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## Hopf plumbing and minimal diagrams

S. Baader

**Abstract.** We determine minimal diagrams and braid indices for fibered arborescent knots arising from plumbing positive or negative Hopf bands along trees.

### 1. Introduction

One of the most striking applications of the Jones polynomial concerns crossing numbers of knots. Indeed, several proofs of the first Tait conjecture were announced shortly after the discovery of the Jones polynomial (see [8], [11] and [15]). Yet there is another bound for the crossing number of knots coming from the HOMFLY polynomial (see [12] and [4]). In this paper we show that the latter estimate works especially well for fibered knots. More precisely, we exhibit a large class of fibered arborescent knots and find minimal diagrams for them. This class contains 50 knots of Rolfsen's table ([13]) and is not contained in the class of Montesinos links, for which minimal diagrams are known, already (see [9]).

Let  $\Gamma$  be a planar tree with signed vertices, as shown in Figure 1.

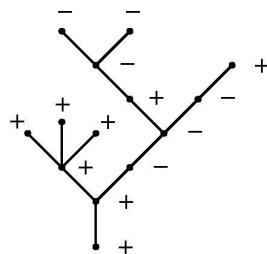


Figure 1. A planar tree with signs.

There is a well-known procedure, called Hopf plumbing, which associates a link  $K(\Gamma)$  to a planar tree with signs  $\Gamma$ :

- (1) Draw a positive or negative Hopf band (see Figure 2) at each vertex of  $\Gamma$ , according to its sign.
- (2) Plumb the Hopf bands together along the edges of  $\Gamma$ , as shown in Figure 3.

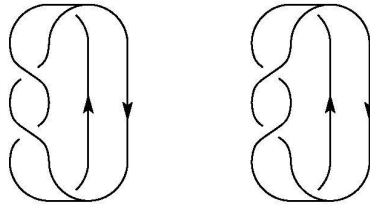


Figure 2. A positive and a negative Hopf band.

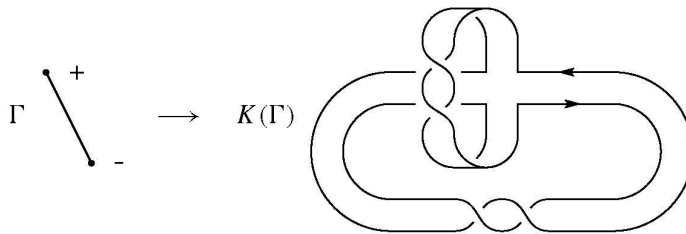


Figure 3. Plumbing along an edge.

We shall determine the minimal crossing number and draw minimal diagrams of knots associated with trees with signs. For this purpose we have to introduce two quantities of trees with signs  $\Gamma$ . Deleting all negative vertices of  $\Gamma$  we get a forest  $\Gamma_+$ , i.e. a union of trees (with positive signs). An analogous procedure (deleting all positive vertices of  $\Gamma$ ) yields  $\Gamma_-$ . We set

$$P(\Gamma) = \sum_{T \in \Gamma_+} s(T),$$

$$N(\Gamma) = \sum_{T \in \Gamma_-} s(T),$$

where the sums run over all trees  $T$  of the forests  $\Gamma_+$  or  $\Gamma_-$ , respectively, and the function  $s$  is defined as follows:

$$s(T) = 1 + \min\{\#S \mid S \subset E(T), T - S \text{ has no vertices of valency greater than two}\}.$$

Here  $E(T)$  is the set of edges of the tree  $T$ . We remark that  $s$  depends on the abstract structure of a tree only, whereas  $P$  and  $N$  depend on the abstract structure and the signs of a tree. Now we are ready to state our main result about the minimal crossing number  $c(K(\Gamma))$ .

**Theorem 1.** *Let  $\Gamma$  be a tree with signs such that  $K(\Gamma)$  is a knot with one component. Then*

$$c(K(\Gamma)) = V(\Gamma) + P(\Gamma) + N(\Gamma).$$

Here  $V(\Gamma)$  is the number of vertices of  $\Gamma$ .

**Remark.** The class of knots associated with trees with signs contains the class of slalom divide knots (see N. A'Campo [1] for a definition of slalom divide knots). Indeed, according to M. Hirasawa ([5], see also M. Ishikawa [6]), we know that slalom divide knots correspond to knots of certain slalom trees with positive signs only. Thus Theorem 1 proves a conjecture of M. Ishikawa ([7]) about the minimal crossing number of slalom divide knots.

