_L \times \mathbb{P}^d \) from (1.14). Inside \( U_L \times \mathbb{P}^d \) we have the union of the \( \bar{W}_{H,u} \)s from specializing the coefficients of \( W_H \) over \( u \in U_L \).

**Proof of (2.5b):** Suppose \( \psi' : W' \to V' \) is finite cover of normal projective varieties. The ramification locus is defined on \( V' \) locally by the discriminant locus. Suppose, locally in the Zariski topology, that \( \psi' \) is defined by \( \text{Spec}(S) \to \text{Spec}(R) \),
an embedding of integral domains, with $R = S[w']$, and $F(w) = F_{w'}(w)$ the irreducible polynomial for $w'$ over $S$, with $\deg(F) = m$. The discriminant, $d(F)$ – also known as the resultant of $F$ and $\frac{\partial F}{\partial w'}$ – then locally defines the discriminant locus of the cover [La71, Chap. V, §10].

It is the determinant of a $2m - 1 \times 2m - 1$ matrix with $i$th row entries as in (2.6), from $i = 1$ to $m - 1$ (top) and $i = m$ to $2m - 1$ (bottom):

\[
\begin{align*}
 i = 1, \ldots, m - 1 : & \; 0^{i-1} \times a_0 & a_1 & \cdots & a_m & 0^{m-i-1} \\
 i = m, \ldots, 2m - 1 : & \; 0^{m-1} \times ma_0 & (m-1)a_1 & \cdots & a_{m-1} & 0^{2m-i-1}
\end{align*}
\]

(2.6)

When $S$ is not generated by a single element $w'$, write $S$ as $R[w'_1, \ldots, w'_k]$. Then use the ideal generated by all the $d(F_{w'_i})$ to define the discriminant locus as the ideal they generate. In a Zariski neighborhood of the generic point of $U_H$, the discriminant is defined by specializing the discriminant at the generic point over $K$. Since the discriminant at the generic point is defined over $K$, the discriminant is everywhere the same in this Zariski neighborhood.

**Proof of (2.5c):** From the above, we have an analytic family $\tilde{W} \to U_L \times V$ with fiber over $u \in U_L$, an unramified cover $\varphi_u : W_{H,u} \to V$, defined in an analytic neighborhood $U'$ of the generic point, $u^*$, of $V$ with the branch locus fixed. Therefore, all covers in this continuous family are defined by using the same generating paths of the finitely generated $\pi_1(V, v_0)$. This final result uses topology. It does not hold in positive characteristic even when $\dim(V) = 1$ (Rem. 1.3). We now show that $W_H \to V$ is analytically isomorphic to $W_{H,u}$ and conclude the lemma as above.

From the implicit function theorem, given a sufficiently small neighborhood $U'$ of $u^*$ and $w'(u^*) \in \varphi_{u^*}^{-1}(v_0)$, there is a continuous section

$s_{w'(u^*)} : U' \to \tilde{W} \to U_L \times V$ through $(u^*, w'(u^*))$.

This section allows us to identify $w'(u^*)$ with a unique element $w'(u) \in \varphi_{u}^{-1}(v_0)$. We show there is an isomorphism from $W_H$ to $W_{H,u}$ for $u$ close to $u^*$. In the style of Ch. 1 §3.1.1, let $P_0$ be generators of $\pi_1(V, v_0)$.

The covers $W_H$ and $W_{H,u}$ are defined by respective permutation representations $\tau_{u^*}, \tau_u : \pi_1(V, v_0) \to S_n$, with the integers $\{1, \ldots, n\}$ identified respectively in each representation with $\{w'(u^*) \in \varphi_{u^*}^{-1}\}$ and $\{w'(u) \in \varphi_{u}^{-1}\}$.

Reminder: The result of $\tau_u(P)$ is the endpoint of the unique path-lift of $P$ to the path starting on $W_{H,u}$ at any $w'(u) \in \varphi_{u}^{-1}(v_0)$. Denote that unique path lift by $P_{u,w'(u)}$. If for each $P \in P_0$, the effect of $P$ on the respective fibers is the same, then the two covers are equivalent. Use any convenient metric, $D$, in $U_L \times P^1$. Designate a path $P$ in $V$ by $t \in [0, 1] \mapsto P(t)$.

Then, $P_{u,w'(u)}(t)$ is a continuous function of $(u, t)$. With $w''(u^*) \in \varphi_{u^*}^{-1}(v_0)$ distinct from $w'(u^*)$, (use the sections $s_{w'(u^*)}$ above) then $P_{u,w''(u)}(t) \neq P_{u,w'(u)}(t)$ for $u, u' \in U'$ and $U'$ small, and any $t \in [0, 1]$. Therefore, for $U'' \subset U'$ a small
compact subneighborhood of $u^\bullet$:

$$D(P_{u,w'(u)}(t), P_{u',w'(u')}(t)) < D(w'(u^\bullet), w''(u^\bullet)),$$

for $(u, u', t) \in U'' \times U'' \times [0, 1]$.

In particular, running over all $P \in P_0$ and $w'(u^\bullet)$, $P_{u,w'(u)}(1) = P_{u^\bullet, w'(u^\bullet)}(1)$. This concludes the argument that the covers $W_H$ and $W_{H,u}$ are equivalent. □

Remark 1.2 (The “old” topology). Suppose $V$ is an algebraic variety over $K$, a subfield of $\mathbb{C}$. Then, its fundamental group, $\pi_1(V, v_0)$, with $v_0$ with coordinates in $K$, is discrete. The topological properties of a (quasi-projective) algebraic variety over the complexes is an old subject for which one of the last treatments can be found in [Z71, Chap. VI] based much on many works of Lefshetz, listed in the volumes bibliography. Although this is very detailed, and theoretically it applies only to a nonsingular projective variety of dimension 2, the idea of a Lefshetz pencil is presented in detail, as is the relation between the fundamental group of a generic curve and the fundamental group of the algebraic variety, and the homology groups of the variety. This is done through putting a CW complex structure on the variety. The use of resolutions of singularities doesn’t affect the fundamental group as we have all of our varieties normalized, so the singularities have codimension 2 and don’t affect it. [Sp66, p. 147] has the theorem that there is a topological space $V$ for which $\pi_1(V, v_0) = G$ with $G$ any a priori discrete group.

Remark 1.3 (Lem. 1.1 in positive characteristic). It is wild ramification that causes Lem. 1.1 to be false even when $V$ has dimension 1. [FrM02] replaces the configuration space $U_r$ for covers of $\mathbb{P}_1$ in positive characteristic by a configuration space (target) for families of sphere covers based on a definition of ramification data and regular ramification data, with the latter a generalization of higher ramification groups even when the local ramification is not Galois. Even the Galois closure of the covers in such families is not preserved, though the configuration spaces are of finite type, and locally versal for the finite topology. Grothendieck’s famous theorem in the case of curves, when ramification is tame, says Lem. 1 then holds, though expected covers in that case might be missing if the prime of the characteristic divides the monodromy group. [FrM02] thus produces just one-half of a wildly ramified version of [Gr71].

1.3. Polarizations from the canonical class. Since we concentrate on Hurwitz spaces of covers of $\mathbb{P}_1$, §1.3 added comments on the canonical (divisor) class.

A reasonable model of it starts with a curve. Denote the genus of a compact Riemann surface $X$ by $g_X$. For this discussion, assume $g > 0$; $g = 0$ is an easier case. Polarizations of curves come from the Riemann-Roch theorem: Take as your divisor, $D'$, any point. You need, however, a divisor invariant under $G_Q$ for an embedding that presents the curve with equations over $\mathbb{Q}$. See Rem. 1.4
Even, however, for compact, complex, torii, that are algebraic, there can be several different polarizations. So, the subject of abelian varieties includes giving a specific polarization. We later make contact with the following particular case. For Jacobian varieties, of a projective curve \( X \), there is a canonical polarization. Consider the \( g \times g \)-fold symmetric product, \( W = X^{g-1}/S_{g-1} \), of \( X \). These are positive divisors on \( X \) of degree \( g-1 \). Thus, if we translate \( W \) by some divisor \( D_0 \) of degree \( g-1 \) on \( X \), the result represents a divisor on the Jacobian \( J_X \) of degree 0 divisors on \( X \) module linear equivalence.

To make this divisor even more canonical, Riemann took \( D_0 \) to be very special, a half-canonical divisor (\( 2D_0 \) is in the class of the divisors of holomorphic differentials). He differentiated between the dimensions of the linear systems (even or odd). Eventually he used each type for different purposes in his descriptions of objects – differentials of various kind in particular – on \( X \). [Fa73] is an older, still relevant, source for the story of Riemann’s – and subsequent – attempts to form such objects. These deal in local coordinates on the moduli of genus \( g \) curves. We will deal with coordinates on Hurwitz spaces.

**Remark 1.4.** There is a subtlety as to whether a divisor class over \( K \) with a nonempty linear system \( L_{D'} = \{ f \in K(X) \mid (f) + D' \geq 0 \} \) suffices to give a map of \( X \) into a projective space \( P_L \) with image having coordinates over \( K \). Yes, \( P_L \) is a projective space over \( \bar{\mathbb{Q}} \). Yet, unless the space has a point over \( K \), it is just a Brauer-Severi variety – defining an element of the Brauer Group \( H^2(G, K^*) \) since they predominantly work over an algebraically closed field. The canonical divisor class, though, is defined over the same field as is \( X \).

**1.4. Extension of constants.** As we intend applications belonging to number theory, we have included the field \( K \), which may be a number field: \( [K : \mathbb{Q}] < \infty \) (often \( \mathbb{Q} \) itself). We state several goals starting with the RIGP for a given \( G \).

**Problem 1.5.** Find an absolutely irreducible Galois cover \( \hat{\varphi} : \hat{W} \to \mathbb{P}_z^1 \) with group \( G \) defined, with all its automorphisms (commuting with \( \hat{\varphi} \)), over \( K \). That is, we seek an inner Nielsen class, \( \text{Ni}(G, C)^{\text{in}} \), containing a cover, \( \hat{\varphi} \), defined over \( K \). Our Main Theorem, followed by the BCL (acronym definition in Ch. 1) expands the value of Hurwitz spaces. To state the most useful version of this result we need one general definition.

---

1[Se67, Prop. 3] spells out key points about the Brauer group over a number field, including that it is determined by the induced cohomology in the completions of the field where it is locally trivial.
DEFINITION 1.6. Refer to \( \varphi : W \to \mathbb{P}_2^1 \), a cover in \( \text{Ni}(G, C)^{\text{abst}} \), as a \((G, G^*)\) regular realization over \( K \), if \( \varphi \) is defined over \( K \), and its Galois closure \( \hat{\varphi} : \hat{W} \to \mathbb{P}_2^1 \) of \( \varphi \) over \( K \) has group \( G^* \). That means (§2.1), \( \hat{W} \) has \(|G^* : G| \) connected components over \( \bar{K} \).

THEOREM 1.7. [FrV91, Main Thm.] If \( G \) has no center, then the complete set of inequivalent RIGP realizations of \( G \) over \( K \) corresponds to this set:

\[
G \overset{\text{def}}{=} \bigcup_{\text{conjugacy class collections } C \subset G} \{ \hat{\varphi} \in \mathcal{H}(G, C)^{\text{in}}(K) \}.
\]

That is, for given \( G \), if for even one conjugacy class collection \( C \), there is any \( K \) point \( \hat{\varphi} \in \mathcal{H}(G, C)^{\text{in}} \), then this regularly realizes \( G \) over \( K \) with a Galois cover \( \hat{\varphi} : \hat{W} \to \mathbb{P}_2^1 \).

Assume \((G, T)\) is self-normalizing, \( n = \deg(T) \). Then, \( \varphi \in \mathcal{H}(G, C)^{\text{abst}}(K) \) corresponds to a \((G, G^*)\) realization with \( G^* \leq \text{NS}_n(G, C) \) (§3). For any \( \hat{\varphi} \in \mathcal{H}(G, C)^{\text{in}} \) over \( \varphi \), as in (1.33), \( K(\hat{\varphi}) = \bar{K} \) is a definition field of

- (2.8a) all components of \( \hat{W} \) and \( \hat{\varphi} \) automorphisms; and
- (2.8b) \( G(\bar{K}/K) = G^*/G \).

COMMENTS. The ability to set up both the absolute and inner versions (2.7) uniformly – without having to stipulate precise finite groups – to go after the RIGP and IGP requires configuration spaces with obvious projective coordinates as natural targets. Here they are the collections \( \{U_r\}_{r=3}^\infty \).

Referencing these gives meaning to the field generated by the coordinates of \( \hat{\varphi} \in \mathcal{H}(G, C)^{\text{in}} \) (et. al.) over which the corresponding \( \mathbb{P}_2^1 \) cover is defined. Abstract schemes, though reasonable as moduli spaces, cannot provide a consistent meaning to giving coefficients of equations over a desired field.

Precise reference to covers by branch cycles in (2.7) does contrast with the more abstract stipulation of \((G, G^*)\) realizations in (2.8). Still, as in Thm. 4.4, it produces very big Galois groups over certain fields \( K \).

DEFINITION 1.8 (Extension of Constants). Refer to \( \hat{K}/K \) in (2.8) as the extension of constants for (the Galois closure of the cover of) \( \varphi \).

Thm. 1.7 strikes into using the tools of §2 to understand specifics about Hurwitz spaces referenced by \((G, C)\). By attending to the conjugacy classes, \( C \), with \( G \) fixed, we open the discussion these issues.

(2.9a) How the RIGP for \((G, C)\) for one type of \( C \), can be almost trivial, while it is allied to famous unsolved problems for other \( C \).

(2.9b) How in certain contexts, even if the fine moduli hypotheses don’t hold, with no loss we can adjust \((G, C)\) to assure they do.
2. Braid Action for Reduced Equivalence

(2.9c) Where we can use (2.8) to build upon an IGP realization of a group we identify as $G^*/G$ to get an IGP realization of $G^*$.

(2.9d) What to think of our difficulties, starting with certain conjugacy classes $C'$, upon allowing each class in $C'$ to repeat many times.

2. Braid Action for reduced equivalence

[Fr77, §4] gives generators and relations for Hurwitz monodromy acting on Nielsen classes. (2.10) lists memorable generating elements. From (1.24d), $H_r$ orbits on a Nielsen class correspond to irreducible components of the Hurwitz space.

2.1. Braids acting on reduced Nielsen classes. §2.1.1 gives the generators and relations of $H_r$ and $B_r$, while §2.1.2 shows paths on $U_r$ that gives the generators, and compute the most obvious relations. Details on relations that appear in our use of these groups follows in subsequent sections.

2.1.1. Generators of $H_r$. Braids on Branch cycles generate the action of $H_r$, the Hurwitz monodromy group, on a Nielsen class element $g$:

$$q_i : g \overset{\text{def}}{\mapsto} (g_1, \ldots, g_{i-1}, g_i g_{i+1}^{-1}, g_i, g_{i+2}, \ldots, g_r);$$

$$sh : g \mapsto (g_2, g_3, \ldots, g_r, g_1) \quad \text{and} \quad H_r \overset{\text{def}}{=} \langle q_2, sh \rangle$$

with

$$sh q_{i} sh^{-1} = q_{i+1}, \ i = 1, \ldots, r-1.$$

We call $q_i$ the $i$th twist. Then, $sh$, sensibly enough is the (left) shift. The case $r = 4$ is so important in our examples, that when we get to reduced Nielsen classes, we conveniently refer to $q_2$ as the middle twist.

Braids lead this subsection, and §3 has detailed examples for using them. We develop this more in the main examples of Ch. 5. It is the BCL that starts us into a serious discuss about the spaces. Here are other important points.

(2.11a) From product-one (1.18c) on Nielsen classes $\text{Ni}(G, C)$, $sh$ is an $r$ cycle on all such classes.

(2.11b) (2.11a) allows reducing the subscript of $q_i$ modulo $r$. Easily check this by starting with a given $g$.

(2.11c) Conjugating by $sh$, shows $sh$ and $q_2$ generate $H_r$.

Braid, $B_r$, relations: The group $H_r$ is a quotient of the

$$\text{Artin Braid group, } B_r = \langle Q_1, \ldots, Q_{r-1} \rangle,$$

by its (minimal normal) subgroup generated by

$$Q_1 Q_2 \cdots Q_{r-1} Q_r \cdots Q_2 Q_1, \ r \geq 3.$$

These are the standard $B_r$ relations.

(2.13a) $Q_i Q_j = Q_j Q_i$ for $|i-j \mod r-1| > 1$;

(2.13b) $Q_i Q_{i+1} Q_i = Q_{i+1} Q_i Q_{i+1}, i \mod r-1$. 
The quotient map is given by $Q_i \mapsto q_i$, $1 \leq i \leq r-1$. Calculate the action of (2.12) on $g = (g_1, \ldots, g_r)$ in a Nielsen class to see the result is $g_1 g g_1^{-1}$.

**Remark 2.1** (How sh works). The operation $q_1 q_2 \cdots q_{r-1}$ on Nielsen classes represents sh. Direct calculation on $g = (g_1, \ldots, g_r) \in G^r$ shows its effect:

$$g \mapsto (g_1 g_2 g_1^{-1}, \ldots, g_1 g_r g_1^{-1}, g_1 g_1 g_1^{-1})$$

then, conjugate by $g_1$.

**Problem 2.2.** Running over all conjugates of (2.12), conclude that the minimal equivalence on $\text{Ni}(G, C)$ that affords an $H_r$ action is $\text{Ni}(G, C)^{\text{in}}$.

Hint: Use the generators of (6.22).

**2.1.2. Explicit effect of braiding.** [Fr77, p. 49–53] breaks the problem of computing the effect of dragging a cover by its branch points into two parts. First, only branch points restricted to lie on $\mathbb{P}_x^1 \setminus \{\infty\} = \mathbb{A}^+$. Here the $i$th "cut" runs from the initial branch point $z_0^i \in \mathbb{A}^+$ to $-\infty$ parallel to the (negative) real axis.

This allows taking as a basepoint a simply-defined value: $z_0 = 1 + \max(\Re z_0^i)_{i=1}^r$. The presentations take pains how to handle ‘cuts’ — while dragging branch points — when two or more points happen, at some time $t'$, to lie on a line parallel to the negative $x$-axis.

**Problem 2.3.** Given $r$ distinct points $z_1, \ldots, z_r$ on $\mathbb{A}^+$, and another point $z_0$ distinct from them, show there are always smooth pairwise nonintersecting, except at $z_0$, paths $\gamma_1, \ldots, \gamma_r$ starting (respectively) at $z_0$ and ending at $z_i$, that emanate from $z_0$ in clockwise order of their subscripts. Hint: Inductively, assume you have achieved this for $i$, and use that $\mathbb{A}^+ \setminus \{\gamma_1, \ldots, \gamma_i\} \cup \{z_0\}$ is connected by contracting all the paths to $z_0$.

Use Prob. 2.3 to show with no loss, up to homotopy, we may initially assume $\Im(z_0^i) < \cdots < \Im(z_0^r)$. Let $Q_i$ be the automorphism of $F_r = \pi_1(\mathbb{A}^+, z_0)$ that maps the $r$-tuple of generators $(\bar{g}_1, \ldots, \bar{g}_r)$, in order, to the new $r$-tuple of generators

$$\bar{g} = (\bar{g}_1, \ldots, \bar{g}_{i-1}, \bar{g}_i \bar{g}_{i+1} \bar{g}_i^{-1}, \bar{g}_i, \bar{g}_{i+2}, \ldots, \bar{g}_r), \quad i = 1, \ldots, r-1.$$  

Fig. 1 gives a specific path $\Gamma_i$ on $\mathbb{A}^r$, that has the effect of achieving $Q_i$, as the acting of dragging branch points and pulling along classical generators lying entirely on $\mathbb{A}^+$ that represent $\bar{g}$. It starts at $z_0^i$ and ends at

$$(z_0^0, z_0^1, z_0^{i-1}, z_0^{i+1}, z_0^i, z_0^0, \ldots, z_0^r) = (z_0^\sigma)^i, \quad \sigma = (i+1)i.$$  

Its coordinates are constant, excluding the $i$th and $i+1$th. The $i$th coordinate $z_i$ moves from $z_i^0$ to $z_i^0$, the $i+1$th coordinate $z_{i+1}$ moves from $z_{i+1}^0$ to $z_{i+1}^0$.

Consider the bounded component, $W$, of $\mathbb{A}^1 \setminus \lambda$, where $\lambda$ is the set of points on the path $\delta_i \bar{c}_i (\bar{d}_{i+1})^{-1}$. With no loss assume that $\bar{c}_i$ is outside $W$. Finally, let $\lambda_i$
(resp., $\Lambda_{i+1}'$) be the clockwise path from $b_i$ to $b_i'$ (resp., $b_{i+1}'$ to $b_{i+1}$). It follows automatically (as in Part 3 of the proof of Theorem 2.10) that the paths $\gamma_i\epsilon_i\gamma_{i+1}(\epsilon_i)^{-1}$ and $\lambda_i(\epsilon_i)^{-1}\Lambda_{i+1}(\epsilon_i)^{-1}$ are homotopic (say, with $b_i$ and $b_{i+1}$ fixed) and that the bounded components of their complement contain $z^0\epsilon$ and $z^0_{i+1}$ and exclude $z^0_j$ for $j \neq i, i + 1$. With a judicious choice, however, of $\epsilon_i'$ this can be arranged without appeal to previous results. We use the notation of Def. 4.8.

**Proposition 2.4.** Let $\bar{\Gamma}_i$ be the path $(z^0, ..., z^0_{i-1}, (\epsilon_i')^{-1}, \epsilon_i, z^0_{i+1}, ..., z_r)$. Then, $(\bar{\Gamma}_i) Q^r$ is $Q_i$, the element of 4.10, $i = 1, ..., r - 1$.

**Proof.** Apply a section $\Phi$ along $\Gamma$ (Theorem 4.7). As before, assume that $\bar{\Gamma}_i : [0, 1] \rightarrow H^r \setminus \Delta_r$. This is what we must show: that $\gamma_i^1$ is homotopic to $\gamma_i^0, \gamma_{i+1}(\epsilon_i)^{-1}$; that $\gamma_{i+1}^1$ is homotopic to $\gamma_i^0$; and that $\gamma_j^1$ is homotopic to $\gamma_j^0$ for $j \neq i, i + 1$. Note that none of the coordinates of $z^0$ can be located in the component $W$ of $\mathbb{P}^1 \setminus \lambda$ (above), or else there would be an $a_j$ on the clockwise path along $\delta_0$ from $a_i$ to $a_{i+1}$, contrary to Ex. 2.9.

Choose $d''$ as in the proof of Theorem 4.7. There exists $d'' > 0$ such that for $\gamma \in B(z^0, d'')^+$ we have $\Phi(t)(\gamma) \in B(\Phi(t)z^0, d'')^+$ for all $t \in [0, 1]^{[4, 4]}$. As in the last paragraph of the proof of Theorem 4.7 conclude:

\begin{itemize}
  \item[(2.14a)] $\gamma_i^1$ is homotopic to $\delta_i \lambda_i(\epsilon_i')^{-1}\Lambda_{i+1}(\epsilon_{i+1})^{-1}\gamma_{i+1}(\lambda_i)^{-1}(\delta_i)^{-1}$;
  \item[(2.14b)] $\gamma_{i+1}^1$ is homotopic to $\delta_{i+1}(\epsilon_i)^{-1}\gamma_i(\delta_{i+1})^{-1}$; and
  \item[(2.14c)] $\gamma_j^1$ is homotopic to $\gamma_j^0$ for $j \neq i, i+1$.
\end{itemize}

The same argument as in Part 2 of Theorem 2.10 shows that $\delta_i\epsilon_i$ is homotopic to $\delta_{i+1}$ (with initial and endpoints fixed). From 4.11b this immediately gives $\gamma_i^{i+1}$ homotopic to $\gamma_i^0$.

Finally, $\gamma_i\epsilon_i\gamma_{i+1}$ and $\lambda_i(\epsilon_i')^{-1}\Lambda_{i+1}$ are homotopic. Therefore 4.11a gives $\gamma_i^1$ homotopic to $\delta_i\gamma_i\epsilon_i\gamma_{i+1}(\epsilon_i)^{-1}(\gamma_i)^{-1}(\delta_i)^{-1}$. This, in turn, is homotopic to

$$\gamma_i^0(\delta_i)^{-1}(\gamma_i)^{-1}(\gamma_i)^{-1} = \gamma_i^0(\gamma_i)^{-1}(\gamma_i)^{-1}$$

through an insertion of $(\delta_i)^{-1}\delta_i$ (resp., $(\epsilon_i)^{-1}\delta_i$) between the terms $\gamma_i$ and $\epsilon_i$ (resp., $(\epsilon_i)^{-1}$ and $(\gamma_i)^{-1}$). This concludes the proof of the lemma. \hfill \Box

Thm. 2.5 summarizes what we use of $B_r$ [ArE25], [ArE47], [B47].
Theorem 2.5. The natural homomorphism $Q^*$ from dragging branch points maps $\pi_1(A^r \setminus D_r, x_0)$ onto the conjugacy class preserving automorphisms of $F_r$ that also preserve $\bar{g}_1 \cdots \bar{g}_r$, induces an isomorphism between the former group and $B_r = \langle Q_1, \ldots, Q_{r-1} \rangle$. This gives a presentation of $B_r$ by the normal subgroup generated by the relations in (2.13).

2.1.3. Reduced equivalence. There are other equivalences † than inner or absolute. Yet, in each case we understand many properties of the space of covers through $H_r$ acting on $\text{Ni}(G, C)^\dagger$. For $F$ a field, recall the group (under composition) of Möbius transformations on $\mathbb{P}_1^F$:
\begin{equation}
\text{Möb}(F) \overset{\text{def}}{=} \{ z \mapsto \frac{az+b}{cz+d} \mid ad-bc = 1, a, b, c, d \in F \}.
\end{equation}
For $F = \mathbb{C}$ these give the group of automorphisms of $\mathbb{P}_1^1$. Identify these with equivalence classes of matrices $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ satisfying the same conditions, modulo diagonal matrices $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $a \in F^\ast$. This is also denoted $\text{PSL}_2(F)$. §1.1.2 has a list of related affine groups.

Definition 2.6 (Reduced action). A cover $f : W \to \mathbb{P}_1^1$ is reduced equivalent to $\alpha \circ f : W \to \mathbb{P}_1^1$ for $\alpha \in \text{PSL}_2(\mathbb{C})$.

Also, $\alpha$ acts on $z \in U_r$ by acting on each entry. That extends to an action on any cover $\Phi^\dagger : \mathcal{H}(G, C)^\dagger \to U_r$ and a reduced Hurwitz space cover:
\begin{equation}
\Phi^\dagger,\text{rd} : \mathcal{H}(G, C)^{\dagger,\text{rd}} \to U_r / \text{PSL}_2(\mathbb{C}) \overset{\text{def}}{=} J_r.
\end{equation}
Reduced uses: Here are two reasons for its use, each connecting to a different half of the applications in this book. Recall the upper half space
\[ \mathbb{H}^{\text{up}} = \{ z \in \mathbb{C} \mid \text{the imaginary part of } z > 0 \} . \]
(2.17a) If a cover $\hat{\phi} : \hat{X} \to \mathbb{P}_1^1$ gives an RIGP realization of $G$ over $\mathbb{Q}$, then so does $\alpha \circ \hat{\phi}$ for $\alpha \in \text{PSL}_2(\mathbb{Q})$.
(2.17b) For $r = 4$, reduced Hurwitz spaces are quotients of $\mathbb{H}^{\text{up}}$ (Thm. 2.13).

Comment on (2.17a): We separate the RIGP from the IGP. From an RIGP realization of $G$, applying Hilbert’s Irreducibility Theorem §5.1.1 by specializing $z$ in $\mathbb{Q}$ immediately produces infinitely many IGP realizations of the given group $G$. The specializations that work are dense in any particular topology on $\mathbb{P}_1^1(\mathbb{Q})$. Comparing those to IGP realizations not coming from an RIGP realization is still nontrivial (as in §5.1).

Whether there are infinitely many RIGP realizations of $G$, or more general parameters for their realizations, is also significant. Using the equivalence of (2.17a) precludes trivial changes in such realizations.
Comment on (2.17b): Not only are the two halves of this book connected, but we can easily use the properties of the spaces on which they rely to see they have analogs of the properties of modular curves. That starts with the upper half-plane paradigm below. There, we get to ask questions about the nature of the finite index subgroup of \( \text{PSL}_2(\mathbb{Z}) \) that defines a reduced Hurwitz space when \( r = 4 \). Especially about its cusps when it is compactified to a cover of \( \mathbb{P}^1 \), the classical \( j \)-line. The comparison comes clearer after we have introduced \( \text{M}(\text{odular}) \text{T}(\text{owers}) \).

2.1.4. The upper half-plane paradigm. A reduced Hurwitz space of 4 branch point covers is a natural \( j \)-line cover – \( \mathcal{H}(G,\mathbb{C})^\dagger \rightarrow \mathbb{P}^1 \) identifies with \( \mathbb{P}^1 \setminus \{\infty\} \) – that completes to \( \mathcal{H}(G,\mathbb{C})^\dagger \rightarrow \mathbb{P}^1 \) ramified over 0, 1, \( \infty \). We refer to this as the upper half-plane paradigm (for \( r = 4 \), a consequence of Thm. 2.7. That demonstrates that modding out by \( \text{PSL}_2(\mathbb{C}) \) on the cover \( \mathcal{H}(G,\mathbb{C})^\dagger \rightarrow U_4 \) produces a natural cover of the classical \( j \)-line \( \mathbb{P}^1 \setminus \{\infty\} = \mathcal{H}(G,\mathbb{C})^\dagger / \text{PSL}_2(\mathbb{Z}) \). We have placed the corresponding images of elliptic fixed points on \( \mathbb{H}^{\text{up}} \) at 0 and 1.

**Theorem 2.7.** The image, \( \mathcal{H}^\dagger / \text{PSL}_2(\mathbb{C}) = \mathcal{H}^\dagger / \text{rd} \), of any component, \( \mathcal{H}^\dagger \) of \( \mathcal{H}(G,\mathbb{C})^\dagger \) is a quotient of the upper half-plane \( \mathbb{H}^{\text{up}} \) by a finite index subgroup of \( \text{PSL}_2(\mathbb{Z}) \). That makes \( \mathcal{H}^\dagger / \text{rd} \rightarrow \mathbb{P}^1 \setminus \{\infty\} \) a cover ramified of order (at most) 3 (resp. 2) over \( j = 0 \) (resp. 1).

For \( r = 4 \), Thm. 2.13 handles the geometric monodromy, and cusps, of reduced Hurwitz space components as covers of the \( j \)-line. In particular, it computes the genus of such reduced components.

Then §3 applies that to give example spaces. We have simplified the treatment of [BFr02, Prop. 2.3 and its proof, §2.3] in respective proofs of Thm. 2.7 and Thm. 2.14 (a tighter relation between \( H_4 \) and \( B_4 \), as in (2.13)) in §4. Taking off from the upper half-plane paradigm, whereby reduced Hurwitz spaces defined by \( r = 4 \) conjugacy classes are actually upper half-plane quotients which we may compare with the special case of modular curves, §4 produces a formula for computing the components and genuses of reduced Hurwitz space components through their being covers of the classical \( j \)-line.

2.2. Reduced Hurwitz spaces for \( r = 4 \). With \( Q = \langle (q_1 q_2 q_3)^2, q_1 q_3^{-1} \rangle \), [BFr02, §4.2] contains the formula whose statement in Thm. 2.13 uses

\[
(2.18) \quad \text{reduced Nielsen classes } \text{Ni}(G,\mathbb{C})^\dagger / \text{rd} \overset{\text{def}}{=} \text{Ni}(G,\mathbb{C})^\dagger / Q.
\]

2.2.1. Universal \( B_r \) and \( H_r \) actions. Consider the free group, \( \tilde{G}_r \), on generators \( \tilde{g}_1, \ldots, \tilde{g}_r \), with \( \pi(\mathbf{g}) = \tilde{g}_1 \cdots \tilde{g}_r \). Denote the conjugacy class of \( \tilde{g}_i \) by \( C_{\tilde{g}_i} \), \( i = 1, \ldots, r \).
1, \ldots, r. Now consider a version of a Nielsen class.

\[ \tilde{N}_r(\bar{G}r, \bar{C}_g)_{\pi'(g)} \overset{\text{def}}{=} \{ g' \in C_g \mid \pi(g') = \pi(g) \text{ and } (g') = \bar{G}r \}. \]

Use the same actions for the \( Q_i \) as for the \( q_i \)s in (2.13). Then, \( \tilde{N}_r(\bar{G}r, \bar{C}_g)_{\pi'(g)} \) would be a universal Nielsen class, except we have replaced product-one with \( \pi(g') \) preserved by \( B_r \) by being fixed at \( \pi(g) \).

Instead, replace this with the condition \( \pi(g) = 1 \) and mod out by the inner action of elements of \( \bar{G}_r \) (\( g' \) is equivalent to \( g'g^{-1} \), \( g \in \bar{G}_r \)). Then, we get an object, \( \tilde{N}_r(\bar{G}r, \bar{C}_g)_{\text{in}} \), that is akin to universal inner Nielsen classes. On it we do have an \( H_r \) action as in ((1.24c) or Prob. 2.2). Denote the image group of this action by \( M_r \), the Mapping Class Group.

For the rest of this section we assume \( r = 4 \) in \( \mathcal{S}4.2.1 \). Then, (6.21) gives the extra relations for \( M_4 \) (beyond those for \( B_4 \)):

\[
\begin{align*}
\tau_1(4) &= (Q_3Q_2)^3 = 1, \\
\tau_2(4) &= Q_1^{-2}Q_3^2 = 1, \\
\tau_3(4) &= (Q_2Q_1)^{-3} = 1 \text{ and } \tau(4) = (Q_3Q_2Q_1)^4 = 1.
\end{align*}
\]

Consider Ch. 6 (6.22) for \( r = 4 \), with \( Q_1Q_2Q_3Q_2Q_1 = R_1(4) \), and

\[
\begin{align*}
R_2(4) &= Q_1^{-1}R_1(4)Q_1, \\
R_2(4) &= Q_3^{-1}R_1(4)Q_3, \\
R(4) &= (Q_1Q_2Q_3)^4.
\end{align*}
\]

Denote an element of \( B_4 \) (resp. \( H_4 \)) that has the effect of conjugating \( g \) by \( \pi(g) \) by \( Q(\bar{g}) \) (resp. \( q(\bar{g}) \)).

**Lemma 2.8.** Both \((Q_1Q_2Q_3)^4 \) and \((Q_3Q_2Q_1)^4 \) have the effect of \( Q(\bar{g}) \).

Then, \( B_4 \) acting on \( \bar{G}_4 \) induces \( \alpha_4 : B_4 \to \text{Aut}(\bar{G}_4) \) with the center \( \langle (Q_1Q_2Q_3)^4 \rangle \) of \( B_4 \) generating the kernel. This induces \( \mu_4 : H_4 \to M_4 \).

The kernel of \( B_4 \to M_4 \) is the direct product of

the free group \( K_4^* = \langle (Q_3Q_2)^3, Q_1^{-2}Q_3, (Q_2Q_1)^{-3} \rangle \) and \( \langle (Q_1Q_2Q_3)^4 \rangle \).

Above, \( Z = i(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4) \) is identical to an element of \( B_4 \). Consider the image \( z \) of \( Z \) in \( H_4 \):

\[ (q_1q_2q_3)^4z = 1 = (q_3q_2q_1)^4z = q_1^2q_3^{-2}z \text{ and } z^2 = 1. \]

In particular, combining this with (2.26) identifies \( M_4 \) with the image of \( H_4 \) in \( \text{Aut}(G_4)/\text{Inn}(G_4) \). So, the image of \( z \) in \( M_4 \) is 1.

**Proof.** The map \( i \) induces \( i : G_4 \to \text{Inn}(G_4) \). Action of \( B_4 \) preserves \( \Pi(\bar{\sigma}) \). Thus, it induces a homomorphism of \( B_4 \) into \( \text{Aut}(G_4) \) where \( D \) goes to the automorphism \( i(\bar{\sigma}_1^{-1}) \), \( \bar{\sigma} \to \bar{\sigma}_1\bar{\sigma}^{-1}_1 \) (as in (??)). Conclude: Modulo inner automorphisms of \( G_4 \), \( D \) acts trivially, producing the desired homomorphism

\[ H_4 \to \text{Aut}(G_4)/\text{Inn}(G_4). \]

Now consider the explicit formulas. Most of the calculation is in (??): \( Q_1Q_2Q_3 \) cycles entries of \( \bar{\sigma} \) back 1, and conjugates all entries by the first entry’s inverse. So
\[(Q_1Q_2Q_3)^4\text{ leaves entries of } \bar{\sigma} \text{ untouched except for conjugating them by} \]
\[
(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4^{-1}\bar{\sigma}_2^{-1}\bar{\sigma}_1^{-1}\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4^{-1}\bar{\sigma}_2^{-1}\bar{\sigma}_1^{-1}\bar{\sigma}_1)^{-1} = (\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4)^{-1}.
\]

Also, \(Q_3Q_2Q_1\) cycles the entries of \(\bar{\sigma}\) forward 1. The new first entry is the old 4th entry conjugated by the inverse of the product of the old first three entries. Thus, \((Q_1Q_2Q_3)^4\) and \((Q_3Q_2Q_1)^4\) act the same. Add that \(D\) maps to 1 in \(H_4\) to see
\[
1 = (q_4^1q_2^3q_3^1q_4^4)^4 = (q_4^4q_2^3q_3^1q_4^1)^4 = (q_4^8q_2^3q_3^1q_4^1)^2 = z^{-2}.
\]

Let \(Q' = Q_1Q_2Q_3\). Extending the calculation above gives the next list:
\[
1 = (Q')^{-1}DQ'(Q_1Q_2)^3i(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4);
\]
\[
1 = (Q'Q_1Q_2^{-1})^2(Q')^{-1}DQ'i(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4); \quad 1 = (Q')^4i(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4); \quad \text{and}
\]
\[
1 = (Q_1Q_2^{-1})^2(Q')^{-1}D(Q_1Q_2Q_3)(Q_1Q_2Q_3)^{-2}D(Q_1Q_2Q_3)^2i(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4).
\]

Add the relation \(Q_1Q_2 = Q_3Q_1\) to deduce, in order, these relations in \(H_4\):
\[
(2.21) \quad \begin{align*}
\text{a)} & (q_4^2q_3)^{2z} = 1; & \text{b)} & (q_4^1q_2q_3)^{2z} = 1; & \text{c)} & (q_4q_2q_3)^{4z} = 1; \\
\text{d)} & (q_4^1q_3)^{2z} = 1; & \text{e)} & q_4q_3 = q_3q_4.
\end{align*}
\]

So, the image of \(z\) in \(M_4\) is 1.

The kernel of \(\alpha_4\) contains elements of \(B_4\) inducing inner automorphisms commuting with conjugation by \(\bar{\sigma}_1\bar{\sigma}_2\bar{\sigma}_3\bar{\sigma}_4 = c\). Since \(c\) generates conjugations commuting with \(c\), \(\langle (Q_1Q_2Q_3)^4 \rangle\) generates the kernel of \(\alpha_4\).

Generators of \(K_4^*\) act on \(G_4\): Respectively, \((Q_3Q_2)^3, Q_1^{-2}Q_3^2, (Q_2Q_4)^{-3}\) induce conjugation by \(g_4, g_1g_2, g_1\). These conjugations on \(G_4\) form a free group. So \(K_4^*\) is a free group on these generators.

From Lem. 2.8, the direct product of the free group \(K_4^* = \langle (Q_3Q_2)^3, Q_1^{-2}Q_3^2, (Q_2Q_4)^{-3}\rangle\) equals \(N_4 \overset{\text{def}}{=} \ker(B_4 \to M_4)\). Denote \(Q_1Q_2Q_3Q_4\) (\(D\) in (??)) by \(R_1\). The following presentation of \(N_4\) is superior for our purposes. It easily follows from the notation and proof of Lemma 2.8.

The effect of \(R_i\) on \(g\) is conjugation by \(g_i\). We consider Prop. 2.9 only for \(r = 4\), though it works for any value of \(r\).

**Proposition 2.9.** Elements of \((2.20)\) generate \(N_4\). Any representative \(g\) in a Nielsen class \(\text{Ni}(G, C) = Ni\) produces an evaluation homomorphism
\[
\psi_g : N_4 \to G/\text{Cen}(G) \text{ mapping } \prod_{i=1}^4 R_i \text{ to } 1.
\]

Conversely, any homomorphism \(\psi : N_4 \to H\) mapping \(\prod_{i=1}^4 R_i \to 1\) produces an associated Nielsen class representative.

For \(Q \in B_4\), act on \(\psi_g\) by applying evaluation of \(Q^{-1}RQ\) to \(g\). An orbit on \(Ni\) is equivalent to a \(B_4\) orbit on the homomorphisms \(\psi_g\) (up to conjugation by \(G\)).
2.2.2. The groups $M_4, M_4$ and $Q''$. Denote the element $q_1q_3^{-1}$ by $\tilde{z}$. Prop. 2.10 shows that $B_4 \to M_4$ factors through $H_4$ to give $H_4/(\langle \tilde{z}^2 \rangle) = M_4$.

It also shows precisely what relations give the quotient for the $H_4$ action on reduced equivalence classes of covers; that reduced equivalence kills $\tilde{z}$.

Set $\gamma_0 = q_1q_2$ and $\gamma_1 = q_1q_2q_3$.

Suppose $\mathcal{P}$ are classical generators of $\pi_1(U_2, z_0)$ relative to $(z, z_0)$ (1.18).

Lemma 2.8 shows adding these relations to $B_4$ is equivalent to adding $q_1^2q_3^{-2} = 1$ to $H_4$. This produces new equations:

$$(2.22) \quad q_1q_2q_1^{-2}q_2q_1 = (q_1q_2q_1)^2 = (q_1q_2)^3 = 1.$$ 

Then, $\gamma_0 = q_1q_2, \gamma_1 = q_1q_2q_1$ and $\gamma_{\infty} = q_2$ satisfy

$$(2.23) \quad \gamma_0\gamma_1\gamma_{\infty} = 1.$$ 

The relation $q_1q_3^{-1} = 1$ is not automatic from (2.26). Crucial, however, is how $M_4$ acts on reduced Nielsen classes: equivalence of branch cycles $g$ in a Nielsen class equivalented by the action of $\text{PGL}_2(\mathbb{C})$. This action does factor through the relation $q_1q_3^{-1} = 1$ (Prop. 2.10). Therefore it factors through the induced quotient $H_4/\mathcal{Q} = M_4$ of Thm. 2.14.

**Proposition 2.10.** The center of $H_4$ contains $\tilde{z}^2$. Both $\text{sh}^4$ and $\tilde{z}^2$ act as the identity on $\text{Ni}_{\text{ir}}$. Thus, $\mathcal{Q}$ acts on $\text{Ni}(\bar{G}, C_{\text{g}})^{\text{in}}$ through $\mathcal{Q}'' = \mathcal{Q}/\langle \tilde{z}^2 \rangle$.

Further, $\mathcal{Q}''$ is normal in $M_4$. Let $O$ be a braid orbit in $\text{Ni}(G, C)^{\text{in}}$. Then, $\mathcal{Q}''$ acts through representations of the Klein 4-group on $O$. So, all of its orbits on $O$ have a common length that is 1, 2 or 4.

Assume $g \in \text{Ni}(G, C)^{\text{in}}$ corresponds to $\varphi_g : W_g \to \mathbb{P}_1^g$ with respect to $\mathcal{P}$.

Then, for $g \in \mathcal{Q}''$, $\varphi(g)_g : W(g)_g \to \mathbb{P}_1^g$ is reduced equivalent to $\varphi_g$.

**Proof.** Apply $\tilde{z}^2$ to $g = (\bar{g}_1, \ldots, \bar{g}_4)$:

$$
(\bar{g}_1\bar{g}_2\bar{g}_1^{-1}, \bar{g}_1, \bar{g}_4, \bar{g}_3\bar{g}_4) \xrightarrow{\tilde{z}^2} (\bar{g}_1\bar{g}_2\bar{g}_1^{-1}, \bar{g}_1, \bar{g}_4, \bar{g}_3\bar{g}_4)^{-1} \bar{g}_3\bar{g}_4).$$

Since $\bar{g}_1 \cdots \bar{g}_4 = 1$, $\bar{g}_1\bar{g}_2 = (\bar{g}_3\bar{g}_4)^{-1}$, the result is conjugation of $g$ by $\bar{g}_1\bar{g}_2$. That shows all the statements of the first paragraph, including that $\mathcal{Q}$ acts on Nielsen classes through $\mathcal{Q}''$.

Now we show $\mathcal{Q}''$ is normal in $M_4^{\text{ir}}$. From relations (2.13) in $B_4$:

$$\tilde{z}^2 = q_1q_2q_3^{-1}q_2q_1 = q_1(q_2q_3q_2)q_1q_2 = q_1(q_2q_3)q_1q_2 = q_3(q_1q_2q_3)q_1q_2 = q_3(q_1q_2q_3)q_1q_2q_3^{-1}.$$ 

and $q_3\tilde{z}q_3^{-1} = \tilde{z}$. Thus $q_3$ normalizes $\mathcal{Q}''$. Since $\tilde{z} = q_1q_3^{-1} \in \mathcal{Q}''$, $q_1$ also normalizes $\mathcal{Q}$. We now show $q_2$ does also.

RETURNM Use $(q_1q_2)^3$ tildez = 1 Apply (2.13a) in the form $q?1q?1q?1 = zq$ q q to get 2 212 121 q?1?1q = $q?1q?1q$ q q = $z(q q q q q)$ q q = $z?2$. 2 2 21232 121323 Also, since $z$ is a central involution, conjugate by $q?1$ to get $q?2q?1 = z??1$. 

Compute the action of $\tilde{\gamma}$ on $g = (g_1, \ldots, g_4)$:

$$g = g_1^{-1} \rightarrow (g_1g_2g_1^{-1}, g_1, g_4, g_4^{-1}g_3g_4) = g_1^{-1} \rightarrow ((g_1g_2)g_1(g_1g_2)^{-1}, g_1g_2g_1^{-1}, g_4^{-1}g_4g_4, (g_3g_4)^{-1}g_4(g_3g_4)).$$

In the bottom row 2nd term (resp. 3th term) substitute $g_2g_2g_2^{-1}$ (resp. $g_3^{-1}g_3g_3$) for $g_2$ (resp. $g_3$). The result is that the first two terms (resp. last two terms) are the corresponding terms of $g$ conjugated by $g_1g_2$ (resp. $(g_3g_4)^{-1}$).

From product-one applied to $g(g(g(g(g(g))))$, $g_1g_2 = (g_3g_4)^{-1}$. Therefore, the result is a conjugation by $g_1g_2$, an inner equivalence occurring in either $\text{Ni}(G, C)^\dagger$. That shows the action of $\tilde{\gamma}$ is trivial on Nielsen classes.

With no loss, consider $Q$ on Nielsen classes as acting through $Q''$. Since $Q''$ is normal in $M_4$, any $Q''$ orbit, $O_m$ is carried to another $Q''$ orbit (in $O$) by any $q \in M_4$. This gives all $Q''$ orbits in $O$ a common length. Conclude by characterizing the Klein 4-group as the dihedral group $D_2$.

First, by definition of $Q''$, $(q_1q_3^{-1})^2$ is trivial, as is $sh^2$. As a group generated by two involutions, $Q''$ in its action on Nielsen classes is the dihedral group $D_n$, with $n$ the order of the action of the product of $q_1q_3^{-1}$ and the $sh$.

The braid relation $q_1q_2q_3q_3q_2q_1$ becomes $q_1q_2q_1q_2q_1 = 1$. Lemma 2.10 shows adding these relations to B4 is equivalent to adding $q_2q_2q_2 = 1$ to $H$. This produces new equations: 134 (2.9) $q_1q_2q_1q_2q_1 = (q_1q_2q_1)^2 = (q_1q_2)3 = 1$. \hfill $\square$

2.2.3. $M_4$ subgroups; reduced fine moduli. Prop. 2.10 shows how $Q'' = Q/\langle \tilde{\gamma} \rangle$ acts on Nielsen classes, an effect critical for what fine moduli means for reduced Hurwitz spaces when $r = 4$. The two groups to keep in mind $r = 4$ are these:

\begin{equation}
\text{Moduli Group: } Q'' \overset{\text{def}}{=} \langle q_1q_3^{-1}, sh^2 \rangle / \langle \tilde{\gamma} \rangle
\end{equation}

\begin{equation}
\text{Cusp Group: } Cu_4 \overset{\text{def}}{=} \langle q_2, Q'' \rangle / Q''.
\end{equation}

(2.25a) $b(\text{irrational})$-fine moduli: $Q''$ must act as a Klein 4-group; and

(2.25b) $e(\text{elliptic})$-fine moduli: neither $\gamma_0$ nor $\gamma_1$ has fixed points (on $O$).

We have given in (2.17) reasons for using reduced spaces. Further, in (2.17b) why the case $r = 4$ stands out to make comparisons with modular curves. There are differences between $r = 4$ and $r > 4$ for fine moduli. We illustrate the outcomes when fine moduli doesn’t hold in this section using our examples, and specifically the case when we work over the field, $\mathbb{R}$, of real numbers Ch. 3 §5.2.

Remark 2.11 (Fine moduli for $r > 4$). The algorithm for using the $sh$-incidence matrix works for $r > 4$ as in Lem. 3.6. There are, though these differences. A group like $Q''$ only appears for $r = 4$, so the first condition of (2.25) is moot. We still, however, have a version of condition (2.25b): existence of elliptic fixed points. These would now would be singular on the reduced Hurwitz space, rather than just ramified in the cover $H_{r,rd} \rightarrow \mathbb{P}^1_j$. 

\begin{equation}
H_{r,rd} \rightarrow \mathbb{P}^1_j.
\end{equation}
For these singular points, each can make a contribution to not having fine reduced moduli, a condition that we may calculate from the Nielsen class directly using branch cycles. See §4.3.3.

Remark 2.12 (Product-one). Product-one, $\gamma_1 \gamma_2 \gamma_3 = 1$, is now a consequence of the Hurwitz braid relation

\[(2.26) \quad q_1 q_2 \cdots q_{r-1} q_{r-2} \cdots q_1\]

combined for $r = 4$ with modding out by $q_1 = q_3$. That immediately gives $\gamma_1^2 = 1$ in its action on reduced Nielsen classes. For $\gamma_0^3 = 1$, use the braid relations

\[(2.27) \quad q_i q_{i+1} q_i = q_{i+1} q_i q_{i+1} \quad \text{and for } |i-j| > 1 \mod r-1, q_i q_j = q_j q_i.\]

The latter says non-contiguous braids commute.

2.2.4. Genus formula for $r = 4$. Thm. 2.13 allows computing properties of reduced Hurwitz spaces when $r = 4$ without needing their descriptions as upper half-plane quotients. Except for our running example of covers from dihedral groups, as in §3.2, they aren’t modular curves, their defining subgroups are not congruence subgroups. Therefore, they would be both hard to find, and even harder to use.

Theorem 2.13. Suppose a component, $\mathcal{H}'$, of $\mathcal{H}(G, C)^{1,rd}$ is given by a braid orbit, $O$, on the corresponding reduced Nielsen classes $Ni(G, C)^{1,rd}$. Then, the ramification, respectively over 0, 1, $\infty$, of $\mathcal{H}' \to \mathbb{P}^1$ corresponds to the disjoint cycles of $\gamma_0 = q_1 q_2$, $\gamma_1 = q_1 q_2 q_1$, $\gamma_{\infty} = q_2$ acting on $O$.

The genus, $g_{\mathcal{H}'}$, of $\mathcal{H}(G, C)^{1,rd}$, à la Riemann-Hurwitz, appears from

\[2(|O| + g_{\mathcal{H}'} - 1) = \text{ind}(\gamma_0) + \text{ind}(\gamma_1) + \text{ind}(\gamma_{\infty}).\]

We recast the proof of [BFr02, Thm. 2.9] on Thm. 2.14 combinatorial results on $H_4$ vs $\bar{M}_4 = H_4/\mathcal{Q}$ in §4.2.

Theorem 2.14 (Cohomology result for Thm. 2.13).

(2.28a) The only involution in $H_4$, $\bar{z}^2 = (q_1 q_3^{-1})^2$, generates its center.

The quotient $H_4/\langle \bar{z}^2 \rangle$ is $\bar{M}_4$.

(2.28b) $\mathcal{Q} \triangleleft H_4$ with $\mathcal{Q}$ he quaternion group $Q_8$.

(2.28c) $H_4/\mathcal{Q} = \bar{M}_4 \cong \text{PSL}_2(\mathbb{Z})$.

(2.28d) Exactly two conjugacy classes of $H_4$ subgroups $U_1 = \langle q_1, q_2 \rangle$ and $U_2 = \langle q_2, q_3 \rangle$ (both containing $\langle \bar{z} \rangle$) are isomorphic to $\text{SL}_2(\mathbb{Z})$.

From (2.28b), $\mathcal{Q}$ is the smallest normal subgroup of $H_4$ containing either $(q_1 q_2 q_3)^2$ or $q_1 q_3^{-1}$. From the braid relation defining $H_4$ from $B_4$, (2.26) (see Rem. 2.12)

\[\bar{M}_4 = \langle \gamma_0, \gamma_1 \rangle = \langle \gamma_1, \gamma_{\infty} \rangle \text{ is } M_4 \text{ modulo the relation } q_1 = q_3.\]
3. sh-incidence on reduced Hurwitz spaces

This section gives a tool for treating in detail Hurwitz spaces of reduced Nielsen classes. Property number one for Hurwitz spaces is to detect their components. We give two geometrically interpretable tools for that: the practical sh-incidence matrix §3.1, and the theoretical lift invariant Ch. 3, which only appears if \( G \) has a nontrivial Schur multiplier.

We start here two of the main examples in the book. §3.2 has the MT description of modular curves (and their cusps). §3.3 does one example based on \( G = A_4 \), that we can use to reflect on the relation between the RIGP and the OIT. This relation arises in MTs, appearing in all our conjectures, starting with the Main Conjecture (3.1). Especially we use this example to illustrate Thm. 2.13 where the need to identify the braid orbits in the Nielsen class is immediate.

**Conjecture 3.1 (Main MT Conjecture).** For \( K \) a number field, at high levels there will be no \( K \)-points on a MT.

Also, high levels will be algebraic varieties of general type (high powers of the canonical bundle embed the variety in projective space) [Fr95].

### 3.1. sh-incidence Algorithm.

The sh-incidence matrix entwines the interaction of the braids and the group \( G \), showing up in invariants of components of Hurwitz spaces by a labeling on cusps.

#### 3.1.1. Twist orbits.

**Definition 3.2.** An element \( g \in \text{Ni}(G, C) \) is a Harbater-Mumford (HM) representative if it has the form \((g_1, g_1^{-1}, \ldots, g_s, g_s^{-1})\) (so \( 2s = r \)). A braid orbit \( O \) is said to be HM, if the orbit contains an HM rep.

To initially address Conjecture (3.1), [Fr95] inspected the properties of the MT for \( \text{Ni}(A_5, C_{3^4}), \ell = 2 \) in sufficient detail that any fair observer could see there was something substantive happening in essentially any MT. The superficial similarity between that Nielsen class, with one braid orbit, and the \( A_4 \) example below (with two braid orbits), is belied by resulting large difference between the two of them. Both have braid orbits with HM reps.

Lem. 3.3, for all \( r \), lists \( q_i \) orbits. Note though, one index \( i \) suffices for the sh-incidence matrix. For historical reasons we choose \( i = 2 \).

**Lemma 3.3.** Let \( g \in \text{Ni}(G, C) \) be a Nielsen class representative. With \( \mu = g_i g_{i+1} \), the orbit of \( Q_i \) on \( g \) is the collection

\[
(g)_{Q_i^k} = \begin{cases} 
(g_1, \ldots, g_{i-1}, \mu^l g_i \mu^{-l}, \mu^l g_{i+1} \mu^{-l}, g_{i+2}, \ldots) & \text{for } k = 2l \\
(g_1, \ldots, g_{i-1}, \mu^l g_i g_{i+1} g_i^{-1} \mu^{-l}, \mu^l g_i \mu^{-l}, g_{i+2}, \ldots) & \text{for } k = 1 + 2l.
\end{cases}
\]

If \( r = 4 \), and \( g \in \text{Ni}(G, C)^4 \) is an HM rep. \((g_1, g_1^{-1}, g_2, g_2^{-1})\), then so are all elements in the \( Q'' \) orbit of \( g \). Then, the \( Q'' \) orbit length on \( O_g \) is \( 4/(m+1) \) with \( m \)
the count of conjugacies, in \( \dagger \) equivalence, given by
\[
hg_1h^{-1} = g_2 \text{ or } g_1 = hg_2h^{-1} \text{ with } h^2 = 1; \text{ or } h(g_1, g_2)h^{-1} = (g_1^{-1}, g_2^{-1}).
\]
If \( G \) (resp. \( N_{S_n}(G, C) \)) has no center (resp. element that centralizes \( G \)) for \( \dagger = \) in (resp. abs) then \( h \) is determined by these conditions.

