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On Hyperbolic π-Orbifolds with Arbitrary many Singular Components

Andrei Vesnin (*)

Summary. - *We construct a family of* $(n+1)$*-component links* $\mathcal{L}_n$ *which are closures of rational 3-string braids* $(\sigma_1^{-1/2}\sigma_2^2)^n$*, and show that for* $n \geq 3$ *they arise as singular sets of hyperbolic* π*-orbifolds. Moreover, their 2-fold branched coverings are described by Dehn surgeries.*

1. Introduction

The concept of a hyperelliptic involution came originally from the theory of Riemann surfaces. Let S_g be a Riemann surface of genus g, $g > 1$. An involution $\tau \in \mathrm{Iso}^+(S_g)$ is said to be *hyperelliptic* if the quotient space $S_g/\langle\tau\rangle$ is homeomorphic to the 2-dimensional sphere S^2. A Riemann surface is said to be *hyperelliptic* if it admits a hyperelliptic involution, i.e. if it can be obtained as a 2-fold branched covering of S^2. For properties of hyperelliptic Riemann surfaces see [4].

This concept can be generalized to higher dimensions in the natural way. Let M be an n-dimensional manifold. Suppose that there exists an involution $\tau : M \to M$ such that the quotient space $M/\langle\tau\rangle$ is homeomorphic to the n-dimensional sphere S^n. Then, τ is said to be a *hyperelliptic* involution and M is said to be a *hyperelliptic*

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Author's address: Andrei Vesnin, Sobolev Institute of Mathematics, Novosibirsk, 630090, Russia; E-mail: vesnin@math.nsc.ru
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manifold. If M admits a geometric structure then we assume in the definition that τ is an isometry.

Three-dimensional hyperelliptic manifolds are objects of a special interest because of the relation with knot theory. If M is a 3-dimensional hyperelliptic manifold, with a hyperelliptic involution τ, then M is the 2-fold branched covering of S^3 branched over some link (in particular, a knot) L. The covering is given by the action of τ and each point of L has branching index 2. According to the terminology of orbifold theory (see [16, 19]), this situation means that M is the 2-fold covering of a π-orbifold $\mathcal{O} = S^3(L)$ with underling set S^3 and singular set L with singular angle π at each point of L.

It is known that in the 3-dimensional case there are eight model geometries: $\mathbb{E}^3$, $\mathbb{H}^3$, $\mathbb{S}^3$, $\mathbb{H}^2 \times \mathbb{E}^1$, $\mathbb{S}^2 \times \mathbb{E}^1$, Sol, Nil, and $\widetilde{PSL}(2, \mathbb{R})$ [16, 19]. It was shown in [8] that for each of these geometries there exist hyperelliptic manifolds (with τ be an isometry).

Examples of hyperbolic 3-manifolds of small volume admitting one, two, or three hyperelliptic involutions can be found in [11]; we note that the maximal number of non-conjugate hyperelliptic involutions of a hyperbolic manifold is nine, see [12], [6].

Let M be a hyperbolic hyperelliptic 3-manifold with hyperelliptic involution τ. Then, the quotient π-orbifold $M/\langle\tau\rangle = S^3(L)$ is also hyperbolic.

A link L in S^3 is said to be *hyperbolic* if the complement $S^3 \setminus L$ is a hyperbolic manifold. We will say that L is π-*hyperbolic* if the π-orbifold $\mathcal{O} = S^3(L)$ is hyperbolic. Obviously, hyperbolicity of a link does not imply π-hyperbolicity of it (for example, hyperbolic 2-bridge links are not π-hyperbolic).

Most of known examples of π–hyperbolic links have few components. Among them are knots 8_{18} and 9_{49}, 2-component link 10^2_{138}, knots and 3-component links arising as closed 3-string braids $(\sigma_1\sigma_2^{-1})^n$, $n \geq 4$ (here we use standard notations for knots and links according to [15] and for braids according to [1]). Discussions of the 2-fold branched coverings of these knots and links can be found in [9, 10, 11].

In the present paper, we construct explicit examples of π-hyperbolic links with an arbitrary number n of components, for any positive integer n. We will present quite simple examples of such a type.

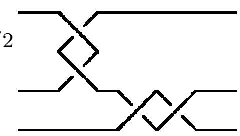


Figure 1: The rational braid $\sigma_1^{-1/2}\sigma_2^2$.

Moreover we describe the 3-manifolds that are the 2-fold branched coverings of the links under consideration.

