



# The lexicographic degree of the first two-bridge knots

Erwan Brugallé, Pierre-Vincent Koseleff, Daniel Pecker

► **To cite this version:**

Erwan Brugallé, Pierre-Vincent Koseleff, Daniel Pecker. The lexicographic degree of the first two-bridge knots. 2018. hal-01108678v2

**HAL Id: hal-01108678**

**<https://hal.archives-ouvertes.fr/hal-01108678v2>**

Submitted on 11 Sep 2018

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# The lexicographic degree of the first two-bridge knots

Erwan Brugallé, Pierre-Vincent Koseleff, Daniel Pecker

September 13, 2018

## Abstract

We study the degree of polynomial representations of knots. We give the lexicographic degree of all two-bridge knots with 11 or fewer crossings. First, we estimate the total degree of a lexicographic parametrisation of such a knot. This allows us to transform this problem into a study of real algebraic trigonal plane curves, and in particular to use the braid theoretical method developed by Orevkov.

**MSC2000:** 14H50, 57M25, 11A55, 14P99

**Keywords:** Real pseudoholomorphic curves, polynomial knots, two-bridge knots, Chebyshev curves

## Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>A lower bound for the total degree of two-bridge knots</b>	<b>3</b>
2.1	Trigonal diagrams of two-bridge knots . . . . .	3
2.2	Total degree of two-bridge knots . . . . .	6
<b>3</b>	<b>Degrees of trigonal plane diagrams</b>	<b>12</b>
3.1	Lower bounds on degrees of plane trigonal diagrams . . . . .	13
3.2	Application of Orevkov’s braid theoretical method . . . . .	13
3.3	The T-reduction . . . . .	15
3.4	The T-augmentation . . . . .	16
<b>4</b>	<b>Two-bridge knots with 11 crossings or fewer</b>	<b>19</b>
4.1	The general strategy . . . . .	19
4.2	Some initial diagrams . . . . .	20
4.3	Two-bridge knots with crossing number at most 6 . . . . .	21
4.4	Two-bridge knots with crossing number 7 . . . . .	22
4.5	Two-bridge knots with crossing number 8 . . . . .	22
4.6	Two-bridge knots with crossing number 9 . . . . .	25
4.7	Two-bridge knots with crossing number 10 or 11 . . . . .	27
<b>5</b>	<b>Conclusion</b>	<b>27</b>

# 1 Introduction

A polynomial parametrisation of a knot  $K$  in  $\mathbf{S}^3$  is a polynomial map  $\gamma : \mathbf{R} \rightarrow \mathbf{R}^3$  whose closure of the image in  $\mathbf{S}^3$  is isotopic to  $K$ . Every knot admits a polynomial parametrisation, see [Sh, Va]. In this paper we are interested in determining the *lexicographic degree* of a knot  $K \subset \mathbf{S}^3$ , i.e. the minimal degree for the lexicographic order of a polynomial parametrisation of  $K$ .

The unknot has lexicographic degree  $(-\infty, -\infty, 1)$ , and it is easy to see that the lexicographic degree of any other knot is  $(a, b, c)$  with  $3 \leq a < b < c$ . *Two-bridge* knots are precisely those with lexicographic degree  $(3, b, c)$ , see [KP2]; they have a  $xy$ -projection which is a trigonal curve. See Figure 1 for two examples of trigonal polynomial parametrisations of a long knot.

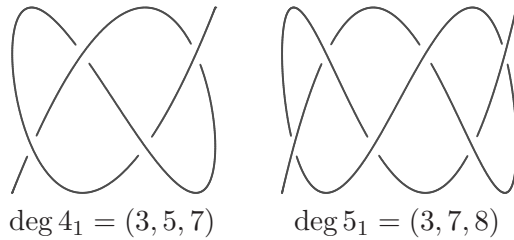


Figure 1: Trigonal polynomial diagrams of the figure-eight knot  $4_1$  and the torus knot  $5_1$

Two-bridge knots are an important family of knots. The first 26 knots (except  $8_5$ ) are two-bridge knots. Moreover these knots are classified by their Schubert fractions, which can be easily computed from any trigonal projection, see Section 2.1.

One might expect that the lexicographic degree of a knot  $K$  is obtained for a minimal-crossing diagram of this knot. This is not true. The diagram on the left of Figure 2 is a minimal crossing diagram of the knot  $9_{15}$ . On the right of the figure is a 10-crossing diagram of smaller degree of the same knot. This is why it is necessary to consider all the diagrams

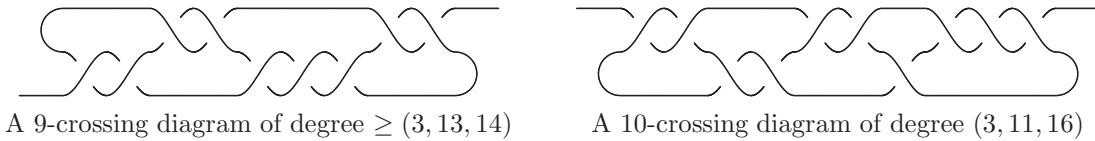


Figure 2: Two diagrams of  $9_{15}$

of two-bridge knots. The enumeration of all possible diagrams of a given two-bridge knot can be efficiently done using Conway's notation.

In this paper, we show:

**Theorem.** *The lexicographic degree of all 186 two-bridge knots with crossing number at most  $N \leq 11$  is  $(3, b, 3N - b)$ , where the values of  $b$  are listed in Table 5, p. 28.*

We prove this result in two steps.

**Proposition 2.9** *The lexicographic degree  $(3, b, c)$  of a knot with crossing number  $N \leq 11$  satisfies  $b + c = 3N$ .*

Proposition 2.9 also holds for all  $N$  when  $b \leq N + 3$  or  $b = \lfloor \frac{3N-1}{2} \rfloor$ . We prove in Theorem 2.5 that  $b + c \geq 3N$  for any polynomial parametrisation of degree  $(3, b, c)$  of a knot with crossing number  $N$ . Furthermore, every two-bridge knot of crossing number  $N$  admits a parametrisation of degree  $(3, b, c)$  with  $b + c = 3N$ , see [KP2]. We do not know if Proposition 2.9 holds for all crossing numbers  $N \geq 12$ .

Proposition 2.9 allows us to reduce the determination of the lexicographic degree of a two-bridge knot to the study of plane curves. For knots with 11 crossings or fewer, it is enough to determine the smallest integer  $b$  such that a plane projection admits a polynomial parametrisation of degree  $(3, b)$ . This reduction to plane curves enlarges the set of tools at our disposal; in particular we make an important use of Orevkov's braid theoretical approach in the study of pseudoholomorphic curves.

Hence the second step in the proof of our theorem is to focus on parametrisations of plane projections. We introduce the T-reduction in Section 3.3, that corresponds to the projection of the Lagrange isotopy on trigonal diagrams. The T-reduction allows us to remove a triangle of crossings from a diagram, and therefore to obtain an upper bound for degrees we are looking for. On the other hand, we introduce the T-augmentation in Section 3.4 that allows us to add a triangle of crossings to a given diagram  $D$ . From a polynomial parametrisation corresponding to  $D$  we deduce a parametrisation for the new diagram.

We propose an algorithm to find the lexicographic degrees of the first 186 two-bridge knots with 11 crossings or fewer. As a byproduct of our computations, we also exhibit in Table 6 the 16 two-bridge knots with 11 crossings or fewer for which the lexicographic degree is smaller than the degree of their minimal-crossing diagrams.

The paper is organised as follows. In Section 2.1 we recall Conway's notation for trigonal diagrams of two-bridge knots. Then we prove the inequality  $b + c \geq 3N$  in Section 2.2 and deduce Proposition 2.9. In Section 3, we consider plane trigonal curves and we first obtain a lower bound for the lexicographic degree of a trigonal polynomial embedding in Proposition 3.2. We obtain another bound for pseudoholomorphic curves and therefore for polynomial embeddings in Proposition 3.7. In Section 4, we obtain the lexicographic degrees of the first 186 two-bridge knots with 11 crossings or fewer.

## 2 A lower bound for the total degree of two-bridge knots

### 2.1 Trigonal diagrams of two-bridge knots

A two-bridge knot admits a diagram in *Conway's open form* (or trigonal form). This diagram, denoted by  $C(m_1, m_2, \dots, m_k)$  where  $m_i \in \mathbf{Z}$ , is explained by Figure 3 (see [Co], [Mu, p. 187]). The number of twists is denoted by the integer  $|m_i|$ , and the sign of  $m_i$  is

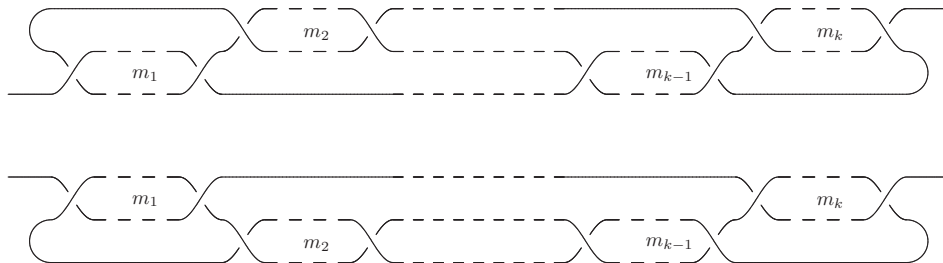


Figure 3: Conway's form for two-bridge knots (or links)

defined as follows: if  $i$  is odd, then the right twist is positive, if  $i$  is even, then the right twist is negative. In Figure 3 the integers  $m_i$  are all positive. Figure 4 shows the examples  $C(0, 1, 3)$ ,  $C(3, 0, -1, -2)$ .



Figure 4: Examples of trigonal diagrams

The two-bridge knots (or links) are classified by their Schubert fractions

$$\frac{\alpha}{\beta} = m_1 + \frac{1}{m_2 + \frac{1}{\dots + \frac{1}{m_k}}}, \quad \alpha \geq 0, \quad (\alpha, \beta) = 1.$$

Given  $[m_1, \dots, m_k] = \frac{\alpha}{\beta}$  and  $[m'_1, \dots, m'_l] = \frac{\alpha'}{\beta'}$ , the diagrams  $C(m_1, m_2, \dots, m_k)$  and  $C(m'_1, m'_2, \dots, m'_l)$  correspond to isotopic knots (or links) if and only if  $\alpha = \alpha'$  and  $\beta' \equiv \beta^{\pm 1} \pmod{\alpha}$ , see [Mu, Theorem 9.3.3].

Every positive fraction  $\alpha/\beta$  admits a continued fraction expansion  $[m_1, \dots, m_k]$  where all the  $m_i$  are positive. Therefore every two-bridge knot  $K$  admits a diagram in *Conway's normal form*, that is an alternating diagram of the form  $C(m_1, m_2, \dots, m_k)$ , where the  $m_i$  are all positive or all negative.

It is classical that one can transform any trigonal diagram of a two-bridge knot into Conway's normal form using the Lagrange isotopies, see [Cr, p. 204].

**Definition 2.1** Let  $C(u, m, -n, -v)$  be a trigonal diagram, where  $m, n$  are integers, and  $u, v$  are (possibly empty) sequences of integers, see Figure 5. The Lagrange isotopy on  $D$  is

$$C(u, m, -n, -v) \rightarrow C(u, m - \varepsilon, \varepsilon, n - \varepsilon, v), \quad \varepsilon = \pm 1, \quad (1)$$

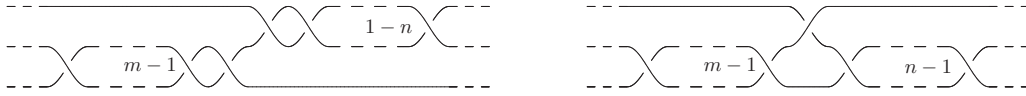


Figure 5: Lagrange isotopy:  $C(u, m, -n, -v) \rightarrow C(u, m - 1, 1, n - 1, v)$

If  $D = C(m_1, \dots, m_k)$  is not in Conway's normal form, then it may happen that  $m_1 = 0$  or  $m_k = 0$ . In this case, the diagram  $D' = C(m_3, \dots, m_k)$  or  $D' = C(m_1, \dots, m_{k-2})$  respectively, is the *reduced diagram* of  $D$ . Since the diagram  $C(m_1, \dots, m_i, 0, 0, m_{i+1}, m_{i+2}, \dots, m_k)$  is identical to  $C(m_1, \dots, m_k)$ , we can assume that if  $m_i = 0$  then  $m_{i-1}m_{i+1} \neq 0$ .

Given a finite integer sequence  $(m_1, \dots, m_k)$ , we say that there is a *sign change* between  $m_i$  and  $m_{i+1}$  if  $m_i m_{i+1} < 0$  or if  $m_i = 0$  and  $m_{i-1} m_{i+1} < 0$ .

**Proposition 2.2** *Let  $C(m_1, \dots, m_k)$  be a diagram of a knot with crossing number  $N$ . Let  $N_0 = \sum_{i=1}^k |m_i|$  be the number of crossings, and  $\sigma$  be the number of sign changes in the sequence  $(m_1, \dots, m_k)$ . Then we have*

$$N \leq N_0 - \sigma.$$

*Proof.* If  $\sigma = 0$ , then the inequality means that the crossing number of a knot is not greater than the number of crossings of a diagram of this knot. Consequently, we can suppose  $\sigma \geq 1$ . Let us prove the result by induction on  $N_0 = \sum_{i=1}^k |m_i|$ . We have to consider two cases.

