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On the Number of Pseudo-Triangulations of Certain Point Sets

Oswin Aichholzer*  David Orden†  Francisco Santos‡  Bettina Speckmann†

Abstract

We pose a monotonicity conjecture on the number of pseudo-triangulations of any planar point set, and check it in two prominent families of point sets, namely the so-called double circle and double chain. The latter has asymptotically $12^n n^{\Theta(1)}$ pointed pseudo-triangulations, which lies significantly above the maximum number of triangulations in a planar point set known so far.

1 Introduction

Pseudo-triangulations, also called geodesic triangulations, are a generalization of triangulations which has found multiple applications in Computational Geometry in the last years. They were originally studied in the context of visibility [10, 11] and ray shooting [5, 6], but recently have also been used in kinetic collision detection [1, 8], rigidity [17], and guarding [16].

A pseudo-triangle is a planar polygon that has exactly three convex vertices, called corners, with internal angles less than $\pi$. A pseudo-triangulation for a set $A$ of $n$ points in the plane is a partition of $\text{conv}(A)$ into pseudo-triangles whose vertex set is exactly $A$. A vertex is pointed if it has an adjacent angle greater than $\pi$.

The set of all pseudo-triangulations of a point set has somewhat nicer properties than that of all triangulations. For example, pseudo-triangulations of a point set with $n$ elements form the vertex set of a certain polyhedron of dimension $3n - 3$ [9]. The diameter of the graph of pseudo-triangulations is $O(n \log n)$ [3] versus the $\Theta(n^2)$ diameter of the graph of triangulations of certain point sets. For standard triangulations it is not known which sets of points have the fewest or the most triangulations, but it was shown in [2] that sets of points in convex position minimize the number of pointed pseudo-triangulations.

Let $A$ be a point set and let $A_I$ be its subset of interior points. Let $PT(A)$ be the set of pseudo-triangulations of $A$. For each subset $W \subseteq A_I$ we denote by $PT_W(A)$ the set of pseudo-triangulations of $A$ in which the points of $W$ are pointed and those of $A_I \setminus W$ are non-pointed.

For example, $PT_{\emptyset}(A)$ and $PT_{A_I}(A)$ are the triangulations and the pointed pseudo-triangulations of $A$, respectively. In [12], the following inequality is proved:

$$3 |PT_{W \setminus \{v\}}(A)| \geq |PT_{W}(A)|.$$

We pose the following conjecture in the opposite direction, implicit in previous work:

**Conjecture 1** For every point set $A$ in general position in the plane, the cardinalities of $PT_W(A)$ are monotone with respect to $W$. That is to say, for any subset $W$ of its interior points and for every $v \in W$, one has

$$|PT_{W}(A)| \geq |PT_{W \setminus \{v\}}(A)|.$$

In this paper we consider three families of point sets in the plane: double circles, double chains and what we call single chains. The first two are the examples with asymptotically the smallest and biggest number of triangulations known (see, e.g., [4, 14]). The third is studied as a step to analyze double chains. Our goal is twofold: check Conjecture 1, and compare the numbers $|PT_{A_I}(A)|$ and $|PT(A)|$ to the number $|PT_{\emptyset}(A)|$ of triangulations in these point sets. Our results are summarized in the following table. In all cases the set has $n$ points and a polynomial factor has been neglected.

<table>
<thead>
<tr>
<th></th>
<th>double circle</th>
<th>single chain</th>
<th>double chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>PT_{\emptyset}(A)</td>
<td>$</td>
<td>$\sqrt{12}n$</td>
</tr>
<tr>
<td>$</td>
<td>PT_{A_I}(A)</td>
<td>$</td>
<td>$\sqrt{28}n$</td>
</tr>
<tr>
<td>$</td>
<td>PT(A)</td>
<td>$</td>
<td>$\sqrt{40}n$</td>
</tr>
<tr>
<td>Conjecture 1</td>
<td>YES</td>
<td>YES</td>
<td>?</td>
</tr>
</tbody>
</table>

Conjecture 1 would imply that the total number of pseudo-triangulations in the double chain is between $16^n$ and $24^n$. We have reasons to believe it to be $20^n$. We show that Conjecture 1 in the double chain would follow from a certain conjecture on pointed pseudo-triangulations of the single chain.

2 The double circle and its relatives

For any given pair of positive integers $v \geq 3$ and $i \leq v$, a point set in *almost convex position* with parameters $(v, i)$ consists of a set of $v$ points forming the vertex set of a convex $v$-gon and a set of $i$ interior points, placed...
sufficiently close to \( i \) different edges of the \( v \)-gon. The double circle is the extremal case \( v = i \).