2. π-hyperbolic links

To define a family of links we start with the notion of a rational 3-string braid.

Let σ_1 and σ_2 be standard generators of the *braid group* $\mathcal{B}_3$ on 3 strings. Elements of $\mathcal{B}_3$ are of the form $\omega = \sigma_{i_1}^{p_1} \cdots \sigma_{i_k}^{p_k}$, where $i_1, \dots, i_k$ are equal to 1 or 2, and $p_1, \dots, p_k$ are integers. To construct a geometric braid corresponding to ω, with each multiplier $\sigma_{i_j}^{p_j}$ we associate $|p_j|$ half-twists on strings i_j and $i_j + 1$ in the direction depending of sign of p_j. In other words, we are putting p_j–tangle with strings i_j and $i_j + 1$ as incoming arcs.

We generalize this construction in the following way (see also [7]). Let p_j and q_j be coprime integers. By $\sigma_{i_j}^{p_j/q_j}$ we denote the geometrical object called a *rational* braid, which is obtained by putting the rational p_j/q_j–tangle with strings i_j and $i_j + 1$ as incoming arcs. The product of two rational braids is defined similarly to the product of usual braids. Thus, an expression $\omega = \sigma_{i_1}^{p_1/q_1} \cdots \sigma_{i_k}^{p_k/q_k}$, with $i_1, \dots, i_k$ equal to 1 or 2, and p_j and q_j be coprime for each $j = 1, \dots, k$, defines a *rational braid* obtained by putting rational tangles in respect to each multiplier.

Consider a rational 3-string braid $\sigma_1^{-1/2}\sigma_2^2$ pictured in Figure 1.

Denote by $\mathcal{L}_n$, $n \geq 1$, the closure of the rational 3-string braid $(\sigma_1^{-1/2}\sigma_2^2)^n$ (see Figure 2, where the 4-component link $\mathcal{L}_3$ is pictured). Obviously, $\mathcal{L}_n$ has $(n+1)$ components.

Theorem 2.1. *For any integer $n \geq 3$ the $(n+1)$-component link $\mathcal{L}_n$ is π-hyperbolic.*

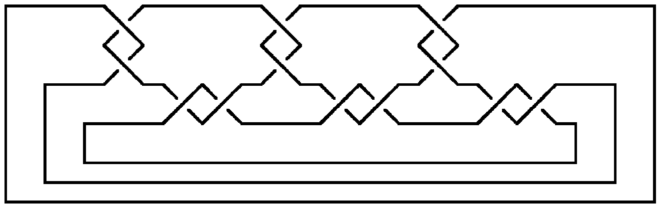


Figure 2: Link $\mathcal{L}_3$.

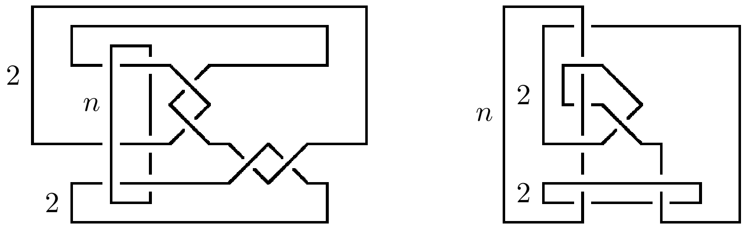


Figure 3: Link $\mathcal{R}$.

Proof. Let $\mathcal{O}_n = S^3(\mathcal{L}_n)$ be the π-orbifold with singular set $\mathcal{L}_n$. By the definition $\mathcal{L}_n$ has a cyclic symmetry ρ of order n which permutes blocks $\sigma_1^{-1/2}\sigma_2^2$. The symmetry ρ induces a cyclic symmetry of order n of the orbifold $\mathcal{O}_n$; we denote this symmetry also by ρ. The singular set of the quotient orbifold $\mathcal{O}'_n = \mathcal{O}_n/\langle\rho\rangle$ is the 3-component link $\mathcal{R}$ presented in the left part of Figure 3, i.e. $\mathcal{O}'_n = S^3(\mathcal{R})$. One of its components is the image of the axis of ρ and has singularity index n. Two other components are images of $\mathcal{L}_n$ and have singularity index 2.

Using Reidemeister moves one can redraw $\mathcal{R}$ as in the right part of Figure 3, and then as in the left part of Figure 4.

