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**EXCEPTIONAL DEHN SURGERY
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YING-QING WU

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YING-QING WU

A Dehn surgery on a knot K in S^3 is exceptional if it produces a reducible, toroidal or Seifert fibered manifold. It is known that a large arborescent knot admits no such surgery unless it is a type II arborescent knot. The main theorem of this paper shows that up to isotopy there are exactly three large arborescent knots admitting exceptional surgery, each of which admits exactly one exceptional surgery, producing a toroidal manifold.

1. Introduction

A Conway sphere for a knot K in S^3 is a sphere S that intersects K at 4 points in such a way that the punctured sphere $S - K$ is incompressible in $S^3 - K$. In this case the sphere S cuts (S^3, K) into two nonsplittable tangles (B_1, τ_1) and (B_2, τ_2) , where B_i is a 3-ball, and the τ_i are pairs of properly embedded arcs in B_i . An arborescent knot is obtained by gluing rational tangles together in various ways. (See, for example, [Wu 1996b] or [Gabai 1986]). An arborescent knot K is *large* if it has a Conway sphere. It is known [Hatcher and Thurston 1985; Oertel 1984; Wu 1996b] that K is large if and only if its complement is large in the sense that it contains an embedded closed essential surface.

A nontrivial Dehn surgery on a hyperbolic knot K in S^3 is *exceptional* if the resulting manifold is either reducible, toroidal, or a small Seifert fiber space. By the Geometrization Conjecture proved by Perelman, nonexceptional surgeries yield hyperbolic manifolds. Thurston [1979] showed that a hyperbolic knot admits only finitely many exceptional surgeries.

All large arborescent knots are hyperbolic. It is known that most large arborescent knots admit no exceptional surgery. Define $T(r, s)$ to be a Montesinos tangle that is the sum of two rational tangles associated to rational numbers r and s . (See Section 2 for more details.) A knot K is an arborescent knot of type II if it has a Conway sphere cutting it into two Montesinos tangles of type $T(r_i, \frac{1}{2})$. It was shown in [Wu 1996b, Theorem 3.6] that if a large arborescent knot K is not of type II, then all nontrivial surgeries on K are Haken and hyperbolic, so

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there is no exceptional surgery on K . When K is an arborescent knot of type II, all nonintegral surgeries are Haken and hyperbolic, and all integral surgeries are laminar in the sense that the resulting manifolds contain essential laminations; in particular, it is irreducible. It remains to determine which type II knots admit integer surgeries producing toroidal or Seifert fibered manifolds. The following is our main theorem, which determines all such knots and the exceptional surgeries on them. The knot K_1 in the theorem is given in Figure 2(b) on page 224. K_3 is actually the mirror image of K_1 , so there are essentially only two knots up to homeomorphism of (S^3, K) . K_2 is obtained from K_1 by changing crossings on the right half of the diagram of K_1 in Figure 2(b).

Theorem 1.1. *Let K_1, K_2, K_3 be the three knots just described (see Definition 2.3 for details). Let K be a large arborescent knot in S^3 , and let δ be a nonmeridional slope on $\partial N(K)$. Then $K(\delta)$ is an exceptional surgery if and only if (K, δ) is isotopic to $(K_1, 3)$, $(K_2, 0)$ or $(K_3, -3)$, in which case $K(\delta)$ is toroidal.*

The essential punctured torus F constructed in the exterior of the knots K has four boundary components, and that is minimal; see Lemma 6.2 and Proposition 5.8 below. The referee pointed out that this is an interesting fact, since there are few examples of classes of knots with such a property. Some examples were given by Eudave-Muñoz [1997] and others, more recently, by Teragaito [2008]. Those were constructed via double branched covers and the punctured torus was not explicitly described in the knot exterior. The examples constructed in this paper are perhaps the simplest known knots whose exterior contains such a punctured torus F , and F is explicitly constructed. We would like to thank the referee for this as well as some other helpful comments.

The paper is organized as follows. In Section 2 we define some special disks in rational tangle spaces. These are the pieces that will be used to build the toroidal surfaces in the exteriors of the knots in Theorem 1.1. Section 3 defines an index $i(G, Q)$ for a surface G relative to Q , and proves its additivity and some other properties. Now let K be a type II knot, which is the union of two Montesinos tangles $T_i = T(r_i, \frac{1}{2})$. Let F be a punctured essential torus in the exterior of K with integer boundary slope, and let F_i be the intersection of F with the tangle space of T_i . The important fact is that F can be chosen so that each component G of F_i must have zero index relative to the tube around the unknotted string of T_i . It is then shown in Section 4 that G must be a special surface in the sense that it is the union of special disks in the two rational tangle spaces. This quickly leads to a proof that $r_i \equiv \pm \frac{1}{3} \pmod{1}$. In Section 5 we define the relative framing for a surface in a tangle space. This can be used to calculate the boundary slope of the surface $F = F_1 \cup F_2$, and to show that if F has integer boundary slope then its intersection with the punctured Conway sphere must have a very special configuration, which

completely determines the gluing map between the two tangles. It follows that if $K(\delta)$ is toroidal, then K must be one of the three knots in the theorem, and there is only one possible choice of F . In Section 6 it is shown that the surface F constructed is incompressible and ∂ -incompressible, and that it gives rise to an essential torus in the surgered manifold. This, together with some known results about surgery on type II knots, will complete the proof of Theorem 1.1.

Unless otherwise stated, a surface in a 3-manifold M is assumed to be either on the boundary of M or properly embedded in M . Given a set X in a surface or 3-manifold, denote by $N(X)$ a regular neighborhood of X , and by $|X|$ the number of components in X . If P is a surface in a 3-manifold M , denote by $M|P$ the manifold obtained by cutting M along P .

2. Special disks in tangle spaces

A tangle T is a pair (B, τ) , where B is a 3-ball with four specified points on ∂B , and $\tau = \tau_1 \cup \tau_2$ is a pair of arcs in B connecting these points. We identify B with either a pillowcase with $\partial\tau$ the four corners, or the one point compactification of the lower half-space, that is, $B = \hat{R}_-^3 = \{(x, y, z) \mid z \leq 0\} \cup \{\infty\}$, with $\partial\tau$ identified to the four points $(\pm 1, \pm 1)$ and the front side of the pillowcase identified to the square $[-1, 1] \times [-1, 1]$ in $\hat{R}^2 = R^2 \cup \{\infty\}$, which is identified to $(R^2 \times \{0\}) \cup \{\infty\} = \partial\hat{R}_-^3$.

Given a tangle $T = (B, \tau)$, let $E(T)$ be the closure of $B - N(\tau)$, called the tangle space of T . Let $S(T) = \partial B = \hat{R}^2$, and let $P(T)$ be the 4-punctured sphere $\partial B \cap E(T)$. Let $S_+(T)$ and $S_-(T)$ be the closures of the right and left half-planes of $\hat{R}^2 = \partial B$, respectively. Similarly, define $P_\pm(T) = S_\pm(T) \cap E(T)$, a twice-punctured disk. Denote by $U(T) = U_+(T) \cup U_-(T)$ the two annuli $\partial E(T) - \text{Int } P(T)$, with $U_+(T)$ the one containing the upper right component of ∂P on \hat{R}^2 . We now have a decomposition of the boundary of $E(T)$:

$$\partial E(T) = P_-(T) \cup P_+(T) \cup U_-(T) \cup U_+(T).$$

We refer the reader to [Conway 1970] or [Wu 1996a] for the definition of rational tangles. Roughly speaking, the strings τ of a rational tangle of slope $r = p/q$ are obtained by pushing into the interior of B the interior of two arcs of slope r on the boundary of the pillowcase B connecting the four corners of B . *Throughout this paper we assume that $q \geq 2$.*

Given two tangles $T_i = (B_i, \tau_i)$, we may construct a new tangle $T_1 + T_2$ by identifying the disk $S_+(T_1) \subset \hat{R}^2$ with $S_-(T_2) \subset \hat{R}^2$, using the map $(x, y) \rightarrow (-x, y)$, and then identifying $B_1 \cup B_2$ to $B = \hat{R}_-^3$ so that a boundary point of B_1 or B_2 on $\partial(B_1 \cup B_2)$ is mapped to the point with the same coordinates on $\partial B = \hat{R}^2$. Denote by $T(r_1, r_2)$ the Montesinos tangle $T(r_1) + T(r_2)$.

Two tangles T_1, T_2 are *weakly equivalent* if T_1 can be deformed to T_2 by an isotopy φ_t of B . They are *P-equivalent* if the isotopy φ_t is rel $\partial P_+(T_1)$, and *equivalent* if φ_t is rel $S(T)$. Thus, for example, $T(r)$ is *P-equivalent* to $T(r+k)$ for any integer k , and $T(\frac{1}{3}, -\frac{1}{2})$ is *P-equivalent* to $T(\frac{1}{3}, \frac{1}{2})$. Two tangles are considered the same if they are equivalent.

A surface F in $E(T)$ is *tight* if $\partial F \neq \emptyset$, and it intersects each of P_\pm and U_\pm in essential arcs or essential circles. In this case, ∂F is a set of essential loops on $\partial E(T)$. Thus a tight disk is an essential disk in $E(T)$ (that is, a compressing disk of $\partial E(T)$), and any essential disk in $E(T)$ is isotopic to a tight disk.