First, let us suppose that the diagram is of the form  $C(u, m, -n, -v)$ ,  $m, n > 0$ . Then by a Lagrange isotopy we see that  $C(u, m - 1, 1, n - 1, v)$  is another diagram of  $K$ . In this new diagram, the number of crossings and the number of sign changes are both diminished by 1. Therefore we obtain by induction:

$$N \leq (N_0 - 1) - (\sigma - 1) = N_0 - \sigma.$$

Next, let us consider a diagram of the form  $C(u, m, 0, -n, v)$ ,  $mn > 0$ . In this case we consider the new diagram  $C(u, m - n, v)$ . If  $\sigma'$  is the number of sign changes of this new diagram, then a case by case inspection shows that  $\sigma' \geq \sigma - 2$ . As the number of crossings is diminished by at least 2, we obtain by induction:

$$N \leq (N_0 - 2) - (\sigma - 2) = N_0 - \sigma,$$

which concludes the proof. □

The proof of Proposition 2.2 also implies the following lemma.

**Lemma 2.3** *In the notation of Proposition 2.2, we have:*

1. If  $\sigma = 0$ , then  $N < N_0$  if and only if  $m_1 \cdot m_k = 0$ .
2. If  $\sigma = 1$ , then we have  $N < N_0 - 1$  if and only if one of the following situations occurs:
  - $m_1 = 0$  or  $m_k = 0$ ,
  - there exists  $i$  such that  $m_i = 0$  and  $m_{i-1}m_{i+1} < 0$ ,
  - $|m_1| = 1$  and  $m_1m_2 < 0$  or  $|m_k| = 1$  and  $m_{k-1}m_k < 0$ .

Let  $D$  be a long knot diagram, and  $\gamma : \mathbf{R} \rightarrow \mathbf{R}^3$  be a parametrisation of  $D$  whose crossing points corresponds to the parameters  $t_1 < \dots < t_{2m}$ . Recall that the *Gauss sequence* of  $D$  is the sequence  $g_1, \dots, g_{2m}$  where  $g_i = 1$  if  $t_i$  corresponds to an overpass, and  $g_i = -1$  otherwise.

**Proposition 2.4** *Let  $C(m_1, \dots, m_k)$ ,  $m_i \neq 0$ , be a trigonal diagram of a knot  $K$ , and  $N_0 = \sum |m_i|$ . Let  $s$  be the number of sign changes in the Gauss sequence of the diagram,  $\sigma$  be the number of sign changes in the sequence  $(m_1, \dots, m_k)$ , and  $\sigma_2$  be the number of consecutive sign changes in the sequence  $(m_1, \dots, m_k)$ . Then, we have*

$$s = 2N_0 - 3\sigma + 2\sigma_2 - 1.$$

*Proof.* We proceed by induction on  $(\sigma_2, \sigma)$ . If  $\sigma = 0$  then  $\sigma_2 = 0$  and the diagram of  $K$  is alternating. In this case we have  $s = 2 \sum |m_i| - 1 = 2N_0 - 1$ .

If  $\sigma_2 = 0$ , we may assume that  $m_1 > 0$ . Let  $j$  be the first index just that  $m_i < 0$ . Then  $j = k$  or  $m_{j+1} < 0$ , because  $\sigma_2 = 0$ . Let us consider the knot  $K'$  defined by  $K' = C(m_1, \dots, m_{j-1}, -m_j, -m_{j+1}, \dots, -m_k)$ . We see that the number of sign changes in the Conway sequence of  $K'$  is  $\sigma' = \sigma - 1$ , and that we still have  $\sigma'_2 = 0$ . By induction we get  $s' + 3\sigma' = 2 \sum |m_i| - 1$ . Since we have  $s' = s + 3$ , this completes the proof when  $\sigma_2 = 0$ .

Now, let us suppose that  $\sigma_2 > 0$  and consider the first index  $j$  such that  $m_{j-1} m_j < 0$  and  $m_j m_{j+1} < 0$ . Consider  $K'$  defined by  $K' = C(m_1, \dots, m_{j-1}, -m_j, -m_{j+1}, \dots, -m_k)$ . We see that the number of sign changes in the Conway sequence of  $K'$  is  $\sigma' = \sigma - 1$  and also  $\sigma'_2 = \sigma_2 - 1$ . By induction we get  $s' + 3\sigma' - 2\sigma'_2 = 2 \sum |m_i| - 1$ . Since we have  $s' = s + 1$ , this concludes the proof.  $\square$

## 2.2 Total degree of two-bridge knots

The next theorem provides a lower bound on the total degree of every trigonal knot diagram. It generalises [BKP2, Theorem 4.3], which proves that the lexicographic degree of a knot of crossing number  $N$  is at least  $(3, N + 1, 2N - 1)$ .

**Theorem 2.5** *Let  $\gamma : \mathbf{R} \rightarrow \mathbf{R}^3$  be a polynomial parametrisation of degree  $(3, b, c)$  of a knot of crossing number  $N$ . Then we have*

$$b + c \geq 3N.$$

*Proof.* We shall denote our polynomial knot  $\gamma(t) = (x(t), y(t), z(t))$ . Without loss of generality, we may assume that  $b$  is not divisible by 3. Let  $C(m_1, m_2, \dots, m_k)$  be the corresponding  $xy$ -diagram. To simplify the exposition, we shall first suppose that  $m_i \neq 0$  for  $i = 2, \dots, k - 1$ .

By the genus formula, the plane curve  $C$  parametrised by  $C(t) = (x(t), y(t))$  has exactly  $b - 1$  nodes in  $\mathbf{C}^2$ . Let  $N_0 = \sum_{i=1}^k |m_i|$  be the number of real crossings of  $C$  (i.e. real nodes of  $C$  which are the intersection of two real branches of  $C$ ), and let  $\delta = b - 1 - N_0$  be the number of other nodes of  $C$ .

The real crossings are ordered by increasing abscissae. A real crossing is called *special* if its Conway sign (for the trigonal diagram) is different from the Conway sign of the preceding crossing.



Figure 6: Special crossings of  $C(3, -1, 1, -1, 1, -2)$  and  $C(2, -1, -1, 2)$

The number of special crossings, denoted by  $\sigma$ , is the number of sign changes in the Conway sequence  $(m_1, m_2, \dots, m_k)$ . By Proposition 2.2, we have  $N \leq N_0 - \sigma$ . Let  $D(x)$  be the monic polynomial of degree  $\sigma + \delta$ , whose roots are the abscissas of the  $\sigma$  special crossings and the abscissas of the  $\delta$  nodes that are not crossings. The polynomial  $D(x)$  is real.

Let  $\mathcal{V}$  be the vector space of polynomials  $V(x, y) \in \mathbf{C}[x, y]$  such that

$$\deg(V(x(t), y(t))) \leq 2b - 4.$$

The monomials  $x^\alpha y^\beta$  such that  $3\alpha + b\beta \leq 2b - 4$  form a basis of  $\mathcal{V}$ , and it is not difficult to see that the number of these monomials is  $b - 1$ .

Let  $\mathcal{F}$  be the vector space of complex functions defined on the set of nodes of  $C$ . The restriction induces a linear mapping  $\iota : \mathcal{V} \rightarrow \mathcal{F}$  between spaces of the same dimension. If  $U(x, y)$  is in the kernel of  $\iota$ , then we have  $U(x(t), y(t)) = 0$  for  $2b - 2$  values of  $t$ . Since  $\deg U(x(t), y(t)) \leq 2b - 4$ , we see that  $U(x, y) = 0$ . Hence  $\iota$  is an injective mapping and then it is an isomorphism.

For each non-special crossing with parameters  $(t_i, s_i)$ , let  $h_i$  be a real number in the open interval  $(z(t_i), z(s_i))$ . Since  $\iota$  is an isomorphism, there exists a unique polynomial  $V(x, y)$  such that  $V(x_i, y_i) = h_i D(x_i)$  for each non-special crossing  $(x_i, y_i)$ , and  $V(x, y) = 0$  for all other nodes of  $C$ . By uniqueness, we see that  $V(x, y)$  is a real polynomial. Let us consider the rational function  $h(t)$  defined by

$$h(t) = \frac{V(x(t), y(t))}{D(x(t))}.$$

Each parameter  $t$  of a special crossing (or *special parameter*) is a zero of the numerator and a simple zero of the denominator. Consequently, the function  $h(t)$  is defined for all



crossing parameters. Up to perturbing  $z(t)$  by a constant if necessary, we can assume that  $z(t_i) \neq h(t_i)$  for all crossing parameters  $t_i$ .

Now, we shall prove that the polynomial equation

$$z(t)D(x(t)) - V(x(t), y(t)) = 0 \quad (2)$$

has at least  $2b - 3$  distinct roots.

First, the two parameters  $t, s$  of a node such that  $V(x, y) = D(x) = 0$  are roots of this equation. The number of such roots is  $2(\sigma + \delta)$ . The other roots are the zeroes of the rational function  $\Delta(t) = z(t) - h(t)$ .

An interval  $[r, s] \subset \mathbf{R}$  is called *minimal* if  $r, s$  are two non-special node parameters, and if  $s > r$  is minimal for this property. In other words, there is no non-special node parameter  $\tau$  in  $(r, s)$ . The number of minimal intervals is exactly  $2(N_0 - \sigma) - 1$ .

We claim that every minimal interval contains a zero of  $\Delta(t)$  that is not a node parameter. Then the number of distinct roots of Equation (2) must be at least

$$2(N_0 - \sigma) - 1 + 2(\sigma + \delta) = 2(N_0 + \delta) - 1 = 2b - 3,$$

and the degree of the equation must be at least  $2b - 3$ .

Since  $\deg V(x(t), y(t)) \leq 2b - 4$ , we deduce that

$$\deg(z(t)D(x(t))) = c + 3(\delta + \sigma) \geq 2b - 3,$$

and then  $b + c \geq 3(b - 1 - \delta - \sigma) = 3(N_0 - \sigma) \geq 3N$ , which conclude the proof in this case.

Let us prove our claim. To do so, we study the sign of the rational function  $\Delta(t)$  on the minimal interval  $[r, s]$ . Let  $j$  be the number of special parameters contained in  $[r, s]$ , and let  $t_0 = r, t_{j+1} = s$ . If  $j \neq 0$ , then let  $t_1 < t_2 < \dots < t_j$  be the special parameters contained in  $[r, s]$ . The function  $\Delta(t)$  is defined for each  $t_i$ , and we have  $\Delta(t_i) \neq 0$ . The poles occur for the parameters  $\tau \in [r, s]$  such that  $D(x(\tau)) = 0$  and  $(x(\tau), y(\tau))$  is not a crossing, they are simple poles. Let  $[t_h, t_{h+1}]$  be the interval where the function  $x(t), \tau \in [r, s]$  has a maximum. On this interval there is either one pole and no alternation in the Gauss sequence of the knot, or no pole and one alternation. Figures 7 and 8 shows the main cases, the interval  $[t_h, t_{h+1}]$  corresponds to the rightmost sub-arc  $AC$  of the arc parametrised by  $[r, s]$ .

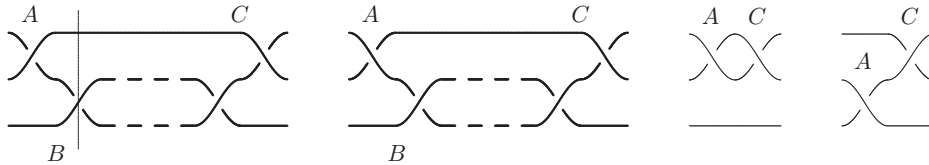


Figure 7: The rightmost sub-arc  $AC$  (ordinary cases)

On the other intervals  $[t_i, t_{i+1}]$ ,  $i \neq h$  there is either one pole and one alternation, or no pole and no alternation, see Figure 9. Consequently, we see that  $\Delta(r)\Delta(s) < 0$  if and only

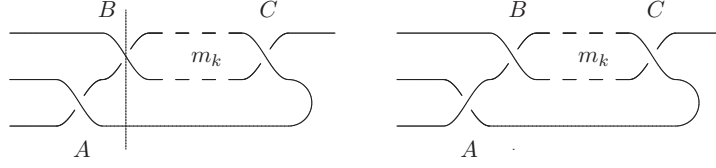


Figure 8: The rightmost sub-arc  $AC$  (exceptional case)

if the number of poles contained in  $[r, s]$  is even. On the other hand, the number of sign changes in  $[r, s]$  of the function  $\Delta(t)$  is odd if and only if  $\Delta(r)\Delta(s) < 0$ . Consequently, whatever the sign of  $\Delta(r)\Delta(s)$  may be, there must be at least one  $u \in [r, s]$  which is not a pole, and where  $\text{sign}(\Delta(t))$  changes. Hence,  $u$  is a root of Equation (2), which proves the claim.

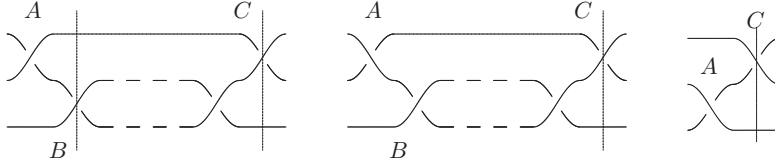


Figure 9: The other sub-arcs  $AC$

In the general case, there may be some  $m_i = 0$  in the diagram  $C(m_1, m_2, \dots, m_k)$ , where  $2 \leq i \leq k - 1$ . We shall inductively select some relevant crossings, and ignore the others.