It is well-known that every knot can be represented as the closure of a braid. The minimal number of strands among all the braids representing  $K$  is called the braid index  $b(K)$  of the knot  $K$ .

**Theorem 2.** *Let  $\Gamma$  be a tree with signs such that  $K(\Gamma)$  is a knot with one component. Then*

$$b(K(\Gamma)) = P(\Gamma) + N(\Gamma) + 1.$$

In the following section we prove a recursive formula for the function  $s$  for trees, which we shall use in the proof of Theorem 1. In the third section we present a lower bound for the minimal crossing number of knots and prove the inequality

$$c(K(\Gamma)) \geq V(\Gamma) + P(\Gamma) + N(\Gamma).$$

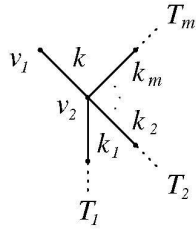
The proofs of Theorems 1 and 2 will be accomplished in the fourth section.

## 2. The function $s$ for trees

Let  $T$  be a tree,  $E(T)$  its set of edges. We call  $S \subset E(T)$  a *grinding subset* for  $T$ , if  $T - S$  has no vertex of valency greater than two. Thus the function  $s(T)$  equals one plus the minimal cardinality among all grinding subsets for  $T$ .

Let  $k$  be an outer edge of  $T$ . Figure 4 shows a section of  $T$  near  $k$ .

Two vertices of  $T$  are incident with  $k$ ; they are labelled  $v_1$  and  $v_2$ . The trees of the forest  $T - \{v_1, v_2\}$  are labelled  $T_1, T_2, \dots, T_m$ . They are attached to the vertex  $v_2$  by the edges  $k_1, k_2, \dots, k_m$ .

Figure 4. A section of  $T$ .**Proposition.**

$$s(T) = \max \{s(T - v_1), \sum_{i=1}^m s(T_i)\}.$$

*Proof.* First we observe that

$$s(T - v_1) \leq s(T) \leq 1 + s(T - v_1).$$

Further, a careful inspection of the definition of  $s$  shows that

$$\sum_{i=1}^m s(T_i) \leq s(T) \leq 1 + \sum_{i=1}^m s(T_i).$$

Indeed, if  $S$  is a grinding subset for  $T$ , then  $S - \{k, k_1, k_2, \dots, k_m\}$  is a grinding subset for the forest  $T - \{v_1, v_2\}$ . This implies the first inequality, since  $\#S \cap \{k, k_1, k_2, \dots, k_m\} \geq m - 1$ . Conversely, if  $S$  is a grinding subset for the forest  $T - \{v_1, v_2\}$ , then  $S \cup \{k_1, k_2, \dots, k_m\}$  is a grinding subset for  $T$ . This implies the second inequality.

In order to prove the proposition, we have to exclude the case

$$s(T) = 1 + s(T - v_1) = 1 + \sum_{i=1}^m s(T_i).$$

Suppose  $s(T) = 1 + s(T - v_1)$ . Let  $S$  be a minimal grinding subset for  $T - v_1$ , i.e. a grinding subset for  $T - v_1$  of minimal cardinality. Since  $s(T) = 1 + s(T - v_1)$ , the vertex  $v_2$  must have valency two in  $T - v_1 - S$ ; say  $k_1, k_2 \in E(T - v_1 - S)$ . We claim that  $S \cap E(T_i)$  is a minimal grinding subset for  $T_i$ ,  $1 \leq i \leq m$ . If  $i \neq 1, 2$ , this is obvious, since then  $k_i \notin E(T - v_1 - S)$ . The case  $i = 1$  (and, analogously, the case  $i = 2$ ) needs a special consideration. Suppose  $T_1$  had a grinding subset  $S_1 \subset E(T_1)$  of smaller cardinality than  $S \cap E(T_1)$ . Then the subset

$$\tilde{S} = S - (S \cap E(T_1)) \cup S_1 \cup \{k_1\} \subset E(T - v_1)$$

were a minimal grinding subset for  $T - v_1$ . Furthermore, the vertex  $v_2$  would have valency one in  $T - v_1 - \tilde{S}$ , which is a contradiction to the assumption  $s(T) = 1 + s(T - v_1)$ . Finally,  $S \cup \{k\}$  is a minimal grinding subset for  $T$  with

$$\#S \cup \{k\} = m - 1 + \sum_{i=1}^m \#S \cap E(T_i) = m - 1 + \sum_{i=1}^m (s(T_i) - 1).$$