**Proof.** The formula of the 1st paragraph comes from the definition of \( q_i \).

Similarly, if you apply \( q_iq_j^{-1} \) or \( \text{sh}^2 \) to an \( \text{HM} \) rep, then it is immediate the result is another \( \text{HM} \) rep.

Now consider the \( Q'' \) orbit length, which is 4 divided by the number of elements \( q \in Q'' \) for which \((g)q = hg^h \) for some \( h \in G \) (resp. \( h \in N_{S_n}(G, C) \)) if \( \dagger = \) in (resp. \( \dagger = \) abs). The cases are similar, so we will just do the 1st.

If \( h^2 = 1 \) for which \( g_1 = hg_2h^{-1} \), then \( g_1^{-1} = hg_2^{-1}h^{-1} \) and
\[
h((g)\text{sh}^2)h^{-1} = h(g_2, g_2^{-1}, g_1, g_1^{-1})h^{-1} = g.
\]
If \( h_1, h_2 \) both satisfied these conditions then \( h_1h_2^{-1} \) would commute with \( g \), contrary to the centralizing assumption. Either one or all three of those conditions are satisfied. Add that number to 1 (for the trivial element in \( Q'' \)) to get \( m \).

**Remark 3.4.** General expectation from Lem. 3.3 is that \( Q_2 \) orbits would have length \( 2 \cdot \text{ord}(g_{i}g_{i+1}) \equiv 2o \). There is an important exception – Ch. 6 Prop. 2.1 – for which the orbit length (even without concerns about centralizers) is half that expectation. The first condition is that \( o \) is odd. It applies to \( \S3.2 \) and to the cusp labeled \( cO^3_{1,3} \) in the \( N_{0}^{+} \) block of 2.

**3.1.2. Listing cusps for the sh-incidence matrix.** Def. 3.5, the \( \text{sh} \)-incidence matrix, is invaluable to compute braid orbits on specific reduced Nielsen classes.

For, \( S \), a set of representatives in \( Ni(G, C) \) and any equivalence relation \( \bullet \) on the Nielsen class, denote by \( S^{q_2, \bullet} \) (resp. \( S^{\text{sh}, \bullet} \)) the collection of \( \bullet \) equivalence classes of \( q_2 \) (resp. \( \text{sh} \)) orbits.

We have been using \( O \) for braid orbits on a Nielsen class. For \( q_2 \) (cusp) orbits the notation will be \( cO \), with the understanding that \( \bullet \)-equivalence has been specified.

If \( r = 4 \) and \( \bullet \) is one of the reduced equivalences, then \( \text{sh} \) has order 2, thereby producing a symmetric matrix.

**Definition 3.5.** List \( \bullet \)-equivalence classes, \( cO_1, \ldots, cO_u \), of \( q_2 \) (cusp) orbits. The \( \text{sh} \)-incidence matrix \( A(G, C) \) has \((i, j)\) term \(|(O_i)\text{sh} \cap O_j|\).

Denote the transpose of an \( n \times n \) matrix by \( ^{t}T \). Equivalence \( n \times n \) matrices \( A \) and \( T^{u}A^{v}T \) running over permutation matrices \( T \) associated to elements of \( S_n \).

Refer to a matrix \( A \) as in block form if there are matrices \( B_1, \ldots, B_u \), for which \( A \) has the form of a \( u \times u \) diagonal matrix with diagonal entries \( B_1, \ldots, B_u \). The proof of Lem. 3.6 is an algorithm. Rem. 3.8 and Rem. 3.10 have extra comments.
3. \textbf{sh}-\textit{incidence on reduced Hurwitz spaces}

\textbf{Lemma 3.6.} For some $T$, $A(G, C)$ is in block form with the block rows (and columns) labeled by cusp orbits whose union of elements consists of a single braid orbit on $Ni(G, C)$ under $\bullet$-equivalence.

\textbf{Proof.} Start with any $q_2$ orbit and label it $cO_{1,1}$. Then form the sequence

$$(2.29) \quad cO_{1,1} \to (cO_{1,1}^{sh})q_2 \to ((cO_{1,1}^{sh})q_2)^{sh} \cdots$$

until the sequence stops. The result will be a union of distinct $q_2$ orbits under $\bullet$-equivalence.

Denote this collection by $cO_1 = \{cO_{1,1}, \ldots, cO_{1,b_1}\}$. Since $H_r = \langle q_2, sh \rangle$, together $cO_1$ contains all elements – modulo $\bullet$-equivalence – in the Nielsen class that are in the $H_r$ orbit of any element of $cO_{1,1}$.

Label the rows and columns of the first block of your matrix, $B_1$, by the elements of $cO_1$. In step 1 of (2.29) you iterate applications of $\text{sh}$ on $cO_{1,1}$ and check for all new $q_2$ orbits. The $(i, j)$-entry is $|cO_{1,i} \cdot \text{sh} \cap cO_{1,j}|$. Call $cO_1$ and $cO_j$ neighbors if $|cO_{1,i} \cdot \text{sh} \cap cO_{1,j}|$ is nonzero for some $t$. If the process stops after one step, then all $q_2$ orbits are neighbors of $cO_{1,1}$. In step 2 you do the same thing to any of the new $q_2$ orbits, etc., until you stop getting new $q_2$ orbits. The resulting $\text{sh}$-incidence matrix is obtained from a maximal sequence of neighbors.

Therefore, this gives exactly one block, $B_1$ as described in the opening paragraph of the lemma. If further $q_2$ orbits in the Nielsen class haven't been used, then start again until you have used them all. Eventually you get blocks $B_1, \ldots, B_u$ corresponding to unions of $q_2$ orbits $cO_{1,1}, \ldots, cO_{1,u}$.

\hfill $\square$

3.1.3. $r = 4$ and finishing the computation.

\textbf{Lemma 3.7.} Now assume $r = 4$, and $\bullet$-equivalence is one of the reduced equivalences, so $q_2$ orbits are $\gamma_\infty$ orbits. Then the $\text{sh}$-incidence matrix is symmetric.

Replacing $\text{sh}$ by either $\gamma_0$ or $\gamma_1$ acting on $\gamma_\infty$ orbits gives the same blocks in the resulting matrix. Then, fixed points of $\gamma_j$, $j = 0$ or 1, on any $\tilde{M}_4$ orbit give nonzero entries along the diagonal of the corresponding block. Then,

$$|(cO_{1,t})\text{sh} \cap cO_{1,t'}| = |(cO_{1,t})\text{sh}^2 \cap (cO_{1,t'})\text{sh}| = |cO_{1,t} \cap (cO_{1,t'})\text{sh}|.$$

That shows the final matrix in block form, has each block symmetric.

\textbf{Proof.} Take $r = 4$ and for $\bullet$-equivalence one of the reduced equivalences, where $\text{sh}^2$ is the identity on braid orbits.

Use that on reduced classes $q_1 = q_3$, with relation (2.13), $q_1 q_2 q_1 = q_2 q_1 q_2$. Now consider what happens if we replace $\text{sh}$ by $\gamma_1$ represented by $q_1 q_2$. Since we start with a $q_2$ orbit, say $cO$, the collection with $\text{sh}$ applied is given by

$$(cO)\text{sh} = (cO)q_1 q_2 q_1 = (cO)q_2 q_1 q_2 = (cO)q_1 q_2.$$
That shows the matrix is the same with $\gamma_0$ replacing $\text{sh}$. Of course, $\gamma_1$ is $\text{sh}$. That finishes the proof of the lemma. \hfill \Box

**Remark 3.8 (The algorithm-Part 1).** Regard the sequence of expression (2.29) as iterated steps – it shows two steps – in computing one braid orbit on the $*$-equivalence classes on $\text{Ni}(G, C)$, Our examples often have one step.

Notice in our $\text{Ni}(A_4, C_{4,32-32})$ example §3.3, the seed for each braid orbit – respectively an $\text{HM}$ rep. Def. 3.2, and a $\text{D}(ouble)I(dentity)$ rep. – end up giving their Hurwitz space components corresponding monikers.

It makes sense to list $q_2$ orbits, referring to the blocks, as
\[ O_{1,1}^{w_{1,1}}, \ldots, O_{1,b_1}^{w_{1,b_1}}, O_{2,1}^{w_{2,1}}, \ldots, O_{2,b_1}^{w_{2,b_1}}, \ldots, O_{u,1}^{w_{u,1}}, \ldots, O_{u,b_1}^{w_{u,b_1}}, \]
with the superscript $w_{i,j}$ the cusp width (cusp orbit length). Still, should there be more than one step, labeling within any one block probably should correspond to the step in which it appears. Especially if the seed orbit has been chosen well.

**Lemma 3.9.** For $r = 4$, in the $i$th block of the $\text{sh}$-incidence matrix, we can read off the degree of the component $\bar{H}_i$ over $P^1_j$ as $\sum_{j=1}^{b_1} w_{i,j}$. Further,
\[ w_{i,j} = \sum_{k=1}^{b_i} |(cO_{i,j})\text{sh} \cap O_{i,k}|, j = 1, \ldots, b_i. \]

**Proof.** This follows by recognizing the cusps as the $q_2$ orbits on the $i$th braid orbit of the Nielsen classes under reduced equivalence. This is a piece of the proof of Thm. 2.7. The rest is from the combinatorics of the $\text{sh}$-incidence matrix. \hfill \Box

**Remark 3.10 (The algorithm-Part 2).** Fixed points of $\gamma_0$ or $\gamma_1$ on a reduced orbit imply that the reduced Hurwitz space component does not have fine moduli. We can almost read that data off directly from the $\text{sh}$-incidence matrix. If there are no nonzero diagonal elements corresponding to that block in Lem. 3.6, then for certain $\gamma_0$ or $\gamma_1$ have no fixed point, and then the only test necessary for fine moduli is that $Q''$ acts on that orbit as a Klein 4-group.

Yet, if there diagonal elements aren’t all 0, there may, or not, be $\gamma_0$ or $\gamma_1$ fixed points. Both cases occur in the $\text{Ni}(A_4, C_{4,32})$ §3.3. That illustrates many part 3 topics of the book. Before that, though, §3.2 returns to modular curves.

**3.2. Dihedral Ex. 2.7 continued.** We lay out – extending [Fr78, §2] – the cusps on the one braid orbit on $\text{Ni}(D_{4k+1}, C_{2k}) \overset{\text{def}}{=} \text{Ni}_k$.

**3.2.1. Listing the cusps for $\text{Ni}_k^{\text{in}}$.** For a given $g \in \text{Ni}_k^{\text{in}}$, conjugate by $\left( \begin{array}{cc} 1 & \alpha^{1/2} \\ 0 & 1 \end{array} \right)$ to assume $g_1 = \left( \begin{array}{cc} -1 & 0 \\ 0 & 1 \end{array} \right)$. For $g \in \text{Ni}_k^{\text{abs}}$, conjugate by $\left( \begin{array}{cc} \alpha & 0 \\ 0 & 1 \end{array} \right)$, $\alpha \in (\mathbb{Z}/\ell^{k+1})^*$ to assume $a_2 - a_3 = \ell^u$, $u \geq 0$:
\[ \left( \begin{array}{cc} \alpha & 0 \\ 0 & 1 \end{array} \right) \left( \begin{array}{cc} 0 & 1 \\ -1 & 0 \end{array} \right) \left( \begin{array}{cc} \alpha^{-1} & 0 \\ 0 & 1 \end{array} \right) = \left( \begin{array}{cc} 0 & \alpha a' \\ -1 & 1 \end{array} \right). \]
(2.31a) Show conjugating by \( H_u = \{ \alpha \equiv 1 \mod \ell^{k+1-u} \} \) in (2.30) has no effect on \( a_2 - a_3 \).

(2.31b) \((a_2,a_3) = (1,1)\) (resp. \((0,1)\)) gives a length 1 (resp. \( \ell^{k+1} \)) \( q_2 \) orbit on \( N_k^{\text{abs,rd}} \), an example of Rem. 3.4.

(2.31c) With \( a_2 - a_3 = \ell^u, 1 \leq u \leq k \), follow the steps of Prop. 3.11 to count \( q_2 \) orbits (cusps), and their widths, on \( N_k^{\text{abs,rd}} \).

(2.31d) Use (2.31b) to show Table 1 is the sh-incidence matrix for \( N_k^{\text{abs,rd}} \). Conclude: \( |N_k^{\text{abs,rd}}| = |N_k^{\text{abs}}| : Q'' \) action is trivial.

(2.31e) Modify (2.31d) to \( N_k^{\text{in,rd}} \); that \( |N_k^{\text{in,rd}}| = |N_k^{\text{in}}| \) and we can braid (Rem. 3.9) all the outer automorphisms from \((\mathbb{Z}/\ell^{k+1})^* / \langle \pm 1 \rangle\).

Hint for (2.31d): From Table 1 – one component of the sh-incidence matrix – you need only test the action of \( Q'' \) on an HM rep.

Hint for (2.31e): See what happens with the HM rep. in (2.31b).

3.2.2. sh-incidence for \( N_k^{\text{abs,rd}} \). Continue notation for (2.31c).

**Proposition 3.11.** For \( u > 0 \), \((g) = D_{\ell k+1} \) implies \((a_2, \ell) = 1\). Conjugating by \( H_u \) assures \( cO_g \) has Nielsen class reps. with distinct 2nd entries, \( a_2 + mt^u \) mod \( \ell^{k+1-u} \). Denote \((\mathbb{Z}/\ell^{k+1-u})^* \mod \text{(additive)} \) translate by \( t^u \) by \( L_{k+1,t^u}^\ast \).

Let \( a_g \) have \( a_2 = 1 \) and \( a_3 = 1 - \ell^u \). Use:

\[(a_g)q_2^j \text{ corresponds to the pair } (a_2, a_3) = (1 + t^u, 1 + (l - 1)t^u)\].

Consider the subgroup \( S_u \leq H_u \) stabilizing (2.32). Then, \(|S_u| = \ell^{\min(u,k+1-u)}\).

This gives a \( q_2 \) orbit of length \( \ell^{k+1-u}/\ell^{\min(u,k+1-u)} \). Each \( u, 1 \leq u \leq k \) contributes \( \varphi(\ell^u)/|H_u| \) orbits of \( q_2 \) of this length.

(2.33a) Cusps corresponding to \( u \) are \( cO_{\ell k+1-2u,a}, a \in L_{k+1,t^u}^\ast \).

(2.33b) For \( 0 \leq u \leq \frac{k+1}{2} \), cusps have widths \( k+1-2u \); and

(2.33c) for \( 0 \leq \frac{k+1}{2} \leq u \leq k+1 \), cusps have width 1.

**Table 1. sh-incidence for \( \text{Ni}(D_{\ell^{k+1}}, C_{2^4})^{\text{abs,rd}} \) listings for \( cO_{\ell^{k+1-2u,a}} \)**

<table>
<thead>
<tr>
<th>Cusp orbit</th>
<th>( u = 0 )</th>
<th>( a \in L_{k+1,t^u}^\ast )</th>
<th>( u \leq k+1-2u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{k+1,t^u}^\ast )</td>
<td>( \ell^{k+1} - \ell^k )</td>
<td>( \ell^{k+1-2u} )</td>
<td>1</td>
</tr>
<tr>
<td>( 1 \leq u \leq \frac{k+1}{2} )</td>
<td>( \ell^{k+1-2u} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( k+1-2u \leq u \leq k+1 )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Remark 3.12.** [Sh94, p. 25] has the traditional way to compute \( X_0(\ell^{k+1}) \) cusp data. Note: In (2.31b), an HM rep. (from \((a_2, a_3) = (0,1)\)) gives the longest \( q_2 \) orbit. Its shift gives the shortest \( q_2 \) orbit.
Remark 3.13. Above, $Q''$ acts trivially on inner (and so absolute) Nielsen classes. As these Nielsen classes have modular curves as their reduced spaces, maybe that is why $Q''$ has not appeared in studies of modular curves. Still, failure of b-fine moduli (as in (2.25)) for both is the same: a Klein 4-group in $\text{PSL}(\mathbb{C})$ stabilizes any four distinct points on $P^1_{\mathbb{C}}$ as in Thm. 2.7 (especially its proof Ch. 6 §4.1).

3.3. $\text{sh}$-incidence on $\text{Ni}(A_4, C_{±3^2})^{\text{in}, \text{rd}}$. We now look at level $k = 0$ for $\ell = 2$ of Ch. 5 (which illustrates generalizing Serre’s OIT). Let $\alpha$ act on $(\mathbb{Z})^2$ as \( \begin{pmatrix} 0 & 1 \\ -1 & -1 \end{pmatrix} \) (of order 3). Take the induced action on $(\mathbb{Z}/2)^2$, and regard $\alpha$ as a generator of $\mathbb{Z}/3$, as a multiplicative group. Then,

\[(2.34) \quad A_4 = (\mathbb{Z}/2)^2 \times^s \mathbb{Z}/3 = \left\{ \left( \begin{array}{cc} a' & (x,y) \\ 0 & 1 \end{array} \right) \right\} \mid j \in \mathbb{Z}/3, (x,y) \in (\mathbb{Z}/2)^2,\]

as in the semi-direct product (left action of $\alpha$) notation of Ch. 1 Def. 1.6. In that general case, we will be using this matrix notation with $\alpha_0 = \left( \begin{array}{cc} 0 & 0 \\ 0 & 1 \end{array} \right)$.

In, however, §3.3.1, we use permutation notation (right action on $\{1,2,3,4\}$), with $\alpha_0 = (1\, 2\, 3) \in A_4$ the special representative of $\alpha$. We also have $A_4 \leq A_5$, used below, as in Lem. 3.14.2

3.3.1. Describing elements in a particular Nielsen class. The Nielsen class we want is $\text{Ni}(A_4, C_{±3^2})^{\text{in}, \text{rd}}$, where $C_{±3}$ (resp. $C_{-3}$) is the class of $\alpha$ (resp. $\alpha^{-1}$) and $C_{±3^2}$ means the collection repeats each class twice. Therefore, it is a rational union of conjugacy classes. So, it defines Hurwitz spaces over $\mathbb{Q}$ from the BCL (Lem. 4.1).

Here is what to expect of the example.\footnote{In Serre’s OIT the primes $\ell = 2$ and 3 have slightly different behavior than the other primes. That happens, too, in our example. In both, we uniformly compare these with the lift invariant and the concept eventually $\ell$-Frattini.}

(2.35a) The reduced Hurwitz space has two components, labeled $\mathcal{H}_0^{±}$, from braid orbits $\text{Ni}_0^{±}$ appearing from the $\text{sh}$-incidence matrix.

(2.35b) Both Hurwitz space components have fine moduli. The reduced space $\mathcal{H}_0^+$ has fine reduced moduli (§2.2.3), while $\mathcal{H}_0^-$ does not.

(2.35c) The genuses of both $\bar{\mathcal{H}}_0^{±}$ are 0.

(2.35d) Neither component is a modular curve, but we can compute their arithmetic and geometric monodromy as $j$-line covers.

Comment on (2.35b): Fine moduli for inner Hurwitz spaces in this case comes from $A_4$ having no center Ch. 1 Lem. 2.3. The check for reduced fine moduli on a braid orbit $O$ for has two steps [BFr02, §4.3.1]: (2.25a), $Q''$ acts as a Klein 4-group; and (2.25b), neither $\gamma_0$ nor $\gamma_1$ has fixed points (on $O$).

Comment on (2.35c): To conclude Main MT conj. 3.1 for this MT requires going to higher levels to assure component genuses rise beyond 1. Each component has
2-cusps (respectively labeled \(cO_{1,1}^4\) and \(cO_{2,1}^4\) Table 2. So, it requires more work to establish the explicit rise of genus, but this is the crucial hypothesis of [Fr06, §5].

**Comment on (2.35d):** In Prop. 3.16 we see there is a natural one-one map from \(\mathcal{H}_0^{rig}\) to \(\mathcal{H}_0^{abs}\), though as moduli spaces they are very different, a difference far less subtle than that referred to in Rem. 3.13 as it involves the very large difference between the jacobians of the curves in their respective moduli [BFr02, §E.2.2], which we revisit in §1.1.1.

List possible parity sequences from \(C_{\pm 3}\) in \(\text{Ni}(A_4, C_{\pm 3})^{in,rd}\):

\[
\begin{align*}
[1] & \quad + - + \\
[2] & \quad + - - \\
[3] & \quad - - - \\
[4] & \quad - - - \\
[5] & \quad - + + \\
[6] & \quad - + -
\end{align*}
\]

These are useful observations.

(2.36a) By applying \(g \in Q''\), assume that a reduced representative of an orbit has (123) as its first entry: Is in \(\{[1], [2], [3]\}.

(2.36b) To check if \((i j k)\) should be a + or -, conjugate by any \(g \in S_4\) that takes it to (123) and check if \(g\) has + or - parity.

3.3.2. **Cusps and the \(sh\)-incidence matrix.** Again, list cusps as \(cO_{i,j}^k\): \(k\) is the cusp width, and \(i, j\) as in Rem. 3.8, corresponds to a labeling of orbit representatives.

The following elements are in a Harbater-Mumford component (3.2).

**HM rep. for** \(cO_{1,1}^4\): \(g_{1,1} = (123, (132), (134), (143))\)

**HM rep. for** \(cO_{3,3}^4\): \(g_{1,3} = (123, (132), (134), (143))\)

**sh of HM rep. for** \(cO_{2,2}^4\): \(g_{1,2} = (123, (124), (142), (132))\).

Consider \(g_{2,1} = (123, (134), (124), (124)) \in [2]\). Its \(\gamma_\infty\) orbit \(cO_{2,1}^4\) is what §3.1.2 calls D(ouble)I(dentity): named for repeated entries in \(g_{2,1}\) (positions 3 and 4). The same for the seed of the DI cusps \(cO_{1,2}^4\) and \(cO_{1,3}^4\) (positions 2 and 3).

In Table 2, each cusp orbit has an element with entries \((g, g^{-1})\) or with entries \((g, g)\): the former in broad orbit \(\text{Ni}_0^+\), the latter in broad orbit \(\text{Ni}_0^-\).

**Table 2.** The two \(sh\)-incidence blocks on \(\text{Ni}(A_4, C_{\pm 3})^{in,rd}\).

<table>
<thead>
<tr>
<th>(\text{Ni}_0^+) Orbit</th>
<th>(cO_{1,1}^4)</th>
<th>(cO_{2,1}^4)</th>
<th>(cO_{1,3}^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(cO_{1,1}^4)</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(cO_{2,2}^4)</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>(cO_{1,3}^4)</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(\text{Ni}_0^-) Orbit</td>
<td>(cO_{2,1}^4)</td>
<td>(cO_{2,2}^4)</td>
<td>(cO_{2,3}^4)</td>
</tr>
<tr>
<td>(cO_{2,1}^4)</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(cO_{2,2}^4)</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(cO_{2,3}^4)</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Prop. 3.16** explains the two blocks – each one step (of (2.29)) – of the \(sh\)-incidence matrix on \(\text{Ni}(A_4, C_{\pm 3})^{in,rd}\). This is our first use of the lift invariant. We need the Frattini central extension of \(A_4\), for which the following is convenient:

(2.37) Pullback of \(A_4 \leq A_5\) to \(\text{SL}_2(\mathbb{Z}/5) \to \text{PSL}_2(\mathbb{Z}/5) = A_5\).
For \( g \in C_{\pm 3} \), \( \hat{g} \) is the (unique) order 3 lift to \( \psi : \hat{A}_4 \to A_4 \), for the cover in (2.37).

This is a case (for \( r = 4 \)) of Def. 1.4 where we are computing

The restricted lift invariant relative to \( \psi \) of the \( O_g \) braid orbit of \( g \):

\[
    s_\psi(g) \overset{\text{def}}{=} s_\psi(O) = \prod_{i=1}^r \hat{g}_i \overset{\text{def}}{=} \prod(\hat{g}) \text{ running over braid components.}
\]

3.3.3. Preliminary on the lift invariant. Regard \( \text{ker}(\psi) \) as \( \{\pm 1\} \). If \( s_\psi(O_g) = +1 \), we say it has trivial lift invariant. To compute \( s_\psi(O) \), we will compare \( \text{Ni}(A_4, C_{\pm 3}) \) with an auxiliary Nielsen class, \( \text{Ni}(A_4, C_{+,3^3}) \): 3 repeats of the class \( C_+ \). Note: \( C_{+,3^3} \) is not a \( \mathbb{Q} \) rational union: \( C_{-,3} = C_{-,3} \).

**Lemma 3.14.** If \( g \in \text{Ni}(A_4, C_{\pm 3^2}) \) is an HM rep., then \( s_\psi(O_g) = +1 \).

There is a lift invariant preserving correspondence between

\[
    g' = (g'_1, g'_2, g'_3) \in \text{Ni}(A_4, C_{\pm 3}) \quad \text{and \ DI reps.}
\]

\[
    (1,4)g = (g_1^{-1}, g_2, g_3, (g_1')^{-1}) \in \text{Ni}(A_4, C_{\pm 3}).
\]

Then, \( s_\psi(O_g) = s_\psi(O_{1,4}g) = -1 \) and \( O_{1,4}g \) contains no HM reps.

*Proof. Assume generation, \( \langle g_1, g_3 \rangle = A_4 \), for \( g = (g_1, g_1^{-1}, g_3, g_3^{-1}) \in C_{\pm 3^2} \).

Then, the lift invariant is the product of the entries in \( (\hat{g}_1, (\hat{g}_1)^{-1}, \hat{g}_3, (\hat{g}_2)^{-1}) \). In multiplicative notation, the lift invariant is trivial for any HM rep.

Now consider \( g' = (g'_1, g'_2, g'_3) \in \text{Ni}(G_{\ell}, C_{3^3}) \). In place of \( g'_3 \) put

\[
    ((g'_3)^{-1}, (g_3')^{-1})
\]

for the reversible correspondence in the Lemma.

Since \( \hat{g}_1 \) has order 3, \( \hat{g}_1^{-1} \hat{g}_1^{-1} = \hat{g}_1 \) is the unique order 3 in \( \hat{A}_4 \) over \( g_1 \) (easy Schur Zassenhaus). So, \( s_\psi(g') = \hat{g}_1 \hat{g}_2 \hat{g}_3 \in \ker(\psi) \) is the same as

\[
    (\hat{g}_1')^{-1} \hat{g}_2 (\hat{g}_3')^{-1} (\hat{g}_1')^{-1} = s_\psi(1,4g).
\]

Now we list two different ways to prove this is -1.

(2.38a) Direct computation: Find \( \alpha_1 \) of order 3 in \( \text{SL}_2(\mathbb{Z}/5) \) over (1 2 3). Then, find a conjugate, \( \alpha_2 \), of \( \alpha_1 \) over (1 3 4) (see Rem. 3.15).

(2.38b) Fried-Serre formula: Use that covers in \( \text{Ni}(A_4, C_{+,3^3})^{\text{abs}} \) have genus 0. So the lift invariant is \((-1)^3\) (as in Ex. 2.10).

Notice there is no problem with the variants on the DI elements; we can braid between them as we did between \( 1,2g \) and \( 1,3g \) in the statement of the lemma. \( \square \)

**Remark 3.15** (More on \( s_\psi \) in Lem. 3.14). Hint on (2.38a): Compute \( \alpha_1 \alpha_2 \) and check its order (it should be 6). Here, where \( \ell = 2 \), the 2-Sylow in \( \hat{A}_4 \) is the quaternion group \( Q_8 \), not the small Heisenberg group (whose elements for \( \ell = 2 \) all have order 2) giving the lift invariant in the other cases of Ch. 5 \$3 for \( \ell > 3 \).
3.3.4. **Properties of both** $H_4$ **orbits on** $\text{Ni}(A_4, C_{\pm32})^{\text{in,rd}}$ **spaces**. Prop. 3.16 has separated the HM and DI components, using the notation $\mathcal{H}^+_0$ and $\mathcal{H}^-_0$ for the braid orbits that contain the corresponding cusp types. We treat each separately after stating Prop. 3.16 by referring to the HM cusps and the DI cusps.

**PROPOSITION 3.16.** On $\text{Ni}(\hat{A}_4, C_{\pm32})^{\text{in,rd}}$ (resp. $\text{Ni}(A_4, C_{\pm32})^{\text{in,rd}}$) $H_4/Q''$ has one (resp. two) orbit(s). So, $\mathcal{H}(\hat{A}_4, C_{\pm32})^{\text{in,rd}}$ (resp. $\mathcal{H}(A_4, C_{\pm32})^{\text{in,rd}}$) has one (resp. two) component(s), $\mathcal{H}^+_0$ (resp. $\mathcal{H}^-_0$).

Conclusions on the inner reduced space $\mathcal{H}^+_0 = \mathcal{H}^{+,\text{in,rd}}_0$:

(2.39a) $\mathcal{H}^{+,\text{in,rd}}_0 \to \mathbb{P}^1_j$ has degree 9, the space has genus 0, and there are cusps of width 4, 3 and 2 (over $\infty$).

(2.39b) $\Phi^{\text{in,rd}}_{\text{abs,rd}}: \mathcal{H}^{+,\text{in,rd}}_0 \to \mathcal{H}^{+,\text{abs,rd}}_0$ is one-one, though the former (resp. latter) is moduli of genus 5 (resp. genus 1) covers.

(2.39c) $\mathcal{H}(\hat{A}_4, C_{\pm32})^{\text{in,rd}}$ maps one-one to $\mathcal{H}^+_0$ (despite the spaces having different moduli).

(2.39d) $\mathcal{H}^{+,\text{in,rd}}_0$ fails both tests in (2.25) for reduced fine moduli.

Conclusions on the inner reduced space $\mathcal{H}^-_0 = \mathcal{H}^{-,\text{in,rd}}_0$:

(2.40a) $\mathcal{H}^{-,\text{in,rd}}_0 \to \mathbb{P}^1_j$ has degree 6, the space has genus 0, and there are 2 cusps of width 1 and one of width 4 (over $\infty$).

(2.40b) $\Phi^{\text{in,rd}}_{\text{abs,rd}}: \mathcal{H}^{-,\text{in,rd}}_0 \to \mathcal{H}^{-,\text{abs,rd}}_0$ is two-one.

(2.40c) There is nothing on $\mathcal{H}(\hat{A}_4, C_{\pm32})^{\text{in,rd}}$ over $\mathcal{H}^-_0$.

(2.40d) $\mathcal{H}^{-,\text{in,rd}}_0$ fails the b-fine moduli test in (2.25) but neither $\gamma_0$ or $\gamma_1$ have fixed points.

**HM cusps:** First consider the braid orbit containing all HM reps. All 3-cycles in $A_4$ are conjugate in $S_4$. Thus, for inner equivalence, assume an HM rep. is

$$g_1 = ((123), (132), g, g^{-1}) \text{ or } g_2 = ((132), (123), g', (g')^{-1})$$

Applying $g_1 g_2^{-1}$ shows $g_1$ is correct up to reduced equivalence. Since $g$ must contain 4, after conjugation by (123) (inner equivalence) it is (1 u 4) with $u = 2$ or 3.

So, there are just two reduced inequivalent HM reps, whose orbits are represented by $g_{1,1}$ and $g_{1,3}$. Conjugate by (13)(24), as in Lem. 3.3, to see sh$^2$ fixes $g_{1,1}$, and the $\hat{M}_4$ orbit does not have b-fine reduced moduli.

Here are representatives of the inner reduced $q_2$ orbits (Lem. 3.3) on the three representatives in HM braids we have already selected above Table 2 in the form $((123), \bullet, \bullet, \bullet)$. The display indicates the $\bullet$s in the 2nd and 3rd positions (with the 4th determined by product-one).

- $\sigma_{1,1}: g_{1,1} = ((132), (134)), [(142), (132)], [(423), (421)], [(143), (423)]$
- $\sigma_{2,1}: g_{1,1} = ((124), (142)), [(142), (124)]$
- $\sigma_{3,1}: g_{1,1} = ((132), (143)), [(241), (132)], [(143), (124)]$
We show these representatives give the three $q_2$ orbits in one (inner) reduced braid orbit, and the $N_i^+$ block is their \textbf{sh}-incidence matrix. Notation for the elements in a $q_2$ orbit is helpful. For example, starting with $g_{1,1}$ iterates of $q_2$ on it (Lem. 3.3) give $g_{j,1}$, $j = 0, 1, 2, 3$ indicating the power of the iterate. With that, connect $cO_{1,2}$ and the other two orbits by

$$(o_{g_{1,2}})_{\text{sh}} = ((1 2 4), (1 4 2), (1 3 2)), (1 2 3)) \overset{\mu}{\rightarrow} o_{g_{1,1}},$$

$$(g_{1,2})_{\text{sh}} = ((1 4 2)(1 2 4), (1 3 2), (1 2 3)) \overset{\mu}{\rightarrow} g_{1,3},$$

with $\mu$ (resp. $\mu'$) given by $q_1q_3^{-1}$ followed by conjugation by $(1 4)(2 3)$ (resp. $(3 2 1)$). That shows the only possible entries in the 2nd row (and column) of $N_i^+$.

Now look at the entries for $(cO_{1,3}^2 \cap cO_{1,1}^4)$ with $\mu^* = \text{sh}^2q_1^{-1}q_3$:

$$(g_{1,3})_{\text{sh}} = ((2 3 4), (1 3 2), (1 4 3), (1 3 4), (1 2 3)) \overset{\mu^*}{\rightarrow} g_{1,1},$$

$$(g_{1,3})_{\text{sh}} = ((1 4 3), (1 2 4), (1 3 4), (1 2 3)) \overset{\mu}{\rightarrow} 2g_{1,1}.$$
In the 2nd row, we used $\mathbf{sh}^{-1}$, but that is $\mathbf{sh}$ modulo $Q''$. Finally, apply $q_1^{-1}q_3 \in Q''$ to the (4th row, 2nd column) to see we get the (2nd row, 1st column).

That is, $\mathbf{sh}$ switches the 2nd and 4th terms of $O_{1,1}^4$. We have filled in everything in $\text{Ni}_0^-$. This shows there are no fixed points of $\gamma_0$ or $\gamma_1$ in the $\text{Ni}_0^-$ cusp orbits, but you immediately see from computation that $\mathbf{sh}^2 q_1 q_3^{-1}$ fixes the DI elements in the length 1 cusps. This shows (2.40d).

To see that we have included all cusp orbits in $\text{Ni}_0^+$ and $\text{Ni}_0^-$, apply elements of $Q''$ to count elements of shape $++--$. Then, up to inner equivalence count the 4-tuples that start $((1\ 2\ 3), (1\ 2\ 3))$ and those that start $((1\ 2\ 3), (1\ 3\ 4))$, modulo the action of $q_1q_3^{-1}$ and conjugation by $(1\ 2\ 3))$.

**Example 3.17 (Component genuses).** Use $(\gamma_0, \gamma_1, \gamma_{\infty})$ from the $\mathbf{sh}$-incidence calculation in Prop. 3.16. Denote their restrictions to lifting invariant +1 (resp. -1) orbit by $(\gamma_0^+, \gamma_1^+, \gamma_{\infty}^+)$ (resp. $(\gamma_0^-, \gamma_1^-, \gamma_{\infty}^-)$).

We read indices of the + (resp. –) elements from the $\text{Ni}_0^+$ (resp. $\text{Ni}_0^-$) matrix block. Fixed points of $\gamma_0$ and $\gamma_1$ appear on the diagonal. Diagonal entries for $O_{1,1}^4$ and $O_{2,1}^4$ are nonzero:

- $\gamma_1$ (resp. $\gamma_0$) fixes 1 (resp. no) element of $O_{1,1}$.
- Neither of $\gamma_i$, $i = 0, 1$, fix any element of $O_{2,1}^4$.

Cusp widths over $\infty$ add to the degree 9 (resp. 6) to give

$$
\text{ind}(\gamma_0^+) = 6, \text{ind}(\gamma_1^+) = 4, \text{ind}(\gamma_{\infty}^+) = 6 \\
\text{ind}(\gamma_0^-) = 4, \text{ind}(\gamma_1^-) = 3, \text{ind}(\gamma_{\infty}^-) = 3.
$$

From RH, the genus, $g_{\pm}$ of $\mathcal{H}_{\pm}$ is 0: $2(9 + g_+ - 1) = 6 + 4 + 6 = 16$ and $2(6 + g_- - 1) = 4 + 3 + 3 = 10$.

## 4. The Branch Cycle Lemma

At the center of applying Hurwitz spaces to problems in number theory is the definition field for them and their components as *moduli spaces*. That means not just the Hurwitz space, say, $\mathcal{H}(G, C)^\dagger$ (or related), but the natural structure parametrized by the Hurwitz space – giving it its moduli space structure – is defined over that field. Notation will reference a particular component or collection of components of the space.

**Example:** In Prop. 4.1, $\mathbb{Q}(G, C)^{\text{in}}$ is that definition field for the whole inner Hurwitz space structure of covers in $\text{Ni}(G, C)^{\text{in}}$. [Fr77, p. 62–64] calls Prop. 4.1 the Branch Cycle Argument. Yet, as exposited here it is a general idea; thus, we refer to its version for $\dagger = \text{in or abs}$ on Hurwitz spaces as

The B(ranch)C(ycle)L(emma).
The organizing principle of [Fr77, Thm. 5.1]: That is the first formula for finding covers (resp. RIGP realizations) over a given field \( K \). It equivalences that to finding points in \( \mathcal{H}_{\mathrm{abs}}^r(K) \) (resp. \( \mathcal{H}_{\mathrm{in}}^r(K) \)) over \( K \) in the corresponding Nielsen class \( \mathrm{Ni}(G, C)^{\mathrm{abs}} \) (resp. \( \mathrm{Ni}(G, C)^{\mathrm{in}} \)). The condition is that \( K \) contains the moduli field of the Hurwitz space. Further, if that holds:

\[
\text{a } K \text{ point } p \in \mathcal{H}_{\mathrm{abs}}^r(K) \text{ (resp. } p \in \mathcal{H}_{\mathrm{in}}^r(K) )
\]

gives such a cover if the Hurwitz space has fine moduli.

Notation, as in comments on Cor. 4.7, will distinguish the moduli definition fields of Hurwitz spaces components when the Hurwitz space has several components.

Beyond the BCL: §4.2 proves the BCL. §4.2.3 addresses Nielsen classes, especially when \( r \geq 4 \), with several components. It raises issues on extending Nielsen class moduli to component distinguishing moduli, in particular to capture its corresponding moduli definition field.

§4.3 has preliminary examples. In §4.3.1, the Hurwitz space (even with its map to the configuration space) can be defined over \( \mathbb{Q} \). Yet, no component total space structure (so no cover in the Nielsen class) has definition field \( \mathbb{Q} \). Reference to the Hurwitz space definition field means – unless otherwise said – as a moduli space.

4.1. The BCL formula. §4.1.1 gives the cyclotomic fields that will be the definition fields of Hurwitz spaces – as moduli spaces – purely in terms of Nielsen classes. §4.1.2 gives a general context for the moduli definition field attached to a particular equivalence class \( E \) for a moduli problem \( \dagger \). We apply it to \( E \), a Nielsen class, under \( \dagger = \) in, to inner or absolute equivalence in §4.1.3 showing the correct cyclotomic moduli definition fields.

4.1.1. Absolute and inner cyclotomic fields. Denote the least common multiple of all elements of \( C \) by \( N_C \).

Use this canonical \( N_C \)th root of 1, \( e^{\frac{2\pi i}{N_C}} = \zeta_C \), and denote \( K(\zeta_C) \) by \( \text{Cyc}_{K,C} \).

Recall: \( G(\text{Cyc}_G/Q, Q) = (\mathbb{Z}/N_C)^*, \) invertible integers mod \( N_C \). Then, the subgroup fixed on \( K \cap \text{Cyc}_G \) is \( G(\text{Cyc}_{K,C}/K) \). For \( \dagger = \) in, define \( \mathbb{Q}_{G,C}^{\mathrm{in}} \) to be the fixed (cyclotomic) subfield of \( \text{Cyc}_{Q,C} \) of the following group:

\[
\{ m \in (\mathbb{Z}/N_C)^* \mid \{ g^m \mid g \in C \} \overset{\text{def}}{=} C^m = C \}.
\]

Similarly, define \( \mathbb{Q}_{G,C,T}^{\mathrm{abs}} \overset{\text{def}}{=} \mathbb{Q}_{G,C}^{\mathrm{abs}} \) (if \( T \) is understood) to be the fixed field of

\[
\{ m \in (\mathbb{Z}/N_C)^* \mid \exists h \in N_{S_n}(G, C) \text{ with } hC^m h^{-1} = C \}.
\]

Recall fine moduli as in Lem. 2.3 for our equivalences:

for \( \dagger = \) abs, \( (G, T) \) is self-normalizing; and for \( \dagger = \) in, \( G \) is centerless.

Write \( \mathrm{Ni}(G, C, T)^{\mathrm{abs}} \overset{\text{def}}{=} \mathrm{Ni}(G, C)^{\mathrm{abs}}. \)
Proposition 4.1. The field $\mathbb{Q}_{G,C}^{\text{in}}$ (resp. $\mathbb{Q}_{G,C}^{\text{abs}}$) is a subfield of any definition field for any cover in $\text{Ni}(G,C)^{\text{in}}$ (resp. $\text{Ni}(G,C)^{\text{abs}}$). If fine moduli holds for $\mathcal{H}(G,C)^{\text{abs}}$, then a representing cover, $\varphi : X_p \to \mathbb{P}^1_z$ satisfies (2.44).

(2.44a) $\varphi_p$ has definition field $\mathbb{Q}_{G,C}^{\text{abs}}(p)$; any cover equivalent to $\varphi_p$ has definition field an extension of $\mathbb{Q}_{G,C}^{\text{abs}}(p)$; and

(2.44b) if $\varphi'_p$, defined over $\mathbb{Q}_{G,C}^{\text{abs}}(p)$, is abs-equivalent to $\varphi_p^{\text{abs}}$, then it is equivalent to it over $\mathbb{Q}_{G,C}^{\text{abs}}(p)$.

Similarly, for fine moduli ($\dagger = \text{in}$), except substitute $\mathbb{Q}_{G,C}$ for $\mathbb{Q}_{G,C}^{\text{abs}}$, and each element of the automorphism group of the Galois extension – with a fixed isomorphism with $G$, up to conjugacy by $G$ – has $\mathbb{Q}_{G,C}(p)$ as definition field.

§4.1.2 gives a context for the idea of moduli definition field. Then, §4.1.3 adds fine moduli to it. §4.2 shows the postulates of (2.46) apply to the various moduli of Hurwitz spaces, thereby giving the proof of the BCL.

Remark 4.2. More generally, apply $\sigma \in G_{\overline{Q}}$ to a specific cover $\varphi : X \to \mathbb{P}^1_z$ over $\overline{Q}$, with the branch point set $z_\varphi$ fixed by $\sigma$. Assume we have two pieces of data:

(2.45a) $n_\sigma \in (\hat{Z})^*$, the restriction of $\sigma$ to the cyclotomic closer of $Q$; and

(2.45b) the permutation by $\sigma$ of the individual points in $z_\varphi$.

The BCL then nails the Nielsen class of the resulting cover $(\varphi^\sigma, X^\sigma)$. For $K = \mathbb{R}$, as in [DFr90], it does better: labeling precisely all real and complex points on a given Hurwitz space, as discussed in [BFr02, §3.2].

4.1.2. Context for moduli definition field. Consider some defining property of equivalence classes of algebraic objects (varieties, diagrams of covers, . . .). Call this $\dagger$. For each $\dagger$-equivalence class, $E$, we assume there is a quasi-projective variety $\mathcal{H}_{E}^{\dagger}$ whose points $p \in \mathcal{H}_{E}^{\dagger}$ correspond to equivalence classes of objects $O_p$ in $E$. Not only must there be a natural operation of $G_{\overline{Q}}$ on $(\dagger, E)$, but we must assure that $G_{\overline{Q}}$ respects (the moduli properties of) $(\dagger, E)$.

Definition 4.3. In addition to the $G_{\overline{Q}}$ action above, assume for $\sigma \in G_{\overline{Q}}$, if $p \in \mathcal{H}_{E}^{\dagger}(\overline{Q})$, those objects $O_p$ in $E$ defined over $\overline{Q}$ go by $\sigma$ to objects representing $p^\sigma \in \mathcal{H}_{E^\sigma}^{\dagger}$, We then say $G_{\overline{Q}}$ respects $(\dagger, E)$.

Families of representations objects: Denote the Zariski or étale topology (depending on circumstances) on $\mathcal{H}_E$ by $\text{Top}_E$. Assume we also have the following.

(2.46a) For each $p \in \mathcal{H}_{E}^{\dagger}((\overline{Q}))$, some representing object $O_p$ is defined over $\overline{Q}$ (say, by applying Lem. 1.1).

(2.46b) Extending (2.46a), for $\sigma \in G_{\overline{Q}}$, $O_p^{\sigma}$ is a representing object for $p^\sigma \in \mathcal{H}_{E^\sigma}^{\dagger}$.
(2.46c) Each \( p \in \mathcal{H}_E^\dagger \) has a neighborhood \( U_p \in \text{Top}_E \) with nonempty families \( \mathcal{F}_U \):

Each \( F \in \mathcal{F}_U \) comes with a flat quasi-projective map \( F \to U \) with fiber at each \( p' \in U \) representing the \( E \) class of \( p' \).

(2.46d) The collections \( \{ \mathcal{F}_U \mid U \in \text{Top}_E \} \) form a presheaf from natural maps \( F_U \to F_V \) for \( V \to U \).

The maps in (2.46d) come from pullback, say, when \( V \) is a cover (or open subset) of \( U \), as explained in §4.3.2. Our families are so explicit, from such tools as §3.1.1, that may use them to approach moduli by nontrivially illustrating their properties.

**Fine moduli** means there is an object in \( \mathcal{H}_E^\dagger \), unique up to a natural equivalence, that induces a similar object in \( \mathcal{U}_E \), \( U \in \text{Top}_E \).

**Especially important is finding explicitly the following notion of a moduli definition field, \( \mathcal{Q}_E^\dagger \), for \( E \).**

(2.47) For each \( p \in \mathcal{H}_E^\dagger \), any definition field for \( O_p \) contains \( \mathcal{Q}_E^\dagger(p) \).

If \( E \) has fine moduli, some \( O_p \) has definition field \( \mathcal{Q}_E^\dagger \).

Of course, when \( \mathcal{Q}_E^\dagger = \mathcal{Q} \), a common target is \( \mathcal{H}_E^\dagger(\mathcal{Q}) \), thereby realizing \( O_p \) over \( \mathcal{Q} \) when fine moduli holds. Much remains of the RIGP precisely because we haven’t located for every \( G, C \) with \( \mathcal{H}(G, C)^\text{in}(\mathcal{Q}) \) nonempty. In examples, when \( \mathcal{H}(G, C)^\text{in} \) has several components, we sometimes need the following.

(2.48a) For a given \((\dagger, E)\) identify the irreducible components \( \mathcal{H}_1^\dagger, \ldots, \mathcal{H}_k^\dagger \) of \( \mathcal{H}_E^\dagger(\mathcal{Q}) \).

(2.48b) Restrict the presheaf of (2.46d), and for any \( G_{\mathcal{Q}_E} \) orbit, \( \mathcal{H}'' \) on \( \mathcal{H}_1^\dagger, \ldots, \mathcal{H}_k^\dagger \), identify a (\( E \)-extending) moduli characterization \( E'' \) for this orbit.

(2.48c) For each orbit \( \mathcal{H}'' \) in (2.48b), and each component, say, \( \mathcal{H}_j^\dagger \), find a field extension \( \mathcal{L}_j^\dagger/\mathcal{Q}_E^\dagger \) as an \( \mathcal{H}_j^\dagger \) replacement for \( \mathcal{Q}_E^\dagger \) applied to \( \mathcal{H}_E^\dagger \).

**Remark 4.4 (Comment on (2.48)).** The \( \mathcal{L}_j^\dagger \)s are conjugate fields running over the components of \( \mathcal{H}'' \) in (2.48c).

The notion of moduli field works: For any \( p \in \mathcal{H}_E^\dagger(\mathcal{Q}) \), consider \( O_p \), defined over \( \mathcal{Q} \) using assumption (2.46c), representing \( p \). Form the set

\[
G_{E,p}^\dagger \overset{\text{def}}{=} \{ \sigma \in G_{\mathcal{Q}} \mid O_{p}^\sigma \text{ is } \dagger\text{-equivalent over } \mathcal{Q} \text{ to } O_p \}.
\]

**Lemma 4.5.** The set \( G_{E,p}^\dagger \) is a group, and its fixed field, \( \mathcal{Q}_{E,p}^\dagger \), in \( \mathcal{Q} \) depends only on \((\dagger, p)\), not on the choice of \( O_p \). Further, if fine moduli holds for \( \mathcal{H}_E^\dagger \), then the equivalence class for \( p \) contains an object defined over \( \mathcal{Q}_{E,p}^\dagger \).

**Proof.** Any \( \sigma \in G_{E,p}^\dagger \) leaves \( p \) fixed. Otherwise its extension to \( O_p \) would represent an object in \( p^\sigma \), an object not equivalent to \( O_p \).

Now, suppose two objects, \( O_p \) and \( O_p' \), defined over \( \mathcal{Q} \) represent \( p \). Denote the graph of an isomorphism between them, postulated for \( G_{E,p}^\dagger \), by \( \Gamma \). Apply postulate
(2.46a) to assume the graph has definition field in \( \overline{\mathbb{Q}} \). Now consider the case \( O'_p = O^*_p \) for \( \sigma \in G_{1,p}^\dagger \), denoting \( \Gamma \) by \( \Gamma_\sigma : O_p \rightarrow O^*_p \). Then, apply \( \tau \in G_{1,E,p}^\dagger \) to \( \Gamma_\sigma \) to get

\[
\begin{align*}
O_p &\xrightarrow{\Gamma_\sigma} O^*_p \\
&\xrightarrow{\Gamma_\sigma \cdot \tau} O^*_p, \text{ showing } \sigma \cdot \tau \in G_{1,E,p}^\dagger \\
\end{align*}
\]

Denote another object, \( O'_p \), representing \( p \) over \( \overline{\mathbb{Q}} \) and \( \Gamma \) the morphism above between them. Temporarily, denote \( G_{1,E,p}^\dagger \) using \( O'_p \) in place of \( O_p \) by \( G_{E,p}^\dagger \). In (2.49) substitute \( O'_p \) for \( O^*_p \) and \( \Gamma \) for \( \Gamma_\sigma \). This shows \( \tau \in G_{E,p}^\dagger \) is also in \( G_{1,E,p}^\dagger \) establishing that the two groups are the same, and independent of the choice of \( O_p \).

Now assume fine moduli holds for \((\dagger, E)\). Return to (2.49). Then, the uniqueness of the maps giving isomorphisms for the equivalent objects tells us that we can assure \( \Gamma_{\sigma \cdot \tau} = (\Gamma_\sigma)^\tau \circ \Gamma_\sigma \) for \( (\sigma, \tau) \in G_{1,E,p}^\dagger \). This is the Weil co-cycle condition – as in [We56] and [We62, p. 15, Thm. 3] – that guarantees we can find \( O_p \) with definition field \( \overline{Q}_{E,p}^\dagger \). Rem. 4.6 adds remarks about relevant to how we use it. □

**Remark 4.6.** Saying that there an \( O_p \) in Lem. 4.5 is defined over the desired field, includes putting natural projective coordinates on that object. Further, we can say that another object defined over \( \overline{Q}_{E,p}^\dagger \) will be \( \dagger \)-equivalent over this field. Finally, sometimes we must add a little extra to the use of the cocycle condition; the conditions don’t at first appear entirely stated in terms of a quasi-projective structure. We see that in applying the Lemma to fine moduli.

4.1.3. **Definition field of components.** Fine moduli in (2.44) assures there is a representing cover \( \varphi_p \) over the minimal possible field \( \overline{Q}_{G,C}(p) \) and that depends only on the coordinates of \( p \in \mathcal{H}(G,C)^\dagger \) and \( \overline{Q}_{G,C}^\dagger \). Indeed, this arithmetic use of fine moduli is much driven by what we need for the co-cycle condition. Without fine moduli such representing objects may not exist (see Rem. 4.9).

Cor. 4.7 says, in one fell swoop, we can pluck the solution of the moduli problem expressed in (2.44b) by picking a point \( \hat{p} \in \mathcal{H}(G,C)^{\text{in}} \) (resp. \( p \in \mathcal{H}(G,C)^{\text{abs}} \)), adjoin \( \overline{Q}_{G,C}^\times \) (resp. \( \overline{Q}_{G,C}^{\text{abs}} \)) to it, and take the associated fiber in (2.50). The following is in [FrV91, Main Thm. (an extension of [Fr77, Thm. 5.1]).]

**Corollary 4.7** (Global-BCL). Assume fine moduli for \( \dagger = \text{in or abs} \) in Thm. 1.7. Then, the minimal definition field of the diagram

\[
\begin{align*}
\mathcal{T}(G,C)^\dagger &\rightarrow \mathcal{H}(G,C)^\dagger \times \mathbb{F}_2 \xrightarrow{\text{proj}_{\mathbb{F}_2}} \mathcal{H}(G,C)^\dagger \rightarrow U_r \text{ is } \overline{Q}_{G,C}^\dagger. \\
\end{align*}
\]

Also, minimal definition fields of all covers in \( \text{Ni}(G,C)^\dagger \) intersect in \( \overline{Q}_{G,C}^\dagger \).

**Definition 4.8** (Definition as a moduli space). Consider the pullback diagram over any component \( \mathcal{H}' \) of \( \mathcal{H}(G,C)^\text{abs} \) in Cor. 4.7. Refer to the definition field \( \overline{Q}_{\mathcal{H}'}^\dagger \) of that diagram as the definition field of \( \mathcal{H}' \) as a moduli space.

**Comments on Cor. 4.7.** §4.2 gives the ingredients of the BCL: why the Hurwitz space diagrams are over the “predicted” fields (here called over \( \overline{Q}_{G,C}^\dagger \)). A rough
statement goes like this. Any \( \sigma \in G_Q \) fixed on \( Q_{G,C}^\dagger \) operating on the equation coefficients describing that diagram, or on individual fibers over \( \bar{Q} \), maps them to diagrams and fibers associated with the exact same Nielsen class.

When fine moduli holds, aided by Weil’s cocycle condition, the whole diagram has definition field \( Q_{G,C}^\dagger \). With the notation of Def. 4.8, two statements are immediate from the Hurwitz spaces as moduli spaces.

(2.51a) \( Q_{H'} \) (resp. \( Q_{H''} \)) contains \( Q_{G,C}^\dagger \) (resp. \( Q_{G,C}^{\text{abs}} \)) permuting the diagrams running over \( H'' \) (resp. \( H' \)).

(2.51b) If in (2.51a), \( H'' \) lies over \( H' \), then \( Q_{H''} \) contains \( Q_{H'} \).

For \( \dagger \) equivalence, Hurwitz spaces are algebraic varieties that are complex manifolds. That is no longer true for any reduced equivalence. Yet, they are still normal varieties. So their components are disjoint, meaning this.

(2.52) Points in different components represent inequivalent covers. The definition field of a point contains that of its component.

Nevertheless, here is all that we can say at the outset.

(2.53) Any \( \sigma \in G_{Q,G,C} \) (resp. \( G_{Q,G,C,T} \)) permuting \( H(G,C)^\dagger \) (resp. \( H(G,C)^{\text{abs}} \)) components as moduli spaces.

Conclude: if even one cover in the Nielsen class has definition field \( K \), then \( Q_{G,C}^\dagger \subset K \), and the component containing a point corresponding to that cover has moduli field contained in \( K \). See Ex. 4.17.

\begin{flushright} \( \square \) \end{flushright}

Remarks 4.9 and 4.10 discuss in general what happens without fine moduli.

**Remark 4.9 (Moduli field without fine moduli).** Without a fine moduli property, we don’t expect (??). That is, a point \( p \in H(G,C)^\bullet(Q_O) \) may not have a representing cover \( X_p \to \mathbb{P}_z^1 \) defined over \( Q(p) \). Still, the moduli space, with its structures, will have its definition field determined by the moduli condition.

For example, suppose \( O \) is a braid orbit on \( \text{Ni}(G,C)^\dagger \), corresponding to a component \( H_O \) of \( H(G,C)^\dagger \), \( \dagger = \text{in or abs} \). Also, that \( V \subset H_O \) is a Zariski or étale open set, defined over \( Q_O \). Then, the following objects will be defined over \( Q_O \):

(2.54a) Maps involved in \( H_O \rightarrow U_r \times \mathbb{P}_z^1 \) and its projections; and

(2.54b) the collection of families \( T_V \rightarrow V \times \mathbb{P}_z^1 \) whose fibers \( T_p \rightarrow p \times \mathbb{P}_z^1 \) represent the points \( p \in V \).

**Remark 4.10 (Reduced spaces moduli field).** There are similar statements with \( \bullet = \{ \dagger, \text{rd} \} \) replacing \( \dagger \); adding reduced equivalence and substituting \( J_r \) for \( U_r \). The major difference is that the criterion for fine moduli changes, §2.2.3.