If there is a subsequence of the form  $(m, 0, -n), m \geq n > 0$ , then we declare the last  $2n$  crossings irrelevant, and we consider the new Conway sequence where  $(m, 0, -n)$  has been changed to  $m - n$ . We iterate this selection (by elimination) until we obtain a diagram  $C(m_1, \dots, m_k)$  such that  $m_i \neq 0$ , for  $i = 2, \dots, k - 1$ . Then, considering only the relevant crossings, we choose the special crossings. We also define  $D(x) = V(x, y) = 0$  for the special crossings, the irrelevant crossings and the nodes that are not crossings. The rest of the proof is similar to the preceding one, except that the number of poles on each minimal interval  $[r, s]$  may be increased by an even number, which does not change the sign of  $\Delta(r)\Delta(s)$ .  $\square$

In [KP2], it is proved that every two-bridge knot of crossing number  $N$  admits an explicit parametrisation of the form  $(T_3, T_b, C)$  where  $T_n$  is the Chebyshev polynomial of degree  $n$  defined by  $T_n(\cos t) = \cos nt$ , and  $b + \deg C = 3N$ . Moreover, the harmonic knot  $H(3, b, c) : (T_3, T_b, T_c)$ , where  $b < c < 2b$ ,  $b + c \equiv 0 \pmod{3}$  has crossing number  $N = \frac{1}{3}(b + c)$ , see [KP2, Corollary 6.6].

Combining with Theorem 2.5 we deduce the following.

**Corollary 2.6** *The lexicographic degree  $(3, b, c)$  of a two-bridge knot of crossing number  $N$  satisfies:*

$$3 < b < c < 2b, b \not\equiv 0 \pmod{3}, b + c \equiv 0 \pmod{3}, b + c \geq 3N, \\ (3, N + 1, 2N - 1) \leq (3, b, c) \leq (3, \lfloor \frac{3N-1}{2} \rfloor, \lfloor \frac{3N}{2} \rfloor + 1).$$

Moreover, these inequalities are best possible.

*Proof.* The transformation  $(x, y, z) \mapsto (x, y - \lambda x^u, z - \mu x^v y^w)$ , where  $u, v, w$  are nonnegative integers and  $\lambda, \mu \in \mathbf{R}$ , does not change the nature of the knot. This ensures that  $b \not\equiv 0 \pmod{3}$  and  $b + c \equiv 0 \pmod{3}$ . Next, it is proved in [KP2], that every two-bridge knot admits a polynomial parametrisation of lexicographic degree  $(3, b, c)$ , with  $b + c = 3N$ . This implies that  $b \leq \lfloor \frac{3N-1}{2} \rfloor$ . Furthermore if  $b = \lfloor \frac{3N-1}{2} \rfloor$ , then  $c \leq 3N - \lfloor \frac{3N-1}{2} \rfloor = \lfloor \frac{3N}{2} \rfloor + 1$ . If  $\gamma : \mathbf{R} \rightarrow \mathbf{R}^3$  is a polynomial parametrisation of degree  $(3, b, c)$  of a knot, then by forgetting the last coordinate we obtain a polynomial map  $\mathbf{R} \rightarrow \mathbf{R}^2$  of degree  $(3, b)$  with at least  $N$  crossings. The genus formula implies that  $b \geq N + 1$ . In the case  $b = N + 1$ , Theorem 2.5 implies that  $c \geq 2N - 1$ .

Let us show that these bounds are sharp. If  $N \not\equiv -1 \pmod{3}$ , then the harmonic knot  $H(3, N+1, 2N-1)$  is of degree  $(3, N+1, 2N-1)$ . If  $N \equiv -1 \pmod{3}$ , then  $b \geq N+2$  and then  $c \geq 2N-2$ . In this case, the harmonic knot  $H(3, N+2, 2N-2)$  is of degree  $(3, N+2, 2N-2)$ . The twist knots of crossing number  $N$  are of maximal degree  $(3, \lfloor \frac{3N-1}{2} \rfloor, \lfloor \frac{3N}{2} \rfloor + 1)$ , see [BKP2].  $\square$

**Remark 2.7** *The degree of a harmonic knot may be smaller than the degree of its harmonic diagram. For example the knot  $H(3, 11, 16) = \bar{9}_{17}$  is of degree  $(3, 10, 17)$ , see Table 4.*

**Proposition 2.8** *Let  $(3, b, c)$  be the lexicographic degree of a two-bridge knot of crossing number  $N$ . If  $b \leq N + 3$  or  $b = \lfloor \frac{3N-1}{2} \rfloor$  then we have  $b + c = 3N$ .*

*Proof.* By Theorem 2.5, we have  $b + c \geq 3N$ , and  $b + c = 3N$  if  $b = \lfloor \frac{3N-1}{2} \rfloor$  by Corollary 2.6. Hence we assume now that  $b \leq N + 3$ . Let  $\gamma(t) = (x(t), y(t), z(t))$  be a polynomial representation of our knot  $K$  of degree  $(3, b, c)$ , and denote by  $D = C(m_1, \dots, m_k)$  the trigonal diagram of  $\gamma$ . If  $s$  denote the number of sign changes in the Gauss sequence of the parametrisation  $\gamma$ , we clearly have  $c \leq s$ . Hence it remains us to obtain an upper bound for  $s$ , using Propositions 2.2 and 2.4.

Let  $N_0 = \sum |m_i|$ , and  $\sigma$  be the number of sign changes in the sequence  $(m_1, \dots, m_k)$ . Combining Propositions 2.2 and the genus formula for plane curves, we obtain

$$N + \sigma \leq N_0 \leq b - 1. \tag{3}$$

First, suppose that  $b = N + 3$ . In this case  $N \not\equiv 0 \pmod{3}$ , and  $c \equiv -N \pmod{3}$ , by Corollary 2.6. Consequently  $c \not\equiv 2N - 1 \pmod{3}$  and  $c \not\equiv 2N - 2 \pmod{3}$ . Hence we only have to prove that  $c \leq 2N - 1$ .

1. First, suppose that  $D = C(x, m, 0, -n, -y)$  with  $mn > 0$ , see Figure 10. Since  $N_0 \leq N + 2$ , we necessarily have  $|m| = 1$  or  $|n| = 1$ . Without loss of generality, we can assume that  $n = 1$  and  $m > 0$ . Consider the diagram  $D' = C(x, m - 1, -y)$  obtained by a type-II Reidemeister move on  $D$ . The diagram  $D'$  has  $N_0 - 2 = N$  crossings, and then is an alternating diagram of  $K$ . Consequently the number  $s'$  of sign changes in the Gauss sequence of  $D'$  is  $s' = 2N - 1$ .

If  $(x, m) \neq (1)$  and  $(n, y) \neq (1)$ , then we have  $s = s' = 2N - 1$  and consequently  $c \leq 2N - 1$ , see Figure 10.



Figure 10:  $C(x, m, 0, -1, -y) \mapsto C(x, m - 1, -y)$

If we have  $(x, m) = (1)$  or  $(n, y) = 1$ , then we can suppose  $(n, y) = (1)$  and  $D = C(x, m, 0, -1)$ . If we change the nature of the last two crossings, then we obtain another diagram  $\tilde{D} = C(x, m - 1, 0, -1, 0, 1)$  of  $K$  with the same  $xy$ -projection. By the previous case, we see that the number of sign changes in the Gauss sequence of  $\tilde{D}$  is  $\tilde{s} = 2N - 1$ . Consequently  $\tilde{D}$  is of degree at most  $(3, N + 3, 2N - 3)$ .

2. Then, suppose that  $D = C(x, n, -1)$  (the case  $D = C(1, -m, y)$  is similar). By changing the nature of the last two crossings of  $D$ , we obtain another diagram  $\tilde{D} = C(x, n - 1, 0, -1, 1)$  of the same knot, see Figure 11. By case 1 above, we see that the number of sign changes in the Gauss sequence of  $\tilde{D}$  is  $\tilde{s} = 2N - 1$  and we deduce that  $\tilde{D}$  is of degree  $(3, N + 3, 2N - 3)$ .

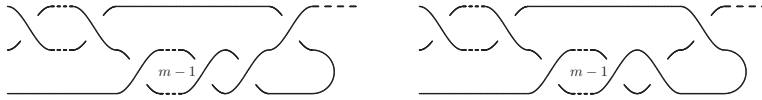


Figure 11:  $C(x, m, -1) = C(x, m - 1, 0, 1, -1) \mapsto \tilde{D} = C(x, m - 1, 0, -1, 1)$

3. Now, suppose that  $D$  is not in the cases 1 and 2 above. If  $\sigma = 2$ , then  $N_0 = N + 2$  and  $\sigma_2 \leq 1$ . By Proposition 2.4, we obtain  $s = (2N_0 - 1) - 3\sigma + 2\sigma_2 \leq 2N - 1$ .

If  $\sigma < 2$ , then by Lemma 2.3 we have  $m_1 \cdot m_k = 0$ . Consider the reduced diagram  $D'$ . If  $\sigma = 0$ , then  $D'$  is alternating and has  $N_0 = N$  crossings. Its Gauss sequence is alternating and has  $s' = 2N - 1$  sign changes. If  $\sigma = 1$ , then  $D'$  may have  $N'_0 = N$  or  $N'_0 = N + 1$  crossings. If  $N'_0 = N$  then  $D'$  is alternating and there are  $s' = 2N - 1$  sign changes in its Gauss sequence. If  $N'_0 = N + 1$ , then  $D'$  is not alternating and  $\sigma'_1 = 1$ . We thus have  $s' = 2N + 1 - 3 = 2N - 2$  by Proposition 2.4.

We then choose a polynomial of degree  $c \leq s' \leq 2N - 2$  as an height function for the reduced diagram  $D'$ . If  $m_1 = 0$  (resp.  $m_k = 0$ ), the signs of the  $|m_2|$  (resp.  $|m_{k-1}|$ ) crossings do not affect the nature of the knot.

At the end we find a polynomial height function  $z(t)$  of degree  $c \leq 2N - 1$ .

If  $b = N + 2$ , then  $N \not\equiv 1 \pmod{3}$  and  $2N - 1 \in \langle 3, b \rangle$ . Hence again, we only have to prove  $c \leq 2N - 1$ . By Inequality (3), we may have  $N_0 = N$  or  $N_0 = N + 1$ .

1. If  $N_0 = N$ , then the diagram is alternating and  $s \leq 2N - 1$ .
2. If  $N_0 = N + 1$ , then  $\sigma \leq 1$ . If  $\sigma = 1$ , then  $s \leq 2N - 1$  by Proposition 2.4. If  $\sigma = 0$ , then  $m_1 \cdot m_k = 0$  by Lemma 2.3. The reduced diagram is alternating and its Gauss sequence has  $s' \leq 2N - 1$  sign changes and so  $c \leq 2N - 1$ .

At the end we find a polynomial function  $z(t)$  of degree  $c \leq 2N - 1$ .

If  $b = N + 1$  then  $N_0 = N$  and the diagram is alternating. We thus have  $c \leq s \leq 2N - 1$ .  $\square$

We deduce

**Proposition 2.9** *The lexicographic degree  $(3, b, c)$  of a knot with crossing number  $N \leq 11$  satisfies  $b + c = 3N$ .*

*Proof.* By Proposition 2.6, we have  $(3, b, c) \leq (3, \lfloor \frac{3N-1}{2} \rfloor, \lfloor \frac{3N}{2} \rfloor + 1)$ . If  $b \leq N + 3$  or  $b = \lfloor \frac{3N-1}{2} \rfloor$ , we conclude using Proposition 2.8. If  $b \geq N + 4$  and  $b < \lfloor \frac{3N-1}{2} \rfloor$ , then  $N = 11$ , and  $b = 15$  which is impossible since  $b$  is not divisible by 3.  $\square$

### 3 Degrees of trigonal plane diagrams

Thanks to the relation  $b + c = 3N$  established in Proposition 2.9, we are now reduced to study plane trigonal curves. It is enough to determine the smallest integer  $b$  such that the  $xy$ -projection of some diagram of  $K$  admits a polynomial parametrisation of degree  $(3, b)$ .

Given a long knot diagram  $D$  in  $\mathbf{R}^3$ , we denote by  $|D|$  its projection to  $\mathbf{R}^2$  (i.e. we forget about the sign of the crossings). If  $D = C(m_1, \dots, m_k)$ , we use the notation  $|D| = D(|m_1|, \dots, |m_k|)$ . An isotopy of  $\mathbf{R}^2$  is called an  $\mathcal{L}$ -isotopy if it commutes with the projection  $\mathbf{R}^2 \rightarrow \mathbf{R}$  forgetting the second coordinate.

**Definition 3.1** *The algebraic degree of  $|D|$  is the minimal integer  $b$  such that there exists a real algebraic curve  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  of bidegree  $(3, b)$  such that  $\gamma(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to  $|D|$ .*

We first establish a lower bound for polynomial curves in Proposition 3.2.