The strings τ in a rational tangle $T(p/q) = (B, \tau)$ are rel $\partial\tau$ isotopic to a pair of arcs $\tau' = \tau'_1 \cup \tau'_2$ on ∂B . Specifically, let τ'_2 be the one with an endpoint at $(1, 1) \in \hat{R}^2$. Let τ'_0 be a pair of horizontal arcs on R^2 connecting $\partial\tau$. Let $c_i = \tau'_i \cap P(T)$ for $i = 0, 1, 2$, and let c_3 be the curve on P that separates c_1 and c_2 , which is unique up to isotopy. Thus, for example, for $T(\frac{1}{3})$ the curves c_0, c_1, c_2 are shown in parts (1)–(3) of Figure 1, and for $T(-\frac{1}{2})$ the curves c_1, c_2, c_3 are shown in parts (4)–(6). A disk D in $E(T)$ is a special disk if its intersection with $P(T)$ is one of these curves. It is further required that $q \leq 3$ if $D \cap P(T) = c_1, c_2$, and $q = 2$ if $D \cap P(T) = c_3$. More explicitly, we have Definition 2.1, illustrated by Figure 1;

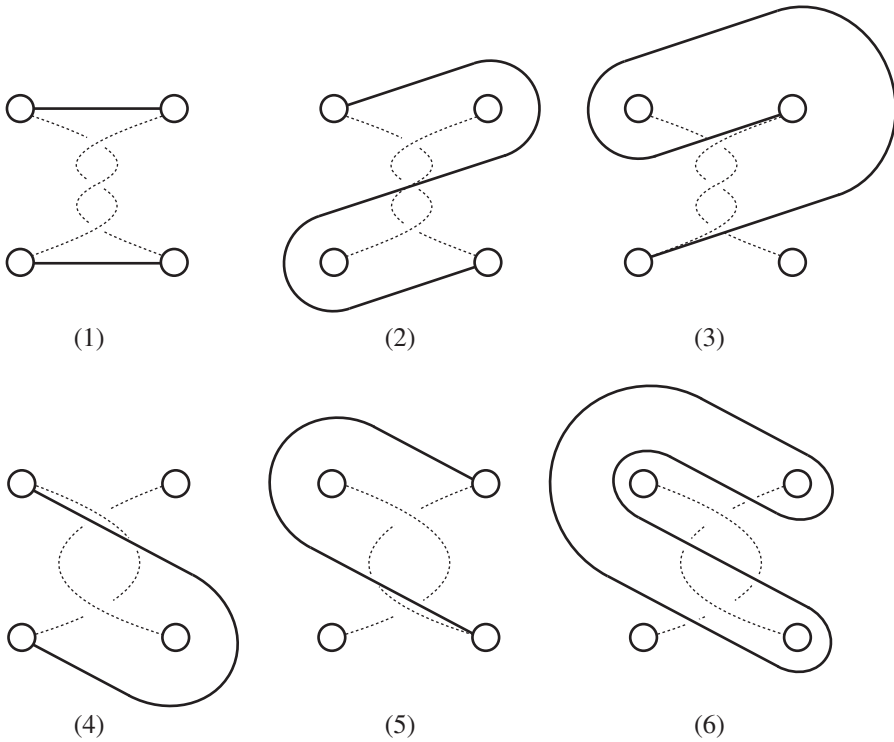


Figure 1

part (k) of the figure (with $k = 1, 2, \dots, 6$) depicts the boundary curve of a type (k) special disk.

Definition 2.1. Let $T = T(\pm 1/q)$. A disk D in $E(T)$ is a *special disk* if it is of one of the following types.

- Type (1): $T = T(\pm 1/q)$, q odd, and $D \cap P(T) = c_0$.
- Type (2): $T = T(\pm \frac{1}{3})$, and $D \cap P(T) = c_1$.
- Type (3): $T = T(\pm \frac{1}{3})$, and $D \cap P(T) = c_2$.
- Type (4): $T = T(\pm \frac{1}{2})$, and $D \cap P(T) = c_1$.
- Type (5): $T = T(\pm \frac{1}{2})$, and $D \cap P(T) = c_2$.
- Type (6): $T = T(\pm \frac{1}{2})$, and $D \cap P(T) = c_3$.

Lemma 2.2. Let $T = T(p/q)$ with $q = 2$ or odd. Let $Q = P_+(T)$ if $q \geq 3$, and $Q = P_-(T) \cup U_+(T)$ if $q = 2$. Suppose D is a tight disk in $T(p/q)$ such that $|D \cap Q| \leq 2$. Then T is P -equivalent to $T(\pm 1/q)$, and D is a special disk. In particular, Q and $Q' = \partial E(T) - \text{Int } Q$ are incompressible, and there is no disk in $E(T)$ intersecting each of Q and Q' at a single essential arc.

Proof. This is essentially [Wu 1996a, Lemmas 2.1 and 2.2]. Let $P = P_+(T)$ if $q \geq 3$, and $P = P_-(T)$ if $q = 2$. Clearly D must intersect P in a nonempty set of arcs, since otherwise we would have $T = T(\frac{1}{0})$. Since $|D \cap P| \leq 2$, D is a monogon or bigon as classified in [Wu 1996a, Lemmas 2.1 and 2.2]. When it is a monogon, D is a special disk of type (5). Bigons appear when T is a torus tangle or wrapping tangle (see [Wu 1996a] for definition), or a twist tangle; but since T is rational and q equals 2 or is odd, the first two cases do not happen. Thus, from the proof of [Wu 1996a, Lemma 2.2], we see that if D is a bigon, then it is one of the types (1), (2), (3), (4) or (6) in Definition 2.1, or T is P -equivalent to $T(\frac{1}{4})$ and D intersects P in two arcs with boundary on the outer component of ∂P , but since we have assumed that q equals two or is odd, the latter case is impossible. \square

Denote by $T(r_1, r_2; n)$ the tangle obtained from $T(r_1, r_2) = (B_3, \tau)$ by twisting the two lower endpoints of τ by n left-hand half-twists. See Figure 2(a) for the tangle $T(\frac{1}{3}, -\frac{1}{2}; 4)$.

Definition 2.3. Let $\eta: \hat{R}^2 \rightarrow \hat{R}^2$ be the map that is a $\pi/2$ counterclockwise rotation about the origin followed by a reflection along the y -axis. Define three knots K_1, K_2, K_3 by

$$\begin{aligned} (S^3, K_1) &= T(\frac{1}{3}, -\frac{1}{2}; 4) \cup_{\eta} T(\frac{1}{3}, -\frac{1}{2}; 4), \\ (S^3, K_2) &= T(\frac{1}{3}, -\frac{1}{2}; 4) \cup_{\eta} T(-\frac{1}{3}, \frac{1}{2}; -4), \\ (S^3, K_3) &= T(-\frac{1}{3}, \frac{1}{2}; -4) \cup_{\eta} T(-\frac{1}{3}, \frac{1}{2}; -4). \end{aligned}$$

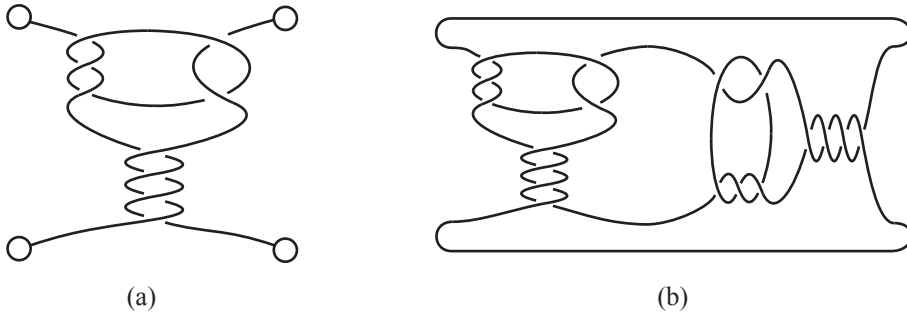


Figure 2

Alternatively, K_i can be obtained by shifting the first tangle to the left, the second tangle to the right, rotating the second tangle counterclockwise by an angle of $\pi/2$, and then connecting the endpoints of the tangles by arcs on R^2 that are horizontal except near the endpoints of the strings of the tangles, as shown in Figure 2(b) for K_1 . Note that K_3 is the mirror image of K_1 , and K_2 is obtained from K_1 by changing the right half of K_1 to its mirror image. Theorem 1.1 shows that these are the only large arborescent knots that admit exceptional surgery, and each of them admits exactly one such surgery.

3. Index of essential surfaces

Let Q and F be surfaces in M , intersecting in general position. Denote by $a(F, Q)$ the number of arc components of $F \cap Q$. The *index of F in M relative to Q* is defined as

$$i(F, Q) = \chi(F) - \frac{1}{2}a(F, Q),$$

where $\chi(F)$ is the Euler characteristic of F . This is the same as the cusped Euler characteristic defined in [Wu 1998] for sutured manifolds, except that now Q is not required to be “cusps”, which by definition is a set of annuli and tori on the boundary of a 3-manifold.

Lemma 3.1. *Let Q be a surface on ∂M , and Q' an essential surface properly embedded in M and disjoint from Q . Let $M' = M \setminus Q'$, and let Q'_1, Q'_2 be the two copies of Q' on $\partial M'$. Let F be a surface in M , and let $F' = F \setminus Q'$ be the corresponding surface in M' . Then*

$$i(F', Q'_1 \cup Q'_2 \cup Q) = i(F, Q).$$

Proof. Put $k = a(F, Q')$. Note that Q'_1, Q'_2, Q are mutually disjoint compact surfaces on $\partial M'$, and hence $a(F', Q'_1 \cup Q'_2 \cup Q) = 2k + a(F, Q)$. Since Q' intersects F in k arcs and possibly some circle components, after cutting F along $F \cap Q'$ we

have $\chi(F') = \chi(F) + k$. It follows that

$$\begin{aligned} i(F, Q) &= \chi(F) - \frac{1}{2}a(F, Q) = \chi(F') - k - \frac{1}{2}a(F, Q) \\ &= \chi(F') - \frac{1}{2}a(F', Q'_1 \cup Q'_2 \cup Q) \\ &= i(F', Q'_1 \cup Q'_2 \cup Q). \end{aligned} \quad \square$$

The lemma shows that index is invariant when cutting along a surface disjoint from Q . It is important to assume that Q is a compact surface and is disjoint from Q' , otherwise the lemma may not be true.

The most useful case is when Q' is a separating surface, cutting M into M_1 and M_2 . The following additivity lemma follows immediately from Lemma 3.1.