Let $\mathcal{O}''_n$ be the 2-fold covering of $\mathcal{O}'_n$, branched over one component of $\mathcal{R}$ having singularity index 2. The singular set of $\mathcal{O}''_n$ is the 2-component link $\mathcal{Q}$ presented in the right part of Figure 4, i.e. $\mathcal{O}''_n = S^3(\mathcal{Q})$. One its component, say $\mathcal{Q}_1$, has singularity index n, and other, say $\mathcal{Q}_2$, has singularity index 2.

Now we construct a 2-fold covering of $\mathcal{O}''_n$ branched over $\mathcal{Q}_2$ as

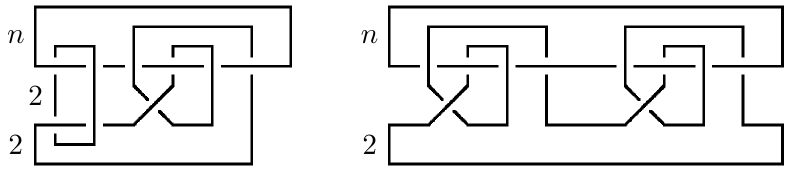


Figure 4: Links $\mathcal{R}$ and $\mathcal{Q}$.

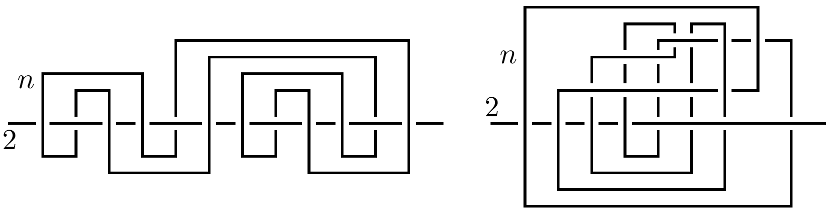


Figure 5: Link $\mathcal{Q}$.

follows. Using Reidemeister moves one can redraw $\mathcal{Q}$ as in the left part of Figure 5, and then as in the right part of Figure 5.

Let us denote by $\mathcal{O}_n'''$ the 2-fold covering of $\mathcal{O}_n''$ branched over $\mathcal{Q}_2$. The singular set of $\mathcal{O}_n'''$ is the 2-component link $\mathcal{P}$ presented in Figure 6, i.e. $\mathcal{O}_n''' = S^3(\mathcal{P})$. Both its component have singularity index n.

Using Reidemeister moves $\mathcal{P}$ can be redrawn as in the left part of Figure 7, and then as in the right part of Figure 7. Comparing Figure 7 with the standard picture for a 2-bridge link (see, for example [3, p. 195], one can conclude that $\mathcal{P}$ is the 2-bridge link corresponding to the rational parameter $40/9 = 4 + \cfrac{1}{2 + \frac{1}{4}}$.

Thus $\mathcal{O}_n'''$ is the orbifold with the singular set the 2-bridge 40/9-link and the singularity index n on both components. The hyperbolicity of orbifolds $\alpha/\beta(n)$ with singular set a 2-bridge knot or link α/β and singularity index n is described in [2, Example A.0.2, p. 174] and in [5]. In particular, $\alpha/\beta(n)$ is hyperbolic if $\alpha > 5$, $|\beta| > 1$, and $n \geq 3$. Therefore, the orbifold $\mathcal{O}_n'''$ is hyperbolic if $n \geq 3$. Since by the construction $\mathcal{O}_n'''$ is commensurable with $\mathcal{O}_n$, the π-orbifold $\mathcal{O}_n$

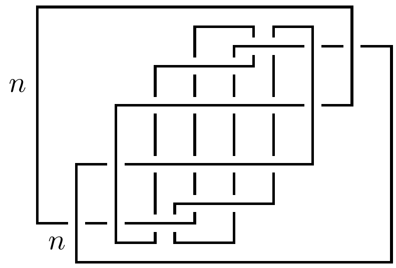


Figure 6: Link $\mathcal{P}$.