### 3.1 Lower bounds on degrees of plane trigonal diagrams

**Proposition 3.2** *Let  $|D|$  be the plane diagram  $D(m_1, m_2, \dots, m_k)$ , with  $m_i \geq 2$  for  $i = 1, \dots, k$ . Then the algebraic degree of  $|D|$  is at least  $3k - 1$ . If in addition we have  $m_i \geq 3$  for some  $i$ , then the algebraic degree of  $|D|$  is at least  $3k + 1$ .*

*Proof.* Let  $\gamma(t) : (x(t), y(t))$  be a polynomial parametrisation of  $|D|$  with  $x(t)$  of degree 3, and let  $C$  be the image of  $\gamma$ . The complement of  $C$  contains  $m_j - 1$  disks corresponding to the  $j$ th group of crossings of  $|D|$ . Let us choose a point  $P_j$  in one of these disks. There is a polynomial curve of equation  $y = P(x)$  with  $\deg P = k - 1$  containing the  $k$  points  $P_j$ . Since

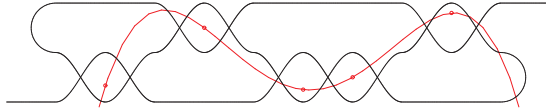


Figure 12: The plane diagram  $D(2, 2, 3, 2)$

the number of intersections of this curve and  $C$  is at least  $2k + (k - 1) = 3k - 1 > 3(k - 1)$ , we deduce that  $\deg(y(t)) \geq 3k - 1$ .

If in addition some  $m_i \geq 3$ , we choose one more point  $P_{k+1}$  in another disk of the  $i$ th group of two-sided domains. Then we count the intersections of  $C$  with a curve  $y = P(x)$   $\deg(P(x)) = k$  containing the  $k + 1$  points  $P_j$ ,  $j = 1, \dots, k + 1$ . Since this number is at least  $2(k + 1) + (k - 1) = 3k + 1 > 3k$ , we deduce that  $\deg(y(t)) \geq 3k + 1$  (see Figure 12 in the case of  $D(2, 2, 3, 2)$ ).  $\square$

### 3.2 Application of Orevkov's braid theoretical method

To obtain lower bounds on the algebraic degree  $b$ , it is convenient to enlarge the category of objects under interest, and to consider *real pseudoholomorphic curves* rather than real algebraic curves. Doing so, we can use the full power of the braid theoretical approach developed by Orevkov to study real curves in  $\mathbf{C}^2$ . Using this strategy, we determined in [BKP2] the lexicographic degree of all torus knots  $C(m)$  and generalised twist-knots  $C(m, n)$ . We refer to [BKP2, Section 3.2] for the definition of a real pseudoholomorphic curve  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  of bidegree  $(3, b)$  where  $b$  is a positive integer. Recall that a real algebraic map  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  of degree  $(3, b)$  is an example of a real pseudoholomorphic curve of bidegree  $(3, b)$ . Without loss of generality, we only consider in this text nodal pseudoholomorphic curves.

**Definition 3.3** *The pseudoholomorphic degree of  $|D|$  is the minimal integer  $b$  such that there exists a real pseudoholomorphic curve  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  of bidegree  $(3, b)$  such that  $\gamma(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to  $|D|$ . It is not greater than the algebraic degree of  $|D|$ .*

Recall that the *group of braids with 3-strings* is defined as

$$B_3 = \langle \sigma_1, \sigma_2 \mid \sigma_1 \sigma_2 \sigma_1 = \sigma_2 \sigma_1 \sigma_2 \rangle.$$

We refer to [BKP2, Sections 2 and 3] for an algorithm that associates an  $\mathcal{L}$ -scheme and a braid  $\mathfrak{b}_C \in B_3$  to any real pseudoholomorphic curve  $C = \gamma(\mathbf{C})$ , with  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  a real pseudoholomorphic curve of bidegree  $(3, b)$ . A braid  $\mathfrak{b} \in B_3$  is said to be *quasipositive* if it can be written in the form

$$\mathfrak{b} = \prod_{i=1}^l w_i \sigma_1 w_i^{-1} \quad \text{with } w_1, \dots, w_l \in B_3. \quad (4)$$

Note that a braid with algebraic length 0 is quasipositive if and only if it is the trivial braid. The quasipositivity problem in  $B_3$  has been solved by Orevkov [Or3]. We will use the following proposition in order to obtain lower bounds in lexicographic degree of knots.

**Proposition 3.4** *Let  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  be a real pseudoholomorphic curve of bidegree  $(3, b)$ , and let  $C = \gamma(\mathbf{C})$ . We denote by  $\pi : \mathbf{C}^2 \rightarrow \mathbf{C}$  the projection to the first coordinate, and we assume that the two critical points of the map  $\pi \circ \gamma$  are real. Then the braid  $\mathfrak{b}_C$  satisfies the three following properties:*

- (i)  $\mathfrak{b}_C$  is quasipositive;
- (ii) the closure of  $\mathfrak{b}_C$  is a link with three components;
- (iii) the linking number of any two strings of  $\mathfrak{b}_C$  is non-negative.

*Proof.* Property (i) is a consequence of [Or1, Proposition 7.1]. Properties (ii) and (iii) are easy consequences of the Riemann–Hurwitz formula applied to the map  $\pi \circ \gamma$ , see [BKP2, second paragraph of the proof of Proposition 3.1].  $\square$

**Remark 3.5** *Proposition 3.4(i) can be strengthened in order to get an equivalence. Given  $l \in \mathbf{Z}_{\geq 1}$  and  $\varepsilon = 1$  or  $2$ , we define  $b = 3l - \varepsilon$ . Let  $\mathcal{L}_S$  be the trigonal  $\mathcal{L}$ -scheme*

$$\mathcal{L}_S = \bullet_{i_1} \cdots \bullet_{i_{\alpha_1}} \subset_* \times_{j_1} \cdots \times_{j_{N_0}} \supset_* \bullet_{i_{\alpha_1+1}} \cdots \bullet_{i_{\alpha}} \star, \quad (5)$$

where  $\star = \downarrow$  or  $\uparrow$  if  $\varepsilon = 1$ , and  $\star = \vee$  or  $\wedge$  if  $\varepsilon = 2$ . Then one can associate a braid  $\mathfrak{b}_C$ , depending on  $b$ , to the  $\mathcal{L}$ -scheme  $\mathcal{L}_S$  using the algorithm given in [BKP2, Section 2.2]. Following [Or1, Proposition 7.1], we have that  $\mathcal{L}_S$  is realised by a real pseudoholomorphic curve of bidegree  $(3, b)$  in  $\mathbf{C}^2$  if and only if the braid  $\mathfrak{b}_C$  can be written in the form

$$\mathfrak{b}_C = \prod_{i=1}^{\ell} w_i \sigma_1^2 w_i^{-1} \quad \text{with } w_1, \dots, w_{\ell} \in B_3. \quad (6)$$

Note that in this case, we necessarily have  $\deg \mathfrak{b}_C = 2\ell = b - 1 - \alpha - N_0$ .

**Remark 3.6** *Proposition 3.2 also holds for the pseudoholomorphic degree of a plane trigonal diagram, and the proof is essentially the same. Nevertheless we will not need this more general version here.*

We end this section by proving a slight generalisation of [BKP2, Proposition 3.1].

**Proposition 3.7** *Let  $D = C(m_1, \dots, m_k)$  be a trigonal diagram of a knot  $K$ , with  $m_1, \dots, m_{k-1}$  even integers. As usual, we define  $N_0 = m_1 + \dots + m_k$ . If  $\gamma : \mathbf{C} \rightarrow \mathbf{C}^2$  is a real rational pseudoholomorphic curve of bidegree  $(3, b)$  such that  $\gamma(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to  $|D|$ , then  $2b \geq 3N_0 - 2$ .*

*Proof.* Let us write  $b = 3l - 1$  or  $b = 3l - 2$ , let  $\alpha$  be the number of solitary nodes of  $C = \gamma(\mathbf{C})$ , and  $2\beta$  be the number of complex conjugated nodes. By the genus formula, we have

$$N_0 + \alpha + 2\beta = b - 1.$$

The  $\mathcal{L}$ -scheme realised by  $C$  has the form

$$\bullet_{i_1} \cdots \bullet_{i_{\alpha_1}} \subset_* (\times_{j_1})^{m_1} \cdots (\times_{j_k})^{m_k} \supset_* \bullet_{i_{\alpha_1+1}} \cdots \bullet_{i_{\alpha}} \star,$$

where  $\star = \downarrow, \uparrow, \vee$  or  $\wedge$ . The braid  $\mathfrak{b}_C$  has 3 components  $L_1, L_2$  and  $L_3$ , and  $\text{lk}(L_i, L_j) \geq 0$  by Proposition 3.4. Furthermore, as in [BKP2, proof of Proposition 3.1], we have  $0 \leq \text{lk}(L_i, L_j) \leq \beta$ .

By the assumptions made on  $D$ , there are two strings of  $\mathfrak{b}_C$ , say  $L_1$  and  $L_3$ , that do not cross at the crossing points of  $\mathbf{R}C$ . Each  $\bullet_j \bullet_{j'}$  contributes at least  $-1$  to  $\text{lk}(L_1, L_3)$ . Hence as in [BKP2, Proof of Proposition 3.1], we obtain

$$2\beta \geq 2\text{lk}(L_1, L_3) \geq l - \alpha - 2,$$

and thus

$$b - 1 = N_0 + \alpha + 2\beta \geq N_0 + l - 2.$$

We then deduce  $3b - 3N_0 \geq 3l - 3 \geq b - 2$ , and  $2b \geq 3N_0 - 2$ .  $\square$

### 3.3 The T-reduction

**Definition 3.8** *Let  $x, y$  be (possibly empty) sequences of nonnegative integers and  $m, n$  be nonnegative integers. The plane diagram  $D(x, m, n, y)$  is called a T-reduction of the diagram  $D(x, m + 1, 1, n + 1, y)$  (see Figure 13).*

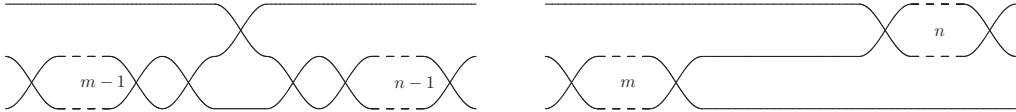


Figure 13: T-reduction

Propositions 3.9 and 3.11 below relate the pseudoholomorphic and algebraic degrees of two plane trigonal diagrams differing by a T-reduction.



**Proposition 3.9** *Let  $|D_1|$  and  $|D_2|$  be two plane trigonal diagrams such that  $|D_2|$  is obtained from  $|D_1|$  by a T-reduction. If  $|D_1|$  has pseudoholomorphic degree  $b$ , then  $|D_2|$  has pseudoholomorphic degree  $b - 3$ .*

*Proof.* Let  $|D_1| = D(m_1, \dots, m_k)$  and  $|D_2| = D(n_1, \dots, n_l)$ . Suppose that there exists a real pseudoholomorphic curve  $\gamma_1 : \mathbf{C} \rightarrow \mathbf{C}^2$  of bidegree  $(3, b)$  such that  $\gamma_1(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to  $|D_1|$ , and suppose that its associated  $\mathcal{L}$ -scheme is

$$\bullet_{i_1} \cdots \bullet_{i_{\alpha_1}} \subset_* (\times_{j_1})^{m_1} \cdots (\times_{j_k})^{m_k} \supset_* \bullet_{i_{\alpha_1+1}} \cdots \bullet_{i_\alpha} \star. \quad (7)$$

The braid associated to  $\gamma_1$  is the same that the braid associated to the  $\mathcal{L}$ -scheme

$$\bullet_{i_1} \cdots \bullet_{i_{\alpha_1}} \subset_* (\times_{j_1})^{n_1} \cdots (\times_{j_l})^{n_l} \supset_* \bullet_{i_{\alpha_1+1}} \cdots \bullet_{i_\alpha} \star. \quad (8)$$

Hence according to Remark 3.5, there exists a real pseudoholomorphic curve  $\gamma_2 : \mathbf{C} \rightarrow \mathbf{C}^2$  of bidegree  $(3, b - 3)$  such that  $\gamma_2(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to  $|D_2|$ .  $\square$

**Corollary 3.10** *The pseudoholomorphic degree of the plane diagram  $D(0, n)$  is  $\lfloor \frac{3n}{2} \rfloor + 1$ .*

*Proof.* The plane diagram  $D(0, n)$  is obtained by a T-reduction from  $D(1, 1, n + 1)$ . Since  $D(1, 1, n + 1)$  and  $D(2, n)$  may be reduced to each other by slide isotopies, they have the same pseudoholomorphic degree by Proposition 4.3. By [BKP2, Theorem 3.9], the degrees are  $\lfloor \frac{3n}{2} \rfloor + 4$ , which completes the proof.  $\square$

### 3.4 The T-augmentation

Proposition 3.9 admits a weaker version for the algebraic degree of a plane diagram. We make use the T-augmentation that consists in adding a triangle of crossing points in a given plane diagram.

