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IRREDUCIBILITY OF MODULI SPACES OF CYCLIC UNRAMIFIED COVERS OF GENUS g CURVES

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ABSTRACT. Let $(C_1, \ldots, C_r, G) = (\mathbf{C}, G)$ be an r-tuple consisting of a transitive subgroup G of S_m and r conjugacy classes $C_1, \ldots, C_r$ of G. We consider the concept of the moduli space $\mathcal{H}(\mathbf{C}, G)$ of compact Riemann surface covers of the Riemann sphere of *Nielsen class* $(\mathbf{C}, G)$. The irreducibility of $\mathcal{H}(\mathbf{C}, G)$ is equivalent to the transitivity of a specific permutation representation of the *Hurwitz monodromy group* (§1), but there are few general tools to decide questions about this representation. Theorem 2 gives a class of examples of $(\mathbf{C}, G)$ for which $\mathcal{H}(\mathbf{C}, G)$ is irreducible. As an immediate corollary this gives an elementary proof and generalization of the irreducibility of the moduli space of cyclic unramified covers of genus g curves (for which Deligne and Mumford [**DM**, Theorem 5.15] applied Teichmüller theory and Dehn's theorem). This contrasts with the examples of $(\mathbf{C}, G)$ in [**BFr**] for which $\mathcal{H}(\mathbf{C}, G)$ is reducible. These kinds of questions combined with the study of the existence of rational subvarieties of $\mathcal{H}(\mathbf{C}, G)$ have application to the realization of a group G as the Galois group of a regular extension of $\mathbb{Q}(t)$ [**Fr3**, §4].

1. Introduction to the fundamental moduli spaces. The most well-known moduli spaces of compact Riemann surfaces are the moduli spaces, denoted $\mathcal{M}_g$, of compact Riemann surfaces of genus $g \geq 1$ (in the case $g = 0$, $\mathcal{M}_g$ can be taken to be a point). Each point of $\mathcal{M}_g$ corresponds to exactly one isomorphism class of surfaces of genus g. Furthermore, $\mathcal{M}_g$ is a complex analytic set (actually, algebraic) with the following key property. Let $\Phi: \mathcal{X} \to \mathcal{P}$ be a family of compact Riemann surfaces of genus g. Here that will mean that $\mathcal{X}$ and $\mathcal{P}$ are compact analytic sets, that Φ is a complex analytic map, and that for each point $\mathfrak{p} \in \mathcal{P}$ the set $\{x \in \mathcal{X} \mid \Phi(x) = \mathfrak{p}\} = \mathcal{X}_\mathfrak{p}$, *the fiber over* $\mathfrak{p}$, naturally inherits the structure of a compact Riemann surface of genus g. Then the natural map,

$$\Phi: \mathcal{P} \to \mathcal{M}_g, \tag{1.1}$$

defined by $\mathfrak{p} \to [\mathcal{X}_\mathfrak{p}]$ (the isomorphism class of $\mathcal{X}_\mathfrak{p}$) is complex analytic. A succinct story, with references, on the *irreducibility of* $\mathcal{M}_g$ appears in [**Fu**].

Deligne and Mumford [**DM**, Theorem 5.15] prove the irreducibility of spaces ${}_n\mathcal{M}_g$, $n \geq 1$, $g \geq 2$, that generalize the classical moduli spaces, $\mathcal{C}_n$, of elliptic curves with level n structure. The irreducibility of $\mathcal{C}_n$ follows from the identification of it

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with the quotient of the complex upper half plane by the action of

$$\Gamma(n) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}(2,\mathbb{Z}) \mid \begin{pmatrix} a & b \\ c & d \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \bmod(n) \right\}.$$

In the [**DM**] generalization, Teichmüller theory [**W**] and Dehn's theorem allow for a presentation of ${}_n\mathcal{M}_g$ as a quotient of a ball. These heavy tools limit the possibility of immediate generalization. This we give in a framework, considerably more elementary than that of [**DM**], that follows the classical tradition of [**Hu**].

For the sake of simplicity, but still allowing for fair comparison with [**DM**, Theorem 5.15] we generalize (Theorem 3) the proof of the irreducibility of ${}_o\mathcal{C}_{n,g}$, the *moduli space of cyclic unramified covers of degree n of genus g curves*. This corollary of [**DM**, Theorem 5.15] generalizes the irreducibility of the curves ${}_o\mathcal{C}_n$ that are classically identified with the quotient of the upper half plane by the group $\{\left(\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right) \in \mathrm{SL}(2,\mathbb{C}) \mid c \equiv 0 \bmod(n)\}$. In the special case $g = 4$ and 5, $n = 2$, this is an essential ingredient of the results of [**B**] on the number of components of the space of singular theta divisors of dimensions 4 and 5. Following a precise description of the spaces with which we shall deal, this section concludes with a paragraph of exposition on direct and general motivation for such irreducibility results through [**Fr2** and **Th**], connecting them to the classical inverse Galois group problem over $\mathbb{Q}$.

Riemann's existence theorem allows us to use combinatorial techniques in our analysis of moduli spaces. Each compact Riemann surface X can be presented as a cover $\varphi: X \to \mathbb{P}^1$ of the projective line. Let $z_1, \ldots, z_r$ be a list of the distinct points of $\mathbb{P}^1$ over which φ is ramified, and let $m(\varphi) = m$ denote the degree of φ. For a given surface X, it can be difficult to describe the possible values of r and m. But, there is a one-one correspondence between the elements of the following two sets [**Fr1**, §1]:

(1.2) (a) the quotient of $\{\boldsymbol{\sigma} = (\sigma(1), \ldots, \sigma(r)) \in (S_m)^r \mid \sigma(1)\sigma(2)\cdots\sigma(r) = 1$ and $\langle\sigma(1), \ldots, \sigma(r)\rangle = G(\boldsymbol{\sigma})$ is a transitive subgroup of $S_m\}$ by the relation that equivalences $\boldsymbol{\sigma}$ and $\gamma^{-1}\cdot\boldsymbol{\sigma}\cdot\gamma = (\gamma^{-1}\cdot\sigma(1)\cdot\gamma, \ldots, \gamma^{-1}\cdot\sigma(r)\cdot\gamma)$ for each $\gamma \in S_m$; and

(b) the quotient of $\{\varphi': X' \to \mathbb{P}^1$ of connected covers of degree m with branch locus in $\{z_1, \ldots, z_r\}\}$ by the relation that equivalences $\varphi': X' \to \mathbb{P}^1$ and $\varphi' \circ \psi: X'' \to \mathbb{P}^1$ for $\psi: X'' \to X'$ an isomorphism.