For example, Prop. 3.16 gives \( (G,C) = (A_4, C_{+3^2\ldots3^2}) \) with two inner components with \( Q_O = Q \), for both. Here, the Hurwitz spaces have fine moduli, but reduction of neither of its components has fine moduli. This also shows a refined
4. THE BRANCH CYCLE LEMMA

4.1. The BCL Proof and Moduli Extension. Here we see how to apply Lem. 4.5 (and Rem. 4.6) to the case where \( \dagger \) is one of our equivalences and \( E \) is a Nielsen class. Mainly this is checking the hypotheses (2.46). Our proof is a more efficient version of [Fr77, p. 33–35]. We start, say, when \( \dagger = \text{abs} \), with a specific cover \( \varphi : X \to \mathbb{P}^1_\mathbb{C} \) in \( \text{Ni}(G, \mathbb{C})^{\text{abs}} \) over \( K \). The essence of [Fr77, (5.10)] (or the slower treatment of [Fr12, (5.2)]) is to compute the resulting Nielsen class upon applying \( \sigma \in G \) to \( \varphi \). That includes its action on the set of branch points, defined over \( K \), even when individual such points may not be.

4.2.1. \( G_\mathbb{Q} \) action on covers in \( \text{Ni}(G, \mathbb{C})^{\dagger} \). Continue the notation of §4.1.1, with \( N \) the least common multiple of the orders of elements in \( C \), defining the Nielsen class \( \text{Ni}(G, \mathbb{C}) \). With \( \zeta_t = e^{2\pi i t} \), \( t \geq 1 \), identify the group \( G(\mathbb{Q}(\zeta_N)/\mathbb{Q}) \) with the multiplicative group \( (\mathbb{Z}/N)^* \) of invertible integers modulo \( N \).

As in §4.16, \( N_{S_n}(G, C) \) is the normalizer of \( G \) that permutes the elements of \( C \). Then, denote the image conjugacy class of \( C_i \) under (conjugation by) \( \beta \in N_{S_n}(G, C) \) by \( C_i^\beta \). We define two sets:

\[
\hat{M} = \{ a \in (\mathbb{Z}/N)^* | \text{there exists } \beta \in N_{S_n}(G, C) \text{ with } C_i^\beta = C_i^a, i = 1, \ldots, r \},
\]

\[
M = \{ a \in (\mathbb{Z}/(N))^* | \text{there exists } \gamma \in S_r \text{ and } \beta \in S_r \text{ with } \text{Con} \left( \sigma(i)^a, G(g) \right) = \text{Con} \left( \gamma^{-1} \cdot \sigma(i)^\beta, G(g) \right) \text{ for } i = 1, \ldots, r \}.
\]

It is easy to demonstrate the \( M \) (and therefore \( \hat{M} \)) is a group. Let \( K_M \) (resp. \( K_{\hat{M}} \)) be the fixed field of \( M \) (resp. \( \hat{M} \)) in \( \mathbb{Q}(\zeta_N) \).

**Theorem 4.1.** We assume that condition (5.1) holds. Then the collection \( \hat{M}(Y, \varphi; r) \) has a minimal field of definition which we denote by \( K_F \).

We have \( K_M \subset K_F \). In addition, if the Hurwitz number of \( (\sigma(1), \ldots, \sigma(r)) = g \) is 1 (see Section 4.B), then we have \( K_M = K_F \).

We use the notation of Section 0.C. The field \( K_F(P) \) is contained in \( K_F(\mathbb{P}^n)^{\text{symm}} \). Let \( K_F(\mathbb{P}^n)^{\text{symm}} \) be the Galois closure of \( K_F(\mathbb{P}^n)^{\text{symm}}/K_F(P \times \mathbb{P}^1) \), and let \( \hat{K}_F(P) \) be the algebraic closure of \( K_F(P) \) in \( K_F(\mathbb{P}^n)^{\text{symm}} \). Then we have \( K_{\hat{M}} \subset \hat{K}_F(P) \).

**Note:** In the notation at the end of Section 2, \( K_M \) is a portion of a fixed component of the extension of constants for the family fiber by (5.2). Also, it is an unsolved problem as to whether \( K_M = K_{mcF} \) when the Hurwitz number of \( g \) is not 1.
Proof. We consider first the collection:

\[ M^0(Y, \varphi; r) = \{ F_{\text{symm}}, \psi_{\text{symm}}, P_{r1}, P_{r2} \} \]

where:

\[ (2.4) \]

a) \( F_{\text{symm}} \xrightarrow{\psi_{\text{symm}}} U_{P_{r}} \times P^1 \xrightarrow{\overline{P_{r1}}} U_{P_{r}} \) and;

b) \( \psi_{\text{symm}} = (\psi \circ \overline{P_{r1}} \circ \Phi_{\text{symm}}, \overline{P_{r2}} \circ \Phi_{\text{symm}}) \)

Our first task is to show that the collection \( M^0(Y, \varphi; r) \) has all the properties attributed to \( M(Y, \varphi; r) \) in the statement of the theorem.

Let \( K \subset \mathbb{C} \) be a field of finite type over \( \mathbb{Q} \) containing a field of definition for each member of the collection \( M^0(Y, \varphi; r) \). An argument based on the proof of Lemma (??)1.2 allows us to assume: \( [K : \mathbb{Q}] < \infty \) [nh, i.e., a finite extension]. We also assume that \( K/\mathbb{Q} \) is Galois.

For \( \gamma \in G(K/\mathbb{Q}) \) we define:

\[ M^0(Y, \varphi; r)_\gamma = \{ (F_{\text{symm}})_\gamma, (\psi_{\text{symm}})_\gamma, \overline{P_{r1}}_\gamma, \overline{P_{r2}}_\gamma \} \]

to be the transform of the collection \( M^0(Y, \varphi; r) \) under \( \gamma \). We say that \( M^0(Y, \varphi; r)_\gamma \) is isomorphic to \( M^0(Y, \varphi; r) \) if there is an isomorphism \( \alpha(F_{\text{symm}})_\gamma \) rendering commutative the diagram:

\[ (2.5) \]

nh triangular commutative diagram goes here

Let \( H \) be the subgroup of \( G(K/\mathbb{Q}) \) consisting of those \( \gamma \) for which \( M^0(Y, \varphi; r)_\gamma \) is isomorphic to \( M^0(Y, \varphi; r) \). Let \( K_F \) be the fixed field in \( K \) of \( H \). So far we have not used the fact that \( \text{Aut}(Y, \varphi) = \{ \text{Id.} \} \). We call \( K_F \) the field of moduli of the collection \( M^0(Y, \varphi; r) \), in analogy with (??), pp. 32-35). This concept will be used again in comments in Section 6 (example 8).

Since we assume \( \text{Aut}(Y, \varphi) = \{ \text{Id.} \} \), we see that if \( M^0(Y, \varphi; r)_\gamma \) and \( M^0(Y, \varphi; r) \) are isomorphic, there is a unique isomorphism \( \alpha(F_{\text{symm}})_\gamma \) making (5.5) commutative. Therefore, from [?] we may assume that \( K_F \) is a minimal field of definition of \( M^0(Y, \varphi; r) \) (in analogy with the definition preceding the statement of this theorem).

We refer to our next computation as: The Branch Cycle Argument. An approximation to this was used earlier in [?].

Let \( Z \xrightarrow{\varphi(Z)} \mathbb{P}^1 \) be a cover (non-singular and projective) defined over a number field \( L \), with: a description of its branch cycles given by \( \sigma(1, Z), \ldots, \sigma(r, Z) \), corresponding respectively to branch points \( u(1, Z), \ldots, u(r, Z) \). In analogy with previous notation consider: \( e(1, Z), \ldots, e(r, Z); N(Z); L(Z), \hat{L}(Z) \), and; the algebraic closure of \( L \) in \( L(Z) \), denoted \( \hat{L} \) if no confusion will occur. Let \( x \) be a uniformizing parameter for \( \mathbb{P}^1 \).
4. THE BRANCH CYCLE LEMMA

Consider the automorphism $\sigma(i)$ of $\overline{Q}\Bigl((x - u(i, Z))^{1/e(i, Z)}\Bigr)$ [nh seems like unnecessary parentheses] which is the identity on $\overline{Q}$ and maps $(x - u(i, Z))^{1/e(i, Z)}$ to $\zeta_{e(i, Z)} \cdot (x - u(i, Z))^{1/e(i, Z)}$. We remind that $x - u(i, Z)$ is replaced by $1/x$ when $u(i, Z) = \infty$. We have the embedding, via Puiseux expansions

\begin{equation}
\widehat{L}(Z) \xrightarrow{\psi(i, Z)} \overline{Q}\Bigl((x - u(i, Z))^{1/e(i, Z)}\Bigr), \quad i = 1, \ldots, r
\end{equation}

where $\sigma(i, Z)$ is the restriction to $\widehat{L}(Z)$ of $\sigma(i)$. For any other embedding (fixed on $L(x)$)

\begin{equation}
\widehat{L}(Z) \xrightarrow{\psi'(i, Z)} \overline{Q}\Bigl((x - u(i, Z))^{1/e(i, Z)}\Bigr)
\end{equation}

$\sigma(i)$ restricts to some element of $\text{Con}\bigl(\sigma(i, Z), G(\widehat{L}(Z)/L(P^1))\bigr)$. If $\psi'(i, Z)$ is fixed on $\widehat{L}$ then the restriction of $\sigma(i)$ is in $\text{Con}\bigl(\sigma(i, Z), G(\widehat{L}(Z)/\widehat{L}(P^1))\bigr)$.

Suppose now that $G(\widehat{L}(Z)/\widehat{L}(P^1))G(\widehat{L}(Z)/\widehat{L}(P^1))$ is isomorphic to $\text{Con}(\overline{C(Z)}/C(P^1))$, and suppose also that in the isomorphism $\sigma(i, Z) \in \text{Con}(\overline{C(Z)}/C(P^1))$. In particular, from the computations of Section 4, this holds for all covers in the family given by expression (5.2). We now show that $K_M \subset L$ (see statement of the theorem).

Suppose, in fact, that $K_M \notin L$. Then, there exists $\omega \in G(\overline{Q}/Q)$ such that $\omega$ is fixed on $L$, but $w$ is not fixed on $K_M$. Thus, the restriction of $\omega$ to $Q(\zeta_N)$ corresponds to $a(\omega) \in (Z/(N))^*$ [nh what is a??] such that: there does not exist a $\beta \in S_r$ and a $\gamma \in S_n$ with

\begin{equation}
\text{Con}\bigl(\sigma(i)^{-a(\omega)}, G(g)\bigr) = \text{Con}\bigl(\gamma^{-1} \cdot \sigma((i)\beta) \cdot \gamma, G(g)\bigr) \quad \text{for all } i = 1, \ldots, r
\end{equation}

Let $\omega^*$ be an element of $G(\widehat{L}(Z)/L(P^1))$ whose restriction to $\widehat{L}$ is equal to $\omega$ restricted to $\widehat{L}$. We extend $\omega$ to $\overline{Q}\Bigl((x - u(i, Z))^{1/e(i, Z)}\Bigr)$ by: $\omega(\sum_k a_k(x - u(i, Z))^{1/e(i, Z)}) = \sum_k \omega(a_n)(x - u(i, Z))^{1/e(i, Z)}$ where $\omega(u(i, Z)) = u(j, Z)$. Note that we automatically have $e(i, Z) = e(j, Z)$.

Thus we obtain:

\begin{equation}
\widehat{L}(Z) \xrightarrow{\omega \psi(i, Z)} \overline{Q}\Bigl((x - u(i, Z))^{1/e(i, Z)}\Bigr).
\end{equation}

For $\alpha \in \widehat{L}(Z)$ we compute the restriction of $g(j)$ to $\alpha$ as:

$$\psi(i, Z)^{-1} \circ \omega^{-1} \circ g(j) \circ \omega \psi(i, Z).$$

By direct computation on the Puiseux expansion $\psi(i, Z)(\alpha)$ we see that this is the same as:

$$\psi(i, Z)^{-1} \circ \sigma(i)^{-a(\omega)} \circ \psi(i, Z),$$

which is $\sigma(i)^{-a(\omega)}$. Since $\psi(i, Z)^{-1} \circ \omega^{-1} \circ g(j) \circ \omega \psi(i, Z)$ is the identity on $\widehat{L}$ (when applied to $\widehat{L}(Z)$), this is in $\text{Con}(\sigma(j), G(\widehat{L}(Z)/\widehat{L}(P^1)))$, or
However, with the aforementioned identification of $G(g)$ with $G(\widehat{L}/\hat{L}(P^1))$, etc., expression (5.9) contradicts (5.7). Therefore $K_M \subset L$.

Now we show that $K_{\delta} \subseteq \hat{L}$. If we assume that $K_{\delta} \not\subseteq \hat{L}$ and proceed as above, we end up with the expression:

$$\text{Con}(\sigma(j) \cdot G(\hat{L}(Z)/\hat{L}(P^1))) = \text{Con}(\sigma(i) \cdot G(\hat{L}(Z)/\hat{L}(P^1)))$$

where $j$ is defined by $\omega(u(i, Z)) = u(j, Z)$. Again, this is a contradiction (from the definitions of $K_{\delta}$ and $a(\omega)$).

We need and addition to the branch cycle argument to describe what happens when we apply $\omega \in G(\mathbb{Q}/\mathbb{Q})$ to $Z \xrightarrow{\varphi(Z)} P^1$ when $\omega$ is not the identity on $L$.

Let $l^\omega$ be the image of $L$ under $\omega$. Let $Z^\omega \xrightarrow{\varphi(Z)^\omega} (P^1)$ be the transform of $Z \xrightarrow{\varphi(Z)} P^1$ by $\omega$. By operating on the coefficients of the Puiseux expansions, as above, we obtain:

$$\omega : \overline{Q}((x - u(i, Z))^{1/e(i, Z)}) \rightarrow \omega : \overline{Q}((x - u(i, Z))^{1/e(i, Z)})$$

We define $\tilde{\omega}$ so as to make the following diagram commutative:

\[
\begin{array}{ccc}
\text{Con}(\sigma(i) \cdot G(\hat{L}(Z)/\hat{L}(P^1))) & \xrightarrow{\text{Con}(\sigma(j) \cdot G(\hat{L}(Z)/\hat{L}(P^1)))} & \text{Con}(\sigma(j) \cdot G(\hat{L}(Z)/\hat{L}(P^1))) \\
\end{array}
\]

From $\tilde{\omega}$ we obtain an isomorphism between the group $G(\hat{L}(Z)/\hat{L}(P^1))$ and $G(\widehat{L}(Z)/\hat{L}(P^1))$ given by: $\sigma \rightarrow \tilde{\omega} \cdot \sigma \cdot \tilde{\omega}^{-1} = \sigma^\omega$ for $\sigma \in G(\hat{L}(Z)/\hat{L}(P^1))$. Also, if $\sigma$ is fixed on $\hat{L}$, then $\tilde{\omega} \cdot \sigma \cdot \tilde{\omega}^{-1}$ is fixed on $\hat{L}^\omega$, so we have an isomorphism of $G(\hat{L}(Z)/\hat{L}(P^1))$ to $G(\widehat{L}(Z^\omega)/\hat{L}(P^1))$.

If we identify these two groups by this isomorphism and call the resulting abstract group $G$, then (by an argument analogous to that above) we see that $Z^\omega \xrightarrow{\varphi(Z)^\omega} P^1$ has a description of its branch cycles give by $\sigma(i, Z^\omega)$ (the branch cycle cover over $\omega(u(i, Z))$ where:

$$\sigma(i, Z^\omega) \in \text{Con}(\sigma(i, Z)^{-a(\omega)}, G).$$

With this we conclude the computations we need from the branch cycle argument.

4.2.2. Finish of the proof of Theorem (4.1) 5.1. At the beginning of this proof we showed that $\mathbb{M}^0(Y, \varphi; r)$ has a minimal field of definition, designated $K_Y$. We finish the proof in three steps.

Step 1. We show that $K_Y$ is a minimal field of definition of the collection $\mathbb{M}(Y, \varphi; r)$.

Again using the proof of Lemma (??) 1.2, we may assume that $\mathbb{M}(Y, \varphi; r)$ is defined over a finite extension of $Q$ and, for $\gamma \in G(\overline{Q}/Q)$ we may consider $\mathbb{M}(Y, \varphi; r)^\gamma$
(the transform of the collection $\mathcal{M}(Y, \varphi; r)$. Consider $\gamma \in G(\overline{\mathbb{Q}}/K_F)$. Apply $\gamma$ to:

\begin{equation}
\text{(2.11) a) } \mathbb{P}^\text{symm}(Y, \varphi; r) \xrightarrow{\Phi^\text{symm}} \mathbb{P}(Y, \varphi; r) \times \mathbb{P}^1 \xrightarrow{\psi \times \text{Id.}} U_{P_r} \times \mathbb{P}^1
\end{equation}

to obtain:

\begin{equation}
\text{(2.11) b) } \mathbb{P}^\text{symm}(Y, \varphi; r) \xrightarrow{(\Phi^\text{symm})^\gamma} \mathbb{P}(Y, \varphi; r)^\gamma \times \mathbb{P}^1 \xrightarrow{\psi^\gamma \times \text{Id.}} U_{P_r} \times \mathbb{P}^1
\end{equation}

For $p \in \mathcal{P}(Y, \varphi; r)$, there is a unique point in $\mathcal{P}(Y, \varphi; r)^\gamma$ (denoted $\alpha(\gamma)(p) \in \mathcal{P}(Y, \varphi; r)^\gamma$) over $\psi(p)$ such that:

\begin{equation}
(\mathbb{P}^\text{symm}(Y, \varphi; r))_p \rightarrow (p) \times \mathbb{P}^1
\end{equation}

is isomorphic to:

\begin{equation}
(\mathbb{P}^\text{symm}(Y, \varphi; r))_{\alpha(\gamma)(p)} \rightarrow \alpha(\gamma)(p) \times \mathbb{P}^1
\end{equation}

From the construction of Hurwitz families in Section 4, the map:

\begin{equation}
\alpha(\gamma) : \mathcal{P}(Y, \varphi; r) \rightarrow \mathcal{P}(Y, \varphi; r)^\gamma
\end{equation}

is easily shown to be an analytic isomorphism. Also the maps:

\begin{equation}
\alpha(\gamma') \circ \alpha(\gamma)^{-1} : \mathcal{P}(Y, \varphi; r)^\gamma \rightarrow \mathcal{P}(Y, \varphi; r)^{\gamma'} \text{ for } \gamma, \gamma' \in G(\overline{\mathbb{Q}}/K_F)
\end{equation}

satisfy Weil’s cocycle criteria. Therefore $\mathcal{P}(Y, \varphi; r)$ can be defined over $K_F$. It is a cumbersome, but essentially obvious, calculation to show now that $\mathcal{M}(Y, \varphi; r)$ is defined over $K_F$.

**Step 2.** We show $K_M \subset K_F$ and $K_M \subset \widehat{K_F(P)}$. 

Suppose $K_M$ is not contained in $K_F$, so that $[K_M : K_F] > 1$. Then from Hilbert’s Irreducibility Theorem there exists a point $p \in \mathcal{P}$, algebraic over $K_F$, such that $K_F(p)$ is disjoint from $K_M \cdot K_F$ over $K_F$. Therefore:

\begin{equation}
(\mathbb{P}^\text{symm}(Y, \varphi; r))_p \xrightarrow{\text{rest. of } \mathcal{P}(Y, \varphi; r)^{\gamma}} \mathbb{P}^1
\end{equation}

is a cover defined over $K_F(p)$. This contradicts that part of the Branch Cycle Argument which showed that any field of definition of (5.12) contains $K_M$.

A calculation similar to this using Lemma (??) 2.3 can be used to show that $K_M \subset \widehat{K_F(P)}$.

**Step 3. When the Hurwitz Number is 1, $K_M = K_F$.**

Suppose the Hurwitz Number is 1 and $K_F \not\subset K_M$. Then there exists $\gamma \in G(\overline{\mathbb{Q}}, K_M)$ such that $\gamma$ is not fixed on $K_F$. Let $p \in \mathcal{P}(Y, \varphi; r)$ be algebraic over $K_F$. We apply $\gamma$ to the diagram:

\begin{equation}
\text{nh rectangular commutative diagram goes here}
\end{equation}

to obtain:

\begin{equation}
\text{nh rectangular commutative diagram goes here}
\end{equation}
However, the last calculation of the Branch Cycle Argument tells us that if \( \sigma(1), \ldots, \sigma(r) \) are a description of the branch cycles over the cover in the left vertical in the diagram (5.13)a), then \( \tau(1), \ldots, \tau(r) \) is a description of the branch cycles in the cover in the left vertical diagram (5.13)b), where: \( \tau(1), \ldots, \tau(r) \) generates \( G(g) \), and, \( \tau(i) \) is conjugate to \( \sigma(i) \) in \( G(g) \) for \( i = 1, \ldots, r \). Since the Hurwitz number is 1, this implies that the cover of the left vertical diagram (5.13)b) actually appears as a fiber in the family

\[
\mathcal{P}^{\text{symm}}(Y, \varphi; r) \to \mathcal{P}(Y, \varphi; r) \times \mathbb{P}^1.
\]

From the uniqueness of the Symmetrized Hurwitz Family containing the cover of the left vertical of diagram (5.13)b) (under condition (5.1)), this implies that the cover:

\[
(\mathcal{P}^{\text{symm}}(Y, \varphi; r))^{\gamma} \xrightarrow{\varphi^{\text{symm}}} \mathcal{P}(Y, \varphi; r)^{\gamma} \times \mathbb{P}^1
\]

is isomorphic to the cover (5.14). Since \( \gamma \) is not fixed on \( K_f \) this contradicts the properties we have proven for \( K_f \) (it is a field of moduli for \( M(Y, \varphi; r) \)). With this contradiction, we conclude the proof of Step 3 and of Theorem (4.1) 5.1. \( \square \)

Let \( Y \xrightarrow{\varphi} \mathbb{P}^1 \) be a cover (as in the beginning of this section) with a description of its branch cycles given by \( \sigma(1), \ldots, \sigma(r) \). We do not assume that \( \text{Aut}(Y, \varphi) = \{ \text{Id.} \} \).

**Corollary 4.11.** Let \( L \) be any field of definition of \( (Y, \varphi) \). Then \( K_M \subset L \). Let \( \hat{L} \) be the algebraic closure of \( L \) in \( \hat{L}(Y) \) (the Galois closure of \( L(Y)/L(\mathbb{P}^1) \)). Then \( K_{\hat{M}} \subset \hat{L} \).

**Proof.** This was proven in the Branch Cycle Argument part of the proof of Theorem (4.1) 5.1. \( \square \)

As part of Theorem (4.1) 5.1 we immediately obtain:

**Corollary 4.12.** Assume in addition to the hypotheses of Corollary 5.2 that \( \text{Aut}(Y, \varphi) = \{ \text{Id.} \} \) and, the Hurwitz number of \( \sigma(1), \ldots, \sigma(r) \) is 1. Then the Hurwitz Parameter Space (Hurwitz scheme) \( \mathcal{P}(Y, \varphi; r) \) is defined over \( K_M \).

**Note.** There are simple examples (e.g., three branch point case) to show that the cover:

\[
\mathcal{P}(Y, \varphi; r) \xrightarrow{\psi} U_{\mathbb{P}^1}
\]

may be defined over a field strictly contained in \( K_M \). However, since \( \text{Aut}(\mathcal{P}(Y, \varphi; r), \psi) \) is usually not the identity group, it can be a difficult problem to directly compute the ‘correct’ field of definition of \( \mathcal{P}(Y, \varphi; r), \psi) \).

**Corollary 4.13.** Assume that \( (Y, \varphi) \) satisfies the hypotheses of Corollary 5.3. Let \( K(g) \) be the intersection of all fields of definition of all pairs \( (Z, \varphi(Z)) \) where
\( \mathbb{Z} \xrightarrow{\varphi(Z)} \mathbb{P}^1 \) has a description of its branch cycles given by \( \sigma(1), \ldots, \sigma(r) \). Then \( K(g) = K_M \).

**Proof.** For \( p \in \mathcal{P}(Y, \varphi; r) \), the cover \( \mathbb{P}^\text{symm}(Y, \varphi; r) \to p \times \mathbb{P}^1 \) (obtained from the fiber over \( p \) of \( \mathbb{P}^\text{symm}(Y, \varphi; r) \to \mathcal{P}(Y, \varphi; r) \times \mathbb{P}^1 \) is defined over \( K_M(p) \). From Hilbert's irreducibility theorem applied to \( \mathcal{P}(Y, \varphi; r) \xrightarrow{\varphi} U_{\mathbb{P}^1} \) the field:

\[
\bigcap_{p \in \mathcal{P}(Y, \varphi; r)} K_M(p) = K_M.
\]

\( \square \)

Let \( G \) be a finite group, and let \( L \) be a number field. We now discuss some important problems. [nh an important problem?]

**Problem 4.14.** Show that there exists \( Y \xrightarrow{\varphi(Y)} \mathbb{P}^1 \) such that: \( (Y, \varphi) \) is defined over a number field \( K \); \( G(\hat{Y}/\hat{K}\mathbb{P}^1) = G \), and; \( \hat{K} \) is disjoint from \( L \) over \( \mathbb{Q} \).

Consider a group \( G \) with a faithful transitive representation \( T : G \to S_n \) with:

\[(2.15) \quad N(G(1))/G(1) = \{Id.\} \quad \text{(notation of Lemma (2.2)) 2.1}\]

Suppose we could show that:

\[(2.16) \quad \begin{array}{l}
a) \text{even if the Hurwitz number of } (Y, \varphi(Y)) \text{ is not } 1, \text{ then } \mathcal{M}(Y, \varphi; r) \\
\quad \text{(see above) is defined over } K_M, \text{ and;}
\end{array}
\]

\[\begin{array}{l}
b) \text{for } \sigma(1), \ldots, \sigma(r) \quad \text{(a description of the branch cycles of } (Y, \varphi)) \\
\quad \text{including all conjugacy classes of } G, \text{ then } K_M(\mathbb{P}^\text{symm}(Y, \varphi; r)) \\
\quad \text{(Galois closure of the cover } \mathbb{P}^\text{symm}(Y, \varphi; r) \to \mathcal{P}(Y, \varphi; r) \times \mathbb{P}^1) \\
\quad \text{has its absolute constants equal to } \hat{K}_M.
\end{array}\]

Under these conditions, we can choose \( \sigma(1), \ldots, \sigma(r) \) so that for each integer \( a \) there exists \( \beta \in S_r \) such that:

\[\text{Con}(\sigma(i)^a, G(g)) = \text{Con}(\sigma((i)\beta), G(g)) \text{ for } i = 1, \ldots, r\]

(discussion before Theorem (4.1) 5.1).

Then \( \hat{K}_M = \mathbb{Q} \), and by the assumption of (5.16)b) and an application of Hilbert's Irreducibility Theorem (as in the proof of Corollary 5.3), we can affirm a positive solution to Problem 5.5 for \( (G, T) \) satisfying (5.15). However, there is no special reason at this time to believe either (5.16)a) or b).

It is an extremely important problem to consider groups \( G \) equipped with a faithful representation \( T \) for which (5.15) does not hold. In order to consider this
problem, it is necessary to consider covers $Y \xrightarrow{\phi} \mathbb{P}^1$ equipped with an extra structure coming from a characteristic subgroup $H$ of $\text{Aut}(Y, \varphi)$. Suppose we are given two such structures $(Y_1, \varphi_1), H(Y_1, \varphi_1), S(Y_1)$ and $(Y_2, \varphi_2), H(Y_2, \varphi_2), S(Y_2)$ where: $S(Y_i) : H(Y_i, \varphi_i) \rightarrow H$ is an isomorphism of $H(Y_i, \varphi_i)$ with the abstract group $H$. We say that these two structures are isomorphic if there exists an analytic isomorphism $\alpha : Y_1 \rightarrow Y_2$ with:

\[
\text{nh triangular commutative diagram goes here}
\]

The construction of moduli schemes and total families analogous to the construction of $\mathcal{P}(Y, \varphi; r)$ and $\mathbb{P}^{\text{sym}}(Y, \varphi; r)$ is considered in [?]. The search for the fields of definition of these new objects is a contribution to the extension of the results of this section to the more general class. Unfortunately, when the center of $\text{Aut}(Y, \varphi)$ is not the identity, there are great difficulties which require consideration of still further structure utilizing the Jacobian variety of $Y$.

4.2.3. Component distinguishing moduli. It also discusses that having several Nielsen class components raises issues on extending Nielsen class moduli to a component distinguishing moduli, to capture its corresponding moduli definition field. We have many examples of Nielsen classes having several distinct components. When $r = 3$, this seemingly happens haphazardly. Yet, when $r \geq 4$, and the braid group dominates the nature of Hurwitz spaces, most components – so far – have a natural significance for being separate from the other components. Sometimes, as happens with the Nielsen class $\text{Ni}(\mathbb{Z}/\ell^k+1\mathbb{Z}/2, \mathbb{C}^2_4)$, when the spaces are recognized as modular curves ($\S ??$), the reason is significant but related to famous classical situations. In that particular case, all the components are conjugate through the action of a cyclotomic Galois group. We say simply, the components are conjugate. There is no chance they are going to contribute RIGP solutions, though they certainly contribute meaningfully, as the heart of Serre’s OIT.

In other cases, though maybe one component separates out as defined over $\mathbb{Q}$ while others are conjugate through a more complicated action of $G_\mathbb{Q}$. That’s what happens in both Ch. 4 and Ch. 5. In both cases the lift invariant plays a major role. In the former it provides a result that allows every group to play a role, while the latter is our example of going beyond Serre’s OIT.

Or perhaps, as in $\S ??$, where the Nielsen class is $\text{Ni}(A_n, C_3^r)$, $r \geq n$, there are exactly two components, both defined over $\mathbb{Q}$, separated by a nonobvious moduli problem detected by the $\text{Spin}_n \rightarrow A_n$ cover. If, for all $n$ there are 3-cycle realizations of $A_n$ as RIGP realization, they must/would/could come from any $\mathbb{Q}$ point on one of these spaces. Since, however, there are two spaces, from which would you look? There is a clear choice, for only one of those spaces has attributes like those
of the spaces \( \text{Ni}(D_{\ell k+1}, C_{2^4}) \), extending to \( \text{Ni}(D_{\ell k+1}, C_{2^2}) \), which leads directly to comparing the RIGP to famous conjectures on torsion on abelian varieties.

There are other examples, too, that show how the structure on cusps on our Hurwitz spaces, that inspire naming components according to attributes that come in seemingly magical ways from representations of finite groups. So, we do name them, and pose the task of finding if it always happen that there is a convenient way to attribute a moduli problem to these situations. It simplifies everything to use the BCL and to assume that \( C \) forms a rational union. Then, we ask if we can identify the \( G_\mathbb{Q} \) orbits of components on a Nielsen class \( \text{Ni}(G, C) \). We know we can starting with our assumption as in Ch. 4 when each conjugacy class in \( C \) appears sufficiently often as in (3.19).

Finding that components \( H'' \) have different fields attached to them doesn’t change the fact that the BCL still applies to them. Yet, if for good reasons, even though \( C \) is a rational, the space has a different moduli definition field \( \mathbb{Q}_{H''} \), it is a contributor to our understanding of where it is that those RIGP solutions for \( G \) are hiding.

**Remark 4.15.** \([\text{CmHa85}, \text{Prop. 2.5}]\).  

**4.3. Definition field examples.** §4.3.1 gives examples, with fine moduli, in which both the inner and absolute BCL can be compared while clarifying subtleties on the meaning of the phrase *as a moduli space*.

While passing to reduced spaces doesn’t change the definition field of the Hurwitz space, the fine moduli condition does. §4.3.2 augments slightly the consideration of definition field *as a moduli space*, when fine moduli doesn’t hold, especially to include the reduced Hurwitz space cases.

Singular points on the moduli space, \( M_g \), of genus \( g \) correspond to curves with extra automorphisms. For reduced Hurwitz spaces when \( r > 4 \), §4.3.3 introduces the elliptic fine moduli condition that, as for \( r = 4 \) in (2.25b), has a Nielsen class interpretation. There is no analog for \( r > 4 \) of b-fine moduli (2.25a).

**4.3.1. Fine abs and in examples.** Ex. 4.16 fulfills the remark after \([\text{FrV91}, \text{Thm. 1}]\). To wit: Assume \((G, C, T)\) has fine moduli. Let \( \mathcal{H}' \) be a component of \( \mathcal{H}(G, C)^\text{abs} \) and \( \mathcal{H}'' \) a component of \( \mathcal{H}(G, C)^\text{in} \) over it.

Then, we can have \( \mathbb{Q}_{\mathcal{H}'} = \mathbb{Q} \), but \( \mathbb{Q}_{\mathcal{H}''} \neq \mathbb{Q} \). We intend Ex. 4.17 to clarify distinguishing the definition field of the Hurwitz space cover \( \Phi : \mathcal{H}(G, C) \to U_r \) from its definition as a moduli space (which includes the definition field of \( \Phi \) together with structure of families of covers).

**Example 4.16 (Absolute vs Inner BCL).** All conjugacy classes in \( S_n \) are rational. In \( A_n \) (\( T \) the standard representation), not so. For example, for \( n \) odd, there
apply the BCL with conjugacy classes $C_n$. For $g \in C_n$, $g^{-1} \in C'$ for $n \equiv 3 \mod 4$ (but not if $n \equiv 1 \mod 4$). For $n$ even, the same holds with conjugacy classes $C_{n-1}$ and $C'_{n-1}$ given by $n-1$-cycles, $n-1 \equiv 3 \mod 4$.

Take $n$ even to match the case $\ell = 2$ in Ch. 5 §3 and $C_{(n-1)\cdot(n-1)\cdot(n-1)}$ to be $k \geq 1$ repetitions of $C_{n-1}$ and $k' \geq 0$ representations of $C'_{n-1}$. If $k > k'$, then

\begin{equation}
(C_{(n-1)\cdot(n-1)\cdot(n-1)})^{-1} = (C_{(n-1)\cdot(n-1)\cdot(n-1)})^{-1}.
\end{equation}

Apply the BCL to conclude the diagram of (2.50), with $q = n$, has definition field

\[ Q(A_n, C) = Q(\sqrt{(-1)^{n-1} n-1}) = Q(\sqrt{-(n-1)}). \]

Yet, if we add mod $S_n$ to the right side of (2.50), conclude $Q(A_n, C, T) = Q$.

From the extension of the Conway-Fried-Völklein-Parker lemma [FrV91, App.] (see §4), for $k$ and $k'$ both large, $\mathcal{H}(G, C)^{in}$ is irreducible. \(\triangle\)

Example 4.17 (Definition field as a moduli space). Take two Nielsen classes $\Ni(G, C_i)^{abs}$, $i = 1, 2$. Suppose they have definition fields $Q_{G, C_i, T_i}$, $i = 1, 2$, with $Q_{G, C_i, T_1} = Q_{G, C, T_2}$ a quadratic extension of $Q$. Then, it is possible that:

\begin{equation}
\Phi_i : \mathcal{H}(G, C_i, T_i) \to U_r \text{ are equivalent as covers, defined over } Q;
\end{equation}

and they might even have a dense set of $Q$ points.

Yet, according to Cor. 4.7, none of the covers in those Nielsen classes will have definition field $Q$.

We will have many examples, including for inner spaces replacing absolute spaces. Still, this example is done so explicitly in the literature, it is easy to trace any misunderstandings. It is the first discovered (family of) Davenport polynomial pairs. These are their specs, with $G = \PSL_3(\mathbb{Z}/2)$.

(2.19a) $T_1$ (resp. $T_2$) is its (degree 7) action on points (resp. lines) of $\mathbb{P}^2$.

(2.19b) $C_i = \{2, 3 \cdot C_i\}$, $i = 1, 2$, with $\{C_1, C_2\}$ the two distinct 7-cycle classes in $G$, 2 indicating 3 repetitions of the involution class.

(2.19c) The corresponding $\Phi_i$'s in (2.18) are equivalent as covers of $U_4$.

(2.19d) The reduced Hurwitz spaces are degree 7 genus 0 covers of $\Pi_j$.

(2.19e) $Q_{G, C_i, T_i} = Q(\sqrt{-7})$, the fixed field in $Q(e^{2\pi i/7})$ of

\[ \langle 3 \rangle \leq (\mathbb{Z}/7)^* = G(Q(e^{2\pi i/7})/Q). \]

This started in [Fr73]. With improved techniques it went into an exposition on the complete series of Davenport polynomial pairs in [Fr12, §1-4] to explain, with little abstraction, how braid monodromy works. [CoCa99] uses Magma to explicitly write out the equations for all 21 Davenport-pair families, still using the theory developed in [Fr73]. \(\triangle\)
4.3.2. **Hurwitz spaces and stacks.** Add comments to start on the moduli structure of Hurwitz spaces even without fine moduli, addending Rem. 4.9 especially to include reduced spaces. Also, do some exposition on [Fr77, p. 46-48, Prop. 3] on the criterion for representing families to exist in the Zariski topology.

4.3.3. **Elliptic fine moduli on reduced spaces.** Fill out the Rem. 2.11 in terms of branch cycles as in the first Fried-Gusic etc. paper.
CHAPTER 3

The Lift Invariant and Hurwitz space components

§4 Gives one culmination of the classical period of this subject: The first structure theorem on the absolute Galois group, \( \mathcal{G}_\mathbb{Q} \), of \( \mathbb{Q} \). To show that this work had practical applications, §4.2 explains, as an immediate aftermath, undeniable strides on the RIGP. gives two tools – braid action and the BCL— that help us detect their definition fields and sometimes their irreducible components. §4 uses (2.1) to give precise results about the absolute Galois group, \( \mathcal{G}_\mathbb{Q} \). §4.2 shows the previous somewhat abstract results, can be explicit in applying to the RIGP.

This chapter is a prelude to Part II of the paper. Comparing with the first half is akin to distinguishing monodromy of covers from monodromy of \( \ell \)-adic representations. §2 moves to the second part by introducing (finite) groups that put the RIGP in a context with these topics.

(3.1a) The RIGP (or IGP) is not nearly done, even were it known for all simple groups (§4.2).

(3.1b) Every finite group, excluding nilpotent (see Shafarevich §4), has associated canonical \( \ell \)-adic representations.

Recall from Cor. 4.7 the first RIGP needs for an RIGP regular realization over \( K \leq \mathbb{C} \) of group \( G \) with classes \( \mathcal{C} \):

(3.2a) \( K \) contains \( \mathbb{Q}_G, \mathcal{C} \).

(3.2b) \( \mathcal{H}(G, \mathcal{C})^{\text{in}} \) has at least one absolutely irreducible \( K \) component.

We apply this where \( K = \mathbb{Q} \). The immediate RIGP application of these:

(3.3a) Conditions (3.2) are necessary if the ramification from \( \mathcal{C} \) corresponds to even a single RIGP realization for \( G \).

(3.3b) (3.2) is sufficient for a \( (G, \mathcal{C}) \) RIGP realization over \( K \). In particular it gives such a realization if \( K \) is PAC.

Formulas (2.42) and (2.43) are a consequence of a formula useful for considering the definition field of a specific cover in the Nielsen class as noted in the comments of Lem. 4.1. Over \( \mathbb{R} \), this gives a compact description of all real points on any Hurwitz space directly from \( \mathcal{C} \) and the loci of branch points according to which are real, which fall in complex conjugate pairs \([DFr90]\). This therefore produces other necessary conditions, but again easily decided upon according to properties of \( \mathcal{C} \).
1. The restricted lift invariant

First a naive version of how to effectively fulfill the basic needs of (3.2). We restrict here to being over \( \mathbb{Q} \), and to inner equivalence, though, as with the BCL we can be precise over any (characteristic 0) field and any cover equivalence.

1.1. Commutators and Nielsen classes. Start with a rational union,

\[ \cdot C = \cdot C_1, \ldots, \cdot C_r, \]

of distinct conjugacy classes in the group \( G \). For any vector \( \mathbf{n} \in (\mathbb{Z}^+)^r \) consider just those rational conjugacy class sets of the form \( \cdot C^\mathbf{n} = \cdot C_1^{n_1} \ldots \cdot C_r^{n_r} \). These form a semi-group under slotwise multiplication which we denote by \( R_{\cdot C} \). From the branch cycle lemma, these are the classes we need to form Hurwitz space components whose points correspond to covers over \( \mathbb{Q} \).

For technical reasons we also need classes not restricted to be a rational union but still supported in \( \cdot C \). Denote these \( R_{\cdot C}^{un} \). Assuming \( \cdot C \) fixed, regard \( R_{\cdot C}^{un} \) as a subset of \( (\mathbb{Z}^+)^r \).

For nontrivial considerations, assume that \( \cdot C \) generates \( G \).

Lem. 1.7 then guarantees that \( \text{Ni}(G, \cdot C) \) is nonempty if the multiplicity of the support of all elements in \( \cdot C \) is sufficiently high. Denote by \( N_{\cdot C} \) the least common multiple of the orders of the elements in \( \cdot C \).

**Problem 1.1.** Running over \( R_{\cdot C} \), identify all absolutely irreducible \( \mathbb{Q} \) components of \( \mathcal{H}(G, \cdot C^\mathbf{n}) \).

Again, components of \( \mathcal{H}(G, \cdot C^\mathbf{n}) \) corresponds to orbits of \( H_r \), the Hurwitz monodromy group, on \( \text{Ni}(G, \cdot C^\mathbf{n}) \) with \( r = \sum r_i n_i \). Our treatment of the topic differs considerably from that in [FrV91] and [FrV92] to take advantage of Frattini cover insights for two reasons (see Rem. 2.1):

(3.4a) to avoid an overly restrictive topology condition on \( H_2(G, \mathbb{Z}) \) that \( G \) be a perfect group; and

(3.4b) to display the relation between this topic and the Modular Tower topic that is the main goal of this paper.

For \( \ell \in D_G \) \( \text{def} \) \( \{ \ell \mid \ell || G \} \), there is a universal \( \ell \)-Frattini cover

\[ \Psi_{G,\ell} : U_{G,\ell} \rightarrow G \]  

\( \text{ker}(\Psi_{G,\ell}) \) is a pro-free (finitely generated), pro-\( \ell \) group, and \( \Psi_{G,\ell} \) factors through any \( \ell \)-Frattini cover of \( G \). The fiber product of the \( \Psi_{G,\ell} \)s over \( G \), \( \Psi_G : U_G \rightarrow G \), is versal for factoring (surjectively) through any Frattini cover of \( G \) (§1.3). Mod out by the commutator of \( \text{ker}(\Psi_{G,\ell}) \) to get the universal abelianized \( \ell \)-Frattini cover,

\[ \Psi_{G,\ell,ab} : U_{G,\ell,ab} = U_{G,\ell} / [\text{ker}(\Psi_{G,\ell}), \text{ker}(\Psi_{G,\ell})] \rightarrow G. \]
Definition 1.2. A Frattini cover, \( \psi : H \to G \), is central if \( \ker(\psi) \) is nontrivial and in the center of \( H \). Like all Frattini covers it is a fiber product of \( H_\ell \)'s over \( G \). Denote those \( \ell \) for which \( \psi_\ell : H_\ell \to G \) is nontrivial by \( D^*_\psi \).

Notation: The number of classes in \( C \) is \( r_C \); and the least common multiple of orders of elements in \( \ast C \) is \( N_{\ast C} \).

For \( g \in G, \ell \in D_G \) and \( (\ell, \text{ord}(g)) = 1 \), an elementary piece of the Schur-Zassenhaus lemma says a unique \( \hat{g} \in H_\ell \) over \( g \) has \( \text{ord}(\hat{g}) = \text{ord}(g) \). As Prop. 1.8 shows, this is a special case of this more general property.

Definition 1.3. Refer to the class, \( C_g \), of \( g \in G \) as liftable (to \( \psi \)) if for \( \hat{g} \in H_\ell \) over \( g \), \( |C_{\hat{g}}| = |C_g| \); unliftable if not. As \( \psi \) is central, liftability depends only on \( g \), not on \( \hat{g} \).

That is, there is no non-trivial (single) commutator \( h\hat{g}h^{-1}\hat{g}^{-1} \in \ker(\psi), h \in H \). Checking this can be nontrivial, even if you know \( G \) well.

Definition 1.4. Assume all classes in \( \ast C \) are liftable to \( \psi \).

For \( C \in \mathcal{R}_C \) and \( g \in \text{Ni}(G, C) \), define \( \hat{g}_{\ast} = (\hat{g}_1, \ldots, \hat{g}_{r_C}) \).

For \( g \) in any braid orbit \( O \) on \( \text{Ni}(G, C) \),

\[
\text{ord}(g) = \prod_{i=1}^{r_C} \hat{g}_i \text{ def } = \prod (\hat{g}) \text{ is the restricted lift invariant.}
\]

For a given \( C \) and \( \ell \in D_G \), define

\[
\mathcal{S}_{G,C,\psi} \text{ def } = \{ s_\psi(O) | \text{running over all braid orbits } O \text{ on } \text{Ni}(G, C) \}.
\]

We concentrate on a subconcern of Prob. 1.1.

Problem 1.5. Say something definitive about \( C \in \mathcal{R}_C \) by which we can separate braid orbits on \( \text{Ni}(G, C) \) by lift invariants.

§4.2 reminds of examples that cover much territory:

(3.6a) a solved but serious puzzle on simple branched covers;

(3.6b) how Riemann’s most famous invention – half-canonical classes – arises with alternating groups; and

(3.6c) unfinished business relating regular realizations of dihedral groups with torsion points on hyperelliptic jacobians.

With any central Frattini extension such as \( \psi \) we use the subscript \( \ell \) on the kernel, as in \( \ker_\ell \), to indicate its \( \ell \)-Sylow. Denote the (generated by) commutator(s) subgroup, \([H, H]\) intersected with \( \ker(\psi) \) by \( V_H = \prod_{\ell \mid \ker(\psi)} V_{\psi,\ell} \).

For \( C \) a conjugacy class in \( G \), and \( g \in C \), refer to \( g_ug_u^{-1}g_1^{-1}, g_u \in G \), as a \( C \) commutator. Denote the group they generate, the commutator subgroup of \( G \), by...
We need an estimate on the multiplicity, $v_i = 1$, every element of $G$ is the
better than that.)

**Theorem 3.8** distinguishes between products of commutators in $V$ and a single
commutator.

**Definition 3.6.** For any $C$ supported in $C^*$ consider
\[
\prod(C) \overset{\text{def}}{=} \{ \prod(g) \mid g \in C \}.
\]
Refer to $C$ as satisfying product 1 if $1 \in \prod(C)$. Denote the complete collection of
such $C$ as $\text{Prod}(1, C_1)$.

Note: $\text{Prod}(1, C_1)$ includes those $C$ such that $N(G, C)$ is a nonempty Nielsen
class. Denote the latter set as $N_1, C$.

**Lemma 3.7.** There is a natural semi-group homomorphism, $\pi_{ab}$, from $R_{\times C}^{un}$ into
$G_{ab}$, by $g \in C \mapsto \prod(g)_1$, for which $C \in \text{Prod}(1, C_1) \mapsto 1$.

For $C \in \text{Prod}(1, C_1)$, any $g \in \prod(C)$ is in $[G, G]$.

Suppose $C \in \text{Prod}(1, C_1)$ and each class in $\ast C$ appears in $C$ with sufficient
multiplicity. Then, running over $C'$ in $\ast C$:

- (3.7a) $\prod(C' \cdot C)$ is the coset of $[G, G]$ represented by $\pi_{ab}(C')$; and
- (3.7b) $\prod(C)$ is $[G, G]$ and $C \in N_1, C$.

**Proof.** The range of $\pi_{ab}$ is $G_{ab}$, the maximal abelian quotient of $G$. So, the
image of $C$ doesn’t depend on the choice of $g \in C$, or the order of elements in $g$.
Thus, it is well defined on the semigroup of elements in $R_{\times C}^{un}$. Therefore, everything
in $\text{Prod}(1, C_1)$ is in $\ker(\pi_{ab})$ and is a products of commutators.

Now, suppose $C \in \text{Prod}(1, C_1)$. We have really established (3.7a) above. The
rest of the proof is dedicated to (3.7b). Consider the results of the union of the
collection $\prod(C)$ running over all $C \in R_{\times C}^{un}$ (a subset of $G$). If $g_i \in \prod(C_i)$, $i = 1, 2$, then $g_1 \cdot g_2 \in \prod(C_1 \cdot C_2)$.

(3.8) Use that $\ast C$ generates $G$ to conclude the complete collection is $G$.

Suppose there is a $C$ for which $\prod(C)$ is $[G, G]$, or a $C'$ in $\ast C$ for which $C' \cdot C$
is the $g' = \pi_{ab}(C')$ coset of $[G, G]$. Both cases are similar, so we assume the first.
We need an estimate on the multiplicity, $v_1, \ldots, v_r$, of elements in $\ast C$ that assures
every element of $G_{ab}$ has the form $\sum_{i=1}^r a_i u_i$, with $1 \leq a_i \leq v_i$, $u_i = \pi_{ab}(C_i)$,
i = 1, \ldots, r. (Clearly, $v_i \leq |G_{ab}|$ works, but in practice you might want much
better than that.)

For any $g' \in G$, $\{g' \cdot g\}_{g \in \prod C}$ is a coset of $[G, G]$. Consider the multiplicity,
w_1, \ldots, w_r, of appearance of classes in $\ast C$ in $C$. Then, an appropriate bound for
the multiplicities of appearance of the classes in $\star C$ for the conclusion of in (3.7b) is
given by $(w_1+v_1, \ldots, w_r+v_r)$. Finally, if there is no such $C$ we get a contradiction
to (3.8).

\[ \square \]

Prop. 1.8 works for classical applications with $G$ a group, as in Ex. 2.9, of which
most have heard. Prop. 4.9 is general – though similar – in handling all finite groups.
That forces an adjustment on the lift invariant. When we know $|V_H|$ a priori, (3.10d)
is very helpful:

\[(3.9) \quad \text{that } (N_{\star C}, |V_H|) = 1 \text{ implies } \star C \text{ is liftable.} \]

\textbf{Proposition 1.8.} Suppose all elements of $\star C$ are liftable to $\psi$. This allows
identifying the classes of $\star C$ with classes in $H$. If $O$ is a braid orbit on $Ni(G, C)$,
then the following hold.

\[(3.10a) \quad \text{The restricted lift invariant in } \ker(\psi) \text{ is independent of } g \in O \text{ and distinct}
\text{values in } s_{G,C,\psi} \text{ correspond to distinct braid orbits.} \]

\[(3.10b) \quad \text{For } g'_1, g'_2 \in \prod(C), (\text{resp. } s_1, s_2 \in S_{G,C,\psi}), g'_1(g'_2)^{-1}
(\text{resp. } s_1s_2^{-1}) \text{ is an}
\text{explicit product of } C \text{ commutators in } G \text{ (resp. in } H). \]

\[(3.10c) \quad \text{If } (3.9) \text{ holds, then, all elements of } \star C \text{ are liftable to } \psi. \]

\[(3.10d) \quad \text{If } Ni(G, C) \text{ is a nonempty Nielsen class (resp. } 1 \in S_{G,C,\psi}), \text{ then each}
g \in \prod(C) \text{ (resp. } s \in S_{G,C,\psi}) \text{ is an explicit product of } C \text{ commutators in}
G \text{ (resp. in } H). \]

\[(3.10e) \quad \text{If all } \star C \text{ in } \star C \text{ appear in } C \text{ with high multiplicity, then each}
v \in \ker(\psi) \text{ is a product of } C \text{ commutators and } \ker(\psi) = S_{G,C,\psi}. \]

Denote the collection of orbits of $g \in Ni(G, C)$ for which $s_\psi(g) = 1$ by $N_1$. Then, if $C$ is a rational union, $G_Q$ permutes their corresponding components (as inner or absolute moduli spaces, Def. 4.8).

\section*{1.3 has the proof of Prop. 1.8, several of whose pieces will be used elsewhere. It
also aids in distinctions with Prop. 4.9. It is preceded by \S 1.2 on a universal
construction of Frattini central extensions based on the Universal Frattini cover.}

\textbf{Remark 1.9 (Lem. 1.7 explicitness).} Points of explicitness start in Lem. 1.7.
We can write $\prod(g), g \in C$, for $C$ in $\text{Prod}(\star C)_1$, explicitly as a product of $C$
commutators (3.10d). Being explicit on the multiplicity in $C$ of the classes in $\star C$
is harder. Example: Specifically comparing production of $w_1, \ldots, w_r$ with (3.8)
requires producing the coset representation expressing $G_{ab}$. The Todd-Coxeter (a
la Shreier's) algorithm suffices [Ar91, Chp. 6, \S 9], because combining branch cy-
cles with the commutator expressions is a quotient of the free group presentation
required of the algorithm.
Even more involved is how to deal, for \( C \in \mathcal{N}_i \), with the number and nature of braid orbits. Prop. 1.8 and Prop. 4.9 show that involves computational statements about central Frattini extensions (see §2.1).

1.2. **Central Frattini covers.** Recall the universal abelian \( \ell \)-Frattini cover \( \Psi_{G,\ell,ab} : U_{G,\ell,ab} \to G \) (from (3.5)). We use it to locate the Frattini central extensions of \( G \) by which we construct the lift invariant.

Form a versal central extension \( R_{G,\ell} \) for Frattini central covers of \( G \) with kernel an abelian \( \ell \)-group as follows.

1.2.1. (a) For a maximal quotient of \( \ker(\Psi_{G,\ell,ab}) \) with trivial \( G \) action, mod out by \( W_{G,\ell} = [U_{G,\ell,ab}, \ker(\Psi_{G,\ell,ab})] \) on \( \ker(\Psi_{G,\ell,ab}) \).

1.2.1. (b) Prop. 1.8 shows elements in \( W_{G,\ell} \) that are lift invariant differences come from products of commutators:

\[
V_{G,\ell} = \ker(\Psi_{G,\ell,ab}) \cap [U_{G,\ell,ab}, U_{G,\ell,ab}]/W_{G,\ell}.
\]

Similarly there is a \( V_G \). Notice that the map \( \Psi_{G,\ell,ab} \) restricts to send the product of all the \( V_{G,\ell} \)s surjectively to \( V_H \). The lift invariant is a tool for investigating Hurwitz space components, via \( \ell \)-Frattini central extensions of \( G \), to see the effect of those components for a given \( C \).

**Definition 1.10 (Representation covers).** There is a central Frattini cover \( \psi_{G,\ell} : R_{G,\ell} \to G \) (resp. \( \psi_G : R_G \to G \)) – an \( \ell \)-representation cover – in which \( V_{G,\ell} \) (resp. \( V_G \)) is the exact kernel. Prop. 2.3 shows its existence, et. al.

Schur first showed the existence of \( V_G \) (the Schur multiplier of \( G \)). We see it as a maximal possible \( \ker(\psi) \), \( \psi \) a central Frattini cover with commutator kernel as in Cor. 2.6. While \( R \) – a representation cover – does not uniquely present it unless \( G \) is perfect, Cor. 2.6 locates representation covers among all central Frattini covers.

[Is94, p. 118] expostulates, “We shall not attempt to explain why anyone would be interested in such a thing.” We have been giving motivation for this: It immediately produces and explains many distinct Hurwitz space components, though as in §3.1.2 §3.2, not all, once we get into the territory of Serre’s OIT. We have two goals for the remainder of this subsection.

Ex. 1.11 and Prop. 4.9 handle differently the mysterious, but finite (in many cases, trivial), group \( V_G \). There are three disparate applications in which we ask about components related to lift invariants.

1.2.2. (a) Draw precise conclusions about a natural family of (related) pairs \((G,*,C)\) running over all \( C \in \mathcal{R}_*C \).

1.2.2. (b) For each \( G \), include all its nontrivial classes in \( *C \).

1.2.2. (c) Instead of changing \( C \), in MTs it makes sense to consider a natural series of groups \( \{G_k\}_{k=0}^\infty \) covering one fixed group, \( G = G_0 \).
In (3.12c) we make sense of $C$ not changing, though $G$ does. In these applications the goal remains to identify components of Nielsen classes defined (as moduli spaces) over $\mathbb{Q}$. In §1.1, as with the other applications, we take a natural family of groups in (3.12c), but even there we fix $C$. For the application to Thm. 4.4 and its like, given by (3.12b), it suffices to draw conclusions about components for a cofinal family of finite groups as is stated in Prop. 4.9. That is because once $G$ is realized regularly, so is every quotient of $G$.

1.3. Proof of Prop. 1.8. Generating braids are in (2.10). Write $g \in \prod(C)$ as a product of elements in the respective conjugacy classes. Then, any braid applied to the $r_C$ tuple, preserves the product of the entries, as we now illustrate by example. That the lift invariant is a braid invariant only needs that in $H$, replacing, say

$$\hat{g}_k \hat{g}_{k+1} \text{ by } g_k g_{k+1} g_k^{-1} \hat{g}_k$$

gives the same lift invariant. That is, $g_k g_{k+1} g_k^{-1} = \hat{g}_k \hat{g}_{k+1} \hat{g}_k^{-1}$; both are the same element over $g_k g_{k+1} g_k^{-1}$, the left side given by conjugating a representative of that conjugacy class through the formula $|C_\hat{g}| = |C_g|$.

