2-torsion in the $n$-solvable filtration of the knot concordance group

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Abstract

Cochran–Orr–Teichner introduced in [‘Knot concordance, Whitney towers and $L^2$-signatures’, Ann. of Math. (2) 157 (2003) 433–519] a natural filtration of the smooth knot concordance group $C$

$$\ldots \subset F_{n+1} \subset F_{n,5} \subset F_n \subset \ldots \subset F_1 \subset F_{0,5} \subset F_0 \subset C,$$

called the $(n)$-solvable filtration. We show that each associated graded abelian group $\{G_n = F_n / F_{n,5} \mid n \in \mathbb{N}\}$, $n \geq 2$, contains infinite linearly independent sets of elements of order 2 (this was known previously for $n = 0, 1$). Each of the representative knots is negative amphichiral, with vanishing $s$-invariant, $\tau$-invariant, $\delta$-invariants and Casson–Gordon invariants. Moreover, each is slice in a rational homology 4-ball. In fact we show that there are many distinct such classes in $G_n$, distinguished by their Alexander polynomials and, more generally, by the torsion in their higher-order Alexander modules.

1. Introduction

A (classical) knot $K$ is the image of a smooth embedding of an oriented circle in $S^3$. Two knots, $K_0 \hookrightarrow S^3 \times \{0\}$ and $K_1 \hookrightarrow S^3 \times \{1\}$, are concordant if there exists a proper smooth embedding of an annulus into $S^3 \times [0, 1]$ that restricts to the knots on $S^3 \times \{0, 1\}$. Let $C$ denote the set of (smooth) concordance classes of knots. The equivalence relation of concordance first arose in the early 1960s in the work of Fox, Kervaire and Milnor in their study of isolated singularities of 2-spheres in 4-manifolds and, indeed, certain concordance problems are known to be equivalent to whether higher-dimensional surgery techniques ‘work’ for topological 4-manifolds [1, 15, 28]. It is well known that $C$ can be endowed with the structure of an abelian group (under the operation of connected sum) called the smooth knot concordance group. The identity element is the class of the trivial knot. Any knot in this class is concordant to a trivial knot and is called a slice knot. Equivalently, a slice knot is one that is the boundary of a smooth embedding of a 2-disk in $B^4$. In general, the abelian group structure of $C$ is still poorly understood; but much work has been done on the subject of knot concordance (for excellent surveys, see [19, 37]). In particular, [11] introduced a natural filtration of $C$ by the subgroups

$$\ldots \subset F_{n+1} \subset F_{n,5} \subset F_n \subset \ldots \subset F_1 \subset F_{0,5} \subset F_0 \subset C,$$

called the $(n)$-solvable filtration of $C$ and denoted by $\{F_n\}$ (defined in Section 3). The non-triviality of $C$ can be measured in terms of the associated graded abelian groups $\{G_n = F_n / F_{n,5} \mid n \in \mathbb{N}\}$ (here we ignore the other ‘half’ of the filtration, $F_{n,5} / F_{n+1}$, where almost nothing is known). This paper is concerned with elements of order 2 in $C$ and, more generally, with elements of order 2 in $G_n$.

We review some of the history of 2-torsion phenomena in $C$ in the context of the $n$-solvable filtration. One of the earliest results concerning $C$ was the following epimorphism constructed...
by Fox and Milnor [15]:

\[ \text{FM : } \mathcal{C} \to \mathbb{Z}_2^\infty. \]

Soon thereafter, Levine constructed an epimorphism

\[ \mathcal{C} \to \mathcal{AC} \cong \mathbb{Z}^\infty \oplus \mathbb{Z}_2^\infty \oplus \mathbb{Z}_4^\infty, \tag{1.1} \]

to a group, \( \mathcal{AC} \), that became known as the algebraic knot concordance group. Any knot in the kernel of (1.1) is called an algebraically slice knot. In terms of the \( n \)-solvable filtration, Levine’s result is [11, Remark 1.3.2, Theorem 1.1]:

\[ \mathcal{G}_0 \cong \mathbb{Z}^\infty \oplus \mathbb{Z}_2^\infty \oplus \mathbb{Z}_4^\infty. \]

It is known that there exist elements of order 2 in \( \mathcal{C} \) that realize some of the above 2-torsion invariants. Let \( \overline{K} \) denote the mirror image of the oriented knot \( K \), obtained as the image of \( K \) under an orientation-reversing homeomorphism of \( S^3 \); and let \( r(K) \) denote the reverse of \( K \), which is obtained by merely changing the orientation of the circle. Then it is known that \( K \# r(\overline{K}) \) is a slice knot, so the inverse of \([ K ]\) in \( \mathcal{C} \), denoted by \( -[ K ] \), is represented by \( r(\overline{K}) \), denoted by \( -K \). A knot \( K \) is called negative amphichiral if \( K \) is isotopic to \( r(\overline{K}) \). It follows that, for any negative amphichiral knot \( K, K \# K \) is a slice knot, since it is isotopic to \( K \# -K \). Hence negative amphichiral knots represent elements of order either 1 or 2 in \( \mathcal{C} \).

It is a conjecture of Gordon that every class of order 2 in \( \mathcal{C} \) can be represented by a negative amphichiral knot [19].

In fact the work of Milnor and Levine in the 1960s resulted in a more precise statement:

\[ \mathcal{G}_0 \cong \bigoplus_{p(t)} (\mathbb{Z}_p^t \oplus \mathbb{Z}_2^m_p \oplus \mathbb{Z}_4^n_p) \]

where the sum is over all primes \( p(t) \in \mathbb{Z}[t] \), where \( p(t) \equiv p(t^{-1}) \) and \( p(1) = \pm 1 \) (see [24, p. 131; 34, Sections 10, 11 and 24; 48]); that is, the algebraic concordance group (and \( \mathcal{G}_0 \)) admits a certain \( p(t) \)-primary decomposition, wherein a knot has a non-trivial \( p(t) \)-primary part only if \( p(t) \) is a factor of its Alexander polynomial. (Indeed, Levine and Stoltzfus classified \( \mathcal{G}_0 \) by first splitting the Witt class of the Alexander module (with its Blanchfield form) into its \( p(t) \)-primary parts).

In the 1970s the introduction of Casson–Gordon invariants in [2, 3] led to the discovery that the subgroup of algebraically slice knots was of infinite rank and contained infinite linearly independent sets of elements of order 2 (see [27, 36]). In terms of the \( n \)-solvable filtration this implies the existence of

\[ \mathbb{Z}^\infty \oplus \mathbb{Z}_2^\infty \subset \mathcal{G}_1. \]

Different \( \mathbb{Z}^\infty \)-summands were exhibited in [16, 31]. More the recent work of Kim [29] on the ‘polynomial splitting’ properties of Casson–Gordon invariants led to a generalization analogous to the result of Milnor–Levine:

\[ \bigoplus_{p(t)} \mathbb{Z}^\infty \subset \mathcal{G}_1. \]

Thus there is evidence that \( \mathcal{G}_1 \) also exhibits a \( p(t) \)-primary decomposition. Further strong evidence is given in [30]. Although a similar statement for the 2-torsion in \( \mathcal{G}_1 \) has not appeared, it is expected from combining the work of [29] and [36]. Several authors have shown that certain knots that projected to classes of order 2 and 4 in \( \mathcal{AC} \) are in fact of infinite order in \( \mathcal{C} \) (see [20, 26, 35, 38, 39]). A number of papers have addressed the non-triviality of \( \{ \mathcal{G}_n \} \) (see [11–13, 16–18, 31]) culminating in [9], where it was shown that, for any integer \( n \), there exists

\[ \mathbb{Z}^\infty \subset \mathcal{G}_n. \]
Moreover, the recent work \cite{10} of the authors resulted in a generalization of the latter fact, along the lines of the Levine–Milnor primary decomposition and \cite{30}: for each ’distinct’ \(n\)-tuple \(\mathcal{P} = (p_1(t), \ldots, p_n(t))\) of prime polynomials with \(p_i(1) = \pm 1\), there is a distinct subgroup \(\mathbb{Z}^\infty \cong \mathcal{I}(\mathcal{P}) \subset G_n\), yielding a subgroup

\[
\bigoplus_{\mathcal{P}_n} \mathbb{Z}^\infty \cong \bigoplus_{\mathcal{P} \in \mathcal{P}_n} \mathcal{I}(\mathcal{P}) \subset G_n.
\]  

(1.2)

Given a knot \(K\), such an \(n\)-tuple encodes the orders of certain submodules of the sequence of higher-order Alexander modules of \(K\). Thus one can distinguish concordance classes of knots not only by their classical Alexander polynomials, but also, loosely speaking, by their higher-order Alexander polynomials. This result indicates that \(G_n\) decomposes not just according to the prime factors of the classical Alexander polynomial, but also according to types of torsion in the higher-order Alexander polynomials.

Here we show corresponding results for 2-torsion; that is, for any \(n \geq 2\), not only do we exhibit

\[
\mathbb{Z}_2^\infty \subset G_n,
\]  

(1.3)

but we also many distinct such subgroups

\[
\bigoplus_{\mathcal{P}_{n-1}} \mathbb{Z}_2^\infty \subset G_n,
\]  

(1.4)

parameterized by their Alexander polynomials and the types of torsion in the higher-order Alexander polynomials. The representative knots are distinguished by families of von Neumann signature defects associated to their classical Alexander polynomials and ‘higher-order Alexander polynomials’. The precise statement is given in Theorem 5.8. Each of these concordance classes has a negative amphichiral representative that is smoothly slice in a rational homology 4-ball. Thus the classical signatures and the Casson–Gordon signature-defect obstructions \cite{2} (indeed all metabelian obstructions) vanish for these knots \cite[Theorem 9.11]{11}. In addition, the \(s\)-invariant of Rasmussen \cite{45}, the \(\tau\)-invariant of Ozsváth and Szabó \cite{43}, and the \(\delta_{p^n}\)-invariants of Manolescu–Owens and Jabuka (see \cite{25, 41, 42}) vanish on these concordance classes, since each of these invariants induces a homomorphism \(C \to \mathbb{Z}\) and so must have value zero on classes representing torsion in \(C\). Our examples are inspired by those of Livingston, who provided examples that can be used to establish (1.3) in the case \(n = 1\) \cite{36}. His examples are distinguished by their Casson–Gordon signature defects. Our examples are distinguished by their higher-order \(L^{(2)}\)-signature defects. It is striking that elements of finite order can sometimes be detected by signatures. The key observation is that, unlike invariants such as the classical knot signatures, the \(s\)-invariant, the \(\tau\)-invariant or the \(\delta\)-invariants, the invariants arising from higher-order signature defects (including Casson–Gordon invariants) are not additive under connected sum. Therefore there is no reason to expect that they would vanish on elements of finite order.

Our work is further evidence that \(G_n\) exhibits some sort of primary decomposition, but wherein not only the classical Alexander polynomial, but also some higher-order Alexander polynomials are involved.

We remark that \cite{11} also defined a filtration \(\{F_n^{\top}\}\) of the topological concordance group \(C^{\top}\). Since it is known, by the work of Freedman and Quinn, that a knot lies in \(F_n^{\top}\) if and only if it lies in \(F_n\), all of the results of this paper apply equally well, without change, to the filtration \(\{F_n^{\top}\}\). Therefore, for simplicity, in this paper we always work in the smooth category.
2. The examples

Our examples are inspired by those of Livingston [36], who exhibited an infinite ‘linearly independent’ set of negative amphichiral algebraically slice knots. His examples can be used to establish the existence of the aforementioned

\[ \mathbb{Z}_2^\infty \subset G_1. \]

2.1. The building blocks

Consider the knot shown on the left-hand side of Figure 2.1. Here \( J \) is an arbitrary pure 2-component string link [21, 32]. The disk containing the letter \( J \) symbolizes replacing the trivial 2-string link by the 2-string link \( J \). Viewing the knot diagram as being in the \( xy \)-plane (\( y \) being vertical), the mirror image can be defined as the image under the reflection \((x, y, z) \mapsto (x, y, -z)\), which alters a knot diagram by replacing all positive crossings by negative crossings and vice versa. Recall that the image of \( J \) under this reflection is denoted by \( \overline{J} \). We also consider a ‘flip’ homeomorphism of \( S^3 \) that flips over a diagram, given by a rotation of \( 180^\circ \) about the \( y \)-axis or \( f(x, y, z) = (-x, y, -z) \). Note that these homeomorphisms commute.

Special cases of the following elementary observation appeared in [4, p. 60; 36, Lemma 2.1; 37, p. 326].

**Lemma 2.1.** Suppose that \( J \) is an arbitrary pure 2-component string link. Then the knot \( K \) on the left-hand side of Figure 2.1 is negative amphichiral.

**Proof.** The knot on the right-hand side of Figure 2.1 is a diagram for \( r(\overline{K}) \), since it is obtained by a reflection, in the plane of the paper, of the diagram for \( K \), followed by a reversal of the string orientation. Here we use that \( f \) commutes with the reflection. We claim that the result is isotopic to \( K \). Flipping the diagram (rotating by \( 180^\circ \) about the vertical axis in the plane of the paper), we arrive at the diagram shown on the left-hand side of Figure 2.2. This is identical to the original diagram of \( K \) except that the left-hand band passes under the right-hand band instead of over; but the left-hand band can be ‘swung’ around by an isotopy as suggested in the right-hand side of Figure 2.2, bringing it on top of the other band, at which point one arrives at the original diagram of \( K \). \[ \square \]

The following result was shown for the figure-eight knot (the case where the string link \( J \) is a single twist) by the first author (inspired by [14]). It was extended, by Cha, to the case where \( J \) is an arbitrary number of twists in [4, p. 63]. Our contribution here is just to note that Cha’s proof suffices to prove this more general result.

![Figure 2.1. Families of negative amphichiral knots \( K \).](image-url)
**Lemma 2.2.** Each knot $K$ in the family shown in Figure 2.1 is slice in a rational homology 4-ball.

**Proof.** We follow the argument of [4], only indicating where our more general argument deviates. It suffices to show that the zero-framed surgery $M_K$, as shown on the left-hand side of Figure 2.3, is rational homology cobordant to $S^1 \times S^2$. After adding, to $M_K \times [0, 1]$, a four-dimensional 1-handle and 2-handle (going algebraically twice over the 1-handle) and performing certain handle slides (see [4, pp. 62–64]), one arrives at a 3-manifold $M'$ given by surgery on the 3-component link drawn as the solid lines on the right-hand side of Figure 2.3. Therefore $M_K$ is rationally homology cobordant to $M'$.

Next one shows, as follows, that this underlying 3-component link $L_1$ is concordant to the simple 3-component link $L_4$ shown on the right-hand side of Figure 2.4. Ignoring the framings on $L_1$, add a band as shown by the dashed lines on the right-hand side of Figure 2.3, resulting in the 4-component link $L_2$ shown on the left-hand side of Figure 2.4. Here $-J$ is the image of the (unoriented) string link under the map $(x, y, z) \mapsto (x, -y, z)$. One must be careful here since $J$, which is reflection in the plane of the paper, is not the correct notion of the mirror image for a string link. Since our $y$-axis is the true axis of the string link (the $[0, 1]$ factor in $D^2 \times [0, 1]$), $-J$ is the concordance inverse of $J$ in the string link concordance group $[22, 32]$, so $J + (-J)$ is concordant to the trivial 2-string link. Hence the link $L_2$ is concordant to the 4-component link $L_3$, which would result from taking $J$ to be trivial. Capping off the right-most
unknotted component of $L_3$, we arrive at the 3-component link $L_4$ shown on the right-hand side of Figure 2.4. This describes the desired concordance from $L_1$ to $L_4$. Consequently, $M'$ is homology cobordant to the 3-manifold described by the framed link on the right-hand side of Figure 2.4, which is known to be homeomorphic to $S^1 \times S^2$.