Lemma 3.2 (Additivity of index). *Suppose Q is a compact subsurface of ∂M , and Q' is a separating surface in M disjoint from Q , cutting M into M_1 and M_2 . Let Q'_i be the copy of Q' on ∂M_i , let $Q_i = (Q \cap M_i) \cup Q'_i$, and let $F_i = F \cap M_i$. Then*

$$i(F, Q) = i(F_1, Q_1) + i(F_2, Q_2). \quad \square$$

Lemma 3.3. *Let $T = T(p/q)$ with $q = 2$ or odd. Let $Q = P_+(T)$ for $q > 2$, and $Q = P_-(T) \cup U_+(T)$ for $q = 2$. Let F be a tight disk in $E(T)$. Then $i(F, Q) \leq 0$, and equality holds if and only if T is P -equivalent to $T(\pm 1/q)$ and F is a special disk.*

Proof. It is easy to check that each special disk in Definition 2.1 intersects Q in two arcs and hence has $i(F, Q) = 0$. Conversely, if $i(F, Q) \geq 0$ then $|F \cap Q| \leq 2$, so by Lemma 2.2 it is a special disk and hence $i(F, Q) = 0$. \square

Lemma 3.4. *Suppose $T = T(p/q, \frac{1}{2})$ and F is a tight surface in $E(T)$. Let $U = U_+(T)$. Then $i(F, U) \leq 0$. In particular, $P(T)$ and $\partial E(T) - U$ are incompressible, and there is no disk in $E(T)$ intersecting $U_+(T)$ at a single essential arc.*

Proof. If $i(F, U) > 0$, then F is a disk and $F \cap U$ has at most one arc component. Isotope the decomposition surface P in $E(T) = E(T(p/q)) \cup_P E(T(\frac{1}{2}))$ so that $F \cap P$ is minimal. Then an innermost circle/outermost arc argument would lead to a contradiction of Lemma 3.3 because one of the (at least two) disks cut off by outermost arcs will be disjoint from U and hence is isotopic to a tight disk with positive index. \square

4. Special surfaces in knot exterior

Throughout this section we assume that K is a type II knot that is the union of two length 2 Montesinos tangles $T_i = (B_i, \tau_i) = T(p_i/q_i, \frac{1}{2}) = T_{i1} + T_{i2}$, where $T_{i1} = T(p_i/q_i)$ and $T_{i2} = T(\frac{1}{2})$.

Let $S = \partial B_i$, and let $P = P(T_1) = P(T_2) = S \cap E(K)$, which cuts $E(K)$ into $E(T_1)$ and $E(T_2)$. Let $P_i = E(T_{i1}) \cap E(T_{i2})$ be the twice-punctured disk cutting

$E(T_i)$ into $E(T_{i1})$ and $E(T_{i2})$. Write $T_{ij} = (B_{ij}, \tau_{ij})$. Thus $E(K)$ is the union of four rational tangle spaces $E(T_{ij})$, $i, j = 1, 2$. Let $U_i = U_+(T_i)$, which is the component of $U(T_i)$ lying in $E(T_{i2})$.

Definition 4.1. A surface F in $E(K)$ or $E(T_i)$ is a *special surface* if it intersects each $E(T_{ij})$ in special disks.

The purpose of this section is to show that if F is an essential punctured torus in $E(K)$ with integer slope, then it is a special surface up to isotopy. We use this result to show that $q_i = 3$ for $i = 1, 2$.

If F is a compact surface in $E(T)$ intersecting $U(T)$ in arcs on ∂F , then $F - U(T)$ is F with the arcs $F \cap U(T) \subset \partial F$ removed, so it is noncompact. An arc β in $F - U(T)$ is considered *essential* if it does not cut off a compact disk from $F - U(T)$. Thus, for example, if F is a disk intersecting $U(T)$ in two arcs on ∂F , then there is exactly one essential arc on $F - U(T)$ up to isotopy.

A *P-compressing disk* of a surface F in $E(T)$ is a disk D in $E(T)$ such that $\partial D = \alpha \cup \beta$, where α is an arc on P and $\beta = D \cap (F - U(T))$ is an arc on $F - U(T)$ that is essential. If such a disk exists, then F is *P-compressible*; otherwise it is *P-incompressible*.

Lemma 4.2. *Let F be a punctured essential torus in $E(K)$ such that ∂F has integer slope on $\partial E(K)$, and the complexity $(|F \cap \partial P|, |F \cap P|)$ is minimal in lexicographic order. Let F_j be a component of $F \cap E(T_i)$. Then*

- (i) F_j is tight,
- (ii) $i(F_j, U_i) = 0$, and
- (iii) F_j is incompressible and *P-incompressible*.

Proof. (i) Since $|F \cap \partial P|$ is minimal, F intersects each of the four annuli $\partial N(K) | \partial P$ in essential arcs. By [Wu 1996a, Lemma 3.3], each $E(T_i)$ is a handlebody and hence irreducible, so if $F \cap P$ contains a trivial loop on P , then an innermost circle argument would show that one could isotope F to reduce $|F \cap P|$ without increasing $|F \cap \partial P|$, which is a contradiction. If $F \cap P$ has a trivial arc on P , then an outermost one would cut off a ∂ -compressing disk for F , which is impossible because F is essential.

(ii) Since P is incompressible [Wu 1996a, Lemma 3.3], each circle component of $F \cap P$ is also essential on F . It follows that each boundary component of $F \cap E(T_i)$ is a nontrivial loop on $\partial E(T_i)$, so each disk component of $F \cap E(T_i)$ is an essential disk in $E(T_i)$.

Let \hat{F} be the torus obtained from F by capping off each boundary component of F with a disk. Define a graph Γ on \hat{F} with the attached disks as fat vertices and $P \cap F$ as edges. A component of $P \cap F$ is either a *circle edge* or an *arc edge* of

Γ , depending on whether it is a circle or arc. A circle edge is not incident to any vertex, so Γ is actually a graph in which some edges are loops without vertices.

Since ∂F has integer boundary slope and P has 4 boundary components, each vertex v of Γ has valence 4. Denote by C the number of corners at all vertices of Γ that lie in either U_1 or U_2 , where $U_i = U_+(T_i)$, which is the component of $\partial N(K) \cap E(T_i)$ lying in the $E(T_{i2}) = E(T(\frac{1}{2}))$ part. Denote by V and E the numbers of vertices and arc edges of Γ . Since the boundary of each vertex of Γ travels through each of U_1 and U_2 once, we have $C = 2V$. Since each vertex is incident to 4 arc edge endpoints, we also have $E = 2V$. Let F_j be the faces of Γ , and assume it lies in $E(T_i)$. The Euler characteristic formula, whose validity for graphs with circle edges one can verify, gives

$$\begin{aligned} 0 &= \chi(\hat{F}) = V - E + \sum \chi(F_j) = -V + \sum \chi(F_j) = -\frac{1}{2}C + \sum \chi(F_j) \\ &= \sum (\chi(F_j) - \frac{1}{2}|F_j \cap U_i|) = \sum i(F_j, U_i). \end{aligned}$$

By (i) and Lemma 3.4, we have $i(F_j, U_i) \leq 0$ for each component F_j of $F \cap E(T_i)$. Since these are exactly the faces of Γ , it follows that $i(F_j, U_i) = 0$ for all F_j .

(iii) Since F is incompressible and $|F \cap P|$ is minimal, it is easy to see that F_j is also incompressible. By (ii), F_j is either a disk intersecting U_i twice or an annulus disjoint from U_i . Suppose D is a P -compressing disk for F_j as in the definition, and let $\alpha = D \cap P$. Since $\beta = |D \cap F_j|$ is essential on $F_j - U_i$, the two points $\partial\alpha = \partial\beta$ lie on distinct components of $F_j \cap P$, and hence an isotopy of F via D would create a surface F' that has the same or smaller complexity than F , and yet one of the faces F'_j deformed from F_j has $i(F'_j, U_i) > 0$, which is a contradiction of (ii). \square

Lemma 4.3. *If F is a special surface in $E(K)$ then it is not a punctured sphere.*

Proof. This follows from the proof of Lemma 4.2(ii). If \hat{F} is a sphere, then $2 = \chi(\hat{F}) = \sum i(F_j, U_i)$, which is a contradiction since $i(F_j, U_i) \leq 0$ for all i, j . \square

Lemma 4.4. *Let F be an essential punctured torus in $E(K)$ with integer boundary slope. Then F, P_1, P_2 can be isotoped so that F is a special surface.*

Proof. We may assume that $(|F \cap \partial P|, |F \cap P|)$ is minimal up to isotopy, so Lemma 4.2 applies, and we have $i(F_k, U_i) = 0$ for any component F_k of $F \cap E(T_i)$. We show below that P_i can be isotoped so that each component D of $F \cap E(T_{ij})$ is a tight disk. In that case, by Lemma 3.3, we will have $i(D, U_i) \leq 0$; since F_k is a union of such disks, by the Additivity Lemma 3.2 we will have $i(D, U_i) = 0$ for all D , and hence by Lemma 3.3 D is a special disk in $E(T_{ij})$, which will complete the proof.

Let $Q_i = F \cap E(T_i)$. Isotope P_i so that $(|Q_i \cap \partial P_i|, |Q_i \cap P_i|)$ is minimal. This implies that for $R = P_-(T_{i1}), P_+(T_{i2})$ or a component of $U(T_{ij})$, each arc

component of $Q_i \cap R$ is essential on R . By Lemma 4.2, Q_i is incompressible and P -incompressible, so the above minimality and the ∂ -incompressibility of F imply that each component of $Q_i \cap P_i$ is also essential on $P_i = P_+(T_{i1}) = P_-(T_{i2})$. Therefore all components of $F \cap E(T_{ij})$ are tight. It remains to show that each component of $F \cap E(T_{ij})$ is a disk.

By Lemma 2.2, P_i is incompressible and ∂ -incompressible in $E(T_i) - U_i$, so no component of $P_i \cap Q_i$ is a trivial loop on Q_i , or an arc that is trivial on $Q_i - U_i$ in the sense that it cuts off a disk on Q_i disjoint from U_i . Thus if a component F_k of Q_i is a disk, then P_i cuts F_k into disks. Similarly, if F_k is an annulus, then no component of $F_k \cap P_i$ is an inessential arc or inessential circle on F_k . It now suffices to show that $\partial F_k \cap P_i \neq \emptyset$, because then $F_k \cap P_i$ is a nonempty set of essential arcs on F_k , cutting it into disks.