Such a correspondence, however, depends on additional data, and cannot be regarded as functional.

Let $(C_1, \ldots, C_r, G) = (\mathbf{C}, G)$ be an r-tuple consisting of a transitive subgroup G of S_m and r conjugacy classes $C_1, \ldots, C_r$ of G. Denote the set {equivalence classes of $\boldsymbol{\sigma} \in (S_m)^r \mid$ such that $G(\boldsymbol{\sigma}) = G$ and there exists $\beta \in S_r$ with $\sigma(\beta(i)) \in C_i$, $i = 1, \ldots, r\}$ by $\mathrm{Ni}(\mathbf{C}, G)$, the *Nielsen class of* $(\mathbf{C}, G)$. We assume, from here on, that $(\mathbf{C}, G)$ is so chosen that $\mathrm{Ni}(\mathbf{C}, G)$ is nonempty.

We now list $r - 1$ operators $Q_1, \ldots, Q_{r-1}$ that naturally act as permutations of the elements of $\mathrm{Ni}(\mathbf{C}, G)$ by a right-hand action. Indeed, Q_i maps the equivalence class of $\boldsymbol{\sigma} = (\sigma(1), \ldots, \sigma(r))$ to the equivalence class of

$$(1.3) \quad (\boldsymbol{\sigma})Q_i = \left(\sigma(1), \ldots, \sigma(i-1), \sigma(i)\cdot\sigma(i+1)\cdot\sigma(i)^{-1}, \sigma(i), \ldots, \sigma(r)\right), \quad i = 1, \ldots, r-1.$$

Our discussion continues with a brief review from [**BFr**, pp. 89–95]. Identify $\mathbb{P}^r$ with the quotient of the nonzero polynomials in x of degree at most r,

$$\left\{ \sum_{j=0}^{r} a_j \cdot x^j \not\equiv 0 \mid a_j \in \mathbb{C},\ j = 0, \ldots, r \right\},$$

by the relation that equivalences $\sum_{i=0}^{r} a_i \cdot x^i$ and $\sum_{i=0}^{r} a \cdot a_i \cdot x^i$ for $a \in \mathbb{C} - \{0\}$.

Consider the natural map—the *Noether cover*—

$$\Phi_r : (\mathbb{P}^1)^r \to \mathbb{P}^r \tag{1.4}$$

that maps $(z_1, \ldots, z_r) \in (\mathbb{P}^1)^r$ to the equivalence class of $\prod_{j=1}^{p}(x - z_j)$ with the proviso that the factor $x - z_j$ is replaced by 1 if $z_j = \infty$. Let Δ_r be the subset of $(\mathbb{P}_1)^r$ consisting of points with two or more equal coordinates, and let D_r, the *discriminant locus of the Noether cover*, be the image of Δ_r under Φ_r. For $\mathbf{a}^0 \in \mathbb{P}^r - D_r$, the fundamental group, $\pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$, is the quotient of the free group generated by elements $Q_1, \ldots, Q_{r-1}$ by the following list of relations [**FaBu**]:

$$\begin{aligned} &\text{(a)}\quad Q_i \cdot Q_j = Q_j \cdot Q_i, \qquad |i - j| \geq 2,\ 1 \leq i, j \leq r - 1; \\ &\text{(b)}\quad Q_i \cdot Q_{i+1} \cdot Q_i = Q_{i+1} \cdot Q_i \cdot Q_{i+1}, \qquad 1 \leq i \leq r - 1; \\ &\text{(c)}\quad Q_1 \cdots Q_{r-2} \cdot (Q_{r-1})^2 \cdot Q_{r-2} \cdots Q_1 = 1. \end{aligned} \tag{1.5}$$

From (1.5) the action given by (1.3) gives a permutation representation of $\pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ on the set $\mathrm{Ni}(\mathbf{C}, G)$. Let $Br_1, \ldots, Br_t$ be the distinct orbits of this action. Covering space theory associates to each Br_i an equivalence class of unramified covers

$$\mathcal{H}(Br_i) \to \mathbb{P}^r - D_r, \qquad i = 1, \ldots, t. \tag{1.6}$$

Define the (absolute) Hurwitz space $\mathcal{H}(\mathbf{C}, G)$ of $\mathrm{Ni}(\mathbf{C}, G)$ to be the disjoint union of the spaces $\mathcal{H}(Br_i)$, $i = 1, \ldots, t$. In [**BFr**, p. 104] (or [**Fr1**, §4] without the use of (1.5)) it is shown that $\mathcal{H}(\mathbf{C}, G)$ is a (coarse) moduli space for covers of Nielsen type $\mathrm{Ni}(\mathbf{C}, G)$ (i.e., covers $\varphi: X \to \mathbb{P}^1$ for which the $\boldsymbol{\sigma}$ given by (1.2)(a) is in $\mathrm{Ni}(\mathbf{C}, G)$). Then $\mathcal{H}(\mathbf{C}, G)$ is irreducible if and only if $t = 1$. Denote t by $\mathrm{Hur}(\mathbf{C}, G)$, the *Hurwitz number* of $(\mathbf{C}, G)$.

Theorem 2 of this paper shows that $\mathrm{Hur}(\mathbf{C}, G) = 1$ in the following case. Let S_m act on $(\mathbb{Z}/(n))^m$ by permutation of the coordinates. Denote the semidirect product of S_m and $(\mathbb{Z}/(n))^m$ by $(\mathbb{Z}/(n))^m \times^s S_m = \overline{G}$. Indicate elements of $\overline{G}$ by $(\alpha_1, \ldots, \alpha_m; \sigma) = (\boldsymbol{\alpha}; \sigma)$, $\alpha_k \in \mathbb{Z}/(n)$, $k = 1, \ldots, m$ and $\sigma \in S_m$. Let G be the subgroup of $\overline{G}$ consisting of $(\boldsymbol{\alpha}; \sigma)$ such that $\alpha_1 + \cdots + \alpha_m = 0$. Clearly G is normal in $\overline{G}$ and $\overline{G}$ may be regarded as a subgroup of $S_{m \cdot n}$. Then $\mathrm{Hur}(\mathbf{C}, G) = 1$ if $C_1 = C_2 = \cdots = C_r$ are the conjugacy class of $(\mathbf{0}; (1\ 2))$, $r \geq 4$ is an even integer and $m \geq 3$. The evenness of r assures that $\mathrm{Ni}(\mathbf{C}, G)$ is nonempty. Theorem 3 is a corollary, based on general principles, of Theorem 2.