In this paper we will only need the special case of these lemmas wherein the string link $J$ consists of two twisted parallels of a single knotted arc as indicated by the examples in Figures 2.5 and 2.6. Here an $m$ inside the rectangle indicates $m$ full positive twists between the two strands, and the $J$ inside the rectangle indicates that the trivial 2-component string

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{fig2.4}
\caption{L_2 and L_4.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{fig2.5}
\caption{Negative amphichiral knots E^m.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{fig2.6}
\caption{Families of negative amphichiral knots E^m(J).}
\end{figure}
link has been replaced by two parallel zero-twisted copies of a single knotted arc \( J \). This is explained more fully in Subsection 2.2.

**Proposition 2.3.** If \( m \) and \( n \) are distinct positive integers, then the Alexander polynomials \( \Delta_m(t) \) of \( \mathbb{E}^m \) and \( \Delta_n(t) \) of \( \mathbb{E}^n \) are distinct and irreducible, hence coprime.

**Proof.** A Seifert matrix for \( \mathbb{E}^m \) with respect to the obvious basis is

\[
\begin{pmatrix}
  m & 0 \\
  -1 & -m
\end{pmatrix}
\]

Thus the Alexander polynomial of \( \mathbb{E}^m \) is \( \Delta_m(t) = m^2t^2 - (2m^2 + 1)t + m^2 \). The discriminant \( 4m^2 + 1 \) is easily seen, for \( m \neq 0 \), to never be the square of an integer, so the roots of \( \Delta_m(t) \) are real and irrational. Hence \( \Delta_m(t) \) is irreducible over \( \mathbb{Q}[t, t^{-1}] \). It follows that if \( \Delta_m(t) \) and \( \Delta_n(t) \) had a common factor, then they would be identical up to a unit; but the equations \( m^2 = qn^2 \) and \( 2m^2 + 1 = q(2n^2 + 1) \) imply \( q = 1 \), so \( m = \pm n \). \( \square \)

2.2. Doubling operators

To construct knots that lie deep in the \( n \)-solvable filtration, we use iterated generalized satellite operations.

Suppose that \( R \) is a knot in \( S^3 \) and \( \alpha = (\alpha_1, \alpha_2, \ldots, \alpha_m) \) is an ordered oriented trivial link in \( S^3 \), that misses \( R \), bounding a collection of oriented disks that meet \( R \) transversely as shown on the left-hand side of Figure 2.7. Suppose that \( (K_1, K_2, \ldots, K_m) \) is an \( m \)-tuple of auxiliary knots. Let \( R_\alpha(K_1, \ldots, K_m) \) denote the result of the operation pictured in Figure 2.7, that is, for each \( \alpha_j \) take the embedded disk in \( S^3 \) bounded by \( \alpha_j \), cut off \( R \) along the disk, grab the cut strands, tie them into the knot \( K_j \) (such that the strands have linking number zero pairwise) and reglue as shown schematically on the right-hand side of Figure 2.7.

We call this the result of infection performed on the knot \( R \) using the infection knots \( K_j \) along the curves \( \alpha_j \) (see [12]). In the case where \( m = 1 \), this is the same as the classical satellite construction. This construction has an alternative description. For each \( \alpha_j \), remove a tubular neighborhood of \( \alpha_j \) in \( S^3 \) and glue in the exterior of a tubular neighborhood of \( K_j \) along their common boundary, which is a torus, in such a way that (the longitude of) \( \alpha_j \) is identified with the meridian \( \mu_j \) of \( K_j \), and the meridian of \( \alpha_j \) is identified with the reverse of the longitude \( \ell_j \) of \( K_j \) as suggested by Figure 2.8. The resulting space can be seen to be homeomorphic to \( S^3 \) and the image of \( R \) is the new knot.

It is well known that if the input knots \( K_1 \) and \( K_2 \) are concordant, then the output knots \( R_\alpha(K_1) \) and \( R_\alpha(K_2) \) are concordant. Thus the functions \( R_\alpha \) descend to \( C \).

**Definition 2.4** [8, 10]. A doubling operator, \( R_\alpha : C \times \cdots \times C \to C \) is a function, as in Figure 2.7, that is given by infection on a ribbon knot \( R \) wherein, for each \( i \), \( \text{lk}(R, \alpha_i) = 0 \). Often we suppress \( \alpha_i \) from the notation.

**Figure 2.7.** \( R_\alpha(K_1, \ldots, K_m) \): infection of \( R \) by \( K_j \) along \( \alpha_j \).
Figure 2.8. Infection as replacing a solid torus by a knot exterior.

Figure 2.9. Negative amphichiral doubling operators $R^m \equiv E^m \# E^m$.

These are called doubling operators because they generalize untwisted Whitehead doubling. In particular we consider the family of doubling operators $R^m_{\eta_1, \eta_2} (-, -)$ shown in Figure 2.9. Note that, since $E^m$ is negative amphichiral by Lemma 2.1,

$$R^m \equiv E^m \# E^m \cong E^m \# - E^m,$$

which is well known to be a ribbon knot [46, Exercise 8E.30]. Thus $R^m$ is a negative amphichiral ribbon knot. For the case $m = 1$, this was already noted in [36].

We also consider the family of doubling operators $R^m_{\alpha}$ shown in Figure 2.10 (where the $-m$ inside a box symbolizes $m$ full negative twists between the bands but where the individual bands remain untwisted), equipped with a specified circle $\alpha$ that can be shown to generate its Alexander module.

Figure 2.10. Doubling operators $R^m_{\alpha}$. 
2. Elements of order 2 in $\mathcal{F}_n$

Now we describe large families of examples of negative amphichiral knots that lie in $\mathcal{F}_n$. Let $K^0$ be any knot with $\text{Arf}(K^0) = 0$. Let $K^{n-1}$ be the image of $K^0$ under the composition of any $n-1$ doubling operators (each requiring a single input), that is, 

$$K^{n-1} \equiv R^{n-1} \circ \ldots \circ R^1(K^0). \quad (2.1)$$

Then, for any integer $m$, we define $K^n$ as in Figure 2.11, that is, $K^n \equiv R^m_{\eta_1, \eta_2}(K^{n-1}, \overline{K^{n-1}})$.

**Proposition 2.5.** For any $n \geq 1$, any $m$, any composition of $n-1$ doubling operators and any Arf invariant zero input knot $K^0$, the knot $K^n$ of Figure 2.11 satisfies the following:

1. $K^n$ is negative amphichiral;
2. $K^n \in \mathcal{F}_n$;
3. $K^n$ is (smoothly) slice in a smooth rational homology 4-ball;
4. $K^n \# K^n$ is a slice knot.

**Proof.** It was shown in [9, Theorem 7.1] that, for any any doubling operator $R$,

$$R(\mathcal{F}_i, \ldots, \mathcal{F}_i) \subset \mathcal{F}_{i+1}.$$

Since any knot of Arf invariant zero is known to lie in $\mathcal{F}_0$ (see [11, Remark 8.14, Theorem 8.11]), and since $K^n$ is the image of $K^0$ under a composition of $n$ doubling operators, it follows that $K^n \in \mathcal{F}_n$.

Note that $K^n$ is the connected sum of two knots each of which is of the form shown in Figure 2.6 (hence of the form of Figure 2.1). Thus, by Lemma 2.2, each such $K^n$ is slice in a rational homology 4-ball. Moreover, by Lemma 2.1, $K^n$ is negative amphichiral, so $K^n \# K^n$ is isotopic to $K^n \# r(K^n)$; but the latter is a ribbon knot and hence a slice knot.

For specificity we define the following infinite families.

**Definition 2.6.** Given an $n$-tuple $(m_1, \ldots, m_n)$ of integers and an Arf invariant zero knot $K^0$, we define $K^n(m_1, \ldots, m_n, K^0)$ to be the image of $K^0$ under the following composition of $n$ doubling operators. Specifically let

$$K^n \equiv K^n(m_1, \ldots, m_n, K^0) \equiv R^{m_n}_{\eta_1, \eta_2}(K^{n-1}, \overline{K^{n-1}}),$$

as shown in Figure 2.11, where $K^{n-1}$ is

$$R^{m_{n-1}} \circ \ldots \circ R^1(K^0),$$
where the $R^{m_i}$ are the operators of Figure 2.10. In other words, we recursively set
\[
K^1 = R^{m_1}_a(K^0);
K^2 = R^{m_2}_a \circ R^{m_1}_a(K^0);
\vdots
K^{n-1} = R^{m_{n-1}}_a \circ \ldots \circ R^{m_1}_a(K^0);
K^n = R^{m_n}_{m_1,n_2}(K^{n-1}, K^{n-2}).
\]
Even though $K^n$ depends on $(m_1, \ldots, m_n, K^0)$, we often suppress the latter from the notation.

3. Commutator series and filtrations of the knot concordance groups

To accomplish our goals, we must establish that many of the knots in the families given by Figure 2.11, and specifically those in Definition 2.6, are not in $F_{n,5}$ and, indeed, are distinct from each other in $F_n/F_{n,5}$. To this end we review recent work of the authors that introduced refinements of the $n$-solvable filtration parameterized by certain classes of group series that generalized the derived series. In particular the authors defined specific filtrations of $C$ that depend on a sequence of polynomials. These filtrations can then be used to distinguish between knots with different Alexander modules or different higher-order Alexander modules. All of the material in this section is a review of the relevant terminology of [10, Sections 2 and 3].

Recall that the derived series $\{G^{(n)} \mid n \geq 0\}$ of a group $G$ is defined recursively by $G^{(0)} \equiv G$ and $G^{(n+1)} \equiv [G^{(n)}, G^{(n)}]$. The rational derived series (see [23]) $\{G^{(n)}_r \mid n \geq 0\}$ is defined by $G^{(0)}_r \equiv G$ and
\[
G^{(n+1)}_r = \ker \left( \frac{G^{(n)}_r}{[G^{(n)}_r, G^{(n)}_r]} \rightarrow \frac{G^{(n)}_r}{[G^{(n)}_r, G^{(n)}_r]} \otimes \mathbb{Q} \right).
\]

More generally, we have the following definition.

**Definition 3.1** [10, Definition 2.1]. A commutator series defined on a class of groups is a function $*$ that assigns to each group $G$ in the class a nested sequence of normal subgroups
\[
\ldots < G^{(n+1)}_* < G^{(n)}_* < \ldots < G^{(0)}_* \equiv G,
\]
such that $G^{(n)}_*/G^{(n+1)}_*$ is a torsion-free abelian group.

**Proposition 3.2** [10, Proposition 2.2]. For any commutator series $\{G^{(n)}_*\}$, we have the following:
1. $\{x \in G^{(n)}_* \mid \exists k > 0, x^k \in [G^{(n)}_*, G^{(n)}_*] \subset G^{(n+1)}_* \}$ (and in particular $[G^{(n)}_*, G^{(n)}_*] \subset G^{(n+1)}_* \equiv G^*$, whence the name commutator series);
2. $G^{(n)}_* \subset G^{(n)}_*$, that is, every commutator series contains the rational derived series;
3. $G/G^{(n)}_*$ is a poly-(torsion-free abelian) group (abbreviated PTFA);
4. $\mathbb{Z}[G/G^{(n)}_*]$ and $\mathbb{Q}[G/G^{(n)}_*]$ are right (and left) Ore domains.

Any commutator series that satisfies a weak functoriality condition induces a filtration $\{F^{(n)}_*\}$ of $C$ by subgroups. These filtrations generalize and refine the $(n)$-solvable filtration $\{F_n\}$ of [11]. Let $M_K$ denote the closed 3-manifold obtained by zero-framed surgery on $S^3$ along $K$. 
Definition 3.3 [10, Definition 2.3]. A knot $K$ is an element of $\mathcal{F}_n^*$ if the zero-framed surgery $M_K$ bounds a compact, connected, oriented, smooth 4-manifold $W$ such that:

1. $H_1(M_K;\mathbb{Z}) \to H_1(W;\mathbb{Z})$ is an isomorphism;
2. $H_2(W;\mathbb{Z})$ has a basis consisting of connected, compact, oriented surfaces $\{L_i, D_i \mid 1 \leq i \leq r\}$ embedded in $W$ with trivial normal bundles, wherein the surfaces are pairwise disjoint except that, for each $i$, $L_i$ intersects $D_i$ transversely once with positive sign;
3. for each $i$, $\pi_1(L_i) \subset \pi_1(W)^{(n)}$ and $\pi_1(D_i) \subset \pi_1(W)^{(n)}$.

A knot $K \in \mathcal{F}_{n,5}^*$ if, in addition,

4. for each $i$, $\pi_1(L_i) \subset \pi_1(W)^{(n+1)}$.

Such a 4-manifold is called an $(n,5)$-solution or an $(n,5,\ast)$-solution, respectively, for $K$ and it is said that $K$ is $(n,\ast)$-solvable or $(n,5,\ast)$-solvable, respectively, via $W$.

The case where the commutator series is the derived series (without the torsion-free abelian restriction) is denoted by $\mathcal{F}_n$ and we speak of $W$ being an $(n)$-solution, and $K$ or $M_K$ being $(n)$-solvable via $W$ (see [11, Section 8]).

Definition 3.4. A commutator series $\{G_\ast(n)\}$ is weakly functorial (on a class of {groups, maps}) if $f(G_\ast(n)) < \pi_\ast(n)$ for each $n$ and for any homomorphism $f : G \to \pi$ (in the class) that induces an isomorphism $G/G_\ast(1) \cong \pi/\pi_\ast(1)$ (that is, induces an isomorphism on $H_1(-;\mathbb{Q})$).

Proposition 3.5 [10, Proposition 2.5]. Suppose that $\ast$ is a weakly functorial commutator series defined on the class of groups with $\beta_1 = 1$. Then $\{\mathcal{F}_n^*\}_{n \geq 0}$ is a filtration by subgroups of the classical (smooth) knot concordance group $\mathcal{C}$:

$$\ldots \subset \mathcal{F}_{n+1}^* \subset \mathcal{F}_{n,5}^* \subset \mathcal{F}_n^* \subset \ldots \subset \mathcal{F}_1^* \subset \mathcal{F}_{0.5}^* \subset \mathcal{F}_0^* \subset \mathcal{C}.\$$

Moreover, for any $n \in \frac{1}{2}\mathbb{Z}$,

$$\mathcal{F}_n \subset \mathcal{F}_n^*.\$$

3.1. The derived series localized at $\mathcal{P}$

Fix an $n$-tuple $\mathcal{P} = (p_1(t), \ldots , p_n(t))$ of non-zero elements of $\mathbb{Q}[t, t^{-1}]$, such that $p_1(t) \equiv p_1(t^{-1})$. For each such $\mathcal{P}$ we now recall from [10] the definition of a partial commutator series that we call the (polarized) derived series localized at $\mathcal{P}$, that is defined on the class of groups with $\beta_1 = 1$.