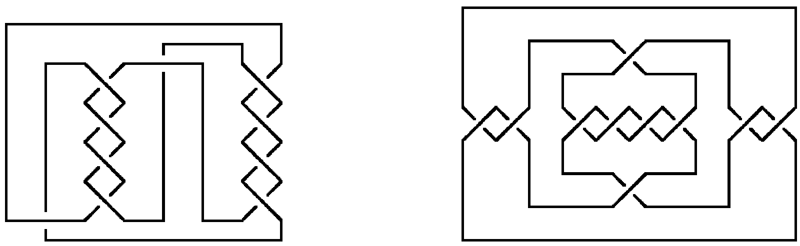


Figure 7: Link $\mathcal{P}$ as the 2-bridge link 40/9.

is also hyperbolic, and the link $\mathcal{L}_n$ is π-hyperbolic for $n \geq 3$. □

Geometrical invariants of manifolds and orbifolds from the proof can be found by using a computer program *SnapPea* [17]. Thus, one can see that $vol(S^3 \setminus \mathcal{R}) = 7.70691\ldots$ and $vol(S^3 \setminus \mathcal{P}) = 8.51908\ldots$. Moreover, for initial values of n the following table of volumes holds:

n	$vol\,(S^3 \setminus \mathcal{L}_n)$	$vol\,\mathcal{O}_n$	$vol\,\mathcal{O}'_n$	$vol\,\mathcal{O}'''_n$
3	$16.59112\ldots$	$2.56897\ldots$	$0.85632\ldots$	$3.42529\ldots$
4	$25.76187\ldots$	$5.60143\ldots$	$1.40036\ldots$	$5.60143\ldots$
5	$34.42142\ldots$	$8.32706\ldots$	$1.66541\ldots$	$6.66165\ldots$

3. 2-fold branched coverings of links

In this section we will describe 3-manifolds M_n that are 2-fold coverings of S^3 branched over links $\mathcal{L}_n$.

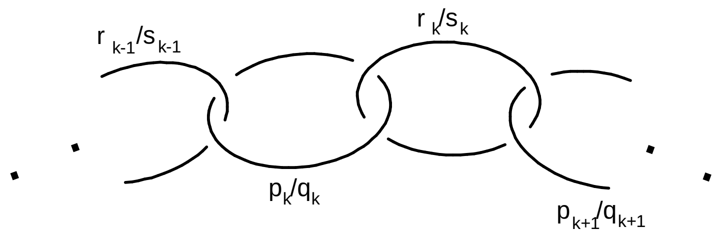


Figure 8: Surgeries along the link $\mathcal{T}_n$.

In [18] there was introduced a family of closed orientable 3-manifolds *Takahashi manifolds* obtained by Dehn surgery with rational coefficients p_k/q_k and r_k/s_k, $k = 1, \ldots, n$, on S^3, along the $2n$-component link $\mathcal{T}_n$ (see Figure 8) which is a closed chain of $2n$ unknotted components. These manifolds have been studied and generalized in [7, 13].

A Takahashi manifold is said to be *periodic* when the surgery coefficients have the same cyclic symmetry of order n as the $2n$-component link $\mathcal{T}_n$, i.e. the coefficients are $p_k/q_k = p/q$ and $r_k/s_k = r/s$ alternately, for $k = 1, \ldots, n$. Let us denote such Takahashi manifold by $M_n(p/q; r/s)$. By [7, 18] the manifold $M_n(p/q; r/s)$ is a 2-fold branched covering of S^3 branched over the link that is the closure of a rational 3-string braid $(\sigma_1^{p/q}\sigma_2^{r/s})^n$. By the definition, if $p/q = -1/2$ and $r/s = 2/1$ then we get the link $\mathcal{L}_n$ from the previous section. Therefore, the following description of 2-fold branched coverings of $\mathcal{L}_n$ holds.

Proposition 3.1. *For any $n \geq 1$ the two-fold covering of S^3 branched over $\mathcal{L}_n$ is the periodic Takahashi manifold $M_n = M_n(-1/2; 2/1)$.*

In virtue [13, 18] the fundamental group of $M_n(p/q; r/s)$ has the following presentation:

$$\langle x_1, \ldots, x_n, y_1, \ldots, y_n \mid y_i^{-p} = x_{i-1}^s x_i^{-s}, \quad x_i^{-r} = y_{i+1}^q y_i^{-q}, \quad i = 1, \ldots, n \rangle,$$

where all indices are taken by mod n. Hence the following cyclic presentation holds:

$$\pi_1(M_n(-1/2;2/1)) = \langle x_1, \dots, x_n \quad | \quad w(x_i, x_{i+1}, x_{i+2}) = 1, \\ i = 1, \dots, n \rangle.$$

with the defining word $w(x_i, x_{i+1}, x_{i+2}) = x_i^2 (x_i x_{i+1}^{-1})^2 (x_i x_{i-1}^{-1})^2$.