The main theorem of [**Fr1**, §5] shows that under very mild group theoretic conditions on $(\mathbf{C}, G)$, the space $\mathcal{H}(\mathbf{C}, G)$ parametrizes a family of covers $\{\varphi_\mathfrak{p}: X_\mathfrak{p} \to \mathbb{P}^1 \mid \mathfrak{p} \in \mathcal{H}(\mathbf{C}, G)\}$ where the family, the map from the family to $\mathcal{H}(\mathbf{C}, G)$ and $\mathcal{H}(\mathbf{C}, G)$ are all algebraic sets defined over some cyclotomic field—*in the case that* $\mathrm{Hur}(\mathbf{C}, G) = 1$. It even gives the precise cyclotomic field K in question. Little, however, is known in the case that $\mathrm{Hur}(\mathbf{C}, G)$ exceeds 1, except that this can happen [**BFr**, §3]. If, furthermore, $\mathcal{H}(\mathbf{C}, G)$ contains a *K-rational subvariety* (even K-unirationality often suffices, as [**Fr3**, §4] explains), the K-rational points of this variety parametrize a family of curves $f(x, y) = 0$ defined over K for which $K(x, y)/K(x)$ is a regular Galois extension with group G. This is all sufficiently combinatorial to suggest a program for finding $\mathbf{C}$, given G, so as to get the cyclotomic field in question to be $\mathbb{Q}$. Thompson [**Th**] has stated such in the case that $r = 3$ (where $\mathcal{H}(\mathbf{C}, G)$ is covered by $(\mathbb{P}^1)^3 - \Delta_3$, and is always $\mathbb{Q}$-rational). This continues with work of Feit [**Fe**], Matzat [**Ma**] and Walter [**Wa**].

Since it is unlikely that a general technique will carry the program through with just the case $r = 3$, [**Fr3**, Theorem 4.2] states a condition that has produced nontrivial examples with $\mathcal{H}(\mathbf{C}, G)$ a rational variety for $r > 3$. It suggests a program that adds additional conditions to $\mathbf{C}$ to assure the rationality (and, when appropriate, $\mathbb{Q}$-rationality) of $\mathcal{H}(\mathbf{C}, G)$. Even in the case that $r = 4$, there are pairs $(\mathbf{C}, G)$ with $\mathcal{H}(\mathbf{C}, G)$ nonunirational (e.g., [**Fr2**, Theorem 3.3] gives an example where $\mathcal{H}(\mathbf{C}, G)$ maps surjectively to the modular curve ${}_o\mathcal{C}_n$; its genus exceeds o for n suitably large, and therefore a well-known generalization of Luroth's theorem shows that $\mathcal{H}(\mathbf{C}, G)$ is nonunirational). The argument of §3 of this paper, combined with [**HM**], shows that for $(\mathbf{C}, G)$ given in Theorem 2 with r suitably large, investigation of $\mathcal{H}(\mathbf{C}, G)$ is not amenable to any present day techniques that generalize the use of unirationality.

2. The group theory of moduli spaces of cyclic covers. Let $\varphi: X \to \mathbb{P}^1$ be a cover of degree m for which there are at least $m - 1$ points of X over each point of $\mathbb{P}^1$. If $\boldsymbol{\sigma}$ corresponds to this cover by (1.2)(a), then $\sigma(i)$ is a transposition, $i = 1, \ldots, r$. Such a cover is called *simple.* We are interested in the following situation. Let

$$X' \xrightarrow{\psi} X \xrightarrow{\varphi} \mathbb{P}^1 \tag{2.1}$$

be a sequence of covers of compact (connected) Riemann surfaces with these properties: the genus of X is g, φ is a simple cover of degree m; and ψ is an unramified Galois cover with group $\mathbb{Z}/(n)$. Our first theorem computes the Nielsen class of the cover $\varphi \circ \psi: X' \to \mathbb{P}^1$.

Let G be the subgroup of $\overline{G} = (\mathbb{Z}/(n))^m \times^s S_m$ given in §1. The *Galois closure* of $\varphi \circ \psi: X' \to \mathbb{P}^1$ is a Galois cover $\hat{\varphi}: \hat{X} \to \mathbb{P}^1$ of smallest possible degree such that there exists a sequence of covers

$$\hat{X} \xrightarrow{\hat{\psi}} X' \xrightarrow{\varphi\circ\psi} \mathbb{P}^1 \tag{2.2}$$

with $(\varphi \circ \psi) \circ \hat{\psi} = \hat{\varphi}$. Up to equivalence the Galois closure is unique.

THEOREM 1. *Suppose that $m \geq 3$ in the above notation. Then the Galois group of the Galois closure of $\varphi \circ \psi: X' \to \mathbb{P}^1$ given by (2.1) is isomorphic to G. If a correspondence given by (1.2) is set up, then this cover corresponds to $\boldsymbol{\sigma}' = (\sigma(1)', \ldots, \sigma(r)')$ where*

$$\sigma(i)' = \left(0, \ldots, 0, \underset{\substack{\uparrow \\ j\text{th pos.}}}{\alpha}, 0, \ldots, 0, \underset{\substack{\uparrow \\ k\text{th pos.}}}{-\alpha}, 0, \ldots, 0; \sigma(i) \right)$$

with $\sigma(i) = (j\ k) \in S_m$ *and* $\alpha \in \mathbb{Z}/(n)$ *(j, k and α dependent on i), $i = 1, \dots, r$, $\sigma(1)' \cdots \sigma(r)' = 1$ and $G(\boldsymbol{\sigma}') = G$. In particular, $r \geq 2m$, and the cover is in the Nielsen class* $\mathrm{Ni}(\mathbf{C}, G)$ *with $C_1 = C_2 = \cdots = C_r$, where C_1 is the conjugacy class of* $\{\mathbf{0}; (1\ 2)\}$.

PROOF. The second of the three parts of the proof includes some notation for manipulation within the group $\overline{G}$ to which we will refer later.

PART A. *The Galois group of* $\hat{\varphi}: \hat{X} \to \mathbf{P}^1$. There is a notational simplification if we compute using the function fields of the Riemann surfaces. Let $\mathbb{C}(X)$ (resp., $\mathbb{C}(X')$, $\mathbb{C}(\hat{X})$) be the field of meromorphic functions on X (resp., X', $\hat{X}$). Also, let $\mathbb{C}(\mathbf{P}^1) = \mathbb{C}(z)$ for some indeterminate z. Then (the primitive element theorem), $\mathbb{C}(X) = \mathbb{C}(z, x)$ for some $x \in \mathbb{C}(X)$. Let $x = x_1, \dots, x_m$ be the conjugates of x over $\mathbb{C}(z)$. Since $\mathbb{C}(X')/\mathbb{C}(X)$ is a cyclic extension with group $\mathbb{Z}/(n)$, we may choose $y = y_1 \in \mathbb{C}(X)$ so that $\mathbb{C}(X') = \mathbb{C}(z, x_1, y_1^{1/n})$. Thus, $\mathbb{C}(\hat{X}) = \mathbb{C}(z, x_1, y_1^{1/n}, \dots, x_m, y_m^{1/n})$ with $y_1, \dots, y_m$ the conjugates of y_1 over $\mathbb{C}(z)$.