There are two statements in (3.10b) acceding to similar arguments. So we just show the difference of the lift invariants of $g, g' \in \Ni(G, C)$ is an explicit product of $C$ commutators. With no loss, as above, apply a braid to $g'$ to assure that $g'_i$ is conjugate to $g_i$, $i = 1, \ldots, r$. Then, with $C^{-1}$ the conjugacy classes of the inverse of the classes of $C$, express their difference as the lift invariant of the juxtaposition $(g, (g')^{-1})$ in $\Ni(G, C \cdot C^{-1})$.

With $g' = (h_1 \hat{g}_1 h_1^{-1}, \ldots, h_r \hat{g}_r h_r^{-1}), h_1, \ldots, h_r \in H_\ell$, apply a sequence of braids to express the invariant differences as $\prod_{i=1}^r \hat{g}_i \cdot \prod_{i=r}^\ell h_i \hat{g}_i^{-1} h_i^{-1} = \prod_{i=1}^r \hat{g}_i h_i' \hat{g}_i^{-1} (h_i')^{-1} \cdots \hat{g}_i h_i' \hat{g}_i^{-1} (h_i')^{-1}$: a product of $C$ commutators in $\ker(\psi)$.

(3.13)

For example, $h_r = h'_r, h'_{r-1} = g_r h_{r-1} g_r^{-1} h_{r-1} g_r h_{r-1} g_r^{-1}$, \ldots, tedious, but fairly obvious. The result, in $\ker(\ell)$, is a product of commutators in $H_\ell$. Conversely, given (3.13), we can reverse the braids to express it as the lift invariant of two distinct braid orbits in $\Ni(G, C)$.

That finishes (3.10a) and (3.10b). For each case of (3.10d), apply (3.10b) using the hypothesized expression of 1 as $\prod(g')$ (resp. $\prod(\hat{g}')$) for $g' \in C$.

Now assume (3.9). Since $([\ker(\psi)], N, C) = 1$, Schur Zassenhaus says there is a unique same-order lift $g \in C$ to $\hat{g} \in H$. If $h \hat{g} h^{-1}$ also lies over $g$, then it is the unique same order lift. So it equals $\hat{g}$, finishing (3.10c).

Now apply Lem. 1.7 to get (3.10d). Then, once we know $g \in \Ni(G, C)$, from the Frattini property it follows that $\hat{g} \in \Ni(H, C)$, and (3.10e) follows.

Now suppose the subset of $g \in \Ni(G, C)^{\text{in}}$ with $s_\psi(g) = 1$ is nonempty. Relative to any classical generators, take a cover, $\hat{\varphi} : \hat{X} \to \mathbb{P}^1_\mathbb{Z}$ that represents an element in
Ni\((G, C)\). Then, there is a cover \(\hat{\varphi}_H : \hat{X}_H \to \mathbb{P}^1\) with group \(H\) that factors through \(\hat{\varphi}\) and is unramified from \(\hat{X}_H \to \hat{X}\). Indeed, branch cycles for \(\hat{\varphi}_H\) are given by \(\hat{g}\), the lift of \(g\). The no-ramification property is a consequence of what Grothendieck called Abhyankar’s Lemma. We will refer to \(\hat{\varphi}_H\) later as the Trivial Invariant lift (of \(\hat{\varphi}\)).

We assumed \(C\) is rational union of conjugacy classes. We show, therefore, that covers having trivial lift invariant will be recognized by \(G_Q\). From the BCL, \(\sigma \in G_Q\) will send \(\hat{\varphi}\) to an element in the same Nielsen class. That action will extend to \(\hat{\varphi}_H\), including to any local parameters for ramification, preserving those ramification indices. Thus, covers in \(\mathcal{H}'\) are mapped by \(\sigma\) into covers in \(\mathcal{H}'\). A single cover in a moduli space component determines the lift (braid) invariant. That concludes the statement that the components of \(\mathcal{H}'\) are mapped among themselves by \(G_Q\).

Prop. 1.8 says, assuming high multiplicity of all the support conjugacy classes from \(\mathcal{C}\), we achieve all lift invariants as products of \(C\) commutators if and only \(\pi_{ab}(C) = 1\). Ex. 1.11 does a special case that simplifies most of the explicitness complications of Rem. 1.9. In this example, the remaining mystery is how to directly know central Frattini covers, a problem finessed by the general lift invariant in Prop. 4.9. It also emphasizes the value for rational unions of classes to satisfy the last paragraph of Prop. 1.8.

**Example 1.11.** Assume \(\mathcal{C}\) is a single rational (generating) conjugacy class \(C\) of odd, \(d\), order elements, with \(|V_G|, d\) = 1. First let \(\psi_R : R \to G\) be a representation cover of \(G\). It is a Frattini cover, and so \(C\) lifts to a generating conjugacy class in \(R\). Therefore, for any \(m \in \ker(\psi_R)\), If \(r \geq r'\) by noting that we can write any integer exceeding \(d\) in the form \(2a_2 + da_d\) with \(a_2, a_d\) nonnegative integers.

Indeed, take \(m\) as above, and let \(g\) be any representative of \(C\). Write \(r - r_m\) as \(2a_2 + da_d\). With \((g, \ldots, g)\) the juxtaposition of \(g\) taken \(d\) times, take as a representative with lift invariant \(r_m\) the Nielsen class element
\[
(mg, g^{-1}a_2, (g, \ldots, g)ad)
\]
with subscripts \(a_2\) and \(a_d\) indicating repetition. \(\triangle\)

2. **The general lift invariant**

Prop. 1.8 used the restricted lift invariant, for which the assumption was that \(\mathcal{C}\) is liftable. Ex. 2.9, satisfying the special case where \((N, C, \ker(\psi)) = 1\) for any central Frattini extension \(\psi\) of \(G\), guided the author (see Serre’s reference to our interchange in the footnote in [Se90a, p. 480 and Ref. 4], or [Fr10, Inv. Cor. 2.3]).

The difference between Prop. 1.8 and Prop. 4.9 is the removal of the liftable condition. That came through John Thompson from Conway and Parker. Völklein thought to reduce the problem to the case of one braid orbit. That, however, is
neither necessary (from the last paragraph of Prop. 1.8) nor always wise, since it removes the classical connections and applications now feasible to 1-dimensional reduced Hurwitz spaces. Even those well-acquainted with this area should be surprised at the relevance in Ex. 2.11 of the oldest example: simple branched covers of the sphere.

2.1. Commutator kernels and Schur multipliers. To define the lift invariant start with \( g \) in one of the conjugacy classes \( \ast C \) in \( \ast C \). Define \( \hat{g} \) to be any lift of \( g \) to a representation cover \( \psi_R : R \to G \) (or one prime at a time to \( \psi_{\ell} : R_\ell \to G \)). The big difference is that condition (3.10a) no longer holds: a difference of achieved lift invariants can be a single commutator in a representation cover \( \psi_R : R \to G \) Frattini central extension. The case \( A_4, \ell = 2 \) starts two very different series of examples: Ex. 2.9 or Ex. 4.8.

This confounds that the lift invariant for \( g \in \text{Ni}(G, C) \) is a braid invariant. That results from \( g k g_{k+1}^{-1} \) as in the proof of Prop. 1.8. To restore this formula we have only to mod out \( V_G \) or \( V_{G,\ell} \) by the subgroup, \( SC_{\ast C} \), generated by single commutators from \( \ast C \). Since \( R/SC_{\ast C} \to G \) is still a central Frattini extension, this changes almost nothing in the natural extension of Prop. 1.8 to Prop. 4.9.

**Definition 2.1 (General lift invariant).** Extend the lift invariant from Def. 1.4 by putting its value in \( V_G/SC_{\ast C} \). We await Prop. 4.9 to find, for each \( G \), a rational union \( C \) having

\[
\text{(3.14)} \quad \text{a braid component } \mathcal{H}' \text{ of } \mathcal{H}(G, C)_{\text{in}} \text{ defined over } \mathbb{Q}.
\]

It is by dealing with each prime \( \ell | |G| \) one-at-a-time that we affect (3.4a). The Universal \( \ell \)-Frattini cover of \( G \) in §1.2 applied in § 1.3 to see the important Frattini central extensions that give us the lift invariant. This replaced a Hopf use of a free group and a presentation of \( G \) to define \( H_2(G, \mathbb{Z}) \) with its motivation as a definition of a particular (group) homology group (discussion [Br82, p. 2]). We conclude this subsection by relating the ingredients of a long story in group theory to our considerations.

**Definition 2.2.** Refer to a central cover \( \psi : R \to G \) as having **commutator kernel** if \( \ker(\psi) \) consists of elements in \( [R, R] \).

The restricted lift invariant condition applied to \( \psi \) says that \( \ker(\psi) \) is not only a product of commutators, but it is a product of \( C \) commutators, so long as these necessary conditions hold (3.10e):

\[
\text{(3.15a) elements of } \ast C \text{ appear suitably often in } C; \text{ and}
\]

\[
\text{(3.15b) the image of } C \text{ in the commutator quotient of } G \text{ is trivial.}
\]

That leaves us two goals for the remainder of this subsection.
(3.16a) Prop. 2.3 comments: Find a good route to explaining the Schur multiplier, in the generality required in applications.

(3.16b) Cor. 2.6 and Cor. 1.6: Exploit the universal ℓ-Frattini cover as a sometimes effective computation of lift invariants.

We apply (3.17) when $G$ acts trivially on $A$ in our search for central Frattini extensions of $G$, though it holds for any abelian $G$ module $A$.

The comments explain terms, including Ext and $h$. Cor. 2.6 connects to primes for which $G$ is not perfect using $H_1(G, \mathbb{Z}) = G/[G,G] \overset{\text{def}}{=} G_{ab}$. As in §1.1 denote the canonical map $G \to G_{ab}$ by $\psi_{ab}$. Ch. 6 §1.2 puts Ext in a context.

**Proposition 2.3.** [Sp66, Thm. 3, Chap. 5, §5] calls the split exact sequence a universal-coefficient theorem for cohomology:

(3.17) $0 \to \text{Ext}(H_{q-1}(G, \mathbb{Z}), A) \to H^q(G, A) \xrightarrow{h} \text{Hom}(H_q(G, \mathbb{Z}), A) \to 0$.

Take $q = 2$ in (3.17). Apply $h$ to the class of an extension of $G$ by $A$ to produce the element of $\text{Hom}(H_2(G, \mathbb{Z}), A)$ that derives from it.

The image of an extension $\psi_E : E \to G_{ab}$ realizing an element of $\text{Ext}(H_1(G, \mathbb{Z}), A)$ defines the extension $\psi_E^* : E^* \to G$ by pullback, giving the image of $\psi_E$ in $H^2(G, A)$.

Expression (3.18) gives this map at the cocycle level defining the cohomology classes.

**Comments.** Denote the $q$-chains over $\mathbb{Z}[G]$ by which we compute cohomology by $C_q$. Compute $h$ in (3.17) by recognizing that an element of $H^q(G, A)$ is given by $f$ in the kernel of the derivative operator applied to $\text{Hom}(C_q, A)$. Use the same chains to compute homology. Elements of $H_q(G, A')$, in the kernel of the derivative operator, have the form $\sum c_i \otimes a'_i$, with the $c_i$ s in $C_q$. Then, $\sum f(c_i) \otimes a'_i$ makes sense upon checking independence of $f$ (resp. $\sum c_i \otimes a'_i$) modulo respective boundaries. That defines $h$.

While [Br82, p. 306] refers to the universal coefficient theorem, the spots those references appear – based on spectral sequences – don’t use the phrase. I eventually found it buried in exercises [Br82, p. 60, #3]. By contrast, [Br82, p. 97, #7] has a long exercise on Universal Central Extensions.

Alas, it assumes $G$ is perfect – we can’t – concluding then that

$H^2(G, A) = \text{Hom}(H_2(G, \mathbb{Z}), A)$ (A with trivial $G$ action).

Here the universal coefficient is $H_2(G, \mathbb{Z})$; or $H_2(G, \mathbb{Z})$ represents $H^2(G, A)$ (a functor of $A$). Even then, it uses another telegraphic exercise, Yoneda’s Lemma. [Sp66] is about topological spaces; though [Br82] stresses that group cohomology extends compatibly singular cohomology of topological spaces. Cor. 2.6 refers to [Br82]’s, often clever, exercises.

In Brown or Spanier, Ext refers to $\text{Ext}^1_{Z}$, the first Ext functor for which $\text{Ext}^1_{R}(M, A)$, with $R$ modules $M$ and $A$, representing classes of abelian extensions $0 \to A \to$
Another extension $E' \to M$, with $A \leq E'$, is equivalent to $\nu$, if there is a module homomorphism $\mu : E \to E'$ with $\nu' \circ \mu = \nu$. Here we extend $G_{ab}$ by $A$.

Now consider a cocycle $(u_1, u_2) \in G_{ab} \to c(u_1, u_2) \in A$ defined by an element in $\text{Ext}(G_{ab}, A)$. It creates a new multiplication on $A \times G_{ab}$:

$$(a_1, u_1) +^* (a_2, u_2) = (a_1 + a_2 + c(u_1, u_2)(a_1, a_2)) \mid u_1, u_2 \in G_{ab}, a_1, a_2 \in A.$$ 

The key condition in defining a cocycle is that the law of addition, $+$, be associative. The natural map that sends the cocycle representative to a cocycle representative, $c^*(g_1, g_2)$ in $H^2(G, A)$ is given by the formula

$$(3.18) \quad c^*(g_1, g_2)(a_1, a_2) = c(\psi_{ab}(g_1), \psi_{ab}(g_2))(a_1, a_2).$$

Now, easily trace that the multiplication on $c^*(g_1, g_2)$ is defining the pullback. This concludes the proof. \qed

For $M$ an abelian group, denote by $\Phi_{M_{ab}} : \hat{M}_{ab} \to M$ the natural profree abelian group of the same rank that covers $M$. The composition into $\ell$ components is given by $\hat{M}_{ab} = \prod_{\ell \mid |M|} \hat{M}_{\ell, ab}$ where $\hat{M}_{\ell, ab}$ is the pro-$\ell$ abelian group of the same rank as the $\ell$ component, $M_{\ell}$, of $M$.

**Corollary 2.4.** With $M$ and $A$ abelian groups, elements of $\text{Ext}(M, A)$ giving abelian (so central) Frattini covers of $M$ are quotients $\psi : E \to M$ of $\hat{M}_{ab} \to M$ with kernel $A$.

For $M = G_{ab}$, and $E$ above, the pullback of $\psi_{ab}^*(E)$ of $E$ over $G$ (as in Prop. 2.3) is a central Frattini cover. Then, the fiber product $G \times_{G_{ab}} E$ is also a central Frattini cover of $G$ (see Rem. 2.8).

**Proof.** The elementary divisor theorem allows us to write $M$ as a sum of its (cyclic) $\ell$-primary parts. Since $\text{Ext}(M, A)$ is an additive functor in each variable, and since Frattini covers are given by fiber products of their $\ell$ parts, it suffices to take $M = \mathbb{Z}/\ell^t$. Then, the abelian Frattini covers of $M$ are $\mathbb{Z}/\ell^u$ for any $u \geq t$. Combine these over all the primary parts of $M$.

Now take $M = G_{ab}$, and consider a nontrivial abelian Frattini cover $\psi : E \to G_{ab}$ from above. The kernel of $\psi_{ab}^* : G_E \overset{\text{def}}{=} G \times_{G_{ab}} E \to G$ has the form $\{(1, e) \mid e \in \ker(E \to G_{ab})\}$. Clearly that is in the center of $G_E$.

Suppose $G_E$ is not a Frattini cover of $G$ (by projection onto the first factor). Then, some $H < G_E$ projects onto $G$: $\text{pr}_H : H \to G$ is a cover. Then, $\ker(\text{pr}_H)$ is isomorphic to $\mathbb{Z}/\ell^v$ with $v < u - t$. Assume $E$ has cocycle $c : G_{ab} \times G_{ab} \to A$ as at the end of the proof of Prop. 2.3.

Then $\ell^v \cdot c : (u_1, u_2) \in G \mapsto \ell^v c(u_1, u_2)$ defines a nontrivial element of $\text{Ext}(G_{ab}, \mathbb{Z}/\ell^{u-t-v})$ whose image in $H^2(G, \mathbb{Z}/\ell^{u-t-v})$ is trivial.
Apply (3.17) with $A$ above replaced by $A' = \mathbb{Z}/\ell^{u-t-v}$.

That says $\text{Ext}(G_{ab}, A') \to H^2(G, A')$ is an embedding. Here, though, the trivial element of $\text{Ext}(G_{ab}, A')$ and the element defined by $\ell^v \cdot c$ both go to the trivial element. Thus, $v = u-t$, and $H = G_E$ is a Frattini cover of $G$. That concludes the proof of the lemma. □

**Definition 2.5.** According to (3.17), the middle term is a direct sum its left and right sides (see Rem. 2.7). Our main case is $q = 2$. It is convenient to refer to the left (resp. right) as the Ext (resp. Comm) side.

Cor. 2.6 differentiates the central Frattini extensions from Ext side from those from the Comm side. While the latter are significant in the description of the lift invariant, both play serious roles in the OIT. As previously, use $\psi_{G,\ell}: R_G \to G$ to be an $\ell$-representation cover of $G$. Also, denote the $\ell$ part of $G_{ab}$ by $G_{ab,\ell}$.

**Corollary 2.6.** A central cover $\psi: H \to G$ from the Comm side is a Frattini cover. In particular, for any finite group $G$ (resp. prime $\ell||G|$) there is a representation (resp. $\ell$-representation) cover

$$\psi_G: R_G \to G$$

Assume the natural cover, $\psi_{ab,\ell}: G \to G_{ab,\ell}$, splits. Further, for a choice of splitting, $\mu: G_{ab,\ell} \to G$, the commutation action of $\mu(G_{ab,\ell})$ extends to the $\ell$ part of a representation cover $\psi': R_{\ker(\psi_{ab,\ell})} \to \ker(\psi_{ab,\ell})$, centralizing $\ker(\psi')$. Then the restriction of $\psi_{G,\ell}$ over $\ker(\psi_{ab,\ell})$ is $\psi'$.

**Proof.** Suppose $\psi$ is a central cover with commutator kernel, but it is not a Frattini cover. Then, their exists $H_1 < H$ for which the restriction of $\psi$ is surjective to $G$. Then $H = \bigcup_{i=1}^t H_1 c_i$ with $t > 1$, with the $c_i$s coset reps that centralize $H_1$.

Thus, commutators in $H$ have the form

$$ch_1c'h_1'(ch_1)^{-1}(c'h_1')^{-1} = h_1h_1'(h_1)^{-1}(h_1')^{-1}$$

with $c, c' \in \ker(\psi), h_1, h_1' \in H_1$.

This is, all commutators reside in $H_1$, and $\psi$ does not have commutator kernel.

A representation cover arises by taking $A = H_2(G, \mathbb{Z})$ and the identity map in $\text{Hom}(H_2(G, \mathbb{Z}), A)$. The fiber of $h$ lying over this element then includes an element identified with 0. Once we have one representation cover, $\psi_G: R_G \to G$, and we know it is Frattini, then it has a representation as the fiber product over $G$ of $\psi_{G,\ell}: R_{G,\ell} \to G$ where $\ker(\psi_{G,\ell})$ is the $\ell$ part of $\ker(\psi_G)$. Then, $\psi_{G,\ell}$ is an $\ell$-representation cover of $G$. □

**Remark 2.7 (Direct sum in (3.17)).** That the Ext and Comm sides are direct summands of the middle term in (3.17) is based in the proof on the choice of (coefficient) chains used. For $q = 2$ see this directly. Everything on the Ext side
is a sum of quotients from $\hat{\mathcal{M}}_{ab} \to M$. Everything on the $\mathbf{Comm}$ side is a sum of quotients of the finite representation cover.

There is no overlap between the summands on the two sides as the kernel of extensions of $G$, because the Ext side is a quotient of a free abelian group. A free abelian subgroup of a finitely generated abelian group automatically splits off by the elementary divisor theorem.

**Remark 2.8 (Fiber products vs Frattini covers).** Forming a universal Frattini cover (Lem. 1.15) uses subgroups of a fiber product of two Frattini covers, $H_i, i = 1, 2$, of $G$. Then, a subgroup of $H_1 \times_G H_2$ that is a Frattini cover of $G$ automatically factors surjectively through both $H_i$s.

### 2.2. Example lift invariants vs Hurwitz components.

We know $\mathbf{C}$ commutators — represented in the quotient $V_G = \prod_{\ell | |G|} V_{G, \ell}$ by $\mathbf{SC}_\ast \mathbf{C}$ of Def. 2.1 — correspond to distinct braid orbits in $\mathfrak{Ni}(G, \mathbf{C})$. Those modules have a description, as a quotient of $H_2(G, \mathbb{Z})$ (resp. $H_2(G, \mathbb{Z}_\ell)$) — a second homology group, where $G$ has trivial action on $\mathbb{Z}$ (resp. $\mathbb{Z}_\ell$) [Br82, p. 2].

We achieve all such $\mathbf{C}$ commutators, given the necessary conditions, (3.15), on $\mathbf{C}$ given the following ubiquitous condition:

\[(3.19) \quad \text{Each element of } \mathbf{\ast C} \text{ appears in } \mathbf{C} \text{ with "high" multiplicity.}\]

The condition in this case comes from Lem. 1.7. Finite group homology and cohomology are finite groups, annihilated by $|G|$ [Br82, III. Cor. 10.2]. So the kernels of representation covers, and the quotients above, are bounded by invariants dependent only on $G$, giving a lower bound on the cardinality of braid orbits on $\mathfrak{Ni}(G, \mathbf{C})$ assuming (3.19).

Further reminder: We need the definition field of Hurwitz space components corresponding to braid orbits for all applications of this paper. That leaves these goals for given $G$ and $\mathbf{C}$.

\[(3.20a) \quad \text{When is there a } \mathbf{C} \text{ with support precisely in } \mathbf{\ast C} \text{ with just one braid orbit on } \mathfrak{Ni}(G, \mathbf{C}) \text{ with general lift invariant 1?}\]

\[(3.20b) \quad \text{Effectiveness 1: Assume (3.19) holds, components correspond to the general lift invariant, and we know their definition fields?}\]

\[(3.20c) \quad \text{Effectiveness 2: Same as (3.20b) except we are either effective on (3.19) or we may drop it altogether?}\]

#### 2.2.1. Examples with liftable conjugacy classes.

Theoretically, from the last paragraph of Prop. 1.8, all we need to finish Prop. 4.9 is the conclusion (3.20a) (for all $G$). That gives us a component of $\mathcal{H}(G, \mathbf{C})^{\text{in}}$ over $\mathbb{Q}$ from the component associated with a trivial (general) lift invariant. Our examples require knowing
Which elements of $\mathcal{C}$ are liftable. What is $V_G/SC_{\mathcal{C}}$?

The spin cover, $\psi: \text{Spin}_n \rightarrow O_n(\mathbb{R})$, $n \geq 3$, of the orthogonal group – the most famous central Frattini extension – arises in quantum mechanics to the hermitian observable: spins of electrons around atoms. Regard $\ker(\psi)$ as $\{\pm 1\}$. The natural permutation embedding of $A_n$ in $O_n$ induces

$$\psi: \text{Spin}_n \overset{\text{def}}{=} \hat{A}_n \rightarrow A_n,$$

abusing notation a little.

All this section’s examples, of $A_n$ and $S_n$, involve the spin cover. Ex. 1.10 has more perspective using the Universal Frattini cover of $A_n$.

Two conjugacy classes in $A_n$ stand out: $C_3$ of 3-cycles, and $C_{2^2}$ of products of two disjoint 2-cycles. Exs. 2.9 has the case where $\mathcal{C} = \{C_3\}$, a definitive answer in this case to Prob. 1.1, identifying all components by values of the restricted lift invariant. It also notes that if $\mathcal{C}$ contains $C_{2^2}$, then the general lift invariant (in $V_G/SC_{\mathcal{C}} = \{1\}$) must be trivial, even if $\mathcal{C}$ contains $C_{2^2}$ only once. Exs. 2.10 notes recent results for $A_n$, for low values of $n$, allowing $\mathcal{C}$ to be arbitrary.

**Example 2.9** ($A_n$ Examples 1). With the spin cover as above, [BFr02, Prop. 5.10] uses the Clifford algebra to conclude this. For $g \in C_{2^s}$ (products of $2s$ disjoint 2-cycles), any lift $\hat{g} \in \hat{A}_n$ of $g$ has order 4 if $s$ is odd and 2 if $s$ is even. If $s = 1$, then, there is an $h \in \hat{A}_n$ such that $h\hat{g}h^{-1}\hat{g}^{-1}$ is the nontrivial element in $\hat{A}_n$. This follows by direct computation in $A_4$ using the notation of $M(x, y, z)$ from (5.5):

$$M(1, 0, 0)M(0, 1, 0)M(1, 0, 0)^{-1}M(0, 1, 0)^{-1} = M(0, 0, 1).$$

Use $A_4 \leq A_n$ acting on $\{1, 2, 3, 4\}$ in $A_n$ to see this applies to $C_{2^2}$ in any $A_n$. Here’s what that means. Let $\mathcal{C} = C_3^{r_1}(2^2)^{\geq r_2}$ refer to the repetition of $r_1$ (resp. $r_2$) of $C_3$s (resp. $C_{2^2}$s) in $A_n$. For $r_2 \geq 1$, the general lift invariant (Def. 2) can only take the value 1 even under assumption (3.19).

If, however, $r_2 = 0$, then [Fr10, Main Thm.] shows the lift invariant is $(-1)^{n-1}$ starting with $-1$ at $n = 4$ for $r = n-1$ (covers of genus $g = 0$). It assumes both values for $r \geq n$ ($g > 0$), precisely distinguishing braid orbits (Hurwitz space components) of all components when $r_2 = 0$.

One hard point is that you can braid the outer automorphism (Rem. 3.9) from $S_n$. Thus, in $\mathcal{H}(A_n, C_3^{r})^{\text{in}} \rightarrow \mathcal{H}(A_n, C_3^{r})^{\text{abs}}$, for all $r \geq n-1$,

$$\text{(3.22)} \quad \text{each image component has only one preimage.} \ \triangle$$

Again, under assumption (3.19), (3.22) can be applied to all finite groups in Prop. 4.9, if $\mathcal{C}$ contains all classes of $G$. 
Alternating group examples distinguish between Hurwitz spaces of genus $g = 0$ and $g > 0$ covers (as in Ex.2.10). §2 compares this computation with new cases of a computable lift invariant.

**Example 2.10 (Aₙ Examples II).** Refer to $g \in Aₙ$ as pure-cycle if it has but one disjoint cycle of length exceeding 1. When that length, $l$ is odd, define $\omega(g) = \frac{(l-1)^2}{8}$. For a general odd order $g \in Aₙ$ define $\omega(g)$ as the sum over its disjoint cycle. There is a precise formula for the lift invariant in $\text{Ni}(Aₙ, C)$ – in $\pm 1$ – when $C$ consists of odd order classes, and $g = 0$ (absolute Hurwitz spaces) extending the case $C = C_{3n-1}$ in Ex. 2.9:

$$s_{Aₙ, C} = (-1)\sum \omega(g_i), \; g \in \text{Ni}(Aₙ, C)$$ [Se90a] or [Fr10, Cor. 2.3].

Def. 1.4 references a braid orbit, and a particular central Frattini cover. We assume the Spin cover. More significantly the result is independent of the braid orbit. Reference #2 in (3.23) inducts using only $C_{3n-1}$ modulo one case: Computing the lift invariant of $((1...k)^{-1}, (1 2 3), (1 4 5...k))$ for odd $k \geq 5$, where reference #1 uses the Clifford algebra.

[LO08] considered absolute Hurwitz spaces with covers in $\text{Ni}(G, C)^{\text{abs}}$ having genus 0, and pure-cycle classes: They conclude transitive braid action on Nielsen classes. That overlaps with part of the 1 braid orbit (Ex. 2.9) result for genus zero when $C = \{C₃\}$. [LO08, §5] suggests that all these Hurwitz spaces are without significant distinguishing properties.

[Fr09, §9], however, dispels that by considering the inner (rather than absolute) Hurwitz spaces. [Fr09, Prop. 5.15] uses the sh-incidence matrix to display cusps, elliptic fixed points, and genuses of the inner Hurwitz spaces in two infinite lists of [LO08] examples. In one there are two level 0 components (conjugate over a quadratic extension of $\mathbb{Q}$). For the other just one. These examples have seriously diverging behaviors in their associated Modular Towers, at their level 1 cusps.

Similarly, going beyond one conjugacy class, [JMS15] treated just $A₅$, but possible conjugacy class collections, $C$, in that group. After an initial step of listing the nonempty Nielsen classes – mostly from checking non-negative genus from Riemann-Hurwitz – they find in each case, the lift invariant determines the orbits. They concentrated on inner Nielsen classes, the harder case, and noted (as in Ex. 2.9, the lift invariant is trivial if $C_2$ is contained in the collection.

Respectively, Firkin and James, students of Shpectorov, did $G = A₄$ and $G = A₆$ for Nielsen classes of genus $g = 0$. For genus $g > 0$, but $C = \{C₃\}$, $A₆$ was a tough case in [Fr10] requiring special techniques.

**2.2.2. Examples with non-liftable classes.** In $Sₙ$ the standout class is $C₂$ of 2-cycles. Ex. 2.11, with $C = \{C₂\}$ reappears constantly in the literature, since its
contribution to Prob. 1.1 is so definitive: one Hurwitz space component, a generalization of the connectedness of the moduli of curves of genus \(g\). Alas, it is totally misleading about general expectations for complicated reasons.

Despite the extremely short proof ([Vo96, Lem. 10.15], repeated essentially from [BiFr86]), this finesses that there are nontrivial central Frattini extensions. That is, it is not obvious that \(V_{S_n}/SC_c = \{1\}\). So, it must be that the class of 2-cycles, \(C_2\) in \(S_n\) is unliftable in any nontrivial quotient of \(V_{S_n}\). Otherwise, as in Prop. 1.8, consider \(C_2^t\) denoting \(2^t\) repetitions of \(C_2\). Then, for \(t\) large, a central 2-Frattini extension of \(S_n\) with commutator kernel (of order 2) would give at least two braid orbits on \(N(S_n, C_2^t)\).

Prop. 4.9, (3.59a) has a general case when \(V_G/SC_c = \{1\}\), showing that every group has a finite cover, and corresponding rational classes, where this applies. Finally, Cor. 1.6 carries out, in more detail, a special case of Cor. 2.6, the start for the part of this paper that explains its title.

**Example 2.11 (Simple branching).** [Se92, p. 97–98] lists three separate copies of \(\mathbb{Z}/2\) that realize the inequivalent extensions given by \(H^2(S_n, \mathbb{Z}/2)\) (2nd cohomology with \(A = \mathbb{Z}/2\) in (3.17)), as kernels of central Frattini extensions. (Said differently.) This presentation was early in the topic of lift invariants. Its purpose there – close to the end of [Se92] was toward quadratic forms. I now show directly \(V_{S_n}/SC_c = \{1\}\) when \(SC_c = \{C_2\}\). Reason: either only single commutators appear (Def. 1.4), so \(C_2\) is unliftable, or the lift invariant is constant on the Nielsen class.

In writing \(H^2(S_n, \mathbb{Z}/2) = (\mathbb{Z}/2)^2\), there is a contribution from the Ext (left) side of (3.17), since \(S_n/[S_n, S_n] = \mathbb{Z}/2\). We have already shown we don’t have to deal with that for separating braid orbits. Still, this shows \((S_n, \{C_2\})\) gives a mixing of the two types of central Frattini extensions. The \(H_2(G, \mathbb{Z}/2)\) (right) side of (3.17) is another matter. Serre notes (from the [Atlas]) that this extension is related to that we used above by restriction. By accepting facts about \(A_n\), we can get that from just the case \(n = 4\), where we also see that \(C_2\) is not liftable.

Use the \(M(x, y, z)\) matrix notation in §3. Indeed, we only need that the small Heisenberg presentation for \(A_4 = (\mathbb{Z}/2)^2 \times \mathbb{Z}^3\) extends (as a central Frattini cover) to \(S_4 = (\mathbb{Z}/2)^2 \times S_3\). Our action of \(\mathbb{Z}/3\) on \(M(x, y, z)\) leaves \(z\) untouched, and it regards \((x, y)\) as the first two coordinates of \(\mathbb{Z}^3\), acting as a cycle \((x, y, t) \mapsto (t, x, y)\) by the 3-cycle \(\alpha\). Then, mod out by the subspace generated by \((1, 1, 1)\). Now extend the natural permutation representation from \(A_4\) to \(S_4\). In this extension, an element of \(C_2\) lifts to an element of order 2. This is an explicit description of the one case Serre doesn’t do (it is useful to solve his exercise [Se92, 2 c, p. 98]).

We show \(C_2\) is unliftable. Liftability means that, for \(g_1 \in C_2, \ |C_{g_1}| = C_{g_1}\) for \(g_1 \in \widehat{S}_n\) over \(g_1\). Take any \(g_2 \in C_2\) with support disjoint from that of \(g_1\). It, too, will
have a well defined lift, \( \hat{g}_2 \). Then, \( \hat{g}_1 \hat{g}_2 \) is a lift of \( g_1 g_2 \) to \( \hat{S}_n \). Consider, for \( \hat{h} \in \hat{A}_n \),
\[
\hat{h} \hat{g}_1 \hat{h}^{-1} \hat{g}_2 \hat{h}^{-1} \overset{\text{def}}{=} (\hat{g}_1 \hat{g}_2)^{\hat{h}}.
\]

Then, \( C_{22} \) would be liftable if, when \((\hat{g}_1 \hat{g}_2)^{\hat{h}} \) lies over \( \hat{g}_1 \hat{g}_2 \), then \( \hat{h} \hat{g}_1 \hat{h}^{-1} = \hat{g}_j \), for \( j = 1 \) or \( 2 \). Since this expression is true in \( S_n \) (without the \( \hat{\cdot} \)'s), and the elements with the \( \hat{\cdot} \)'s on them are uniquely defined, the result follows. Since the conjugacy class \( C_{22} \) is the same in \( A_n \) and in \( S_n \), this gives \( g_1 g_2 \) a unique lift in \( \hat{S}_n \), so certainly in \( \hat{A}_n \), contrary to Ex. 2.9.

\[\triangle\]

Assume \( G \) is a group for which we know the primes \( \ell || G_{ab} \) (for which \( G \) is not \( \ell \)-perfect). As previously, we may deal one \( \ell \) at a time for they recombine using the fiber product over \( G \). Therefore, we also fix \( \ell \). In case you haven’t guessed by now, the biggest mystery is what values of \( A \), an abelian \( \ell \)-group, are sufficient to pick up \( \ell \)-representation covers (Def. 1.10).

(3.24a) Since (3.17) is split, every \( \ell \) central Frattini cover of \( G \) has a canonical Comm (which may be trivial) cover attached to it.

(3.24b) For any Comm cover \( \psi : H \to G \), \( |\ker(\psi)| = \ell^u \) is maximal value when \( \psi \) is an \( \ell \)-representation cover.

(3.24c) As with the fundamental Frattini cover property (Lem. 1.15), the fiber product of any two central \( \ell \)-Frattini covers \( \psi_i : H_i \to G \), \( i = 1, 2 \), has a subcover \( \psi : H \to G \) that is (central) \( \ell \)-Frattini.

(3.24d) If \( \psi_1 \) (resp. \( \psi_2 \)) is an Ext (resp. Comm) cover in (3.24c), both nontrivial, then \( H \) is a proper subgroup of the fiber product.

We are not likely to have a priori knowledge of \( u \) in (3.24b). So, it makes sense to take \( A = \mathbb{Z}/\ell \), and deal with fiber products of the Ext and Comm covers associated with that choice in \( H^2(G, \mathbb{Z}/\ell) \), if warranted going to higher values of \( u \). Inside \( H^2(G, \mathbb{Z}/\ell) \) any extensions (covers) would have associated factor sets, and those have an abelian group structure – can be added, another way to combine them.

§2.3 reviews an effective computation of the 1st level of the universal \( \ell \)-Frattini cover of \( G \) in [Fr02, Prop. 2.8]. That can classify Schur quotients: central \( \ell \)-Frattini covers of \( \psi : H \to G \) with \( \mathbb{Z}/\ell \) kernels. [Fr02, §4] generalizes Serre’s example \((G = S_n, \ell = 2)\) alluded to in Ex. 2.11 by using what happens to the order of lifts of \( \ell \) order elements going from \( G \) to \( H \) to distinguish these Schur quotients.

2.3. Properties of \( \ell M_G \). Ch. 6 §1.4 shows how, in practice, properties (and proofs) in Prop. 2.18 work. It is a primer on Loewy displays, and how they tie irreducible representations together into (sometimes very) long chains. It also should dissuade anyone from thinking that production of characteristic \( \ell \)-Frattini covers of, say a simple group, follows from elementary principles.
The proof of Prop. 2.18 uses Prop. 1.29, when an \(\ell\)-Sylow of \(G\) is a normal \(\ell\)-Sylow of \(G\), to explicitly construct the characteristic module \(\ell M_G\) in all cases. To a modular representation theorist we haven’t described such modules unless we have written out the Loewy display of this indecomposable module completely, as described by, say, the Heller description Prop. 2.16. Our needs are often much less. Example: Rem. 1.2 notes our concern with the appearance of \(1_G\) in \(\ell M_G\).

Recall, \(\ell \tilde{F}_t\) is pro-free pro-\(\ell\) group of rank \(t\). Explicate means to give the module in terms of its Loewy decomposition into simple \(\mathbb{Z}/\ell[G]\) modules. Here we run into the big difference between irreducible (or simple \(\mathbb{Z}/\ell[G]\) modules – no proper submodules – and indecomposable modules – no proper direct summands. Those are the same when \(\ell \not| |G|\), a condition that never applies with \(\ell\)-Frattini covers and their characteristic modules.

2.3.1. Submodules of projective modules. A good part of homological algebra is built on the construction of submodules of projective modules. Within that, we must distinguish when a submodule of a projective is a direct summand.

**Lemma 2.12.** A direct summand, \(P^*\), of a project module \(P\) is projective. Consider a surjective map from a projective module \(\alpha_i : P_i \to M\), \(i = 1, 2\). Then:

\[
(3.25) \text{the fiber product } P_1 \times_M P_2 \text{ is isomorphic to } P_1 \oplus \ker(\alpha_2) \equiv P_2 \oplus \ker(\alpha_1).
\]

**Proof.** Consider the first sentence. Given \(\alpha P^* : P^* \to M\) and \(\beta : N \to M\) onto morphisms, extend \(P^*\) to \(\alpha P : P \to M\) just be mapping the complement to \(P^*\) to 0. Then use projectivity of \(P\) to construct \(\beta P : P \to N\) for which \(\beta \circ \beta P = \alpha P\). Form \(\beta P^* : P^* \to N\) by restricting \(\beta P\) to \(P^*\) to conclude \(P^*\) is projective.

Now consider the fiber product. Since \(P_1\) is projective, its projection to \(P_1\) splits. The kernel of that projection is \(\ker(\alpha_2)\). Combining that with the result of projection to \(P_2\), that proves (3.25). \(\Box\)

Any \(\mathbb{Z}/\ell[G]\) module \(M\) has a smallest projective cover \(P \to M\). That means, for no direct summand \(P^*\) of \(P\) does its map to \(M\) go to 0. This defines

\[
(3.26) 0 \to \Omega(M) \to P \to M \to 0.
\]

Benson [Be91] calls this Heller’s construction [He61]. Lem. 2.13 shows the uniqueness of \(\Omega(M)\). Inductively, for \(i \geq 1\), define \(\Omega^i(M) \overset{\text{def}}{=} \Omega(\Omega^{i-1}(M))\).

All modules are finitely generated \(\mathbb{Z}/\ell[G]\) modules. As already appeared in Prop. 2.3, \(\text{Ext}^{i}_G(M, N)\) and \(H^{i+1}(G, N)\), even when computing the latter is the main goal, often appear together. They do so in Prop. 2.16. This follows [Se88] and is based on [Fr95, Lem. 2.3], but with many more details.

We use this to describe \(\ell M_G \overset{\text{def}}{=} \ell M_{0.1}\), the characteristic \(\mathbb{Z}/\ell[G]\) module, (1.8). Ch. 6 §1.2 reminds of the following topics.
2. THE GENERAL LIFT INVARIANT

(3.27a) \( H^i(G, N) \) is just \( \text{Ext}^i(1, N) = \text{Ext}^i_G(1, N) \) [Nor62, p. 223, Thm. 4].

(3.27b) \( \text{Ext}^1(M, N) \) is equivalence classes of extensions of \( M \) by \( N \) [Nor62, p. 129].

(3.27c) Projective and injective \( \mathbb{Z}/\ell[G] \) modules are the same; a maximal simple quotient determines an indecomposable projective [Be91, p. 10, §1.6].

(3.27d) Resulting exact sequences of “cohomology” from applying \( \text{Ext}^* \) (or \( H^* \)) to a short exact sequence of modules in either slot (see (3.30)).

**Lemma 2.13.** Extension (3.26) canonically defines \( \alpha_M \in \text{Ext}^1(M, \Omega(M)) \), uniquely up to equivalence for extensions. Similarly, there is the operator \( \Omega^{-1}(M) \): the cokernel of the embedding of \( M \) in a minimal injective module. Here, \( P \) is a minimal injective module containing \( \Omega(M) \).

**Proof.** Suppose \( P' \) is another projective module with the same properties. Then, their projectivity gives maps \( \nu_{P', P} : P \to P' \) and \( \nu_{P, P'} : P' \to P \) each commuting with the surjective maps from \( P \) and \( P' \) to \( M \).

Define \( f = \nu_{P, P'} \circ \nu_{P', P} \) (acting on the left), and the composition of \( f, n \) times, by \( f^n \). Since \( K_n \overset{\text{def}}{=} \ker(f^n) \) is increasing with \( n \), it stabilizes for large \( n \).

For such an \( n \) \( f^n \overset{\text{def}}{=} F : P_n \overset{\text{def}}{=} \text{im}(f^n) \to P_n \) is an isomorphism. Thus,

\[ P = K_n \oplus P_n : \text{direct sum decomposition into kernel and image} \]

(as vector spaces, that happen to be \( G \) modules). As \( K_n \) – a projective summand of a projective module – goes to 0 under the map from \( P \) to \( M \), from the minimality of \( P \), it must be trivial. That proves \( f \) is an isomorphism defining \( \Omega(M) \) uniquely.

Now apply (3.27c) to conclude \( P \) above is both the minimal projective covering \( M \) and the minimal injective containing \( \Omega(M) \). \( \square \)

**2.3.2. Homological characterizations of \( \ell M_G \).** Lem. 2.15 gives a simply-stated characterization of a Frattini cover \( \psi : H \to G \) as an element \( \alpha_\psi \in H^2(G, \ker(\psi)) \). We put that to use in Prop. 2.16 based on the fundamental objects of modular representation theory, projective indecomposable \( \mathbb{Z}/\ell[G] \) modules.

**Definition 2.14.** An \( \alpha \in \text{Ext}^1(M, N) \) is supported on a submodule \( N' \subset N \) if \( \alpha \) is the image of some \( \alpha' \in \text{Ext}^1(M, N') \) from the natural map to \( \text{Ext}^1(M, N) \).\(^1\)

The word universal in (3.28c) means each \( \alpha \in H^2(G, N) \), not supported on a submodule of \( N \) is the image of \( \alpha_{\psi} \) from a homomorphism \( \ker(\ell \psi) \to N \).

\(^1\)The special case, for \( M = 1_G \): \( \alpha \in H^1(G, N) \): \( \alpha \) is supported by \( \mathbb{Z}/\ell[G] \) module \( N' \subset N \) if \( \alpha \) is the image of \( \alpha' \in H^1(G, N') \) (from inclusion).
LEMMA 2.15. As above, denote by $\alpha_\psi \in H^2(G, \ker(\psi))$ the equivalence class of the cover $\psi : H \to G$. Then $\psi$ is a Frattini cover if and only if $\alpha_\psi$ is not supported on a (proper) submodule, $N'$, of $\ker(\psi)$. This is equivalent to $\alpha_\psi$ does not go to 0 in $H^2(G, \ker(\psi)/N')$.

Here are three properties of the extension $\frac{1}{\ell}\psi : E = \frac{1}{\ell}G \to G$.

(3.28a) $\frac{1}{\ell}\psi$ is not supported on a submodule of $\ker(\frac{1}{\ell}\psi)$.

(3.28b) $\frac{1}{\ell}\psi$ is minimal among $\ell$-projective covers of $G$ with $\mathbb{Z}/\ell[G]$ kernel.

(3.28c) $(\ker(\frac{1}{\ell}\psi), \alpha_{1,\psi})$ is universal among pairs $(N, \alpha)$ with $\alpha \in H^2(G, N)$ not supported on a submodule of $N$.

PROOF. We will use the following principle. Given a $\mathbb{Z}/\ell[G]$ module homomorphism $\mu : N' \to N$, an extension $\psi' : E' \to G$ defined by $\alpha' \in H^2(G, N')$ naturally maps to the extension defined by the image, $\alpha$, of $\alpha'$ in $H^2(G, N)$. See this directly from the factor set $c_\psi'(g_1, g_2), g_1, g_2 \in G$ defined by $\alpha'$, Ch. 1 §1.2.2.

Recall: if $s' : G \to E'$ is a section, then with $s(g_i) = n'_i, i = 1, 2$,

$$s'(g_1)s'(g_2) = c_\psi'(g_1, g_2)s'(g_1g_2),$$

defines $c_\psi : G \times G \to N'$.

Regard $\psi'$ as giving a group structure on $N' \times G$ (with right action) by

$$\left( \begin{smallmatrix} g_1 & 0 \\ n'_1 & 1 \end{smallmatrix} \right) \left( \begin{smallmatrix} g_2 & 0 \\ n'_2 & 1 \end{smallmatrix} \right) = \left( \begin{smallmatrix} n'_1 g_2 & 0 \\ n'_1 n'_2 + c_\psi'(g_1, g_2) & 1 \end{smallmatrix} \right).$$

Then the image $\alpha$ is defined by the factor set $\mu(c_\psi'(g_1, g_2)) : G \times G \to N$. Substitute any $(n_1, n_2) \in N \times N$ into this formula to get $\psi : E \to G$, defined by $\alpha$, giving the homomorphism from $E' \to E$ commuting with the maps to $G$.

Suppose $\psi : H \to G$ is supported on a submodule $N' \subset N$, by $\alpha' \in H^2(G, N')$. Then, from the above, the image of the extension, $E'$, given by $\alpha'$ is a proper subgroup of $H$, that maps surjectively to $G$ by $\psi$. Thus, $\psi$ is not a Frattini cover.

Finally, consider the part of the exact sequence of cohomology in (3.27d) by applying $H^2(G, \cdot)$ to $0 \to N' \to N \to N/N' \to 0$. Then,

$$\alpha' \in H^2(G, N') \mapsto \alpha_\psi \in H^2(G, N) \mapsto 0 \in H^2(G, N/N').$$

That is, the cover $E'' \to G$ with kernel $N/N'$, from the image of $\alpha_\psi$, splits the cover $\psi$; again a contradiction to $\psi$ being a Frattini cover.

For (3.28b) use that $\tilde{\psi} : \frac{1}{\ell}G \to G$ is universal for covers of $G$ with profinite pro-$\ell$ kernel. Consider any cover $\psi_H : H \to G$ with $\mathbb{Z}/\ell[G]$ kernel. Then there is a cover $\mu : \tilde{\psi} \to \tilde{G}$ for which $\psi_H \circ \mu = \tilde{\psi}$, and $\mu$ factors through $\frac{1}{\ell}\psi : \frac{1}{\ell}G \to G$.

This shows $\frac{1}{\ell}\psi$ is projective for covers to $G$ with $\mathbb{Z}/\ell[G]$ kernel. To show it is minimal among such projective covers, assume $\psi_H$ is projective. Then, there is $\mu' : H \to \frac{1}{\ell}G$ that commutes with the maps to $G$. Again use that $\frac{1}{\ell}G$ is Frattini to conclude $\mu'$ is surjective. So, $\frac{1}{\ell}\psi$ is minimal in the sense of (3.28b).
The arguments above have already shown (3.28c) from the universality of $\frac{1}{\psi}$ when it is combined with the characterization of Frattini covers above. □

**Dimension shifting to comfort:** The proof of Prop. 2.16 uses dimension shifting to take advantage of computing Ext$^i(M, N)$ from a projective projective cover of $M$. We know from Lem. 2.15 that the universal $\mathbb{Z}/\ell[G]$ module $N$ having $\alpha \in \text{Ext}^2(1, N)$ not supported on a submodule $N' < N$ is $\ell M_G$.

We now generalize this property, for a given $\mathbb{Z}/\ell[G]$ module $M$, to find a universal pair $(\cdot, \alpha)$, $\alpha \in \text{Ext}^i(M, \cdot)$ when the module $N$ put in the place holder $\cdot$ is not supported on a submodule. Recall (3.26):

\begin{equation}
0 \to \Omega(M) \to P \to M \to 0 \text{ defines } \alpha_{M,1} \in \text{Ext}^1(M, \Omega(M)).
\end{equation}

(3.30) Dimension shift in the $M$ position: Ext$^i(M, N) = \text{Ext}^{i-1}(\Omega(M), N)$.

Prop. 2.16 uses both the contravariant $(M)$ slot of Ext$^\bullet(M, N)$ (here); then, in assiduously applying the definition of ‘not supported’ on a submodule, the covariant slot $(N)$. We very much need both slots when we end up at the same place in a particular value $E^2(M, N)$.

**Proposition 2.16.** Consider the pair $(\Omega^i(M), \alpha_{M,i})$, defined from dimension shifting in (3.30) from $(\Omega(M), \alpha_{M,1})$ for $i \geq 1$. It has these properties.

(3.31a) $\alpha_{M,i}$ is not supported on a submodule of $\Omega^i(M)$ $\Leftrightarrow$ it doesn’t go to 0 in a nontrivial quotient of $\Omega^i(M)$.

(3.31b) It is universal for elements of $\alpha \in \text{Ext}^i(M, N)$ with $\alpha$ not defined on a submodule of $N$.

In particular, identify $\ell M_G$ as $\Omega^2(1 G)$. It is an indecomposable module.

Iterate this to see it applies with $(G_k, M_{k,k+1})$ replacing $(G, \ell M_G)$, $k \geq 0$.

**Proof.** We do an induction first assuming (3.31) holds for $i = 1$:

$(\Omega(M), \alpha_{M,1})$ is not supported on a submodule, and universal.

For the induction step from $i-1$ to $i$, assume – for all $M$ – that $(\Omega^{i-1}(M), \alpha_{M,i-1})$ is universal for $\alpha \in \text{Ext}^{i-1}(M, N)$, for $\alpha$ not supported on a submodule of $N$.

**Not-supported on a submodule hypothesis:** Assume $(N, \alpha), \alpha \in \text{Ext}^i(M, N)$ is not supported on a submodule. Then, $\alpha' \in \text{Ext}^{i-1}(\Omega(M), N) = \text{Ext}^i(M, N)$, the image of $\alpha$, is also not supported on a submodule $N' < N$. Otherwise

$\alpha'' \in \text{Ext}^i(M, N') = \text{Ext}^{i-1}(\Omega(M), N')$

would have image $\alpha$ in Ext$^i(M, N)$, contrary to our assumption. By the induction hypothesis, $\alpha_{M,i-1} \in \text{Ext}^{i-1}(\Omega(M), \Omega^i(M))$ maps to $\alpha'$ from some homomorphism

\[\ldots \text{Ext}^{i-1}(P, N) \to \text{Ext}^{i-1}(\Omega(M), N) \to \text{Ext}^i(M, N) \to \text{Ext}^i(P, N) \ldots\]

is exact and $P$ is projective.
\[ \mu : \Omega^i(M) \rightarrow N. \] Everything pulls back to \( \operatorname{Ext}^i \), including the homomorphism effect of \( \mu \) on \( \operatorname{Ext}^i(M, \Omega^i(M)) \rightarrow \operatorname{Ext}^i(M, N) \).

Conclude the universal property for \( i \). The equivalence of the statements in (3.31a) is the exact \( \operatorname{Ext} \) analog of the cohomology observation in (3.29).

**Proof for the case** \( i = 1 \): For the initial induction step we show \( \alpha_{M,1} \):

(3.32a) \( \not\rightarrow 0 \) in \( \operatorname{Ext}^1(M, N) \) with \( N \) a nontrivial quotient of \( \Omega(M) \); and
(3.32b) it is universal for \( \alpha \in \operatorname{Ext}^1(M, N) \) for \( N \) unsupported on a submodule.

Suppose (3.32a) is false for \( N = \Omega^1(M)/O' \). Then, if \( O' \leq O'' < \Omega^1(M) \), from the analog argument of (3.29), conclude \( \alpha_{M,1} \not\rightarrow 0 \) in \( \operatorname{Ext}(M, \Omega^1(M)/O'') \).

Therefore, with no loss we may assume \( \Omega^1(M)/O'' \) is a nontrivial simple quotient of a direct summand \( P' \) of \( P \) in the definition of \( \Omega(M) \), and \( P \rightarrow B \) splits. That splitting contradicts that \( B \) uniquely determines \( P' \), (3.27c).

Finally, return to \( \alpha \in \operatorname{Ext}^1(M, N) \) not supported on a submodule of \( N \), with \( \alpha \) corresponding to the short exact sequence \( N \rightarrow W \rightarrow M \). Since \( P \) is projective, the morphism \( P \rightarrow M \) induces the short exact sequence \( \Omega(M) \rightarrow P \rightarrow W \) that gives a natural diagram:

\[
\begin{array}{ccc}
\Omega(M) & \rightarrow & P \\
\downarrow & & \downarrow \\
N & \rightarrow & W \\
\end{array}
\]

From [Nor62, p. 129], the exact sequence of cohomology on the covariant 2nd slot produces \( \operatorname{Ext}^1(M, \Omega(M)) \rightarrow \operatorname{Ext}^1(M, N) \). The element of \( \operatorname{Ext}^1(M, \Omega(M)) \) defining the upper row of (3.33) maps to the element of \( \operatorname{Ext}^1(M, N) \) defining the lower row of (3.33). This shows universality of the upper row extension.

**Indecomposability of \( \ell M_G \)**: Take \( M = 1_G \). In (3.28c), we have established that \( \alpha_{i,\ell} \in H^2(G, \ell M_G) \), the universal Frattini cover with \( \mathbb{Z}/\ell[G] \) kernel is the universal object for \( \operatorname{Ext}^2(1_G, N) = H^2(G, N) \), the formula given by (3.27a). Therefore the above shows \( \ell M_G = \Omega^2(1_G) \), We give two arguments for its indecomposability.

Here is a version of the argument in [Be91, p. 11, Exec. 1]. Up to a direct summand by a projective module, \( \Omega^{-1}(\Omega(M)) = M \). Assuming \( M \) has no projective summands, since the powers of \( \Omega \) are all additive operators, \( M \) is indecomposable if and only if \( \Omega^i(M) \) is. Now use that, from (3.26), the operators \( \Omega \) give objects minimal in the sense of having no additional projective summands. Therefore, since \( 1_G \) is indecomposable and \( \Omega^2(1_G) \) has no projective summands, it is too.

**Remark 2.17** (Significance of \( \ell M_G \) indecomposability). Knowing from Prop. 2.16 that \( \ell M_G \) is indecomposable allows displaying explicitly some of the territory that
2. THE GENERAL LIFT INVARIANT

has yet to be touched by the RIGP, and further, to bound and make connection to classical situations. In, however, considering its relation to the OIT, we do use \( \ell \)-Frattini extensions \( \psi : H \to G \) where \( \ker(\psi) \) is significantly decomposable. The standout example is where we go from a sequence of \( \ell \)-Frattini Nielsen classes \( \{ \text{Ni}(\ell^{k+1}G, C) \}_{k=0}^{\infty} \) to Jacobian Nielsen classes \( \{ \text{Ni}(\ell^{k+1}G_{\text{jac}}, C) \}_{k=0}^{\infty} \). This, for example, occurs in both Serre’s case Ch. 6 §3.3 and in our illustrating case Ch. 5 §4, wherein the \( \mathbb{Z}/\ell^k[G] \) modules in the kernel of \( \ell^{k+1}G_{\text{jac}} \to G \) are decomposable.

2.3.3. \( \ell \) and \( \ell' \) elements in \( \ell G \). There are several explicitness questions on the construction(s) in Prop. 2.16, should they be necessary to determine appropriate properties of \( \text{MT} \) levels. Use the notaton of Ch. 1 (1.7).

(3.34a) Can you seriously construct the modules \( \ell M_{k,k+1}(G) \), inductively?
(3.34b) Ditto for the groups \( \ell G \), at least to determine appropriate properties?