**Proposition 3.11** *Let  $|D_1|$  and  $|D_2|$  be two plane trigonal diagrams such that  $|D_2|$  is obtained from  $|D_1|$  by a reduction T. If  $|D_2|$  has algebraic degree  $b - 3$ , then  $|D_1|$  has algebraic degree at most  $b$ . Furthermore, if the pseudoholomorphic degree of  $|D_2|$  is also  $b - 3$ , then  $|D_1|$  has algebraic degree exactly  $b$ .*

*Proof.* The last assertion simply follows from the fact that a real rational algebraic curve in  $\mathbf{C}^2$  is a pseudoholomorphic curve. Let

$$\begin{aligned} \gamma : \mathbf{C} &\longrightarrow \mathbf{C}^2 \\ t &\longmapsto (P(t), Q(t)) \end{aligned} \quad (9)$$

be a real algebraic map with  $P(t)$  of degree 3 and  $Q(t)$  of degree  $b - 3$ , and such that  $\gamma(\mathbf{R})$  is  $\mathcal{L}$ -isotopic to the plane diagram  $D(x, m, n, y)$ , where  $x, y$  are (possibly empty) sequences of nonnegative integers and  $m, n$  are nonnegative integers. Without loss of generality, we

can suppose that the line  $x = 0$  separates the  $m$  crossings from the  $n$  crossings. The curve parametrised by  $t \mapsto (P(t), P(t) \cdot Q(t))$  has the same double points as  $\gamma(\mathbf{R})$  and an additional ordinary triple point at  $(0, 0)$ . For  $\varepsilon$  small enough the curve  $(P(t + \varepsilon), P(t) \cdot Q(t))$  is  $\mathcal{L}$ -isotopic to either  $D(u, m + 1, 1, n + 1, v)$  or  $D(u, m, 1, 1, 1, n, v)$ , depending on the sign of  $\varepsilon$  (see Figure 3.12).  $\square$

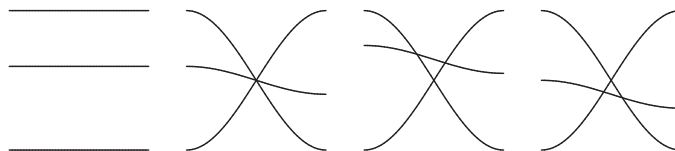


Figure 14: Perturbation of a triple point in  $\mathbf{R}^2$

**Example 3.12** Let us consider the polynomial parametrisation  $(T_3(t), T_4(t))$  of the diagram  $D(1, 1, 1)$ , where  $T_n$  denotes the Chebyshev polynomial of degree  $n$ . We choose to add a triple point in  $(-3/4, 0)$ , by considering the curve  $t \mapsto (T_3(t), Q(t))$ , where  $Q(t) = (T_3(t) + 3/4) \cdot (T_4(t) + 1)$ . Then the curve in  $(P_3(t), Q(t + \varepsilon))$  is  $\mathcal{L}$ -isotopic to  $D(2, 1, 2, 1)$  for  $\varepsilon > 0$  small

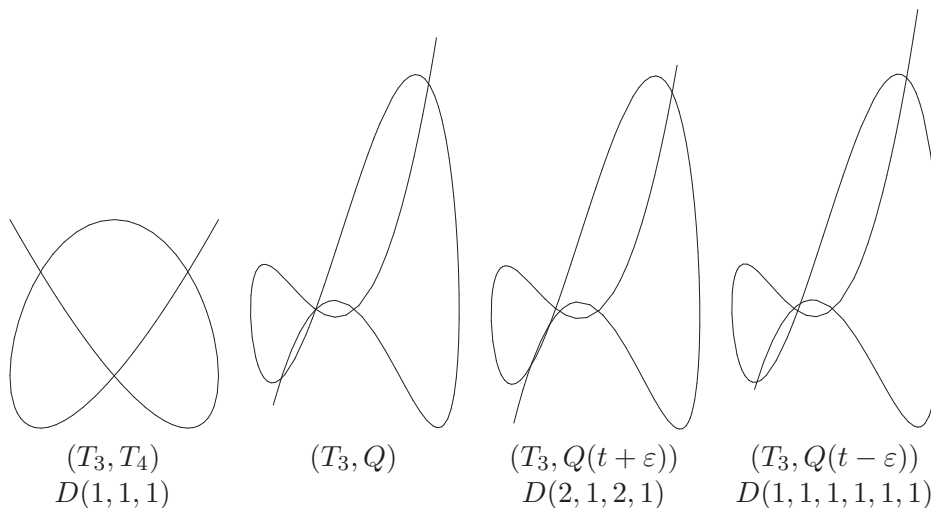


Figure 15: Adding three crossings to the trefoil

enough and is  $\mathcal{L}$ -isotopic to  $D(1, 1, 1, 1, 1, 1)$  for  $\varepsilon < 0$ , see Figure 15.

**Example 3.13** Figure 16 shows that the algebraic degree of  $D(2, 2, 2, 1, 3)$  is at most 11, starting from a parametrisation of the plane diagram  $D(1, 0)$  of degree  $(3, 2)$ .

Proposition 3.11 can be extended to spatial trigonal curves. The next result provides constructions of polynomial knot diagrams.

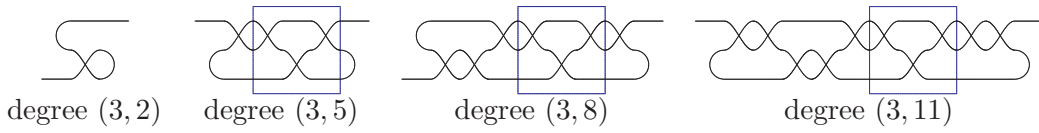


Figure 16: From  $D(1, 0)$  to  $D(2, 2, 2, 1, 3)$

**Proposition 3.14** *Let  $e = \pm 1$ . If the diagram  $C(u, m, n, v)$  has lexicographic degree  $(3, b - 3, c - 6)$ , then the diagram  $C(u, m + e, e, e + n, v)$  has lexicographic degree at most  $(3, b, c)$ .*

*Proof.* Let  $t \mapsto (P(t), Q(t), R(t))$  be a parametrisation of degree  $(3, b, c)$  of the diagram  $C(u, m, n, v)$ . Up to a change of coordinates, we may assume that the part  $(u, m)$  (resp.  $(n, v)$ ) of the diagram is contained in the half-space  $x < 0$  (resp.  $x > 0$ ), and that the three points of the diagram in the plane  $x = 0$  have  $z$ -coordinates of the same sign. We consider the map  $\varphi(t) = (P(t), P(t)Q(t), P^2(t)R(t))$ . The image of  $\varphi$  is a singular diagram with the three branches tangent to the plane  $z = 0$  at the point  $(0, 0, 0)$ . Extending the notations of diagram in the obvious way to this particular case, we see that the image of  $\varphi$  realises the singular diagram  $C(u, m, *, n, v)$ , where  $*$  stands for the triple point. By slightly perturbing the roots of the factor  $P(t)$  of the polynomial  $P(t)Q(t)$ , we obtain a polynomial  $Q_1(t)$  of degree  $b + 3$  such that the triple point of the curve  $(P(t), P(t)Q_1(t))$  will be perturbed as depicted in Figure 17a or b, depending on the perturbation  $Q_1(t)$ . Perturbing the roots of the factor  $P^2(t)$  of the polynomial  $P^2(t)R(t)$  as depicted by the blue dots on Figure 17, we obtain a parametrisation of the diagram whose existence is claimed in the theorem.  $\square$

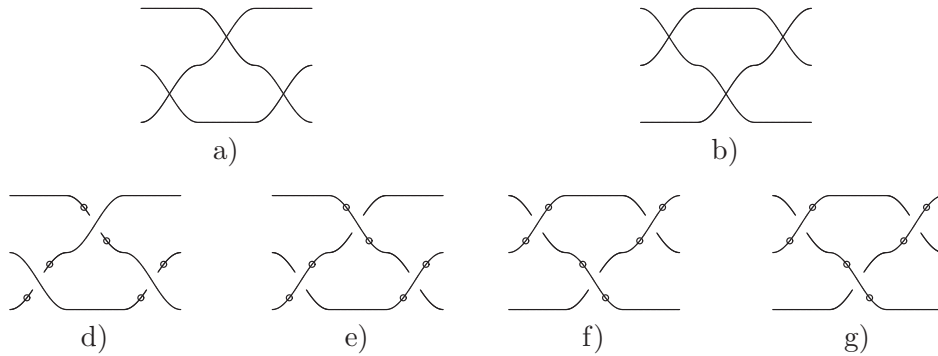


Figure 17: Perturbation of a triple point in  $\mathbf{R}^3$

**Example 3.15** *The trefoil admits the parametrisation  $(T_3, T_4, T_5)$  of degree  $(3, 4, 5)$ . We thus deduce that  $6_2 = C(2, 1, 3)$  and  $6_3 = C(2, 1, 1, 2)$  admit parametrisations of degree  $(3, 7, 11)$ . By Corollary 2.6, these are the lexicographic degrees of  $6_2$  and  $6_3$ .*

Thanks to Proposition 2.9, we will not need Proposition 3.14 to determine the lexicographic degrees of the first knots, but it may be useful for further results.

## 4 Two-bridge knots with 11 crossings or fewer

Simple diagrams of two-bridge knot have been introduced in [BKP1]. The *complexity*  $c(D)$  of a trigonal diagram  $D = C(m_1, \dots, m_k)$  is defined as

$$c(D) = k + \sum_{i=1}^k |m_i|.$$

**Definition 4.1** *We shall say that an isotopy of trigonal diagrams is a slide isotopy if the number of crossings never increases during the isotopy, and if all the intermediate diagrams remain trigonal. A trigonal diagram is called a simple diagram if it cannot be simplified into a diagram of lower complexity by using slide isotopies only.*

The next two propositions motivate the consideration of simple diagrams.

**Proposition 4.2** ([BKP1, Corollary 3.9]) *Let  $D$  be a trigonal diagram of a two-bridge knot. Then by slide isotopies, it is possible to transform  $D$  into a simple diagram  $C(m_1, \dots, m_k)$  such that for  $i = 2, \dots, k$ , either  $|m_i| \neq 1$ , or  $m_{i-1} m_i > 0$ .*

**Proposition 4.3** ([BKP2, Corollary 3.7]) *Let  $D_1$  and  $D_2$  be two trigonal long knot diagrams such that  $D_2$  is obtained from  $D_1$  by a slide isotopy. Then the pseudoholomorphic degree of  $|D_1|$  is greater than or equal to the pseudoholomorphic degree of  $|D_2|$ .*

In [BKP2] we proved that the lexicographic degree of the torus knot  $C(n)$  or the twist knot  $C(n, m)$  is precisely  $(3, \lfloor \frac{3N-1}{2} \rfloor, \lfloor \frac{3N}{2} \rfloor + 1)$  by showing first that the only simple diagrams of these knots are the alternating diagrams and showing that the algebraic degrees of the corresponding plane diagrams are  $\lfloor \frac{3N-1}{2} \rfloor$ .

### 4.1 The general strategy

Given a two-bridge knot with crossing number  $N \leq 11$ , our strategy to determine its lexicographic degree consists in:

1. Find a first upper bound  $b_0$  on  $b$  using constructions from [KP2] based on Chebyshev plane diagrams parametrised by  $(T_3, T_b)$ , where  $T_n$  is the Chebyshev polynomial  $T_n(\cos t) = \cos nt$ .
2. Compute all finitely many simple diagrams of  $K$  with  $b_0 - 1$  crossings or fewer. This is done by computing all continued fractions corresponding to the Schubert fractions of  $K$ .
3. For all these simple diagrams,
  - (a) Compute a lower bound of their algebraic degree using Propositions 3.2 and 3.7.
  - (b) Using T-reductions, try to obtain explicit constructions of these diagrams out of known constructions for diagrams with a lower number of crossings. This provides a lower bound on the lexicographic degree of the knot.

- (c) If necessary, compute all possible braids associated to hypothetical plane curves of degree  $b < b_0$  that are  $\mathcal{L}$ -isotopic to the diagram, and check if these braids satisfy Proposition 3.4. This may improve the lower bound obtained in step (a) above.
  - (d) If the lower bound and the upper bound coincide, then we have determined the lexicographic degree of the knot.
4. If the lower bound and the upper bound do not coincide, improve the upper bound by looking at non-simple diagrams on which one can perform T-reductions to reduce to knots with lower crossing number.

In Table 5, p. 28, we give the lexicographic degree of all two-bridge knots with 11 crossings or fewer. In Tables 1, 2, 3, and 4 below, we give refinements of Table 5 for two-bridge knots with crossing number at most 9. The columns 1, 2 and 3 identify the knot. The column 4 gives the lexicographic degree. The fifth column gives the upper bound on  $b$  obtained by considering Chebyshev diagrams; the sixth column gives a diagram that can be realised in the corresponding lexicographic degree; the last column gives the construction of the corresponding plane diagram, when one needs to improve the bound given by Chebyshev knots.

## 4.2 Some initial diagrams

Here we compute the algebraic degrees of a few trigonal plane diagrams. These computation will be used in the next sections to determine the algebraic degree of trigonal plane diagrams that reduce to the diagrams considered in this section by T-reduction. The next proposition is proved in [KP1].

**Proposition 4.4** *The plane diagram  $D(4n - 1)$  has algebraic degree  $6n - 2$ .*

This gives an explicit parametrisation for the plane diagrams  $D(3)$  and  $D(7)$ .