Let ς_n be a primitive nth root of 1. The conjugates of $y_1^{1/m}$ over $\mathbb{C}(z)$ are exactly $\varsigma_n^\alpha \cdot y_j^{1/n}$, $j = 1, \dots, m$, $\alpha \in \mathbb{Z}/(n)$. Let $\tau \in G(\mathbb{C}(\hat{X})/\mathbb{C}(z))$. Associate to τ the element $F(\tau) \in \overline{G}$ by the following formula: if τ maps $(x_j, \varsigma_n^\alpha \cdot y_j^{1/n})$ to $(x_k, \varsigma_n^\beta \cdot y_k^{1/n})$, then

$$F(\tau) = \Big(\dots,\ \underset{\substack{\uparrow \\ j\text{th pos.}}}{\beta - \alpha},\ \dots; \sigma\Big) \quad \text{where } \sigma(j) = k,\ j = 1, \dots, m. \tag{2.3}$$

Check that F is a group homomorphism that embeds $G(\mathbb{C}(\hat{X})/\mathbb{C}(z))$ into $\overline{G}$. Let $D(\varphi)$ be the set of branch points of the cover $\varphi: X \to \mathbf{P}^1$.

The correspondence of (1.2) arises by choosing a suitable set $\mathcal{L}_1, \dots, \mathcal{L}_r$ of closed paths on $\mathbf{P}^1 - D(\varphi)$, all based at $z_0 \in \mathbf{P}^1 - D(\varphi)$, so that the homotopy classes of these paths generate the fundamental group $\pi_1(\mathbf{P}^1 - D(\varphi), z_0)$. Then the cover $\varphi: X \to \mathbf{P}^1$ corresponds to $(\sigma(1), \dots, \sigma(r))$, where $\sigma(i)$ gives the effect of analytically continuing the functions $x_1, \dots, x_m$ around the path $\mathcal{L}_i$. In more detail, express $x_1, \dots, x_m$ as power series in a neighborhood of z_0. Then analytically continue each around $\mathcal{L}_i$ to get a permutation, $\sigma(i)$, of these power series expressions, $i = 1, \dots, r$.

Since $X' \to X$ is unramified, the paths $\mathcal{L}_1, \dots, \mathcal{L}_r$ suffice to compute $\boldsymbol{\sigma}'$ for the cover $\varphi \circ \psi: X' \to \mathbf{P}^1$, and $\sigma(i)'$ is of the same order as $\sigma(i)$, $i = 1, \dots, r$. Because $\varphi: X \to \mathbf{P}^1$ is a simple branched cover, $\sigma(i)' = (\alpha_1, \dots, \alpha_m; \sigma(i))$ is of order 2, and as an element in $S_{m \cdot n}$ it consists of n disjoint 2-cycles. For example, if $\sigma(i) = (j\ k)$, then a suitable notation would have

$$\sigma(i)' = (j \cdot n + 1\ \ k \cdot n + u_1)(j \cdot n + 2\ \ k \cdot n + u_2) \cdots ((j+1) \cdot n\ \ k \cdot n + u_n)$$

where $u_1, \dots, u_n$ is a permutation of $1, 2, \dots, n$ that is determined by u_1, $i = 1, \dots, r$.

PART B. *Notation within the group* $\overline{G}$. In the notation of Part A we can write $\sigma(i)'$ as $(\alpha_1, \dots, \alpha_m; (j\ k))$ with $\alpha_j = u_1 - 1 = \alpha$, $\alpha_k = -\alpha$ and $\alpha_l = 0$ for $l \neq j, k$. For future computations designate this element by $(\alpha_{jk}; (j\ k))$. More generally, write $(\alpha_{jk}; \sigma)$ for σ any element of S_m, where α_{jk} denotes the first part of $\sigma(i)'$.

Let $\mathrm{pr}: \overline{G} \to S_m$ denote the natural projection onto S_m. Thus $G(\mathbb{C}(\hat{X})/\mathbb{C}(P^1)) =$

$G(\boldsymbol{\sigma}')$ is a subgroup H of $\overline{G}$ with the following properties:

(2.4) (a) H is generated by elements of the form $(\alpha_{jk}; (j\ k))$;
(b) $\mathrm{pr}(H) = G(\boldsymbol{\sigma})$; and
(c) $H \cap ((\mathbb{Z}/(n))^m \times 1)$ projects surjectively onto any factor of $(\mathbb{Z}/(n))^m$.

Property (2.4)(a) implies that H is contained in G. Since $G(\boldsymbol{\sigma})$ is a transitive subgroup of S_m generated by 2-cycles, it is well known that $G(\boldsymbol{\sigma}) = S_m$. The conclusion that $H = G$ follows easily if we show that H contains $(\alpha_{12}; 1)$ for each $\alpha \in \mathbb{Z}/(n)$. Indeed, this gives $(\alpha_{1k}; 1) \in H$, $k = 2, \dots, m$, and therefore $(-\alpha_2 - \cdots - \alpha_m, \alpha_2, \dots, \alpha_m; 1) \in H$ for each $\alpha_2, \dots, \alpha_m \in \mathbb{Z}/(n)$. Suppose that $\tau = (\beta_1, \dots, \beta_m; \sigma) \in \overline{G}$. Explicitly compute the conjugate of $(\alpha_{jk}; (j\ k))$ by this element as

$$\tau \cdot (\alpha_{jk}; (j\ k)) \cdot \tau^{-1} = (\beta_1, \dots, \beta_m; \sigma) \cdot (\alpha_{jk}; (j\ k)) \cdot (-\beta_{\sigma(1)}, \dots, -\beta_{\sigma(m)}; \sigma^{-1})$$
$$= ((\alpha + \beta_{\sigma(j)} - \beta_{\sigma(k)})_{\sigma(j)\sigma(k)}; (\sigma(j)\ \sigma(k))).$$

PART C. *Conclusion of the proof.* Consider all conjugates of elements of $\{\sigma(1)', \dots, \sigma(r)'\}$ (by elements of H) to elements of the form $(\alpha_{12}; (1\,2))$. Since $G(\boldsymbol{\sigma}) = S_m$, (2.5) gives at least one for each $\sigma(i)'$, $i = 1, \dots, r$. Denote the collection of first coordinates so obtained by A. From $(\alpha'_{12}; (1\ 2)) \cdot (\alpha_{12}; (1\ 2)) = ((\alpha' - \alpha)_{12}; 1)$ and (2.4)(c) deduce that H contains $(\alpha_{12}; 1)$ for each $\alpha \in \mathbb{Z}/(n)$. This concludes the proof that $G(\boldsymbol{\sigma}') = G$.