Hence

$$s(T) = \sum_{i=1}^m s(T_i). \quad \square$$

### 3. The HOMFLY polynomial and crossing numbers

The HOMFLY polynomial is a Laurent polynomial in two variables  $a$  and  $z$ , which is normalized to one for the trivial knot and satisfies the following relation (see [2]):

$$\frac{1}{a} P_{\times}(a, z) - a P_{\times}(a, z) = z P_{\cup}(a, z).$$

We denote the minimal degree in the variable  $a$  of  $P_K(a, z)$  by  $e(K)$ , the maximal degree by  $E(K)$ . The following theorem is mainly due to K. Murasugi ([12]); an explicit formulation can be found in H. Gruber (see Lemma 3.2. and Corollary 6.1. in [4]).

**Theorem 3.** (i)  $c(K) \geq \frac{1}{2}(E(K) - e(K)) + 2g(K)$ .

(ii) If  $c(K) = \frac{1}{2}(E(K) - e(K)) + 2g(K)$ , then

$$b(K) = \frac{1}{2}(E(K) - e(K)) + 1.$$

Here  $g(K)$  is the minimal genus among all orientable surfaces spanning the knot  $K$ .

*Proof.* Let  $D$  be a minimal diagram of the knot  $K$ . There is a natural Seifert surface  $S(D)$  associated with  $D$ . Its Euler characteristic  $\chi(S(D))$  equals  $s(D) - c(D)$ , where  $s(D)$  and  $c(D)$  denote the number of Seifert circles and the number of crossings of the diagram  $D$ , respectively. We conclude

$$c(K) = c(D) = s(D) - \chi(S(D)) \geq b(K) + 2g(K) - 1.$$

The last inequality follows from a theorem of S. Yamada ([17]) which asserts that the number of Seifert circles in any diagram of a knot  $K$  cannot be smaller than the braid index of  $K$ . An alternative simple proof of this fact is due to P. Vogel ([16]). Now

both statements of Theorem 3 follow immediately by Morton's inequality (see [10]; a thorough discussion on braid index criteria can be found in A. Stoimenow [14]):

$$b(K) \geq \frac{1}{2}(E(K) - e(K)) + 1. \quad \square$$

We observe that the plumbing construction of Hopf bands along a tree provides a natural fiber surface of minimal genus (see [3]). Therefore

$$2g(K(\Gamma)) = V(\Gamma),$$

in case  $K(\Gamma)$  is a knot. Comparing the first statement of Theorem 3 and Theorem 1, we see that it remains to settle the equation

$$E(K(\Gamma)) - e(K(\Gamma)) = 2P(\Gamma) + 2N(\Gamma)$$

to establish the desired lower bound for the crossing number of Theorem 1. It turns out that the range in the variable  $a$  of  $P_K(a, z)$  is not affected by the specialization  $z = 1$ . Therefore we restrict our computations to the polynomial in one variable

$$O_K(a) = P_K(a, 1).$$

Further we redefine  $e(K)$  and  $E(K)$  as the minimal and maximal degree of  $O_K(a)$ , respectively. In order to compute  $e(K)$  and  $E(K)$ , we have to keep track on the signs of the extremal coefficients very carefully. Thus let us write  $\sigma_e(K)$  and  $\sigma_E(K)$  for the signs of the minimal and maximal coefficients of  $O_K(a)$ , respectively.