Ch. 6 Prop. 1.6 and Prop. 1.7 combined with §1.4 – to show it works – demonstrate a reasonably positive answer to both these questions. The context, though, of this book isn’t to push on in this direction without a guide from the arithmetic geometry questions about Hurwitz spaces.

That is, the problem we emphasize isn’t to classify the \( \ell \)-Frattini modules. Rather, where they arise for any pair \((G, \ell)\), especially for \( G \) that is \( \ell \)-perfect, they pose simply stated problems, interpreted on \( \text{MT} \) levels, that relate the RIGP and the OIT. These problems take advantage of the attention brought, and value adhering, to modular curves. Prop. 2.18 is the archetype of a problem that translates to group theory properties immediately applicable to \( \text{MT} \) levels.

**Proposition 2.18 (\( \ell \) pieces: Part 3).** The \( \ell' \) elements generate \( G \), if and only if, \( G \) is \( \ell \)-perfect. If \( G \) is centerless, and \( \ell \)-perfect, then so are \( \ell' G \), and \( \ell' G_{\text{ab}} \), for \( k \geq 0 \). Further, for \( g \in G \):

(3.35a) if \((\text{ord}(g), \ell) = 1\), then \( g \) has an \( \ell' \) lift all the way to \( \tilde{G} \);
(3.35b) if \((\text{ord}(g), \ell) = \ell \) and \( k g \in \ell' G \), \( (\text{or in } \ell' G_{\text{ab}}) \), \( k \geq 0 \), lies over \( g \), then \( \text{ord}(k g) = \ell^k \cdot \text{ord}(g) \)

**Proof.** [BFr02, Lem. 3.19] shows that the collection of \( \ell' \) elements generate \( G \) if and only if it is \( \ell \)-perfect. The argument is quite simple, for \( \ell' \) elements generate a normal subgroup of \( G \). Then, the quotient by that subgroup must be an \( \ell \)-group, that therefore has a \( \mathbb{Z}/\ell \) quotient. Further, if \( G \) has a \( \mathbb{Z}/\ell \) quotient, some lift of an order \( \ell \) element in it is necessary to generate \( G \).

[BFr02, Prop. 3.21] does the inductive argument that if \( 0 \ell G = G \) is centerless and \( \ell \)-perfect, then so is \( \ell' G \) for all \( k \). Assume, for our inductive hypothesis that \( \ell G \) is centerless and \( \ell \)-perfect. Suppose \( \alpha : \ell^{k+1}G \to \mathbb{Z}/\ell \) is a cover. Then, \( \ker(\alpha) \to \ell G \)
induced by the canonical map $\ell^{k+1}G \rightarrow \ell^kG$ – a Frattini cover – implies $\ker(\alpha)$, a proper subgroup of $\ell^{k+1}G$ is not onto $\ell^kG$.

Thus, $\ker(\alpha)$ has image an index $\ell$ normal subgroup of $\ell^kG$. That gives $\ell^kG$ a $\mathbb{Z}/\ell\mathbb{Z}$ quotient, contrary to our assumptions. Therefore $\ell^kG$ is $\ell$-perfect.

Now we show $\ell^{k+1}G$ has no center. Consider the simple module $111G = 111$. [Fr95, Lem. 5.6] characterizes that $\ell^{k+1}G$ is centerless if (and only if):

\begin{align*}
(3.36a) \quad & \ell^kG \text{ has no center; and with notation of (??),} \\
(3.36b) \quad & \ell M_{k,k+1} \text{ has no } \ell^kG \text{ subquotient of Loewy type } 111 \rightarrow 111.
\end{align*}

If a $G$ module has Loewy type $111 \rightarrow 111$ (distinct from $111 \oplus 111$), this gives a representation of $G$ of form $g \mapsto \begin{pmatrix} 1 & a_g \\ 0 & 1 \end{pmatrix}$. If such exists, then this gives a homomorphism, $G \mapsto \mathbb{Z}/\ell\mathbb{Z}$, from $g \in G \mapsto a_g$. Apply this to $\ell^kG$, which, from above, is $\ell$-perfect. So (3.36b) holds. This concludes the proof of the proposition’s first part.

From [Be91, Prop. 3.1.2], an irreducible module at the far right of the Loewy display of a principle indecomposable is also at the far left of the Loewy display. Thus $111$ can’t appear at the far left of the Loewy display of $P$ either. Prop 2.7, however, says $\Omega_2(1) = \ker n / \ker n + 1$ is some part on the left of the $P$ Loewy display. Thus $111$ is not a submodule of $\ker n / \ker n + 1$. Thus, the Center Hypothesis holds for $\hat{1}G$.

Assume $G$ [Fr95, Lem. 3.6] has the argument that if $\ell^kG = G_k$ is centerless, then so is $G_{k+1}$, and $\ker k / \ker k + 1$ has no subquotient of Loewy type $111 \rightarrow 111$. Inductively use that if $G_k$ is centerless, then the only way $G_{k+1}$ can have a center is if $111G_k$ appears at the far left of the Loewy display of $M_k$.

[FrK97, Rem. 2.5] Gives an example of a Frattini kernel that decomposes. Frattini covers $\psi_i : H_i \rightarrow G$, $i = 1, 2$ where the $H_i$s are simple nonisomorphic modules. Then the fiber product is still Frattini and has $\ker(\psi_1) \oplus \ker(\psi_2)$ as kernel.

Two series of simple groups agree when $n = 8$: $A8 ?= SL(4,Z/2)$. Let $M4$ be the standard 4 dimensional representation of $SL(4, Z/2)$. [Be] shows $H 2 (A8 , M4 )$ has dimension 1. This gives a Frattini extension of $A8$ not factoring through the universal central extension of $A8$. It is an example of the above.

This is in [Be] D. J. Benson, The Loewy structures for the projective indecomposable modules for $A8$ and $A9$ in characteristic 2, Comm. in Alg. 11 (1983), 13951451. [FrK97] says [Be2], the wrong reference.

Lem. 2.6 there is a one-one correspondence between simple $G$ modules and simple $\ell^kG$ modules. Also for $M$ simple, the principle indecomposable for $M$ as a $G$ module is a quotient of the principle indecomposable for $M$ as a $\ell^kG$ module. Therefore expression (2.10) shows how to construct $\ell^kG$ inductively as given in Prop. 2.7. Section II.E actually constructs $\hat{A}_5 1 2$ and this gives a posing of the questions about it, that are essentially answered in [BFr02].
3. MTS AND THE RIGP

We need to compare $\tilde{P} \times sN_P/P$ with $\psi^{-1}(N_P)$ and $\tilde{\psi}: \tilde{G} \to G$, and to see that indecomposable for $\ell M_G$, determines it as a component of the induced from $\ell M_N$. Then, for any $C$ that are $\ell'$ classes (assume generating) then the inner Hurwitz spaces are all fine moduli. Part of it appeals to Fr95, Lem. 3.6]: $G_{k+1}$ is centerless if $G_k$ has no center, and $\ker_k/\ker_{k+1}$ has no subquotient of Loewy type $1 \to 1$. That module is distinct from $1 \oplus 1$ and it comes from a nontrivial representation of $G_k$ of form $g \mapsto \left( \begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array} \right)$ giving the map By hypothesis this doesn’t exist. (see the rest)

RETURNM

2.4. Lift invariant effect on Definition fields. Given $\text{Ni}(G, C)^{in}$ we compare the definition fields of the components of Hurwitz spaces with those of $\text{Ni}(\hat{G}, C)^{in}$ with $\hat{G} \to G$ a central Frattini cover from the Comm side, as in Prop. 2.6. RETURNM

PROPOSITION 2.19.

3. MTS and the RIGP

Most groups are neither simple nor solvable. For example, starting with any one (finite) $G$, $\ell$-perfect and centerless, we can canonically create infinitely many $\ell$-perfect and centerless covers of it.

All those covers give opportunities to relate the RIGP and the OIT that enhance classical results, while simultaneously posing novel problems with good prospects for technical progress.

§3.1 explains this, starting with an elementary RIGP success, followed by a listing of progress barriers. Modulo being $\ell$-perfect and centerless, no $G$ escapes being entwined with some of the most honored classical unsolved problems we know. §3.3 explains the main conjectures, and puts them in a context with classical diophantine conjectures.

We use the extension (3.37) to formulate a context for what is seriously unknown about the RIGP. That moves us away from questions that are without structure, say, about what isn’t known about realizing simple groups, even in §3.4 where explicit Nielsen classes is the theme.

3.1. RIGP unknowns. From Ch. 1 (1.10), there is $\nu(G, \ell) > 0$ and

(3.37) an extension $1 \to (\mathbb{Z}_\ell)^{\nu(G, \ell)} \to \ell \hat{G}_{ab} \xrightarrow{\ell \tilde{\psi}_{ab}} G \to 1$,

universal for covers of $G$ with abelian $\ell$-group kernel. Further, $\nu(G, \ell) > 1$, unless $G$ has a rank 1 normal $\ell$-Sylow (Rem. 3.10).
Consider a centerless group $G$, a prime $\ell$ for which $G$ is $\ell$-perfect, and a rational union (Def. 1.4) of distinct $\ell'$ (generating) conjugacy classes $\mathcal{C}$. There has as yet arisen no obstruction to the following conjecture

**Conjecture 3.1.** For infinitely many $\mathcal{C}$ supported in $\mathcal{C}$ – they must be rational unions of classes from the BCL, Lem. 4.1 – $H(G, \mathcal{C}) \neq \emptyset$.

Generally, with $K$ a number field containing $\mathbb{Q}_{G,\mathcal{C}}$ (from the BCL), the conclusion would replace $\mathbb{Q}$ in $H(G, \mathcal{C}) \neq \emptyset$ by $K$.

**Definition 3.2.** From Cor. 4.7, the conclusion of Conj. 3.1 is phrased as $G$ has infinitely many regular realizations supported in $\mathcal{C}$ over $\mathbb{Q}_{G,\mathcal{C}}$.

Now consider the sequence of groups in (1.10):

\[
\ell \tilde{G}_{ab}/\ell^k V_{G,\ell} \overset{\text{def}}{=} k \tilde{G}_{ab} \to G, k \geq 0.
\]

Since $\mathcal{C}$ are $\ell'$ classes, Schur-Zassenhaus lifts these uniquely to $\ell \tilde{G}_{ab}$.

This makes sense of $\ell \mathbb{H}(G, \mathcal{C})^{\text{in,rd}} \overset{\text{def}}{=} \{H(k \tilde{G}_{ab}, \mathcal{C})^{\text{in,rd}}\}_{k=0}^\infty$, a projective sequence of Hurwitz spaces. The maps between the corresponding Nielsen classes induce the Hurwitz space maps.

**Definition 3.3.** A M(odular)T(ower) is a projective sequence of (absolutely irreducible) components $H' \overset{\text{def}}{=} \{H'_k\}_{k=0}^\infty$ on $\ell \mathbb{H}(G, \mathcal{C})^{\text{in,rd}}$.

Actually, that is an abelianized MT. We occasionally adjust this to consider the MT construction under these adjustments:

- (3.39a) replacing $k \tilde{G}_{ab}$ by $k \tilde{G}$, a full MT; or
- (3.39b) replacing inner classes by absolute classes, when appropriate, as under the $\ell'$ condition on $H \leq G$ in Prop. 1.28; or
- (3.39c) dropping the extra equivalence of rd, and just considering inner or absolute MTs; or
- (3.39d) dropping the $\ell$-perfect condition on $G$ in a special way.

Statements (3.40) combine Conj. 3.1 and the collection (3.38), toward question (3.40) about $(G, \mathcal{C})$. Use $r_{\mathcal{C}}$ as the number of classes in $\mathcal{C}$.

- (3.40a) As a function of $k$, where might you find $C_k$ supported in $\mathcal{C}$ with $H(k \tilde{G}_{ab}, C_k)^{\text{in,rd}}(\mathbb{Q}) \neq \emptyset, k \geq 0$?
- (3.40b) In (3.40a) is it possible that there might be an $r_0$ for which a positive conclusion holds with $r_{\mathcal{C}} < r_0$ for all $k$.

It seems easier to solve the RIGP for the collection (3.38) if the only restriction on $\mathcal{C}$ is that it be $\ell'$. Even easier if we drop reference to $C_k$ being, as in (3.40a), supported in $\mathcal{C}$.
Implications of (3.40): Prop. 3.4 shows – with the \( r_0 \) constraint of (3.40b), but without reference to \( C \) – a single MT will have RIGP solutions land on each of its levels.

Again, \( G \) is centerless and \( \ell \)-perfect, and \( K \) is a number field. We use the following with \( G_k \) either \( G_k \) or \( \overline{G}_{ab} \), and \( K \) any Nielsen class equivalence.

\[
\text{(3.41) } \text{Going Down: If } \mathcal{H}(G_k, C_k) \neq \emptyset, \text{ then the same is true of } \mathcal{H}(G_{k'}, C_{k'}) \text{ with } k' \leq k \text{ and } \mathcal{C}_{k'} \text{ the image classes in } G_{k'}.
\]

In the proofs of Prop. 3.4 and its corollaries \( \hat{p}_k \) denotes a point of \( \mathcal{H}_k(K), k \geq 0. \)

Proposition 3.4. Consider whether there can be any bound, \( r_0 \), for which each \( \overline{G}_{ab} \) has a \( K \) regular realization with no more than \( r_0 \) branch points.

If so, then there exists \( C \), \( \ell' \) classes of \( G \) \( (r_0 \leq r_0) \), and a MT

\[
\text{(3.42) } \mathbb{H}^0 = \{ \mathcal{H}_k^{\infty} \subset \ell \mathcal{H}(G, C)_{\text{in,rd}} \text{ for which } \mathcal{H}_k^{\infty} \neq \emptyset, k \geq 0. \}
\]

Proof. There are only finitely many Nielsen classes \( \Ni(G, C) \) with \( r_0 \leq r_0. \)

The RIGP realization assumption implies there are infinitely many pairs \( (\overline{G}_{ab}, C_k) \) for which: \( \mathcal{H}(\overline{G}_{ab}, C_k) \neq \emptyset, r_0 \leq r_0, \) and a component \( \mathcal{H}_k \) of \( \mathcal{H} \) with a \( K \) point, also defined over \( K \) (the comments (2.52) and (2.53)). There are two possible cases:

\[
\text{(3.43) } S_{\ell'}: \text{Infinitely many } C_k \text{ consist of } \ell' \text{ classes; or } S_{\ell}: \text{Not } S_{\ell'}.
\]

First assume \( S_{\ell'} \), and restrict consideration to just those cases where \( C_k \) is \( \ell' \). Then (from Schur-Zassenhaus as previously), we may assume \( C_k \) is the canonical lift of some \( C'_k \) collection of \( \ell' \) classes in \( G \). There are only finitely many such. Without loss, there exists infinitely many \( \ell' \) collections \( C_k, k \in I \), all lying over the same \( C' \) collection of classes in \( G \).

So, \( \{ \mathcal{H}_{k'} \}_{k \in I} \) is a cofinal collection of \( K \) components of \( \{ \mathcal{H}(G_k, C'_k) \}_{k=0}^{\infty} \) containing \( K \) points. Apply (3.41) to replace \( k \in I \) by \( k \geq 0 \). Such components form a system, finite but nonempty at each level. By the Tychonov Theorem, that implies there is a projective system of such components.

That gives an inner MT. To get a MT of reduced spaces, just apply reduced equivalence, whereby \( K \) components and points are mapped (resp.) to \( K \) components and points. To complete the proof of (3.42), we have only to show that \( S_{\ell} \) is not possible. The original argument is [FrK97, Lem. 4.1 combined with Thm. 4.4].

We give a variant on this.

Whatever are the realizations of \( \overline{G}_{ab} \), as a function of \( k \), there must be infinitely many that accumulate over a particular Nielsen class \( \Ni(G, C) \) using (3.41).

Each such realization, say of \( \overline{G}_{ab} \), for which, compatible with previous notation, we use the symbol \( \hat{p}_k \) – lies on a Hurwitz space component of a Nielsen class \( \Ni(\overline{G}_{ab}, C_{\hat{p}_k}) \) with at most \( r_0 \) classes in \( C_{\hat{p}_k} \).
We are assuming $S_{p'}$ doesn’t hold. So, again conclude from (3.41), with no loss, there is a $k_0$ with none of $C_{p_k'}$ or its images in $\ell^r G_{ab}$ being $\ell'$ for $k \geq k' \geq k_0$. Again applying the Tychonov Theorem, we find a projective sequence of conjugacy classes, $\{C_k' \defeq C_{p_k'} \}_{k=k_0}^\infty$, with these properties:

(3.44a) one of the $C_k'$, say, $C_k'$ has elements of order divisible by $\ell$;

(3.44b) giving a projective sequence of $g = \{g_k' \in C_k' \}_{k=k_0}^\infty$ with $\ell | \text{ord}(g_k)$.

The proof of the proposition will follow if we show (3.45b).

(3.45a) For $k \geq k_0$, $\text{ord}(g_{k+1}') = \ell \cdot \text{ord}(g_k')$.

(3.45b) The definition field of a component containing $\hat{p}_k$ grows with $k$.

Apply (3.35b) to conclude (3.45a). Now we use that by applying the BCL Cor. 4.7 to show (3.45b). A cover, $\hat{p}_k \in \text{Ni}(k \mathbb{G}, C_k)$, to be defined over $K$ requires $K \geq \mathbb{Q} \mathbb{G},C_k$. So, $[\mathbb{Q} \mathbb{G},C_k : \mathbb{Q}] \leq [K : \mathbb{Q}]$. Also, $C_k^m = C_k$ if and only if $m \in (\mathbb{Z}/N_{C_k})^*$. (3.46a) one of the $C_k''$ requires on $\mathbb{Q} \mathbb{G},C_k$.

Yet, elements $g_k' \in C_k'$ have order $\text{ord}(g_k') \cdot \ell^{k-k_0}$. Since $\ker(\ell^r G_{ab} \to G)$ is abelian, the number of conjugates of $g_k'$ cannot exceed those of its image, $g_0'$, in $G_0$, RETURNM

Therefore, the number of distinct classes among the powers of $(g_k')^m$ with $m$ running over a finite set of cosets grows with $k$, eventually exceeding the bound $r_0$ on the total allowable conjugacy classes in $C_k$. This concludes the proof of (3.45b), and thereby the proposition. \hfill $\square$

**Corollary 3.5.** Continue the notation of Prop. 3.4 and consider the MT \{H_k'\}_{k=0}^\infty produced there.

(3.46a) There is no projective system \{\hat{H}_k\}_{k=0}^\infty of $K$ points on \{H_k'\}_{k=0}^\infty.

(3.46b) Further, there can be no $k_0$ for which $|H_k'(K)| < \infty$.

In particular, if $r_C \leq 4$, high levels of $\mathfrak{H}(G,C)^{\text{in,rd}}$ have no $K$ points.

§3.2 starts with two, simply-stated, classically motivated, examples that show what Prop. 3.4 is about. More than that, we find essentially every $\ell$-perfect finite group has a version of this.

In the proof of Prop. 3.4, we considered one prime $\ell$ for which $G$ is $\ell$-perfect, and found if we had a prayer to bound number of branch points of the collection of extensions, then eventually we could deal with one $\ell'$ collection of classes $C$ for all $k$, and the corresponding $\mathbb{Q}$ points would fall on the levels of one MT for $(G,C)$. Immediately that raises a bunch of issues.

**Remark 3.6** (Two primes $\ell_1, \ell_2$). Suppose $G$ is $\ell_i$-perfect, $i = 1, 2$. Then, the version of Prop. 3.4 for both primes would ask how to simultaneously locate one such $C$ with which we could find $k_1 G \times G_k \ell_2 G$, for all $(k_1, k_2)$. RETURNM
Remark 3.7 (Bounded def. fields on MTs). Let $K$ be a number field. For a (n abelianized) MT to have $K$ points at all levels, there must be a uniform bound on the definition fields of all levels of the MT $\mathbb{H}'$. We know how to find a cyclotomic field that includes the definition field of all levels of $\mathfrak{h}(G, \mathbb{C})^{\text{in.rd}}$. The problem is we need a MT whose (absolutely irreducible) component levels have a number field definition bound. Yet, as we see clearly later, many MTs have no such bounding definition field. So, it is valuable to know that for a given $(G, \ell)$ we can explicitly find many $(G, C, \ell)$ for which there are such MTs.

3.2. Context for Prop. 3.4. Conj. 3.8, the Main MT conjecture says (3.42) is impossible. Subex.: Even for $G = A_5$, where $\nu(G, 2) = 5$, for no $k > 0$ has $2\widehat{A}_{5,ab}/2^k\ker(\ell \widehat{\psi}_{ab}) = \frac{k}{2}A_{5,ab}$ been realized (regularly or not) over $\mathbb{Q}$.

Assume $r$ conjugacy classes, $C$ of $G$; all containing elements of order $\ell'$. Also, do the dihedral group example, and turn back to the previously dihedral examples to figure out what you want to say about the characteristic $\ell$-Frattini you care about.

3.2.1. The Main Conjecture.

Conjecture 3.8. High MT tower levels have general type and no $\mathbb{Q}$ points. A special case (joint with Pierre Debes) is $G = D_\ell$, $\ell$ an odd prime. That interprets as existence of $\ell^{k+1}$ cyclotomic points for each $k$, on hyperelliptic jacobians of a fixed dimension $d$ (independent of $k$, but the Jacobian may change with $k$).

Thm: [Outlined in [Fr06]] The Main Conjecture is true for $r = 4$, based on the genus formula and methods for distinguishing different types of cusps. It suffices to show the genus rises with the MT levels.

[CaTa09] proved the disappearance of rational points at high levels, without engaging the reduced Hurwitz spaces or their cusps. [CaD09] showed the Torsion Conjecture on abelian varieties $\implies$ $\mathbb{Q}$ statement of the Main Conjecture in general.

We state Lem. 3.9 with the universal Frattini covers of $G$ and $H$, but the same results hold by replacing them by their abelianized versions (for example, $\ell G$ by $\ell G_{ab}$, and $\ell H$ by $\ell H_{ab}$). Let $P_\ell$ be an $\ell$-Sylow of $G$, and $M_{0,1}(G) = M(G)$ the characteristic $\ell$-Frattini module.

Lemma 3.9. For $H \leq G$, $\ell \widehat{H}$ embeds in $\ell \widehat{G}$. Further, for each $k \geq 0$, $\ell \frac{k}{\ell} H$ naturally embeds in $\ell \frac{k}{\ell} G$. If $\text{rk}(M_{1,0}(W)) = \text{rk}(M_{1,0}(G))$, then $\ell \widehat{W}$ appears from the universal $\ell$-Frattini cover $\widehat{\phi} : \ell \widehat{G} \to G$ as $\widehat{\phi}^{-1}(W)$.

For $H = N_G(P_\ell)$ this applies if $\text{rk}(P_\ell) = \text{rk}(M(G))$.

Proof. The Sylow Theorems say an $\ell$-Sylow of $\ell \widehat{G}$ contains an $\ell$-Sylow of $\widehat{\phi}^{-1}(W)$. So, the latter is profree, which is now a closed subgroup of a profree
group of finite index, so profree. Prop. 1.29 characterizes \( \hat{\ell}W \) as the minimal cover of \( W \) with pro-free \( \ell \)-Sylow.

That implies there is a natural map \( \gamma_W : \hat{\varphi}^{-1}(W) \to \hat{\ell}W \) commuting with the map to \( W \). As \( \hat{\ell}W \) is an \( \ell \)-Frattini cover of \( W \), the map must be surjective. Since the natural map \( \hat{\varphi}^{-1}(W) \to W \) has a pro-\( \ell \) group as kernel, the natural map \( \hat{\ell}W \to W \) produces \( \psi_W : \hat{\ell}W \to \hat{\varphi}^{-1}(W) \) commuting with the projections to \( W \).

The composition \( \gamma_W \circ \psi_W \) (commuting with the projections to \( W \)) is an endomorphism of \( \hat{\ell}W \). The image of \( \gamma_W \circ \psi_W \) is a closed subgroup of \( \hat{\ell}W \) mapping surjectively to \( W \). Again, from the Frattini property, \( \gamma_W \circ \psi_W \) is onto. An onto endomorphism of finitely generated profinite groups is an isomorphism [FrJ86, Prop. 15.3]. In particular, \( \psi_W \) is an injection.

The characteristic quotients have maps between them induced by \( \psi_W \), and \( W_k \) injects into \( G_k \), inducing an injection of

\[
\ker_k(W)/\ker_{k+1}(W) \to \ker_k(G)/\ker_{k+1}(G).
\]

If \( k = 0 \), \( M(W) \) and \( M(G) \) have the same dimension, they are isomorphic. These groups characterize \( \ker_0(W) \) and \( \ker_0(G) \). That implies they are equal, giving an isomorphism of \( \ker_0(H) \) and \( \ker_0(G) \) in the special case.

Let \( O_{\ell'}(G) \) be the maximal \( \ell' \) normal subgroup of any finite group \( G \). Prop. 3.10, uses the following designations: an \( \ell \)-Sylow of \( G \) is \( P_{\ell} \); its universal \( \ell \)-Frattini is \( \hat{P}_{\ell} \); and the rank of either is \( \text{rk}_\ell \) defined \( \text{rk}_{G,\ell} \). It characterizes when the characteristic \( \ell \)-Frattini module of \( G \) has rank 1; at its core it is a rather clear generalization of our beginning case, where \( G = \mathbb{Z}/\ell^{k+1} \times s\mathbb{Z}/2 \).

Assume, as often, that \( G \) is \( \ell \)-perfect, but see Rem. 3.12.

**Proposition 3.10** (\( \nu(G, \ell) = 1 \)). Schreier’s formula (1.5b) implies the rank of \( \ker(\hat{P}_{\ell} \to P_{\ell}) \) is \( 1 + |P_{\ell}|\|\text{rk}_{\ell}-1\| \).

If \( P_{\ell} \) is normal then, this is the correct rank of \( \ker(\hat{\ell}G \to G) \) (Prop. 1.29), and therefore of \( \ker(\hat{\ell}G_{ab} \to G) \), say, from Lem. 3.9. That leaves \( \text{rk}_{\ell} = 1 \) (cyclic \( \ell \)-Sylow) as the only possibility that \( \nu(G, \ell) = 1 \). Then, \( \nu(G, \ell) = 1 \) if and only if:

\[ P_{\ell} = \mathbb{Z}/\ell^{t} \text{ is normal; and } G/O_{\ell'}(G) \leq \mathbb{Z}/\ell^{t} \times s(\mathbb{Z}/\ell)^{s}. \]

In analogy to \( O_{\ell'}(G) \), denote the maximal normal \( \ell \)-subgroup of \( G \) by \( O_{\ell}(G) \). That is, \( O_{\ell}(G/O_{\ell'}(G)) \) defined \( G \) mod \( \ell' \text{, mod } \ell \) is the result of first modding out \( G \) by a maximal normal \( \ell' \) part, followed by modding out by the maximal normal \( \ell \) part.

**Definition 3.11.** We say \( G \) is \( \ell \)-supersolvable if \( G \) mod \( \ell' \text{, mod } \ell \) is abelian of exponent dividing \( \ell-1 \).

---

\( ^3 \)G is supersolvable if a chain of subgroups

\[ G = G_u > G_1 > \cdots > G_1 > 1 = G_0 \text{ has } G_i \text{ normal in } G \]

with \( [G_{i+1} : G_i] \) prime, \( 0 \leq i \leq u-1 \) [Is94, p. 102].
Remark 3.12 (Continue Prop. 3.10). Without assuming $G$ is $\ell$-perfect, [GS78] characterizes $\nu(G, \ell) = 1$. Then, $G$ is $\ell$-supersolvable with a cyclic $\ell$-Sylow. We used that the $\ell$-Frattini extension captures the characteristic module, when it need not contend with the Ext side of the Universal Coefficient Theorem, Def. 2.5.

Remark 3.13. Cyclic $\ell$-Sylow itself is far from giving $\dim(M_{0,1}) = 1$. For example, $A_5$ has a cyclic 5-Sylow, though, $5M_{0,1}(A_5)$ has dimension 6 (Ch. 6 §1.4 or [Fr95, Prop. 2.4]). Its Loewy display has one copy of the adjoint representation of $\text{PSL}_2(\mathbb{Z}/5) = A_5$ on top of another. Each $A_n, n \geq 5$, has a cyclic $\ell$-Sylow (say, $\ell > n/2$) with $\nu(G, \ell) > 1$.

Remark 3.14 (Addendum to Dihedral Ex. Ch. 2 §3.2). We excluded, for the moment, $\ell = 2$ in considering $\ell M_G$ with $G = D_{\ell k + 1}$. In, however, Ex. ??,

3.3. Including both $G$ and $C$ in the RIGP. Much of the RIGP treatment in [FrJ86] is dedicated to showing how far elementary considerations about groups can extend. Here we show when elementary group assumptions affront unsolved problems in classical arithmetic situations.

Here is a natural generalization of our running dihedral group example:

(3.48) Assume $G$ has an $\ell$-Sylow, $P_\ell$, that is abelian and normal.

In (3.48), denote the rank of $P_\ell$ by $\nu(\ell), \tilde{\psi}_{\ell,\text{ab}} : \tilde{P}_{\ell,\text{ab}} = (\mathbb{Z}_\ell)_{\nu(\ell)} \to P_\ell$ the universal free-abelian $\ell$-extension of $P_\ell$ (as in Cor. 2.4), and $G/P_\ell$ by $H$. We will use comments on the $\ell$ contribution to RIGP realization of $\tilde{\hat{G}}_{\text{ab}}$ from the Prop. 3.15 proof.

Proposition 3.15. The $G$ action on $P_\ell$ extends to $\tilde{P}_\ell$, inducing an $H$ action on $\tilde{P}_{\ell,\text{ab}}$ extending that on $P_\ell$.

If $G/P_\ell$ has a regular realization over an Hilbertian field $K$, then so does each of the quotient groups $\tilde{P}_{\ell/\ell^{k+1}} \ker(\tilde{\psi}_{\ell,\text{ab}}) \times^s H, k \geq 0$.

Proof. From Prop. 1.29, the $H$ action on $P_\ell$ extends to $\tilde{\hat{G}}$. That action preserves $[P_\ell, P_\ell]$, giving the 1st paragraph. It also preserves $\ell^{k+1}\tilde{\psi}_{\ell,\text{ab}}$ giving an $H$ action on the quotient by that group. Suppose we have a regular realization of $G$ over an Hilbertian field $K$, where $G$ acts on a finite abelian group $A$.

[FrJ86, Prop. 16.4.4]2, mostly due to [Ik], has this phrasing.

(3.49) Then the regular realization of $G$ extends to a regular realization of $A \times^s G$.

The wreath product $A/ H = A[H] \times^s H$ explains this. Write the wreath product by listing elements in $H$ as $(h_1, \ldots, h_n)$. Write elements of $A/H$ as $\left( \begin{array}{c} h \\ 0 \end{array} \right) \left( \begin{array}{c} \alpha_{h_1} \ldots \alpha_{h_n} \end{array} \right)$ with $h \ast (a_{h_1} \ldots, a_{h_n})$ as having its $hh_i$ entry equal to $(a_{h_i})$.

\[ \text{4The wreath product works as well with the cosets of } H_1 \leq H \text{ labeling the copies of } A \text{ to give } A[H/H_1] \times^s H. \text{ In some situations a right action of } H \text{ on } A \text{ is warranted to account for using cosets, as in } \S 1.2. \]
So far we haven’t used the $H$ action on $A$, which to here could be any group. Still, when $A$ is abelian, $A \times^* H$ appears as a quotient of $A \wr H$:

\[(3.50) \quad \left( \begin{array}{cc} h & a \\ 0 & 1 \end{array} \right) \xrightarrow{\alpha} \left( \begin{array}{cc} h & \prod_i h_{h_i}^{-1}(a_{h_i}) \\ 0 & 1 \end{array} \right)\]

with the right side making sense because $A$ is abelian. Direct computation that this is a homomorphism comes down to showing that $\alpha(h * a) = h * \alpha(a)$. With $a' = h * a$, substitute $h'_{hi}$ for $hh_i$ in

\[\prod_i h_{h_i}^{-1}(a_{h_i}) \mapsto \prod_i h((h'_{hi})^{-1}(a_{h_i})) = h * \alpha(a).\]

Use the principle that a quotient of a regular realization over $K$ is also a regular realization to conclude the whole proposition by applying $\alpha$ to a regular realization of $A \wr H$. For this there are two steps:

- (3.51a) There is a regular realization of $A$ over $K$ \cite[Prop. 16,3,5]{FrJ86}.
- (3.51b) Combine regular realizations of $H$ and $A \mid H$ to give one of $A \wr G$.

Comments on (3.51): (3.51a) follows, by the elementary divisor theorem, from the case where $A$ is cyclic. In characteristic 0, deduce this easily from finding that regular extension over $K((t))$ (the Laurent series field).

The argument for (3.51b) is essentially a field crossing argument in \cite[Lem. 13.8.1]{FrJ86}, whereby independent variables $\{t_1, \ldots, t_n\}$ for a regular realization for each copy of $A$ in $A \mid H$ are entwined with a basis $\{c_1, \ldots, c_n\}$ for an extension $L/K$ with group $G$ in the form of a system of linear equations $S = \{\sum_{i=1}^n c_i t_i \mid \sigma \in G(L/K)\}$.

Then, combine $M/K(u)$ and $L(S)/K(t_1, \ldots, t_n)$ into the extension $M \cdot L(S)/K(u, t_1, \ldots, t_n)$ with its group $G \times G$ and take the fixed field of the diagonal action of $G$ to RE-RETURNM p. 259 FrJ.

\[\square\]

If, as above, $P_\ell$ is not normal in $G$, say when $G$ is simple, then for no $k > 0$ has any $\ell^k G$ been regularly realized ($A_5$, and $\ell = 2$, worthy on its own).

The \textbf{R(egular)}\textbf{|I(nverse)}\textbf{G(alois)}\textbf{P(roblem)}

and \textbf{M(odular)} \textbf{T(ower)s} \textbf{RETURNM}

- (3.52a) Frattini cover: $\psi : H \to G$; if $H^* \leq H$ and $\psi(H^*) = G \implies H^* = H$.
- $\ell$-perfect: $\ell || G|$, but $G$ has no $\mathbb{Z}/\ell$ quotient.

(3.52b) Problem: Most groups are not like simple or solvable.

(3.52c) Example: Take $G$, $\ell$-perfect and centerless: $\exists \nu(G, \ell) > 0$ ($> 1$, outside supersolvable) and an extension

\[1 \to (\mathbb{Z}_\ell)^{\nu(G, \ell)} \to \hat{G}_{ab} \xrightarrow{\hat{\psi}_{ab}} G \to 1 : 8\]

\(\hat{G}_{ab}\) universal for $\ell$-Frattini covers of $G$ with abelian kernel.
3. MTS AND THE RIGP

(3.52d) Subex.: Even for $G = A_5$, and where $v(G, 2) = 5$, for no $k > 0$ has $2 \tilde{A}_{5,ab}/2^k \ker(\rho_{ab}) = \frac{k}{2} A_5$ been realized over $\mathbb{Q}$.\(^9\)

Which is more important/serious/...:

Cases similar to $(G, \ell) = (D_\ell, \ell = \ell)$ or to $(A_5, \ell = 2)$.

MT definition

(3.53a) Assume $r$ conjugacy classes, $C$ of $G$; elements of order $\ell'$. Schur-Zassenhaus lifts these classes uniquely to $\ell_g G_{ab}$.

(3.53b) Makes sense of $\ell \mathbb{H}(G, C)^{\text{in,rd}} \overset{\text{def}}{=} \{ \mathcal{H}(k \ell G, C)^{\text{in,rd}} \}_{k=0}^{\infty}$.

MT: Projective sequence of components on $\ell \mathbb{H}(G, C)^{\text{in,rd}}$.\(^9\)

(3.53c) $\ell \mathbb{H}(D_\ell, C_{2^r})^{\text{in,rd}} = \{ X_1(\ell k + 1) \}_{k=0}^{\infty}$ for $\ell$ odd.

(3.53d) Example: $2 \tilde{A}_4$ is the pullback of $A_4 \leq A_5$ to $2 \tilde{A}_5$.

(\Z_2)^{5}: As $A_4$ (but not $A_5$) module has $(\Z_2)^2$ as a quotient.

$\mathcal{H}(A_5, C_{3^r})^{\text{in,rd}}$ has one genus 0 component.\(^10\)

Remark 3.16 (Conj. 3.1). Indeed, we make the conjecture with $\frac{k}{2} G \rightarrow G$ replacing $\tau G_{ab} \rightarrow G$. Our point in making it in the latter case was to show an edge closer to examples of regular realizations that update common knowledge about the RIGP. Further, we can treat the conjecture as defining $\ast C$ regular realizations of $G$ over a field $K$: it corresponds to a $K$ point on a Hurwitz space defined by $C$ with support in $\ast C$, and it is absolutely necessary that such a point lies of on Hurwitz space component defined over $K$, with the BCL merely giving the minimal definition field of the whole Hurwitz space.

3.4. Explicit Nielsen classes.

(3.54a) Thompson and Völklein produced large series of Chevalley groups, $G$, rank $> 1$, as $\mathbb{Q}$ regular realizations (3 total such groups had been achieved previously) by finding $C$ so the Hurwitz space, $\mathcal{H}(G, C)$, corresponding to $(G, C)$ has $\mathbb{Q}$ points.

(3.54b) Applying the Branch cycle Lemma, the Fried-Serre Lift Invariant, the Conway-Fried-Parker-Völklein component bound, for each $G$, gave infinitely many explicit $C$ with $\mathcal{H}(G, C)$ nonempty and having a $\mathbb{Q}$ component.

(3.54c) Fried produced infinitely many explicit $C$ (called Harbater-Mumford) for which the canonical projective system of Hurwitz spaces $\{ \mathcal{H}(G, C) \}_{u=0}^{\infty}$ contains a subsystem, $\{ \mathcal{H}_u \}$, of nonempty (absolutely irreducible) components over $\mathbb{Q}$.

Found explicit connected Hurwitz spaces $\mathcal{H}(G, C)$ with:

- $\mathcal{H}(G, C)$ transcendental parametrizing parameters;
- $C$ as a collection rational over $\mathbb{Q}$. 

\begin{itemize}
  \item Guarantees RIGP for those groups over \( \mathbb{Q} \).
  
  For any subset, \( S \), of a group \( G \), refer to it as \( \ell' \) if all elements in \( S \) have order prime to \( \ell \). The Hurwitz space objects as explicit encoders of all regular realizations raise myriad questions. The following projects responded to that.
\end{itemize}

4. PAC fields; A presentation of \( \mathcal{G}_\mathbb{Q} \)

This section continues §3 through consequences to the RIGP through using the field analogy to finite fields called PAC fields (Def. 4.1). It features a place of success, whereby non-classical subfields of \( \overline{\mathbb{Q}} \) have benefitted the RIGP, Thm. 4.4.

§4.2 joins both versions of the BCL – for inner and absolute equivalence – to investigate \( \mathcal{G}_\mathbb{Q} \) by a paradigm new in [FrV92]. §4.2 does this by guaranteeing there exist \( \mathbb{Q} \) Hurwitz space components indexed by \( (G,C) \) for infinitely many \( C \), a particular case of the theme of §3.3. §4.3 completes Thm. 4.4 by combining techniques in this PAC context that allow us to deal with all groups.

**Definition 4.1 (PAC).** Refer to a field \( L \subset \overline{\mathbb{Q}} \) as
\[
P(\text{pseudo})A(\text{gebraically})C(\text{losed}) \text{ if } V(L) \neq \emptyset,
\]
for each absolutely irreducible (quasi-projective) variety \( V \) over \( L \).

Using Weil’s restriction of scalers, and the Bertini-Noether theorem, the test for PAC reduces to checking on just those \( V \) that are absolutely irreducible curves over \( \mathbb{Q} \): [FrJ86, Thm. 10.4] or [FrJ86, Thm. 11.2.3]. Note also, that allowing \( V \) to be quasi–projective means there are \( L \) points lying off any particular proper algebraic subset of \( V \).

**Remark 4.2.** If \( L \) [?, Thm. 2] is not PAC, then there is an absolutely irreducible curve in \( \mathbb{P}^1 \) over \( L \) with no \( L \) points. That is, the test of plane projective curves for \( L \) points suffices to separate PAC fields from non-PAC fields.

4.1. Absolute Galois groups of PAC, Hilbertian fields.

**Definition 4.3.** Denote the profree group on a countable set of generators by \( F_\omega \). We call a field \( L \) \( \omega \)-free if \( G_L \equiv F_\omega \). So, \( G_L \) has every finite group as a quotient: it satisfies the IGP for every finite group \( G \). Such a field is also Hilbertian (see §5.1.1 for the definition) as we discuss below. Similarly, denote the group that is profree on a countable set of involutions to be \( F_\infty^2 \), and refer to any field having it as absolute Galois group as Inv-free.

**Theorem 4.4 (\( \mathcal{G}_\mathbb{Q} \) structure).** A PAC field \( L \) is Hilbertian if and only if \( L \) is \( \omega \)-free. For \( K \) a number field, then \( K \leq L \), with \( L \) Galois over \( K \) and PAC.
Further, we may choose \( L \) so that \( \mathcal{G}_K \) has a presentation

\[
1 \to F_\omega = \mathcal{G}_L \to \mathcal{G}_K \to \Pi_{n=2}^\infty S_n \overset{\text{def}}{=} S_\infty \to 1
\]

The left side of (3.55) is a corollary of the first sentence. The heart of

“PAC+ Hilbertian \( \implies \) \( \omega \)-free”

comes from choosing \( C \) (as in answers to (2.9b)) for convenience and tying together the abs and in spaces (as in (2.9c)), to build large IGP realizations over Hilbertian PAC fields (Prop. 4.9). The right side of (3.55), was created with this thought: Our technique for constructing it was based on a simple principle about presenting curves over \( \mathbb{Q} \) as covers, and from that we wanted a (relatively small) group, \( S_\infty \), recognizable by most mathematicians. Rems. 5.8 and 5.9 give the subtleties of that choice.

We say a PAC field \( K \) is Frobenius if \( \mathcal{G}_K = \mathcal{G} \) has the following property.

**Definition 4.5 (Embedding Property).** For any group covers \( \psi : \mathcal{G} \to A \) and \( \psi' : B \to A \), with \( B \) a quotient of \( \mathcal{G} \), there exists a cover \( \gamma : \mathcal{G} \to B \) for which \( \psi' \circ \gamma = \psi \) [FrJ86, Defs. 24.1.2 and 24.1.3].

Frobenius fields include the case of \( e \)-free fields where \( 1 \leq e \leq \infty \), with \( \infty \)-free the same as \( \omega \)-free, our case here. The \( 1 \)-free fields arose as the exact PAC analog of finite fields (Rem. 5.7). Lem. 4.6, implying the Hilbertian property for PAC fields that are \( \omega \)-free, comes from a trick

– the F(ield)C(rossing)A rgument –

that goes back to Chebotarev’s proof of his renown Density Theorem. §5.1.1 reminds of the history of that Chebotarev-HIT connection from [Fr74, §2–3].

In extending the ideas of [FrS76], aimed at solving an Ax-Kochen problem about finite fields, the PAC condition replaces the so-called Lang-Weil argument: an absolutely irreducible variety over a suitably large finite field \( \mathbb{F}_q \) has a \( \mathbb{F}_q \) point. The length and complication of the proof in [FrJ86, §24.1] (or [FrJ86, §23.1]) comes from passing back and forth between covers and fields, instead of, say, the treatment in [FrS76] which used covers, their fibers and fiber products directly.

The material of the FCA in this application starts with two finite extensions of our base field \( L \), \( E_1 = \hat{L}/L \) which is Galois and \( E_2 = F/L(z) \), which is regular, with Galois closure \( E_2^* = \hat{F}/L(z) \). They have these properties.

\[(3.56a) \ E_1 \text{ and } E_2^* \text{ both have group identified with } G; \text{ and} \]

\[(3.56b) \ E_3 = \hat{M}/F, \text{ with group } H, \text{ is the extension of constants of } \hat{F}/L(z) \text{ through which } E_1 \text{ factors.} \]
Now form the covers $\mathbb{P}^1_{\hat{L}} \overset{\text{def}}{=} \mathbb{P}^1_\hat{z} \times \text{Spec}(\hat{L}) \rightarrow \mathbb{P}^1_\hat{z}$ and $\hat{\varphi} : \hat{X} \rightarrow \mathbb{P}^1_\hat{z}$ with $\hat{X}$ the projective, normalization in the function field $\hat{F}$. Then the fiber product

$$\hat{\varphi}_L = \mathbb{P}^1_\hat{L} \times_{\mathbb{P}^1_\hat{z}} \hat{X} \rightarrow \mathbb{P}^1_\hat{z}$$

has group identified with $G \times_H G$.\(^5\)

**Lemma 4.6.** Assume $L$ is **PAC** and $\omega$-free. Then, $L$ is Hilbertian.

**Comments.** Use the notation of (3.57). To show that $L$ is Hilbertian, we use the Galois version of the Hilbertian property (**HIT; §??**) and show it applies to $\hat{\varphi}$. [FrJ86, p. 230] has a short summary of the various results (Weissauer’s and the Diamond Theorem; that are proved after that) that give infinite extensions of $\mathbb{Q}$ that are Hilbertian. The basic one we use is Weissauer’s, restated in §?? with relevant examples to our discussion.

Construct the field extension $\hat{L}$ immediately by using that $L$ is $\omega$-free. Rem. 5.7 explains why, even though $G_L$ is automatically projective, that is insufficient for such a conclusion.

Now take the diagonal $\Delta(G)$ on $G \times_H G$. Quotient out by $\Delta(G)$ acting on $\mathbb{P}^1_\hat{L} \times_{\mathbb{P}^1_\hat{z}} \hat{X}$ to get $\varphi_Y : Y \rightarrow \mathbb{P}^1_\hat{z}$ an absolutely irreducible cover over $L$. Running over the infinitely $y \in Y$ given by the **PAC** property, allows us to assure $\varphi_Y(y)$ avoids any branch points of $\hat{\varphi}$. It is now automatic from the construction that the decomposition group of $\varphi_Y(y)$ in $\hat{\varphi}$ is $G$. That establishes Hilbertianity. \(\square\)

Prop. 4.9 gives the other direction that proves (3.55), based on the relation between inner and absolute spaces. It also opens the topic, for a given finite group $G$, of which classes, $C$, suit a specific application. We continue here with lessons on what we have learned from **PAC** fields.

Conj. 4.7 replaces the hypothesis that $L$ is **PAC** with the projective property that **PAC** implies. There are projective fields that aren’t **PAC**, but are Hilbertian. Example: The cyclotomic closure, $K^{\text{cyc}}$, with a $K$ a number field for which there are elliptic curves over $K^{\text{cyc}}$ with rational points. This simultaneously generalizes a Conjecture of Shafarevich, and Thm. 4.4.

**Conjecture 4.7.** [FrV92, ] Any Hilbertian field $L \subset \bar{\mathbb{Q}}$ is $\omega$-free if and only if $G_L$ is projective.

This raises three aspects of **PAC** fields which we take up in the remarks.

(3.58a) Are they Serious?: Rem. 5.7 clarifies why they can’t be dismissed.

(3.58b) Are they useful?: For **PAC** fields such properties as Hilbertian and RG-Hilbertian are group-theoretic (Rem. 5.10).

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\(^5\)The conditions in (3.56) that the fields are extensions of $L(z)$ and that $E_1$ and $E_2$ have the same groups, rather than the group of $E_1$ being a subgroup of that of $E_2$, are expedients to move the argument along more quickly.
(3.58c) Are they apparent?: Do PAC fields appear in serious applications? What about projective fields (Rem. 5.8 and Rem. 5.9)?

4.2. Completion of presenting $G_Q$. We now complete the hard half of Thm. 4.4. To do so required coming to grips with aspects of the effect, for a fixed $G$, of different choices of $C$. The essence of it is to construct covers $\varphi : X \to \mathbb{P}_1$, over any PAC Hilbertian subfield of $C$, that achieve $(G, G^\ast)$ realizations (Def. 1.6) using the diagram of Thm. 1.7. That will also be a model for what to expect in achieving such results over number fields, where the problem arises naturally in specific cases ($\S$ 5.1.3). We must do this in the generality required to consider the problem for all pairs $(G, G^\ast)$.

As in $\S$1.1, assume $\ast C$ is a rational union of conjugacy classes. Prop. 4.9 lists sufficient conditions for $(G, \ast C)$ that guarantee $\text{Ni}(G, C)^{\text{in}}$ has $\mathbb{Q}$ components for infinitely many $C \in \mathcal{R}_{C}$ (rational unions of classes containing each class of, and supported in, $\ast C$). It further shows that every finite group is a quotient of some $G$ that occurs among these pairs, for some extending classes $\ast C$.

These appeared in [FrV91] to give sufficient absolutely irreducible $\mathbb{Q}$-components from the desired list of Prob. 1.1 so as to finish the proposition. By 1988, Ex. 2.9 guided me in simplifying what was going on with braid orbits, so long as high multiplicity condition (3.19) holds.

Definition 4.8. An extreme opposite to all classes in $\ast C$ being liftable (Def. 1.4) to a central Frattini cover $\psi : H \to G$, is that the generalized lift invariant is trivial. It is equivalent that single commutators from $\ast C$ generate $\ker(\psi)$ (as in Ex. 2.11). We say $(\ker(\psi), \ast C)$ has trivial lift invariant.

If $(\ker(\psi), \ast C)$ has trivial lift invariant, then for any $C \in \mathcal{R}_{C}$, the lift invariant of any $g \in \text{Ni}(G, C)$ is trivial. When $\ast C$ consists of all nontrivial classes in $G$, [FrV91] refers to Def. 4.8 as $\ker(\psi)$ is generated by commutators. If $G$ has no center, then the group of automorphisms, $\text{Aut}(G)$, extends the action of $G$ as conjugations on $G$.

Proposition 4.9. By replacing $G$ by a finite cover of $G$, with no loss we may assume the following.

(3.59a) For a representation cover, $\psi_G : R \to G$, single commutators generate $\ker(\psi)$.

(3.59b) In addition to (3.59a), $G$ is centerless and, if $\ast C$ contains all nontrivial classes of $G$, then $(\ker(\psi_G), \ast C)$ has trivial lift invariant.

Consider $G^\ast$ the cover of $G$ for which $G^\ast/G$ consists of all outer automorphisms of $G$. Assume RETURN, if (3.19) holds, for $C \in \mathcal{R}_{C}$, from the diagram $\mathcal{H}^{\text{in}} \to \mathcal{H}^{\text{abs}}$.
there is a \( \mathbb{Q} \) component (as a moduli space) of \( \mathcal{H}^{\text{in}} \) from which we can achieve \((G, G^*)\) over every PAC field, \( L \leq \overline{\mathbb{Q}} \).

(3.60a) with \( L^*/L \) Galois with group \( G^*/G \) we may achieve the realization of (3.59b), from a regular cover \( \varphi : X \to \mathbb{P}^1 \) whose constant field extension is \( L^*/L \).

In particular, \( G_L \) is profree on a countable number of generators.

The next three subsections prove and comment on the pieces of Prop. 4.9.

4.3. Producing the cover of (3.59). We produce a centerless cover of \( G \) whose representation cover has trivial lift invariant. Choose \( \psi_G : R_G \to G \), a representation cover of \( G \) (Def. 1.10). Then, consider a representation cover \( \psi_{G,2} : R_{G,2} \to R_G \). As a composition of Frattini covers,

\[
\psi \coloneqq \psi_G \circ \psi_{G,2} : R_{G,2} \to G
\]

is a Frattini cover, but it may not be central.

Now, let \( T \coloneqq \psi_{G,2}^{-1}(\ker(\psi_G)) \). Then, \( Z \coloneqq [R_{G,2}, T] \leq \ker(\psi_{G,2}) \) is a subgroup generated by single commutators. Thus, \( \psi / Z : R_{G,2} / Z \to G \), with \( \ker(\psi / Z) = T / Z \), is a central Frattini cover with commutator kernel (Def. 1.10). As \( \psi_G \) is a maximal central Frattini cover of \( G \) with commutator kernel, and \( \psi / Z \) factors through it, conclude that \( R_{G,2} / Z = R_G \).

(3.61) So, \( Z = \ker(\psi_{G,2}) \): Single commutators generate \( \ker(\psi_{G,2}) \).

Suppose we replace \( G \) by \( R_G \). Then, we have a cover of \( G \) with a representation cover whose kernel is generated by single commutators. Therefore, no matter what is \( \mathcal{C} \), the lift invariant for any Nielsen class will be trivial. That still leaves a problem.

Even if \( G \) has no center, \( R_G \) does if it is a nontrivial cover of \( G \). [FrV91, Lem. 2] produces a cover of \( G \) that adds property (3.59b) to (3.59a). RETURN

Remark 4.10 (Explicitness in Prop. 4.9). §3.59 produces the group satisfying (3.59), replacing the original group, in two steps. First: By forming a representation cover \( R_G \to G \). Second: By forming a wreath product of \( R_G \) with an explicit group. Thus, the resulting group is explicit if there is an explicit construction of \( R_G \). As with all things Frattini, consider the construction one \( \ell \mid |G| \) at a time. The module \( M_{G,\ell} \) appears as the \( \ell \)-part of \( H_2(G, \mathbb{Z}) \), an abelian group killed by multiplying by \( |G| \), [Br82, III. Cor. 10.2] from the restriction-corestriction sequence.

RETURN That bounds the power of \( \ell \) dividing \( M_{G} \). In particular, that bounds the \( \ell \)-Frattini level in which \( M_{G} \), with trivial \( G \) action can appear, as a split summand of kernel of \( \to G \). Therefore, the explicitness results from the explicit construction of the 1st \( \ell \)-Frattini cover level, as in Prop. 2.18.
5. The meaning of “Field Arithmetic”

“Field Arithmetic,” the title of [FrJ86] comes from these ideas.

(3.62a) Measure the dependence between diophantine properties by the nature of the fields for which they simultaneously hold.

(3.62b) Expand on using, for a projective algebraic set $V$ over $\mathbb{Q}$, the nature of those residue classes $\mathbb{Z}/\ell$ for which $V(\mathbb{Z}/\ell) \neq \emptyset$.

This section is mostly expositional, tying together historical subjects to our topics. The absolute Galois group of $\mathbb{Q}$, $G_{\mathbb{Q}}$, and the collection, $\mathbb{B} = \{B_r\}_{r=3}^{\infty}$, of braid groups are the heart of many of the great disciplines of mathematics.

The former starts with forms of the IGP, giving explicit descriptions of various quotients of $\mathbb{Q}$, especially the maximal abelian (commutator) and then attempts at the maximal nilpotent quotient of $\mathbb{Q}$. Here are two milestones:

(3.63a) Ihara’s description of the 2nd commutator quotient of $G_{\mathbb{Q}}$; and
(3.63b) Shafarevich’s proof that all nilpotent groups are quotients of $G_{\mathbb{Q}}$.

The study of $\mathbb{B}$ drives descriptions of various spaces through fundamental groups. Also, we relate it and $G_{\mathbb{Q}}$, by producing spaces whose points and definition fields over specific fields reflect on the RIGP and the OIT. Concentrating on properties of particular Hurwitz spaces, often with classical connections, is our focus.

General too is the connection of the RIGP and OIT to a sometimes dismissed element in this discussion: $H$ (Hilbert’s) $I$ (irreducibility) $T$ (heorem). Hilbert introduced it to connect the RIGP and the IGP. It became an adjective Hilbertian, a property of fields. §5 describes how it illustrated the goals of [FrJ86] using PAC fields.

Somewhat confusing – in the classical literature – is with what weight should we emphasize fields vs algebraic sets. To whit: What algebraic sets – say, complete intersections of various degrees, or abelian varieties – were assured of having rational points over which fields. §5.2 reminds of this. In particular that special result called Chevalley’s Theorem §5.4 – that culminated in a PAC avatar conjectured by Ax and proved by Kollár.

Then, there are the various results and conjectures of Ax, Jarden, Shafarevich §5.2.2 that motivated so much of what lay behind [FrJ86] and the result (with its natural conjecture) of the Fried-Voelklein Conj. 4.7 on Hilbertian fields with projective absolute Galois group.

Extending those concerns to Hurwitz spaces, where describing properties of components of Hurwitz spaces defined by various groups and their conjugacy classes gets us to the most modern considerations §5.2.3. The properties in question are birational. Then, extracting such properties from $\mathbb{B}$ opens a new subject, birational algebraic geometry, for which homotopy theory is a requisite tool.
Finally, we can’t avoid connecting to two of Grothendieck’s famous topics, dessins d’enfant and his Teichmüller group §5.3, especially because of his comment relating correspondences on curves to the OIT.

5.1. IGP and RIGP comparison. §5.1.1 reviews the nature of the hilbertian property, comparing the IGP, the RIGP and hilbertianity and its surprising behavior on the lattice of subfields of \( \bar{\mathbb{Q}} \) in the spirit of Field Arithmetic.