We are done if we show that the conjugacy class of $(\alpha_{ij}; (i\ j))$ contains $(\mathbf{0}; (1\ 2))$. This uses that $m \geq 3$. Choose $\sigma \in S_m$ so that $\sigma(j) = 1$, $\sigma(k) = 2$ and choose $\beta_1 = -\alpha$, $\beta_2 = 0$, $\beta_3 = \alpha$ and $0 = \beta_4 = \cdots = \beta_m$. Now apply (2.5). □

Identify $\mathbb{Z}/n$ with the group generated by $(1\ 2 \cdots n)$ in S_n. This identification is compatible with the Galois theory of Theorem 1. Then the normalizer of G in $(S_n)^m \times^s S_m$ is $(N_n)^m \times^s S_m$, where N_n is the normalizer of $\langle(1\ 2 \cdots n)\rangle$ in S_n. Clearly N_n is the semidirect product $\mathbb{Z}/(n) \times^s (\mathbb{Z}(n))^*$ of $\mathbb{Z}/(n)$ and the invertible elements of $\mathbb{Z}/(n)$. These groups too, may be regarded as subgroups of $S_{m \cdot n}$.

DEFINITION 1. Call a sequence of the type given by (2.1) a *simple by cyclic sequence of type* (m, r, n).

EXAMPLE 1. *The case* $m = 2$. This case was excluded by Theorem 1. The proof, up to the point of showing that the Galois group is G, still holds. But, if n is even, then an application of (2.5) shows that $(0_{12}; (1\ 2))$ and $(1_{12}; (1\ 2)) = (1, -1; (1\ 2))$ are in distinct conjugacy classes of G. □

3. Irreducibility of spaces of simple by cyclic sequences. From Theorem 1 we may identify the space of simple by cyclic sequences of type (m, r, n), $m \geq 3$, with the covers $\gamma' \colon X' \to \mathbb{P}^1$ of Nielsen type $\mathrm{Ni}(\mathbf{C}, G)$, where $\deg(\gamma') = m \cdot n$ and G and $\mathbf{C}$ are given in the statement of the theorem. Here is a typical representative of a class in $\mathrm{Ni}(\mathbf{C}, G)$:

$$(3.1)\quad \boldsymbol{\sigma}' = ((\mathbf{0}; (1\ 3)), (\mathbf{0}; (1\ 3)), \dots, (\mathbf{0}; (1\ m)), (\mathbf{0}; (1\ m)); (1_{12}; (1\ 2)), (1_{12}; (1\ 2)), (\mathbf{0}; (1\ 2)), \dots, (\mathbf{0}; (1\ 2)), (\mathbf{0}; (1\ 2)), (\mathbf{0}; (1\ 2))).$$

In words, the first $2(m-2)$ entries generate $\mathbf{0} \times S_{m-1}$, where S_{m-1} is the subgroup of S_m that fixes 2; the next two entries are both $(1_{12}; 1\ 2)) = (1, -1, 0, \dots, 0; (1\ 2))$; and the final $r - 2 \cdot (m-1)$ entries are repetitions of $(0; (1\ 2))$.

From §1 the irreducibility of the space of simple by cyclic sequences of type (m, r, n) or, equivalently, of the space $\mathcal{H}(\mathbf{C}, G)$ follows if for $\boldsymbol{\sigma}'' \in \mathrm{Ni}(\mathbf{C}, G)$ we show the existence of $\tau \in (N_n)^m \times^s S_m$ (end of §2) and $Q \in \pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ such that

$$(\tau \cdot \boldsymbol{\sigma}'' \cdot \tau^{-1})Q = \boldsymbol{\sigma}'. \tag{3.2}$$

The special case with $n = 1$ has been a part of many papers [**Fu**], and, in the main, it goes back to Clebsch [**C**]. We state it here, but, for completeness, include a brief proof in an appendix. Note again that r is of necessity even in the next result so that $\mathrm{Ni}(\mathbf{B}, S_m)$ is nonempty.

PROPOSITION 1. *The space $\mathcal{H}(\mathbf{B}, S_m)$ is irreducible, where $\mathbf{B} = (B_1, \ldots, B_r)$ and $B_1 = \cdots = B_r$ with B_1 the conjugacy class of $(1\ 2)$ in S_m.*

Following the next three lemmas we state the main theorem.

LEMMA 1. *Denote the element*

$$(0, \ldots, 0, \underset{\substack{\uparrow \\ kth\ pos.}}{(v, u)}, 0, \ldots, 0; \sigma)$$

with $\sigma \in S_m$ and $(v, u) \in (\mathbb{Z}/(n)) \times^s \mathbb{Z}/(n)^*$ by $((v, u)_k; \sigma)$. By generalization of (2.5), $((v, u)_k; 1) \cdot (\alpha'_{ij}; (i\ j)) \cdot ((v, u)_k; 1)^{-1}$ is equal to the following expression:

$$\begin{aligned} &\text{(a) } ((u \cdot \alpha' + v)_{ij}; (i\ j)) \text{ if } k = i; \\ &\text{(b) } ((u^{-1} \cdot \alpha' - u^{-1} \cdot v)_{ij}; (i\ j)) \text{ if } k = j; \text{ or} \\ &\text{(c) } (\alpha'_{ij}; (i\ j)) \text{ if } k \neq i, j. \end{aligned} \tag{3.3}$$

PROOF. This follows from the natural action of N_n on $\mathbb{Z}/(n)$ (as at the end of §2, $(v, u) \in N_n$ maps $\alpha' \in \mathbb{Z}/(n)$ to $u \cdot \alpha' + v$). □

LEMMA 2. *Let $\sigma'_i = (c_{12}^{(i)}; (1\ 2)) \in G$, $i = 1, 2, \ldots, r'$. Assume that $\sigma'_1 \cdots \sigma'_{r'} = (\mathbf{0}; 1)$. Then $\sum_{i=1}^{r'} (-1)^i \cdot c^{(i)} = 0$. Assume further that $n = p \cdot n_1$, where p is a prime, and if $n_1 > 1$, then*

$$c^{(1)} \equiv c^{(2)} \equiv 1 \bmod (n_1) \quad \text{and} \quad c^{(j)} \equiv 0 \bmod (n_1), \quad j = 3, \ldots, r'. \tag{3.4}$$