Suppose that $G$ is a group such that $G/G_\ast(1) \cong \mathbb{Z} = \langle \mu \rangle$. Then we define the derived series localized at $\mathcal{P}$ recursively in terms of certain right divisor sets $S_{pn} \subset \mathbb{Q}[G/G_\ast(n)]$.

Definition 3.6. For $n \geq 0$, let

$$G_\mathcal{P}^{(0)} \equiv G;$$

$$G_\mathcal{P}^{(1)} \equiv G_\ast(1);$$

and for $n \geq 1$,

$$G_\mathcal{P}^{(n+1)} \equiv \ker \left( G_\mathcal{P}^{(n)} \to \left[ G_\mathcal{P}^{(n)}, G_\mathcal{P}^{(n)} \right] \otimes_{\mathbb{Z}[G/G_\ast(n)]} \mathbb{Q}[G/G_\ast(n)] S_{pn}^{-1} \right).\quad (3.1)$$
To make sense of (3.1), one must realize that, for any \( H < G, \frac{H}{[H, H]} \) is a right \( \mathbb{Z}[G/H] \)-module, where \( g \) acts on \( h \) by \( h \mapsto g^{-1}hg \). One must also verify, at each stage, that \( G_p^{(n)} \) has been defined in such a way that \( G_p^{(k)}/G_p^{(k+1)} \) is a torsion-free abelian group for each \( k < n \), so \( G/G_p^{(n)} \) is a PTFA, from which it follows that \( \mathbb{Q}[G/G_p^{(n)}] \) is a right Ore domain. Therefore, for any right divisor set \( S_p \subset \mathbb{Q}[G/G_p^{(n)}] \) we may define the Ore localization \( \mathbb{Q}[G/G_p^{(n)}]S_p^{-1} \) as in (3.1) (see [10, Sections 3 and 4]).

For the (polarized) derived series localized at \( P \) we use the following right divisor sets.

**Definition 3.7.** The (polarized) derived series localized at \( P \) is defined as in Definition 3.6 by setting

\[ S_p = S_{p_1}(G) = \{ q_1(\mu) \ldots q_r(\mu) \mid (p_1(t), q_j(t)) = 1; \quad G/G_r^{(1)} \cong \{ \mu \} \subset \mathbb{Q}[G/G_r^{(1)}]; \] (3.2)

and for \( n \geq 2, \)

\[ S_p = S_{p_n}(G) = \{ q_1(a_1) \ldots q_r(a_r) \mid (p_n, q_j) = 1; \quad q_j(1) \neq 0; \quad a_j \in G_p^{(n-1)}/G_p^{(n)} \}, \] (3.3)

so \( S_p \subset \mathbb{Q}[G_p^{(n-1)}/G_p^{(n)}] \).

Here \( p_1(t) \) and \( q_j(t) \) are in \( \mathbb{Q}[t, t^{-1}] \). By \( (p_1, q_j) = 1 \) we mean that \( p_1 \) is coprime to \( q_j \) in \( \mathbb{Q}[t, t^{-1}] \), as usual; but by \( (p_n, q_j) = 1 \) we mean something slightly stronger.

**Definition 3.8** [10, Definition 4.4]. Two non-zero polynomials \( p(t), q(t) \in \mathbb{Q}[t, t^{-1}] \) are said to be strongly coprime, denoted by \( (p, q) = 1 \) if, for every pair of non-zero integers, \( n, k, p(t^n) \) is relatively prime to \( q(t^k) \). Alternatively, \( (p, q) \neq 1 \) if and only if there exist non-zero roots, \( r_p, r_q \in \mathbb{C}^* \), of \( p(t) \) and \( q(t) \), respectively, and non-zero integers \( k, n, \) such that \( r_p^k = r_q^n \).

Clearly, \( (p, q) = 1 \) if and only if, for each prime factor \( p_i(t) \) of \( p(t) \) and \( q_j(t) \) of \( q(t) \), \( (p_i, q_j) = 1 \).

Note that \( \mathbb{Q} - \{ 0 \} \subset S_{p_n} \) (take \( q_j \) to be a non-zero constant). It is easy to see (and was proved in [10, Section 4]) that \( S_{p_n} \) is closed (up to units) under the involution on \( \mathbb{Q}[G/G_p^{(n)}] \).

Here we need \( p_1(t) = p_1(t^{-1}) \).

**Example 3.9.** Consider the family of quadratic polynomials

\[ \{ q_m(t) = (mt - (m+1))(m+1)t - m) \mid m \in \mathbb{Z}^+ \}, \]

whose roots are \( \{ m/(m+1), (m+1)/m \} \). The polynomial \( q_m \) is the Alexander polynomial of the ribbon knot \( \mathcal{R}^m \) shown in Figure 2.10. It can easily be seen (and was proved in [10, Example 4.10]) that \( (q_m, q_n) = 1 \) if \( m \neq n \).

**Theorem 3.10** [10, Theorem 4.16]. The (polarized) derived series localized at \( P \) is a weakly functorial commutator series on the class of groups with \( \beta_1 = 1 \).

4. von Neumann signature defects as obstructions to \((n,5,\ast)\)-solvability

To each commutator series there exist signature defects that offer obstructions to a given knot lying in a term of \( \mathcal{F}^* \). Given a closed oriented 3-manifold \( M \), a discrete group \( \Gamma \) and a representation \( \phi : \pi_1(M) \to \Gamma \), the von Neumann \( \rho \)-invariant \( \rho(M, \phi) \in \mathbb{R} \) was defined by Cheeger and Gromov [5]. If \( (M, \phi) = \partial(W, \psi) \) for some compact, oriented 4-manifold \( W \) and
ψ : π₁(W) → Γ, then it is known that ρ(M, φ) = σ₁(2)(W, ψ) − σ(W), where σ₁(2)(W, ψ) is the $L^1$-signature (von Neumann signature) of the equivariant intersection form defined on $H_2(W; \mathbb{Z} Γ)$ twisted by ψ, and σ(W) is the ordinary signature of W (see [13, Section 2; 40]). Thus the ρ-invariants should be thought of as signature defects. They were first used to detect non-slice knots in [11]. For a more thorough discussion, see [11, Section 5; 12, Section 2; 13, Section 2]. All of the coefficient systems Γ in this paper will be of the form π/π⁺, where π is the fundamental group of a space. Hence all such Γ will be PTFA. Aside from the definition, the properties that we use in this paper are the following.

**Proposition 4.1.** (1) If φ factors through φ' : π₁(M) → Γ', where Γ' is a subgroup of Γ, then ρ(M, φ') = ρ(M, φ).[3]
(2) If φ is trivial (the zero map), then ρ(M, φ) = 0.
(3) If M = M_K is the zero-surgery on a knot K and φ : π₁(M) → Z is the abelianization, then ρ(M, φ) is denoted by ρ_0(K) and is equal to the integral over the circle of the Levine–Tristram signature function of K (see [12, Proposition 5.1]). Thus ρ_0(K) is the average of the classical signatures of K.
(4) If K is a slice knot or link and φ : M_K → Γ (Γ PTFA) extends over π₁ of a slice disk exterior, then ρ(M_K, φ) = 0 by [11, Theorem 4.2].
(5) The von Neumann signature satisfies Novikov additivity, that is, if W_1 and W_2 intersect along a common boundary component then σ₁(2)(W_1 ∪ W_2) = σ₁(2)(W_1) + σ₁(2)(W_2) (see [11, Lemma 5.9]).
(6) For any 3-manifold M, there is a positive real number C_M, called the Cheeger–Gromov constant [5, 13, Section 2] of M such that, for any φ,

$$|ρ(M, φ)| < C_M.$$  

We also need the following generalization of property (4).

**Theorem 4.2** [10, Theorem 5.2]. Suppose that * is a commutator series (no functoriality is required). Suppose K ∈ $F_{n,5}$, so the zero-framed surgery M_K is (n,5, *)-solvable via W as in Definition 3.3. Let $G = π₁(W)$ and consider

$$φ : π₁(M_K) → G → G/G^{(n+1)} → Γ,$$

where Γ is an arbitrary PTFA group. Then

$$σ₁(2)(W, φ) − σ(W) = 0 = ρ(M_K, φ).$$

5. Statements of main results and the outline of the proof

We will show that, for any $n \geq 2$, not only does there exist

$$\mathbb{Z}_2^\infty \subset G_n \equiv F_n/F_{n,5},$$

but there are also many distinct such classes

$$\bigoplus_{p_{n-1}} \mathbb{Z}_2^\infty \subset G_n,$$

distinguished by the sequence of orders of certain higher-order Alexander modules of the knots.

Given the sequence $P = (p_1(t), ..., p_n(t))$, we have defined (in Definitions 3.6 and 3.7) an associated commutator series called the derived series localized at $P$. 
Let $\{F^P_n\}$ denote the filtration of $\mathcal{C}$ associated, by Definition 3.3, to the derived series localized at $P$.

Since, for any group $G$ and integer $n$ (or half-integer), $G^{(n)} \subset G^{(n)}$, one sees that $F_n \subset F^P_n$. In particular $F_{n,5} \subset F^P_{n,5}$, so there is a surjection $\frac{F_n}{F_{n,5}} \to \frac{F^P_n}{F^P_{n,5}}$.

The point of the filtration $\{F^P_n\}$ is that any knot $K \in F_n$, whose classical Alexander polynomial is coprime to $p_1(t)$, will lie in the kernel of $\pi$. Moreover, the idea of Theorem 5.3 below is that a knot will of necessity lie in the kernel of $\pi$, unless $p_1(t)$ divides its classical Alexander polynomial and, loosely speaking, the higher $p_i(t)$ are related to torsion in its $i$th higher-order Alexander module.

**Definition 5.2.** Given $P = (p_1(t), \ldots, p_n(t))$ and $Q = (q_1(t), \ldots, q_n(t))$, we say that $P$ is strongly coprime to $Q$ if either $(p_1, q_1) = 1$, or $(p_k, q_k) = 1$ for some $k > 1$.

**Theorem 5.3** [10, Theorem 6.5]. For any $n \geq 1$, let $R^{n-1}_{\alpha_{n-1}}, \ldots, R^1_{\alpha_1}$ be any doubling operators and $K^0$ be any Arf invariant zero input knot. Consider the knot $K^n \equiv R^m_{\eta_1, \eta_2}(K^{n-1}, K^{n-1})$, where $K^{n-1} = R^{n-1}_{\alpha_{n-1}} \circ \ldots \circ R^1_{\alpha_1}(K^0)$. Then $K^n \in F^P_{n+1}$

for each $P = (p_1(t), p_2(t), \ldots, p_n(t))$, with $p_1(t) \equiv p_1(t^{-1})$, that is strongly coprime to $(\Delta_m(t), q_{n-1}(t), \ldots, q_1(t))$, where $\Delta_m$ is the Alexander polynomial of $E^m$ and $q_i$ is the Alexander polynomial of $R^i$.

This applies, in particular, to the families of Definition 2.6, constructed using the ribbon knots of Figures 2.9 and 2.10.

**Corollary 5.4.** For any $(m_1, \ldots, m_n)$ and any input knot $K^0$ with Arf invariant zero, $K^n(m_1, \ldots, m_n, K^0) \in F^P_{n+1}$

for each $P = (p_1(t), p_2(t), \ldots, p_n(t))$ that is strongly coprime to $(\Delta_{m_n}(t), q_{n-1}(t), \ldots, q_1(t))$, where $\Delta_{m_n}$ is the Alexander polynomial of $E^{m_n}$ and $q_i$ is the Alexander polynomial of $R^{m_i}$.

Now we need a non-triviality theorem to complement Theorem 5.3.

**Theorem 5.5.** Suppose $K^n \equiv R^m_{\eta_1, \eta_2}(K^{n-1}, K^{n-1})$, where $K^{n-1}$ is the result of applying any sequence of $n-1$ doubling operators $R^{n-1}_{\alpha_{n-1}} \circ \ldots \circ R^1_{\alpha_1}$ to an Arf invariant zero 'input' knot $K^0$. Suppose additionally that $n \geq 2$ and that:

1. $m \neq 0$;
2. for each $i$, $\alpha_i$ generates the rational Alexander module of $R^i$, and this module is non-trivial;
3. $|\rho_0(K^0)|$, the average Levine–Tristram signature of $K^0$, is greater than twice the sum of the Cheeger–Gromov constants of the ribbon knots $\mathcal{R}^m$, $R^1$, $\ldots$, $R^{n-1}$ (see Section 4).
If $\mathcal{P}$ is the sequence of classical Alexander polynomials of the knots $(\mathbb{E}^m, R^{n-1}, \ldots, R^1)$, then

$$K^n \notin \mathcal{F}_{n,5}^P.$$ 

This can be applied to the specific families of Definition 2.6.

**Corollary 5.6.** Fix $n \geq 2$ and an $n$-tuple of positive integers $(m_1, \ldots, m_n)$. Suppose that $K^0$ is chosen so that $|\rho_0(K^0)|$ is greater than twice the sum of the Cheeger–Gromov constants of the ribbon knots $R^{m_n}, R^{m_{n-1}}, \ldots, R^{m_1}$. If $\mathcal{P}$ is the $n$-tuple of Alexander polynomials of the knots $(\mathbb{E}^{m_n}, R^{m_{n-1}}, \ldots, R^{m_1})$, then

$$K^n \notin \mathcal{F}_{n,5}^P.$$ 

The proofs of Theorems 5.3 and 5.5 will constitute Sections 6 and 7. Assuming these theorems, we now derive our main results.

**Theorem 5.7.** Fix $n \geq 2$. For any $n$-tuple of positive integers $(m_1, \ldots, m_n)$ choose an Arf invariant zero knot $K^0(m_1, \ldots, m_n)$ such that $|\rho_0(K^0)|$ is greater than twice the sum of the Cheeger–Gromov constants of $R^{m_n}, R^{m_{n-1}}, \ldots, R^{m_1}$. Then the resulting set of knots

$$\{K^n(m_1, \ldots, m_n, K^0) \mid m_i \in \mathbb{Z}^+\},$$

as in Definition 2.6, represent linearly independent, order 2 elements of $\mathcal{F}_n/\mathcal{F}_{n,5}$. They also represent linearly independent order 2 elements in $\mathcal{C}$. In particular this gives

$$\mathbb{Z}^\infty \subset \mathcal{G}_n \equiv \frac{\mathcal{F}_n}{\mathcal{F}_{n,5}},$$

where each class is represented by a negative amphichiral knot that is slice in a rational homology 4-ball.

**Proof** (assuming Theorems 5.3 and 5.5). By Proposition 2.5, $K^n$ is negative amphichiral, $K^n \notin \mathcal{F}_n$, and $K^n \# K^n$ is a slice knot. Thus $2[K^n] = 0$ in $\mathcal{F}_n/\mathcal{F}_{n,5}$. By Corollary 5.6, for a certain $\mathcal{P}$, $K^n \notin \mathcal{F}_{n,5}^P$, so in particular $K^n \notin \mathcal{F}_{n,5}$ by Proposition 3.5. Therefore each $[K^n]$ has order precisely 2 in $\mathcal{G}_n$.