Let F_k be an annulus component of Q_i , with ∂F_k disjoint from P_i . This implies that $F_k \cap U_-(T) = \emptyset$, because each component of $F_k \cap U_-(T_i)$ is a component of $F \cap U_-(T_i)$, which intersects P_i at two points. Since $i(F_k, U_i) = 0$, we also have $F_k \cap U_+(T_i) = \emptyset$. Therefore $\partial F_k \subset P$. No component C' of ∂F_k is parallel to a component C of ∂P , since otherwise the arc components of $F \cap P$ with endpoints on C would lie in the annulus between C and C' , and hence would be trivial arcs, and there are $|\partial F|/2 > 0$ of them, which can be used to ∂ -compress F , a contradiction to the fact that F is essential. Therefore the two components of ∂F_k are both parallel to the circle $P_i \cap P$, and hence bound an annulus A on P . By Lemma 4.2(iii), F_k is incompressible, and by [Wu 1996a, Lemma 3.3] $E(T_i)$ is a handlebody, so $F_k \cup A$ must bound a solid torus V in $E(T_i)$. Now A cannot be meridional on V because P is incompressible, and A cannot run more than once along the longitude of V , since otherwise the union of V and a regular neighborhood of a disk on ∂B_i bounded by a component of ∂F_k would be a punctured lens space in the 3-ball B_i , which is absurd. It follows that A is longitudinal on ∂V and hence F_k is P -compressible, which contradicts Lemma 4.2 (iii). \square

Proposition 4.5. *Suppose K is an arborescent knot of type II, and suppose $E(K)$ contains an essential punctured torus with integer boundary slope. Then K is the union of T_1, T_2 , each of which is weakly equivalent to $T(\frac{1}{3}, \frac{1}{2})$ or $T(-\frac{1}{3}, \frac{1}{2})$.*

Proof. By definition, K is the union of T_1, T_2 with $T_i = T(p_i/q_i, \frac{1}{2}) = T_{i1} + T_{i2}$. By Lemma 4.4, we may assume that F intersects each $E(T_{ij})$ in special disks. If some $q_i > 3$, then the only special disk in $E(T_{i1})$ is of type (1), and hence each component of $F \cap P_i$ is an arc with only one endpoint on the circle $P_i \cap P$, where P_i is the twice-punctured disk $E(T_{i1}) \cap E(T_{i2})$. From the definition, we see that the only special disks in $E(T_{i2}) = E(T(\frac{1}{2}))$ intersecting P_i in such arcs are those of type (4), which are disjoint from $U_+(T_i)$. Therefore $F \cap U_+(T_i) = \emptyset$, which is a contradiction, since F must intersect each $U_{\pm}(T_i)$ in exactly $|\partial F| > 0$ arcs. \square

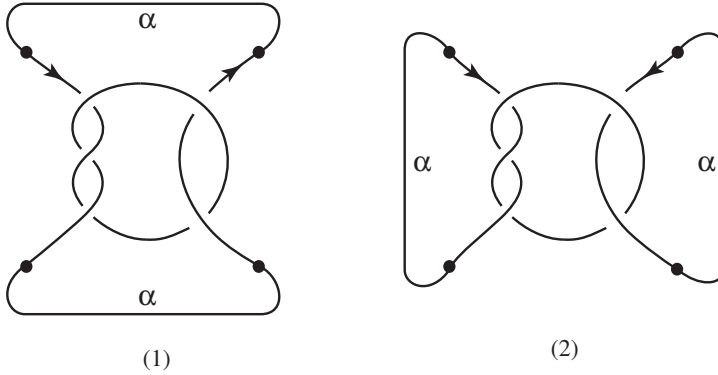


Figure 3

5. Boundary slopes of special surfaces

Let $T = (B^3, \tau)$ be a tangle, with B^3 identified to \hat{R}^3_- . We assume that τ is oriented. Let α be a pair of arcs on $R^2 - \text{Int} I^2$, shown in Figure 3(1) when the orientations of τ are opposite near the two upper endpoints, or in Figure 3(2) otherwise. Then $\hat{\tau} = \tau \cup \alpha$ is a link in R^3 with orientation induced from that of τ .

Let γ be a set of essential arcs on $U(T)$, and assume that $n = |\gamma \cap U_-(T)| = |\gamma \cap U_+(T)|$. Each component of γ is isotopic in $N(\tau)$ to a component of τ , so the orientation of τ induces an orientation on γ . Let $p : R^3_- \rightarrow R^2 = \partial R^3$ be the standard projection. We always assume that τ and γ are in *regular position* in the sense that

- $p(\tau) \subset I^2$, where $I = [-1, 1]$;
- $p : \tau \cup \gamma \rightarrow R^2$ is an immersion with only double crossings; and
- $p(\gamma) \cap \alpha = \emptyset$.

The third condition is to guarantee that all crossings between $p(\gamma)$ and $p(\tau \cup \alpha)$ appear inside of the square I^2 , so if we close up γ by arcs parallel to α to obtain $\hat{\gamma}$, then the linking number between $\hat{\gamma}$ and $\hat{\tau} = \tau \cup \alpha$ can be calculated using crossings between τ and γ .

Since τ and γ are oriented, each crossing is assigned a sign according to the right hand rule, as given in [Rolfsen 1990, p. 132].

Definition 5.1. (i) The *relative linking number* between τ and γ , denoted by $lk(\tau, \gamma)$, is the sum of the signs of crossings at which γ passes below τ .

(ii) Let F be a surface in $E(T)$ such that $F \cap U(T)$ is in regular position. Then the *relative framing* of F in $E(T)$ is defined as $\theta(F) = lk(\tau, F \cap U(T))$.

An isotopy of $\tau \cup \gamma$ is a *regular isotopy* if $\tau \cup \gamma$ is in regular position at any time during the isotopy. Similarly, an isotopy of a surface F in $E(T)$ is a regular isotopy if its restriction to $F \cap U(T)$ is a regular isotopy.

Consider the four disks $\cup D_i = R^2 - \text{Int } P(T)$. Since γ has n endpoints on each ∂D_i , we can connect $\partial \gamma$ by $2n$ arcs γ' on $\partial N(\hat{\tau})$ lying in the upper half-space R^3_+ . Define $\hat{\gamma} = \gamma \cup \gamma'$, with orientation induced by that of γ . Since $\hat{\tau} \cup \hat{\gamma}$ is an oriented link, the linking number $lk(\hat{\tau}, \hat{\gamma})$ is well defined.

Lemma 5.2. (i) $lk(\tau, \gamma) = lk(\hat{\tau}, \hat{\gamma})$.

(ii) $lk(\tau, \gamma)$ and $\theta(F)$ are regular isotopy invariants .

(iii) Let ψ be a rotation of R^3_- along the z -axis by an angle of $\pi/2$, deforming τ to τ' and a surface F to F' . Then $\theta(F) = \theta(F')$.

(iv) Suppose F_j are the components of F in $E(T)$. Then $\theta(F) = \sum \theta(F_j)$.

Proof. (i) It is well known that $lk(\hat{\tau}, \hat{\gamma})$ can be calculated as the sum of the signs of crossings at which $\hat{\gamma}$ passes below $\hat{\tau}$. By definition, γ does not pass below α , and γ' does not pass below $\hat{\gamma}$ because it lies in R^3_+ while $\hat{\gamma}$ lies in R^3_- . Therefore the crossings at which $\hat{\gamma}$ passes below $\hat{\tau}$ are exactly where γ passes below τ , and the result follows.

(ii) A regular isotopy does not change the relative position of $\partial \tau$ to α , and hence it extends to an isotopy of $\hat{\tau} \cup \hat{\gamma}$, and the result follows from (i) because the linking number of a link is an isotopy invariant.

(iii) This follows from the definition, because ψ gives a sign preserving one-to-one correspondence between the crossings.

(iv) This follows from the definition. □

Let $T = T_1 + T_2$, where $T_1 = T(\frac{1}{3})$ and $T_2 = T(-\frac{1}{2})$. Let F be a special surface in $E(T)$ intersecting each $U_{\pm}(T)$ in n arcs. By definition, each component of $F \cap E(T_i)$ is a special disk. We may assume that F is a union of a_i copies of A_i for $i = 1, \dots, 6$. From Figure 1 we see that $F \cap P(T_i)$ is as shown in Figure 4(i), $i = 1, 2$, where an arc with label a_j indicates a_j parallel copies of that arc.

Lemma 5.3. Let $r = n/2$, and $s = a_6$. Then there is a special surface F in $E(T)$ consisting of a_k copies of disks of type (k) and intersecting each $U_i(T)$ at n arcs, if and only if the nonnegative integers a_k satisfy the following equations.

- (i) $n = 2r$ is even.
- (ii) $a_1 = r - s$.
- (iii) $a_2 = a_3 = r + s$.
- (iv) $a_4 = a_5 = a_1 + a_2 = a_1 + a_3 = n$.
- (v) $a_6 = s$.

Proof. Suppose F is such a surface. Then (v) is from definition, and (iv) follows from the fact that F intersects each boundary component of P at n points. By (iv) we have $a_2 = a_3$. Let $P' = P_+(T_1) = P_-(T_2)$ be the twice-punctured disk cutting $E(T)$ into $E(T_1)$ and $E(T_2)$. Then on $\partial E(T_1)$, there are $a_2 + a_3$ arcs of $F \cap P'$ with both endpoints on the circle $P' \cap P(T)$, while there are $a_5 + 2a_6$ such arcs on $\partial E(T_2)$. Hence $2a_2 = a_2 + a_3 = a_5 + 2a_6 = n + 2s$, which shows that $n = 2r$ is even, and $a_2 = a_3 = r + s$. Item (ii) follows from this and the equation $a_1 + a_2 = n = 2r$, as shown in Figure 4(a).

Conversely, given a set of nonnegative numbers a_k satisfying the above equations, let E_k be a_k copies of disks of type (k) . Then one can check that the arcs $(E_1 \cup E_2 \cup E_3) \cap P'$ are isotopic to the arcs $(E_4 \cup E_5 \cup E_6) \cap P'$ on P' , and hence one can glue these together to form a surface F in $E(T)$. \square

The curves in parts (a) and (b) of Figure 4 can be represented by the weighted train tracks shown in parts (c) and (d), where an arc of the train track with weight x represents x parallel copies of that arc. The weights on the train tracks are calculated using the above lemma.