Then there exists $Q \in \pi_1(\mathbb{P}^{r'} - D_{r'}, \mathbf{a}^0)$ such that $(\boldsymbol{\sigma}')Q = \boldsymbol{\sigma}''$ with $\sigma''_i = (d_{12}^{(i)}; (1\ 2))$, $i = 1, \ldots, r'$, with these properties:

(3.5) (a) *$d^{(1)} \equiv d^{(2)} \bmod (n)$ and $d^{(j)} \equiv 0 \bmod (n)$, $j = 3, \ldots, r'$, if $n_1 > 1$; and*
(b) *there exists $t \geq 0$ such that $d^{(1)} \equiv d^{(2)} \equiv \cdots \equiv d^{(t)} \bmod (p)$ and $d^{(j)} \equiv 0 \bmod (p)$, $j = t + 1, \ldots, r'$, if $n_1 = 1$.*

PROOF. For $u \geq 1$ we first compute the effect of $(Q_u)^m$ on $\boldsymbol{\sigma}'$. The uth and $(u + 1)$th entries of $(\boldsymbol{\sigma}')Q_u$, are, respectively, $((2 \cdot c^{(u)} - c^{(u+1)})_{12}; (1\ 2))$ and $(c_{12}^{(u)}; (1\ 2))$; the uth and $(u+1)$th entries of $(\boldsymbol{\sigma}')Q_u^2$ are $((3 \cdot c^{(u)} - 2 \cdot c^{(u+1)})_{12}; (1\ 2))$ and $((2 \cdot c^{(u)} - c^{(u+1)})_{12}; (1\ 2)), \ldots$; and the uth and $(u+1)$th entries of $(\boldsymbol{\sigma}')(Q_u)^m$ are

$$\begin{aligned} &((m \cdot (c^{(u)} - c^{(u+1)}) + c^{(u)})_{12}; (1\ 2)) \quad \text{and} \\ &(((m - 1) \cdot (c^{(u)} - c^{(u+1)}) + c^{(u)})_{12}; (1\ 2)). \end{aligned} \tag{3.6}$$

Use $\langle c\rangle$ to denote the (additive) subgroup of $\mathbb{Z}/(n)$ generated by c. After an application of an element Q' of $\pi_1(\mathbb{P}^{r'} - D_{r'}, \mathbf{a}^0)$ to $\boldsymbol{\sigma}'$ we may assume that there is an integer t for which $c^{(j)} \equiv 0 \bmod(n)$ for $j \geq t+1$. Furthermore, assume that Q' has been chosen so that t is as small as possible. In particular, $c^{(1)}, \ldots, c^{(t)}$ are not congruent to 0 mod(n). From this point on we will work with elements of $\pi_1(\mathbb{P}^{r'} - D_{r'}, \mathbf{a}^0)$ that affect only the coordinate entries $1, \ldots, t$.

First assume that $n_1 > 1$. Suppose that $t > 2$. Then apply (3.6) to the case $u = 2$. Since $c^{(2)} - c^{(3)}$ is a unit mod(n), we may choose m so that $m\cdot(c^{(u)} - c^{(u+1)}) + c^{(u)} \equiv 0 \bmod(n)$. Furthermore, there exists an element $Q'' \in \pi_1(\mathbb{P}^{r'} - D_{r'}, \mathbf{a}^0)$ that moves only the coordinate entries $2, \ldots, t$, and which moves the second coordinate entry, otherwise unchanged, to the tth coordinate. Thus, the last $r'-t+1$ coordinate entries of $(Q_2)^m \circ Q''$ applied to $\boldsymbol{\sigma}'$ are of the form $(\mathbf{0}; (1\ 2))$, contrary to our assumption about t. This concludes the proof of (3.5)(a) under the assumption that $n_1 > 1$. Now assume that $n_1 = 1$ and that p is a prime.

Assume that there exists $i < t$ such that $d^{(i)} \not\equiv d^{(i+1)} \bmod(p)$. Then $d^{(i)} - d^{(i+1)}$ is a unit mod(p). The same argument as in the preceding paragraph then applies with $i = u$. This gives (3.5)(b) and the lemma. □

LEMMA 3 [**BFr**, LEMMA 3.8]. *Let $\boldsymbol{\sigma} \in (S_{m'})^{r'}$ with $G(\boldsymbol{\sigma})$ transitive and $\sigma(1)\cdots\sigma(r') = 1$. Let $\tau \in G(\boldsymbol{\sigma})$. Then there exists $Q \in \pi_1(\mathbb{P}^{r'} - D_{r'}, \mathbf{a}^0)$ such that $\tau^{-1}\cdot\boldsymbol{\sigma}\cdot\tau = (\boldsymbol{\sigma})Q$.*

THEOREM 2. *Let $\mathrm{Ni}(\mathbf{C}, G)$ be the Nielsen class which contains the equivalence class represented by $\boldsymbol{\sigma}'$ of* (3.1). *Then $\mathrm{Hur}(\mathbf{C}, G) = 1$. In particular, the space of equivalence classes of simple by cyclic sequences of type (m, r, n), with even $r \geq 2m$ and $m \geq 3$, is irreducible.*

PROOF. As discussed above, we must establish (3.2). From Proposition 1, there exist $Q' \in \pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ and $\tau_1 \in \mathbf{0} \times S_m$ such that

$$(3.7)\quad (\tau_1\cdot\boldsymbol{\sigma}''\cdot\tau_1^{-1})Q' = ((\alpha_{13}^{(3)}; (1\ 3)), (\beta_{13}^{(3)}; (1\ 3)), \ldots, (\alpha_{1m}^{(m)}; (1\ m))(\beta_{1m}^{(m)}; (1\ m)); (\gamma_{12}^{(1)}; (1\ 2)), \ldots, (\gamma_{12}^{(r-2\cdot(m-2))}; (1\ 2))).$$