Suppose that there exists a non-trivial relation

$$J = \hat{K}^{11}(m_{11}, \ldots, m_{1n}, K_1^0) \# \cdots \# \hat{K}^{11}(m_{kn}, \ldots, m_{kn}, K_k^0) \in \mathcal{F}_{n,5}.$$ 

Set $\mathcal{P} = (p_1, \ldots, p_n) = (\Delta_{1n}, q_{1n-1}, \ldots, q_{11})$, the reverse of the sequence of Alexander polynomials of the operators corresponding to the first summand of $J$. For each of the other summands of $J$, the corresponding $n$-tuple $(m_{i1}, \ldots, m_{in})$ is assumed distinct from $(m_{11}, \ldots, m_{1n})$. Therefore, the (reversed) sequence of Alexander polynomials of the operators corresponding to this other summand is strongly coprime to $\mathcal{P}$ by Proposition 2.3 and Example 3.9. Thus, by Theorem 5.3, each summand of $J$, aside from the first, lies in $\mathcal{F}_{n,5}^P$ and hence in $\mathcal{F}_{n,5}^P$. Since $J \in \mathcal{F}_{n,5}$, it follows that $J \in \mathcal{F}_{n,5}^P$ by Proposition 3.5. Since $\mathcal{F}_{n,5}^P$ is a subgroup, it would follow that the first summand of $J$ also lay in $\mathcal{F}_{n,5}^P$, contradicting Corollary 5.6.

More generally, we have the following theorem.

**Theorem 5.8.** Suppose $n \geq 2$. Let $\mathcal{P}_n$ be any set of $n$-tuples $\mathcal{P} = (\delta_1(t), \delta_2(t), \ldots, \delta_n(t))$ of prime polynomials $\delta_i(t) \in \mathbb{Z}[t, t^{-1}]$ such that $\delta_i(1) = \pm 1, \delta_1(t) = \Delta_m = m^2 t^2 - (2m^2 + 1)t + m^2$ and with the property that, for any distinct $\mathcal{P}, \mathcal{P}' \in \mathcal{P}_n$, $\mathcal{P}$ and $\mathcal{P}'$ are strongly coprime.
Then there exists a set of negative amphichiral n-solvable knots indexed by \( \mathbb{P}_n \) that is linearly independent modulo \( \mathcal{F}_{n,5} \), that is, that spans
\[
\bigoplus_{\mathbb{P}_n} \mathbb{Z}_2 \subset \mathbb{G}_n,
\]
where the knot corresponding to the sequence \((\delta_1(t), \delta_2(t), \ldots, \delta_n(t))\) admits a sequence of higher-order Alexander modules containing submodules whose orders are determined by the sequence \((\delta_1(t) \delta_1(t^{-1}), \ldots, \delta_n(t) \delta_n(t^{-1}))\) with the classical Alexander polynomial being \(\delta_1(t) \delta_1(t^{-1})\). Moreover each class is represented by a negative amphichiral knot that is slice in a rational homology 4-ball.

**Proof (assuming Theorems 5.3 and 5.5).** By [49], for any prime \(\delta(t)\) with \(\delta(1) = \pm 1\) there exists a ribbon knot whose Alexander module is cyclic of order \(\delta(t)\delta(t^{-1})\). Hence, given \(\mathcal{P} = (\delta_1(t), \delta_2(t), \ldots, \delta_n(t))\), choose such ribbon knots \(R_{\alpha_1}^{n-1}, \ldots, R_1^1\) whose Alexander polynomials are \(\delta_2(t)\delta_2(t^{-1}), \ldots, \delta_n(t)\delta_n(t^{-1})\), respectively, and choose curves \(\alpha_i\) (unknotted in \(S^3\)) that generate the Alexander modules of the \(R_i\). Thus doubling operators \(R_{\alpha_i}^1, 1 \leq i \leq n-1\), are defined. Since \(\delta_1(t) = \Delta_m = m^2 t^2 - (2m^2 + 1) t + m^2\), there is a ribbon knot, namely \(R_m = \mathbb{E}^m \# \mathbb{E}^m\) of Figure 2.9, whose Alexander polynomial is \(\delta_1(t)\delta_1(t^{-1})\). The hypotheses imply \(m \neq 0\). Choose any Arf invariant zero knot \(K^0\) such that \(|p_0(K^0)| > 2\) the sum of the Cheeger–Gromov constants of \(\mathbb{R}^m, R_{\alpha_1}^{n-1}, \ldots, R_1^1\). Then set
\[
K^p_m \equiv R_{\alpha_1}^m \cdots R_{\alpha_1}^1 (K^{n-1}, K^{n-1}), \quad (5.1)
\]
where \(K^{n-1} = R_{\alpha_1}^{n-1} \circ \cdots \circ R_{\alpha_1}^1 (K^0)\). To each \(\mathcal{P}\) there is an associated n-tuple \(\mathcal{P}^* = (\delta_1(t) \delta_2(t) \delta_2(t^{-1}), \ldots, \delta_n(t) \delta_n(t^{-1}))\), which gives the sequence of Alexander polynomials of the knots \(\mathbb{E}^m, R_{\alpha_1}^{n-1}, \ldots, R_1^1\) that define \(K^p_m\).

By Lemma 2.1 and Proposition 2.5, each \(K^p_m\) is negative amphichiral and n-solvable. By Theorem 5.5,
\[
K^p_m \not\in \mathcal{F}_{n,5}^{P^*}, \quad (5.2)
\]
so \(K^p_m \not\in \mathcal{F}_{n,5}\). Thus \([K^p_m]\) has order precisely 2 in \(\mathbb{G}_n\). Suppose that there were a non-trivial relation
\[
J = \sum_{i=1}^k K^p_{\mathcal{P}_i} \in \mathcal{F}_{n,5}.
\]
By hypothesis, if \(i \neq 1\), then \(\mathcal{P}_i\) is strongly coprime to \(\mathcal{P}_1\). It follows that \(\mathcal{P}_i^*\) is strongly coprime to \(\mathcal{P}_1^*\). Thus, by Theorem 5.3, if \(i \neq 1\) then
\[
K^p_{\mathcal{P}_i} \in \mathcal{F}_{n+1}^{\mathcal{P}_i} \subset \mathcal{F}_{n,5}.
\]
Since \(J \in \mathcal{F}_{n,5}\), it follows that \(J \in \mathcal{F}_{n,5}^{\mathcal{P}_1}\). Since the latter is a subgroup, it follows that
\[
K^p_{\mathcal{P}_1} \in \mathcal{F}_{n,5}^{\mathcal{P}_1},
\]
contradicting (5.2).

It remains only to relate the sequence \(\mathcal{P}\) to the higher-order Alexander modules of the knots \(K^p_m\). Since this is not central to our results, we sketch the proof. We recall the following.

**Definition 5.9** [6, Definition 2.8; 23, Definition 5.3]. The ith, \(i \geq 1\), higher-order (integral) Alexander module of a knot \(K\) is
\[
\mathcal{A}_i^H(K) \equiv H_1(M_K; \mathbb{Z}/[G/G_r^{(i+1)}]) \cong \frac{G_r^{(i+1)}}{[G_r^{(i+1)}, G_r^{(i+1)}]},
\]
where \(G \equiv \pi_1(M_K)\). Note that the case \(i = 0\) would give the classical Alexander module.
Thus $\mathcal{A}_i^G(K^i_p)$ is a module over $\Gamma_i \equiv G/G^{(i+1)}$, where $G \equiv \pi_1(M_{K^i_p})$. The following lemma shows that the (two) images of the classical Alexander polynomial $\delta_{i+1}(t)\delta_{i+1}(t^{-1})$ of the constituent operator $R^{i-1}$ under certain maps

$$Z[t, t^{-1}] \rightarrow Z[G^{(i)}/G^{(i+1)}] \subset Z\Gamma_i,$$

wherein $t \mapsto x_1$ and $t \mapsto x_2$, appear as the orders of cyclic submodules of $\mathcal{A}_i^G(K^i_p)$.

**Lemma 5.10.** Fixing $\mathcal{P} = (\delta_1(t), \delta_2(t), \ldots, \delta_n(t))$ for each $1 \leq i \leq n-1$, the $i$th higher-order Alexander module of $K^i_p$ (the knot defined in (5.1)) contains two non-trivial summands

$$\frac{\delta_{i+1}(x_1)\delta_{i+1}(x_1^{-1})Z\Gamma_i}{\delta_{i+1}(x_2)\delta_{i+1}(x_2^{-1})Z\Gamma_i}$$

for certain $x_1, x_2 \in G^{(i)}/G^{(i+1)}$.

**Proof.** Recall that $K^i_p$ is defined as the image of $K^0$ under a composition of $n$ doubling operators. In particular $K^{n-1} = R_{\alpha, n-1}^* \circ \ldots \circ R_{\alpha, 1}^* (K^0)$. Sequences of satellite operations have a certain associativity property yielding, for each $i \geq 2$, an alternative description of $K^{n-1}$ as a single infection on a single ribbon knot $\tilde{R}^i$ along a curve lying in $\pi_1(S^3 - \tilde{R}^i)^{(i-1)}$, using the knot $K^{n-1}$ (see [7, Proposition 4.7; 8, Proposition 5.10]). Specifically,

$$K^{n-1} = R_{\alpha, n-1}^* \circ \ldots \circ R_{\alpha, n-i+1}^* (R_{\alpha, n-i, \ldots, \alpha, 1}^* (K^0))$$

$$K^{n-1} = R_{\alpha, n-1}^* \circ \ldots \circ R_{\alpha, n-i+1}^* (K^{n-i})$$

$$K^{n-1} = R_{\alpha, n-1}^* \circ \ldots \circ R_{\alpha, n-i+2}^* (R_{\alpha, n-i+1}^* (K^{n-i}))$$

$$K^{n-1} = \tilde{R}_{\beta_i}^* (K^{n-i}),$$

where

$$\tilde{R}_{\beta_i}^* = R_{\alpha, n-1}^* \circ \ldots \circ R_{\alpha, n-i+2}^* (R_{\alpha, n-i+1}^* (K^{n-i}))$$

and $\beta_i$ is the image of $\alpha_{n-i+1}$. The specific nature of $\tilde{R}^i$ is not important to our present considerations. If $i = 1$, let $\tilde{R}_{\beta_i}^*$ be the identity operator. Then, for any $i \geq 1$, it follows that

$$K^{n} = \mathfrak{R}_{\gamma_1, \gamma_2}^m (\tilde{R}_{\beta_i}^* (K^{n-i}), \overline{\tilde{R}_{\beta_i}^* (K^{n-i})}).$$

This can be reformulated, by the same considerations as above, to yield

$$K^{n} = \mathfrak{R}_{\gamma_1, \gamma_2}^m (K^{n-i}, \overline{K^{n-i}})$$

where $\mathfrak{R} = \mathfrak{R}_{\gamma_1, \gamma_2}^m (\tilde{R}^i, \tilde{R}^i)$ and $\{\gamma_1, \gamma_2\}$ are the images of the two copies of $\beta_i$. These curves can inductively be shown to lie in $\pi_1(S^3 - \tilde{R}^i)^{(i)}$ (see [7, Proposition 4.7; 8, Proposition 5.10]. The latter computation is very similar to the computation we perform in (7.15).

Now we can apply known results about the effect of single infection on the higher-order Alexander modules [6, Theorem 8.2; 33, Theorem 3.5]:

$$\mathcal{A}_i^G(K^n) = \mathcal{A}_i^G(\tilde{R}^i) \oplus (\mathcal{A}_i^G(K^{n-i}) \otimes_{Z[t, t^{-1}]} Z\Gamma_i) \oplus (\mathcal{A}_0^G(\overline{K^{n-i}}) \otimes_{Z[t, t^{-1}]} Z\Gamma_i).$$

where $\mathcal{A}_0^G$ denotes the classical Alexander module, and the first tensor product is given by $t \mapsto x_1 = \gamma_1$ and the second by $t \mapsto x_2 = \gamma_2$; but

$$\mathcal{A}_0^G(K^{n-i}) \cong \mathcal{A}_0^G(R^{n-i}) \cong \frac{Z[t, t^{-1}]}{\delta_{i+1}(t)\delta_{i+1}(t)Z[t, t^{-1}]}.$$

where $t \mapsto x_1$. The Alexander modules of $\overline{R^{n-i}}$ and $R^{n-i}$ are isomorphic. Thus $\mathcal{A}_i^G(K^n)$ contains two cyclic summands as claimed. By [6, Theorem 8.2; 33, Theorem 3.5] these summands are
non-zero precisely when \(x_1\) and \(x_2\) are not zero in \(\Gamma_i\). The verification of the latter requires further computation as in [7, Theorem 4.11; 8, Proposition 5.14]. These calculations are entirely similar to and easier than the ones we do to verify our Proposition 7.4. They are not included.

This concludes what we say about the connections between \(P\) and the orders of the higher-order Alexander modules of \(K^p\).

This concludes the proof of Theorem 5.8. 

6. Sketch of proof of Theorem 5.3

Theorem 5.3 is a consequence of [10, Theorem 6.5]. However, we shall sketch the proof since the basic idea is elementary and it also shows that \(K^n \in \mathcal{F}_n\).

**Proof of Theorem 5.3.** We set \(K^1 = R^i(K^0), \ldots, K^n = R^i(K^{n-1}, K^{n-1})\). Recall from [9, Lemma 2.3, Figure 2.1] that, whenever a knot \(L\) is obtained from a knot \(R\) by infection using knots \(K_1, K_2, \ldots\) there is a cobordism \(E\) whose boundary is the disjoint union of the zero surgeries \(M_{L}, -M_{R}\) and \(-M_{K_1}, -M_{K_2}\) and so on, as shown on the left-hand side of Figure 6.1. Therefore, since \(K^n = R^m(K^{n-1}, K^{n-1})\), there is a cobordism \(E_n\) whose boundary is the disjoint union of the zero surgeries on \(K^n, K^{n-1}, K^{n-1}\) and \(R^m\) as shown on the right-hand side of Figure 6.1 and schematically in Figure 6.2. Similarly there is a cobordism \(E_i\), for \(1 \leq i < n\), whose boundary is the disjoint union of the zero surgeries on \(K^i, K^{i-1}\) and \(R^i\). Consider \(X = E_n \cup E_{n-1} \cup E_{n-1} \cup \ldots \cup E_1 \cup E_1\), gluing \(E_i\) to \(E_{i-1}\) along their common boundary component \(M_{K_{i-1}}\), and gluing \(E_i\) to \(E_{i-1}\) along their common boundary component \(M_{K_{i-1}}\), as shown schematically in Figure 6.2. The boundary of \(X\) is a disjoint union of \(M_{K_n}, -M_{R^n}, -M_{K_0}, -M_{R^n}\) and two copies each of \(\pm M_{R^{n-1}}, \ldots, \pm M_{R^n}\).

For \(1 \leq i < n\), let \(S_i\) denote the exterior of any ribbon disk in \(B^4\) for the ribbon knot \(R^i\). Let \(S_n\) denote the exterior of any ribbon disk in \(B^4\) for the ribbon knot \(R^m\). Since \(\text{Arf}(K^0) = 0\), \(K^0 \in \mathcal{F}_0\) via some \(V\) (see [12, Section 5]). Gluing \(V, \overline{V} = -V\) and all the \(S_i\) and \(\overline{S}_i\) to \(X\), we obtain a 4-manifold, \(Z\) as shown in Figure 6.2. Note \(\partial Z = M_{K^n}\).