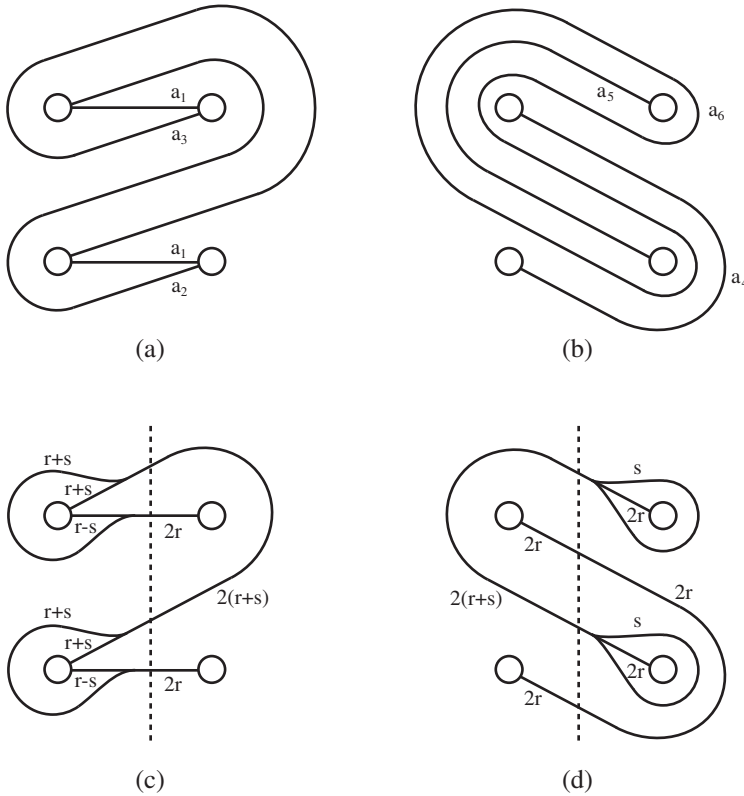


Figure 4

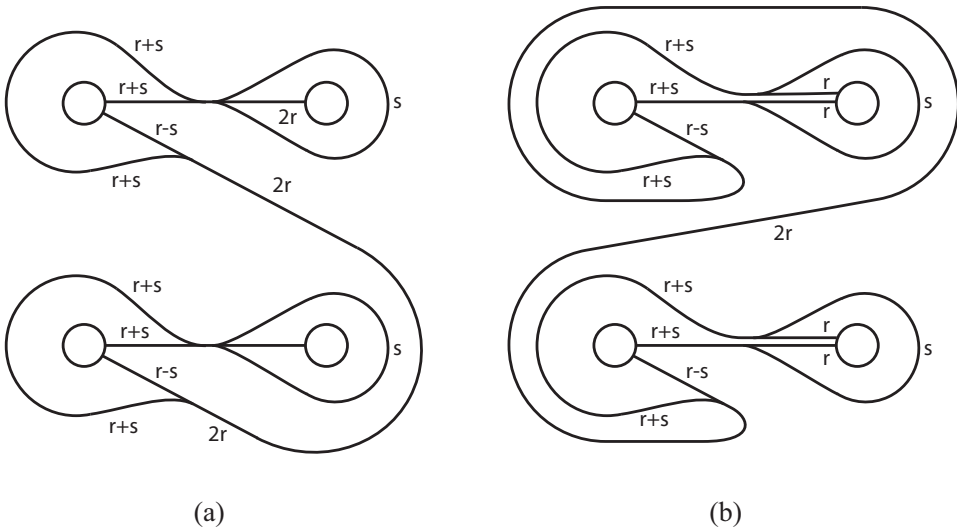


Figure 5

Recall that $T(\frac{1}{3}, -\frac{1}{2}) = T_1 + T_2$ is formed by gluing $P_+(T_1)$ to $P_-(T_2)$ using a reflection map along the y -axis on R^2 . Since the train tracks on these two half-planes match each other under this reflection, after gluing we obtain a special surface F in $E(T)$ with $F \cap P$ represented by the train track γ in Figure 5(a).

To simplify the diagram, we perform a counterclockwise full twist on both the top two tangle endpoints and the bottom two tangle endpoints. This is equivalent to twisting the two lower endpoints by four left-hand half-twists, so by definition it deforms the tangle $T(\frac{1}{3}, -\frac{1}{2})$ to the tangle $T(\frac{1}{3}, -\frac{1}{2}; 4)$ defined in Section 2. The train track, after splitting along two edges, becomes that in Figure 5(b).

After a further splitting and isotopy, we obtain the train track γ in Figure 6(a). Up to isotopy we can move the end points of γ around ∂P , but so far we have not done that. By moving some endpoints of train track around ∂P , we obtain the one in Figure 6(b).

The two strings of $T = T(\pm 1/q)$ are said to be *consistently oriented* if they both run from the upper endpoints to the lower endpoints or both from the lower endpoints to the upper endpoints. For $T(\frac{1}{3})$ we will always assume that its two strings are consistently oriented. For $T(-\frac{1}{2})$, we introduce a new variable ϵ and set $\epsilon = 1$ if the two strings of $T(-\frac{1}{2})$ are oriented consistently, and $\epsilon = -1$ otherwise. Recall that a surface F in $E(T)$ is regular if $F \cap U(T)$ is a set of regular curves on $U(T)$.

Lemma 5.4. *Let A_k be a regular special disk such that $A_k \cap P(T)$ is the curve in part (k) of Figure 1.*

- (i) $\theta(A_1) = 6, \theta(A_2 \cup A_3) = 4, \theta(A_4 \cup A_5) = -2\epsilon,$ and $\theta(A_6) = 0.$

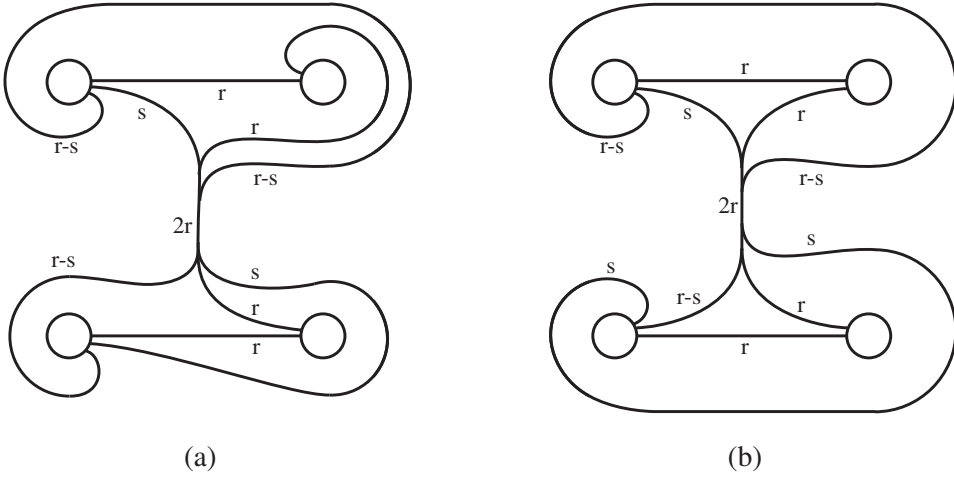


Figure 6

- (ii) A special surface F in $T(\frac{1}{3}, -\frac{1}{2})$ is isotopic to a regular surface F' such that $\partial F' \cap P$ is represented by the weighted train track in Figure 5(a), and $\theta(F') = (5 - 2\epsilon)n - 2s$, where $s = a_6$ is the number of type (6) special disks in F .
- (iii) A special surface F in $T(\frac{1}{3}, -\frac{1}{2}; 4)$ is isotopic to a regular surface F' such that $F' \cap P$ is carried by the weighted train track in Figure 6(b), and $\theta(F) = (6 - 4\epsilon)n - 2s$.

Proof. (i) follows by drawing the curves γ of ∂A_i on $U(T)$ and counting the signed crossings where γ passes below τ . We omit the details.

(ii) By definition, F is the union of a_k copies of A_k , which can be put in regular position. We leave it to the reader to check that the regular surfaces in $E(T(\frac{1}{3}))$ and $E(T(-\frac{1}{2}))$ can be combined together to create the surface F in $E(T(\frac{1}{3}, -\frac{1}{2}))$ without creating new crossings between $F \cap U(T)$ and τ . Since $a_2 = a_3$ and $a_4 = a_5$, we have $\theta(F) = a_1 \theta(A_1) + a_2 \theta(A_2 \cup A_3) + a_4 \theta(A_4 \cup A_5) + a_6 \theta(A_6)$. It follows from (i) and Lemma 5.3 that

$$\theta(F) = 6a_1 + 4a_2 - 2\epsilon a_4 = 6(r - s) + 4(r + s) - 2\epsilon n = (5 - 2\epsilon)n - 2s.$$

(iii) By definition, $T = T(\frac{1}{3}, -\frac{1}{2}; 4)$ is obtained from $T(\frac{1}{3}, -\frac{1}{2})$ by two counter-clockwise full twists of the two lower endpoints of the tangle, which deforms the surface F'' in (ii) to a new surface F' in $E(T)$ with boundary curve represented by the train track shown in Figure 6(a). After the twists, each arc component of $\alpha' = F' \cap \partial N(\tau)$ passes below τ four more times than $\alpha'' = F'' \cap \partial N(\tau)$ does, two of those times in the positive direction, and the other two in the positive direction if and only if $\epsilon = -1$. (The two strings twisted have the same orientation if and

only if the two strings in the tangle $T(-\frac{1}{2})$ have opposite orientation.) Hence $\theta(F') = \theta(F'') + (2 - 2\epsilon)n$, so by (ii) we have $\theta(F') = (7 - 4\epsilon)n - 2s$.

We now perform an isotopy of F' to obtain the surface F whose boundary curve on P is carried by the train track in Figure 6(b). To do this one needs to turn $2r = n$ endpoints of $F \cap P$ on ∂P clockwise for an angle of almost 2π . The isotopy on each endpoint creates one more crossing at which α' passes below τ , and it is in the negative direction. Therefore we have $\theta(F) = \theta(F') - n = (6 - 4\epsilon)n - 2s$. \square

Lemma 5.5 can be used to calculate the boundary slope of a surface in $E(K)$.