**Lemma.** *Let  $\Gamma$  be a tree with signs (here  $K(\Gamma)$  may have several components).*

- (i)  $e(K(\Gamma)) = V(\Gamma_+) - V(\Gamma_-) - 2N(\Gamma)$ .
- (ii)  $E(K(\Gamma)) = V(\Gamma_+) - V(\Gamma_-) + 2P(\Gamma)$ .
- (iii)  $\sigma_e(K(\Gamma)) = (-1)^{V(\Gamma_-) + N(\Gamma)}$ .
- (iv)  $O_{K(\Gamma)}(a)$  is either even or odd and alternating, i.e. there are natural numbers  $c_k \neq 0$ ,  $e \leq k \leq E$  such that

$$O_{K(\Gamma)}(a) = (-1)^{\sigma_e} \sum_{l=0}^{\frac{1}{2}(E-e)} (-1)^l c_{e+2l} a^{e+2l}.$$

$$\text{In particular, } \sigma_E(K(\Gamma)) = (-1)^{V(\Gamma_-) + P(\Gamma)}.$$

*Proof.* First we observe that the lemma is true if  $\Gamma$  has one vertex only. Indeed,

$$O_{K(\bullet+)} = 2a - a^3,$$

$$O_{K(\bullet, \cdot)} = a^{-3} - 2a^{-1}.$$

Now let us assume that all the statements of the lemma are true for all trees  $\Gamma$  with  $n$  ( $\geq 1$ ) vertices, at most. We have to verify the statements for a tree  $\Gamma$  with  $n+1$  ( $\geq 2$ ) vertices. Let  $k$  be an outer edge of  $\Gamma$ , as shown in Figure 4. As before, two vertices ( $v_1$  and  $v_2$ ) are incident with  $k$ . In addition, each vertex carries a sign. Now let us remember the defining relation for  $O_K(a)$ :

$$\frac{1}{a} O_{\times}(a) - a O_{\times}(a) = O_{\setminus}(a). \quad (1)$$

We shall apply this relation to a crossing of the Hopf band at the vertex  $v_1$ . For this purpose, we have to understand the effect of the following two operations:

- (1) Smoothing a crossing at  $v_1$  (in an oriented manner) causes a small collapse; the Hopf band at  $v_1$  disappears. At this point, it may be helpful to look at Figure 3.

$$K(\Gamma) \longrightarrow K(\Gamma - \{v_1\}).$$

- (2) A crossing change at  $v_1$  causes a big collapse; the Hopf bands at  $v_1$  and  $v_2$  disappear, and we end up with a connected sum of all the arborescent links corresponding to the trees of the forest  $\Gamma - \{v_1, v_2\}$ . We notice that these trees  $T_1, T_2, \dots, T_m$  are trees with signs.

$$K(\Gamma) \longrightarrow K(T_1) \# \dots \# K(T_m), \quad T_i \in \Gamma - \{v_1, v_2\}.$$

After these preparations, we are in a position to carry out the inductive step. However, we have to consider four cases corresponding to the signs of the vertices  $v_1$  and  $v_2$ , separately.

**Case 1.**  $v_1$  and  $v_2$  carry negative signs. Relation (1) for  $K(\Gamma)$  at  $v_1$  reads

$$\frac{1}{a} O_{K(T_1)}(a) \dots O_{K(T_m)}(a) - a O_{K(\Gamma)}(a) = O_{K(\Gamma - \{v_1\})}(a),$$

since the HOMFLY polynomial is multiplicative under the connected sum operation. Thus

$$O_{K(\Gamma)}(a) = \frac{1}{a^2} O_{K(T_1)}(a) \dots O_{K(T_m)}(a) - \frac{1}{a} O_{K(\Gamma - \{v_1\})}(a). \quad (2)$$

We remark that

$$P(\Gamma) = P(\Gamma - \{v_1\}) = \sum_{i=1}^m P(T_i).$$

Therefore, the maximal degrees and the signs of the maximal coefficients of  $\frac{1}{a^2} O_{K(T_1)}(a) \dots O_{K(T_m)}(a)$  and  $-\frac{1}{a} O_{K(\Gamma - \{v_1\})}(a)$  agree, and we conclude that  $O_{K(\Gamma)}(a)$  is either even or odd and alternating. Furthermore,

$$E(K(\Gamma)) = V(\Gamma_+) - V(\Gamma_-) + 2P(\Gamma),$$



$$\sigma_E(K(\Gamma)) = (-1)^{V(\Gamma_-) + P(\Gamma)}.$$

As to the minimal degree, we need the statement of the proposition in the second section:

$$N(\Gamma) = \max \{N(\Gamma - \{v_1\}), \sum_{i=1}^m N(T_i)\}.$$

In any case, we conclude

$$e(K(\Gamma)) = V(\Gamma_+) - V(\Gamma_-) - 2N(\Gamma).$$

**Case 2.**  $v_1$  carries a negative sign,  $v_2$  carries a positive sign. As in the first case, equation (2) holds for  $O_{K(\Gamma)}(a)$ . The crucial quantities are