We claim that

\[ K^n \in \mathcal{F}_n \text{ via } Z, \]  

and if \(P\) is strongly coprime to \((\Delta_{m}(t), q_{n-1}(t), \ldots, q_1(t))\), then

\[ K^n \in \mathcal{F}_{n+1}^P \text{ via } Z. \]  

Figure 6.1. The cobordism.
First, simple Mayer–Vietoris sequences together with an analysis of the homology of the $E_i$ (as given by Lemma 6.1 below) imply that $H_2(Z) \cong H_2(V) \oplus H_2(\overline{V})$ since $H_2(S_i) = 0$. Since $V$ is a 0-solution, $H_2(V)$ has a basis of connected compact oriented surfaces, $\{L_j, D_j|1 \leq j \leq r\}$, satisfying the conditions of Definition 3.3; similarly for $H_2(\overline{V})$. We claim that

$$\pi_1(V) \subset \pi_1(Z)^{(n)}$$

and if $P$ is strongly coprime to $(\Delta_m(t), q_{n-1}(t), \ldots, q_1(t))$ then

$$\pi_1(V) \subset \pi_1(Z)^{(n+1)}.$$  

Indeed equations (6.3) and (6.4) were shown inductively in the proof of [10, Theorems 6.2 and 6.5] using the fact that, for each $i$, the doubling operator $R_i^{\alpha_i}$ satisfies $\ell k(\alpha_i, R_i) = 0$ leading to the fact that

$$\pi_1(M_{K_i-1}) \subset \pi_1(E_i)^{(1)}.$$  

Then

$$\pi_1(L_j) \subset \pi_1(V) \subset \pi_1(Z)^{(n)},$$

and if $P$ is strongly coprime to $(\Delta_m(t), q_{n-1}(t), \ldots, q_1(t))$, then

$$\pi_1(L_j) \subset \pi_1(V) \subset \pi_1(Z)^{(n+1)}.$$

and similarly for $\pi_1(D_j)$. The same holds for $\overline{V}$. This would complete the verification of claims (6.1) and (6.2) since $\{L_j, D_j\}$ (together with their counterparts in $\overline{V}$ would then satisfy the criteria of Definition 3.3.

This concludes our sketch of the proof as given in [10, Theorem 6.5]. We include the relevant result about the elementary topology of the cobordism $E$. We will need several of these properties in later proofs.

**Lemma 6.1** [9, Lemma 2.5]. With regard to $E$ on the left-hand side of Figure 6.1, the inclusion maps induce the following:

1. an epimorphism $\pi_1(M_L) \to \pi_1(E)$ whose kernel is the normal closure of the longitudes of the infecting knots $K_i$ viewed as curves $\ell_i \subset S^3 - K_i \subset M_L$;
(2) isomorphisms $H_1(M_L) \to H_1(E)$ and $H_1(M_R) \to H_1(E)$;
(3) isomorphisms $H_2(E) \cong H_2(M_L) \oplus H_2(M_K) \cong H_2(M_R) \oplus H_2(M_K)$;
(4) the meridian of $K$, $\mu_K \subset M_K$ is isotopic in $E$ to both $\alpha \subset M_R$ and to the longitudinal push-off of $\alpha$, often called $\alpha \subset M_L$ by abuse of notation;
(5) the longitude of $K$, $\ell_K \subset M_K$ is isotopic in $E$ to the reverse of the meridian of $\alpha$, $(\mu_\alpha)^{-1} \subset M_L$ and to the longitude of $K$ in $S^3 - K \subset M_L$ and to the reverse of the meridian of $\alpha$, $(\mu_\alpha)^{-1} \subset M_R$ (the latter bounds a disk in $M_R$).

7. Proof of Theorem 5.5

The proof of Theorem 5.5 will occupy the remainder of the paper.

Proof of Theorem 5.5. We assume that
\[ P = (p_1(t), \ldots, p_n(t)) = (\Delta_m, q_{n-1}(t), \ldots, q_1(t)) \]
is the $n$-tuple of Alexander polynomials of the knots $(E^m, R^{n-1}, \ldots, R^1)$. Suppose that $K^n \in P_{n,5}$. Let $V$ be the putative $(n,5,P)$-solution. We derive a contradiction.

Let $W_0$ be the 4-manifold (refer to Figure 7.1) obtained from $V$ by adjoining the cobordisms $E_n$, $E_{n-1}$, $E_{n-1}$, $\ldots$, $E_1$, $E_1$ as defined in the proof of Theorem 5.3. For specificity, set
\[ W_n = V, \]
\[ W_{n-1} = W_n \cup E_n, \]
\[ W_{n-2} = W_{n-1} \cup E_{n-1} \cup E_{n-1}, \]
\[ \vdots \]
\[ W_0 = W_1 \cup E_1 \cup E_1. \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7_1}
\caption{W_0.}
\end{figure}
Note that, unlike in the manifold $Z$ of Figure 6.2, we do not cap off the zero surgeries on the various ribbon knots. Thus the boundary of $W_0$ is the disjoint union of the zero surgeries on the ribbon knots $\mathbb{R}^m$, $R^{n-1}$, $\ldots$, $R^1$, $\mathbb{R}^{n-1}$, $\ldots$, $\mathbb{R}^1$, together with the zero surgeries on $K^0$, $\overline{K}^0$.

Below we define a commutator series $\{\pi_S^{(i)}\}$ that is slightly larger than the derived series localized at $P$. In particular,

$$\pi_1(W_0)^{(n+1)}_P \subset \pi_1(W_0)^{(n+1)}_S.$$ (7.1)

Then we consider the coefficient system on $W_0$ given by the projection

$$\phi : \pi_1(W_0) \longrightarrow \pi_1(W_0)/\pi_1(W_0)^{(n+1)}_P \longrightarrow \pi_1(W_0)/\pi_1(W_0)^{(n+1)}_S.$$

The bulk of the work of the proof will be to show that:

- the restriction of $\phi$ to $\pi_1(M_{K^0} \subset \partial W_0)$ factors non-trivially through $\mathbb{Z}$; and
- the restriction of $\phi$ to $\pi_1(M_{K}^0 \subset \partial W_0)$ is zero. (7.2) (7.3)

We now show that (7.1)–(7.3) imply Theorem 5.5. Consider the von Neumann signature defect of $(W_0, \phi)$:

$$\sigma^{(2)}(W_0, \phi) - \sigma(W_0).$$

By the additivity of these signatures (property (5) of Proposition 4.1), this quantity is the sum of the signature defects for $V$ and those of the $E_i$ and $\overline{E}_i$. Note that the coefficient system on $\pi_1(V)$ factors

$$\pi_1(V) \longrightarrow \pi_1(V)^{(n+1)}_P \longrightarrow \pi_1(W_0)^{(n+1)}_P \longrightarrow \pi_1(W_0)^{(n+1)}_S$$

where we use Theorem 3.10 to establish the second map and we use (7.1) for the third map. Thus, since $V$ is an $(n,5,P)$-solution, the signature defect of $V$ vanishes by Theorem 4.2. All of the signature defects of the $E_i$ vanish by [9, Lemma 2.4] (essentially because $H_2(E)$ comes from $H_2(\partial E)$). Therefore the signature defect vanishes for $W_0$. On the other hand, by Section 4,

$$\sigma^{(2)}(W_0, \phi) - \sigma(W_0) = \rho(\partial W_0, \phi).$$

Hence

$$0 = \rho(M_{\mathbb{R}^m}, \phi) + \ldots + \rho(M_{R^1}, \phi) + \rho(M_{\mathbb{R}^n}, \phi) + \rho(M_{K^0}, \phi) + \rho(M_{\overline{K}^0}, \phi).$$

By (7.2) and properties (1) and (3) of Proposition 4.1,

$$\rho(M_{K^0}, \phi) = \rho_0(K^0);$$

while by (7.3) and properties (1) and (2) of Proposition 4.1

$$\rho(M_{\overline{K}^0}, \phi) = 0.$$

However, by choice, $|\rho_0(K^0)|$ is greater than twice the sum of the Cheeger–Gromov constants of the 3-manifolds $M_{\mathbb{R}^m}, \ldots, M_{R^1}$, which is a contradiction (see property (6) of Proposition 4.1).

Therefore the proof of Theorem 5.5 is reduced to defining a commutator series $\{\pi_S^{(n)}\}$ such that (7.1)–(7.3) hold.

The commutator series $\pi_S^{(i)}$ will be defined only for the groups $\pi = \pi_1(W_i)$, because we need not be concerned with any other groups. It will be defined exactly as in Definition 3.6 except that the sequence of right divisor sets $S_1, \ldots, S_n$ will be slightly different from those of Definition 3.7. We now define $S_1, \ldots, S_n$. In these definitions $\pi$ is the fundamental group of one of the $W_i$.

We define

$$S_1 = S_1(\pi) = S_{p_1}(\pi) = \{q_1(\mu) \ldots q_r(\mu) \mid (p_1(t), q_j(t)) = 1; \pi/\pi^{(1)} \cong \langle \mu \rangle\}.$$
(Note that \( \pi^{(1)} = \pi_r^{(1)} = \pi_p^{(1)} = \pi_S^{(1)} \). Before defining the other \( S_i \) we make a few remarks. Since \( p_1(t) \) is a knot polynomial \( p_1(t) \equiv p_1(t^{-1}) \), so \( S_1 \) is closed (up to units) under the natural involution. In fact, since \( p_1(t) = \Delta_m(t) \) is the Alexander polynomial of \( \mathbb{Z}^n \), \( p_1(t) \) is prime. Hence one sees that

\[
S_1 = \mathbb{Q}[\mu, \mu^{-1}] - \langle \Delta_m(\mu) \rangle.
\]

Therefore, for any \( \mathbb{Q}[\mu^{\pm 1}] \)-module \( M, MS_1^{-1} = M(\Delta_m) \), the classical localization of \( M \) at the prime ideal \( \langle \Delta_m \rangle \).

Therefore, by (3.1),

\[
\pi_S^{(2)} = \pi_p^{(2)} = \ker \left( \pi^{(1)} \longrightarrow \frac{\pi^{(1)}}{[\pi^{(1)}, \pi^{(1)}]} \otimes \mathbb{Q}[\mu, \mu^{-1}]S_1^{-1} \equiv \mathcal{A}(W)S_1^{-1} = \mathcal{A}(W)(\Delta) \right),
\]

where \( \mathcal{A}(W)(\Delta) \) is the classical localization of \( \mathcal{A}(W) \) at the prime \( \langle \Delta_m \rangle \). (If \( W \) is any space with \( \pi_1(W) = \pi \) and \( H_1(W) \cong \mathbb{Z} \), then by its integral Alexander module, denoted by \( \mathcal{A}(W) \), we mean \( H_1(W; \mathbb{Z}[\mu, \mu^{-1}]) \cong \pi^{(1)}/\pi^{(2)}(2) \). By its rational Alexander module, denoted by \( \mathcal{A}(W) \), we mean \( H_1(W; \mathbb{Q}[\mu, \mu^{-1}]) \).

Now let \( \Gamma = \pi/\pi_S^{(2)} = \pi/\pi_p^{(2)} \) and \( A = \pi^{(1)}/\pi_S^{(2)} \equiv \pi^{(1)}/\pi_p^{(2)} \subset \Gamma \). Thus \( \Gamma \) is the semidirect product of the abelian group \( A \) with \( \pi/\pi^{(1)} \cong \mathbb{Z} \). Note that the circle \( \eta_2 \) (see Figure 2.9) represents an element of \( \pi_1(\mathbb{R}^n_\alpha) \) and hence, under inclusion, an element of \( \pi_1(\mathbb{R}^n) \) for each of the groups \( \pi = \pi_1(W_i) \) under consideration. Hence, for any \( \pi, \eta_2 \) has an unambiguous interpretation as an element of \( A \). By abuse of notation we allow \( \eta_2 \) to stand for its image in any of the appropriate groups. Recall that a set \( S \subset \Gamma \) is \( \Gamma \)-invariant if \( gsg^{-1} \in S \) for all \( s \in S \) and \( g \in \Gamma \). Note that the set \( \{ \mu^i\eta_2\mu^{-i} \mid i \in \mathbb{Z} \} \) is \( \Gamma \)-invariant, where \( \mu \in \Gamma \) generates \( \pi/\pi^{(1)} \).

Then we define the other \( S_n \) as follows.

**Definition 7.1.** Let \( S_2 = S_2(\pi) \subset \mathbb{Q}[\pi^{(1)}/\pi_S^{(2)}] \subset \mathbb{Q}[\pi/\pi_S^{(2)}] \) be the multiplicative set generated by

\[
\{ q(a) \mid (q, p_2) = 1, q(1) \neq 0, a \in A \} \cup \{ p_2(\mu^i\eta_2\mu^{-i}) \mid i \in \mathbb{Z} \};
\]

and for \( 2 < i \leq n \) let

\[
S_n = S_n(\pi) = \{ q_1(a_1) \ldots q_r(a_r) \mid (p_n, q_j) = 1; q_j(1) \neq 0; a_j \in \pi_S^{(n-1)}/\pi_S^{(n)} \}. \tag{7.5}
\]

Since \( S_2 \) is a multiplicative subset of \( \mathbb{Q}[\mathbb{A}] \) that is \( \Gamma \)-invariant, it is a right divisor set of \( \mathbb{Q}[\mathbb{A}] \) by [10, Proposition 4.1]. Therefore Definition 3.6 applies to give a partially defined commutator series \( \{ \pi_S^{(i)} \} \). Since \( p_2(t) = q_{n-1}(t) \) is a knot polynomial, \( p_2(t) \equiv p_2(t^{-1}) \). Thus \( S_2 \) is closed (up to units) under the natural involution.

**Lemma 7.2.** For each \( \pi \) and each \( 0 \leq i \leq n + 1 \)

\[
\pi_p^{(i)} \subset \pi_S^{(i)} \tag{7.6}
\]

**Proof.** The proof is by induction on \( i \). By Definition 3.6, \( \pi_p^{(i)} = \pi^{(i)} = \pi_S^{(i)} \), so the lemma is true for \( i = 0, 1 \). Suppose it is true for all values up to some fixed \( i \geq 1 \). Let \( j : \pi \rightarrow \pi \) be the identity map. By [10, Proposition 3.2], it suffices to show that the induced ring map

\[
j_* : \mathbb{Z}[\pi/\pi_S^{(i)}] \longrightarrow \mathbb{Z}[\pi/\pi_S^{(i)}]
\]

has the property that \( j_*(S_p(\pi)) \subset S_i(\pi) \). For \( i = 1 \), \( j_* \) is the identity map and \( S_1(\pi) \) is, by definition, identical to \( S_p(\pi) \). It follows that \( \pi_p^{(2)} = \pi_S^{(2)} \) as already observed in (7.4). Thus,
for $i = 2$, $j_*$ is again the identity map and, by Definitions 7.1 and 3.7, $S_2(\pi)$ strictly contains $S_{\psi}(\pi)$. For $i > 2$, the map $j_*$, although induced by the identity, will be a surjection with non-zero kernel. Nonetheless, by the inductive hypothesis, $j$ induces a homomorphism

$$j_*: \pi_p^{(i-1)}/\pi_p^{(i)} \to \pi_S^{(i-1)}/\pi_S^{(i)}.$$ 

Recall from Definition 3.7 that

$$S_{\psi}(\pi) = \{ q_1(a_1) \ldots q_r(a_r) | (p_1,q_j) = 1; q_j(1) \neq 0; a_j \in \pi_p^{(i-1)}/\pi_p^{(i)} \},$$

which is the multiplicative set generated by the described set of polynomials $q(a)$. If $q(a)$ is any such polynomial, then $j_*(q(a)) = q(j_*(a))$ and since

$$a \in \frac{\pi_p^{(i-1)}}{\pi_p^{(i)}}, \text{ then } j_*(a) \in \frac{\pi_S^{(i-1)}}{\pi_S^{(i)}}.$$ 

Thus, upon examining (7.5), we see that $q(j_*(a)) \in S_i(\pi)$. Hence $j_*(S_{\psi}(\pi)) \subset S_i(\pi)$ as desired.