Lemma 5.5. *Suppose F_i is a regular surface in $E(T_i)$. Let $\eta : \partial B_1 = \hat{R}^2 \rightarrow \hat{R}^2 = \partial B_2$ be the reflection along the y -axis, such that $\eta(F_1 \cap P(T_1)) = F_2 \cap P(T_2)$. Let $(S^3, K) = (B_1, \tau_1) \cup_\eta (B_2, \tau_2)$ with orientation of τ_i induced by that of K , and let $F = F_1 \cup_\eta F_2$. Suppose F has m boundary components with slope p/q , where p, q are coprime and $q > 0$. Then $mp = \theta(F_1) + \theta(F_2)$. In particular, $q = 1$ if and only if $\theta(F_1) + \theta(F_2) \equiv 0 \pmod n$, where $n = mq$ is the number of times ∂F intersects each meridian of K .*

Proof. We can shift $T_1 = (B^3, \tau_1)$ to the left and $T_2 = (B^3, \tau_2)$ to the right so that τ_1, τ_2 are separated by the yz -half-plane in $B^3 = R^3_-$. Now $K \subset R^3$ is isotopic to the knot K' obtained by adding four arcs on R^2 , each connecting an endpoint p_i of τ_1 to $\eta(p_i)$ on τ_2 , with two below the line $y = -1$ and the other two above the line $y = 1$. We may also assume that near $\partial\tau_i$ these arcs match the arcs α in Figure 3, so they are disjoint from the projection of $F_i \cap U(T_i)$ because F_i are regular. The isotopy from K to K' extends to an isotopy which deforms F in $E(K)$ to the surface F' in $E(K')$ obtained from $F_1 \cup F_2$ by connecting their boundary on R^2 by bands in the upper half-space. More explicitly, let $C = F_1 \cap R^2$ and embed $C \times I$ in $R^3_+ \cap E(K')$ so that $C \times \{-1\} = F_1 \cap R^2$, $C \times \{1\} = F_2 \cap R^2$, and $\partial C \times I$ lies on $\partial N(K')$. Then $F' = F_1 \cup (C \times I) \cup F_2$. Note that $(\partial C) \times I$ does not pass below K' , so $lk(K', \partial F')$ is the sum of the signs of crossings where ∂F_i passes below τ_i , and hence $mp = lk(K, \partial F) = lk(K', \partial F') = \theta(F_1) + \theta(F_2)$.

If $q = 1$ then $mp \equiv 0 \pmod n = mq$. Conversely, if $mp \equiv 0 \pmod n = mq$ then p is a multiple of q . Since p, q are coprime and $q > 0$, this is possible only if $q = 1$. \square

We now assume that K is a type II knot and F is an essential punctured torus in $E(K)$ with integer boundary slope. By Proposition 4.5, K is the union of two tangles T_1, T_2 , each weakly equivalent to $T(\frac{1}{3}, -\frac{1}{2})$ or $T(-\frac{1}{3}, \frac{1}{2})$. Hence, up to weak isotopy, we may assume that $T_i = T(\frac{1}{3}, -\frac{1}{2}; 4)$ or its mirror image $T(-\frac{1}{3}, \frac{1}{2}; -4)$. By Lemma 4.4, we may assume that $F_i = F \cap E(T_i)$ is a special surface, so by Lemma 5.4(iii) we may assume that F_i is regular, and $F_i \cap P(T_i)$ is represented by the train track γ_i in Figure 6(b) if $T_i = T(\frac{1}{3}, -\frac{1}{2}; 4)$, and by its reflection along the y -axis if $T_i = T(-\frac{1}{3}, \frac{1}{2}; -4)$. The gluing map $\eta : \partial B_2 \rightarrow \partial B_1$ could be any orientation-reversing map that maps $P(T_2)$ to $P(T_1)$ and $F_1 \cap P(T_1)$ to $F_2 \cap P(T_2)$.

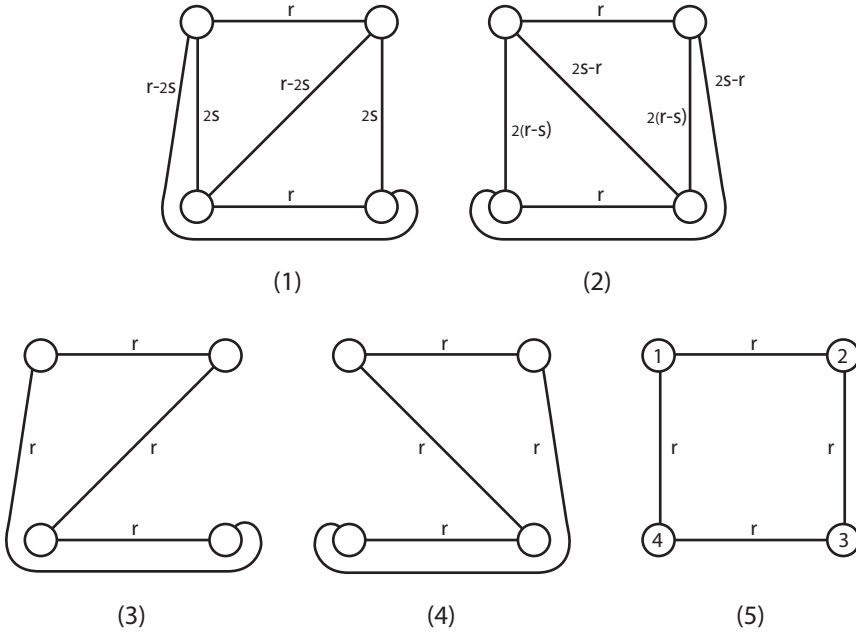


Figure 7

As in Lemma 5.3, let n be the number of times F intersects a meridian of K on $N(K)$, $r = n/2$, and let s_i be the number of type (6) special disks in F_i . There are five possible ways to split γ_i , according to the values of s_i :

- (1) $r - s_i > s_i > 0$ (2) $s_i > r - s_i > 0$ (3) $s_i = 0$
- (4) $r - s_i = 0$ (5) $r - s_i = s_i$

One can check that for $T_i = T(\frac{1}{3}, -\frac{1}{2}; 4)$ the train track in Figure 6(b) splits to γ_i in the corresponding parts of Figure 7, where $s = s_i$. When $T_i = T(-\frac{1}{3}, \frac{1}{2}; -4)$, γ_i is the reflection of those in the figure along the y -axis. We say that γ_i is of type (k) if it is the one shown in part (k) of Figure 7.

Lemma 5.6. *For each i , $s_i \in \{0, r, r/2\}$. Hence γ_i is not of type (1) or (2).*

Proof. We need to show that γ_i cannot be of type (1) or (2). Because of symmetry we may assume without loss of generality that $T_1 = T(\frac{1}{3}, -\frac{1}{2}; 4)$, and γ_1 is of type (1). By Lemma 5.4(iii) we have $\theta(F_1) = (6 - 4\epsilon)n - 2s_1$.

The graph in part (1) is not homeomorphic to those in (3)–(5), so γ_2 must be of type (1) or (2). Let $\eta : \partial B_2 \rightarrow \partial B_1$ be the gluing map, which is orientation-reversing. Since the two horizontal edges of γ_i have higher weights than the other edges, η must map horizontal edges to horizontal edges. Without loss of generality we may assume that η maps the upper horizontal line of γ_2 to the upper horizontal line of γ_1 by a reflection along the vertical axis. This fully determines η on γ_2 .

First assume that $T_2 = T(\frac{1}{3}, -\frac{1}{2}; 4)$. If γ_2 is the one in Figure 7(2), then η is simply a reflection along the vertical line, and hence it maps the two right vertices of γ_2 to the two left vertices of γ_1 , but since the two left (right) vertices of γ_i belong to the same component of τ_i , K would be a link of two components, which is a contradiction. Therefore γ_2 must be the graph in Figure 7(1), which is redrawn in Figure 8(1). One can modify the graph by turning the lower horizontal edge clockwise by a half-twist to obtain the one in Figure 8(2), then isotope some of the edge endpoints at the two lower boundary components of P around to obtain the graph in Figure 8(3). The map η is the composition of this isotopy followed by a reflection along a vertical line.

The isotopies above are not regular isotopies. They have changed the relative framing of the surface F_2 . By Lemma 5.4(iii), the framing of F_2 with boundary graph in Figure 8(1) is given by $(6 - 4\epsilon)n - 2s_2$. After twisting the two lower vertices of the graph by a half-twist, each boundary arc of F_2 on the tubes $\partial E(T_2) - P$ passes below the part of τ near the vertex 3 in the figure once in the negative direction, but does not pass below the other string of τ , and hence the new framing is $(4 - 4\epsilon)n - 2s_2$. The isotopy from Figure 8(2) to 8(3) moves r edge endpoints clockwise and another r edge endpoints counterclockwise around vertex 3 and 4 respectively, and hence will not change the relative framing. Therefore we have $\theta(F_2) = (4 - 4\epsilon)n - 2s_2$ for the surface F_2 corresponding to Figure 8(3).

In order to glue F_2 to F_1 by η , the weight of the left vertical edge in Figure 8(3) must match the weight of the right vertical edge of Figure 7(1), and hence we have $r - 2s_2 = 2s_1$. Thus $\theta(F_1) = (6 - 4\epsilon)n - (r - 2s_2)$, so

$$\begin{aligned} \theta(F_1) + \theta(F_2) &= ((6 - 4\epsilon)n - (r - 2s_2)) + ((4 - 4\epsilon)n - 2s_2) \\ &= (10 - 8\epsilon)n - r \equiv r \pmod{n}. \end{aligned}$$

Since $r = n/2$, this is a contradiction to Lemma 5.5 and the assumption that F has integer boundary slope. □

Lemma 5.7. $s_1 = s_2 = r/2$, so both γ_i are of type (5).

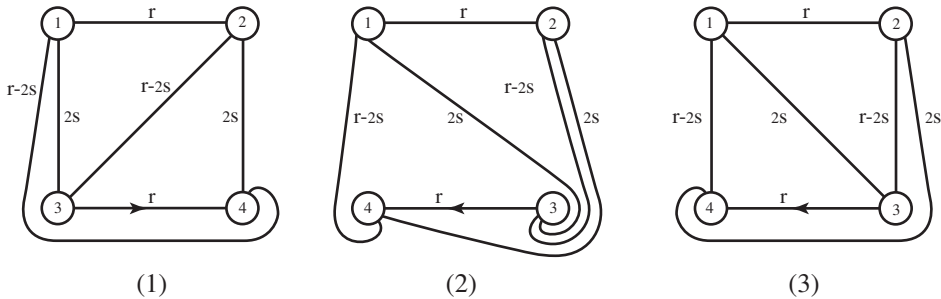


Figure 8

Proof. If γ_i is of type (3) or (4), then the endpoints of a string of τ_i are separated by those of the other string on γ_i , which is a circle. Hence if both γ_i are of type (3) or (4) then $K = \tau_1 \cup \tau_2$ would be a link of two components, which is a contradiction. Therefore at least one γ_i , say γ_1 , is of type (5). If the result is not true then γ_2 must be of type (3) or (4). We assume it is of type (3). The other case is similar.