**Lemma 4.5** *We give below the algebraic degree of a few plane diagrams (see Figure 18 for the image of a polynomial parametrisation of the given degree).*

- $b = 1$ :  $D(0, 0)$
- $b = 2$ :  $D(0, 1)$
- $b = 4$ :  $D(0, 2)$ ,  $D(2, 1)$
- $b = 5$ :  $D(0, 1, 1, 0)$ ,  $D(2, 2)$ ,  $D(1, 1, 1, 1)$ ,  $D(0, 3)$ ,  $D(1, 2, 0)$
- $b = 7$ :  $D(5)$ ,  $D(1, 4)$ ,  $D(0, 4)$

*Proof.* These plane diagrams are obtained with the following parametrisations – here we use the monic Chebyshev polynomials (also called Dickson polynomials) defined by  $T_n(2 \cos x) = 2 \cos nx$ :

- $D(0, 0)$ :  $(T_3, T_1)$
- $D(0, 1)$ :  $(T_3, T_2 - \frac{3}{2}T_1)$

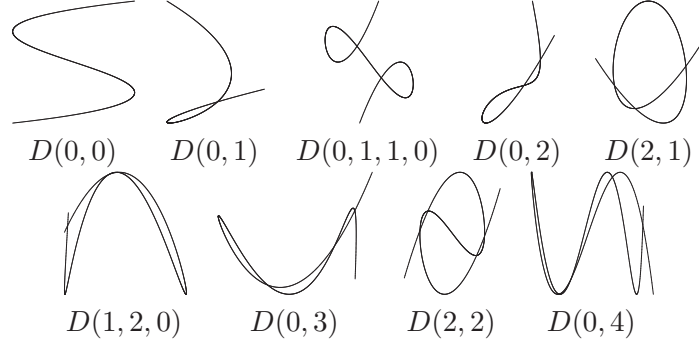


Figure 18: Algebraic degree of a few plane diagrams

- $D(0, 1, 1, 0)$ :  $(T_3, t^5 - 4t^3 + 4t)$
- $D(0, 2)$ :  $(T_3, T_4 + 3T_2 - 4T_1)$
- $D(2, 1)$ :  $(T_3, T_4 - T_2 + \frac{1}{4}T_1)$
- $D(0, 3)$ :  $(T_3, t^5 - \frac{9}{4}t^4 - t^3 + \frac{13}{4}t^2 + \frac{1}{8}t)$
- $D(1, 2, 0)$ :  $(T_3, T_5(6t/5 + 1/2))$
- $D(2, 2)$ :  $(T_3, T_5 - \frac{13}{12}T_1)$
- $D(0, 4)$ :  $(T_3, T_7(-\frac{3}{2}t + 1))$
- $D(5)$ :  $(T_3, P_7)$  where  $P_7 = t^7 - \frac{93659}{10000}t^5 - \frac{13549}{5000}t^4 + \frac{16453}{1000}t^2 + \frac{57281}{1000}t$
- $D(1, 4)$ :  $(T_3, Q_7)$  where  $Q_7 = t^7 - \frac{84497}{10359}t^5 - \frac{47123}{18875}t^4 + \frac{54585}{2759}t^3 + \frac{85741}{7122}t^2 - \frac{208133}{17097}t - \frac{242151}{26615}$

It is shown in [BKP2] that the degree is minimal for  $D(n, m)$ ,  $n, m \geq 0$ . In the case of  $D(0, 1, 1, 0)$ , every line passing through the two crossing points meets the curve at 5 points at least, and therefore the degree is at least 5, which is the degree of our parametrisation.  $\square$

**Remark 4.6** One can prove using dessins d'enfants (see for example [Or2]) that the algebraic degree of the plane diagram  $D(0, n)$  is precisely  $\lfloor \frac{3n}{2} \rfloor + 1$ .

### 4.3 Two-bridge knots with crossing number at most 6

**Proposition 4.7** The lexicographic degrees of all two-bridge knots with crossing number at most 6 are given in Table 1.

*Proof.* The knots  $3_1$ , and  $5_1$  are torus knots, and the knots  $4_1$ ,  $5_2$ , and  $6_1$  are twist knots. Hence their lexicographic degrees are computed in [BKP1]. The knots  $6_2$  and  $6_3$  admit parametrisations with  $b = N + 1$ , hence their lexicographic degree is  $(3, 7, 11)$ .  $\square$

Name	Fraction	Conway Not.	Lex. deg.	Cheb. deg.	diagram	Constr.
$3_1$	3	$C(3)$	(3, 4, 5)	4	$C(3)$	$D(3)$
$4_1$	5/2	$C(2, 2)$	(3, 5, 7)	5	$C(2, 2)$	$D(2, 2)$
$5_1$	5	$C(5)$	(3, 7, 8)	7	$C(5)$	$D(5)$
$5_2$	7/2	$C(3, 2)$	(3, 7, 8)	7	$C(3, 1, 1)$	$D(2, 0) + T$
$6_1$	9/2	$C(4, 2)$	(3, 8, 10)	8	$C(4, 2)$	$D(3, 0) + T$
$6_2$	11/3	$C(3, 1, 2)$	(3, 7, 11)	8	$C(3, 1, 2)$	$D(2, 1) + T$
$6_3$	13/5	$C(2, 1, 1, 2)$	(3, 7, 11)	7	$C(2, 1, 1, 2)$	$D(0, 0) + 2T$

Table 1: Lexicographic degree of two-bridge knots with crossing number at most 6

#### 4.4 Two-bridge knots with crossing number 7

**Proposition 4.8** *The lexicographic degrees of all two-bridge knots with crossing number 7 are given in Table 2.*

Name	Fraction	Conway Not.	Lex. deg.	Cheb. deg.	diagram	Constr.
$7_1$	7	$C(7)$	(3, 10, 11)	10	$C(7)$	$D(7)$
$7_2$	11/2	$C(5, 2)$	(3, 10, 11)	10		Cheb.
$7_3$	13/3	$C(4, 3)$	(3, 10, 11)	10		Cheb.
$7_4$	15/4	$C(3, 1, 3)$	(3, 8, 13)	10	$C(3, 1, 3)$	$D(1) + 2T$
$7_5$	17/5	$C(3, 2, 2)$	(3, 10, 11)	10	$C(2, 1, 1, -4)$	$D(5) + T$
$7_6$	19/7	$C(2, 1, 2, 2)$	(3, 8, 13)	10		$D(1) + 2T$
$7_7$	21/8	$C(2, 1, 1, 1, 2)$	(3, 8, 13)	8		Cheb.

Table 2: Lexicographic degrees of two-bridge knots with crossing number 7

*Proof.* The lexicographic degree of such a knot is (3, 8, 13) or (3, 10, 11). The torus knot  $7_1$  and the twist knots  $7_2$  and  $7_3$  have lexicographic degree (3, 10, 11), see [BKP2]. The Fibonacci knot  $7_7$  has degree (3, 8, 13), see [KP2]. The knots  $7_4$  and  $7_6$  are obtained from  $C(1)$  by T-augmentation. Their degrees is (3, 8, 13). The alternating diagram of the knot  $7_5$  is  $C(3, 2, 2)$ . By Proposition 3.2 the the degree of this diagram is at least (3, 10, 11). Since a non-alternating diagrams of  $7_5$  has at least 8 crossings, we see that its degree is at least (3, 10, 11). Hence the lexicographic degree of  $7_5$  is at least (3, 10, 11).  $\square$

#### 4.5 Two-bridge knots with crossing number 8

**Proposition 4.9** *The lexicographic degrees of all two-bridge knots with crossing number 8 are given in Table 3.*

Name	Fraction	Conway Not.	Lex. deg.	Cheb. deg.	diagram	Constr.
8 <sub>1</sub>	13/2	$C(6, 2)$	(3, 11, 13)	11		Cheb.
8 <sub>2</sub>	17/3	$C(5, 1, 2)$	(3, 10, 14)	11		$D(4, 1) + T$
8 <sub>3</sub>	17/4	$C(4, 4)$	(3, 11, 13)	11		Cheb.
8 <sub>4</sub>	19/4	$C(4, 1, 3)$	(3, 10, 14)	11	$C(4, 1, 2, 1)$	$D(2, 0) + 2T$
8 <sub>6</sub>	23/7	$C(3, 3, 2)$	(3, 10, 14)	11	$C(2, 2, 1, -4)$	$D(1, 2) + 2T$
8 <sub>7</sub>	23/5	$C(4, 1, 1, 2)$	(3, 10, 14)	10		Cheb.
8 <sub>8</sub>	25/9	$C(2, 1, 3, 2)$	(3, 10, 14)	10		Cheb.
8 <sub>9</sub>	25/7	$C(3, 1, 1, 3)$	(3, 10, 14)	11		$D(5) + T$
8 <sub>11</sub>	27/8	$C(3, 2, 1, 2)$	(3, 10, 14)	11		$D(2, 0) + 2T$
8 <sub>12</sub>	29/12	$C(2, 2, 2, 2)$	(3, 11, 13)	11		Cheb.
8 <sub>13</sub>	29/8	$C(3, 1, 1, 1, 2)$	(3, 10, 14)	10		Cheb.
8 <sub>14</sub>	31/12	$C(2, 1, 1, 2, 2)$	(3, 10, 14)	11		$D(2, 0) + 2T$

Table 3: Lexicographic degrees of two-bridge knots with crossing number 8

*Proof.* The lexicographic degree of such a knot is (3, 10, 14) or (3, 11, 13). The lexicographic degree (3, 11, 13) of the twist knots 8<sub>1</sub> and 8<sub>3</sub> has been obtained in [BKP2]. Combining Propositions 3.2 with Chebyshev knots we obtain the following.

- The knots 8<sub>7</sub>, 8<sub>8</sub>, and 8<sub>13</sub> have minimal lexicographic degree (3, 10, 14), obtained as Chebyshev knots.
- The plane projection of 8<sub>2</sub> =  $C(5, 1, 2)$  reduces to  $D(4, 1)$  by T-reduction. Since  $D(4, 1)$  has algebraic degree 7, the diagram  $D(5, 1, 2)$  has algebraic degree 10. Consequently, 8<sub>2</sub> has lexicographic degree (3, 10, 14).
- The plane projection of 8<sub>9</sub> =  $C(3, 1, 1, 3)$  reduces to  $D(5)$  by T-reduction. Hence the algebraic degree of  $D(3, 1, 1, 3)$  is 10, and 8<sub>9</sub> has lexicographic degree (3, 10, 14).
- $D(2, 0)$  is obtained by two successive T-reductions from the plane projections of diagrams of 8<sub>4</sub>, 8<sub>11</sub> and 8<sub>14</sub>. Consequently, 8<sub>4</sub>, 8<sub>11</sub> and 8<sub>14</sub> have lexicographic degree (3, 10, 14).
- Using two T-reductions, the plane diagram  $D(2, 2, 1, 4)$  reduces to  $D(1, 2)$ , which has algebraic degree 4. By Proposition 3.11, the plane diagram  $D(2, 2, 1, 4)$  has algebraic degree 10, and the knot 8<sub>6</sub> has lexicographic degree (3, 10, 14).
- The knot 8<sub>12</sub> admits only three simple diagrams with 9 crossings or fewer:  $C(2, 2, 2, 2)$ ,  $C(2, 1, 1, -3, -2)$  and  $C(2, 2, 1, 1, -3)$ . By Proposition 3.2, the plane diagram  $D(2, 2, 2, 2)$  has degree at least 11. The plane diagrams  $D(2, 1, 1, 3, 2)$  and  $D(2, 2, 1, 1, 3)$  reduce, with two T-reductions, to  $D(3, 0)$  or  $D(0, 3)$  that have pseudoholomorphic degree 5. By Proposition 3.11, the lexicographic degree of 8<sub>12</sub> is then (3, 11, 13).  $\square$

The next result shows that the knot 8<sub>6</sub> is the first example of a knot for which the lexicographic degree cannot be obtained for the alternating diagram.



**Proposition 4.10** *Let  $t \mapsto (P(t), Q(t))$ , be a parametrisation of the diagram  $D(2, 3, 3)$ , where  $\deg P = 3$ . Then  $\deg Q \geq 11$ .*

*Proof.* Without loss of generality, we may assume that  $P(t)$  is positive for  $t$  large enough, and  $\deg Q \not\equiv 0 \pmod{3}$ . Let us denote by  $C$  the complex algebraic curve image of the map  $t \in \mathbf{C} \mapsto (P(t), Q(t)) \in \mathbf{C}^2$ . The curve  $C$  has exactly  $\deg Q - 1$  nodes in  $\mathbf{C}^2$  and then  $\deg Q \geq 10$ . Let us suppose that  $\deg Q = 10$ . Since  $C$  has 8 real crossings, it also has a ninth solitary real point. We see that there are exactly eight possibilities for the  $\mathcal{L}$ -scheme



Figure 19:  $C(2, 3, 3)$

realised by  $C$  (here we use the notations of [BKP2, Section 2.2]):

$$\begin{array}{l}
\mathfrak{D}_2 \quad C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \bullet_1 \quad C_1 \mathfrak{D}_1 C_1 \\
\mathfrak{D}_1 \quad C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \bullet_1 \quad C_2 \mathfrak{D}_2 C_2 \\
\mathfrak{D}_2 \quad \bullet_1 C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \quad C_1 \mathfrak{D}_1 C_1 \\
\mathfrak{D}_1 \quad \bullet_1 C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \quad C_2 \mathfrak{D}_2 C_2 \\
\mathfrak{D}_2 \quad C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \bullet_2 \quad C_1 \mathfrak{D}_1 C_1 \\
\mathfrak{D}_1 \quad C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \bullet_2 \quad C_2 \mathfrak{D}_2 C_2 \\
\mathfrak{D}_2 \quad \bullet_2 C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \quad C_1 \mathfrak{D}_1 C_1 \\
\mathfrak{D}_1 \quad \bullet_2 C_1 \times_2 \times_2 \times_1 \times_1 \times_1 \times_2 \times_2 \times_2 \mathfrak{D}_1 \quad C_2 \mathfrak{D}_2 C_2
\end{array}$$

We compute all corresponding braids and obtain

$$\begin{aligned}
\mathfrak{b}_1 &= \sigma_2^{-1} \sigma_1^{-1} \sigma_2^{-1} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-3} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_2 &= \sigma_1^{-1} \sigma_2^{-2} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-2} \sigma_2^{-1} \sigma_1 \sigma_2^{-1} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_3 &= \sigma_2^{-1} \sigma_1^{-1} \sigma_2 \sigma_1^{-1} \sigma_2^{-2} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-2} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_4 &= \sigma_1^{-2} \sigma_2^{-2} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_2^{-1} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_5 &= \sigma_2^{-1} \sigma_1^{-1} \sigma_2^{-1} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_2^{-1} \sigma_1^{-1} \sigma_2 \sigma_1^{-1} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_6 &= \sigma_1^{-1} \sigma_2^{-2} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_2^{-2} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_7 &= \sigma_2^{-2} \sigma_1^{-1} \sigma_2^{-1} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-2} (\sigma_1 \sigma_2 \sigma_1)^4, \\
\mathfrak{b}_8 &= \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_2^{-1} \sigma_1^{-1} \sigma_2^{-1} \sigma_1^{-3} \sigma_2^{-3} \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_2^{-1} (\sigma_1 \sigma_2 \sigma_1)^4.
\end{aligned}$$

These 8 braids have integer length 0, and none of them is the trivial braid. Hence the result follows from Proposition 3.4.  $\square$

Combining Propositions 3.2 and 4.10, we obtain

**Corollary 4.11** *The lexicographic degree of  $8_6 = C(2, 3, 3)$  is not obtained for the alternating diagram.*

This phenomenon will appear with other knots (see Table 6).