$$P(\Gamma) = P(\Gamma - \{v_1\}),$$

$$\left| P(\Gamma) - \sum_{i=1}^m P(T_i) \right| \leq 1,$$

$$N(\Gamma) = 1 + N(\Gamma - \{v_1\}) = 1 + \sum_{i=1}^m N(T_i).$$

Thus  $\frac{1}{a^2} O_{K(T_1)}(a) \dots O_{K(T_m)}(a)$  contributes to the required minimal degree of  $O_{K(\Gamma)}(a)$  with the correct sign, whereas  $-\frac{1}{a} O_{K(\Gamma - \{v_1\})}(a)$  contributes to the required maximal degree of  $O_{K(\Gamma)}(a)$  with the correct sign. In particular,  $O_{K(\Gamma)}(a)$  is either even or odd and alternating.

The remaining two cases (i.e.  $v_1$  carries a positive sign) can be treated analogously; no new phenomena occur. Alternatively, we may consider the mirror image of  $K(\Gamma)$  and replace the variable  $a$  of  $O_{K(\Gamma)}(a)$  by  $-a^{-1}$ .  $\square$

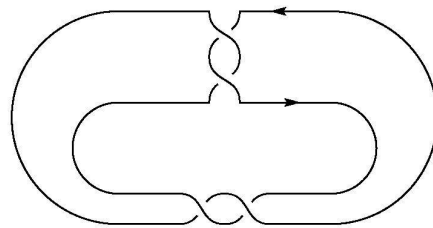
As an immediate consequence of the lemma, the width of  $O_{K(\Gamma)}(a)$  equals  $2P(\Gamma) + 2N(\Gamma)$ . However, the width of  $P_{K(\Gamma)}(a, z)$  in the variable  $a$  could still be greater than  $2P(\Gamma) + 2N(\Gamma)$ . In any case, due to the first statement of Theorem 3, we get the required lower bound for the number of crossings:

$$c(K(\Gamma)) \geq V(\Gamma) + P(\Gamma) + N(\Gamma),$$

in case  $K(\Gamma)$  is a knot.

#### 4. Construction of minimal diagrams

In this section, we construct minimal diagrams for knots associated with trees with signs and accomplish the proofs of Theorems 1 and 2. First we remark that a knot  $K(\Gamma)$  has a natural diagram with  $2V(\Gamma)$  crossings. This fact is illustrated in Figure 5 for the knot  $K(\text{X})$ .

Figure 5. A natural diagram of  $K(\Gamma)$ .

If the signs of the vertices of  $\Gamma$  are distributed in an alternating pattern, then  $P(\Gamma) + N(\Gamma) = V(\Gamma)$ , and Theorem 1 is true. This is no surprise, since in this case, the natural diagram of  $K(\Gamma)$  is alternating. Now suppose  $\Gamma$  contains an edge  $k$  with two positive vertices. Then we can change the natural diagram of  $K(\Gamma)$  in order to eliminate one crossing, as shown in Figure 6. The two squares contain the parts of the diagram of  $K(\Gamma)$  corresponding to  $\Gamma - k$ ; we may possibly have to flype a square through the corresponding twisted band before we can apply such a reduction move.

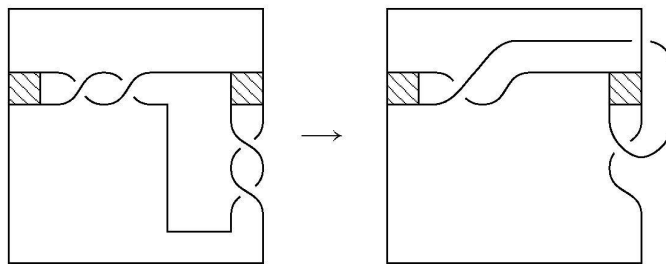


Figure 6. Eliminating a crossing at a positive edge.