4. Covering diagram

To complete the discussion of links $\mathcal{L}_n$ and manifolds M_n let us describe a covering diagram in which they are involved.

Before formulating the main result of this section we have to talk about the types of n-fold cyclic branched coverings of links we want to consider. Obviously, a knot has an unique n-fold cyclic branched covering. Let $L = K_1 \cup K_2$ be a link in the 3-sphere with two components. Denote by $\pi_1(S^3 \setminus L)$ the fundamental group of the link complement and by m_1 and m_2 meridians of the components $K_1 \cup K_2$ of the link, oriented in an arbitrary way. The homology group $H_1(S^3 \setminus L)$ of the link complement is isomorphic to $\mathbb{Z}^2$ and generated by the homology classes of the meridians. Each surjection $\psi : \pi_1(S^3 \setminus L) \to H_1(S^3 \setminus L) \to \mathbb{Z}_n$ onto the cyclic groups $\mathbb{Z}_n$ of order n defines a cyclic n-fold branched covering $M = M(\psi)$ of S^3 branched over L. According to [14] we call M a *strictly–cyclic* n-fold covering of L if the corresponding surjection ψ maps (the homotopy class of) meridians m_1 and m_2 of L to the same generator of the cyclic group $\mathbb{Z}_n$. Note that strictly–cyclic coverings are also called *uniform* coverings in [20].

Let us denote by M_n' the strictly–cyclic n-fold covering of S^3 branched over the 2-component 2-bridge link 40/9. Remark that M_n' is a generalized periodic Takahashi manifold in the sense of [13].

THEOREM 4.1. *For the above described manifolds and orbifolds the following diagram of coverings holds:*

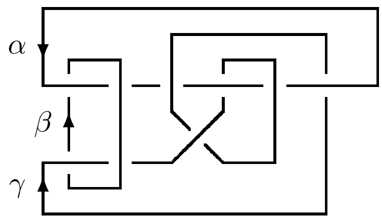
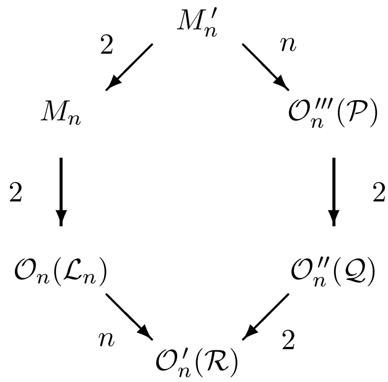


Figure 9: Generators of $\pi_1(S^3 \setminus \mathcal{R})$.



where singular sets $\mathcal{L}_n$, $\mathcal{R}$, $\mathcal{Q}$, and $\mathcal{P}$ of orbifolds $\mathcal{O}_n$, $\mathcal{O}_n'$, $\mathcal{O}_n''$, and $\mathcal{O}_n'''$ are presented in Figures 2, 3, 4, and 7, respectively.

Proof. By the proof of Theorem 2.1 and by Proposition 3.1 we already have the following sequences of coverings:

$$M_n \xrightarrow{2} \mathcal{O}_n \xrightarrow{n} \mathcal{O}_n'$$

and

$$M_n' \xrightarrow{n} \mathcal{O}_n''' \xrightarrow{2} \mathcal{O}_n'' \xrightarrow{2} \mathcal{O}_n'.$$

Let us denote by Γ_n' the group of the orbifold $\mathcal{O}_n'$, i.e. $\mathcal{O}_n' = \mathbb{H}^3/\Gamma_n'$. Let α, β, and γ be generators of Γ_n' corresponding to generators of $\pi_1(S^3 \setminus \mathcal{R})$ pictured in Figure 9.

Using the Wirtinger algorithm [3] one can see that Γ_n' has the following presentation:

$$\begin{aligned}\langle \alpha, \beta, \gamma \quad | \quad & \alpha^n = 1, \quad \beta^2 = 1, \quad \gamma^2 = 1, \quad \beta\alpha\gamma = \alpha\gamma\beta \\ & \alpha^{-1}\gamma\beta^{-1}\alpha^{-1}\beta\gamma^{-1}\beta^{-1}\alpha\gamma^{-1}\alpha^{-1}\beta\gamma \cdot \\ & \qquad \cdot \beta^{-1}\alpha\beta\gamma^{-1}\beta^{-1}\alpha\gamma\alpha^{-1}\beta\gamma\beta^{-1}\alpha\beta\gamma^{-1} = 1\rangle.\end{aligned}$$