In particular this establishes (7.1).

**Lemma 7.3.** The commutator series $\{ \pi_S^{(i)} \}$ is functorial with respect to any inclusion, $W_i \to W_j$, where $i > j$.

**Proof.** Note that any such inclusion induces an isomorphism $H_1(W_i) \cong H_1(W_j) \cong \mathbb{Z} = \langle \mu \rangle$. If $\pi_S^{(i)}$ were actually the polarized derived series localized at $P$, then the functoriality would follow directly from our Theorem 3.10 [10, Theorem 4.16]. But since $\pi_S^{(i)}$ is slightly different, we must actually repeat some of the proof of [10, Theorem 4.16]. Suppose $A = \pi_1(W_i), B = \pi_1(W_j)$ and $\psi: A \to B$ is induced by inclusion. We show, by induction on $i$, that $\psi(A_S^{(i)}) \subset B_S^{(i)}$. This holds for $i = 0$, so suppose that it holds for $i = n$. We will show that $\psi(A_S^{(n+1)}) \subset B_S^{(n+1)}$. The induction hypothesis guarantees that, for each $1 \leq k \leq n$, $\psi$ induces a homomorphism of pairs

$$\psi: (A/A_S^{(k)}, A_S^{(k-1)}/A_S^{(k)}) \longrightarrow (B/B_S^{(k)}, B_S^{(k-1)}/B_S^{(k)}).$$

By [10, Proposition 3.2] (or by examining (3.1)) it suffices to show that this map satisfies

$$\psi(S_k(A)) \subset S_k(B)$$

(7.7)

for each $1 \leq k \leq n$. First consider $k = 1$. Recall that

$$S_1(A) = \{ q_1(\mu) \ldots q_r(\mu) | (p_1(t), q_j(t)) = 1; A/A^{(1)} \cong \langle \mu \rangle \} \subset \mathbb{Q}[A/A^{(1)}].$$

Since $\psi$ induces an isomorphism $\psi: A/A^{(1)} \to B/B^{(1)}$, $\psi(\mu) = \pm \mu$. By choosing generators once and for all, we may assume that $\psi(\mu) = \mu$. So, for any such $q_j(t)$,

$$\psi(q_1(\mu) \ldots q_r(\mu)) = q_1(\psi(\mu)) \ldots q_r(\psi(\mu)) = q_1(\mu) \ldots q_r(\mu) \in S_1(B).$$

This verifies (7.7) for $k = 1$.

Now suppose $k > 1$. Recall that

$$S_k(A) = \{ q_1(a_1) \ldots q_r(a_r) | (p_n,a_j) = 1; q_j(1) \neq 0; a_j \in A_S^{(k-1)}/A_S^{(k)} \}.$$ 

Thus, for any such $q_j(t)$,

$$\psi(q_1(a_1) \ldots q_r(a_r)) = q_1(\psi(a_1)) \ldots q_r(\psi(a_r)) \in S_k(B),$$

since $\psi(a_j) \in B_S^{(k-1)}/B_S^{(k)}$.

Thus $\psi(S_k(A)) \subset S_k(B)$.

\[ \square \]
7.1. Establishing (7.2) and (7.3)

Since \( \pi_1(M_{K^0}) \subset \pi_1(W_0) \) is normally generated by its meridian \( \mu_0 \), and \( \pi_1(M_{K^0}) \) is normally generated by its meridian (that we denote) \( \mu_0 \), the case \( i = 0 \) of the following Proposition will establish (7.2) and (7.3). Therefore the rest of the paper will be spent establishing Proposition 7.4.

**Proposition 7.4.** For any \( 0 \leq i \leq n - 2 \), \( \mu_i = \alpha_{i+1} \) is non-trivial, while \( \overline{\mu}_i = \overline{\alpha}_{i+1} \) is trivial in

\[
\frac{\pi_1(W_i)^{(n-i)}}{\pi_1(W_i)^{(n-i+1)}}.
\]

To clarify the notation of this proposition, recall that, for \( 0 \leq i \leq n - 1 \), \( \partial W_i \) contains the disjoint union of the zero surgeries on the knots \( K^i \) (refer to the schematic Figure 7.2), and \( K^i \). Let \( \mu_i \) and \( \overline{\mu}_i \) denote the meridians of \( K^i \) and \( \overline{K}^i \) in these copies of \( M_{K^i} \) and \( M_{\overline{K}^i} \), respectively. Also recall that \( K^{i+1} = R_{\alpha_{i+1}}(K^i) \) for some circle \( \alpha_{i+1} \) that generates the Alexander module of \( R_{\alpha_{i+1}}(K^i) \); and \( \overline{K}^{i+1} = \overline{R}_{\alpha_{i+1}}(\overline{K}^i) \). Let \( \alpha_{i+1} \) denote (a push-off of) this circle in \( M_{K^{i+1}} \subset \partial W_{i+1} \) (referring to Figure 7.2); and let \( \overline{\alpha}_{i+1} \) denote (a push-off of) the other copy of \( \alpha_{i+1} \) in \( M_{\overline{K}^{i+1}} \subset \partial W_{i+1} \). Note that, by property (4) of Lemma 6.1, \( \mu_i \) is isotopic to \( \alpha_{i+1} \) in \( E_{i+1} \) and \( \overline{\mu}_i \) is isotopic to \( \overline{\alpha}_{i+1} \) in \( \overline{E}_{i+1} \). Hence \( \mu_i = \alpha_{i+1} \) and \( \overline{\mu}_i = \overline{\alpha}_{i+1} \) as elements of \( \pi_1(W_i) \).

**Proof of Proposition 7.4.** The proof is by reverse induction on \( i \), starting with \( i = n - 2 \).

Before proving the base case \( i = n - 2 \), we need to work out the ‘pre-base-case’, \( i = n - 1 \), where the situation is slightly different. Note that \( \alpha_n \) and \( \overline{\alpha}_n \) are what we have previously called \( \eta_1 \) and \( \eta_2 \), respectively.

**Lemma 7.5.** Both \( \mu_{n-1} = \eta_1 \) and \( \overline{\mu}_{n-1} = \eta_2 \) are non-trivial in

\[
\frac{\pi_1(W_{n-1})^{(1)}}{\pi_1(W_{n-1})^{(2)}}.
\]
Proof. Throughout the proof of this lemma we abbreviate $W = W_{n-1}$, $\pi = \pi_1(W_{n-1})$ and $\Delta = \Delta_n$. We make use of the fact that the integral and rational Alexander modules of a knot agree with those of its zero-framed surgery. Specifically we use $\mathcal{A}(K)$ to denote both the rational Alexander module of $K$ and that of $M_K$. The inclusion maps induce a commutative diagram of maps between integral and rational Alexander modules as shown below:

![Diagram](attachment:image.png)

Note that $\mathcal{A}^\mathbb{Z}(\mathbb{R}^m) \cong \mathcal{A}^\mathbb{Z}(\mathbb{K}^n) \cong \mathcal{A}^\mathbb{Z}(M_{K_n}) \cong \mathcal{A}^\mathbb{Z}(\partial V)$. The maps $j_*$ and $k_*$ are induced by inclusion. The map $i$ is induced by the connected sum decomposition, where $\mathbb{E}^m$ denotes the ‘left-hand’ copy in $\mathbb{R}^m \equiv \mathbb{E}^m \# \mathbb{E}^m$. The existence and injectivity of $i_3$ is given by (7.4). Since the $\eta_i$ represent elements in the Alexander module of $\mathbb{E}^m$, it suffices to show that the composition in the top row is injective. For this it suffices to show that the composition $k_* \circ j_* \circ i_1' \circ i_1''$ is a monomorphism. Since it is well known that the integral Alexander modules $\mathcal{A}^\mathbb{Z}(\mathbb{E}^m) \cong \mathcal{A}^\mathbb{Z}(S^3 - \mathbb{E}^m)$ are $\mathbb{Z}$-torsion-free, $i_1''$ is injective. Since $\mathcal{A}(\mathbb{E}^m)$ is a $\Delta$-torsion module, $i_1'$ is injective. Under the connected sum decomposition the localized Alexander module of $\mathbb{R}^m$ decomposes as the direct sum of the localized Alexander modules of its summands $\mathbb{E}^m$. The Blanchfield form decomposes similarly. Hence $i$ is injective. Now consider the map $j_*$ induced by the inclusion $\partial V \hookrightarrow V$:

$$j_* : \mathcal{A}(\partial V)(\Delta) \cong \mathcal{A}(\mathbb{R}^m)(\Delta) \equiv H_1(M_{\mathbb{R}^m}; \mathbb{Q}[t, t^{-1}]S_{p_1}^{-1}) \longrightarrow H_1(V; \mathbb{Q}[t, t^{-1}]S_{p_1}^{-1}) \equiv \mathcal{A}(V)(\Delta).$$

Since $V$ is an $(n,5,\mathcal{P})$-solution for $\partial V$, and $\pi_\mathcal{P}^{(i)} \subset \pi_\mathcal{S}^{(i)}$, $V$ is an $(n,5,\mathcal{S})$-solution, so it is certainly a $(1,\mathcal{S})$-solution. Consider the coefficient system $\psi : \pi_1(V) \rightarrow \pi_1(W) / \pi_1(V(1)) \cong \mathbb{Z}$ (recall $G_1^{(1)} = G_1^{(2)}$ for any group $G$). Then [9, Theorem 7.15] applies to say that the kernel of $j_*$ is isotropic with respect to the classical Blanchfield form on $\mathcal{A}(\mathbb{E}^m)(\Delta)$. Hence the kernel $P$, of $i \circ j_*$ is isotropic with respect to the classical Blanchfield form on $\mathcal{A}(\mathbb{E}^m)(\Delta)$; but, since the Alexander polynomial of $\mathbb{E}^m$ is irreducible by Proposition 2.3, the rational Alexander module of $\mathbb{E}^m$ has no proper submodules. The case $P = \mathcal{A}(\mathbb{E}^m)(\Delta)$ is not possible since the localized classical Blanchfield form is non-singular and $\mathcal{A}(\mathbb{E}^m)(\Delta) \neq 0$. Thus $P = 0$, so $i \circ j_*$ is injective.

It only remains to show that the lower map $k_*$ is injective (actually an isomorphism). Since localization is an exact functor, this is equivalent to showing that the inclusion map induces an isomorphism between the rational Alexander modules of $V$ and $W$. Recall that $W = W_n = V \cup E_n$. Recall from property (1) of Lemma 6.1, applied to $E_n$, that the kernel on $\pi_1$ of the inclusion $M_{K_n} = \partial V \rightarrow E_n$ is normally generated by the longitudes of the infecting knots $K_n$ and $\overline{K}_n$ as curves in $\pi_1(M_{K_n})$. These lie in the second derived subgroups of $\pi_1(S^3 - K_n)$ and $\pi_1(S^3 - \overline{K}_n)$, respectively, and so lie in the third derived subgroup of $\pi_1(M_{K_n})$ (refer to Figure 2.8). Since the rational Alexander module of any space $X$ with $H_1(X) \cong \mathbb{Z}$ may be described as $G^{(1)} / G^{(2)} \otimes \mathbb{Q}$, where $G = \pi_1(X)$, this shows that the rational Alexander modules of $V$ and $W$ are isomorphic.
The crucial base case, $i = n - 2$, in the (reverse) inductive proof of Proposition 7.4 is the following.

**Lemma 7.6.** While $\mu_{n-2} = \alpha_{n-1}$ is non-trivial, $\overline{\mu}_{n-2} = \overline{\alpha}_{n-1}$ is trivial in

$$\frac{\pi_1(W_{n-2})^{(2)}}{\pi_1(W_{n-2})^{(3)}}.$$

**Proof.** It might be helpful to refer to Figure 7.2 with $i = n - 2$. By property (1) of Lemma 6.1, the kernel of the map

$$\pi_1(W_{n-1}) \longrightarrow \pi_1(W_{n-1} \cup E_{n-1} \cup \overline{E}_{n-1}) = \pi_1(W_{n-2})$$

is normally generated by the longitudes, $\ell_{n-2}, \overline{\ell}_{n-2}$, of the infecting knots $K^{n-2}$ and $\overline{K}^{n-2}$ viewed as curves in $S^3 \setminus K^{n-2} \subset M_{K^{n-1}} \subset \partial W_{n-1}$ and $S^3 \setminus \overline{K}^{n-2} \subset M_{\overline{K}^{n-1}} \subset \partial W_{n-2}$. But of course these lie in the second derived subgroups of $\pi_1(S^3 \setminus K^{n-2})$ and $\pi_1(S^3 \setminus \overline{K}^{n-2})$, respectively, and so lie in the second derived subgroups of $\pi_1(M_{K^{n-1}})$ and $\pi_1(M_{\overline{K}^{n-1}})$, respectively. But, as observed in Lemma 7.5

$$\pi_1(M_{K^{n-1}}) = \langle \mu_{n-1} \rangle \subset \pi_1(W_{n-1})^{(1)},$$

and similarly for $\pi_1(M_{\overline{K}^{n-1}})$. It follows that both $\ell_{n-2}$ and $\overline{\ell}_{n-2}$ lie the third derived subgroup of $\pi_1(W_{n-1})$ and hence lie in $\pi_1(W_{n-1})^{(3)}$. Thus the inclusion $W_{n-1} \rightarrow W_{n-2}$ induces an isomorphism

$$\frac{\pi_1(W_{n-1})}{\pi_1(W_{n-1})^{(3)}} \cong \frac{\pi_1(W_{n-2})}{\pi_1(W_{n-2})^{(3)}},$$

by weak functoriality and by [10, Proposition 4.7].

Therefore, to prove Lemma 7.6, it suffices to let $\pi = \pi_1(W_{n-1})$, and show that $\alpha_{n-1}$ is non-trivial in $\pi^{(2)}/\pi^{(3)}$ and that $\overline{\alpha}_{n-1}$ is trivial in $\pi^{(2)}/\pi^{(3)}$. Throughout the rest of the proof of Lemma 7.6, we abbreviate $W = W_{n-1}$, $\pi = \pi_1(W_{n-1})$, $J = K^{n-1}$ and $\overline{J} = \overline{K}^{n-1}$. Thus $\partial W = M_{\partial W} \cup M_{J} \cup M_{\overline{J}}$.