Write out that the product of the entries of (3.7) is $(\mathbf{0}, 1)$. The first coordinate gives these expressions in order:

$$(3.8)\quad \begin{aligned} &\text{(a) } \alpha^{(3)} - \beta^{(3)} + \alpha^{(4)} - \beta^{(4)} + \cdots + \alpha^{(m)} - \beta^{(m)} \\ &\qquad + \textstyle\sum_{j=1}^{r-2\cdot(m-2)} (-1)^{j-1}\cdot\gamma^{(j)} \equiv 0 \bmod(n); \\ &\text{(b) } \textstyle\sum_{j=1}^{r-2\cdot(m-2)} (-1)^{j}\cdot\gamma^{(j)} \equiv 0 \bmod(n); \text{ and} \\ &\text{(c) } \alpha^{(k)} - \beta^{(k)} \equiv 0 \bmod(n),\ k = 3, \ldots, m. \end{aligned}$$

With no loss therefore assume that

$$(3.9)\quad \boldsymbol{\sigma}'' = ((\alpha_{13}^{(3)}; (1\ 3)), (\alpha_{13}^{(3)}; (1\ 3)), \ldots, (\alpha_{1m}^{(m)}; (1\ m)), (\alpha_{1m}^{(m)}; (1\ m)); (\gamma_{12}^{(1)}; (1\ 2)), \ldots, (\gamma_{12}^{(r-2\cdot(m-2))}; (1\ 2))) \text{ with } \sum_j (-1)^j\cdot\gamma^{(j)} \equiv 0 \mod(n).$$

For simplicity of notation, denote $r - 2\cdot(m-2)$ by r' throughout the remainder. The rest of the proof divides into four parts.

PART A. *Conjugation by elements of* $\overline{G}$. Apply Lemma 1 in the case that $(v,u)_k = (-\alpha^{(k)}, 0)_k$, which we denote just by $(-\alpha^{(k)})_k$. Therefore if we conjugate (3.9) by the product of $((-\alpha^{(j)})_j; 1)$, $j = 3, \ldots, m$, and by $((-\gamma^{(r')})_2; 1)$, we may assume that $\boldsymbol{\sigma}''$ is

$$(3.10)\quad ((\mathbf{0};(1\ 3)),(\mathbf{0};(1\ 3)),\ldots,(\mathbf{0};(1\ m)),(\mathbf{0};(1\ m));(\gamma_{12}^{(1)};(1\ 2)),\ldots, (\gamma_{12}^{(r'-1)};(1\ 2)),(\mathbf{0};(1\ 2))),\quad \text{with } \gamma^{(1)}-\gamma^{(2)}+\cdots+(-1)^{r'}\cdot\gamma^{(r'-1)}\equiv 0 \mod(n).$$

Also, the conditions of (2.4) imply that $\gamma^{(1)}, \ldots, \gamma^{(r'-1)}$ generate $\mathbb{Z}/(n)$. For the moment we assume that the conclusion of the theorem holds if n is a prime.

PART B. *Induction on* n. Assume that n is not a prime and write n as $p \cdot n_1$ with $n_1 > 1$. By the induction assumption, the conclusion of the theorem holds for n_1. Reduce the entries of (3.10) mod(n_1) to conclude that there exists $Q^{(3)} \in \pi_1(\mathbf{P}^r - D_r, \mathbf{a}^0)$ such that the last r' entries of $Q^{(3)}$ applied to $\boldsymbol{\sigma}''$ (given by (3.10)) satisfy hypothesis (3.4). Thus Lemma 2 gives an element of $\pi_1(\mathbf{P}^r - D_r, \mathbf{a}^0)$ that acts only on the last r' coordinates of $(\boldsymbol{\sigma}'')Q^{(3)}$ to give $\boldsymbol{\sigma}'$, except for the possibility that the $(2m-4)+1$ and $(2m-4)+2$ entries are both $(c;(1\ 2))$. In this case apply Lemma 1 by conjugating $(\boldsymbol{\sigma}'', Q_3)$ by $((0, c^{-1})_2; 1)$. This concludes the theorem if n is not a prime.

PART C. *The case that* $n = p$ *is a prime.* Again apply Lemma 2, but this time under the assumption that $n_1 = 1$. Thus, according to (3.5)(b), we may assume that

(3.11)

$$\gamma^{(1)} \equiv \gamma^{(2)} \equiv \cdots \equiv \gamma^{(t)} \mod(p) \qquad \text{and} \qquad \gamma^{(j)} \equiv 0 \mod(p), \quad j = t+1, \ldots, r'.$$

Note that since $\gamma^{(1)} - \gamma^{(2)} + \cdots + (-1)^{t-1} \cdot \gamma^{(t)} \equiv 0 \mod(p)$, t must be even. Let $m' = 2 \cdot (m-2)$. Apply $Q_{m'} \circ Q_{m'+1} \circ \cdots \circ Q_{m'+t}$ to (3.10) to get

(3.12)(a)

$$(\ldots,(\mathbf{0};(1\ m)),(-\gamma_{2m}^{(1)};(2\ m)),\ldots,(-\gamma_{2m}^{(1)};(2\ m)),(\mathbf{0};(1\ m)),(\mathbf{0};(1\ 2)),\ldots),$$

where the first $(\mathbf{0};(1\ m))$ is in the $m'-1$ position and the second is in the $m'+t$ position: then apply conjugation by $(-\gamma_m^{(1)}; 1)$ (as in the notation of Part A) to get

(3.12)(b)

$$(\ldots,(\gamma_{1m}^{(1)};(1\ m)),(\mathbf{0};(2\ m)),\ldots,(\mathbf{0};(2\ m)),(\gamma_{1m}^{(1)};(1\ m)),(\mathbf{0};(1\ 2)),\ldots);$$

and finally apply $Q^{(4)} \in \pi_1(\mathbf{P}^r - D_r, \mathbf{a}^0)$ that moves the two coordinate entries of the form $(\gamma_{1m}^{(1)};(1\ m))$ out to the positions $r-1$ and r and leaves all other entries of the form $(\mathbf{0};(i\ j))$. As in Part B, Lemma 1 allows us to assume $\gamma^{(1)} = 1$. Lemma 3 allows us to apply $Q^{(3)} \in \pi_1(\mathbf{P}^r - D_r, \mathbf{a}^0)$ to achieve the effect of conjugation by $(2\ m)$. Therefore assume that $\boldsymbol{\sigma}''$ has these properties:

(3.13) (a) $\sigma(i)''$ is of the form $(\mathbf{0};(j\ k))$ (with j and k dependent on i), $i = 1, \ldots, r-2$;
(b) the second entries in $\sigma(1)'', \ldots, \sigma(r-2)''$ generate S_m; and
(c) $\sigma(r-1)'' = \sigma(r)'' = (1_{12};(1\ 2))$, and therefore $\sigma(1)'' \cdots \sigma(r-2)'' = (\mathbf{0};1)$.