## 4.6 Two-bridge knots with crossing number 9

**Proposition 4.12** *The lexicographic degrees of all two-bridge knots with crossing number 9 are given in Table 4.*

Name	Fraction	Conway Not.	Lex. deg.	Cheb. deg.	diagram	Constr.
$9_1$	9	$C(9)$	(3, 13, 14)	13		Cheb.
$9_2$	15/2	$C(7, 2)$	(3, 13, 14)	13		Cheb.
$9_3$	19/3	$C(6, 3)$	(3, 13, 14)	13		Cheb.
$9_4$	21/4	$C(5, 4)$	(3, 13, 14)	13		Cheb.
$9_5$	23/4	$C(5, 1, 3)$	(3, 11, 16)	13	$C(5, 1, 2, 1)$	$D(3, 0) + 2T$
$9_6$	27/5	$C(5, 2, 2)$	(3, 13, 14)	13		Cheb.
$9_7$	29/9	$C(3, 4, 2)$	(3, 13, 14)	13		Cheb.
$9_8$	31/11	$C(2, 1, 4, 2)$	(3, 11, 16)	13	$C(2, 1, 4, 1, 1)$	$D(1, 2, 0) + 2T$
$9_9$	31/7	$C(4, 2, 3)$	(3, 13, 14)	13		Cheb.
$9_{10}$	33/10	$C(3, 3, 3)$	(3, 11, 16)	13	$C(3, 2, 1, -4)$	$D(0, 1) + 3T$
$9_{11}$	33/7	$C(4, 1, 2, 2)$	(3, 10, 17)	13		$D(3) + 2T$
$9_{12}$	35/8	$C(4, 2, 1, 2)$	(3, 11, 16)	13		$D(3, 0) + 2T$
$9_{13}$	37/10	$C(3, 1, 2, 3)$	(3, 10, 17)	13		$D(1, 2) + 2T$
$9_{14}$	37/8	$C(4, 1, 1, 1, 2)$	(3, 11, 16)	11		$D(3, 0) + 2T$
$9_{15}$	39/16	$C(2, 2, 3, 2)$	(3, 11, 16)	13	$C(2, 2, 2, 1, -3)$	$D(1, 0) + 3T$
$9_{17}$	39/14	$C(2, 1, 3, 1, 2)$	(3, 10, 17)	11		$D(3) + 2T$
$9_{18}$	41/12	$C(3, 2, 2, 2)$	(3, 13, 14)	13		Cheb.
$9_{19}$	41/16	$C(2, 1, 1, 3, 2)$	(3, 11, 16)	11		$D(3, 0) + 2T$
$9_{20}$	41/11	$C(3, 1, 2, 1, 2)$	(3, 10, 17)	13		$D(3) + 2T$
$9_{21}$	43/12	$C(3, 1, 1, 2, 2)$	(3, 11, 16)	13		$D(3, 0) + 2T$
$9_{23}$	45/19	$C(2, 2, 1, 2, 2)$	(3, 10, 17)	13		$D(0, 0) + 3T$
$9_{26}$	47/13	$C(3, 1, 1, 1, 1, 2)$	(3, 11, 16)	11		$D(3) + 2T$
$9_{27}$	49/18	$C(2, 1, 2, 1, 1, 2)$	(3, 10, 17)	13		$D(3) + 2T$
$9_{31}$	55/21	$C(2, 1, 1, 1, 1, 1, 2)$	(3, 10, 17)	10		Cheb.

Table 4: Lexicographic degree of two-bridge knots with crossing number 9

*Proof.* The lexicographic degree of such a knot is (3, 10, 17), (3, 11, 16), or (3, 13, 14). Furthermore, any diagram with at least 11 crossings has degree (3, 13, 14) at least. It is proved in [KP2] that  $9_{31}$  is the harmonic Fibonacci knot  $(T_3, T_{10}, T_{17})$ . The torus knot  $9_1$  and the twist knots  $9_2, 9_3, 9_4$ , have lexicographic degree (3, 13, 14), see [BKP2]. For the remaining knots, we proceed as follows.

- By T-reduction, the diagram  $D(2, 2, 1, 2, 2)$  reduces to  $D(0, 0)$ , that has algebraic degree 1. We deduce that the knot  $9_{23} = C(2, 2, 1, 2, 2)$  has lexicographic degree  $(3, 10, 17)$ .
- The alternating diagrams of  $9_{11}, 9_{13}, 9_{17}, 9_{20}, 9_{26}$  and  $9_{27}$  can be reduced to  $D(3)$  by two T-reductions. Their lexicographic degree is then  $(3, 10, 17)$ .
- The plane alternating diagram of  $9_8$  is reduced to  $D(1, 3, 2)$  by T-reduction. The algebraic degree of  $D(1, 3, 2)$  is at most the degree of  $D(4, 2)$ , that is 8. On the other hand, the plane projection of the diagram  $C(2, 1, 4, 1, 1)$  can be reduced to  $D(1, 2, 0)$  that has degree 8.
- The plane alternating diagrams of the knots  $9_5, 9_{12}, 9_{14}, 9_{19}$  and  $9_{21}$  can be reduced by two T-reductions to  $D(3, 0)$ . Hence these diagrams have algebraic degree 11. On the other hand, any other diagram of these knots will be non-alternating with at least 10 crossing points. Hence the lexicographic degree of these knots is then  $(3, 11, 16)$ .
- The alternating diagram of  $9_{15}$  is  $C(2, 2, 3, 2)$ . From Proposition 3.2, its lexicographic degree is at least  $(3, 13, 14)$ . Any other non alternating diagram of  $9_{15}$  will have 10 or more crossings. Consider the diagram  $C(2, 2, 2, 1, -3)$  of  $9_{15}$ . Its projection  $D(2, 2, 2, 1, 3)$  can be reduced to  $D(1, 0)$  by three T-reductions. Consequently  $9_{15}$  has degree  $(3, 11, 16)$ .
- The alternating diagram of  $9_6$  is  $C(5, 2, 2)$ . From Proposition 3.2, its lexicographic degree is at least  $(3, 13, 14)$ . The only diagrams of  $9_6$  having 10 crossings are  $C(2, 1, 1, -6)$  and  $C(5, 1, 1, -3)$ , whose plane diagrams reduce to  $D(7)$  by T-reductions. Hence the lexicographic degree of  $9_6$  is  $(3, 11, 16)$ .
- The alternating diagram of  $9_7$  is  $C(3, 4, 2)$ . From Proposition 3.2, its lexicographic degree is at least  $(3, 13, 14)$ . The only diagrams of  $9_7$  having 10 crossings are  $C(2, 3, 1, -4)$ , and  $C(3, 3, 1, -3)$ . The plane diagrams  $D(2, 3, 1, 4)$  reduces to  $D(2, 2, 3)$  and  $D(3, 3, 1, 3)$  to  $D(3, 2, 2)$  by a T-reduction. Their degrees are at least 14 by Proposition 4.10.
- The alternating diagram of  $9_9$  is  $C(4, 2, 3)$ . From Proposition 3.2, its lexicographic degree is at least  $(3, 13, 14)$ . The only diagrams of  $9_9$  having 10 crossings are  $C(3, 1, 1, -5)$  and  $C(4, 1, 1, -4)$ , whose plane diagrams reduce to  $D(7)$  by T-reductions. Their lexicographic degrees are then  $(3, 13, 14)$ .
- The alternating diagram of  $9_{18}$  is  $C(3, 2, 2, 2)$ . From Proposition 3.2, its lexicographic degree is at least  $(3, 13, 14)$ . The only diagrams of  $9_{18}$  having 10 crossings are  $C(3, 1, 1, -3, -2)$  whose plane projection reduces to  $D(5, 2)$ ,  $C(2, 2, 1, 1, -4)$  whose plane projection reduces to  $D(2, 5)$ ,  $C(2, 1, 1, -3, -3)$  whose plane projection reduces to  $D(4, 3)$ , and  $C(3, 2, 1, 1, -3)$ , whose plane projection reduces to  $D(3, 4)$ . By Proposition 3.7, the degree of these four plane diagrams with seven crossings is at least 10, so the degree of the four plane diagrams with 10 crossings is at least 13 by Proposition 3.9.
- The alternating diagram of  $9_{10}$  is  $C(3, 3, 3)$ . Suppose that there exists a polynomial parametrisation  $\gamma : t \mapsto (P(t), Q(t))$  of the plane diagram  $D(3, 3, 3)$  with  $\deg(P) = 3$

and  $\deg(Q) = 10$ . We denote by  $C = \gamma(\mathbf{C})$ . Since the curve  $C$  has 9 real crossings, it has no additional nodes. The braid associated to  $C$  is

$$b_C = \sigma_1^{-1} \sigma_2^{-1} \sigma_1^{-2} \sigma_2^{-3} \sigma_1^{-3} \sigma_2^{-2} (\sigma_1 \sigma_2 \sigma_1)^4.$$

Since this braid is not the trivial braid, we obtain a contradiction. Hence the alternating diagram  $C(3, 3, 3)$  has degree at least  $(3, 11, 16)$ . On the other hand, the projection of the diagram  $C(3, 2, 1, -4)$  of  $9_{10}$  reduces to  $D(2, 2)$ . Since this latter has algebraic degree 5, we deduce that  $9_{10}$  has lexicographic degree  $(3, 11, 16)$ .  $\square$

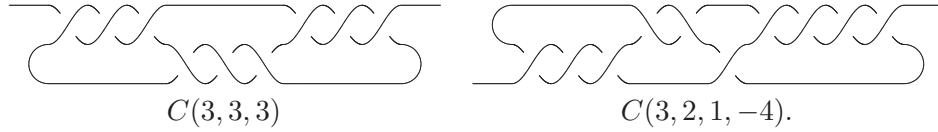


Figure 20: Two diagrams of  $9_{10}$

#### 4.7 Two-bridge knots with crossing number 10 or 11

The lexicographic degrees of the torus knot  $C(11)$  and the twist knots  $C(8, 2)$ ,  $C(9, 2)$ ,  $C(8, 3)$ ,  $C(6, 4)$ ,  $C(7, 4)$  and  $C(6, 5)$  have been established in [BKP2]. For the 129 remaining knots with 10 or 11 crossings, we simply sketch all computations. For only 11 knots among the 186 knots with 11 crossings or fewer —  $10_{11}$ ,  $10_{13}$ ,  $11a_{98}$ ,  $11a_{166}$ ,  $11a_{230}$ ,  $11a_{235}$ ,  $11a_{238}$ ,  $11a_{311}$ ,  $11a_{335}$ ,  $11a_{359}$  and  $11a_{365}$  — the lower bounds differ from the upper bounds in the strategy described in Section 4.1, i.e. one has to go through step 4. The projections of all the corresponding diagrams reduce by T-reduction to a finite list of eleven plane diagrams:

- $D(3, 3, 3)$  and  $D(3, 3, 4)$ , that have degree 13 at least,
- $D(3, 3, 5)$  and  $(3, 5, 3)$ , that have degree 14 at least,
- $D(3, 3, 6)$ ,  $D(3, 5, 4)$ ,  $D(3, 2, 3, 4)$ ,  $D(3, 2, 3, 5)$ ,  $D(3, 2, 5, 3)$ , that have degree 16 at least,
- $D(3, 3, 2, 5)$  and  $D(4, 2, 3, 4)$  that have degree  $(3, 17)$  at least.

These results have been obtained by computing all possible braids associated to hypothetical plane curves of degree  $b < b_0$  that are  $\mathcal{L}$ -isotopic to the diagram, and checking, like in Proposition 4.10, if these braids satisfy Proposition 3.4.