By the same proof as in that of Lemma 5.6, we can isotope γ_2 by twisting the lower level edge of γ_2 by a half-twist, followed by an isotopy that moves some endpoints of γ_2 around ∂P , to change γ_2 to a graph of type (5). As in the proof of Lemma 5.6, this will not change $\theta(F_2) \pmod n$. By Lemma 5.4(iii), we have $\theta(F_1) + \theta(F_2) \equiv -2s_1 - 2s_2 \pmod n$. Since γ_2 is of type (3), we have $s_2 = 0$, and since γ_1 is of type (5), we have $2s_1 = r = n/2$. Hence $\theta(F_1) + \theta(F_2) \equiv r \pmod n$, which by Lemma 5.5 implies that the boundary slope of the punctured torus F is not an integer slope, a contradiction. \square

Proposition 5.8. *Let K be a type II knot, and let F be an essential punctured torus in $E(K)$ with integer boundary slope δ . Then $|\partial F|$ is a multiple of 4, and $(K, \delta) = (K_1, 3), (K_2, 0)$ or $(K_3, -3)$, where K_i are the knots defined in Definition 2.3.*

Proof. By Proposition 4.5, we have $(S^3, K) = T_1 \cup T_2$, where each T_i is weakly equivalent to $T(\frac{1}{3}, \frac{1}{2})$ or $T(-\frac{1}{3}, \frac{1}{2})$. Up to weak equivalence we may assume that each T_i is either $T(\frac{1}{3}, -\frac{1}{2}; 4)$ or $T(-\frac{1}{3}, \frac{1}{2}; -4)$.

Denote by u_1, \dots, u_4 the four disks $\partial B_i - \text{Int } P(T_i)$, which we consider as fat vertices. By Lemma 5.7, the train track γ_1 is of type (5), so it is a cycle containing those four vertices, labeled in cyclic order, as shown in Figure 7(5). Similarly, γ_2 contains the vertices v_1, \dots, v_4 in the same order. Orient γ_i clockwise. Let $\eta : \partial B_1 \rightarrow \partial B_2$ be the gluing map. Then up to isotopy η is determined by its restriction on γ_1 , which is then determined by the image of u_1 and whether $\eta|_{\gamma_1}$ is orientation-preserving or not. Although η must be orientation-reversing on ∂B_1 , it may map the disk inside of γ_1 to the disk outside of γ_2 , so $\eta|_{\gamma_1}$ could be orientation-preserving.

Since K is a knot, the endpoints of a string of τ_2 must be mapped to endpoints of different strings of τ_2 , which excludes four possible η . Also, if τ_i is considered as lying in a pillowcase B_i , then from Figure 2(a) one can see that a π -rotation along a horizontal axis will preserve the tangle. One can now easily check that all the four possible choices of η give rise to the same knot, so we may assume that η is obtained by rotating γ_2 counterclockwise by an angle of $\pi/2$ and then reflecting along a vertical line, as described in Definition 2.3. Therefore K is one of the three knots in the statement.

The surface F is cut into F_i in $E(T_i)$. By Lemma 5.2(iii), the $(\pi/2)$ -rotation above will not change $\theta(F_1)$, so by Lemma 5.5 the boundary slope of F is given by $(\theta(F_1) + \theta(F_2))/n$. Examining the orientation of the strings in τ_i we see that

they are consistently oriented in the tangle $T(\pm\frac{1}{2})$, and hence $\epsilon = 1$ for both T_i . Since γ_i are of type (5), by definition we have $2s_i = r$, so by Lemma 5.4(iii) we have $\theta(F_i) = (6 - 4\epsilon)n - 2s_i = 2n - r$ if $T_i = T(\frac{1}{3}, -\frac{1}{2}; 4)$, and $\theta(F_i) = -2n + r$ if $T_i = T(-\frac{1}{3}, \frac{1}{2}; -4)$. Hence if $K = K_1 = T(\frac{1}{3}, -\frac{1}{2}; 4) \cup_\eta T(\frac{1}{3}, -\frac{1}{2}; 4)$, then by Lemma 5.5 the boundary slope of T is $[(2n - r) + (2n - r)]/n = 3$. Similarly for the other two cases.

By Lemma 5.3, we have $|\partial F| = n = 2r$, and by Lemma 5.7 we have $r = 2s_i$, and hence $|\partial F|$ is a multiple of 4. □

6. Toroidal surgery

Let (K, δ) be one of the three pairs described in Theorem 1.1. In this section we show that there is a punctured torus F in $E(K)$ with boundary slope δ , and that the torus \hat{F} obtained by capping off the boundary components of F with meridional disks in the Dehn filling solid is indeed an essential torus in the surgered manifold $K(\delta)$.

Let $T = T(\frac{1}{3}, \frac{1}{2}) = T_1 \cup T_2$, where $T_1 = T(\frac{1}{3})$ and $T_2 = T(\frac{1}{2})$.

Lemma 6.1. *A special surface Q in $E(T)$ is incompressible and P -incompressible.*

Proof. By considering a component if necessary, we may assume that Q is connected. By Lemma 3.3, each special disk has zero index, so by the Additivity Lemma 3.2 Q also has zero index and hence is either an annulus disjoint from $U_+(T)$ or a disk intersecting $U_+(T)$ in two arcs. If Q is a disk then it is automatically incompressible, and a P -compression will produce two disks D_i , each intersecting $U_+(T)$ at a single arc, which contradicts Lemma 3.4.

Now assume Q is an annulus. Let $P' = P_+(T_1) = P_-(T_2)$ be the twice-punctured disk cutting $E(T)$ into $E(T_1)$ and $E(T_2)$. By definition, P' cuts Q into a set of special disks, each of which is an essential bigon in the sense that it intersects P' in two arcs, and an arc on the bigon with one endpoint on each of these arcs is not rel ∂ homotopic to an arc on P' . Using this and the fact that P' is incompressible, one can easily show, by an innermost circle/outermost arc argument, that Q is incompressible in $E(T)$. To show it is P -incompressible, one need only show that there is no ∂ -compressing disk D of Q in $E(T)$ disjoint from $U_+(T)$. Suppose $\partial D = \alpha \cup \beta$, where α is an essential arc on Q and $\beta \subset \partial E(T) - U_+(T)$. Since P' is incompressible, we may assume $D \cap P'$ has no circle components; since $P' \cap Q$ is a set of essential arcs on Q , α is isotopic to a component of $P' \cap Q$, so by an isotopy of D we may also assume that $\alpha \cap P' = \emptyset$. Hence $D \cap P'$ is a set of arcs with endpoints on β . Choose D so that $|D \cap P'|$ is minimal. If $D \cap P' = \emptyset$, then one can use D to ∂ -compress a special disk to produce a pair of disks D_j in some $E(T_i)$ with ∂D_j the union of an essential arc on P' and another arc on $\partial E(T_i) - P' \cup U_+(T)$, which will lead to a contradiction to Lemma 3.3. Now an

outermost arc γ cuts off a disk D' from D which lies in one of the $E(T_i)$. Using Lemma 3.3, one can show that $\partial D'$ is trivial on $\partial E(T_i)$, so it cuts off a 3-ball which can be used to reduce $|D \cap P'|$, contradicting its minimality. \square

By definition, the knot K is the union of two tangles T_1, T_2 , each of which is either $T(\frac{1}{3}, -\frac{1}{2}; 4)$ or its mirror image $T(-\frac{1}{3}, \frac{1}{2}; -4)$. Let $n = 4, s = 1$, and define a_k by $a_1 = a_6 = 1, a_2 = a_3 = 3$, and $a_4 = a_5 = 4$. One can check that these numbers satisfy the equations in Lemma 5.3. Since $T(\frac{1}{3}, -\frac{1}{2}; 4)$ is weakly equivalent to $T(\frac{1}{3}, \frac{1}{2})$, by Lemma 5.3 there is a special surface F_i in $E(T_i)$ that is the union of a_k copies of special disks of type (k) for $k = 1, \dots, 6$. By Lemma 5.4(iii), the curves $F_i \cap P(T)$ are represented by the train track in Figure 6(b), which splits to the one in Figure 7(5) because $r = 2 = 2s$. Similarly for $T_i = T(-\frac{1}{3}, \frac{1}{2}; -4)$. The graph in Figure 7(5) is preserved by the gluing map $\eta : \partial B_1 \rightarrow \partial B_2$, which by definition is a $(\pi/2)$ -rotation followed by a reflection along the vertical line. It follows that $F_1 \cup_\eta F_2$ form a surface F in $E(K)$.

Lemma 6.2. *F is a connected essential punctured torus in $E(K)$, with ∂F consisting of 4 circles of slope δ .*

Proof. The boundary slope δ of F is calculated in the proof of Proposition 5.8. In particular, δ is an integer in all three cases of K . Since $n = 4$ in the construction, we see that $|\partial F| = 4$.

Each F_i consists of $\sum a_i = 16$ disks, glued along $4r + 2(r + s) = 14$ edges as shown in Figure 4(c)–(d), and hence $\chi(F_i) = 16 - 14 = 2$. By Lemma 5.7, $F_i \cap P(T_i)$ is as shown in Figure 7(5), and hence it consists of $4r = 8$ arcs. Therefore $\chi(F) = \chi(F_1) + \chi(F_2) - 8 = -4$. Denote by \hat{F} the surface obtained from F by capping off each boundary component of F with a disk. Since $|\partial F| = 4$, we have $\chi(\hat{F}) = 0$. By Lemma 4.3, no component of \hat{F} is a sphere. It follows that each component of \hat{F} is a torus. In particular, no component of F is an annulus.