This situation is a special case of what is called “almost-convex polygons” in [7]. There it is shown that the number of triangulations of such a point set does not depend on the choice of the \( i \) edges of the \( v \)-gon. Indeed, if we call this number \( n(v, i) \), the recursive formula

\[
n(v, i) = n(v + 1, i - 1) - n(v, i - 1).
\]

allows to compute \( n(v, i) \) starting with \( n(v, 0) = C_{v-2} \) (Catalan numbers). The array obtained by this recursion (difference array of Catalan numbers) appears in Sloane’s Online Encyclopedia of Integer sequences [15] with ID number A059346. The double circle, with \( n = \sqrt{28} \) pointed pseudo-triangulations and \( \sqrt{40} \) pseudo-triangulations in total, modulo a polynomial factor. Adding the numbers over all the possible subsets of interior points gives

\[
\sum_{k=0}^{i} \binom{i}{k} 4^v 3^{i-k} 7^k = 4^v 10^i.
\]

Hence, a double circle (the case \( i = v = n/2 \)) has \( \sqrt{28} \) pointed pseudo-triangulations and \( \sqrt{40} \) pseudo-triangulations in total, modulo a polynomial factor.

3 The single chain

By a single chain we mean the following point set \( A \): three extremal vertices and a concave chain of \( t \) points \( p_1, \ldots, p_t \) next to an edge. Let \( p \) be the extremal point opposite to the chain. We call \( p \) the top of \( A \).

We classify the pointed pseudo-triangulations of the single chain according to which interior points are joined to the top. For any subset \( W \subset A \), we denote by \( PPT_W(A) \) the set of pointed pseudo-triangulations of \( A \) in which \( p \) is joined to \( p_i \) if and only if \( p_i \in W \). For example, \( PPT_{\emptyset}(A) \) is in bijection to the set of triangulations of the convex \( l+2 \)-gon, hence its cardinality is the Catalan number \( C_l \). It is easy to show that:

**Lemma 1** For every \( W \subset A \) not containing \( p \) (so that \( W \) is also a set of interior points of \( B \) and \( C \)) one has:

1. \( |PPT_W(A)| = |PPT_W(C)| - |PPT_W(B)| \).
2. \( |PPT_{W\cup\{p\}}(A)| = 2|PPT_W(C)| - |PPT_W(B)| \).

**Proof:** 1. It is clear that there are bijections between:

(1) pseudo-triangulations of \( C \) pointed at \( W \) that use the edge \( qr \) and pseudo-triangulations of \( B \) pointed at \( W \) and (2) pseudo-triangulations of \( C \) pointed at \( W \) that do not use the edge \( qr \) and pseudo-triangulations of \( A \) pointed at \( W \). These bijections give the statement.

2. Pseudo-triangulations of \( A \) in which \( p \) is pointed come in three flavors: those using the edges \( pq \) and \( pr \) (and hence having no other edge incident to \( p \)), those using \( pq \) but not \( pr \), and those using \( pr \) but not \( pq \). The first set is in bijection with the pseudo-triangulations of \( B \). Each of the other two is in bijection with pseudo-triangulations of \( C \) that do not use the edge \( qr \), that is pseudo-triangulations of \( C \) minus those of \( B \). Since the bijections preserve pointedness at interior points (other than \( p \)), we get

\[
|PPT_{W\cup\{p\}}(A)| = |PPT_W(B)| + 2(|PPT_W(C)| - |PPT_W(B)|),
\]

as desired. □

Observe that Lemma 1 implies that \( A \) satisfies Conjecture 1 and that the number \( |PT_W(A)| \) depends only on \( v, i \) and \( k := |W| \). Let \( n(v, i, k) \) denote this number. Since \( n(v, i, 0) = 4^v 3^i \) (modulo a polynomial factor) and since

\[
n(v, i, k) = 2(v + 1, i - 1, k - 1) - n(v, i - 1, k - 1),
\]

we conclude that \( n(v, i, k) \sim 4^v 3^{i-k} 7^k \), modulo a polynomial factor. Adding the numbers over all the possible subsets of interior points gives

\[
\sum_{k=0}^{i} \binom{i}{k} 4^v 3^{i-k} 7^k = 4^v 10^i.
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**Lemma 2** For every \( W \):

\[
|PPT_W(A)| = \sum_{W \subset W} |PPT_{W\setminus\{p\}}(A)|.
\]

Hence, Conjecture 1 holds for \( A \).