Consider a group

$$H_n = \mathbb{Z}_n \oplus \mathbb{Z}_2 \oplus \mathbb{Z}_2 = \langle a \,|\, a^n = 1\rangle \,\oplus\, \langle b \,|\, b^2 = 1\rangle \,\oplus\, \langle c \,|\, c^2 = 1\rangle$$

and define an epimorphism $\varphi_n : \Gamma'_n \to H_n$ by setting $\varphi_n(\alpha) = a$, $\varphi_n(\beta) = b$, $\varphi_n(\gamma) = c$. Let Γ_n, Γ''_n, Γ'''_n, G_n, and G'_n be such groups that $\mathcal{O}_n = \mathbb{H}^3/\Gamma_n$, $\mathcal{O}_n'' = \mathbb{H}^3/\Gamma''_n$, $\mathcal{O}'''_n = \mathbb{H}^3/\Gamma'''_n$, $M_n = \mathbb{H}^3/G_n$, and $M'_n = \mathbb{H}^3/G'_n$.

For the covering $\mathcal{O}''_n \to \mathcal{O}'_n$ a lift of the loop β is a trivial loop, lifts $\tilde{\alpha}$ and $\tilde{\gamma}$ of α and γ are loops about components of the singular set $\mathcal{Q}$ of $\mathcal{O}''_n$ generating subgroups $\mathbb{Z}_n$ and $\mathbb{Z}_2$, respectively. Thus, $\Gamma''_n = \varphi_n^{-1}(\langle a|a^n = 1\rangle \oplus \langle c|c^2 = 1\rangle)$. For the covering $\mathcal{O}'''_n \to \mathcal{O}''_n$ a lift of the loop $\tilde{\gamma}$ is a trivial loop, a lift $\tilde{\tilde{\alpha}}$ of the loop $\tilde{\alpha}$ is a loop about the singular set $\mathcal{P}$ of $\mathcal{O}'''_n$ generating subgroup $\mathbb{Z}_n$. Thus, $\Gamma'''_n = \varphi_n^{-1}(\langle a|a^n = 1\rangle)$. For the covering $M'_n \to \mathcal{O}'''_n$ the preimage of the loop $\tilde{\tilde{\alpha}}$ is a trivial loop. Thus, $G'_n = \mathrm{Ker}(\varphi_n)$.

For the covering $\mathcal{O}_n \to \mathcal{O}'_n$ a lift of the loop α is a trivial loop, lifts $\widehat{\beta}$ and $\widehat{\gamma}$ of loops β and γ are loops about components of the singular set $\mathcal{L}_n$ of $\mathcal{O}_n$ generating subgroups $\mathbb{Z}_2$ and $\mathbb{Z}_2$. Thus, $\Gamma_n = \varphi_n^{-1}(\langle b|b^2 = 1\rangle \oplus \langle c|c^2 = 1\rangle)$. For the group $\mathbb{Z}_2 \oplus \mathbb{Z}_2 = \langle b|b^2 = 1\rangle \oplus \langle c|c^2 = 1\rangle$ we denote $d = b + c$ and consider a group $\mathbb{Z}_2 = \langle d|d^2 = 1\rangle$. For the covering $M_n \to \mathcal{O}_n$ loops $\widehat{\beta}$ and $\widehat{\gamma}$ lift to trivial loops. Thus, $G_n = \varphi_n^{-1}(\langle d|d^2 = 1\rangle)$.

Therefore we get the following diagram of subgroups (where $A \xrightarrow{m} B$ denotes that A is a subgroup of B of index m)

$$
\begin{array}{ccccc}
 & & G'_n = \mathrm{Ker}(\varphi_n) & & \\
 & \overset{2}{\swarrow} & & \overset{n}{\searrow} & \\
G_n = \varphi_n^{-1}(\langle d \rangle) & & & & \Gamma'''_n = \varphi_n^{-1}(\langle a \rangle) \\
2 \downarrow & & & & \downarrow 2 \\
\Gamma_n = \varphi_n^{-1}(\langle b \rangle \oplus \langle c \rangle) & & & & \Gamma''_n = \varphi_n^{-1}(\langle a \rangle \oplus \langle c \rangle) \\
 & \underset{n}{\searrow} & & \underset{2}{\swarrow} & \\
 & & \Gamma'_n & &
\end{array}
$$

that implies the diagram of coverings. □

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