Consider the following commutative diagram (which we justify below), where $\Gamma = \pi/\pi_S^{(2)}$ and $\mathcal{R} = \mathbb{Q}\Gamma S_2^{\mathcal{R}}$. Since we may view $\alpha_{n-1} \in \pi_1(M_J)^{(1)}$ and $\overline{\alpha}_{n-1} \in \pi_1(M_{\overline{J}})^{(1)}$, we have reduced Lemma 7.6 to showing that $\alpha_{n-1}$ is not in the kernel of the top row of the diagram while $\overline{\alpha}_{n-1}$ does lie in this kernel.

$$\pi_1(M_J)^{(1)} \oplus \pi_1(M_{\overline{J}})^{(1)} \xrightarrow{j_*} \pi^{(2)} \xrightarrow{\phi} \frac{\pi_S^{(2)}}{\pi_S^{(3)}}$$

$$\downarrow \pi \downarrow$$

$$(\mathcal{A}(J) \oplus \mathcal{A}(\overline{J})) \otimes \mathcal{R} \xrightarrow{\cong} H_1(M_J \cup M_{\overline{J}}; \mathcal{R}) \xrightarrow{j_*} H_1(W; \mathcal{R}) \xrightarrow{\cong} \frac{\pi_S^{(2)}}{[\pi_S^{(2)}, \pi_S^{(2)}]} \otimes \mathcal{R}$$

The $j_*$ in the upper row of the diagram is justified by our observation (7.8), which says that $\pi_1(M_J) \subset \pi^{(1)}$ and $\pi_1(M_{\overline{J}}) \subset \pi^{(1)}$. Now we consider the first map in the bottom row. By Lemma 7.5 the coefficient system $\pi \rightarrow \Gamma$, when restricted to $\pi_1(M_J)$, is non-trivial:

$$\pi_1(M_J) = \langle \mu_{n-1} \rangle \hookrightarrow \frac{\pi^{(1)}}{\pi_S^{(2)}} \hookrightarrow \frac{\pi^{(2)}}{\pi_S^{(2)}} \equiv \Gamma,$$
but also factors through \( \pi_1(M_J)/\pi_1(M_J)^{(1)} \cong \mathbb{Z} \) using (7.8). It follows that
\[
H_1(M_J; \mathbb{Q} \Gamma) \cong H_1(M_J; \mathbb{Q}[t, t^{-1}]) \otimes \mathbb{Q} \Gamma \cong \mathcal{A}(J) \otimes \mathbb{Q}[t, t^{-1}] \mathbb{Q} \Gamma,
\]
where \( \mathbb{Q}[t, t^{-1}] \) acts on \( \mathbb{Q} \Gamma \) by \( t \to \mu_{n-1} \) (equivalently \( t \to \eta_1 \)). Hence
\[
H_1(M_J; \mathcal{R}) \cong \mathcal{A}(J) \otimes \mathcal{R};
\]
and similarly for \( \overline{J} \), where \( t \) acts by \( \overline{\mu}_{n-1} = \eta_2 \). This explains the first map in the lower row of the diagram. To justify the last map in the lower row, recall that \( H_1(W; \mathbb{Z} \Gamma) \) has an interpretation as the first homology module of the \( \Gamma \)-covering space of \( W \). The fundamental group of this covering space is the kernel of \( \pi \to \Gamma \). Hence
\[
H_1(W; \mathbb{Z} \Gamma) \cong \frac{\pi_2(\mathbb{Q} \Gamma)}{[\pi_2(\mathbb{Q} \Gamma), \pi_2(\mathbb{Q} \Gamma)]}.
\]
Since the Ore localization \( \mathcal{R} \) is a flat \( \mathbb{Z} \Gamma \)-module, the \( \cong \) is justified. This completes the explanation of the diagram. Since, by Definitions 3.7 and 7.1,
\[
\pi_3^{(3)} = \ker \left( \frac{\pi_2(\mathbb{Q} \Gamma)}{[\pi_2(\mathbb{Q} \Gamma), \pi_2(\mathbb{Q} \Gamma)]} \right) \to \frac{\pi_2(\mathbb{Q} \Gamma)}{[\pi_2(\mathbb{Q} \Gamma), \pi_2(\mathbb{Q} \Gamma)]} \otimes \mathbb{Q} \Gamma S_2^{-1},
\]
it follows that the vertical map \( j \) (in the diagram) is injective. Hence, to establish Lemma 7.6, it suffices to show that the class represented by \( \alpha_{n-1} \otimes 1 \) is not in the kernel of the bottom row of the diagram while that represented by \( \overline{\alpha}_{n-1} \otimes 1 \) does lie in this kernel.

Recall that \( \overline{J} \equiv \overline{\mathbb{K}}^{n-1} = \overline{\mathbb{K}}^{n-1}_{\overline{\alpha}_{n-1}}(\overline{\mathbb{K}}^{n-2}) \), where \( \overline{\alpha}_{n-1} \) generates \( \mathcal{A}(\overline{\mathbb{K}}^{n-1}) \) (note that this implies that the latter module is cyclic). Therefore \( \mathcal{A}(\overline{J}) \cong \mathcal{A}(\overline{\mathbb{K}}^{n-1}) \). By hypothesis, the Alexander polynomial of \( \mathbb{K}^{n-1} \) is \( q_{n-1}(t) = p_2(t) \). Thus
\[
\langle \overline{\alpha}_{n-1} \rangle \cong \mathcal{A}(\overline{J}) \cong \frac{\mathbb{Q}[t, t^{-1}]}{p_2(t) \mathbb{Q}[t, t^{-1}]}
\]
and
\[
\langle \overline{\alpha}_{n-1} \otimes 1 \rangle \cong \mathcal{A}(\overline{J}) \otimes \mathcal{R} \cong \left( \frac{\mathbb{Q} \Gamma}{p_2(\eta_2) \mathbb{Q} \Gamma} \right) S_2^{-1} \cong 0,
\]
where the last equality holds since \( p_2(\eta_2) \in S_2 \), by Definition 7.1 (see [10, Theorem 4.12] for more detail). Therefore \( \overline{\alpha}_{n-1} \otimes 1 \) lies in the kernel of the bottom row of the diagram.

Suppose that \( \alpha_{n-1} \otimes 1 \) were in the kernel of the bottom row of the diagram. We shall reach a contradiction. Recall that \( W_{n-1} \equiv V \cup E_n \). Recall that \( V \) is an \((n, 5, \mathcal{P})\)-solution. Since \( n \geq 2 \), \( V \) is a \((2, \mathcal{P})\)-solution. One easily checks that
\[
\frac{H_2(W_{n-1})}{i_*(H_2(\partial W_{n-1}))} \cong H_2(V).
\]
Hence this group has a basis consisting of surfaces that satisfy parts (2) and (3) of Definition 3.3 (with \( n = 2 \)); but \( W_{n-1} \) fails to satisfy part (1) of that definition and \( \partial W_{n-1} \) is disconnected. Such a manifold was named a \((2, \mathcal{P})\)-bordism in [10, Definition 7.11]. By [10, Theorems 7.14 and 7.15], if \( P \) is the kernel of the map
\[
j^* : H_1(M_J; \mathcal{R}) \to H_1(W; \mathcal{R}),
\]
as in the bottom row of the diagram, then \( P \) is an isotropic submodule for the Blanchfield linking form on \( H_1(M_J; \mathcal{R}) \). Since we have supposed that \( \alpha_{n-1} \otimes 1 \in P \) and since this element is a generator of \( H_1(M_J; \mathcal{R}) \), it would follow that this Blanchfield form was identically zero on \( H_1(M_J; \mathcal{R}) \); but by [10, Lemma 7.16] this form is non-singular. This would imply that \( H_1(M_J; \mathcal{R}) \) was the zero module. This is a contradiction once we show that
\[
\mathcal{A}(J) \otimes \mathcal{R} \cong \left( \frac{\mathbb{Q} \Gamma}{p_2(\eta_1) \mathbb{Q} \Gamma} \right) S_2^{-1} \neq 0.
\]
This is a non-trivial result since we are dealing with a non-commutative localization.

Note that, by the hypotheses of Theorem 5.5, $p_2(t) = q_{a-1}(t)$ is not a unit in $\mathbb{Q}[t, t^{-1}]$. The map $\mathbb{Z} \to \Gamma$ given by $t \to \eta_1$ is not zero by Lemma 7.5. Since $\Gamma$ is PTFA, it is torsion-free, so $\langle \eta_1 \rangle \subset \Gamma$. Hence $\mathbb{Q}\Gamma$ is a free left $\mathbb{Q}[\eta_1, \eta_1^{-1}]$-module on the right cosets of $\langle \eta_1 \rangle \in \Gamma$ [44, Chapter 1, Lemma 1.3]. Thus, upon fixing a set of coset representatives, any $x \in \mathbb{Q}\Gamma$ has a unique decomposition

$$x = \Sigma_{\gamma} x_{\gamma}\gamma,$$

where $x_{\gamma} \in \mathbb{Q}[\eta_1, \eta_1^{-1}]$ and the sum is over a set of coset representatives $\{\gamma \in \Gamma\}$. It follows that $p_2(\eta_1)$ has no right inverse in $\mathbb{Q}\Gamma$ since if $p_2(\eta_1)x = 1$, then

$$p_2(\eta_1)x = p_2(\eta_1)\Sigma_{\gamma} x_{\gamma}\gamma = \Sigma_{\gamma} p_2(\eta_1)x_{\gamma}\gamma = 1.$$

Looking at the coset $\gamma = 1$, we have $p_2(\eta_1)x_e = 1$ in $\mathbb{Q}[\eta_1, \eta_1^{-1}]$, contradicting the fact that $p_2(t)$ is not a unit in $\mathbb{Q}[t, t^{-1}]$. Therefore, since $\mathbb{Q}\Gamma$ is a domain,

$$\frac{\mathbb{Q}\Gamma}{p_2(\eta_1)\mathbb{Q}\Gamma} \neq 0.$$

Continuing, by [47, Corollary 3.3, p. 57], the kernel of

$$\frac{\mathbb{Q}\Gamma}{p_2(\eta_1)\mathbb{Q}\Gamma} \rightarrow \left( \frac{\mathbb{Q}\Gamma}{p_2(\eta_1)\mathbb{Q}\Gamma} \right) S_2^{-1}$$

is precisely the $S_2$-torsion submodule. Hence to establish (7.9), it suffices to show that the generator of $\mathbb{Q}\Gamma/p_2(\eta_1)\mathbb{Q}\Gamma$ is not $S_2$-torsion. Suppose $[1] = 0$, implying that $\mathbb{Q}\Gamma/p_2(\eta_1)\mathbb{Q}\Gamma$ is $S_2$-torsion-free. If $[1]$ were $S_2$-torsion, then $1 = p_2(\eta_1)y$ for some $y \in \mathbb{Q}\Gamma$. We examine this equation in $\mathbb{Q}\Gamma$.

Recall that $\Gamma = \pi/\pi_S(2)$. Let $A = \pi(1)/\pi_S(2) < \Gamma$. Since $A \subset \Gamma$, $\mathbb{Q}\Gamma$, viewed as a left $\mathbb{Q}A$-module, is free on the right cosets of $A$ in $\Gamma$. Thus any $y \in \mathbb{Q}\Gamma$ has a unique decomposition

$$y = \Sigma_{\gamma} y_{\gamma}\gamma,$$

where the sum is over a set of coset representatives $\{\gamma \in \Gamma\}$ and $y_{\gamma} \in \mathbb{Q}A$. Therefore we have

$$s = p_2(\eta_1)\Sigma_{\gamma} y_{\gamma}\gamma.$$

Recall from Definition 7.1 that $s \in S_2 \subset \mathbb{Q}A$. It follows that, for each coset representative $\gamma \neq 1$, we have $0 = p_2(\eta_1)y_{\gamma}$, so $y_{\gamma} = 0$ (note that $p_2(\eta_1) \neq 0$ since $\mathbb{Q}[\eta_1^{\pm 1}] \subset \mathbb{Q}\Gamma$). Hence $y \in \mathbb{Q}A$ and we have

$$s = p_2(\eta_1)y$$

(7.10)
as an equation in $\mathbb{Q}A$. Recall from Definition 7.1 that an arbitrary element of $S_2$ is a product of terms of the form $q(a)$ and terms of the form $p_2(\mu^i\eta_2\mu^{-i})$ for some $a \in A$, $q(t)$ in $\mathbb{Q}[t, t^{-1}]$, where $(p_2, q) = 1$, $q(1) \neq 0$ and $\mu$ generates $\pi/\pi^{(1)}$. Since $A$ is a torsion-free abelian group, (7.10) may be viewed as an equation in $\mathbb{Q}F$ for some free abelian group $F \subset A$ of finite rank $r$. Since $\mathbb{Q}F$ is a UFD and since $(p_2, q) = 1$, we can apply the following.

**Proposition 7.7 [10, Proposition 4.5].** Suppose $p(t), q(t) \in \mathbb{Q}[t, t^{-1}]$ are non-zero. Then $p$ and $q$ are strongly coprime if and only if, for any finitely-generated free abelian group $F$ and any non-trivial $a, b \in F$, $p(a)$ is relatively prime to $q(b)$ in $\mathbb{Q}F$ (a unique factorization domain).

Thus the greatest common divisor, in $\mathbb{Q}F$, of $p_2(\eta_1)$ and $q(a)$ is a unit (note that if $a$ is trivial in $F$, then $q(a) = q(1) \neq 0$ is itself a unit). Thus $p_2(\eta_1)$ divides the product of the terms of the form $p_2(\mu^i\eta_2\mu^{-i})$. Choose a basis $\{x, x_2, \ldots, x_r\}$ for $F$ in which $\eta_1 = x^r$ for some $r > 0$
\( \text{(since } \eta_1 \neq 0 \text{ by Lemma 7.5) and } \mu^i \eta_2 \mu^{-i} = x^{n_i} x_2^{n_2} \ldots x_r^{n_r}. \text{ Then we may regard } \mathbb{Q} \mathbb{F} \text{ as a Laurent polynomial ring in the variables } \{x, x_2, \ldots, x_r\}. \text{ Since } p_2 \text{ is not zero and not a unit, there exists a non-zero complex root } x = \tau \text{ of } p_2(x^i). \text{ Suppose that } \tilde{p}(x) \text{ is an irreducible factor (in } \mathbb{Q} \mathbb{F}) \text{ of } p_2(x^i) \text{ of which } \tau \text{ is a root. Then, for some } i, \text{ } \tilde{p}(x) \text{ divides } p_2(x^n x_2^{n_2} \ldots x_r^{n_r}). \text{ Then } \tau \text{ must be a zero of } p_2(x^n x_2^{n_2} \ldots x_r^{n_r}) \text{ for every complex value of } x_2, \ldots, x_r. \text{ This is impossible unless each } n_{i,j} = 0. \text{ Thus, for this value of } i, \mu^i \eta_2 \mu^{-i} = x^n, \text{ in } \mathbb{F}, \text{ for some } n. \text{ Note that } n \neq 0 \text{ since } \eta_2 \text{ is non-trivial by Lemma 7.5. Thus}
\]
\[
\mu^i \eta_2 \mu^{-i} = (\mu^i \eta_2 \mu^{-i})^r = x^{nr} = \eta_1^n, \tag{7.11}
\]

for some \( i \) and some non-zero integers \( n \) and \( r \). This equation holds in \( A \). However, the circles \( \mu, \eta_2 \) and \( \eta_1 \) all live in \( M_{9\mathbb{m}} \) and in fact can be interpreted in \( A^2(\mathbb{F}^m) \) (the left-hand copy of \( \mathbb{E}^m \)); but recall that in the proof of Lemma 7.5 we showed that the map

\[
A^2(\mathbb{F}^m) \longrightarrow A^2(W) \longrightarrow \pi_2^2(\mathbb{S}) \equiv A
\]

is injective. Hence if (7.11) holds in \( A \), then it holds as an equation in \( A^2(\mathbb{F}^m) \), and hence also in \( A(\mathbb{E}^m) \), where, in module notation, it has the form

\[
(t_*)^i(r \eta_2) = n \eta_1.
\]

However, the simple computation in the following lemma proves that this is impossible.