## 5 Conclusion

We list in Table 5 the lexicographic degrees of the first 186 two-bridge knots. We only write  $b$ , bearing in mind that the corresponding lexicographic degree is  $(3, b, 3N - b)$ . Details of our results will be available in <https://.../2bk-lexdeg.html>

Name	Deg.	Name	Deg.	Name	Deg.	Name	Deg.	Name	Deg.	Name	Deg.
3 <sub>1</sub>	4	4 <sub>1</sub>	5	5 <sub>1</sub>	7	5 <sub>2</sub>	7	6 <sub>1</sub>	8	6 <sub>2</sub>	7
6 <sub>3</sub>	7	7 <sub>1</sub>	10	7 <sub>2</sub>	10	7 <sub>3</sub>	10	7 <sub>4</sub>	8	7 <sub>5</sub>	10
7 <sub>6</sub>	8	7 <sub>7</sub>	8	8 <sub>1</sub>	11	8 <sub>2</sub>	10	8 <sub>3</sub>	11	8 <sub>4</sub>	10
8 <sub>6</sub>	10	8 <sub>7</sub>	10	8 <sub>8</sub>	10	8 <sub>9</sub>	10	8 <sub>11</sub>	10	8 <sub>12</sub>	11
8 <sub>13</sub>	10	8 <sub>14</sub>	10	9 <sub>1</sub>	13	9 <sub>2</sub>	13	9 <sub>3</sub>	13	9 <sub>4</sub>	13
9 <sub>5</sub>	11	9 <sub>6</sub>	13	9 <sub>7</sub>	13	9 <sub>8</sub>	11	9 <sub>9</sub>	13	9 <sub>10</sub>	11
9 <sub>11</sub>	10	9 <sub>12</sub>	11	9 <sub>13</sub>	10	9 <sub>14</sub>	11	9 <sub>15</sub>	11	9 <sub>17</sub>	10
9 <sub>18</sub>	13	9 <sub>19</sub>	11	9 <sub>20</sub>	10	9 <sub>21</sub>	11	9 <sub>23</sub>	10	9 <sub>26</sub>	10
9 <sub>27</sub>	10	9 <sub>31</sub>	10	10 <sub>1</sub>	14	10 <sub>2</sub>	13	10 <sub>3</sub>	14	10 <sub>4</sub>	13
10 <sub>5</sub>	13	10 <sub>6</sub>	13	10 <sub>7</sub>	13	10 <sub>8</sub>	13	10 <sub>9</sub>	13	10 <sub>10</sub>	13
10 <sub>11</sub>	13	10 <sub>12</sub>	13	10 <sub>13</sub>	14	10 <sub>14</sub>	13	10 <sub>15</sub>	13	10 <sub>16</sub>	11
10 <sub>17</sub>	13	10 <sub>18</sub>	13	10 <sub>19</sub>	13	10 <sub>20</sub>	13	10 <sub>21</sub>	13	10 <sub>22</sub>	13
10 <sub>23</sub>	13	10 <sub>24</sub>	13	10 <sub>25</sub>	13	10 <sub>26</sub>	13	10 <sub>27</sub>	13	10 <sub>28</sub>	11
10 <sub>29</sub>	11	10 <sub>30</sub>	11	10 <sub>31</sub>	13	10 <sub>32</sub>	13	10 <sub>33</sub>	11	10 <sub>34</sub>	13
10 <sub>35</sub>	14	10 <sub>36</sub>	13	10 <sub>37</sub>	13	10 <sub>38</sub>	11	10 <sub>39</sub>	13	10 <sub>40</sub>	13
10 <sub>41</sub>	11	10 <sub>42</sub>	11	10 <sub>43</sub>	11	10 <sub>44</sub>	11	10 <sub>45</sub>	11	11a <sub>13</sub>	14
11a <sub>59</sub>	14	11a <sub>65</sub>	14	11a <sub>75</sub>	13	11a <sub>77</sub>	13	11a <sub>84</sub>	13	11a <sub>85</sub>	13
11a <sub>89</sub>	13	11a <sub>90</sub>	13	11a <sub>91</sub>	13	11a <sub>93</sub>	13	11a <sub>95</sub>	13	11a <sub>96</sub>	14
11a <sub>98</sub>	14	11a <sub>110</sub>	13	11a <sub>111</sub>	13	11a <sub>117</sub>	13	11a <sub>119</sub>	14	11a <sub>120</sub>	13
11a <sub>121</sub>	14	11a <sub>140</sub>	13	11a <sub>144</sub>	13	11a <sub>145</sub>	14	11a <sub>154</sub>	14	11a <sub>159</sub>	14
11a <sub>166</sub>	14	11a <sub>174</sub>	13	11a <sub>175</sub>	13	11a <sub>176</sub>	13	11a <sub>177</sub>	13	11a <sub>178</sub>	13
11a <sub>179</sub>	13	11a <sub>180</sub>	13	11a <sub>182</sub>	13	11a <sub>183</sub>	13	11a <sub>184</sub>	13	11a <sub>185</sub>	13
11a <sub>186</sub>	13	11a <sub>188</sub>	13	11a <sub>190</sub>	13	11a <sub>191</sub>	13	11a <sub>192</sub>	13	11a <sub>193</sub>	13
11a <sub>195</sub>	14	11a <sub>203</sub>	13	11a <sub>204</sub>	13	11a <sub>205</sub>	13	11a <sub>206</sub>	13	11a <sub>207</sub>	13
11a <sub>208</sub>	13	11a <sub>210</sub>	14	11a <sub>211</sub>	14	11a <sub>220</sub>	13	11a <sub>224</sub>	13	11a <sub>225</sub>	13
11a <sub>226</sub>	14	11a <sub>229</sub>	14	11a <sub>230</sub>	14	11a <sub>234</sub>	16	11a <sub>235</sub>	16	11a <sub>236</sub>	16
11a <sub>238</sub>	16	11a <sub>242</sub>	16	11a <sub>243</sub>	16	11a <sub>246</sub>	16	11a <sub>247</sub>	16	11a <sub>306</sub>	13
11a <sub>307</sub>	13	11a <sub>308</sub>	13	11a <sub>309</sub>	13	11a <sub>310</sub>	13	11a <sub>311</sub>	14	11a <sub>333</sub>	14
11a <sub>334</sub>	16	11a <sub>335</sub>	16	11a <sub>336</sub>	13	11a <sub>337</sub>	13	11a <sub>339</sub>	16	11a <sub>341</sub>	13
11a <sub>342</sub>	16	11a <sub>343</sub>	14	11a <sub>355</sub>	16	11a <sub>356</sub>	13	11a <sub>357</sub>	13	11a <sub>358</sub>	16
11a <sub>359</sub>	14	11a <sub>360</sub>	13	11a <sub>363</sub>	14	11a <sub>364</sub>	16	11a <sub>365</sub>	14	11a <sub>367</sub>	16

Table 5: Two-bridge knots with crossing number at most 11 and their  $y$ -lexicographic degree

In Table 6, we list all knots for which the algebraic degrees of their alternating diagrams are greater than their lexicographic degrees. The third column of Table 6 gives a diagram obtained by a polynomial parametrisation of lexicographic degree, the fourth column indicates a construction of the corresponding  $xy$ -plane diagram (the notation is explained in Section 3), the fifth column gives the alternating trigonal diagram of the knot, and the last column gives a lower bound on its  $y$ -degree.

Name	$y$ -lex. degree	Lex. deg. diagram	Constr.	Alt. diagram	$y$ -lex. degree $\geq$
8 <sub>6</sub>	10	$C(2, 2, 1, -4)$	$D(3) + 2T$	$C(3, 3, 2)$	11
9 <sub>10</sub>	11	$C(3, 2, 1, -4)$	$D(0, 1) + 3T$	$C(3, 3, 3)$	13
9 <sub>15</sub>	11	$C(2, 2, 1, -3, -2)$	$D(1, 0) + 3T$	$C(2, 2, 3, 2)$	13
10 <sub>24</sub>	13	$C(2, 2, 1, -3, -3)$	$D(0, 2) + 3T$	$C(3, 2, 3, 2)$	14
11a <sub>75</sub>	13	$C(2, 1, 3, 2, 1, -3)$	$D(3) + 3T$	$C(2, 1, 3, 3, 2)$	14
11a <sub>84</sub>	13	$C(2, 2, 1, -3, -1, -1, -2)$	$D(0, 0) + 4T$	$C(2, 1, 1, 2, 3, 2)$	14
11a <sub>144</sub>	13	$C(2, 2, 2, 1, -5)$	$D(3) + 3T$	$C(4, 3, 2, 2)$	14
11a <sub>186</sub>	13	$C(2, 2, 2, 1, -3, -2)$	$D(0, 0) + 4T$	$C(2, 2, 3, 2, 2)$	16
11a <sub>193</sub>	13	$C(2, 1, 1, 1, 2, 1, -4)$	$D(3) + 3T$	$C(3, 3, 1, 1, 1, 2)$	14
11a <sub>205</sub>	13	$C(2, 2, 1, -2, -1, -1, -3)$	$D(3) + 3T$	$C(3, 1, 1, 1, 3, 2)$	14
11a <sub>208</sub>	13	$C(2, 1, 1, -2, -1, -2, -3)$	$D(3) + 3T$	$C(3, 2, 1, 1, 2, 2)$	14
11a <sub>224</sub>	13	$C(3, 2, 1, -3, -1, -2)$	$D(0, 0) + 4T$	$C(3, 3, 2, 1, 2)$	14
11a <sub>225</sub>	13	$C(2, 3, 1, -2, -4)$	$D(3) + 3T$	$C(4, 1, 4, 2)$	14
11a <sub>229</sub>	14	$C(2, 2, 1, -3, -4)$	$D(0, 3) + 3T$	$C(4, 2, 3, 2)$	16
11a <sub>341</sub>	13	$C(3, 1, 3, 1, -4)$	$D(3) + 3T$	$C(3, 1, 4, 3)$	14
11a <sub>356</sub>	13	$C(3, 2, 1, -3, -3)$	$D(3) + 3T$	$C(3, 2, 3, 3)$	16

Table 6: Knots for which the alternating diagram is not of minimal degree

For  $N \geq 12$  and  $N + 4 \leq b < \lfloor \frac{3N-1}{2} \rfloor$ , it could be interesting to determine the lexicographic degree, as we do not know if  $b+c = 3N$ . For some knots, it could be interesting to determine explicit constructions with the lexicographic degree.

## References

- [BKP1] E. Brugallé, P. -V. Koseleff, D. Pecker. *Untangling trigonal diagrams*, Journal of Knot Theory And Its Ramifications (JKTR), **25(7)**, 2016.
- [BKP2] E. Brugallé, P. -V. Koseleff, D. Pecker, *On the lexicographic degree of two-bridge knots*, Journal of Knot Theory And Its Ramifications (JKTR), **25(7)**, 2016.
- [Co] J. H. Conway, *An enumeration of knots and links, and some of their algebraic properties*, Computational Problems in Abstract Algebra (Proc. Conf., Oxford, 1967), 329–358 Pergamon, Oxford (1970)
- [Cr] P. R. Cromwell, *Knots and links*, Cambridge University Press, Cambridge, 2004.
- [KP1] P. -V. Koseleff, D. Pecker, *A polynomial parametrization of torus knots*. Appl. Algebra Engrg. Comm. Comput. Vol **20 (5-6)** (2009), 361-377

- [KP2] P. -V. Koseleff, D. Pecker, *Chebyshev diagrams for two-bridge knots*, *Geom. Dedicata* 150 (2010), 405–425
- [Mu] K. Murasugi, *Knot Theory and its Applications*, Boston, Birkhäuser, 341p., 1996.
- [Or1] S. Yu. Orevkov. *Link theory and oval arrangements of real algebraic curves*, *Topology*, **38(4)**, 779–810, 1999.
- [Or2] S. Yu. Orevkov., *Riemann existence Theorem and construction of real algebraic curves*, *Annales de la Faculté des Sciences de Toulouse*, **12(4)**, 517–531, 2003.
- [Or3] S. Yu. Orevkov., *Quasipositivity problem for 3-braids*, *Proceedings of 10th Gokova Geometry-Topology Conference 2004*, 89–93. Reprinted in: *Turkish Journal of Math.*, **28**, 89–93, 2004.
- [Sh] A.R. Shastri, *Polynomial representation of knots*, *Tôhoku Math. J.* **44** (1992), 11-17.
- [Va] V. A. Vassiliev, *Cohomology of knot spaces*, *Theory of singularities and its Applications*, *Advances Soviet Maths Vol 1* (1990)

---

Erwan BRUGALLÉ  
Université de Nantes,  
Laboratoire de Mathématiques Jean Leray (CNRS LMJL UMR 6629)  
e-mail: [erwan.brugalle@math.cnrs.fr](mailto:erwan.brugalle@math.cnrs.fr)

Pierre-Vincent KOSELEFF  
Sorbonne Université (UPMC–Paris 6),  
Institut de Mathématiques de Jussieu (CNRS IMJ-PRG UMR 7586) & Inria-Paris  
e-mail: [pierre-vincent.koseleff@upmc.fr](mailto:pierre-vincent.koseleff@upmc.fr)

Daniel PECKER  
Sorbonne Université (UPMC–Paris 6),  
Institut de Mathématiques de Jussieu (CNRS IMJ-PRG UMR 7586),  
e-mail: [daniel.pecker@upmc.fr](mailto:daniel.pecker@upmc.fr)