There is an ongoing project that delves into the role of HIT the relation between the RIGP and the IGP. §5.1.2 does an exposition on it comparing over a field \( F \), for a given group \( G \), realizations of \( G \) as a Galois extension of \( F \), \( F \supseteq \text{IGP} \) and \( F \supseteq \text{RIGP} \):

The specializations of RIGP realizations of \( G \) using HIT. At this stage, with both problems still so unsolved, the comparison is often qualitative, comparing densities of elements of \( F \supseteq \text{RIGP} \) resulting from specific RIGP realizations of \( G \) with those of \( F \supseteq \text{IGP} \).

Finally, §5.1.3 notes the ubiquitous appearance in absolute Hurwitz families of covers \( X \to \mathbb{P}^1 \) that are absolutely irreducible, but whose Galois closures in the related inner Hurwitz spaces may not be regular. Prevalence of such families are precisely what motivated much of this book, as they include and generalize so many classical diophantine problems, starting with problems from modular curves.

5.1.1. Hilbertian fields and universal Hilbert subsets. The simplest statement of the Hilbertian property for a field \( K \) is this: for \( f(x, y) \in K[x, y] \), irreducible (over \( K \)), then \( f(x_0, y) \) remains irreducible as a polynomial in one variable over \( K \) for infinitely many \( x_0 \in K \). This statement leaves open many ways we might indicate some properties of the Hilbertian set

\[
H_f(K) = \{x_0 \in K \mid f(x_0, y) \text{ is irreducible over } K\}.
\]

For example, we might consider finding an infinite set \( H \subset \mathbb{Q} \), a universal Hilbert subset, for which up to finite sets \( H \subset H_f(K) \) for every irreducible \( f \in \mathbb{Q}[x, y] \). [FrJ86, p. 289] which lists results on this from [Fr85]. Specifically, it notes, to our knowledge, that the first explicit version of such is \( H = \{e^{\sqrt{\log(\log(m))} + m!2m^2}\}_{m=1}^{\infty} \) in [Spr81]. More arithmetically enlightening is the example of [DZ98, Thm. 1], \( \{2^n + n\} \), a special case where you can replace 2 by \( b \ (|b| > 2) \) and \( n \) by \( p(n) \) where \( p \in \mathbb{Z}[z] \) is any nonconstant polynomial.

Still, there is the question of effectiveness, as all these results rely on Siegel’s Theorem that a function \( f(w) \) on an affine curve in \((z, w)\) will have at most finitely many \( \mathbb{Z}[1/a] \) values at rational points of the curve, unless \( f(w) \) has at most two poles, and a special form at that. Then, that taking on the special values listed in these papers is possible only finitely many times. Siegel’s result though is (still) ineffective. Another approach is that of [D96, Cor. 3.7]. This effectively bounds the elements appearing in a given \( H_f \), indeed, it allows any finite collection of
polynomials in two variables. [D96, Express. (23)] makes no assumption on absolute irreducibility. It gives an explicit bounding expression depending on bounds \(d\) on the total degrees and heights \(h\) of the polynomials. This is explicit, and a polynomial in \(h\). Whether such a bound is possible that is polynomial in both \(d\) and \(h\) appears not yet to be known.

The historical roots of the relation between the Chebotarev density theorem, especially its non-reregular analog [Fr74, §2] and its relation to [FrS76], where it was assiduously applied, and a proof of the HIT as given in [Fr74, §3]. The more general Field Crossing argument as in [FrV92, Lem. 1] appears entirely field theoretically in [FrJ86, §23.1].

Finally, there is Weissauer’s result for which one immediate conclusion is that the Hilbertianity property for fields can jump around a lot.

**Theorem 5.1 (Weissauer).** We assume \(K \subset \bar{Q}\). If \(K\) is Hilbertian, and \(L/K\) is Galois, then any extension \(K^* / L\) is Hilbertian if the inequalities \(\infty > [K^* : L] > 1\) hold [FrJ86, Thm. 13.9.1].

*Independence of RIGP, IGP and Hilbertianity*: Now that we know there exist many PAC fields that lie deep in the algebraic numbers, we use them to consider what holds for all PAC fields. Rem. 5.3 gives one hint at the independence of the RIGP and the IGP. The RIGP holds for \(\bar{Q}\) from RET, but clearly the IGP does not. The following property is relevant to connecting the RIGP and hilbertianity.

**Definition 5.2.** If, for a field \(L\), each regular Galois cover \(\tilde{\phi} : \tilde{Y} \to \mathbb{P}^1_{\bar{z}}\) over \(L\) has infinitely many irreducible fibers \(\tilde{Y}_{z_0}, z_0 \in \mathbb{P}^1_{\bar{z}}\), we say \(L\) is RG-Hilbertian.

**Remark 5.3.** The IGP can hold for a PAC field that is not Hilbertian, giving an independence statement of the relation between the two properties HIT and IGP. [FrV92, p. 480] constructs such an overfield of a PAC, Hilbertian, field \(P\) defined as the fixed field of a subgroup \(\hat{H} \leq F_\omega\) that happens to be the Universal Frattini cover of the following *small* group: \(\prod_{i=2}^{\infty} G_i\), where each finite group appears in \(\{G_i\}_{i=2}^{\infty}\) exactly once.

5.1.2. Relating \(\mathcal{F}_{G,IGP}\) and \(\mathcal{F}_{G,RIGP}\).

5.1.3. Diophantine problems calling for \((G, G^*)\) realizations.

**5.2. Finite fields, \(\mathbb{R}\) and \(p\)-adic fields.** From the viewpoint of this book, [FrJ86, Chap. 19] (resp. [FrJ86, Chap. 21]) barely scratches the surface of the historical motivation around the problems of arithmetic geometry. Each edition of the book emphasizes model theory of fields more than the previous. Yet, the p. 268 (resp. p. 452) statement
Each of these concrete problems focuses our attention on rich historically motivated concepts that could be overlooked in an abstract model theoretic viewpoint.

Overlooked, because model theory tries to encompass any possible problem, while arithmetic geometry aims to develop new tools to handle bottlenecks previously blocking progress in understanding fields which provide solutions to various structured sets of algebraic equations. This subsection emphasizes the history, starting with Chevalley’s Theorem §5.4. It certainly motivated the formulation of results about PAC fields, instigated by James Ax.

5.2.1. Chevalley’s and Kollár’s Theorems. Chevalley’s Theorem drove diophantine considerations in many directions primarily by distinguishing for fields – among a collection $V$ of varieties – between a member $V \in V$ having an absolutely irreducible component defined over the field and having a rational point in the field.

There was nothing diophantine in the work of Abel, Galois or Riemann. Their work recognizes the mystery in relating all zeros of an irreducible polynomial over a field, and the role of the Galois group of the polynomial to it. Yet, earlier than these, was the work of Gauss (quadratic reciprocity specifically), Lagrange (Pell’s equation and the values of forms), the great body of work on the nature of primes (say, Dirichlet’s proof of primes in arithmetic progressions and $L$-functions attached to number field extensions), the attempt to solve Fermat’s last theorem by so many (Dedekind’s codifying results on algebraic number fields).

Still, if you had to take one theorem that had inordinate influence to its proof and sweep, it had to be Thm. 5.4. Use these notations for fields: a finite field of order $q$ is $\mathbb{F}_q$; a completion of a number field $K$ at a prime $p$ is $K_p$; and the formal power series in a variable $t$ over $\mathbb{F}_q$ is $\mathbb{F}_q[[t]]$.

**Theorem 5.4 (Chevalley).** A form $F$ of degree $d$ in $\mathbb{P}^d$ over a finite field $\mathbb{F}_q$ has a point in $\mathbb{F}_q$. So, that form, over $\mathbb{F}_q$ contains an absolutely irreducible $\mathbb{F}_q$ variety.

E. Artin, its formulator, also apparently suggested the next step up:

(3.64) A degree $d$ form in $\mathbb{P}_p^d$ over a $p$-adic field $K_p$ should have a point in $K_p$.

Lang [La52] suggested this might be true by proving it held for $\mathbb{F}_q[[t]]$. Ax and Kochen showed that any nontrivial ultraproduct of $\{\mathbb{Q}_p \mid \text{primes } p\}$ is isomorphic to the same ultraproduct of the fields with $\mathbb{F}_p[[t]]$ replacing $\mathbb{Q}_p$. So, any arithmetic geometry statement quantifying algebraic sets that could be interpreted in this set for either ultraproduct would be true for almost all $p$ in one if and only if in the other. Thus this Artin Conjecture, followed in this form from Lang’s Theorem.

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6[BvSh66, p. 5] reproduces the proof after an introduction to polynomials modulo $p$. It does the proof over $\mathbb{Z}/p$, but says it works over any finite field. The main replacement is $a^p = a^q$ in Euler’s Theorem on the multiplicative group of nonzero elements in $\mathbb{F}_q$. 
These are statements (not pure existential) in the first order predicate theory of finite fields. That means – given \( d \) – there are collections of variables quantified by \( \forall \) (for all) and by \( \exists \) (there exists). Here: \( \forall \) set of coefficients of a hypersurface of degree \( d \), \( \exists \) values of the variables in \( \mathbb{F} \) (placeholder for a finite field).

Question \( Q_d \): is this statement true for all, or all but infinitely many, or infinitely many \( q \), with \( \mathbb{F}_q = \mathbb{F} \)? It is those problems that drove Ax, and for which he and Simon Kochen won their Cole Prize.\(^7\)

The major shock, in a way, was that unlike Chevalley’s Theorem, the Artin Conjecture was true only for almost all \( p \): For each fixed \( d \) there were usually a host (but finite) of primes \( p \) for which there were hypersurfaces of degree \( d \) in \( \mathbb{P}^d \) that had no \( \mathbb{Q}_p \) points.\(^8\)

Ax knew the algebraic numbers for certain ultraproducts aren’t PAC, for essentially the same reason that \( p \)-adic fields aren’t. Yet, he still conjectured that Chevalley’s Theorem held for any perfect PAC field. In particular for any case where the algebraic numbers in an ultraproduct were PAC. Indeed, the case when a PAC field had abelian absolute Galois group followed from Chevalley’s Theorem. Such a field could not be Galois over \( \mathbb{Q} \), and perhaps that constrained his thinking about PAC field. He even conjectured that being both PAC and Galois over \( \mathbb{Q} \) was not possible, except for \( \overline{\mathbb{Q}} \). That was shown wrong in \([FrJ78]\). That negative comes out in a positive way in Ch. 4.

**Conjecture 5.5 (Ax).** A hypersurface of degree \( d \) in \( \mathbb{P}^d \) over a perfect PAC field \( K \), contains an absolutely irreducible \( K \) subspace.

\([Ko07b]\) starts out immediately by using an intrinsic, rather than the hypersurface equation (extrinsic), form of such a hypersurface \( V \). It is a Fano variety: Its canonical class \( \kappa_V \) has the property that its negative is ample.

**Remark 5.6 (Hypersurface intersections).** Following \([DeJL83]\) the actual result in \([Ko07b, Thm. 2]\) extends to the intersections of hypersurfaces in \( \mathbb{P}^d \) whose degrees sum to at most \( d \).

**5.2.2. The Conjectures: Ax, Shafarevich, Fried-Völklein.** Prop. 4.9 plays on finding Hurwitz spaces \( \mathcal{H}(G, C)^* \) with a single absolutely irreducible component. Given \( G \), but allowing \( C \) to vary, we know one component is very common, if all classes in \( C \) appear suitably often. That hypothesis, however, doesn’t hold if – for good reason – we restrict to the case \( r = 4 \), by which we can compare with classical situations, especially with modular curves, as we do in Ch. 5.

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\(^7\)\([BvSh66, p. 58–59]\) includes many comments on this, without reference to Ax-Kochen, including its truth for \( d = 2 \) and 3, and with \( d^2 \) replaced by an explicit, but large, \( N(d) \) its truth without reservation in \([Bra45]\).

\(^8\)Nor is there an obvious rational for the exceptional primes for a given value of \( d \), \([Sch84]\).
Remark 5.7 (HIT vs Chebotarev). Ax found the algebraic closure of \( \mathbb{Q} \) isn’t the only PAC subfield, \( L \), of \( \bar{\mathbb{Q}} \). Almost (but not all) fields of algebraic numbers of a non-trivial ultraproduct of finite fields are PAC. Based on Chevalley’s Theorem and the Lang-Weil result, Ax made conjectures:

(3.65a) A \( \mathbb{Q} \) form of degree \( d \) in projective \( d \) space has an \( L \) point; and
(3.65b) The only PAC field \( L \) that is Galois over \( \mathbb{Q} \) is \( \bar{\mathbb{Q}} \).

He was significantly right about (3.65a) as Kollár [Ko07] showed (§ refchevalley). He was significantly wrong about (3.65b). Not only could it be Galois, it could also be Hilbertian, as [FrJ78] shows by presenting every projective curve \( X \) over \( \mathbb{Q} \) as \( \varphi : X \to \mathbb{P}^1 \) with simple branching (branch cycles are 2-cycles) with an arbitrarily high number of branch points. Thus, the Galois closure cover \( \hat{\varphi} \) is regular with group \( S_{\deg(\varphi)} \) (Rem. 5.8).

Remark 5.8 (Canonical Fields I). The source of PAC, Hilbertian fields is from an arithmetic form of a Lefschetz argument, as in Rem. 5.7. Nonsingular projective curves project birationally over \( \mathbb{Q} \) to give a plane (in \( \mathbb{P}^2 \) ) curve, \( \tilde{X} \), of degree \( \deg(\tilde{X}) = n \), with only ordinary double point singularities. Take a suitably general \( \mathbb{Q} \) point \( u \in \mathbb{P}^2 \) \( X \), so that any lines \( L \) through \( u \) meets \( X \) at at most one point with multiplicity 2. With \( \tilde{X} \) the projective normalization of \( X \), this produces:

(3.66a) A natural map: \( x \in X \mapsto L_{x,u} = \varphi_{X,u}(x) \) the line through \( x \);
(3.66b) by extension to \( \tilde{X} \), \( \tilde{\varphi}_{X,u} : \tilde{X} \to \mathbb{P}^1 \) is a simple-branched (branch cycles are 2-cycles) regular cover; and
(3.66c) the monodromy group of \( \tilde{\varphi}_{X,u} \) is \( S_{n_X} \).

Applying HIT to \( \tilde{\varphi}_{X,u} \) produces \( \infty \) many \( z' \in \mathbb{P}^1(\mathbb{Q}) \) giving decomposition fields \( K'_{z'}/\mathbb{Q} \) with group \( S_{n_X} \) disjoint from any a’ priori given finite extension of \( \mathbb{Q} \). By compositing infinitely many of these \( z' \)’s, we easily get a field over which \( X \) has infinitely many points.

Alas, we want for any one integer \( n \), just one copy of \( S_{n_X} \) to appear in the final composite \( L_{\text{fin}} \), and yet \( X \) has infinitely many \( L_{\text{fin}} \) points. Here is how they come from other distinct copies of \( S_{n} \)’ with \( n' \) varying.

List infinitely many copies of \( X \) as \( \{(X,j)\}_{j=1}^{\infty} \). Now, induct on \( j \) to produce a field \( M_{X,j}/\mathbb{Q} \) with group \( S_{n_{X,j}} \) over which there is a guaranteed new point \( m_{X,j} \in X \) with coordinates not in a field \( M_{X,j-1} \) indicated inductively below. Here is our device for this. Let \( n_{X,j} = n_X \cdot n'_{X,j} \) where \( n'_{X,j} \) has been selected so that \( n_{X,j} > n_{X,j-1} \). Consider among all the degree \( n'_{X,j} \) maps \( f : \mathbb{P}^2 \to \mathbb{P}^2 \) over \( \mathbb{Q} \) one for which the pullback, \( f^*(X) \), of \( X \) still satisfies the Lefshetz singular point condition.

Now, with a choice of \( \mathbb{Q} \) point \( u_{f^*(X)} \) as above, apply HIT to produce the desired \( S_{n_{X,j}} \) extension over \( \mathbb{Q} \) from a point \( m' \) that generates an extension over \( \mathbb{Q} \).
disjoint from $M_{X,j-1}$ and for which $m_{X,j} \overset{\text{def}}{=} f^*(m') \notin M_{X,j-1}$. Define $M_{X,j}$ as the composite of this field with $M_{X,j-1}$.  

**Remark 5.9** (Canonical Fields II). Shafarevich’s case of Conj. 4.7 replaces $\prod_{n=2}^{\infty} G_i$ with a canonical group (and field) $(\mathbb{Z})^* = G(\mathbb{Q}^{\text{cyc}}/\mathbb{Q})$. Mightn’t we form a canonical field based on symmetric groups from the field of composites, $\mathbb{Q}^{S_\infty}$, of all extensions of $\mathbb{Q}$ having $S_n$, for some $n$ as Galois group?

It is a canonical, Galois over $\mathbb{Q}$, projective extension of $\mathbb{Q}$ that contains the intersection of all the PAC fields that could appear in Thm. 4.4. Yet, it is not Hilbertian. No regular extension of $\mathbb{Q}$ with any group $S_n$ would have nontrivial specializations over $\mathbb{Q}^{S_\infty}$: $\mathcal{G}_{\mathbb{Q}^{S_\infty}}$ is not (isomorphic to) $F_\omega$.

Other canonical fields appear for which these questions, especially their relation to Hilbertianity, are valuable. One is the totally real algebraic numbers, $\mathbb{Q}^{tr}$, consisting of algebraic numbers all of whose conjugates are real (see §5.1.1). We comment here on the solvable closure, $\mathbb{Q}^{\text{sol}}$, of $\mathbb{Q}$. Is this a PAC field [FrJ86, Prob. 1 a, p. 748]? It is projective (as a subfield of a projective field $\mathbb{Q}^{\text{cyc}}$). It isn’t Hilbertian or even RG-Hilbertian: No regular solvable group extension has a nontrivial specialization over $\mathbb{Q}^{\text{sol}}$. Iwasawa conjectured $\mathcal{G}_{\mathbb{Q}^{\text{cyc}}} = F_\omega$ [FrJ86, p. 754]. Alas, they can’t both be correct: PAC + $\omega$-free implies Hilbertian (Lem. 4.6).  

**Remark 5.10** (Hilbertian-like Properties). The RG-Hilbertian for a field $L$ considers the specialization property – infinitely many fibers over $z' \in \mathbb{P}_2^1(L)$ have the whole group as decomposition group – only for regular Galois covers $\phi : \hat{X} \to \mathbb{P}_2^1$. The argument of Lem. 4.6 shows, if $L$ is PAC, then it is RG-Hilbertian if and only if the IGP holds [FrV91, Thm. B]. A general construction produces RG-Hilbertian PAC fields that are not Hilbertian [FrV92, p. 479] in the following way. List all finite groups, each just once (up to isomorphism), as $G_1, G_2, \ldots$ with $|G_1| = 2$. Since $\mathcal{H} = \prod_{i=1}^{\infty} G_i$ has countable rank, it is a quotient of $F_\omega$, represented as $\mathcal{G}_L$ with $L$ a PAC field. The projective group formed from the Universal Frattini cover, $\mathcal{H}$ of $\mathcal{H}$ (§1.3), therefore embeds as a subgroup of $\mathcal{G}_L$.

Now denote the fixed field of $\mathcal{H}$ by $L^*$, which by Thm. B (loc. sit.) is RG-Hilbertian. If $L^*$ were Hilbertian, then $\mathcal{G}_L^*$ would also be $F_\omega$ and every finite embedding problem over $L^*$ would be solvable. Consider, however, the covers $\mathcal{H} \to G_1$ (factorization through $\mathcal{H}$) and $\mathcal{H} \to S_5$ (from $F_\omega$ being profree. There is no way to

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9We considered only one $X$. By, however, ordering $\{(X,j)\}$appropriate $X, 1 \leq j < \infty$; the above works by changing $M_{X,j}/\mathbb{Q}$ to include the composite of all the fields associated with those $(X', j')$ that come before $(X,j)$. Further, when you get to $S_{n_{X,j}}$, add any missing $S_n$, s with with $n' < n_{X,j}$ by taking any regular $S_n$'s cover and applying HIT to it, keeping it disjoint from extensions appearing previously in the construction.

10Galois died so long ago. Yet $\mathbb{Q}^{\text{sol}}$ remains such a mystery. I’d bet that $\mathbb{Q}^{\text{sol}}$ is not PAC. Yet, . . . G. Frey showed the nilpotent closure of $\mathbb{Q}$ isn’t PAC, by giving genus 1 curves over $\mathbb{Q}$ without such points. [CW06b, p. 222] exposits on conditions on genus 1 curves that guarantees they do have $\mathbb{Q}^{\text{sol}}$ points using the Weil-Chatalet group of the Jacobian of the curve.
solve this embedding problem as that would give $A_5$ as a subgroup of the kernel of the pullback of $G_1$ in $\mathcal{H}$. That kernel, however, is pronilpotent [FrJ86, Lem. 20.2]$_1$ (§1.3), certainly not simple.

5.2.3. Getting to their applications. [?, §6] explains enough of the Cohen-Lenstra problem to remark on the relevance of (6.8d). Let $C(d)$ count the number of square-free monic polynomials $f \in \mathbb{F}_q[t]$ of degree $2d+1$, and let $N(d)$ be the sum, over $f$, of $h-1$, where $h$ is the number of $\ell$-torsion elements in the class group of $\mathbb{F}_q(t; \sqrt{f})$. They necessarily assume $q$, a prime power (order of a finite field) is large as a function of $\ell$ and $\ell \not| q(q-1)$. Here they are trying to show $C(d)/N(d)$ approaches 1 as $d \to \infty$. The ingredients of this result get to the heart of the paper.

(3.67a) The Jacobian of a curve interprets statements about abelian unramified covers of a curve, and so questions about $\ell$-torsion of class numbers. You then see that counting $\mathbb{F}_q$ points on the Hurwitz space for $G = D_\ell$ (dihedral group of degree $\ell$) is what you are after.

(3.67b) [?, Cor. 5.8.2] is the stable homology result, essentially saying that if the $j$th $\mathbb{Q}$ homology is stable along a system of Hurwitz space components as $d$ gets large, then the $j$th homology is the same for those Hurwitz space components as it is for the configuration space which the Hurwitz space covers.

(3.67c) [?] shows a corresponding isomorphism of the $i$th étale cohomology of the Hurwitz space components and of the configuration space assuming $d$ exceeds some function of $i$.

(3.67d) Now you need a bound on the (count of points contribution of the) cohomology outside the range of values of $i$ for which their stability result holds. They say the argument is exactly as in the proof of [?, Thm. 8.7].

Comment on (3.67d). See (?????) and (?????) for taking advantage of the nice arguments in [?].

5.2.4. Points on Hurwitz spaces. Actually, Pierre and Michel Emsalem have facility with a version of the Deligne Mumford compactification of the Hurwitz space, as does Wewers, which Wewers did at the same time Mochuzuki did it, possibly influenced (Wewers certainly was, I was in Essen at the time; and I was in contact with Ihara at the time) by my 1995 (first) paper on Modular Towers. I gave a compactification in the paper, based on iterated normalization on the boundary, very non-DM. The application there was to giving examples of projective systems of Modular Tower components uniformly defined over $\mathbb{Q}$.

Pierre and Michel aimed at giving $\ell$-adic points on the (full) Modular Tower of any finite group, for a Nielsen class with sufficiently many Harbater-Mumford
representatives (there is a precise quantitative statement). That now seems like a long time ago, and I have not looked back at this topic since that time.

I went in the Modular Tower direction because, as I told Ellenberg when I gave lectures at Wisconsin, I didn’t know enough homotopy theory to go after the specific problem that I wanted, for which one result in that direction was exactly the stable homotopy result that Ellenberg-Venkatesh-Westerland were going after. Conway-Fried-Parker-Voelklein was the stable $H^0$ result. So, for me that problem goes back to, essentially 1993, the beginning formulation of the Modular Tower program, which had a preliminary paper with Pierre. That was the result quoted in the abstract below. The certain types of torsion points being cyclotomic torsion points. This still, as far as I know, unsolved problem – about regular realizations of dihedral groups – was generalized by Modular Towers to (essentially) all finite groups.

29. with P. Debes, Nonrigid situations in constructive Galois theory, Pacific Journal 163 (1994), 81122. This uses the results of "Rigidity and Real Residue Classes" on several problems among which are these.

Show every finite group is realized regularly over the totally real (all conjugates real) numbers. How to construct $S_n$ covers with four branch points with the covers also having real points (can’t be done with three branch points). Based on Mazur’s Theorem on torsion points on elliptic curves over the rationals, if $m$ is a prime larger than 7, then the dihedral group of order $2m$ isn’t regularly realized over the rationals with fewer than 6 branch points. #3 amounts to the formulation of the M(odular) T(ower) program just for dihedral groups (see the html file for URLs to the MT Time Line), a statement equivalent to finding certain types of torsion points on hyperelliptic Jacobians. NonRigidGT.html

5.3. Correspondences and other Grothendieck topics.
CHAPTER 4

Spaces test the RIGP

We assiduously use $\ell$ as a prime involved in the construction of Frattini covers, of a given (finite) group $G$ and the moduli spaces associated to it. While $p$ is reserved for primes that appear for separate purposes, say, reduction of those moduli spaces modulo $p$. §4.2, in particular, has gone through the story of how advantage was made of translating the regular version of the Inverse Galois Problem (at least in characteristic 0) to the story of rational points on Hurwitz spaces.

Here we start the formation of natural towers of moduli spaces: $\text{M}(\text{odular}) \quad \text{T(ower)s (MTs)}$. For simplicity we start with the assumption that $G$ is $\ell$-perfect. In, however, §3, we remove that assumption, by avoiding the Ext-Frattini covers that appear in Cor. 2.6, without removing any significant Frattini covers from consideration. MTs generalize modular curves in precise ways (as in §3.2), while we can use finite group theory to exert control over from.

Further, towers from essentially any pair $(G, \ell)$, with $G$ a finite group that is $\ell$-perfect, have revealed much on how to compare them with modular curve towers. In particular, how their properties, proven and conjectural generalize modular curve properties, especially around properties of cusps.

§1 constructs the towers, including being precise on when they are nonempty. It also explains why our structural statements concentrate on $\ell$-Frattini covers. For example, Ch. 3 Prop. 4.9 dealt with all finite groups of necessity. §2 lists the main MT conjectures, and the progress on them. Here, in using the Branch Cycle Lemma (BCL) as characterized in Ch. 2 Prop. 4.1, we distinguish between two cases.

(4.1a) When all components of a tower have definition field a finite extension of $\mathbb{Q}$ (possibly just $\mathbb{Q}$ itself).

(4.1b) When the definition fields of the tower levels grow with the level, and how much we can figure what they are.

Even modular curve towers display both phenomena.

§4.2 reexamines Serre’s $O$\pen$\text{I}(\text{mage})$\text{T(heorem)}, pointing to the book’s conclusion.

When reduced Hurwitz spaces are one dimensional, parametrizing covers with 4 branch points, they are upper half plane quotients ramified at the expected 3 points of the $j$-line (Ch. 2 Prop. 2.7).
Ch. 5 has MTs whose levels are all such j-line covers. This illustrates with one example that displays phenomena generalizing the OIT subject to them being akin to modular curve towers – which we also regard as one example. Yet, nowhere among its tower levels are there any modular curves.

1. Constructing MTs

Any particular tower has levels indexed by a parameter $0 \leq k < \infty$. All levels are Hurwitz space components defined by Nielsen classes, with level 0 defined by a Nielsen class $\text{Ni}(G, C)$, with $C$ a collection of $r \geq 3$ conjugacy classes in $G$. Typically in our main applications, as does Ch. 3, this starts with a rational union, $\ast C = \ast C_1, \ldots, \ast C_r$, of distinct conjugacy classes in $G$. As previously, denote the gcd of the orders of elements in $\ast C$ by $N_{\ast C}$.

For a fixed, centerless, $G$, the $\mathbb{Q}$ points on the corresponding Hurwitz space $H(G, C)^{in}$ correspond to the complete collection of extensions regular extensions $L/\mathbb{Q}(z)$ realizing $G$ as a Galois group over $\mathbb{Q}$ with $C$ as branch cycles.

Our basic assumption for forming MTs is the following.

\begin{equation} \ell'\text{-condition: } (\ell, N_{\ast C}) = 1; \text{ that is, } \ast C \text{ consists of } \ell' \text{ classes.} \end{equation}

From (4.2), §3.1 canonically produces MTs based on the Ch. 3 Prop. 2.18 construction of the centerless, $\ell$-perfect groups $k^\ell G_{ab}$ that give the Hurwitz spaces $H(k^\ell G_{ab}, C)^{in}$ on which the MT levels fall.

1.1. Constructing Frattini modules. We now outline the proof of [Fr02, §2.2.1-2.2.2, culminating in Thm. 2.8] adding comments on explicitness. First step: Replace $G$ by the normalizer, $N_G(P) \overset{\text{def}}{=} N$, in $G$, to consider the case $P$ is normal in $G$, as in (1.12a). To avoid confusion about the characteristics kernels, refer to them as $K_N = \{ \ker_k(N) \}$. So, start by constructing $\iota M_N$.

As in Ch. 3 Rem. 1.9, the Todd-Coxeter (a la Shreier’s) algorithm suffices to form generators of $M_P$ since we explicit relations from $\ker_1$ as required. Lem. 1.5 assures that the action of $N/P$ extends to $\iota N/\ker_1 = \iota^1 N$.

[Fr02, Thm. 2.10] I SHOULD PUT THIS IN THE PAPER PROPER Suppose $p$ divides the order of $g \in G$. Then, any lift $g \in G_{k+1}$ has order $p \mid \text{ord}(g)$. Assume $g \in G_k$ is a $p$? element. A unique $p$? conjugacy class of $G_{k+1}$ lifts $g$. If $G_0$ is centerless and $p$-perfect, so is $G_k$ for all $k$. The action of $H$ extends to it by applying Prop. 1.29, but now we need some additional information. For (6.7b), this is essentially a special case of (1.12a). Then, except for noting that the rank of $(\mathbb{Z}/\ell)^t$ as a $\mathbb{Z}$ module is the same as the dimension $t$ of the vector space $(\mathbb{Z}/\ell)t$, we get to the real issue: Constructing $\iota M_G$. We will use pieces of this in the body of the book. We regard $\mathbb{F}_p[G_0]$ as $G_0$ as a left $\mathbb{F}_p[G_0]$ module and as a right $\mathbb{F}_p[G_0]$ module. The induced module $\text{ind}G_0$ ($M_0$) is the $G_0$ module $M_0$? $\mathbb{F}_p[G_0]$, $\mathbb{F}_p[G_0] = M_0$? $\mathbb{F}_p$. 

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1. CONSTRUCTING MTs

Fp[G0/G?0]. The notation Fp[G0/G?0] is for the right G0 module written as the vector space ? G0? generated by right cosets of G0 in G0. Then, indG?0 (M0) is a right G0 module. Suppose N is a right G0 module. Any Z/p[G0] homomorphism ? : M ? N G0 g extends to a Z/p[G0] module homomorphism IndG?0 (M) ? M by m ? g ? ?(m) . Recall that M0 is an indecomposable G0 module ([Ben91, p. 11, Exec. 1] or [FK97, Indecom. Lem. 2.4]). To characterize M0 as the versal module for exponent p extensions of G0, we use this result [Fri95, Prop. 2.7]. Proposition 2.5.

The cohomology group H2(G0, M0) has dimension one over Fp. The 2-cocycle for the short exact sequence 1?M0 ?G1 ?G0 ?1 represents a generator. We define any nontrivial ? ? H2(G0,M0) as G1 up to an automorphism fixed on the G0 quotient and multiplying M0 by a scalar. □

Then, a particular MT, formed from (G,ℓ,*,C) starts from a Nielsen class Ni(G, C) with each class of *,C, and no others, appearing in C. Since we have diophantine considerations based on the appearance of groups as Galois groups over Q as a primary goal, eventually those C considered for level 0 will fall among rational conjugacy class sets of the form * C = * Cn1 ... Cnr* from a vector n ∈ (Z+)r. Again: These form a semi-group under slotwise multiplication which, denoted R*,C. 

Now we give the data, based on notation from §??, for the level k Nielsen class from which level k of a particular tower from Ni(G, C) will appear. This subsection concludes with an if and only if condition that there are nonempty MTs from this data.

As in §??, RETURN We list places of increasing difficulty for computing ˜G, given G, including using the idea of lifting orders of ℓ elements to Schur quotients.

(4.3a)

[Fr02, Prop. 2.8] gives a reasonably effective computation of the kernel of G1 → G. Remind of this.

Prop.

REMARK 1.1 (Central Frattini vs Universal Frattini covers). A representation cover ψ : R → G has finite kernel, and it is a Frattini cover. By contrast, ˜ψG → G, being a projective group, has no points of finite order. Yet, ψG factors through ψ. Yet, that central Frattini cover plays a significant role in almost every aspect of MTs.

(4.4a) Starting with Prop. ?? which, in particular, characterizes when a MT is nonempty.

(4.4b) Continuing with the characterization of particular types of cusps in the case when level 0 of a MT is given by Ni(G, C) where C consists of 4 classes.
§1.5 continues this discussion.

**Remark 1.2** (Loewy display need).

2. \(\ell\)-perfect and centerless

[BFr02, Prop. 3.21] has the \(\ell\)-perfect and centerless result that says this replicates up the MT. We went where the motivating problems (the OIT included) led us. They weren’t handpicked to have general ideas apply to make them comprehensible. We discover their definition fields through extensions of the BCL that connect to properties that sometimes – but not always – trace to topics arising with the moduli of curves of genus \(g\). For spaces of 3 branch point covers, I suppose popularly called *dessin d’ enfant*, there do seem to be inexplicable accidents. In our experience, they disappear when \(r \geq 4\).

RETURN Here we will list what we know about the appearance of irreducible \(\mathbb{Q}\) components in inner Hurwitz spaces.

3. Ext-free \(\ell\)-Frattini covers

Cor. 2.6 refers to \(\ell\)-Frattini central extensions of the type Ext-Frattini. They appear from an abelian cover of \(G_{ab}\), the commutator quotient of \(G\). For a prime \(\ell\) that divides \(G_{ab}\), they are the natural generalization of the \(\ell\)-Frattini cover \(\mathbb{Z}/\ell^2 \to \mathbb{Z}/\ell\). If we allow such extensions for a prime \(\ell\), then even if \(G\) is centerless, then the 1st characteristic \(\ell\)-Frattini cover, \(\frac{1}{\ell}G \to G\) of \(G\), would have a nontrivial center, contrary to the conclusion of Prop. 2.18.

On the other hand, if we just remove \(\ell\) from consideration, then we could be leaving out significant \(\ell\)-Frattini extensions of \(G\). For example, \(G = S_n, n \geq 4\), and the prime \(\ell = 2\) as in Ex. 2.11, and the case \(\ell = 2\) of Serre’s OIT as in §3.2 or the case \(\ell = 3\) of our main example, §3.

3.1. M(odular)T(ower)s from \(\ell’\) conjugacy classes \(C\).

**Conjecture 3.1.** There is a \(C \in \mathcal{R}_C\) for which \(\mathcal{H}(G, C)^{\text{in}}\), as a moduli space, has a rational point. In particular, that point would give a regular realization of \(G\) over \(\mathbb{Q}\).

**Lemma 3.2.** Assume (3.1) and also assume the Main Modular Tower conjecture. Then, the \(C\) for which there are \((G, C)\) regular realizations over \(\mathbb{Q}\) RETURN

So, here are natural questions assuming the RIGP is true.

(4.5a) If there are any \(\mathbb{Q}\) points among them, for what \(C\) would they appear? Hurwitz space types depend on cover equivalences.

Use *inner, reduced*: appropriate for RIGP. §?? has brief reminders of elementary, but key, definitions we will use. For example, the meanings of the following
phrases for a group $G$: nilpotent; an $\ell'$ subset; being $\ell$-perfect; $\ell$-Frattini cover; and Schur multiplier and its relation to Frattini central extensions.

**Proposition 3.3. Simple groups: Inadequate for the Inverse Galois Problem**

(set $S \subset G$ is $p'$ if its elements are prime to $p$.)

- $(G, p) \implies \exists$ sequence $G = G_0 \leftarrow G_1 \leftarrow G_2 \leftarrow \ldots$ of group covers and integer $\nu(G, p)$ with these properties:
  - $M_k = \ker(G_{k+1} \to G_0) = (\mathbb{Z}/p^{k+1})^{\nu(G, p)}$,
  - $k \geq 0$ the level.
- If $G$ is centerless, then so are all the $G_k$s.
- $\psi_k : G_{k+1} \to G_0$ is a $p$-Frattini cover.\(^*\)
- There is a maximal $\nu(G, p)$, $\nu(G, p)_{\max}$
  $> 1$ unless $G$ is $\mathbb{Z}/p^t \times H$, $(|H|, p) = 1)$.\(^*\)

[BFr02, §2] cleans up some delicate points related to the action on reduced Nielsen classes.

**Construction comments.** □

**Definition 3.4.**

- Schur-Zassenhaus \implies \exists\{\mathcal{H}(G_k, C)^{in, rd}\}_{k=0}^{\infty} \overset{\text{def}}{=} \mathcal{H}_{G, C, p}$.\(^*\)
- Reduced: Equivalence $\varphi : X \to \mathbb{P}_1$ and $\alpha \circ \varphi$, $\alpha \in \text{PSL}_2(\mathbb{C})$.\(^*\)

**Definition 3.5 (abelianized inner, reduced MT).** Nonempty projective sequence $\{\mathcal{H}'_k\}_{k=0}^{\infty}$ of components on $\mathcal{H}_{G, p}$.

- $\mathcal{H}'_k \to S_r \backslash (\mathbb{P}_1)^r \backslash \Delta/\text{PSL}_2(\mathbb{C}) \overset{\text{def}}{=} J_r$; $J_1 = \mathbb{P}_1 \backslash \{\infty\}$
- $M(G, p, C)$ Main conj.: Number field $K$, $\mathcal{H}'_k(K) = \emptyset$, $k \gg 0$.
  - Generalizes $\{X_1(p^{k+1})(K) = \emptyset \text{ off cusps}\}_{k>0}^{\infty}$.

Any projective sequence $\{\mathcal{H}'_{n_u}\}$ of components of $\{\mathcal{H}(G_u, C)\}_{u=0}^{\infty}$ is a(n abelianized) Modular Tower; over $K$ if all are defined over $K$. This generalizes the tower of modular curves $\{X_1(\ell^n)\}_{u \in \mathbb{N}}$, off their cusps, associated to the dihedral group $D_\ell$, $\ell$ odd. For $p$ a prime, $\mathbb{Q}_{p, \text{unr}}$ is the maximal unramified extension of $\mathbb{Q}_p$, the $p$-adic numbers.

(4.6a) Dèbes and Emsalem, separately Wewers, used a Deligne-Mumford compactification for Fried’s result showing $G_{\mathbb{Q}}$ permutes Harbater-Mumford components.

(4.6b) A Modular Tower in (3.54c) over $\mathbb{Q}$ is subject to the Main Modular Tower conjecture: For any number field $K$, high tower levels should have no $K$ points. Else, one fell-swoop would give RIGP realizations of the mysterious sequence $\{G_u\}_{u=0}^{\infty}$. 
(4.6c) For each allowable pair \((G, \ell)\), Dèbes and Emsalem applied (3.54c) to a fixed Harbater-Mumford \((G, C)\) to regularly realize the whole uniform sequence of groups \(\{ (G_u) \}_{u=0}^{\infty} \) over \(\mathbb{Q}_{p,\text{unr}}\), for each \(p\) not dividing \(|G|\).

Fried formulated the likely generalization of Harbater-Mumford triples \((G, C, \ell)\), under the Modular Tower assumptions, referring to \(C\) as \(g'\ell\). For such \(C\), we can explicitly label the components of \(\mathcal{H}(G, C)\) as being \(g'\ell\) components. Again, in the search for where regular realizations might be hiding, and, in light of the Fundamental Conjecture, where they likely could not be hiding, the following conjectures/results came about.

(4.7a) Fried showed the Fried-Serre lift invariant is trivial for \(g'\ell\) components, and so above such a component there is a nonempty Modular Tower.

(4.7b) Fried conjectured the only Modular Towers with a projective sequence of \(\mathbb{Q}_p\) points must be \(g'\ell\). Emsalem proved a close approximation to this conjecture, and showed the conclusion of (4.6c) holds for these Modular Towers, too.

(4.7c) For \(C\) consisting of \(r = 4\) (or less) elements, Fried gave an explicit proof of the Fundamental conjecture (2005; no \(K\) points at high levels), assuming at any level a \(p\)-cusp. Cadoret and Tamagawa (2008) gave a general inexplicit proof.

Explicit in (4.7c) means Fried developed a formula for the genus of reduced Hurwitz spaces (which for \(r = 4\) are upper half-plane quotients). His computations showed, under the \(p\)-cusp condition – expected at high levels of a \(g'\ell\) Modular Tower, the genus of tower levels rises with \(u\), giving the conjecture as an application of Faltings. Cadoret-Tamagawa is a statement on 1-dimensional families of abelian varieties, without explicit spaces attached to them, but also an application of Faltings. Indeed the two proofs relate to the natural \(\ell\)-adic representations hidden in abelianized Modular Towers stemming from (motivic) components of jacobians from level 0. This led to the natural next step.

Going beyond the case \(C\) has \(r = 4\) four classes leads to tower levels of dimension \(r - 3\), and so beyond a use of any present version of Falting’s Theorem. So, for the fundamental theorem, any use even of Lang-Type conjectures requires an intermediate step that supercedes (4.7c).

The following gives the latest material coming from all involved schools.

(4.8a) Development of cases to test if for \(r > 4\), high Modular Towers levels have general type: Have sufficiently many holomorphic differentials. For certain cases, Fried has developed half-canonical differential forms that can be used for this.
(4.8b) Fried, and Cadoret and Tamagawa, have separate approaches and progress giving a Serre Open Image Theorem. In Fried’s formulation this relates the Galois action on the attached \( \ell \)-adic representations to the arithmetic monodromy group of a Modular Tower, whether over a number field or not.

(4.8c) Dèbes has expanded on the Beckmann-Black conjectures on regular realization based on asking if there could be for each \( G \) a finite number of Nielsen classes corresponding to \((G, C_1, \ldots, C_v)\) so that each regular realization of \( G \) is obtained from pullback of a cover \( \mathbb{P}^1 \rightarrow \mathbb{P}^1 \) of a cover from \((G, C_i)\) for some \( i \in \{1, \ldots, v\} \).

Dèbes and Legrand have produced an invariant that gives a minimal value of \( v \) (dependent on \( G \)). They have computed that invariant in several cases, thereby showing that one Nielsen class \((v_G = 1)\) will not suffice for most groups \( G \). Whether some finite \( v_G \) will always work is still unknown, but it does in some known cases.

### 4. Arithmetic/Geometric monodromy in a MT

§4.1 starts with the key definition – eventually Frattini – that leads quickly to the conjectures that guide us to formulating a generalization of Serre’s OIT.

As defined in Ch. 1 (1.10), the sequences \( k_G \rightarrow G \) that define MTs are \( \ell \)-Frattini covers of \( \mathcal{H}_G = G \). A general case of what we are after would start with \( C, \ell' \) conjugacy classes in \( G, r = r_C \), for which we investigate Question 4.1.

**Question 4.1.** Do the monodromy groups over \( J_r \) of levels of a MT from \( \{H(k_G, C)\}^{\text{in.rd}}_{k=0} \) inherit eventually \( \ell \)-Frattini properties from the defining covers in their Nielsen class definition.

A paraphrase of the full conjectures is that MTs are sequences of moduli spaces whose monodromy groups over the configuration space \( J_r \), and even all their decomposition groups, inherit this eventually \( \ell \)-Frattini property from the moduli problem that defines them.

That moduli problem starts from the RIGP. A case that keeps us close to both problems, where the \( \ell \)-Sylow of \( G \) is both normal and abelian starts in Ch. 3 (3.48).

**4.1. Eventually Frattini sequences.** Prop. 4.3 gives a first consequence of the eventually Frattini property that suffices as a weak OIT, and thereby OIT-Conj\(_1 \) (Conj. 4.5) for MTs that they will satisfy this property. OIT-Conj\(_2 \) is much stronger; even in Serre’s OIT there are still unsolved aspects of it.

**Definition 4.2.** Refer to a sequence of covers of finite groups

\[ \cdots \rightarrow H_{k+1} \rightarrow H_k \rightarrow \cdots \rightarrow H_1 \rightarrow H_0 = G \]
as eventually Frattini (resp. eventually ℓ-Frattini) if for some \( k_0, H_{k_0+l} \to H_{k_0} \) is a Frattini (resp. ℓ-Frattini) cover for \( l \geq 0 \).

Suppose the projective limit of the \( H_k \)'s is \( \tilde{H} \). We say \( \tilde{H} \) is eventually Frattini since the same property will hold for any cofinal sequence of quotients.

Notation for the extension of the OIT uses Serre’s case in §4.2. In our main example, as we do in Serre’s case, we use the relation between two systems of Nielsen classes:

\[
\{ \text{Ni} \left( D_{k+1}, C_{2^l} \right) \}_{k=0}^{\infty} \text{ and } \{ \text{Ni} \left( \mathbb{Z}/2, C_{2^l} \right) \}_{k=0}^{\infty}.
\]

We generalize that relation below before applying it to our case. A reader will benefit from seeing that relation in detail on Serre’s case in Ch. 6 §3.3.

Assume \( \mathbb{H}_{G,C} \) def \( \{ H_k(G, C) \}_{k=0}^{\infty} \), with, say, \( \dagger \) either inner or absolute equivalence, is a tower of Hurwitz spaces defined by the universal abelianized Frattini cover of a group \( G \), with conjugacy classes \( C \) for which \( (N_C, \ell) = 1 \).

Consider a MT: \( \mathbb{H}' \) def \( \{ H'_k \}_{k=0}^{\infty} \subset \mathbb{H}_{G,C} \). The levels of \( \mathbb{H}' \) have definite fields as moduli spaces (as in Def. 4.8). Then, consider the collection of geometric covers \( \{ \Phi_k : H'_k \to J_r \}_{k=0}^{\infty} \) and their corresponding geometric (resp. arithmetic) monodromy groups \( \{ \tilde{G}_{\Phi_k} \}_{k=0}^{\infty} \) (resp. \( \{ \hat{G}_{\Phi_k} \}_{k=0}^{\infty} \)).

Even if, for a given \( k \), it is possible to take a lower definition field of the cover, say, as in Ex. 4.17, that won’t be the right definition field for the RIGP and OIT applications. Denote the projective limit of this sequence by \( \tilde{G}_{h'} \) (resp. \( \hat{G}_{h'} \)).

Here is the first property necessary to generalizing the OIT to a MT,

**Proposition 4.3 (Weak OIT).** Assume \( G_{\Phi_{\infty}} \) is eventually ℓ-Frattini. Then, for a general point \( j' \in J_r(\overline{\mathbb{Q}}) \), the decomposition group of a projective sequence of points \( \{ p_{k,j'} \}_{k=0}^{\infty} \) lying over \( j' \) is \( \tilde{G}_{\varphi_{\infty}} \).

More generally, suppose for \( j' \in J_r(\overline{\mathbb{Q}}) \), the (arithmetic) decomposition group \( D_{j'} \) of a projective sequence of points \( \{ p_{k,j'} \}_{k=0}^{\infty} \) on \( \mathbb{H}' \) lying over \( j' \) intersects \( \tilde{G}_{h'} \) in an eventually ℓ-Frattini subgroup \( D_{j'}^{\geq} \). Then, \( D_{j'} \) is RETURNM.

**Proof.** RETURNM

**Definition 4.4.** If If each MT on \( \mathbb{H}_{G,C} \) satisfies the hypothesis of Prop. 4.3, we say \( \mathbb{H}_{G,C} \) has the Weak OIT property.

**Conjecture 4.5 (OIT-Conj1).** Each MT has the weak OIT property.

**Conjecture 4.6 (OIT-Conj2).** Each MT has the strong OIT property.

**Remark 4.7.** Any open subgroup of \( \tilde{H} \) will also be eventually Frattini (resp. ℓ-Frattini). Further, if \( G^* \to G \) is a Frattini cover of finite groups, then the pullback sequence consisting of \( H_{k_0} \times_G G^*, k \geq 0 \) will be eventually Frattini over \( G^* \). RETURNM.
4.2. Monodromy of $X_0(\ell^{k+1}) \to \mathbb{P}^1_j$. Here is a reminder of the eventually $\ell$-Frattini properties and their application to Hilbert’s Irreducibility Theorem from Serre’s OIT.

(4.9a) For $\ell > 3$, $k_0 = 0$ (resp. $\ell = 3$, $k_0 = 1$; $\ell = 2$, $k_0 = 2$) and $k \geq k_0$:
$$\text{SL}_2(\mathbb{Z}/\ell^{k+1})/\langle \pm I_2 \rangle \to \text{SL}_2(\mathbb{Z}/\ell^{k_0+1})/\langle \pm I_2 \rangle$$ is $\ell$-Frattini, $l \geq 0$.

(4.9b) (a) says for this case ($0 \in \mathcal{G}$): $M(0, G, C_{34})$ is eventually $\ell$-Frattini; $\ell$-Frattini for almost all $\ell$.

(4.9c) Take $x^j = \{ x_{\ell, k+1} \in X_0(\ell^{k+1}) \} \in \mathcal{X}_{\ell, j}$, a projective sequence over $j' \in U_j(K)$; and $H(x^j)_K$ its arithmetic monodromy.

(4.9d) If $H(x_{\ell, k_0+1}) = \text{GL}_2(\mathbb{Z}/\ell^{k_0+1})/\langle \pm I_2 \rangle$, then $H(x^j) = \text{GL}_2(\mathbb{Z}_{\ell})/\langle \pm I_2 \rangle$.

[Se68, IV-23, Lem. 3 and IV-28, exer. 3] [FrH14, Lem. 3.4]

4.3. Jacobian Nielsen class. Consider an inner Nielsen class $\text{Ni}(G, C)^{in}$ with $G < G^*$ for which the natural extension of $C$ to $G^*$ gives nonempty Nielsen classes, $\text{Ni}(G^*, C)$. An example we have been using is $G = A_4$, $G^* = A_5$, and $C = C_{3,2}$ extended to $A_5$ where the proper notation – in the latter where there is only one class of 3-cycles – is $C_{3,4}$. This example alone shows that the results can be quite different, as there are two braid orbits on $\text{Ni}(A_4, C_{3,2})$, but just one on $\text{Ni}(A_5, C_{3,4})$, though for both their compactified components give genus 0 covers of $\mathbb{P}^1_j$ (Prop. 3.16). Here we consider the process of going from $\text{Ni}(G, C)^{in}$ to


Remark 4.8. Note the difference with the lift invariant if you include a conjugacy class of order divisible by $\ell$.

Denote the conjugacy class of $g \in G$ by $C_g = C_{G,g}$.

(4.10a) Frattini cover $G^* \to G$: Group cover with restriction to any proper subgroup of $G^*$ not a cover.

(4.10b) Schur-Zassenhaus: If $g \in G$ and $(|g|, |\ker(G^*/G)|) = 1$, then
$$C_g$$ lifts uniquely to $C_{\hat{g}}$, $\hat{g} \in G^* \to g \in G$ with $|\hat{g}| = |g|$.

(4.10c) Central Frattini extension: $\psi : R \to G$: $\ker(R \to G)$ is a quotient of the Schur multiplier, $\text{SM}_G$, of $G$.

(4.10d) Lift invariant if $C$ is $(p'$ for $p$ dividing $\ker(\psi)) : \ast^{10}$

For $g \in \text{Ni}(G, C)$, $s_{R/G}(g) = \prod_{i=1}^{r} \hat{g}_i \in \ker(R/G)$. 
4.5. $M(G, p, C)$ monodromy statement.

- **Rank 0 Conj.** Any Modular Tower has geometric monodromy (over $J_r$; over $\mathbb{P}^1$ when $r = 4$) eventually $p$-Frattini.

- **$r = 4 \Rightarrow MT$ levels are upper half-plane quotients.**

- **Rank $t \geq 0$ Conj.** Start with $(\mathbb{Z})^t \times H$. Take $G_p = (\mathbb{Z}/p)^t \times H$ and $C$ appropriate.

Then, for a. a. $p$ the Modular Tower is $p$-Frattini:

the $p$-Frattini conclusion for modular curves holds here, too.\textsuperscript{*12}
Comparing general MTs with Serre’s case

$G_K$ orbits on generators of $\ell$-adic lines (with a $\mathbb{Z}/2$-action) on elliptic curve $\ell$-adic 1st cohomology.

1. The Comparison Framework

1.1. Analog to $X_0(\ell^{k+1})$ and $X_1(\ell^{k+1})$ Modular Curves.

(5.1a) All modular curves came from a rank 1 $(D = \mathbb{Z} \times^s \mathbb{Z}/2, C_{2^1})$, or a rank 2

$(2D = (\mathbb{Z})^2 \times^s \mathbb{Z}/2, C_{2^1})$ MT.

(5.1b) To illustrate general ideas:

$D, 2D \Rightarrow G = (\mathbb{Z})^2 \times^s \mathbb{Z}/3, 2G = (\mathbb{Z})^4 \times^s \mathbb{Z}/3.$

(5.1c) $\mathbb{Z}/3 = H = \langle \alpha \rangle$ action on $(\mathbb{Z})^2$: Through $\alpha = \left( \begin{array}{cc} 0 & 1 \\ -1 & -1 \end{array} \right)$, induced on $V_{p^{k+1}} = (\mathbb{Z}/p^{k+1})^2$, and on $2V_{p^{k+1}} = (\mathbb{Z}/p^{k+1})^4$.

$C = C_{\pm 3^2}$ – two copies each of $\alpha$ and $\alpha^{-1}$.

1.1.1. Reduced spaces for $\ell = 2$. Return to Comment on (2.35d).

(5.2a) Our case: $\ell$-adic $H^1$ of genus 2 curves with $\mathbb{Z}/3$ (faithful) action. Compare $G_K$ orbits of 2-dimensional $p$-adic subspaces preserved by $\mathbb{Z}/3$ with MT arithmetic monodromy.

(5.2b) Last slides: Defy mysterious correspondences –Grothendieck (late ’60s):

Detect $G_\mathbb{Q}$ non-conjugate MTs. Cusp geometry $\Rightarrow$ definition fields of level $k$ MT components.

- Branch-Cycle Lemma;
- Fried-Serre Lift invariant on a small Heisenberg group; and
- Weil pairing from a large Heisenberg group.

2. Computation of the Lift Invariant

Michael Fried ¡michaeldavidfried@gmail.com¡ Subject: I thought to add something that I could not include in my one page on what was accomplished on the Open Image Theorem case at Chern Institute Date: January 27, 2017 at 8:44:22 PM MST To: Pierre Dbes ¡Pierre.Debes@univ-lille1.fr¡, Benjamin Collas ¡benjamin.collas@gmail.com¡

Why my first attempt to write the one page failed is explained by my trying to include something of what is below. It just wasn’t possible.
In my writeup I used the term $K$-bound, meaning a Modular Tower had all levels defined over a specific field $K$ (number field usually). The basic result for an OIT is a comparison of what happens in the Decomposition group of a Modular Tower to the Arithmetic monodromy group of the tower. There is a hard, NECESSARY initial step: You must show that the geometric tower monodromy is almost $\ell$-Frattini ($\ell$-Frattini from some point on) and $\ell$-Frattini for almost all $\ell$.

Part of the structure that works with Modular Towers is that the monodromy action of the base on the fibers of the tower is through (a subgroup of) the braid group. The family of Hurwitz spaces I took at Chern had a full set of primes, and four repetitions of a particular conjugacy class, so I could fully compare with modular curve towers. (As always, when there are four conjugacy classes, the reduced Hurwitz space levels are upper-half plane quotients ramified at the expected three points. Of course, these aren’t modular curves, and they aren’t defined by congruence subgroups, or I wouldn’t have taken them.

Unlike modular curves there are several types of Modular Towers. Recall, a(n abelian) Modular Tower is a projective sequence of irreducible components on a sequence of Hurwitz spaces defined by the $\ell$-Frattini (abelianized) characteristic quotients given by a finite group.

These distinct Modular Towers for a given prime $\ell$ are separated by their lift invariants for the appropriate group. Here that comes, for each $\ell$, from the small Heisenberg group for the prime $\ell$. (Recall: For alternating groups it was their spin cover.)

1. Type 1 have Fried-Serre lift invariant that is $\ell'$, falling in $(\mathbb{Z}_\ell)^*$ (it makes sense to take a projective limit of the lift invariants of the levels). At each level the components are all conjugate over $\mathbb{Q}$. There is formula for the lift invariant, different (of course) than the formula for the Alternating groups as given by Fried-Serre. Finding that formula is the hardest result in the paper. The definition field result is a special case of a general theorem never in print previously.

2. Type 2 modular towers have lift invariant in ker($\mathbb{Z}_\ell \to \mathbb{Z}/\ell$). Mod $\ell$ these are Harbater-Mumford components. There are several of them – a precise number dependent on $\ell$ – for each $\ell > 6$. I describe these Modular Towers explicitly.