**Lemma 7.8.** Let \( m \) be a non-zero integer, let \( \mathbb{E}^m \) be the knot of Figure 2.5 and let \( \langle \eta_i \rangle, \ i = 1, 2 \) be the subspace of \( A(\mathbb{E}^m) \) generated by the circle \( \eta_i \) shown in Figure 2.9. Then, under the automorphism

\[
t_* : A(\mathbb{E}^m) \longrightarrow A(\mathbb{E}^m),
\]

for every integer \( k \), \((t_*)^k(\eta_2)) \cap \langle \eta_1 \rangle = \emptyset.

**Proof.** We may assume that \( m > 0 \). If \( V \) is the Seifert matrix for \( \mathbb{E}^m \) as in the proof of Proposition 2.3, with respect to the basis \( \{a_i\} \) consisting of the cores of the obvious bands, where \( \ell(k(a_i, \eta_j)) = 1 \), then the rational Alexander module is presented by \( V - tV^T \) with respect to the basis \( \{\eta_1, \eta_2\} \), where the relations are given by the columns, that is, \( (V - tV^T)\vec{v} = 0 \) for all \( \vec{v} \). Since \( V \) has non-zero determinant, upon left multiplying the latter equation by \( V^{-1} \), one recovers the fact that the automorphism \( t^* \) is given by left multiplication by \( (V^{-1})^T V \). Hence

\[
t^* = \frac{1}{m^2} \begin{pmatrix} m^2 + 1 & m \\ m & m^2 \end{pmatrix} = \frac{1}{m^2} M,
\]

for \( M \) as indicated, with respect to the basis \( \{\eta_1, \eta_2\} \). It then suffices to prove that, for any \( k \), there is no non-zero solution \((x_0, y_0)\) to the equation

\[
M^k \begin{pmatrix} 0 \\ y_0 \end{pmatrix} = \begin{pmatrix} x_0 \\ 0 \end{pmatrix}.
\]

If there were such a solution \((x_0, y_0)\), then there would be one with \( y_0 > 0 \). Let \( B = \{(x, y) \mid x \geq 0, \ y > 0\} \). Since

\[
\begin{pmatrix} m^2 + 1 & m \\ m & m^2 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} (m^2 + 1)x + my \\ mx + m^2 y \end{pmatrix},
\]

we observe that \( M(B) \subset B \); but if \( k \geq 0 \), then \( M^k(B) \subset B \). This is a contradiction since \((0, y_0) \in B \) but \((x_0, 0) \notin B \). Therefore there is no non-zero solution if \( k \geq 0 \). If \( k < 0 \), then we
have
\[
\begin{pmatrix} 0 \\ y_0 \end{pmatrix} = M^{-k} \begin{pmatrix} x_0 \\ 0 \end{pmatrix},
\]
where \(-k = s > 0\). As above if there were a non-zero solution, then there would be one with \(x_0 > 0\). Letting \(A = \{(x, y) \mid x > 0, \ y \geq 0\}\), we observe that \(M^s(A) \subset A\), \((x_0, 0) \in A\) and \((0, y_0) \notin A\), which is a contradiction. \(\square\)

This contradiction establishes \((7.9)\), finally completing the proof of Lemma 7.6. \(\square\)

We now complete the induction step in the proof of Proposition 7.4. Suppose, for some \(i\), \(1 \leq i \leq n - 2\), that Proposition 7.4 holds, that is, \(\mu_i = \alpha_{i+1}\) is non-trivial, while \(\overline{\mu}_i = \overline{\alpha}_{i+1}\) is trivial in
\[
\frac{\pi_1(W_i)^{(n-i)}}{\pi_1(W_i)^{(n-i+1)}}. \tag{7.12}
\]
To complete the inductive step, we need to show that
\[
\overline{\mu}_{i-1} = \overline{\alpha}_i = 0 \in \frac{\pi_1(W_{i-1})^{(n-i+1)}}{\pi_1(W_{i-1})^{(n-i+2)}}, \tag{7.13}
\]
and show that
\[
\mu_{i-1} = \alpha_i \neq 0 \in \frac{\pi_1(W_{i-1})^{(n-i+1)}}{\pi_1(W_{i-1})^{(n-i+2)}}. \tag{7.14}
\]
By the inductive hypothesis and weak functoriality,
\[
\overline{\mu}_i \in \pi_1(W_i)^{(n-i+1)} \subset \pi_1(W_{i-1})^{(n-i+1)}.
\]
However, by property (1) of Lemma 6.1, \(\overline{\mu}_i \in \pi_1(M_{K^i})\) normally generates \(\pi_1(E_i)\), so
\[
\pi_1(E_i) \subset \pi_1(W_{i-1})^{(n-i+1)}_S,
\]
and so by property (1) of Proposition 3.2,
\[
[\pi_1(E_i), \pi_1(E_i)] \subset [\pi_1(W_{i-1})^{(n-i+1)}_S, \pi_1(W_{i-1})^{(n-i+1)}_S] \subset \pi_1(W_{i-1})^{(n-i+2)}_S.
\]
Since \(\ell_k(\overline{\alpha}_i, K^i) = 0\), we have
\[
\overline{\alpha}_i \in [\pi_1(M_{K^i}), \pi_1(M_{K^i})] \subset [\pi_1(E_i), \pi_1(E_i)] \subset \pi_1(W_{i-1})^{(n-i+2)}_S.
\]
This proves \((7.13)\).

Now we need to prove \((7.14)\). By property (1) of Lemma 6.1, the kernel of the map
\[
\pi_1(W_i) \to \pi_1(W_i \cup E_i \cup E_i) = \pi_1(W_{i-1})
\]
is normally generated by the longitudes \(\ell_{i-1}\) and \(\tilde{\ell}_{i-1}\) of the infecting knots \(K^{i-1}\) and \(K^{i-1}\) viewed as curves in \(S^3 \setminus K^{i-1} \subset M_{K^i} \subset \partial W_i\), respectively. But of course these lie in the second derived subgroups of \(\pi_1(S^3 \setminus K^{i-1})\) and \(\pi_1(S^3 \setminus K^{i-1})\), respectively, and so lie in the second derived subgroups of \(\pi_1(M_{K^i})\) and \(\pi_1(M_{K^i})\), respectively. However, by the induction hypothesis \((7.12)\),
\[
\pi_1(M_{K^i}) = \langle \mu_i \rangle \subset \pi_1(W_i)^{(n-i)}_S, \tag{7.15}
\]
and similarly for \(\pi_1(M_{K^i})\). It follows that both \(\ell_{i-1}\) and \(\tilde{\ell}_{i-1}\) lie in
\[
\pi_1(W_i)^{(n-i+2)} \subset \pi_1(W_i)^{(n-i+2)}_S.
\]
Thus the inclusion $W_i \rightarrow W_{i-1}$ induces an isomorphism
\[
\pi_1(W_i)_{S}^{(n-i+1)} \cong \pi_1(W_{i-1})_{S}^{(n-i+1)}
\]
by weak functoriality and by [10, Proposition 4.7].

Consequently, to establish (7.14), it suffices to let $\pi = \pi_1(W_i)$, and show that $\alpha_i$ is non-trivial in $\pi^{(n-i+1)}/\pi_{S}^{(n-i+2)}$. Throughout the rest of the proof, we abbreviate $W = W_i$, $\pi = \pi_1(W_i)$, $J = K^i$ and $\mathcal{T} = \mathcal{T}_J^i$. Thus $M_J \subset \partial W$.

Consider the following commutative diagram (which we justify below), where $\Gamma = \pi/\pi_{S}^{(n-i+1)}$ and $\mathcal{R} = \mathfrak{Q}\mathfrak{G}\mathcal{S}_{n-i+1}^{-1}$. Since $\alpha_i \in \pi_1(M_J)^{(1)}$, we have reduced (7.14) to showing that $\alpha_i$ is not in the kernel of the top row of the diagram.

\[
\begin{array}{ccc}
\pi_1(M_J)^{(1)} & \xrightarrow{j_*} & \pi^{(n-i+1)} \\
\pi & \xrightarrow{} & \pi^{(n-i+1)} \\
\mathcal{A}(J) \otimes \mathcal{R} & \cong & H_1(M_J; \mathcal{R}) \\
\end{array}
\]

The $j_*$ in the upper row of the diagram is justified by (7.15). Now we consider the first map in the bottom row. By the inductive hypothesis (7.14) the coefficient system $\pi \rightarrow \Gamma$, when restricted to $\pi_1(M_J)$, is non-trivial:
\[
\pi_1(M_J) = \langle \mu_i \rangle \subseteq \frac{\pi_{S}^{(n-i+1)}}{\pi_{S}^{(n-i+1)}} \cong \Gamma,
\]
but also factors through $\pi_1(M_J)/\pi_1(M_J)^{(1)} \cong \mathfrak{Z}$ because of (7.15). It follows that
\[
H_1(M_J; \mathcal{Q}\Gamma) \cong H_1(M_J; \mathcal{Q}[t, t^{-1}]) \otimes \mathcal{Q}\Gamma \equiv \mathcal{A}(J) \otimes_{\mathcal{Q}[t, t^{-1}]} \mathcal{Q}\Gamma,
\]
where $\mathcal{Q}[t, t^{-1}]$ acts on $\mathcal{Q}\Gamma$ by $t \rightarrow \mu_i$. Hence
\[
H_1(M_J; \mathcal{R}) \cong \mathcal{A}(J) \otimes \mathcal{R}.
\]

To justify the last map in the lower row, recall that $H_1(W; \mathcal{Z}\Gamma)$ has an interpretation as the first homology module of the $\Gamma$-covering space of $W$ corresponding to the kernel of $\pi \rightarrow \Gamma$. Hence
\[
H_1(W; \mathcal{Z}\Gamma) \cong \left. \frac{\pi_{S}^{(n-i+1)}}{\mathcal{Q}\mathfrak{G}\mathfrak{S}_{n-i+1}^{-1}} \right|_{\langle \mu_i \rangle} = \frac{\pi_{S}^{(n-i+1)}}{\pi_{S}^{(n-i+1)}, \pi_{S}^{(n-i+1)}} \otimes \mathcal{Q}\mathfrak{G}\mathfrak{S}_{n-i+1}^{-1}.
\]

This completes the explanation of the diagram. Since, by Definitions 3.7 and 7.1,
\[
\pi_{S}^{(n-i+2)} = \ker \left( \frac{\pi_{S}^{(n-i+1)}}{\mathcal{Q}\mathfrak{G}\mathfrak{S}_{n-i+1}^{-1}} \right) \cong \frac{\mathcal{Q}\Gamma}{\mathcal{P}_{n-i+1}^{(\mu_i)} \mathcal{Q}\Gamma} \mathcal{S}_{p_{n-i+1}}^{-1}.
\]

Recall that $J = K^i \equiv R_i^k$, $K^{i-1}$, where $\alpha_i$ generates $\mathcal{A}(R_i)$. Therefore $\mathcal{A}(J) \cong \mathcal{A}(R_i)$. By the hypotheses of Theorem 5.5, the Alexander polynomial of $R_i$ is $q_i(t) = p_{n-i+1}(t)$. Thus
\[
\langle \alpha_i \otimes 1 \rangle \cong \mathcal{A}(J) \otimes \mathcal{R} \cong \left( \frac{\mathcal{Q}\Gamma}{\mathcal{P}_{n-i+1}(\mu_i) \mathcal{Q}\Gamma} \right) \mathcal{S}_{p_{n-i+1}}^{-1}.
\]

The last equality holds because, since $1 \leq i \leq n - 2$, it follows that $3 \leq n - i + 1 \leq n$, so $S_{n-i+1} = S_{p_{n-i+1}}$, by Definition 7.1.
Suppose that $\alpha_i \otimes 1$ were in the kernel of the bottom row of the diagram. We shall reach a contradiction. Recall that

$$W = W_i \equiv V \cup E_n \cup E_{n-1} \cup E_{n-1} \cup \ldots \cup E_{i+1} \cup E_{i+1}.$$  

Recall also that $V$ is an $(n, 5, \mathcal{P})$-solution. Thus, by (7.6), $V$ is an $(n, 5, S)$-solution and, since $n - i + 1 \leq n$, $V$ is also an $(n - i + 1, S)$-solution. One easily checks that

$$\frac{H_2(W_i)}{i_* (H_2(\partial W_i))} \cong H_2(V).$$

Hence this group has a basis consisting of surfaces that satisfy parts (2) and (3) of Definition 3.3 (with $n - i + 1$). Thus $W_i$ is an $(n - i + 1, S)$-bordism (see [10, Definition 7.11]). By [10, Theorems 7.14 and 7.15], if $P$ is the kernel of the map

$$j_* : H_1(M; R) \rightarrow H_1(W; R),$$

then $P$ is isotropic for the Blanchfield linking form on $H_1(M; R)$. Therefore if the generator $\alpha_i \otimes 1$ were in $P$, it would follow that this Blanchfield form was identically zero on $H_1(M; R)$; but by [10, Lemma 7.16] this form is non-singular. This would imply that $H_1(M; R) = 0$. This is a contradiction once we show that (7.16) is in fact a non-trivial module. It is shown in [10, Theorem 4.12] that

$$\frac{\mathbb{Q}^\Gamma}{\Gamma} \left( \frac{\mathbb{Q}^\Gamma}{\Gamma} \right)^{-1} \left( \frac{\mathbb{Q}^\Gamma}{\Gamma} \right) S_{p_n-i+1},$$

is a monomorphism (using that $p_{n-i+1}(t) \neq 0$ and that $\mu_i$ lies in the abelian normal subgroup $A = \pi^{(n-i)/2}(n-i+1) \subset \Gamma$). This reduces us to showing that

$$\frac{\mathbb{Q}^\Gamma}{\Gamma} \left( \frac{\mathbb{Q}^\Gamma}{\Gamma} \right)^{-1} \left( \frac{\mathbb{Q}^\Gamma}{\Gamma} \right) \neq 0.$$  

(7.18)

By the hypotheses of Theorem 5.5, $p_{n-i+1}(t) = q_i(t)$ is not a unit. The map $Z \rightarrow \Gamma$ given by $t \mapsto \mu_i$ is not zero by the inductive hypothesis (7.12). Thus $\langle \mu_i \rangle \subset \Gamma$ and $\mathbb{Q}^\Gamma$ is a free $\mathbb{Q}[\mu_i, \mu_i^{-1}]$-module on the cosets of $\langle \mu_i \rangle \subset \Gamma$. In the same manner as we showed earlier in the proof, it follows that $p_{n-i+1}(\mu_i)$ is not a unit in the domain $\mathbb{Q}^\Gamma$. Therefore (7.18) holds.

This completes, finally, the inductive step and hence the entire proof of Proposition 7.4, which in turn completes the proofs of (7.2) and (7.3).

Having established (7.1)–(7.3), the proof of Theorem 5.5 is complete.

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