However, the Hopf bands of the two involved vertices are damaged by this process; they both 'lose one crossing'. Hence we cannot apply this procedure to more than two edges containing the same vertex. If  $T$  is a subtree of  $\Gamma_+$ , then we can choose  $V(T) - P(T)$  edges of  $T$  such that their union does not contain any vertex of valency greater than 2 (by definition of the function  $P$ ). Thus we can eliminate  $V(T) - P(T)$  of the crossings associated with  $T$ , even if  $T$  is a single point (since then  $V(T) - P(T) = 1 - 1 = 0$ ). The same is true for subtrees of  $\Gamma_-$ , of course, replacing  $P(T)$  by  $N(T)$ . Altogether, we can eliminate  $V(\Gamma) - P(\Gamma) - N(\Gamma)$  crossings of the natural diagram of  $K(\Gamma)$ , ending up with

$$2V(\Gamma) - (V(\Gamma) - P(\Gamma) - N(\Gamma)) = V(\Gamma) + P(\Gamma) + N(\Gamma)$$

crossings. As a consequence, Theorem 1 is true. Finally, Theorem 2 is a consequence of the second statement of Theorem 3.

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## 5. Table

The subsequent table lists all knots associated with trees with signs up to ten crossings. We need only consider eight types of trees, on account of Theorem 1. They are drawn in the first column of Table 1. The second column lists all knots with 10 or fewer crossings that arise from the trees of the first column, depending on different choices of signs. We use Rolfsen's notation ([13]).

We may ask ourselves for which knots the inequality





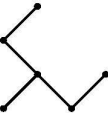
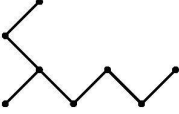
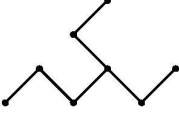
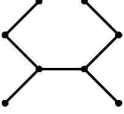
$$c(K) \geq \frac{1}{2}(E(K) - e(K)) + 2g(K)$$

is actually an equality. A result of K. Murasugi says that equality holds for alternating fibered knots (see [12], Theorem A and Corollary 2). It turns out that equality holds for 86 knots, up to ten crossings, namely the 50 knots of Table 1, and 36 more knots:

8<sub>16</sub>, 8<sub>17</sub>, 8<sub>18</sub>, 9<sub>29</sub>, 9<sub>32</sub>, 9<sub>33</sub>, 9<sub>34</sub>, 9<sub>40</sub>, 9<sub>47</sub>, 10<sub>5</sub>, 10<sub>9</sub>, 10<sub>17</sub>, 10<sub>45</sub>, 10<sub>69</sub>, 10<sub>75</sub>,  
10<sub>81</sub>, 10<sub>82</sub>, 10<sub>85</sub>, 10<sub>88</sub>, 10<sub>89</sub>, 10<sub>91</sub>, 10<sub>94</sub>, 10<sub>96</sub>, 10<sub>99</sub>, 10<sub>100</sub>, 10<sub>104</sub>, 10<sub>105</sub>,  
10<sub>106</sub>, 10<sub>107</sub>, 10<sub>109</sub>, 10<sub>110</sub>, 10<sub>112</sub>, 10<sub>115</sub>, 10<sub>116</sub>, 10<sub>118</sub>, 10<sub>123</sub>.

We remark that all these knots are fibered. However, there exist non-fibered knots whose minimal crossing number equals  $\frac{1}{2}(E(K) - e(K)) + 2g(K)$ , e.g. the knots 11a263 and 14n6302 (here we use the Dowker–Thistlethwaite numbering). These examples were found by A. Stoimenow.

Table 1. Trees and knots up to 10 crossings.

tree	knots
	$3_1, 4_1$
	$5_1, 6_2, 6_3, 7_6, 7_7, 8_{12}$
	$7_1, 8_2, 8_7, 8_9, 9_{11}, 9_{17}, 9_{20}, 9_{26}, 9_{27}, 9_{31}, 10_{29}, 10_{41}, 10_{42}, 10_{43}, 10_{44}$
	$9_1, 10_2$
	$8_5, 8_{10}, 8_{19}, 9_{22}, 9_{24}, 9_{28}, 9_{30}, 9_{36}, 9_{43}, 10_{59}, 10_{60}, 10_{70}, 10_{71}, 10_{73}, 10_{78}, 10_{138}$
	$10_{46}, 10_{47}, 10_{48}, 10_{124}$
	$10_{62}, 10_{64}, 10_{139}$
	$10_{79}, 10_{152}$

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