PART D. *Application of Proposition* 1. Apply Proposition 1 to $\sigma(1)'', \dots, \sigma(r-2)''$ to find $Q^{(6)} \in \pi_1(\mathbb{P}^{r-2} - D_{r-2}, \mathbf{a}^0)$ and $\gamma \in S_m$ such that

(3.14)
$$(\gamma^{-1} \cdot (\sigma(1)'', \dots, \sigma(r-2)'') \cdot \gamma) Q^{(6)} = ((\mathbf{0}; (1\ 3)), (\mathbf{0}; (1\ 3)), \dots, (\mathbf{0}; (1\ m)), (\mathbf{0}; (1\ m)), (\mathbf{0}; (1\ 2)), \dots, (\mathbf{0}; (1\ 2))).$$

Indeed, Lemma 3 allows us to assume that $\gamma = 1$. With the natural interpretation of $Q^{(6)}$ in $\pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ it is now an easy matter to find $Q^{(7)}$ and apply it to $(\boldsymbol{\sigma}'')Q^{(6)}$, with $\boldsymbol{\sigma}''$ given by (3.13), to get $\boldsymbol{\sigma}'$. This concludes the proof of the theorem. □

Let ${}_o\mathcal{C}_{n,g}$ be the moduli space of cyclic unramified covers of genus g curves as discussed in §1. There is a natural map from the space $\mathcal{H}(\mathbf{C}, G)$ of simple by cyclic sequences of type (m, r, n): the point $\mathfrak{p} \in \mathcal{H}(\mathbf{C}, G)$ represented by the sequence $X' \xrightarrow{\psi} X \xrightarrow{\varphi} \mathbb{P}^1$ of (2.1) goes to the point of ${}_o\mathcal{C}_{n,g}$ that is represented by the cover $X' \xrightarrow{\psi} X$. From the moduli property this map is complex analytic. It is an old argument, repeated, say, in [**Fr1**, §1], that if $m \geq 2g - 1$, every Riemann surface of genus g can be presented as a simple cover of $\mathbb{P}^1$ of degree m. Thus, in this case, the map from $\mathcal{H}(\mathbf{C}, G)$ to ${}_o\mathcal{C}_{n,g}$ is surjective. Connectness of the manifold $\mathcal{H}(\mathbf{C}, G)$ (and of the complement in it of each finite type analytic subset of codimension 1) from Theorem 2 therefore gives the following:

THEOREM 3. *The moduli space ${}_o\mathcal{C}_{n,g}$ of cyclic unramified covers of genus g curves is irreducible.*

For a given positive integer m, $m(g) = [(g+3)/2]$ is the smallest integer m for which every curve X of genus g has a covering map $\varphi: X \to \mathbb{P}^1$ of degree m [**KL**]. Actually, if m is suitably large compared to g, then the technique of Theorem 3 shows that the irreducibility of the space $\mathcal{H}(\mathbf{C}, G)$ follows from [**DM**, Theorem 5.15]. But Theorem 3 does not give Theorem 2 in the case that $m < [(g+3)/2]$.

Appendix—Proof of Proposition 1. As in the proof of Theorem 2, the proof of Proposition 1 amounts to showing that if $\boldsymbol{\sigma}' \in \mathrm{Ni}(\mathbf{B}, S_m)$ (with r even and of necessity $\geq 2 \cdot (m-1)$), then there exists $\tau \in S_m$ and $Q \in \pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ such that

$$(\text{A.1}) \quad (\tau \cdot \boldsymbol{\sigma}' \cdot \tau^{-1})Q = \boldsymbol{\sigma} = ((1\ m), (1\ m), (1\ m-1), (1\ m-1), \dots, (1\ 3), (1\ 3), (1\ 2), \dots, (1\ 2)).$$

Our choice of $\boldsymbol{\sigma}$ is for the sake of efficiency of proof, rather than for it to match the choices in Theorem 2. Furthermore, Lemma 3 allows us to take $\tau = 1$ and even to conjugate by an element of S_m whenever it is desirable.

First note that we can find $Q^{(1)} \in \pi_1(\mathbb{P}^r - D_r, \mathbf{a}^0)$ so that $(\boldsymbol{\sigma}')Q^{(1)} = ((1\ j_1), (1\ j_2), \dots, (1\ j_t), \sigma(t+1)'', \dots, \sigma(r)'') = \boldsymbol{\sigma}''$, where none of $\sigma(t+1)'', \dots, \sigma(r)''$ contain the integer 1. If the integers $j_1, \dots, j_t$ are all distinct, then the product of the first t coordinate entries of $(\boldsymbol{\sigma}')Q^{(1)}$ is $(1\ j_1\ j_2 \cdots j_t)$. It is thus clearly impossible for the products of all coordinate entries $(\boldsymbol{\sigma}')Q^{(1)}$ to be 1.

Without loss we may therefore move the two identical cycles containing 1 together at the beginning to assume that $j_1 = j_2$. There are two possibilities for the group $\mathcal{H}$ generated by $\sigma(3)'', \dots, \sigma(r)''$:

(A.2) (a) $\mathcal{H} = S_m$; or
(b) $\mathcal{H}$ is the subgroup of S_m that fixes either 1 or j_1.

In case (A.2)(a) we assume that $j_1 = 2$. Transfer the first two coordinate entries, unchanged, down to the right-hand side to assume that

$$\boldsymbol{\sigma}'' = (\sigma(1)'', \dots, \sigma(r-2)'', (1\ 2), (1\ 2)).$$

This is now set up for an induction on r: find $Q^{(2)} \in \pi_1(\mathbb{P}^{r-2} - D_{r-2}, \mathbf{a}^0)$ such that $(\sigma(1)'', \dots, \sigma(r-2)'')Q^{(2)}$ is (A.1) with two fewer (1 2) terms on the right-hand side. With an interpretation of $Q^{(2)} \in \pi_1(\mathbb{P}^r - D_r, \boldsymbol{\alpha}^0)$ (as in Part D of the proof of Theorem 2) we are done if (A.2)(a) holds.

If (A.2)(b) holds, assume with no loss that $j_1 = m$ and that $\mathcal{H}$ acts as S_{m-1} on $\{1, 2, \dots, m-1\}$: $\boldsymbol{\sigma}'' = ((1\ m), (1\ m), \sigma(3)'', \dots, \sigma(r)'')$. Again we are set up for an induction on r (with m changed to $m-1$): find $Q^{(3)} \in \pi_1(\mathbb{P}^{r-2} - D_{r-2}, \mathbf{a}^0)$ such that $(\sigma(3)'', \dots, \sigma(r)'')Q^{(3)}$ is (A.1) with the first two terms on the left side missing. Conclude as in case (A.1)(a).

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