For Type #2, I still have unanswered questions about component definition fields. For example, for the pure Harbater-Mumford types, I don’t know if they are $\mathbb{Q}$-bound, since their lift invariants are 0. This is the best test case I have found for guessing precisely between Towers that have or do not have a $\mathbb{Q}$-bound. I have decided to publish the paper leaving this a puzzle.
3. Our main example, and the Small Heisenberg group

In our examples, we will be illustrating Propositions 3.1, 3.2 and 3.5 of Ch. 1. Denote \((\mathbb{Z}/\ell^{k+1})^2\) by \(\ell^{k+1}V\) and \(\ell^{k+1}V \times \mathbb{Z}/3\) by \(\ell G\). In §3.1 we start with the analog of \(X_1(\mathbb{Z}/\ell^{k+1})\) (for which there is a natural analog also of \(X_0(\mathbb{Z}/\ell^{k+1})\)).

Then, as in the modular curve case Ch. 6 §3.3.1, we go to a Jacobian version in §4. Here we will change from \(\ell G\) to

\[
(5.3) \quad \ell^{k+1}G_{\text{jac}} \overset{\text{def}}{=} (\ell^{k+1}V)^2 \times \mathbb{Z}/3 \quad (C = C_{3,32} \text{ remains the same}).
\]

Analogous to the dihedral case with \(\ell = 2\), until §3.3.1, we avoid \(\ell = 3\). Then:

\[
(5.4) \quad \ell^{k+1}V \pmod{\ell} \text{ has a 1-dimensional } \alpha\text{-eigenspace}
\]

if and only if \(\alpha^2 + \alpha + 1 \equiv 0 \pmod{\ell}\) has a solution \(\leftrightarrow \ell \equiv 2 \pmod{3} \).

**Definition 3.1** (\(\alpha\)-span). For \(\ell^{k+1}G\) (resp. \(\ell^{k+1}G_{\text{jac}}\) in (5.3)) a subset \(U\) of \(\ell^{k+1}V\) (resp. \((\ell^{k+1}V)^2\)) is said to \(\alpha\)-span if \((U, \alpha U) = \ell^{k+1}V\) (resp. \((\ell^{k+1}V)^2\)).

3.1. The Small Heisenberg group. The key group in this section is the Small Heisenberg group for \(\ell > 3\):

\[
(5.5) \quad \mathbb{H}(\mathbb{Z}/\ell^{k+1}) = \left\{ M(x, y, z) \overset{\text{def}}{=} \begin{pmatrix} 1 & x & z \\ 0 & 1 & y \\ 0 & 0 & 1 \end{pmatrix}, x, y, z \in \mathbb{Z}/\ell^{k+1} \right\}.
\]

So, there is a natural map

\[
\psi_{\mathbb{H}} : \mathbb{H}(\mathbb{Z}/\ell^{k+1}) \to \ell^{k+1}V : M(x, y, z) \mapsto (x, y) = v \in \ell^{k+1}V,
\]

for which \(\ker(\psi_{\mathbb{H}}) = \mathbb{Z}/\ell^{k+1}\). As in Ex. 2.7 we use the left action (here of \(\mathbb{Z}/3\)) to describe the extension of \(\mathbb{Z}/3 = \langle \alpha \rangle\) to the group of (5.5).

**Lemma 3.2.** For \(\ell > 2\) each element in \(\mathbb{H}(\mathbb{Z}/\ell^{k+1})\) has order \(\ell^{k+1}\). By contrast, \(\mathbb{H}(\mathbb{Z}/\ell^{k+1})\) has elements of order \(2^{k+2}\), and for \(k = 0\) it is \(D_4\), dihedral of order 8.

**Proof.** Write \(M(x, y, z)\) as \(\text{Id}_3 + A\) and put it to the \(\ell^{k+1}\) power. Since \(A^u\) is the 0 matrix for \(u > 2\), the expansion gives

\[
\text{Id}_3 + \ell^{k+1}A + \frac{\ell^{k+1}(\ell^{k+1} - 1)}{2} A^2
\]

which is \(\text{Id}_3\) unless, \(\ell = 2\) and \(\frac{\ell^{k+1}(\ell^{k+1} - 1)}{2}\) \cdot \(xy\) is nonzero \(\pmod{\ell^{k+1}}\), or \(xy\) \(\pmod{2}\) is nonzero. Therefore, for \(k = 0\), the group is nonabelian and has two classes of elements of order 2. So is dihedral. \(\square\)

3.1.1. Conjugacy classes. Use \(\psi_{\mathbb{H}}\) (with \(\ell\) and its power understood) even with the \(\mathbb{Z}/3\) action. The conjugacy class lift of \(\alpha_0 = \begin{pmatrix} \alpha & 0 \\ 0 & 1 \end{pmatrix}\) to \(\ell^{k+1}G\) is

\[
(5.6) \quad \{ \begin{pmatrix} 1 & v \\ 0 & 1 \end{pmatrix}\alpha_0 \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \alpha & v^{-\alpha}v \\ 0 & 1 \end{pmatrix} \overset{\text{def}}{=} \alpha_v \mid v \in \ell^{k+1}V \}.
\]

We often use \(1 - \alpha v\) for \(v - \alpha v\). Similarly, \(\alpha_v^{-1} = \begin{pmatrix} \alpha^{-1} & 1 - \alpha^{-1}v \\ 0 & 1 \end{pmatrix} \).
Denote the $n \times n$ identity matrix by $\text{Id}_n$. For example, $\left( \begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array} \right) = \text{Id}_2$.

The action of $\alpha$ comes from the permutation action of $S_n$ on $\mathbb{Z}^n$ (here $n = 3$). Then, mod out by the $S_n$ stable module $\langle (1, \ldots, 1) \rangle$, to get $\mathbb{Z}^{n-1}$.

Elements in $\text{Ni}(\frac{k+1}{\ell}G, C_{\pm 32})^n$ will be 4-tuples with entries denoted either $\alpha_v$ or $\alpha_v^{-1}$. Each element in the Nielsen class is inner equivalent to an element in

\begin{equation}
(5.7) \quad T_{\pm \pm} \overset{\text{def}}{=} \{ g_{v_2, v_3} = (\alpha_0, \alpha_{v_2}^{-1}, \alpha_{v_3}^{-1}) \}.
\end{equation}

with the correct extra notation, say $\ell^{k+1}$, understood.

**Lemma 3.3.** Since $\frac{k+1}{\ell}V \rightarrow \frac{1}{\ell}V$ is a Frattini cover, $v \in \frac{k+1}{\ell}V$ $\alpha$-spans if and only if $v \mod \ell$ is in no $\alpha$ eigenspace. By Def. 3.2, an HM rep. in $T_{\pm \pm}$ has $v_2 = 0$, with $v_3 \mod \ell$ in no $\alpha$ eigenspace. From product-one,

\begin{equation}
(5.8) \quad \alpha_{v_2} \alpha_{v_3}^{-1} = \left( \begin{array}{ll}
\alpha & 1 \\
0 & 1
\end{array} \right) \left( \begin{array}{ll}
\alpha^{-1} & 1 \\
0 & 1
\end{array} \right) = \text{Id}_2; \text{ or } 1 - \alpha(v_3 - v_4) = 0.
\end{equation}

That is, $v_3 = v_4$ since $\ker(1 - \alpha) = 0$.

**Proof.** For generation to apply, $\langle \alpha_0, \alpha_{v_3} \rangle = \frac{k}{\ell}G$. Since $\frac{k+1}{\ell}G \rightarrow \frac{0}{\ell}G$ is a Frattini cover, we need only consider when

\[ \langle \alpha_0, \alpha_{v_3} \mod \ell \rangle = \langle \alpha_0, \alpha_0^{-1} \alpha_{v_3} \mod \ell \rangle = \frac{0}{\ell}G. \]

That happens if and only if $1 - \alpha v_3 \alpha$-spans. If $\alpha v_3 = \mu v_3$, $\mu \in \mathbb{Z}/\ell^{k+1}$, then $1 - \alpha v_3 = (1 - \mu) v_3$, an invertible relation. This shows $v_3 \alpha$-spans, and it does $\alpha$-span if and only if it defines an HM rep. by the formula above. $\square$

3.1.2. The lift invariant and DI elements. We already saw the definition of DI elements in the case of $G = A_4$ for the conjugacy classes $C = C_{\pm 32}$.

**Definition 3.4** (D(ouble)I(dentity)). DI elements in $T_{\pm \pm}$ are those for which either $v_3 = 0$, or $v_2 = v_4$.

Prop. 3.5 expands on the exercises [Br82, p. 97, Ex. 8 and p. 127, Exs. 4-5] to describe the Comm part of the universal coefficient theorem for $q = 2$ when $G$ is abelian. Cor. 3.6 concludes that the small Heisenberg group is the universal central extension of $\frac{k}{\ell}G$.

**Proposition 3.5.** Given a central extension $A \rightarrow E \rightarrow B$ with $B$ abelian, denote the factor set associated to it in Ch. 1 §1.2.2 by $c_e$. Define $\tilde{c}_e : B \times B \rightarrow A$ by $(b_1, b_2) \mapsto c_e(b_1, b_2) - c_e(b_2, b_1)$. With $\Lambda^2(B)$ the second exterior product of $B$, this gives a map of $H^2(B, A)$ to $\text{Hom}(\Lambda^2(B), A)$, with the Ext extensions in the kernel. This produces an exact sequence:

\begin{equation}
(5.9) \quad 0 \rightarrow \text{Ext}(B, A) \rightarrow H^2(B, A) \xrightarrow{\tilde{c}_e} \text{Hom}(\Lambda^2(B), A) \rightarrow 0
\end{equation}

\[ 1 \Lambda^2(B) = B \otimes B/(b_1 \otimes b_2 - b_2 \otimes b_1 \mid b_1, b_2 \in B) \]
that is (3.17) in disguise with $\Lambda^2(B)$ identifying with the Schur module $H_2(B, \mathbb{Z})$, for $B$.

PROOF. Consider a central $\ell$-Frattini extension $\psi : H \to B$ defined by a factor set $c_\ell : B \times B \to A$ as in Ch. 1 §1.2.2. With $A = \ker(\psi)$, that gives an element of $H^2(B, A)$. From Cor. 2.6, commutators of $H$ that lie in $\ker(\psi)$ determine the lift invariant to $\psi$. With, however, $B$ abelian, any commutator $h_1h_2^{-1}h_2^{-1}$ is in $\ker(\psi)$. Further, using the factor set, in the description of this extension, we may write this commutator as

$$
(\begin{pmatrix} \ell & a_1 \\ 0 & 1 \end{pmatrix}) (\begin{pmatrix} b_2 & a_2 \\ 0 & 1 \end{pmatrix}) (\begin{pmatrix} \ell & a_1 \\ 0 & 1 \end{pmatrix})^{-1} = (\begin{pmatrix} \ell & b_1 \cdot b_2 \ast (a_1 + c_\ell(b_1, b_2)) \\ 0 & 1 \end{pmatrix}) (\begin{pmatrix} b_2 & b_2 \ast a_1 + a_2 + c_\ell(b_2, b_1) \\ 0 & 1 \end{pmatrix})^{-1}.
$$

Now apply that $b_1b_2 = b_2b_1$ ($B$ abelian) and $b_2 \ast a_1 = a_1$ (central extension) etc. to conclude the result is $c_\ell(b_1, b_2)$ as given in the statement of the lemma.

This shows that the Comm part of $H^2(B, A)$ maps through $\text{Hom}(\Lambda^2(B), A)$, as in Def. 2.2 or Def. 2.5 and Rem. 2.7, with kernel the Ext part. The resemblance of this sequence to the universal coefficient theorem (3.17) suggests that $\Lambda^2(B)$ identifies with the Schur module $H_2(B, \mathbb{Z})$, for $B$.

Indeed, [Br82, V. Thm. (6.4) (iii)] (with $k = \mathbb{Z}$) says exactly that. Then, with the substitution of $\Lambda^2(B)$ for $H_2(G, \mathbb{Z})$ in (3.17) for $q = 2$, [Br82, Exs. 4. (a) and 5] says the sequences may be identified through the map $\tilde{c}_\ell$ above. Ch. 6 §7?

\[ \square \]

COROLLARY 3.6. Extend $\mathbb{Z}/3$ on $B = \mathbb{Z}_{\ell}^{k+1}$ to $\mathbb{H}(\mathbb{Z}/\ell^{k+1})$ by acting trivially on $\ker(\psi_{\mathbb{H}(\mathbb{Z}/\ell^{k+1})})$. Thus, $\mathbb{H}(\mathbb{Z}/\ell^{k+1}) \times \mathbb{Z}/3$ is the universal central extension of $\mathbb{Z}/\ell^{k+1}$ $G$ for $\ell > 3$. For $\ell = 2$, it is

PROOF. In the case at hand, $B = \mathbb{Z}_{\ell}^{k+1}$. Then, $\Lambda^2(B)$ is a 1-dimensional $\mathbb{Z}/\ell^{k+1}[B]$ module. We show $\mathbb{Z}/3$ acts trivially on it. The action of $\alpha$ is through $(\mathbb{Z}/\ell^{k+1})^\ast$, of order $(\ell-1)^{\ell}$, if the action for $k = 0$ is trivial then, on the kernel the action is an element of order $\ell$ contrary to the order of $\alpha$. So, it suffices to see the action is trivial for $k = 0$.

If $\ell \equiv 2 \mod 3$ then $\alpha$ acts irreducibly on $B$. So, it has no eigenvectors in $\mathbb{Z}/\ell$, and it must act trivially. If, however, $\ell \equiv 1 \mod 3$, then $\alpha$ has two distinct eigenvalues $a_1, a_2$, for vectors $v_1, v_2 \in B$ with product 1 (the constant coefficient of $\frac{a^2}{x-1}$). Then, $\Lambda^2(B)$ is generated by $v_1 \wedge v_2$ on which $\alpha$ acts as $v_1 \wedge v_2 \mapsto \alpha(v_1) \wedge \alpha(v_2) = a_1a_2v_1 \wedge v_2 = v_1 \wedge v_2$.

This proves the claim. \[ \square \]

In the next proposition denote $\text{Ni}(k_{\ell}^{+1}G, \mathbb{C}_{\pm 3^2})$ (resp. $\text{Ni}(k_{\ell}^{+1}G, \mathbb{C}_{\pm 3^2})^\ast$) by $\text{Ni}_{\ell^{k+1}, 3^2}$ (resp. $\text{Ni}_{\ell^{k+1}, 3^2}$).
Proposition 3.7. Elements of $\text{Ni}_{\ell k+1,3^3}$ have representatives of form
\[ g_w = (\alpha_0, \alpha_{w_2}, \alpha_{w_3}) \text{ with } w_3 = -w_2^2. \]

All \( g^* \in \text{Ni}_{\ell k+1,3^3} \) have lift invariant \( s_{3^3}(g^*) \in (\mathbb{Z}/\ell k+1)^* \subset \ker(\psi_{3^3}). \)

If for some some \( g^* \in \text{Ni}_{\ell k+1,3^3} \) \( s_{3^3}(g^*) = \mu \), then \( \mu = s_{\pm 3^2}(g) \) for \( g \in \text{Ni}_{\ell k+1,\pm 3^2} \) a DI element [FrH15, Prop. 4.18].

Elements with $\ell$-divisible lift invariant and DI reps. have distinct braid orbits.

Main orbit result on $\text{Ni}(\mathbb{Z}G, \mathbb{C}_{+3^2-3^2})^{\text{in,rd}}$ uses this quantity for $\ell > 3$: \( K_\ell = \ell \pm \frac{1}{6}, \ell \equiv \mp 1 \mod 3 \).

We have already done the result for $\ell = 2$ (and $k = 0$) in Ch. 2 §3.16, where there is one HM and one DI orbit. That case is different in ways from the case of general $\ell$, but mostly because the maximal $\ell$-central Frattini cover is of a different nature for $\ell = 2$, than for $\ell > 3$.

Corollary 3.8 (Level 0 Main Result). For $\ell > 3$ prime and $k = 0$:

(5.11a) Classes with trivial lift invariant fall in $K_p$ HM braid orbits. Each intersects $T_{\ell,\pm 1 - \text{deg}}$ in $\ell(\ell-1)$ elements.

(5.11b) Orbits have nontrivial lift invariant if and only if they are double identity, and that distinguishes the orbits.

(5.11c) Each DI orbit intersects $T_{\ell,\pm 1 - \text{deg}}$ in $K_\ell(\ell-1)$ elements.

§3.1.3 gives the proof of Prop. 3.7 and its corollary, starting from a general idea of computing the universal $\ell$-Frattini extension. §3.1.4 gives a complete description of the braid orbits on these Nielsen classes at all levels. This is an example of where we are able to gives succinct labels to braid orbits based on the types of cusps they contain. That is, at the end of this subsection we precisely know all the braid orbits on $\text{Ni}_{\ell k+1,\pm 3^2}$ for all $\ell$, $(\ell, 3) = 1$, and all $k$.

Remark 3.9. Notation of (5.6) is compatible with Ch. 6 §3.3 for an entry in $g \in \text{Ni}(D_{\ell k+1}, \mathbb{C}_{2^2})$ is \( \begin{pmatrix} -1 & a \\ 0 & 1 \end{pmatrix} \). A more precise analog would be the conjugate
\[ \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -a \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 2a \\ 0 & 1 \end{pmatrix}. \]

Still, with $(\ell, 2) = 1$, there was no loss – and improved notation – in replacing $2a$ by $a$, and regarding \( \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \) as the analog of $\alpha_0$.

3.1.3. Proof of Prop. 3.7.

3.1.4. Proof of Cor. 3.8.

\footnote{Ch. 6 §3.3 makes the large adjustments in Serre’s case for preserving the rubric even when $\ell = 2$, as we will do for this case with $\ell = 3$.}
3.2. 1-degenerates in $\Ni(G^k_{p+1}, C^{3^2+3^2})$in.

- $g_\nu_2, \nu_3 \in T_{\pm \pm}$: product-one $\iff \nu_2 - \nu_3 + \nu_4 = 0$.
- Generation $\iff \langle \nu_2, \nu_3, \nu_4 \rangle$ contains an $\alpha$-gen. of $V^k_{p+1}$.
- 1-degeneracy: $\langle \nu_2, \nu_3, \nu_4 \rangle \cong \mathbb{Z}/p^{k+1}$. Since $p \neq 2$ this is equivalent $\nu_j = m_jp$ with $\nu = \nu_i$ for some $i, j = 1, 2, 3$.

$K^* = \langle q_2^2, q_3^2, sh \rangle$ is the stabilizer of the collection $T_{\pm \pm} \mod Q''$ with $[K^* : \langle q^2_2, q^2_3 \rangle] = 2$.

3.3. Braid orbits $\iff$ 1-degenerates, $T_{\pm, 1-deg}$, in $T_{\pm \pm}$.

3.3.1. The case $\ell = 3$.

4. The Jacobian case, (5.1b)

As above, denote $(\mathbb{Z}/\ell^{k+1})^2$ by $\ell^{k+1}V$ and $(\ell^{k+1}V)^2 \times \mathbb{Z}/3\ell$ by $\ell^kG^\text{jac}$. Then, the Hurwitz spaces on which we form our MTs is given by the Nielsen class $\Ni(\ell^kG^\text{jac}, C^{3^2}) \overset{\text{def}}{=} \Ni(k^{k+1+3^2}_3)$. This is an analog of the modular curve (Jacobian) case given by the notation of Ch. 6.3.1.

Below we refer to the 1st (resp. 2nd) copy of $k^{k+1}_3$ in $(\ell^kV^2)^2$ as the 1st (resp. 2nd) $\frac{1}{\ell}$-space. As in Rem. 2.17, there are good reasons for dealing with decomposable $\ell$-Frattini kernels for all $\ell$ in the Jacobian cases.

4.1. Jacobian Nielsen classes. An analog of $T^\pm_{\pm \pm}$ represents braid orbits of

$$\Ni(\ell^{k+1}G^\text{jac}, C^{3^2}) \overset{\text{def}}{=} \Ni(k^{k+1+3^2}_3)$$

where we understand that $(\nu_2, \nu_2'), (\nu_3, \nu_3')$ determine $(\nu_4, \nu_4')$ (from product-one) and they $\alpha$-span $(\ell^{k+1}V)^2$. Lem. 4.1 says we may take an element $g_{\nu_2, \nu_2'} \in T_{\pm \pm jac}$ so that $\nu$ is in one of the normal forms – HM or DI – given by Cor. 3.8.

From product-one,

$$\ell^{k+1}G = \langle \alpha_0, \alpha_0^{-1}(\nu_2, \nu_2'), \alpha_{(\nu_2, \nu_2')}, \alpha_{(\nu_3, \nu_3')}, \alpha_0^{-1} \rangle$$

(5.13)

where $\nu = 0, 0, 0, 0$ (5.8), an HM orbit case; or

$\nu = (0, \nu_3, \nu_3)$, a DI orbit case.

Then, $g_{\nu, \nu'}$ satisfying (5.12) is equivalent, in case (5.14b) (resp. (5.14c)) to $\nu_3$ (resp. $\nu_2$) $\alpha$-spans and then that $(\nu_2', \nu_3') = \ell^{k+1}_3$.

**Proof.** The natural map $\ell^{k+1}_3 G^\text{jac} \rightarrow \ell^{k+1}_3 G$ extends to the Nielsen classes and is compatible with the braid action. Therefore, with no loss for representatives of
braid orbits, assume for \( g_{w,w} \) that \( g_w \) is one of the normal forms for the orbits. To see that the 4th entry gives product-one in (5.14c), check:

\[
\begin{pmatrix}
\alpha & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
\alpha^{-1} & -1^{-1} w_2 \\
1 & 1
\end{pmatrix}
\begin{pmatrix}
\alpha & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
\alpha^{-1} & -1^{-1} w_2 \\
1 & 1
\end{pmatrix}
= \begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
\alpha^{-1} w_2 \\
1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
\alpha^{-1} w_2 \\
1 & 1
\end{pmatrix}.
\]

For (5.12) to hold requires in case (5.14b) (resp. (5.14c)) that \( \nu_3 \) (resp. \( \nu_2 \)) \( \alpha \)-spans \( \ell^{k+1} V \). For (5.14b), apply (5.13). Then,

\begin{equation}
\alpha^{-1} (0, w'_2) \text{ and } \alpha^{-1} (\nu_3, w'_3) \text{ \( \alpha \)-span } \ell^{1^2} V.
\end{equation}

We know that \( \nu_3 \) \( \alpha \)-spans \( \ell^1 V \), but assume \( w'_2, w'_3 \) do not span \( \ell^1 V \), but lie in a 1-dim subspace. Then, RETURNM \( \square \).
CHAPTER 6

Historical Resources and Perspectives

As usual \( \ell \) refers to a key prime of consideration. We could have regarded this chapter as “Appendices,” since the sections are independent, though they are surely more than that. For example, §3 inspects, in revisiting Serre’s version of the OIT to connect to our main definitions, the following topics:

- **eventually \( \ell \)-Frattini** for the primes 2 and 3;
- visualizing of Weil’s pairing on \( H^1(X, \mathbb{Z}_\ell) \) as a *lift invariant*, with \( X \) an elliptic curve;
- connecting the Jacobian Nielsen class \( \text{Ni}((\mathbb{Z}/\ell)^2 \times^* \mathbb{Z}/2, \mathbb{C}^*) \) and the Nielsen class \( \text{Ni}(\mathbb{Z}/\ell \times^* \mathbb{Z}/2, \mathbb{C}^*) \); and
- passing from specific Nielsen classes to modular curves.

We treated it so as a resource for what we do almost everywhere in the book, enhancing our connection to modular curves, though we have gone into territory controlled by curves that replace elliptic curves as the driver of our problems.

We treated it thus, so the reader unacquainted with Serre’s OIT, or perhaps even having forgotten about it, would not have that dominate the mathematical stories featuring the connection between the RIGP and the expanded OIT.

Or quite differently, how in §1.2 – to augment the treatment of the cohomology of extensions starting in Ch. 1 §1.2.2 – we make a path through the huge topics of cohomology of groups and modular representations. We base this on what we learned/used partly from [Nor62], [Br82] and [Be91], and the many appearances of “small” cohomology arguments in both of Serre’s books [Se68] and [Se92].

In a paraphrase here, of a paraphrase of a statement of Serre’s about the RIGP with which I concluded [Fr94],

> it is astonishing what one can learn of cohomological topics from confronting significant extensions of groups.

1. Groups, covers and homological algebra

The word *rank* usually means number of elements required to generate a group or a vector space over a field. If the group is projective, it refers to topological generation, meaning number of elements required to give a subgroup whose closure is the whole group. In special cases, it can refer to the rank, not of the group, but of
a particularly important subgroup. For a group \( H \), we will denote its (topological)
rank by \( \text{rk}(H) \).

Isomorphism is the criterion for two groups to be alike. Some groups are suf-

ciently similar that they will likely collect together in descriptions for the rest of
time. Like (finite) abelian groups or nilpotent groups (§??), with their rank and the
primes dividing their order, standing out as invariants. §1.3 introduces that groups
this book uses to put the Inverse Galois Problem in a context with other classical
problems of arithmetic geometry.

§1.1 notes, for groups arising from covers, that pure isomorphism isn’t the point.
It also shows how Frattini cover constructions relates to other structural group
constructions, literally going back to Galois.

Mathematicians now accept the classification of finite simple groups as a mile-
stone. We don’t expect a reader to know it in any detail; the author is no expert on
it, either. Our goals use as a starting point only examples that most readers would
have had in a first course in algebra.

1.1. Distinctive finite groups from covers. There are tools for “seeing”
groups using the Galois construction for covers. The easiest way for mathemati-
cians, raised on linear algebra, to see groups is through representations of their
elements as matrices. §1.1.2 reminds of those we use in examples. Less comforting,
but still computationally clear, are permutation groups, as in §1.1.1 which reminds
of the topic of pairs \((G,T)\), a group and an attached faithful permutation repre-
sentation. The short section §1.1.1 reminds that for the most part, when regarding

group elements as functions we apply the elements in the order in which they are
written from left to right. Since that goes against the functional notation used in
linear algebra, we note that exception, and why we give it second place in our
considerations.

1.1.1. Notation for group actions. There is a major difference between them
on how they act naturally on elements as functions. Our major computations are
with Nielsen classes (§2.2). These are \( r \)-tuples of elements from groups, usually
are understood to be permutation groups, though they could be elements of some
algebraic, even affine, group.

Right vs Left Action: Computations often appear as a series of actions formed
from a string of group elements, say, written as \( g_1 g_2 g_3 \cdots g_r \), acting. That is the
multiplication is read as

\[ "g_1, \text{ times } g_2, \text{ times } g_3, \ldots". \]

Here we will mean that \( g_1 \) acts first, then \( g_2 \), etc. Nielsen classes consist of arrays,
say, \( \mathbf{g} \), of such elements on which act elements \( g_i \) (called braids) from the Hurwitz
monodromy group $H_r$. Here, two, we sometimes show that action as a series, as in this notation:

$$(g) \mapsto (g)q' \mapsto ((g)q')q'' \mapsto (((g)q')q'')q''$$

read as $q'$ acts, then $q''$ acts on the result, etc. All of this is compatible with reading multiplication from left to right, and so acting from left to right.

When we must make an exception to regard elements of a group as matrices, acting as functions from linear algebra, we do our best to forwarn the reader; noting how someone could switch to our left-right notation if they wanted. Example: In regarding elements of $\text{PGL}_2(\mathbb{C})$ (linear fractional transformations) as acting from matrices we might have,

from the left: $$(\begin{array}{cc} a & b \\ c & d \end{array})(z) \mapsto (az+b cz+d)$$

versus from the right: $$(z) (\begin{array}{cc} a & c \\ b & d \end{array}) \mapsto (az+b cz+d).$$

**Permutation representations:** We give a permutation representation (of degree $n$) as a pair $(G, T)$ with $T : G \to S_n$ a homorphism of groups. Usually we assume $T$ is transitive: for $i, j \in \{1, \ldots, n\}$ there exists $g \in G$ for which $(i)T(g) = j$. If it is transitive, then giving $(G, T)$ is equivalent to giving $(G, H)$ with $H$ a subgroup of index $(G : H) = n$.

A right coset of $H$ in $G$ is a subset $Hm = \{hm|h \in H\}$. That means, $G$ is a disjoint union of precisely $n$ distinct (we usually take right, but if you are consistent, then you can take left) cosets $\bigcup_{i=1}^n Hm_i = G$.

Then the right action of $G$ on these cosets is well-defined and equivalent to the permutation representation whereby we take

$$H = \{g \in G | (1)T(g) = 1\} \overset{\text{def}}{=} G(T, 1).$$

Usually, we also assume $G$ is faithful, or its kernel $\ker(T)$ is $\{1\}$ (trivial). A permutation representation is primitive if between $G$ and $G(T, 1)$ there are no proper subgroups. In constructing covers in §2, these correspond to covers without decomposition: composition as two covers of degree exceeding 1 as in Lem. 2.3.

There is a classification of groups with a primitive permutation representation. Excluding those related to sporadic simple groups, this divides into two types: those based on the series of finite simple groups, and those related to affine groups $[\text{AsS}]$ with the latter not considered classifiable at this time. This result is called the Aschbaker–O’nan–Scott Theorem.

There are well-known problems that reduce to looking at primitive groups, then solved by a combination of arithmetic geometry interpreting a property about ramification groups theoretically (see §1.2.1). Then, group theorists – who knew the classification well – weeded out those primitive groups for which the ramification
groups appear appropriately. These problems usually had precise phrasings on the Arithmetic/Geometric monodromy of a (usually sphere) cover. Thus, they were not pure RIGP problems. [FrGS] may be the first that required having on the team members who know the classification well, to complete an analysis in this style.

I know of no one in print who has undertaken to provide the tools to enhance this classification precisely to general \((G, T)\), because one must be intrepid with these more sophisticated tools to try it. Still, the tools are there, using wreath products and Frattini covers. That suggests that one can treat finite groups that arise from covers in a way that will one day allow names for covers – through the use of their Galois closures (and permutation representations). I think it enhances this book and the idea of a Galois closure to say that.

1.1.2. Special collections of groups. We list a few.

**Nilpotent:** \(G\) is nilpotent if it is a product of its \(\ell\)-Sylows. Each such \(\ell\)-Sylow is a quotient of the free pro-\(\ell\) group of rank (minimally number of generators) the same as the \(\ell\)-Sylow.

**Affine:** A subgroup of \(\text{GL}_n(\mathbb{F}_q)\) is a (finite) algebraic group, for any finite field \(\mathbb{F}_q\).

The natural action of \(\text{GL}_n(\mathbb{F}_q)\) on \((\mathbb{F}_q)^n\) gives the affine group \((\mathbb{F}_q)^n \times \text{GL}_n(\mathbb{F}_q)\).

More generally, if \(H \leq \text{GL}_n(\mathbb{F}_q)\), its restriction to \((\mathbb{F}_q)^n\) is also regarded as an affine group.

1.2. Homological reminders. The short [Br82, Ch. 1 §0] contains many definitions. We will try to be expedient in imitating it by concentrating on what we require for comfort with cohomology of \(R[G]\) modules in computing, say, \(H^2(G, M)\) or \(\text{Ext}^r_G(M, N)\) where \(R = \mathbb{Z}\) or \(\mathbb{Z}/\ell\) or closely related.

As a guide, consider these general comments. In homological algebra, group cohomology, homotopy theory, etc. there are two different objects that get conjoined in treatments. These are sequences of objects – chain complex – in some category,

\[
C \overset{\text{def}}{=} \cdots C_{i+1} \xrightarrow{d_{i+1}} C_i \xrightarrow{d_i} \cdots,
\]

ostensibly infinite in both directions but usually 0 from some point on to the right, with \(d_{i+1} \circ d_i = 0, i \geq 0\). Notationally, we say \(d = \{d_i\}_{i \in \mathbb{Z}}\) has square-zero differential: \(d \circ d = 0\). The expectation is that the construction of such sequences is categorical. The reason d’ etre for them is that, as in Def. 1.7 and Def. 1.8, the quotient of the kernel of \(d_i\) by the image of \(d_{i+1}\), \(H_i(C)\) will meanfully interpret and compute properties of the object(s) \(M\) (and \(N\)) which gave rise to the sequence.

[Br82] takes an historical approach, starting from simplicial complexes, based on topological CW complexes, and the fundamental group \(\pi_1(X)\) of \(X\), a topological space. From that defines the group cohomology of an arbitrary discrete group (from which we can go to a profinite group easily), as given by forming a \(\mathbb{Z}[G]\) projective
resolution of $\mathbb{Z}$ as a trivial $G$ module. The particular projective resolution is formed from the CW structure (with a $G$ action on it) with $C_i$ the chains of dimension $i$, and a map $C_0 \to \mathbb{Z}$ by $\sum_k u_k p_k \mapsto \sum_i u_i$ where the sum is over a finite set of points. The last is called the augmentation map. Then, remove the augmentation map to get a complex whose cohomology is independent of the CW complex structure.

To generalize to group (including finite) homology, with coefficients in a $G$ module $M$, the replacement is to take any projective resolution of $M$, generalizing the augmentation map. Then prove it doesn’t matter which projective resolution you take. The reason is that any one complex $C' \to M$ will have a chain map, $f : C' \to C$, of degree 0 (preserving the subscripts) to any other such complex $C \to M$, preserving the respective maps to $M$, and commuting with the differentials: $f \circ d' = d \circ f$ from using projective modules.

Further, the homology groups will be the same [Br82, Ch. I Thm. 7.5]. There are three specifics to this that lead to general definitions. First: the idea of a homotopy, $h : C' \to C$, $h_i : C'_i \to C_{i+1}$, $i \geq 0$ between chain maps $k f$, $k = 1, 2$.

\begin{equation}
(6.1) \quad h \circ d' + d \circ h = 1 f - 2 f.
\end{equation}

The key in [Br82, Ch. I Thm. 7.5] is that the augmentation preserving chain maps from two different projective resolutions are unique up to homotopy, and therefore the automatic map $f' : C \to C'$ from the same argument, will induce $f \circ f'$ and $f' \circ f$ to both be homotopic to the identity. Clearly, then the homotopy groups are the same.

If you have an explicit chain complex, then you might be able to explicitly interpret/calculate the homology. Certainly that is what happens in Def. 1.8 to interpret $H^2(G, M)$ via the bar resolution. The $H^1$ and $H^2$ interpretations should suffice to indicate what that resolution is in general.

Comments on $\text{Ext}^2_G(M, N)$:

RETURNM Put the right diagram here.

\begin{equation}
(6.2) \quad \begin{array}{c}
E_j' \mod (\pm 1) \quad \text{degree } \ell \text{ isogeny} \quad E_{j}/C_{j+1} \\
\mathbb{P}^1_w \quad \text{degree } \ell \text{ rational function } f \quad \mathbb{P}^1_z \\
\end{array}
\end{equation}

Since this seems to general, it might seem that mere extensions are just a small part of the topic of cohomology groups. Maybe, but maybe not, since actual computation comes down to explicit cases, and even these (as in Prop. 2.16) entangle group cohomology and Ext. Therefore we comment on the properties of (3.27). Also, in the category that interests us most, that of $\mathbb{Z}/\ell [G]$ modules, how unlike the category of $\mathbb{Z}$ modules in having projectives and injectives the same.
Restriction and corestriction: Suppose \( H \leq G \), a finite group and \( A \) is a (left) \( G \) module, compatible with the notation around Def. 1.8. We add to the properties of \( H^n(G, A) \) and \( H^n(H, A) \) an action of \( G \) induced by conjugation, comparing them just enough to define the operators \( \text{res}_H^G \) and \( \text{cor}_H^G \).

At the level of cocycle functions, if \( Hc \in \text{Hom}_{\mathbb{Z}[H]} : \mathbb{Z}[G]^n \rightarrow A \), we want to act with \( g \in G \) by the diagonal action that maps

\[(g_1, \ldots, g_n) \mapsto g \ast Hc(g_1, \ldots, g_n).\]

For \( g \in H \), the result is

\[g(g^{-1}) \ast Hc(g_1, \ldots, g_n) = Hc(g_1, \ldots, g_n).\]

That is \( Hc \) is invariant by \( g \).

More generally, if \( Hc \) is the restriction of \( Gc \in \text{Hom}_{\mathbb{Z}[G]} : \mathbb{Z}[G]^n \rightarrow A \) to \( H \), then the resulting element is invariant by \( g \in G \). To generalize the action of \( g \in G \), we can just map elements in \((H, A)\) to \((gHg^{-1}, A)\) by \((h, a) \mapsto (ghg^{-2}, g \ast a)\). Call this map \( \text{Con}_g \), and trace through that it gives an isomorphism between \( H^n(H, A) \) and \( H^n(gHg^{-1}, A) \). Again, tracing through the action to cohomology, this gives.

**Lemma 1.1.** If \( H \triangleleft G \), then \( \text{Con}_g, g \in G \) induces an action of \( G/H \) on \( H^n(G, A) \).

1.2.1. Including ramification. Allowing ramification includes using ramification groups (stabilizers of the primes defining crucial points). These appeared in class field theory in the case given by number fields; Riemann’s existence theorem in the case of compact Riemann surfaces. Those join together in the study of curve covers over finite fields.

Those cases were were the idea of normalization arose, and normalization guarantees a unique Galois closure. This has also worked very well in problems where you can guarantee that the maps appearing as \( \varphi : X \rightarrow Z \) are finite and \( X \) and \( Z \) are both nonsingular. In that case, the map is automatically flat, a Grothendieck cover, and the fiber dimensions have locally constant degree.

Normal varieties are always nonsingular in codimension 1 (singularity may have codimension as small as 2). The one problem appears in the normalization in the function field of the fiber product components, which may actually be singular. Fiber products of \( \varphi \) with itself will be singular if there is ramification, but normalization often removes that.

1.3. Modular representations. Following some literature comments, §1.3.1, on why modular representations are hard, we exposit on their classical theory, §1.3.2, especially Loewy layers and projectives. Ch. 1 §1.3 started our series of statements on \( \ell \)-Frattini covers (of finite groups), and their relation to nilpotent groups. §1.3.3 describes when our characteristic \( \ell \)-Frattini covers of \( G \) are truly
characteristic in the sense of being preserved by automorphisms that might not come from their actual construction.

Finally, §1.3.4 concludes with our best shot at two explicit constructions of $\ell M_G$: recognizing it from its homological definition (Prop. 1.6), and taking advantage of its indecomposability (Prop. 1.7).

1.3.1. Modular representations are hard. Classifying the mod $\ell$ representations (up to equivalence) is "wild" in the formal technical sense, whenever the $\ell$-Sylow is not cyclic and, when $\ell = 2$, not dihedral, semi-dihedral, nor generalized quaternion. [BoDr77] and [Ri75] (check with Benson around the subject of quivers).

The technical sense of wild used here implies that a classification of the mod $\ell$ representations of any one such group would provide a classification of the mod $\ell$ representations of any finitely generated algebra over $\mathbb{F}_\ell$. Hence such problems are often referred to as hopeless. Nonetheless, much is known about them. There is a great quote by Mumford in a footnote criticizing the "hopeless" aspect here:

The classification of [two] non-commuting maps $f, g: V \to V$ mod $\text{GL}(V)$ is sometimes referred to as an impossible problem. It is not clear to me why this is said. If $\dim V = n$, then for each $n$, there might be a finite number of explicitly describable algebraic varieties $W^{(n)}_i$ whose points are in natural 1-1 correspondence with suitable strata $S^{(n)}_i$ in the full set $S_n$ of pairs $(f, g): k^n \to k^n$ mod $\text{GL}(n)$ [?, App. C, Ch. 4, footnote p. 167].

2) Over any field $L$, the theory of finite-dimensional $L\langle X, Y \rangle$-modules (non-commutative polynomial ring in 2 variables) is undecidable [Ba75] and [KoMa73].

1.3.2. Loewy layers and projective modules. Despite the above we can wend our way through accessible information about the characteristic $\mathbb{Z}/\ell[G]$ modules, $\ell M_G$, by which we define and divine properties of the moduli spaces at the center of this book. First we consider topics mentioned in (3.27c) and which are necessary to gain some understanding of what possible modules can arise. The author learned these from [Be91], which – unlike here – treats the definitions in far greater generality.

(6.3a) Loewy layers: Defining successive maximal quotients of completely reducible modules.

(6.3b) Frobenius duality: Concluding the regular representation of $\mathbb{Z}/\ell[G]$ (which is automatically projective) is also injective.

(6.3c) A simple quotient determines any projective indecomposable module.

These topics come alive in examples of §1.4.

Comments on (6.3a): Define the radical, $\text{Rad}(M) = \text{Rad}^1(M)$, of a $\mathbb{Z}/\ell[G]$ module $M$ to be the intersection of its maximal proper submodules. Then, $M/\text{Rad}(M)$ is the maximal completely reducible quotient of $M$. This lends itself to an inductive
definition, \(\text{Rad}(\text{Rad}^u(M)) = \text{Rad}^{u+1}(M)\), and its successive sequence – finite in our case – of Loewy layer quotients,

\[
\{\text{Rad}^{u-1}/\text{Rad}^u(M)\}_{u=1}^\infty
\]

with it convenient to define \(\text{Rad}^0(M) = M\).

The complication is how these layers fit together. From Prop. 2.16, \(\ell M_G\) is indecomposable. Therefore, significant examples of nontrivial Loewy layers arise immediately from the case of normal \(\ell\) Sylows in \(G\) that aren’t cyclic; and then from (non-cyclic) simple groups, even when an \(\ell\)-Sylow is cyclic. §1.4 gives explicit examples, uses \(G = A_5\) for \(\ell = 2, 3, 5\).

§1.3.4 gives a procedure, often more effective than finding the Loewy display of \(\ell M_G\), that gives the basic structure needed for properties of the reduced Hurwitz spaces that are the levels of a MT at the core of this book.

Comments on (6.3b): [Be91, Prop. 1.6.2] is a telegraphic treatment of the equivalence of projective and injective modules in the category of \(\mathbb{Z}/\ell \mathbb{Z}[G]\) modules. For our case it starts with the augmentation map:

\[
\lambda: \mathbb{Z}/\ell \mathbb{Z}[G] \to \mathbb{Z}/\ell \text{ by } \sum_{g \in G} a_g g \mapsto \sum_{g \in G} a_g,
\]

and the left and right regular representation modules \(L \mathbb{Z}/\ell \mathbb{Z}[G]\) and \(\mathbb{Z}/\ell \mathbb{Z}[G]_R\). This gives a linear map that turns out ot be a module homomorphism

\[
\varphi_\lambda: L \mathbb{Z}/\ell \mathbb{Z}[G] \to \text{Hom}(\mathbb{Z}/\ell \mathbb{Z}[G]_R, \mathbb{Z}/\ell) \overset{\text{def}}{=} \mathbb{Z}/\ell \mathbb{Z}[G]_R^*: \varphi_\lambda(x): y \in \mathbb{Z}/\ell \mathbb{Z}[G]_R \mapsto \lambda(yx).
\]

**Lemma 1.2.** Define \(\varphi_\lambda\) as a module homomorphism using, for \(g \in G\),

\[
g \varphi_\lambda(x)(y) \mapsto \varphi_\lambda(x)(yg) = \lambda(xy) = \varphi_\lambda(gx)(y).
\]

The equalities are the result of \(\lambda(xy) = \lambda(yx)\). Further, \(\varphi_\lambda\) is injective, and since the range has the same dimension as the image, it is an isomorphism.

Applying the definition of projective to a (finite dimensional) module \(M\) shows that \(\text{Hom}(M, \mathbb{Z}/\ell) = M^*\) is also projective. Ditto for injective. For finite dimensional modules dualizing take injectives to projectives, and vice-versa.

**Proof.** From linearity of \(\lambda\), to show \(\lambda(xy) = \lambda(yx)\) it suffices to take \(y = g', g' \in G\). In that case \(\sum a_g g' g\) clearly has the same coefficients as \(\sum a_g gg'\), just in a different order.

Apply this symmetry to see the equalities in the formula of the lemma. The rest of the observations to give (6.3b) are in the statement of the lemma. \(\square\)

Comments on (6.3c), Projective indecomposables: Denote the algebraic closure of \(\mathbb{Z}/\ell = \mathbb{F}_\ell\) by \(\bar{K}_\ell\). We list ingredients from the theory of modular representations [A86, Chaps. 1-3]. Brauer’s Theorem (below) on simple \(G\) modules forces considering, at times, \(\bar{G} = K_\ell[G]\) modules instead of \(\mathbb{F}_\ell[G] = G\) modules. Translation
between statements about \( \mathcal{G} \) modules to \( \hat{\mathcal{G}} \) modules is usually straightforward. A \( \cdot \)-over notation for a \( \mathcal{G} \) module means we’ve tensored with \( K \ell \) to make it a \( \hat{\mathcal{G}} \) module. In contrast to an indecomposable \( \hat{\mathcal{G}} \) module – one without a nontrivial direct summand – is a simple (or irreducible) \( \hat{\mathcal{G}} \) module – one with no proper submodules.

Let \( H \) be any subgroup of \( G \). Denote the corresponding subalgebra by \( \hat{H} \). For \( M \) a \( \hat{\mathcal{G}} \) module, let \( M_H \) be the corresponding \( \hat{H} \) module. The dimension of \( M \) is its vector space dimension over \( K \ell \).

(6.5a) Brauer’s theorem: The collection of \( \hat{\mathcal{G}} \) modules has the same cardinality as \( G \) conjugacy classes whose elements have order prime to \( \ell \) [A86, p. 14].

(6.5b) Indecomposable projectives \( M \) correspond to simple \( \hat{\mathcal{G}} \) modules via the map \( M \to M/\rad(M) \) [A86, p. 31].

(6.5c) \( M \) is a projective \( \hat{\mathcal{G}} \) module if and only if \( M_{P_\ell} \) an \( \ell \)-Sylow of \( G \), is a free \( K_{\ell}[P_\ell] \) module [A86, p. 33 and 66].

**Induced modules and Shapiro’s Lemma:** Denote an \( \ell \)-Sylow by \( P_\ell \), and its normalizer in \( G \) by \( N_G(P_\ell) \) \( \overset{\text{def}}{=} N_\ell \), etc. Then, consider the characteristic \( \ell \)-Frattini module (for \( N_\ell \) \( \ell \)M(\( N_\ell \)). Yet, it may not be a natural \( G \) module.

For \( H \leq G \), consider a \( \mathbb{Z}/\ell[H] \) module \( M_H \). Then,

\[
M_H^{\mathbb{Z}/\ell[H]} \overset{\text{def}}{=} \text{ind}_{\ell[H]}^G(M_H) \overset{\text{def}}{=} M_H \otimes_{\mathbb{Z}/\ell[H]} \mathbb{Z}/\ell[G]
\]

is naturally isomorphic to \( \text{Hom}_{\mathbb{Z}/\ell[G]}(M_H^{\mathbb{Z}/\ell[H]}, N^{\mathbb{Z}/\ell[H]}_G) \) is naturally isomorphic to \( \text{Hom}_{\mathbb{Z}/\ell[H]}(M_H, N^{\mathbb{Z}/\ell[H]}_G) \).

**Proof.** Given a \( \mathbb{Z}/\ell[H] \) module homomorphism, \( \mu : M_H \to N^{\mathbb{Z}/\ell[H]}_G \), we are forced to associate to it

\[
\mu^G : M_H^G \to N^G \text{ by } m \otimes g_i \in M_H \otimes g_i \mapsto ((m)\mu)g_i.
\]

Assuming, for \( g \in G \), with \( g_\ell g = hg_j \), showing this is a \( \mathbb{Z}/\ell[G] \) homomorphism requires checking if \(((m)\mu)g_i)g = (((m)\mu)h)g_j \), which it does since the action of \( h \) commutes with \( \mu \).

\[\square\]

Cor. 1.4 applies Lem. 1.3 when \( H = N_\ell \), \( M_H = \ell M_H \) and \( N^G = \ell M_G \).

**Corollary 1.4.** With notation as above, there is a \( \mathbb{Z}/\ell[G] \) module homomorphism of \( \ell M_H^G \) into \( \ell M_G \).

Further, from Shapiro’s Lemma: \( H^2(G, \ell M_H^G) = H^2(N_\ell, \ell M_H) \). If this natural generating extension is a Frattini cover, then \( \ell M_H^G \) identifies with \( \ell M_G \).
Proof. Restrict the characteristic cover \( \frac{1}{\ell} G \) to \( N_\ell \). The universal \( \ell \)-Frattini property induces a map \( \frac{1}{\ell} N_\ell \to \frac{1}{\ell} G \) that gives a \( \mathbb{Z}/\ell \mathbb{N} \) homomorphism embedding of \( \ell M_H \to \ell M_G \). From Lem. 1.3 that produces a \( \mathbb{Z}/\ell \mathbb{Z} \) embedding \( \ell M_H \to \ell M_G \). From Lem. 1.3 that produces a \( \mathbb{Z}/\ell \mathbb{Z} \) embedding \( \ell M_H \to \ell M_G \), completing the first line of the corollary.

1.3.3. Characteristic subgroups of \( \ell \hat{G} \). Use the notation of Lem. 1.28.

If \( P \) is an \( \ell \)-group, then as in Lem. 1.23, its Frattini subgroup is (the closure of) \( \text{fr}_P \) def \( = P \ell \mathbb{Z}\langle P, P \rangle \) and \( P \to P/\text{fr}_P P \) is a Frattini cover.

Recover a cofinal family of finite quotients of \( \ell \hat{G} \) through the Frattini kernel of the natural map \( 1 \to \ker_0 \to \ell \hat{G} \to G \to 1 \) as in (1.7).

Terms of \( \mathcal{K}_G = \{ \ker_k \}_{k=0}^{\infty} \) should reference \( G \) unless it is understood. For example, they may not be characteristic subgroups of \( \ell \hat{G} \), as easily seen by example for \( P = \ell \hat{F} \) (as in (1.5b)). Still, Lem. 1.5 extends \([BFr02, \text{Lem. 3.10}]\).

Lemma 1.5. If \( \ker_0 \) is a characteristic subgroup of \( \ell \hat{G} \), then so are all terms of \( \mathcal{K}_G \). Since the intersection of the \( \ell \)-Sylows of \( \ell \hat{G} \) is a characteristic subgroup of \( \ell \hat{G} \) (containing \( \ker_0 \)), \( \ker_0 \) is characteristic if the \( \ell \)-Sylows of \( G \) intersect in \( \langle 1 \rangle_G \), as when \( G \) is simple.

In general, \( \mathcal{K}_G \) is cofinal in the closed subgroups in the profinite topology. In particular, the automorphisms, \( \text{Aut}(\ell \hat{G})_G \) of \( \ell \hat{G} \) that extend those of \( G \) define a profinite group.

Proof. The first statement follows because \( \ker_1 \) is a characteristic subgroup of \( \ker_0 \): Every automorphism of \( \ell \hat{G} \) recognizes \( \ell \)-th powers and commutators. Any automorphism of \( \ell \hat{G} \) will take \( \ker_0 \) into itself by hypothesis. So it will induce an automorphism on the characteristic subgroup \( \ker_1 \), making that a characteristic subgroup of \( \ell \hat{G} \). Proceed by induction to conclude this holds for all the \( \ker_k \)'s.

As with finite groups, all \( \ell \)-Sylows of \( \ell \hat{G} \) are conjugate \([FrJ86, \text{Prop. 22.9.1}]\). Therefore their intersection is a characteristic subgroup, containing \( \ker_0 \). If the \( \ell \)-Sylows of \( G \) intersect in \( \langle 1 \rangle \), then the intersection of the \( \ell \)-Sylows of \( \ell \hat{G} \) is \( \ker_0 \), proving it is characteristic.

From (1.5b), \( \ker_0 \) is pro-free, and \( \{ \ker_i \}_{i=1}^{\infty} \) is a neighborhood base of the origin consisting of characteristic subgroups of \( \ker_0 \). Thus, automorphisms of \( \ell \hat{G} \) that extend those of \( G \) (so mapping \( \ker_0 \) into itself) also act on each of \( \{ \ker_i \}_{i=1}^{\infty} \), and on the quotients \( \ell \hat{G} \). This means, with the natural notation, \( \text{Aut}(\ell \hat{G})_G \) is the projective limit of the finite groups \( \text{Aut}(\ell \hat{G})_G \), concluding the proof.

1.3.4. Constructing \( \ell M_G \). Ch. 1 Prop. 1.29 gives structural statements about the Universal Frattini cover of \( \hat{G} \). Ch. 3 Ch. 2 Prop. 2.16 gave a description of \( \ell M_{k,k+1} \) given \( \ell \hat{G} \). Prop. 1.6 extends this to \( \ell \hat{G} \) given solid information on the
following short exact sequences of $\ell^G$ modules with $P_1$ the principal indecomposable for $1 = \mathbf{1}_{\ell^G}$, and $P$ the minimal projective $\ell^G$ module covering $\Omega^1(1)$.

(6.6a) $1 \rightarrow \Omega^1(1) \rightarrow P_1 \rightarrow 1 \rightarrow 1$.
(6.6b) $1 \rightarrow \Omega^2(1) \rightarrow P \rightarrow \Omega^1(1) \rightarrow 1$.

Compute boundary maps from the standard exact sequences of cohomology:

$$H^0(\ell^G, 1) \rightarrow H^1(\ell^G, \Omega^1(1)) \rightarrow H^2(\ell^G, \Omega^2(1)).$$

Denote a vector space generator of $1$ by $1_1$.

**Proposition 1.6.** The element $\delta_1 \circ \delta_0(1_1) \in H^2(\ell^G, \Omega^2(1))$ represents the group extension $\ell^{k+1}G$ whose class generates $H^2(\ell^G, \Omega^2(1))$, as in Prop. 2.16.

To be explicit, consider the semi-direct product $\Omega^1(1) \ltimes \ell^G$. Choose $m \in P_1$ lying over $1_1$. The cocycle $g \mapsto g(m) - m$ for $g \in G$ represents $\delta_0(1_1)$. This cocycle defines a splitting $\psi : \ell^G \rightarrow \Omega^1(1) \ltimes \ell^G$ by $g \mapsto (g(m) - m, g)$. Then, $\ell^{k+1}G$ is the preimage in $P \ltimes \ell^G$ of $\psi(\ell^G)$ in $\Omega^1(1) \ltimes \ell^G$ from sequence (6.6a).

**Proof.** Follow standard computations for boundary maps. For example, check that $\psi$ defines a homomorphism by computing $\psi(g_1g_2)$ as

$$(g_1, g_2)(m) - m, g_1g_2 = (g_1, g_2)(m) - g_1(m) + g_1(m) - m, g_1g_2 = \psi(g_1)\psi(g_2).$$

The essence of identifying $\ell^{k+1}G$ is to show that pullback of $\psi(\ell^G)$, as an extension of $\ell^G$, has the correct 2-cocycle. Suppose $\alpha$ represents a 1-cocycle. Then, $g \mapsto (\alpha(g), g)$ gives a splitting of $\ell^G$ in $\Omega^1(1) \ltimes \ell^G$. For each $g \in \ell^G$ let $\tilde{\alpha}(g)$ be an element of $P$ lying over $\alpha(g) \in \Omega^1(1)$.

The boundary map differentiates the 1-cycle $g \mapsto \alpha(g)$ to give

$$(g_1, g_2) \mapsto g_1(\tilde{\alpha}(g_2)) - \tilde{\alpha}(g_1g_2) + \tilde{\alpha}(g_1).$$

[Nor62, p. 241] shows this 2-cocycle is the factor system for the associative multiplication on the pullback group.

§1.4 puts Prop. 1.6 into action with the primes dividing $A_5$, using Prop. 1.7, an alternate way to trying construct the Loewy decomposition of $\ell M_G$.

Ch. 1 Def. ?? gives the definition of the universal $\ell$-Frattini cover of $G$. We continue to assume $G$ is $\ell$-perfect.

$$\tilde{\psi}_G : \hat{\ell} \hat{G} \rightarrow G$$

with $\ker(\tilde{\psi}_G)$ profree, pro-$\ell$, of finite rank, $\text{rk}(\hat{\ell} \hat{G})$.

**Proposition 1.7 (\ell pieces: Part 4).** Denote an $\ell$-Sylow of $G$ by $P$.

(6.7a) There is an explicit lower bound on $\text{rk}(\ker(\tilde{\psi}))$ and $\text{rk}(\ker(\ell \tilde{\psi}))$, with the latter $\geq 1 + |P|\text{(rk}(P) - 1)$.

(6.7b) $\text{rk}(\ker(\ell \tilde{\psi}))$ in (6.7a) is the rank of

$$\ell \hat{M}_G \overset{\text{def}}{=} \ker(\ell \tilde{\psi}_G)/[\ker(\ell \tilde{\psi}_G), \ker(\ell \tilde{\psi}_G)]$$

as a $\mathbb{Z}_\ell$ module.
(6.7c) The rank (6.7b) is the $\mathbb{Z}/\ell$ vector space dimension of $\iota M_G$.