By Lemma 6.1, each F_i is incompressible and P -incompressible, and by Lemma 3.4, $P = P(T_1) = P(T_2)$ is also incompressible. By an innermost circle/outermost arc argument, one can thus show that $F = F_1 \cup F_2$ is incompressible in $E(K)$. Since no component of F is an annulus, this implies that F is also ∂ -incompressible, since otherwise two copies of a boundary compression disk and the annulus on $\partial N(K)$ bounded by two components of ∂F would contain a compressing disk of F .

By Proposition 5.8, any essential punctured torus has at least 4 boundary components. Since F has no closed component and $|\partial F| = 4$, it follows that F is connected. \square

Lemma 6.3. *Let M be a handlebody of genus 3, let c_1, c_2 be a pair of curves on ∂M , and let M' be the manifold obtained by attaching two 2-handles along c_1 and c_2 . If $\partial M - c_i$ is compressible for $i = 1, 2$, and $\partial M - c_1 \cup c_2$ is incompressible, then $\partial M'$ is incompressible.*

Proof. This is a standard application of the handle addition lemma [Jaco 1984]. Denote by M_1 the manifold obtained from M by attaching a 2-handle along c_1 . By assumption, there is a compressing disk D of ∂M that is disjoint from c_1 . If D is separating, then one component H of $M|D$ is a handlebody disjoint from c_1 , so we may rechoose D to be a nonseparating disk in H . Thus, after attaching a 2-handle to M along c_1 , D is still a compressing disk of ∂M_1 , so ∂M_1 is compressible. On the other hand, since $\partial M - c_2$ is compressible while $(\partial M - c_2) - c_1$ is incompressible, by the handle addition lemma applied to the pair $(M - c_2, c_1)$ we see that the surface $\partial M_1 - c_2$ is incompressible in M_1 . Now since ∂M_1 is compressible while $\partial M_1 - c_2$ is incompressible, we may apply the handle addition lemma again to conclude that after attaching a 2-handle to M_1 along c_2 , the boundary of the resulting manifold M' is incompressible. \square

Let F_0 be a separating surface in a 3-manifold M with

$$\partial F_0 = c_1 \cup \dots \cup c_n \cup c'_n \cup \dots \cup c'_1,$$

lying successively on a torus component R of ∂M . Let A_1 be the component of $R|\partial F_0$ bounded by $c_1 \cup c'_1$, and let A_k be the annulus on R that is bounded by $c_k \cup c'_k$ and contains A_1 . Starting with F_0 , one can construct a sequence of surfaces F'_k and F_k by adding the annulus A_k to F_{k-1} to obtain F'_k and then pushing the A_k part of F'_k off R to obtain F_k . The surfaces F_k are said to be obtained from F by *successively tubing through A_1* . The following lemma is probably due to Gordon.

Lemma 6.4. *Suppose F_0 is a connected separating incompressible surface in a 3-manifold M with ∂F_0 on a torus component R of ∂M . Let M'_0, M''_0 be the components of $M|F_0$, and let A_1 be an annulus component of $\partial M'_0 - \text{Int } F_0$. If $F'_1 = F_0 \cup A_1$ is incompressible in M'_0 , then the surfaces F_k obtained by successively tubing F through A_1 are all incompressible in M .*

Proof. We use the above notation, and let M'_k, M''_k be the components of $M|F_k$. Note that F_k are all connected and separating, and A_{k+1} is a component of $\partial M'_k - \text{Int } F_k$ or $\partial M''_k - \text{Int } F_k$. Hence, by induction, we need only show that F_1 is incompressible, and that if $n > 1$ then F'_2 is also incompressible in M''_1 .

Since F_1 is obtained by pushing the A_1 part of $F'_1 = F_0 \cup A_1$ into the interior of M , the component M'_1 of $M|F_1$ contained in M'_0 is homeomorphic to M'_0 , with $F_1 \subset \partial M'_1$ identified to $F_0 \cup A_1 \subset \partial M'_0$, and so by assumption F_1 is incompressible in M'_1 . When $n = 1$, the other component M''_1 is obtained by attaching a collar $R \times I$ to M''_0 along the annulus $A'_1 = R - \text{Int } A_1$. It is clear that A'_1 is incompressible in M''_1 . If it is also ∂ -incompressible, then an innermost circle/outermost arc argument shows that F_1 is incompressible in M''_1 , and if it is ∂ -compressible then F_0 must be an annulus that is parallel to A'_1 after cutting off some possible summands, so M''_1 is essentially a product $R \times I$ and hence F_1 is also incompressible. When

$n > 1$, M_1'' is obtained by attaching $A_2 \times I$ to M_0'' along the two annuli P and P' bounded by $c_1 \cup c_2$ and $c_1' \cup c_2'$. The incompressibility of F_0 implies that these annuli are incompressible. Also, there is no disk D in M_1'' intersecting $P \cup P'$ at a single essential arc, since otherwise the frontier of $N(D \cup P \cup P')$ would contain a compressing disk of F_0 . One can now apply an innermost circle/outermost arc argument to show that both F_1 and F_2' are incompressible in M_1'' . \square

Proof of Theorem 1.1. If K is not a type II knot or if δ is not an integer slope, then by [Wu 1996b, Theorems 3.6 and 4.4], $K(\delta)$ is Haken and hyperbolic, so we assume that K is a type II knot and δ is an integer slope. Write

$$(S^3, K) = T_1 \cup T_2,$$

with $T_i = T(p_i/q_i, \frac{1}{2})$. By [Wu 1996b, Theorem 2.3], $E(K)$ contains an essential branched surface \mathcal{B} that remains essential in $K(\delta)$, and hence by [Gabai and Oertel 1989] $K(\delta)$ is irreducible. Also, by the construction in the proof of [Wu 1996b, Theorem 2.3], the exterior of the \mathcal{B} is the disjoint union of $E(T_1)$ and $E(T_2)$, with vertical surface $U_+(T_i)$ on $\partial E(T_i)$.

We claim that $E(T_i)$ is not an I -bundle with $U_+(T_i)$ as a vertical annulus. If this were false, then after attaching a 2-handle to $U_+(T_i)$, the resulting manifold M_i would be an I -bundle over a closed surface, which must be a Klein bottle because ∂M_i is a torus. Since M_i is the exterior of a trefoil knot in S^3 , this would imply that there is a Klein bottle embedded in S^3 , which is absurd.

By [Brittenham 1998], if a small Seifert fiber space contains an essential lamination, then its exterior is an I -bundle; hence this implies that $K(\delta)$ cannot be a small Seifert fiber space. Therefore $K(\delta)$ is exceptional if and only if it is toroidal. By Proposition 5.8, $K(\delta)$ is toroidal only if (K, δ) is one of the three pairs listed, so we need only show that $K(\delta)$ is indeed a toroidal manifold for each of those pairs.

Let F be the surface constructed before Lemma 6.2. By that lemma, F is an essential punctured torus with ∂F consisting of four circles of slope δ given in Theorem 1.1.

Let

$$F_i = F \cap E(T_i), \quad P = P(T_i), \quad P_i = E(T_{i1}) \cap E(T_{i2}).$$

The special disks $F \cap E(T_{ij})$ in $E(T_{ij})$ cut $E(T_{ij})$ into a set of 3-balls B_k . The arcs $P_i \cap F_i$ cut P_i into a set of disks D_r , so the manifold $E(T_i)|F_i$ is obtained by gluing the B_k along the D_r , and hence is a set of handlebodies H_k . Also, $F \cap P$ cuts P into a set of disks D_r' , so $E(K)$ is obtained from the H_k by gluing along the D_r' , and hence is also a set of handlebodies. Since F is a punctured torus with four boundary components, it is separating in $E(K)$, so $E(K)|F$ has two components M_1 and M_2 ; and ∂M_i is the union of F with two annuli on $\partial N(K)$ and hence is a surface of genus 3. It follows that each M_i is a handlebody of genus 3.

Let A_1, A_2 be the two annuli $\partial M_i - \text{Int}(F)$, and let c_j be the core of A_j . Then by Lemma 6.2, the surface $\partial M_i - c_1 \cup c_2$, which is homotopic to F on ∂M_i , is incompressible. Note that $\partial M_i - c_1$ is homotopic to the surface $F \cup A_2$ obtained from F by tubing along A_2 . If this is incompressible, then by Lemma 6.4 the closed surface F' obtained from F by successively tubing through A_2 is incompressible. From the construction, one can see that F' has coannular slope δ on $\partial N(K)$ in the sense that there is an incompressible annulus A' that has interior disjoint from F' , with one boundary component on F' and the other on $\partial N(K)$ with slope δ . It is easy to see that any embedded essential surface in an irreducible 3-manifold has at most one coannular slope on a torus boundary component, and hence there is no disk in S^3 with boundary on F' that intersects K exactly once, so F' is K -essential in the sense of [Wu 1996b]. By Lemma 4.7 of that reference, there is no such closed surface in the exterior of a type II knot, which is a contradiction.

Let \hat{M}_1, \hat{M}_2 be the two components of $K(\delta)|\hat{F}$. Then \hat{M}_i is obtained from M_i by attaching two 2-handles along the curves $c_1, c_2 \subset \partial M_i$. We have shown above that M_i is a handlebody of genus 3, $\partial M_i - c_j$ is compressible, and $\partial M_i - c_1 \cup c_2$ is incompressible. Therefore by Lemma 6.3, the surface $\hat{F} = \partial \hat{M}_i$ is incompressible in \hat{M}_i . Since this is true for $i = 1, 2$, it follows that \hat{F} is an incompressible torus in $K(\delta)$. \square

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YING-QING WU
DEPARTMENT OF MATHEMATICS
UNIVERSITY OF IOWA
14 MACLEAN HALL
IOWA CITY, IA 52242-1419
UNITED STATES
wu@math.uiowa.edu

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chari@math.ucr.edu

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University of California
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long@math.ucsb.edu

Sorin Popa
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
popa@math.ucla.edu

Robert Finn
Department of Mathematics
Stanford University
Stanford, CA 94305-2125
finn@math.stanford.edu

Jiang-Hua Lu
Department of Mathematics
The University of Hong Kong
Pokfulam Rd., Hong Kong
jhlu@maths.hku.hk

Jie Qing
Department of Mathematics
University of California
Santa Cruz, CA 95064
qing@cats.ucsc.edu

Kefeng Liu
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
liu@math.ucla.edu

Alexander Merkurjev
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
merkurev@math.ucla.edu

Jonathan Rogawski
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
jonr@math.ucla.edu

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