**Proof.** Now consider (6.7). Bound any ranks given there by bounding the corresponding ranks of its $\ell$-Frattini constituents. To get a bound on the rank $\ell M_G$, apply that $\text{ker}_0$ RETURN is an index $|P|$ subgroup of any $\ell$-Sylow, $\tilde{P}$, of $\iota G$. Also, from (1.12a), $\tilde{P} = \iota \tilde{F}_{\text{rk}(P)}$. Therefore, from (1.5b), the rank of $\text{ker}_0$ is $1 + |P|(|\text{rk}(P)| - 1)$, the same as that of $\iota M_G$.

Check back on Rem. 3.12 related to how this applies to $[GS78]$. 

**Example 1.8** ($P$ elementary abelian in (1.12a)).

**1.4. Characteristic $A_5$ $\ell$-Frattini covers.** Notice our examples in this section, where we do discuss the Loewy displays of the projective indecomposables, is restricted to the cases at the start of §1.3.1 that are not considered “wild.” Do a primer on Loewy displays, from $[Fr95]$, §II. Use the notation of §2.3.2 for the characteristic Frattini modules and extensions $\bar{\psi}G$ of $G$.

1.4.1. The case $\ell = 5$. A 5-Sylow, $P_5$, is $\mathbb{Z}/5$, and the normalizer $N_{A_5}$ in $A_5$ is a $D_5$ isomorphic to $\langle (1\ 2\ 3\ 4\ 5), (2\ 3)(4\ 5) \rangle$. Therefore, intuition might suggest it is – contrary to Prop. 3.10 – a candidate for the possibility that $\iota M_G$ has rank 1.

If it did, restricting the characteristic 5-Frattini cover $\frac{\iota}{5}D_5 = D_5$ to $\iota M_G$ would assure a nontrivial action. Therefore it could not be the trivial module. Nor could the trivial module be a quotient of $\iota M_G$. Also, the Loewy display could not have a quotient with kernel $1_{A_5}$ since that would give $\frac{\iota}{5}A_5$ with a nontrivial center contrary to Ch. 3 Prop. 2.18. Apply Prop. 1.7 showing that $\iota M_G$ is indecomposable. Do the iterated construction from Prop. 2.16. If the projective indecomposable for $1_G$ has $V_4$ at the head of $\Omega^1(1_G)$, then – in computing $\Omega^2(G)$, the kernel, one $G$ would appear at its head because the projective indecomposable of $V_4$ is the degree 5 permutation representation of $A_5$, which has $1_G$ as the kernel of its map to $V_4$.

Putting this together, $\iota M_G$ is the indecomposable summand of $\text{ind}^A_{D_5}(\iota M_{D_5})$ which has dimension 6, and restricts to contain $\iota M_{D_5}$. The irreducible $A_5$ module subquotients in this module have dimensions that sum to $\leq 6$, and don’t contain $1_{A_5}$. The only possibilities are therefore the adjoint representation, or two copies of the adjoint representation, one on top of the other. We conclude by excluding the former.

**Remark 1.9.** Show how the case $\ell = 5$ applies to $\text{SL}_2(\mathbb{Z}/\ell)$ that $\iota M_G$ is not the adjoint representation.

**1.5. Central extensions vs $\tilde{G} \to G$.** The case $G = \text{PSL}_2(\mathbb{Z}/\ell)$ is important, though somewhat misleading.

At its inception, the formulation of the conjectures on $\text{MT}$s were about the whole extension, $\tilde{\psi} : \tilde{G} \to G$, and its whole $\ell$-Frattini quotients $\iota \tilde{\psi} : \tilde{G}_\ell \to G$, rather
2. BRAID ORBITS

than just about their abelianized versions. The arithmetic list of problems (??) makes a distinction between them, based on the idea that we eventually consider, say, a $k$ quotient, $\tilde{G}_{\ell,k}$ of $\tilde{G}_\ell$. Then, we consider the ker ker ker ker ker ker RETURN As usual we understand ker $p\!n$ ker ker to be the closed subgroup of $p\! G$ with generators from the elements of this set Though Lem. ?? is quite simple, we differentiate a structural group theory statement, say, about the ranks of the kernel of, say, from technical group theory in that Still, the pieces of $\psi_G$ are technically constructive.

**Example 1.10** (A most prestigious example). Ex. 2.9 and 2.11 both engage the universal central extension of $A_n$.

Every finite group has a maximal solvable quotient. Form it by considering the successive commutator subgroups,

$$G \geq [G, G] \overset{\text{def}}{=} G_{1,c} \geq [G_{1,c}, G_{1,c}] \overset{\text{def}}{=} G_{2,c} \cdots \text{ until this sequence stops at } G_{u,c}. $$

Then, $G/G_{u,c}$ is the maximal solvable quotient of $G$.

Similarly, there is a maximal nilpotent quotient, $G_{\text{nil}}$, of $G$:

replace $[G_{j-1,c}, G_{j-1,c}] = G_{j,c}$ by $G_{1,c} \overset{\text{def}}{=} G_{1,n}, [G, G_{1,n}] \overset{\text{def}}{=} G_{2,n}, \cdots$

until this sequence stops at $G_{t,n}$. Then, $G/G_{t,n}$ is $G_{\text{nil}}$.

### 2. Braid orbits

You want the components of the Hurwitz spaces, and you know the subsets with different lift invariants are in different braid orbits. Also, if a collection of generating conjugacy classes repeat often enough, the braid orbits correspond one-one to lift invariants. Here are examples that appear in the author’s paper.

Groups they take, some others, and the lift invariant values.

(6.8a) p. 31: $G$ is the dihedral group, $\mathbb{Z}/\ell \times \{\pm 1\}$ of order $2\ell$, $\ell$ odd, and $c$ is the conjugacy class of involutions.

(6.8b) also p. 31: $G = V_\ell \times S_3$, where $\ell > 3$ is a prime, $V_\ell$ is the 2-dimensional reduced permutation representation of $S_3$, and $c$ is again the conjugacy class of involutions.

(6.8c) In §12, Cohen-Lenstra Heuristics, they take what they call a generalized dihedral group $A \times \{\pm\}$ with $A$ a finite abelian group of odd order with $-1$ acting as -1.

(6.8d) Akin to (6.8b), but much harder: $G = V_\ell \times \mathbb{Z}/3$, $\ell \neq 3$; $c$ consists of the two nontrivial conjugacy classes in $\mathbb{Z}/3$, each repeated with the same, $d'$, multiplicity: $c_{d',d'}$.

Comments on (6.8a): Prop. 6.0.3 shows how their results have gone beyond their previous paper in their bound on the Cohen-Lenstra class numbers. See (????).
I use example (6.8d) in §77.

2.1. Other braid orbit computations. The length of a $q_i$ orbit on $g \in \text{Ni}(G, C)^*$ with $\bullet$ an equivalence relation is crucial to most explicit calculations of braid orbits, and so Hurwitz space components. Typically, we expect that to be $2\text{ord}(g_1g_{i-1})$. Yet, there is an important exception when it is half that length. That occurred, for example, in the orbit labeled $K_{\text{in,r}},$ in Table 2 for the shift of an HM cusp. Prop. 2.1 [BFr02, Prop. 2.17] explains that.

The structure constant formula (§77) calculates $|S(C')|$ using complex representations of $G$. Calculations in §77 compute the length of $\gamma$ orbits on $S(C'_{g_3})$. For $g_1, g_2$ in a group, denote the centralizer of $\langle g_1, g_2 \rangle$ by $Z(g_1, g_2)$.

Let $g_1g_2 = g_3$, and $g_2g_1 = g_3'$. Let $o(g_1, g_2) = o$ (resp. $o'(g_1, g_2) = o'$ be the length of the orbit of $\gamma^2$ (resp. $\gamma$) on $(g_1, g_2)$. If $g_1 = g_2$, then $o = o' = 1$.

**Proposition 2.1.** Assume $g_1 \neq g_2$. The orbit of $\gamma^2$ containing $(g_1, g_2)$ is $(g_3^jg_1g_3^{-j}, g_3^jg_2g_3^{-j})$, $j = 0, \ldots, \text{ord}(g_3)-1$. So,

$$o = \text{ord}(g_3)/|\langle g_3 \rangle \cap Z(g_1, g_2)| \overset{\text{def}}{=} o(g_1, g_2).$$

Then, $o' = 2 \cdot o$, unless $o$ is odd, and with $x = (g_3)^{(o-1)/2}$ and $y = (g_3')^{(o-1)/2}$

(6.9) \( (\text{so } g_1y = xg_1 \text{ and } yg_2 = g_2x) \), $yg_2$ has order 2 and $o' = o$.

**Proof.** For $t$ an integer,

$$(g_1, g_2)\gamma^{2t} = (g_3^tg_1g_3^{-t}, g_3^tg_2g_3^{-t}) \text{ and } (g_1, g_2)\gamma^{2t+1} = (g_3^tg_1g_2g_1^{-1}g_3^{-t}, g_3^tg_1g_1^{-1}g_2^{-1}g_3^{-t}).$$

The minimal $t$ with $(g_1, g_2)\gamma^{2t} = (g_1, g_2)$ is $o(g_1, g_2)$. Further, the minimal $j$ with $(g_1, g_2)\gamma^j = (g_1, g_2)$ is $o(g_1, g_2)$. If $j$ is odd, $j|o(g_1, g_2)$.

From the above, if the orbit of $\gamma$ does not have length $2o(g_1, g_2)$, it has length $o(g_1, g_2)$. Use the notation around (6.9). The expressions $g_1y = xg_1$ and $yg_2 = g_2x$ are tautologies. If $o$ is odd, then $(g_1, g_2)q_2^o = x(g_1, g_2)q_2x^{-1}$. Assume this equals $(g_1, g_2)$, which is true if and only if $xg_1 = g_2x = yg_2$. The expression $(g_1g_2)^o = 1$ and $xg_1yg_2 = 1$ are equivalent. Conclude $(yg_2)^2 = 1$. So long as the order of $yg_2$ is not 1, this shows (6.9) holds. If, however, $yg_2 = xg_1 = g_2x = g_1y = 1$, then $g_1 = g_2$, contrary to hypothesis.

This reversible argument shows the converse: $(g_1, g_2)q_2^o = (g_1, g_2)$ follows from (6.9). This concludes the proof.

2.2. Covers of higher genus curves. We easily extend the restricted and general lift invariants from §1 and §2 to consider ramified covers, $\varphi : W \to Z$, of compact Riemann surfaces, without assuming $Z = \mathbb{P}^1$. This is brief. Excluding that the fundamental group of $Z$ is no longer trivial, this is fairly obvious.
With $g_Z = g$, the genus of $Z$, ramified at points $z_1, \ldots, z_r$. Go to the Galois closure $\hat{\varphi} : \hat{W} \to Z$. Denote the automorphism group by $G_\varphi$, and let $\psi_G : R \to G$ be a representation cover of $G$: a central Frattini cover of $G$ whose kernel – contained in the commutator subgroup in $R$ – is isomorphic to the Schur multiplier of $G$. Denote $|\ker(\varphi_R)|$ by $M_G$. We are now in shape to imitate Cor. 2.6.

Suppose we have classical generators 
\[(a^*_1, b^*_1, \ldots, a^*_g, b^*_g, g^*_1, \ldots, g^*_n) \text{ def } P_{a^* \cdot b^* \cdot g^*},\]
for the fundamental group, $\pi_1$, of $Z \setminus \{z_1, \ldots, z_r\}$. Then $\varphi$ determines a cover $\pi_1 \to G$ that sends the entries of $P_{a^* \cdot b^* \cdot g^*}$ to elements of $G$, which we denote by $P_{a^* \cdot b^* \cdot g^*}$. There is a natural product constructed from the entries of $P_{a^* \cdot b^* \cdot g^*}$. Denote a commutator $(a^*_k)(b^*_k)(a^*_k)^{-1}(b^*_k)^{-1}$ by $[a^*_k, b^*_k]$. Form
\[\Pi_{k=1}^g [a^*_k, b^*_k] \Pi_{i=1}^r g^*_i,\]
referring to the result as $\Pi(a^*, b^*, g^*)$.

Since $P_{a^* \cdot b^* \cdot g^*}$ are classical generators, we have a product-one condition: $\Pi(a^*, b^*, g^*) = 1$. Thus, so do the corresponding entries of $P_{a^* \cdot b^* \cdot g^*}$ satisfy product-one. As previously, the $g_i$ define conjugacy classes $C_1, \ldots, C_r$ in $G$ for which, as previously, use the notation $N_C$ for the least common multiple of the orders of their elements. Here are some facts about this.

(6.10a) If $(N_C, M_G) = 1$, then (mini-Schur-Zassenhaus), we can lift the entries of $g$ to $R$ retaining the prime to $N_G$ condition.

(6.10b) Denote the (6.10a) lifted entries by $P_{\hat{a}^*, \hat{b}^*, \hat{g}^*}$ and their product by $s_{R/G}(\hat{a}, \hat{b}, \hat{g}) \in \ker(R/G)$.

Directly compute that the value of the commutator $[\hat{a}_i, \hat{b}_i]$ won’t depend on the choice of lifts for $a_i$ and $b_i$ to the central extension $R \to G$. Therefore the value of $s_{R/G}(\hat{a}, \hat{b}, \hat{g})$ is well defined. Further, the argument of §1.3 shows that it is an invariant of the deformation of $Z \setminus z_1, \ldots, z_r$. Explanation: The most obvious meaning of that is, we deform $Z$ in the space of genus $g$ compact surfaces while continuously deforming the distinct points $z_1, \ldots, z_r$. While that might look like it calls for a whole new proof, it seriously does not; you can move the complex structure leaving the branch points fixed, and you can get the effect of deforming the branch points by the generalization of braids to a genus $gen$ surface.

Then, the formula for the general lift invariant, should the assumption of (6.10a) not hold, lies exactly in the quotient of Def. 2.1 as for $Z = \mathbb{P}^1_z$.

3. Serre’s OIT

We have put here comments on Serre’s version of his OIT. These are examples illustrating the concepts we use to generalize it. §3.1 starts with the notion of eventually $(\ell)$-Frattini and how it is appropriate for what we are calling the weak OIT.
That using MTs does generalize the OIT is in §3.2. This starts with the observation from [Fr95, §1.A], expanding on [Fr77, §2] that all the standard collections of modular curves,

\[ \mathcal{X}_{0, \ell} \overset{\text{def}}{=} \{(X_0(\ell^{k+1}))_{k=0}^{\infty}, \mathcal{X}_{1, \ell} \overset{\text{def}}{=} \{(X_1(\ell^{k+1}))_{k=0}^{\infty} \text{ and } \mathcal{Y}_\ell \overset{\text{def}}{=} \{(Y(\ell^{k+1}))_{k=0}^{\infty}, \]

as covers of \( \mathbb{P}^1 \), are compactified one-one (and onto) images of the reduced Hurwitz spaces listed on the left in (1).

### 3.1. Eventually \( \ell \)-Frattini and Serre’s OIT

The first Prop. 3.2 statement might well be the most well-known piece from [Se68]. It is the examplar of the \( \ell \)-Frattini property. We emphasize the eventually \( \ell \)-Frattini property (Ch. 4 Def. 4.2). §3.1.1 does preliminaries relevant to our whole approach on SL\(_2\) vs PSL\(_2\). §3.1.2 is the proof of Prop. 3.2.

#### 3.1.1. SL\(_2\) vs PSL\(_2\)

Consider \( \iota \psi : \text{PSL}_2(\mathbb{Z}_\ell) \to \text{PSL}(\mathbb{Z}/\ell) \) (or of SL\(_2(\mathbb{Z}_\ell) \to \text{SL}(\mathbb{Z}/\ell) \)). Then, ker(\( \iota \psi \)) = Ad\(_3(\mathbb{Z}_\ell)\), \( 2 \times 2 \) trace 0 matrices with coefficients in \( \mathbb{Z}_\ell \), is abelian. Though Prop. 3.2 says they are \( \ell \)-Frattini covers for \( \ell > 3 \), PSL\(_2(\mathbb{Z}_\ell) \) is far from the universal \( \ell \)-Frattini cover of PSL\(_2(\mathbb{Z}/\ell) \).

Indeed, it is a proper quotient of \( \iota \tilde{G}_{\text{ab}} \) with \( G = \text{PSL}_2(\mathbb{Z}/\ell) \) since the characteristic module Ad\(_3(\mathbb{Z}/\ell)\) is a proper quotient of \( \iota M_G \) (Rem. 1.9), even though, here, that proper quotient is indecomposable (even irreducible) as a \( \mathbb{Z}/\ell[G] \) module.

The geometric monodromy of modular curves over the \( j \)-line, or of our dihedral group related reduced Hurwitz spaces in §3.2, are directly related to PSL\(_2(\mathbb{Z}_\ell)\) rather than SL\(_2(\mathbb{Z}_\ell)\). It is the Frattini properties of the geometric monodromy for general MTs that are the subject of topics such as Ch. 4 Conj. 4.5.

**Lemma 3.1.** For all \( \ell \), \( \iota \alpha : \text{SL}_2(\mathbb{Z}/\ell) \to \text{PSL}_2(\mathbb{Z}/\ell) \) is a Frattini cover.

**Proof.** A proper subgroup \( G^* \leq \text{SL}_2(\mathbb{Z}/\ell) \), for which \( \iota \alpha \) restricted to \( G^* \) is onto, has index 2 in \( \text{SL}_2(\mathbb{Z}/\ell) \). Thus, \( G^* \) contains all the elements of order \( \ell \) in \( \text{SL}_2(\mathbb{Z}/\ell) \). In particular it contains

\[ A = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \text{ and } B = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}. \]

The effect of multiplying by \( A^a \) (resp. \( B^b \)) on any matrix \( C \) in \( \text{SL}_2(\mathbb{Z}/\ell) \) is to do row operations (of determinant 1) on \( C \). If either the upper right corner or lower left corner of \( C \) is nonzero – say the latter – then multiplying on left by \( A^a \) for some \( a \), then \( B^b \) for some \( b \), can change \( C \) to a matrix with the upper left corner 1, and the lower left corner 0.

Since the resulting \( C \) is in \( \text{SL}_2(\mathbb{Z}/\ell) \), it has the form \( \begin{pmatrix} 1 & b' \\ 0 & 1 \end{pmatrix} = B^{b'} \). That still leaves the case that \( C \) has diagonal form \( C_{a'} = \begin{pmatrix} a' & 0 \\ 0 & (a')^{-1} \end{pmatrix} \). The remedy is to multiply \( C \) on the left by \( B \) to get a nonzero entry in the lower left corner, and proceed as above. \( \square \)
Proposition 3.2. The natural cover $\mathrm{SL}_2(\mathbb{Z}/\ell^{k+1}) \to \mathrm{SL}_2(\mathbb{Z}/\ell)$ is a Frattini cover for all $k$ if $\ell > 3$.

For $\ell = 3$ (resp. 2), $\mathrm{SL}_2(\mathbb{Z}/\ell^{k+1}) \to \mathrm{SL}_2(\mathbb{Z}/\ell^{k+1})$, $k \geq k_0$ where $k_0 = 1$ (resp. 2), is the minimal value for which these are Frattini covers.

That is, for all $\ell$, $\{\mathrm{SL}_2(\mathbb{Z}/\ell^{k+1})\}_{k=0}^\infty$ is eventually Frattini.

Then, $\iota\rho : \mathrm{SL}_2(\mathbb{Z}_\ell) \to \mathrm{SL}_2(\mathbb{Z}/\ell)$ and $\iota\alpha \circ \iota\rho : \mathrm{SL}_2(\mathbb{Z}_\ell) \to \mathrm{PSL}_2(\mathbb{Z}/\ell)$ are $\ell$-Frattini for $\ell > 3$, and eventually $\ell$-Frattini for all $\ell$.

In particular, the same statements apply to $\mathrm{PSL}_2(\mathbb{Z}_\ell) \to \mathrm{PSL}_2(\mathbb{Z}/\ell)$.

3.1.2. Proof of Prop. 3.2. The first sentence is [FrJ86, Cor. 22.13.4], form [Se68, Lem. 3, IV-23] which also has as an exercise that the same statement and proof applies to $\mathrm{SL}_d(\mathbb{Z}/\ell)$. Below we augment those exercises for $\ell = 2$ and 3.

The induction for $\ell > 3$: First, we trim the treatment of [FrJ86, Cor. 22.13.4]. As in the proof of Lem. 3.1, use $A$ and $B$ from (6.11). Following [FrJ86, p. 532], add $C = \begin{pmatrix} 1 & -1 \\ -1 & -1 \end{pmatrix}$ to give three independent generators of $\mathrm{Ad}_3(\mathbb{Z}/\ell)$, all with square 0: every $u \in \mathrm{Ad}_3(\mathbb{Z}/\ell)$ is a sum of square 0 elements.

Our induction hypothesis is that $H \leq \mathrm{SL}_2(\mathbb{Z}/\ell^{k+1}) \to \mathrm{SL}_2(\mathbb{Z}/\ell^k)$ maps surjectively. We have only to show, for $u \in \mathrm{Ad}_3(\mathbb{Z}/\ell)$, there is $h \in H$ of form $1 + \ell^k u$. For getting this, the induction assumption gives $h_0 \in H$ and $v \in \mathrm{Ad}_3(\mathbb{Z}/\ell)$ with $h_0 = 1 + u\ell^{k-1} + v\ell^k$ for some $v \in \mathrm{Ad}_3(\mathbb{Z}/\ell)$. Here are the remaining steps.

(6.12a) Binomially expand $h = (h_0)^{\ell}$ to see it is $1 + u\ell^k \mod \ell^{k+1}$ unless $k = 1$ when it is $1 + u\ell + \ell(u + v\ell)^{\ell}(\bullet) + (u + v\ell)^{\ell}$ with $\bullet \in \mathbb{Z}$.

(6.12b) If $u^2 = 0$ (and $k = 1$), the result is $1 + \ell u \mod \ell^2$, if $(u + v\ell)^{\ell} \equiv 0 \mod \ell^2$.

For $\ell > 3$ this is clearly so (see Rem. 3.3).

(6.12c) Write $u \in \mathrm{Ad}_3(\mathbb{Z}/\ell)$ as a sum of squares $u = \sum_{i=1}^\ell u_i$. From (6.12b) find $h_i \in H$ with $h_i = 1 + u_i\ell$, so that $\prod_{i=1}^\ell h_i = 1 + u\ell \mod \ell^2$.

Then, (6.12c) concludes the induction argument, for the first sentence.

The cohomology for $\ell = 3$: For $\ell = 3$, [Se68, IV-28, Exer. 3] asks to show that $\mathrm{SL}_2(\mathbb{Z}/3^2) \to \mathrm{SL}_2(\mathbb{Z}/3)$ is not Frattini. We say it purely cohomologically. Then, $\mu \in H^2(\mathrm{SL}_2(\mathbb{Z}/3), \mathrm{Ad}_3(\mathbb{Z}/3))$ defines the cohomology class of this extension ([Nor62, p. 241] as in (3.27)).

For any cohomology group, $H^*(G, M)$, with $M$ a $\mathbb{Z}/\ell[G]$ module, restrict to an $\ell$-Sylow $P_\ell \leq G$. This gives an isomorphism onto the $G$ invariant elements of $H^*(P_\ell, M)$ [Br82, III. Prop. 10.4]: see Rem 1.24. So, $\mu$ splits if $\mu_\ell$ splits.

There is an element, $g_3$, of order 3 in $\mathrm{SL}_2(\mathbb{Z}) \to \mathrm{PSL}_2(\mathbb{Z})$ is well-known to be freely generated by an element of order 3 and an element of order 2 – and so in
SL₂(ℤ/3²). This element of order 3 – given, say, by $A = \left( \begin{array}{cc} 1 & -3 \\ 1 & -2 \end{array} \right)$ – generates a 3-Sylow. (In Ch. 5 §3 we have reason to use a different element, $A^* = \left( \begin{array}{cc} 0 & -1 \\ 1 & -1 \end{array} \right)$.)

Conclude that $\mu_3$ splits. Denote the conjugacy class of $A$ by $C_3$, and note that its characteristic polynomial is $x^2 + x + 1$. Any lift of any non-trivial element in

$$\ker(\text{SL}_2(\mathbb{Z}/3^2) \to \text{SL}_2(\mathbb{Z}/3)) = \text{Ad}_3(\mathbb{Z}/3)$$

is an element of order $3^2$ in the Frattini cover

$$\ker(\text{SL}_2(\mathbb{Z}/3^2) \to \text{SL}_2(\mathbb{Z}/3)) = (\mathbb{Z}/3^2)^3 \to (\mathbb{Z}/3)^3.$$

So, the extension $\text{SL}_2(\mathbb{Z}/3^2) \to \text{SL}_2(\mathbb{Z}/3^2)$ certainly does not split.

[Se68, IV-28, Exer. 1.b] states that $\text{SL}_2(\mathbb{Z}/3^{k+2}) \to \text{SL}_2(\mathbb{Z}/3^2)$, $k \geq 0$, is Frattini. Take $v \in \ker(\text{SL}_2(\mathbb{Z}/3^2) \to \text{SL}_2(\mathbb{Z}/3)).$

For $\tilde{v} \in \ker(\text{SL}_2(\mathbb{Z}/3^2) \to \text{SL}_2(\mathbb{Z}/3))$ lifting $v$, $\tilde{v}^3$ identifies with $v$, but in $\ker(\text{SL}_2(\mathbb{Z}/3^3) \to \text{SL}_2(\mathbb{Z}/3^2))$. From that stage on, any subgroup mapping onto $\text{SL}_2(\mathbb{Z}/3)$ has the kernel in it.

The case $\ell = 2$ is similar. Go up a higher level to exploit the free-abelianess of $\ker(\text{SL}_2(\mathbb{Z}/2^k) \to \text{SL}_2(\mathbb{Z}/2^3))$, $k \geq 3$. [Se68, IV-28, Exer. 2] produces a $D_3$ in $\text{SL}_2(\mathbb{Z}/2)$ showing that $\text{SL}_2(\mathbb{Z}/2) \to \text{SL}_2(\mathbb{Z}/2)$ splits.

Using $\text{SL}_2(\mathbb{Z}/\ell) \to \text{PSL}_2(\mathbb{Z}/\ell)$ is Frattini: As the composite of two Frattini covers, $\mu_\alpha \circ \mu_\tilde{\alpha}$ is also a Frattini cover. Finally, at least for $\ell > 3$, the Frattinneness of $\text{PSL}_2(\mathbb{Z}/\ell) \to \text{PSL}_2(\mathbb{Z}/\ell)$ is the converse statement: If $\psi : H \to G$ is Frattini, and $\psi$ factors through $H_1$, then both $H \to H_1$ and $H_1 \to G$ are Frattinni.

The eventually Frattini comment follows from Rem. 4.7. The last sentence follows from Rem. 1.26.

**Remark 3.3 (Simplesness vs Frattinneness for $\text{SL}_2(\mathbb{Z}/\ell)$).** It is well-known that the values of $\ell > 3$ used in Prop. 3.2 coincide with the values for which $\text{PSL}_2(\mathbb{Z}/\ell)$ is simple, say, [Ar91, p. 296]. In (6.12b), the condition $\ell > 3$ arises from the necessity of the equation

$$(u+v\ell)^\ell \equiv ((u+v\ell)^2(u+v\ell)^{\ell-4} \equiv 0 \mod \ell^2,$$

for $u \in \text{Ad}_3(\mathbb{Z}/\ell)$ whose square is 0. Simplesness is not directly related.

**3.2. Modular curves vs MTs.** Starting with the case $\ell$ odd, we follow the braid action in going from

$$\left\{ \text{Ni}_{k+1,1}^{\dagger} \right\}_{k=0}^{\infty} \overset{\text{def}}{=} \text{Ni}(D_{kk+1}, C_{2^4})^{\dagger, rd}$$

$$\left\{ \text{Ni}_{k+1,2}^{\dagger} \right\}_{k=0}^{\infty} \overset{\text{def}}{=} \text{Ni}(\mathbb{Z}/\ell^{k+1})^2 \times \mathbb{Z}/2, C_{2^4})^{\dagger, rd}$$

with a superscript indicating inner or absolute classes.

---

1For reasons unknown [Ar91, Thm. 8.3] left out $\ell = 5$, for which we have the well-known equality $\text{PSL}_2(\mathbb{Z}/5) = A_5$ used, say, in §1.4.
§3.3.3 has the case $\ell = 2$, the type-2 special case of the general idea of how we handle the primes $\ell$ that aren’t perfect. Again, this is an example of the MT approach to the OIT, taking on, in this case, the hardest special prime.

$\mu_{\ell,1}^{\mathrm{abs},\mathrm{rd}}$ and $\mu_{\ell,1}^{\mathrm{in},\mathrm{rd}}$ for $\ell$ odd: In each case of Table 1, the left system maps to the right as a system of moduli spaces; each term is given by a one-one map on the underlying covers of $\mathbb{P}^1_\mathbb{C}$, whose points represent moduli. This is compatible with the corresponding maps on their respective stack structures (as in §4.3.2; the reduced spaces don’t have fine moduli).

<table>
<thead>
<tr>
<th>Table 1. Dihedral Nielsen classes $\mapsto$ Modular Curves</th>
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<tbody>
<tr>
<td>${ \mathcal{H}(D_{k+1}, C_{2^k}) }^{\mathrm{abs},\mathrm{rd}}<em>{k \geq 0} \to \mathbb{P}^1</em>\mathbb{C}$ $\xrightarrow{\mu_{\ell,1}^{\mathrm{abs},\mathrm{rd}}}$ $\mathcal{X}<em>0, \ell \to \mathbb{P}^1</em>\mathbb{C}$</td>
</tr>
<tr>
<td>${ \mathcal{H}(D_{k+1}, C_{2^k}) }^{\mathrm{in},\mathrm{rd}}<em>{k \geq 0} \to \mathbb{P}^1</em>\mathbb{C}$ $\xrightarrow{\mu_{\ell,1}^{\mathrm{in},\mathrm{rd}}}$ $\mathcal{X}<em>1, \ell \to \mathbb{P}^1</em>\mathbb{C}$</td>
</tr>
<tr>
<td>${ \mathcal{H}((\mathbb{Z}/\ell^{k+1})^2 \times \mathbb{Z}/2, C_{2^k}) }^{\mathrm{in},\mathrm{rd}}<em>{k \geq 0} \to \mathbb{P}^1</em>\mathbb{C}$ $\xrightarrow{\mu_{\ell,2}^{\mathrm{in},\mathrm{rd}}}$ $\mathcal{Y}<em>\ell \to \mathbb{P}^1</em>\mathbb{C}$</td>
</tr>
</tbody>
</table>

We attend to $\mu_{\ell,1}^{\mathrm{abs},\mathrm{rd}}$ and $\mu_{\ell,1}^{\mathrm{in},\mathrm{rd}}$ with $\ell$ odd here, to $\ell = 2$ in §3.3.3 and to the more intricate $\mu_{\ell,2}^{\mathrm{in},\mathrm{rd}}$ in Table 1 – Jacobian Nielsen class – in §3.3.

3.2.1. The absolute case. The permutation representation of $D_{\ell k+1}$ is given by the action on $\langle \begin{pmatrix} -1 & 0 \\ 1 & 0 \end{pmatrix} \rangle$ defined $H$ cosets. A conjugate $m^{-1} \begin{pmatrix} -1 & 0 \\ 1 & 0 \end{pmatrix} m$ fixes only the coset $H m$. Given the four branch points $z_f$, and a set of classical generators (as in §2.2), a cover $f : W \to \mathbb{P}^1_\mathbb{C}$ in the Nielsen class $\text{Ni}(D_{\ell k+1}, C_{2^k})$ gets assigned particular branch cycles in $S_{\ell k+1}$

having cycle type $(2)(1)(2)$ (2) repeats $\frac{\ell k+1-1}{2}$ times.

Its genus, $g_f$ is given by

$$2(\ell k+1+g_f-1) = 4\left(\frac{\ell k+1-1}{2}\right), \text{ or } g_f = 0.$$  

Similarly, compute the genus of the Galois closure cover $g_f$ from

$$2(2\ell k+1+g_f-1) = 4(\ell k+1) \text{ or } g_f = 1.$$  

Such a cover represents $p_f \in \mathcal{H}(D_{\ell}, C_{2^k})^{\text{abs}}$. As in, §3.2, we can braid all those outer automorphisms; both Hurwitz spaces are irreducible.

The Galois closure of $f$ corresponds to a point $\hat{p}_f \in \mathcal{H}(D_{\ell k+1}, C_{2^k})^{\text{in}}$ lying over $p_f$. Then, a cover $\hat{f} : \hat{W} \to \mathbb{P}^1_\mathbb{C}$, identified with any component of the fiber product $\ell k+1$-times of $f$ – as constructed in §2.1, represents $\hat{p}_f$. A copy of $D_{\ell k+1}$ identifies with its automorphism group, up to conjugation by $D_{\ell k+1}$. The normalizer, $N_{S_{\ell k+1}}(D_{\ell k+np})$ of $D_{\ell k+1}$ in $S_{\ell k+1}$, gives a listing of points of $\mathcal{H}(D_{\ell k+1}, C_{2^k})^{\text{in}}$ over $p_f$. Here is why.

Pick a component $\hat{W}$ (in notation of (1.15)). You find $D_{\ell k+1}$, as a subgroup of the symmetric group, preserves it. Any other component is given by conjugation of
this one by some \( g \in S_{k+1} \). As in Lem. 2.1, that component is the same as \( \tilde{W} \), if and only if \( g \) conjugates the copy of \( D_{k+1} \) into itself; equivalently, \( g \in N_{S_{k+1}}(D_{k+1}) \).

Further, this component represents an element of \( \text{Ni}(D_{k+1}, \mathbb{C}_{2^t}) \) if and only if \( g \in D_{k+1} \). That is why the natural map from the inner to the absolute space, \( \mathcal{H}_{k+1}^\text{ini} \rightarrow \mathcal{H}_{k+1}^\text{abs} \), over any one component, \( \mathcal{H}' \) of the absolute space, consists of a union of Galois covers \( \mathcal{H}'' \rightarrow \mathcal{H}' \), with the group of this cover identified with a subgroup of the quotient \( N_{S_{k+1}}(D_{k+1})/D_{k+1} : \) as in Spaces III Prop. 3.5. In this example, though, there is only one inner component, again according to §3.2.

3.2.2. The traditional \( X_0(\ell^{k+1}) \). Denote \( X_0(\ell^{k+1}) \) minus its cusps (points over \( j = \infty \)) by \( X_0(\ell^{k+1})' \). A point of it is an equivalence class of an elliptic curve \( E_j \), together with a subgroup \( C_{k+1} \) isomorphic to \( \mathbb{Z}/\ell^{k+1} \) on \( E_j \). Here \( j' \) will be the equivalence class modulo \( \text{PSL}_2(\mathbb{C}) \) of the collection \( \mathbf{z}_j \). Take \( E_j' \) to be the Picard group, \( \text{Pic}(\tilde{W}_j)_0 \), of degree 0 divisor classes on \( \tilde{W}_j \). Then, \( D_{k+1} \) acts on \( E_j' \).

The normalizer, \( N_{S_\ell}(D_\ell) = \mathbb{Z}/\ell^{k+1} \times (\mathbb{Z}/\ell^{k+1})^* \) has the same \( \ell \)-Sylow as does \( D_{k+1} \). Take \( C_{k+1} \) to be the group generated by translations of the origin induced by the \( \ell \)-Sylow. Then, \( \mathcal{H}(D_{k+1}, \mathbb{C}_{2^t})^\text{abs} \rightarrow X_0'(\ell^{k+1}) \)

\[
(6.13) \quad \text{is given by } f : W \rightarrow \mathbb{P}^1 \xrightarrow{\text{mod } (\pm 1)} (E_j', C_{k+1}).
\]

This map factors through the action of \( \text{PSL}_2(\mathbb{C}) \) on the Hurwitz space since that action doesn’t affect the Galois closure cover.

To see this induced map is one-one from \( \mathcal{H}(D_{k+1}, \mathbb{C}_{2^t})^\text{abs,rd} \rightarrow X_0(\ell^{k+1})' \), complete the map to \( \mathbb{P}^1 \), from the projective normalization of \( \mathcal{H}(D_{k+1}, \mathbb{C}_{2^t})^\text{abs,rd} \). Then use (1.19) for the cover degree. Or, we can reverse

\[
p_f \in \mathcal{H}(D_\ell, \mathbb{C}_{2^t})^\text{abs,rd} \mapsto (E_j', C_{k+1}) \text{ in (6.13) by forming the diagram}
\]

\[
(6.14) \quad \begin{array}{ccc}
E_j' & \xrightarrow{\text{degree } \ell \text{ isogeny}} & E_j'/C_{k+1} \\
\text{mod } (\pm 1) & \xrightarrow{\text{degree } \ell \text{ rational function}} & \text{mod } (\pm 1) \\
\mathbb{P}^1_w & \xrightarrow{} & \mathbb{P}^1_z
\end{array}
\]

**Remark 3.4.** Using the degree of the covers over the \( j \)-line can also be done by summing the cusp widths cusps (over \( j = \infty \)) as in Thm. 2.13, from (2.31b). For example: with \( k = 0 \), the degree of \( \mathcal{H}(D_\ell, \mathbb{C}_{2^t})^\text{abs,rd} \rightarrow \mathbb{P}^1_j \) is \( \ell + 1 \); the sum of the widths of an \( \text{HM} \) cusp and its shift (resp. \( \ell \) and 1). In that counting, these are the \( q_2 \) orbits on reduced Nielsen classes of

\[
g_{\text{HM}} = (\left( \begin{array}{cc} -1 & 0 \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & 0 \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & a \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & a \\ 0 & 1 \end{array} \right)) \), and
\]

\[
(g_{\text{HM}})_{\text{sh}} = (\left( \begin{array}{cc} -1 & 0 \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & a \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & a \\ 0 & 1 \end{array} \right), \left( \begin{array}{cc} -1 & 0 \\ 0 & 1 \end{array} \right)).
\]

One problem, though, for general \( k \), is that the cusp widths are not a well-known computation for \( X_0(\mathbb{Z}/\ell^{k+1}) \).
3.2.3. Adjustment from absolute to inner. The adjustment to handle $\mu_{\ell,1}^{\text{in,rd}}$ requires only replacing the subgroup $C_\ell$ on the elliptic curve $E_j'$, with a generator $e'$ of $C_\ell$ in the classical description of $X_1(\mathbb{Z}/\ell^{k+1})$. Then, the natural map $\mathcal{H}(D_\ell, C_{2\mathbb{Z}})^{\text{in}} \to X_1'(\ell)$ is given by $\hat{f} : \hat{W} \to \mathbb{P}^1_\mathbb{F}_2 \to (E_j', e')$.

The equivalence on the right $(E_j', e') \sim (E_j', -e')$ is matched by inner equivalence on the left, conjugation by $(-1 \ 0 \ 0 \ 1)$. As in (2.31e), the whole inner Nielsen class is the braid orbit of an HM rep.

Remark 3.5 (Fine moduli to not fine reduced moduli). The center of $D_{\ell^{k+1}}$ is trivial, as in Thm. 1.7. So, the inner and absolute $D_\ell$ Hurwitz spaces have fine moduli. Over $z' \in z_j$, there is a unique unramified point $w_{z'} \in W_f$. The Klein 4-group, $K_{z_j} < \text{PSL}_2(\mathbb{C})$ preserving $z_j$, gives an absolute equivalence of $f$ with itself, as a cover of $\mathbb{P}^1_\mathbb{F}_2$. Since $Q''$ acts trivially on inner Nielsen classes, each $g \in Q''$ extends to an equivalence of $\hat{f}$ with itself. That is, $Q''$ acting trivially on Nielsen classes in §3.2. Those equivalences are transitive on the collection $\{w_{z'}\}_{z' \in z_j}$.

3.3. Modular curves and MTs: Jacobian case.

3.3.1. Jacobian Nielsen class in Serre’s case. We now find the lift invariant is a replacement for the traditional role of the Weil pairing, following Ch. 4 §4.3 in considering the braid action on $\text{Ni}_{\ell^{k+1},2}$.

$\ell$ is odd: Consider these 4-tuples

\[ A_{\ell^{k+1}} \overset{\text{def}}{=} \{ \mathbf{a} = (a_1, \ldots, a_4) \in (\mathbb{Z}/\ell^{k+1})^4 \mid a_1 - a_2 + a_3 + a_4 \equiv 0 \mod \ell^{k+1}, (a_i - a_j, 1 \leq i < j \leq 4) = \mathbb{Z}/\ell^{k+1} \}. \]

Associate to $g_a \in \text{Ni}_{\ell^{k+1},1}$ the element $\mathbf{a} = (a_1, \ldots, a_4)$ given by

\[ (\begin{array}{cccc}
-1 & a_1 & 0 & 0 \\
0 & a_2 & 1 & 0 \\
0 & a_3 & 1 & 0 \\
0 & a_4 & 1 & 0
\end{array}) \] as in Ex. 2.7.

Then, it makes sense to denote elements in $\text{Ni}_{\ell^{k+1},2}$ by $g_{a,a'}$ by substituting $(a_i, a'_i)$ for $a_i$, $i = 1, \ldots, 4$, in (6.15).

The Nielsen class $\text{Ni}_{\ell^{k+1},1}$ has one braid orbit (§3.2). The action of $H_4$ on $\text{Ni}_{\ell^{k+1},2}$ extends its action on $\text{Ni}_{\ell^{k+1},1}$, to compute braid orbits on $\text{Ni}_{\ell^{k+1},2}$ we may choose any one allowable $\mathbf{a}$, and check possibilities for $\mathbf{a}'$ that go with it. Start where $\mathbf{a}$ corresponds to the shift of an HM rep. $\mathbf{a}_{\text{sh}} = (0, a, a, 0)$ with $a \in (\mathbb{Z}/\ell^{k+1})^*$. The only condition not obviously satisfied is generation.

Lemma 3.6. Substitute $g_{a,a'}$ in $g_a$, or $(a_i, a'_i)$ for $a_i$, $1 \leq i \leq 4$, to represent a class in $\text{Ni}_{\ell^{k+1},2}^{\text{in}}$ modulo these conditions:

\[ (6.16a) \ (a_1, a'_1) = 0 \text{ and } \sum_{i=2}^{4}(a_i, a'_i) \equiv 0 \mod \ell^{k+1}, \]

\[ (6.16b) \ \{(a_i, a'_i) \mod \ell \mid 2 \leq i \leq 4\} \text{ aren’t all on a line through 0}. \]

Starting with $\mathbf{a}_{\text{sh}}$, the allowable $\mathbf{a}'$, up to inner equivalence, have the form

\[ \{(0, a'_2, a'_3, a'_3 - a'_2)\} \text{ with } a'_3 - a'_2 \neq 0 \mod \ell. \]
we may assume \((a_1, a'_1) = 0\). Complete (6.16a) from product-one (1.18c).

Recognize (6.16b) as equivalent to entries of \(g_{a,a'}\) generate \((\mathbb{Z}/\ell k+1)^2 \times^s \mathbb{Z}/2\).

Given that the first entry is now \(\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}\), this says

\[
\langle (a_i, a'_i), i = 2, 3, 4 \rangle = (\mathbb{Z}/\ell k+1)^2 \text{ def } E_k.
\]

Since \(E_k\) is a Frattini cover of \(E_1\), this is equivalent to showing that the image of \(\langle (a_i, a'_i), i = 2, 3, 4 \rangle\) is all of \(E_1\). For this it suffices in the two dimensional space \(E_1\) that the hoped for generators aren’t all on one line (through the origin).

Now consider the allowable \(a'\) that go with \(a_{sh}\). Having the 4th entry nonzero mod \(\ell\) is necessary and sufficient for the second line condition of (6.16), while the first line is automatic from its form.

\[\square\]

3.3.2. Values of the lift invariant. Now we show values of the lift invariant to the small Heisenberg group separate braid orbits on \(\text{Ni}_{\ell k-1,2}\). Indirectly, this accounts for the constants that come from \(\mathbb{Q}(e^{2\pi i/\ell k+1})\) traditionally arising from the Weil pairing. These now interpret as values of a Nielsen class lift invariant.

There is no lift invariant for the Nielsen classes with \(D_{\ell k+1}\) and \(\ell\) odd. Yet, there is one for \(G_{\ell k+1} = (\mathbb{Z}/\ell k+1)^2 \times^s \mathbb{Z}/2, k \geq 0\). It comes from the small Heisenberg group, as in Ch. 5 §3, except the external semidirect product comes from \(\mathbb{Z}/2\) rather than \(\mathbb{Z}/3\) (as in Ch. 5).

So, \(\text{Ni}(\mathbb{H}(\mathbb{Z}/\ell)^s \mathbb{Z}/2, C_{2s})\) elements are 4-tuples with entries of form

\[
\begin{pmatrix}
-1 \\
0 \\
m(a,a',z) \\
1
\end{pmatrix}
\]

with \(m(a,a',z)\) with

\[
M(x,y,z) \text{ def } \begin{pmatrix}
1 & a & z \\
0 & 1 & a' \\
0 & 0 & 1
\end{pmatrix}, a, a', z \in \mathbb{Z}/\ell k+1
\].

Precisely, following Lem. 3.6, \(a_{sh} = a\) as above,

with \(a'\) given by \((0, a'_2, a'_3, a'_3-a'_2)\), with \(a'_3-a'_2 \neq 0\).

Write the action of the \(\mathbb{Z}/2\) on \(M(a,a',z)\) as \(-1 \ast M(a,a',z) = M(-a,-a',z)\); trivial action on \(z\) comporting with

\[
\mathbb{H}(\mathbb{Z}/\ell)^s \mathbb{Z}/2 \rightarrow (\mathbb{Z}/\ell)^2 \times^s \mathbb{Z}/2
\] is a central extension.

**Proposition 3.7.** An element \(\begin{pmatrix} -1 & M(x,x',z) \\ 0 & 1 \end{pmatrix}\) in \(\mathbb{H}(\mathbb{Z}/\ell k+1)^s \mathbb{Z}/2\) has order 2 if and only if \(z = \frac{x+x'}{2}\).

The lift invariant of \(g_{a_{sh}, a'}\) (as above) is \(\frac{a(a'_3-a'_2)}{2} \neq 0\). It has \(|(\mathbb{Z}/\ell k+1)^s|\) values , running over all elements in \(\text{Ni}_{\ell k+1,2}\). In particular:

(6.17a) all braid orbits are separated by their lift invariant values;
(6.17b) their corresponding inner Hurwitz space components are conjugate by the action of $G(Q(e^{2\pi i/k+1})/Q);

(6.17c) The normalizer of $G_{k+1}$ in $S_2$, $N_{S_2}(G_{k+1})$ is $GL_2(Z/\ell);

(6.17d) the geometric (resp. arithmetic) monodromy group of any $Ni_2^n\times_{k+1,2}$ component over $P_2^1$ is $SL_2(Z/\ell^k+1)/(\pm 1)$ (resp. $GL_2(Z/\ell^k+1)/(\pm 1)$).

PROOF. An order 2 lift of $(-1, 0) \begin{pmatrix} x, x' \end{pmatrix}$ to $H(Z/\ell^k+1) \times^* Z/2$ satisfies $M(x, x', z) = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$. From (6.17a), the lift invariant is a braid invariant, preserved by the action of $\text{GL}_{k+1}(Z)$.

Directly calculate that $(-1) \cdot M(x, x', z)M(x, x', z)$ has upper right entry $2z - xx'$, or $z = \frac{a_1}{2}$, as stated in the lemma.

Now compute the lift invariant of $g_{a_{sh}, a'}$, by taking the product of the order 2 lifts of its entries to $H(Z/\ell^k+1) \times^* Z/2$. That calculation amounts to checking the upper right entry of the following product:

$$
\begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
M(0, 0, 0) \\
M(a, a', \frac{aa_1}{1})
\end{pmatrix}
\begin{pmatrix}
M(a, a', \frac{aa_1}{1}) \\
M(0, a', a_2, 0)
\end{pmatrix}
n\begin{pmatrix}
M(-a, -a', \frac{aa_1}{1}) \\
M(a, a', \frac{aa_1}{1})
\end{pmatrix}
$$

Multiply the first two matrices, then and the last two matrices, to get

$$
\begin{pmatrix}
1 & 0 \\
M(-a, -a', \frac{aa_1}{1})
\end{pmatrix}
\begin{pmatrix}
M(a, a', \frac{aa_1}{1}) \\
M(0, a', a_2, 0)
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
M(-a, -a', \frac{aa_1}{1})
\end{pmatrix}
\begin{pmatrix}
M(a, a', \frac{aa_1}{1}) \\
M(0, a', a_2, 0)
\end{pmatrix}
$$

Conclude the upper right entry of $M(a, a', \frac{aa_1}{1})M(-a, -a', \frac{aa_1}{1})$, the lift invariant value, is $\frac{a(a'_1-a_2)}{2} \neq 0$, an element in $(Z/\ell^k+1)^*$ according to the conditions of Lem. 3.6. From (3.10a), the lift invariant is a braid invariant, preserved by the action of $H_4$ on $g_{a_{sh}, a'}$.

Regard $V_k = (Z/\ell^k+1)^2$ as both the letters of a permutation representation and as a subgroup of $S_{(Z/\ell^k+1)^2}$ The automorphisms of $V_k$ are given by $GL_2(Z/\ell^k+1)$ which we can now regard as a subgroup of the symmetric group. The copy of $Z/2$ in $V_k \times^* Z/2$ is in its center, generated by minus the identity matrix.

An element of $GL_2(Z/\ell^k+1)$ acting by conjugation on Nielsen classes is therefore determined by what it does to $(a, a')$. By the conditions, this is determined by what it does to the pair $(a, a'_2), (a, a'_3)$ since that linearly determines what it does to $(0, a'_2-a_2)$. The same holds for any braid $q$ acting on reduced inner Nielsen classes. Therefore, all braid element actions are given by conjugations by $GL_2(Z/\ell^k+1)$.

It remains to braid conjugation by elements of $SL_2(Z/\ell)$ (as in Def. 3.7). To see that action, there are two calculations figured by what the generators of $H_4$ do to the 2nd and 3rd entries of $g_{a_{sh}, a'}$, after the result has been normalized to have $\begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}$ in the first entry, and product one determining the 4th entry:

$$
\text{sh} : g_{a_{sh}, a'} \to (\ast, \begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}, \begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}, \ast)
$$

$$
q_2 : g_{a_{sh}, a'} \to (\ast, \begin{pmatrix}
-1 & 2(a, a'_2-a, -a') \\
0 & 1
\end{pmatrix}, \begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}, \ast).
$$
That is, \( sh \) is represented by \( \begin{pmatrix} -1 & -2 \\ 1 & 1 \end{pmatrix} \) and \( q_2 \) is represented by \( \begin{pmatrix} 2 & 1 \\ -1 & 0 \end{pmatrix} \). The square of \( \begin{pmatrix} -1 & -2 \\ 1 & 1 \end{pmatrix} \) is \( -I_2 \), whose effect is inner equivalent to \( I_2 \) by conjugating \( g_{a,a'} \) by \( \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \). Multiply \( q_1 q_2 q_1 = q_2 q_1 q_2 \) by \( q_2^{-1} \) to get \( q_1 q_2 \). That acts as \( \begin{pmatrix} -1 & -2 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 2 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} -2 & -3 \\ 1 & 1 \end{pmatrix} \).

Check this has order 3. Therefore elements of respective order 3 and 2, independent of \( \ell \), represent the actions of \( \gamma_0 \) and \( sh \).

So, they give generators for \( \text{PSL}_2(\mathbb{Z}) \), as expected. Now, combine the \( \text{PSL}_2 \) action with conjugations on the inner braid components from the action of (6.17b) from the lift invariant. Ch. 3 Prop. 2.19 then gives the full action of \( \text{GL}_2(\mathbb{Z}/\ell)/\langle \pm 1 \rangle \).

That concludes the proof. □

3.3.3. What happens if \( \ell = 2 \). The phrasing, say of [BFr02, §1.1], only referred to \( D_\ell \) (or \( (\mathbb{Z}/\ell)^2 \times \mathbb{Z}/2) \), for \( \ell \) odd, because we assumed \( G \) is \( \ell \)-perfect. We amend this to include all \( \ell \), a special case of our restricting the Frattini covers to avoid the Ext-Frattini covers of Prop. 2.6. By not having considered the prime 2 divisor of \( D_\ell \), when \( \ell \) is odd, we are following the type-1 paradigm in case RETURNM. Now we are following the type-2 paradigm.

At level \( k = 0 \) for \( \ell = 2 \), there are these tiny groups:

(6.19a) For \( X_0(\mathbb{Z}/2) \), \( D_2 \) (a Klein 4-group); and
(6.19b) for \( X(\mathbb{Z}/2) \), \((\mathbb{Z}/2)^2 \times \mathbb{Z}/2) \).

4. Proofs of the Upper half-plane Paradigm

4.1. Proof of Thm. 2.7.

4.2. Proof of Thm. 2.14. [BFr02, §2.6] takes a completely cohomological approach to the properties listed in (2.28). We give an example.

[BFr02, §2.6.4] works on the complements of \( Q'' \) (a Klein 4-group, and therefore abelian according to Prop. 2.10) in \( M_4 \). This starts with seeing directly one splitting by the group \( \Gamma_1' = \langle q_1(\bar{z}), q_2(\bar{z}) \rangle \). As in Def. 1.7, splittings correspond to elements of \( H^1(\Gamma_1', Q'') \). Conclude (2.28d) if this cohomology group has order 2.

Let \( B \) be the largest elementary abelian 2-group quotient of the rank 2 free group \( \text{Cen}_{\Gamma_1}(Q'') \). Then \( B \) and \( Q'' \) are isomorphic as \( \mathbb{F}_2[\Gamma_1'] \) modules. For any group \( G \) with normal subgroup \( H \) acting on a module \( M \), there is an exact sequence [AW67, p. 100]:

(6.20) \[ 0 \to H^1(G/H, M^H) \xrightarrow{\text{inf}} H^1(G, M) \xrightarrow{\text{res}} H^1(H, M)^G \to H^2(G/H, M^H). \]

Apply this with \( M = Q'', G = \Gamma_1' \) and \( H = \text{Cen}_{\Gamma_1}(Q'') \), so \( G/H = S_3 \). Restrict to a 2-Sylow \( P_2 \) of \( S_3 \). Restriction of an element from \( H^*(G, A) \) to \( H^*(P, A) \) is injective
if $P$ is the $p$-Sylow of $G$ [AW67, p. 105] (more precisely in the footnote near the beginning of §1.4). Therefore, if $H^*(P_2, M^H)$ is trivial, so is $H^*(G/H, M^H)$.

The action of $P_2$ on $Q''$ is the regular representation on two copies of $P_2$, so $Q''$ is a free $P_2$ module and the cohomology groups $H^1(G, M)$ and $H^2(G, M)$ are trivial. Conclude: $H^1(\Gamma_1', Q'') = \text{Hom}(B, Q'')^{S_3} = \mathbb{Z}/2$.

Those two conjugacy classes of subgroups of $M_4$ that are isomorphic to $\text{PSL}_2(\mathbb{Z})$ are joined by the relation $q_1q_3^{-1} = 1$.

4.2.1. A presentation of $M_r$. §2.2 defines the mapping class group $M_r$ as the image group of $H_r$ acting on the Nielsen class $\text{Ni}(\bar{G}_r, C_{\bar{g}g})$ in $\mathbb{Z}/2$. This is given by the action by the braids $Q_1, \ldots, Q_{r-1}$ modulo the action by inner automorphisms, $\text{Inn}(\bar{G}_r)$, of $\bar{G}_r$, mapping $\bar{g}_1, \ldots, \bar{g}_r$ to permutations of their conjugates. This maps $B_r$ (relations given by (2.13)) to $M_r$ factoring through $H_r$.

Further, $M_r$ is the quotient of $B_r$ by the relations (6.21):

$$
\tau_1(r) = (Q_{r-1}Q_{r-2} \cdots Q_2)^{r-1}, \quad \tau_2(r) = Q_1^{-2}(Q_{r-1} \cdots Q_4)^{r-2}, \ldots,
$$

$$
\tau_{r+1}(r) = (Q_{r} \cdots Q_1)^{-r-1}(Q_{r-1} \cdots Q_{r+2})^{-r-1}, \ldots,
$$

$$
\tau_{r-1}(r) = (Q_{r-2} \cdots Q_1)^{1-r}, \quad \text{and} \quad \tau(r) = (Q_{r-1} \cdots Q_1)^{r}.
$$

This complicated presentation, from [KMS66, §3.7] or [Ma34], is oblivious to the map $H_r \to M_r$ dominating this paper. Using it conceptualizes $N_r = \ker(B_r \to M_r)$. The switch of emphasis shows in Prop. 2.9.

With $Q_1Q_2 \cdots Q_{r-1}^2 \cdots Q_2Q_1 = R_1$, consider these additional elements:

$$
(6.22) \quad R_2 = Q_1^{-1}R_1Q_1, \ldots, R_r = Q_{r-1}^{-1}R_1Q_{r-1} \quad \text{and} \quad (Q_1Q_2 \cdots Q_{r-1})^r.
$$

The relation between the maps $B_r \to H_r$ and $B_r \to M_r$ amounts to a comparison of (6.21) with (6.22). Thm. 2.14 presents both $M_4$ and $N_4$ memorably. Here our remarks comment on what the argument does for the case of general $r$. 
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