For example, the equality \( |PPT_{\emptyset}(A)| = |PPT_{\emptyset}(A)| \) is the easy observation that triangulations of \( A \) are in bijection to triangulations of the convex \( l+2 \)-gon. Curiously enough, \( PPT_{A_l}(A) \) (that is, the pointed pseudo-triangulations in which the top point \( p \) is joined to everything), have the cardinality of the next Catalan number \( C_{l+1} \), and flips between them form the graph of the corresponding associahedron, by Section 5.3 of [13] (see also the remark and picture on pp. 728–729). The following is a 1-dimensional analog of Conjecture 1.

**Conjecture 2** For every \( W \subset A \) and \( p \in A \setminus W \),

\[
|PPT_{W\cup\{p\}}(A)| \geq |PPT_W(A)|.
\]

We do not know how to compute the numbers \( PPT_W(A) \). But we can compute the sum of all the \( PPT_W(A) \)'s for each cardinality of \( W \), via the following recursive formulae whose bijective proof we omit.
Theorem 3 Let \( a(l, i) := \sum_{|W| = i} |PT_W(A)| \). Then:

1. \( a(l, 0) = C_l \), and \( a(l, 1) = (l + 1)C_l \).
2. For every \( i \geq 2 \),
   \[
   a(l, i) = \binom{l+1}{i} C_l - a(l-1, i-2).
   \]

The first few values of \( a(l, i) \) are as follows:

<table>
<thead>
<tr>
<th>( i \backslash l )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>( a_l = \sum a(l, i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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<tr>
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</tr>
<tr>
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<td>14</td>
<td>70</td>
<td>135</td>
<td>120</td>
<td>42</td>
<td></td>
<td>381</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>252</td>
<td>616</td>
<td>770</td>
<td>495</td>
<td>132</td>
<td>2307</td>
</tr>
</tbody>
</table>

The recursion also tells us that the array \( a(l, i) \) equals the sequence A062991 in [15]. The row sums, that is, the numbers \( |PT_{A_l}(A)| \) of pointed pseudo-triangulations, form the sequence A062992. We can obtain them adding over all values of \( i \) in the formula of Theorem 3:

Corollary 4 The number \( a_l = |PT_{A_l}(A)| \) of pointed pseudo-triangulations of the single chain satisfies:

\[
a_l = 2^{l+1}C_l - a_{l-1}.
\]

Hence, \( a_l = |PT_{A_l}(A)| \in \Theta(8^l l^{-3/2}) \).

We now turn our attention to the total number of pseudo-triangulations \( PT(A) \). Lemma 2 implies that:

\[
|PT(A)| = \sum_{W \subset A} 2^{|A_l-W_l'|} |PT_{W_l'}(A)| = \sum_{i=0}^{l} 2^{l-i} a(l, i).
\]

Corollary 5 The number \( b_l = |PT(A)| \) of pseudo-triangulations of the single chain satisfies:

\[
2b_l = 3^{l+1}C_l - b_{l-1}.
\]

Hence, \( b_l = |PT(A)| \in \Theta(12^l l^{-3/2}) \).

4 The double chain

For any two numbers \( l, m \geq 0 \), a double chain is a convex 4-gon with \( l \) and \( m \) points, respectively, placed forming concave chains next to opposite edges of the 4-gon in a way that the they do not cross the two diagonals of the convex 4-gon (see Fig. 2). The double chain has exactly

\[
C_lC_m \binom{l+m+2}{l+1}.
\]

triangulations. In the extremal case \( l = m = (n-4)/2 \) this gives \( \Theta(8^nn^{-7/2}) \). This is (asymptotically) the point set with the largest number of triangulations known so far.

Let \( A \) be a double chain with \( l \) and \( m \) interior points in the two chains, resp. (so \( A \) has \( l + m + 4 \) points in total). We call the \( l + 2 \) and \( m + 2 \) vertices in the two chains the “top” and “bottom” parts.

To count the number of pointed pseudo-triangulations of \( A \), let us call \( B \) and \( C \) single chains with \( l \) and \( m \) interior points each. \( B \) can be considered the subset of \( A \) consisting of the top part plus a bottom vertex, and analogously for \( C \). Every pseudo-triangulation \( T_A \) of \( A \) induces pseudo-triangulations \( T_B \) and \( T_C \) of \( B \) and \( C \) as follows: consider on the one hand all the pseudo-triangles of \( T_A \) that use at most one vertex of the bottom, and contract these vertices to a single one. Do the same for pseudo-triangles with at most one vertex in the top (see Fig. 3).

Figure 3: Decomposing a pseudo-triangulation of a double chain.

Conversely, given a pair of pseudo-triangulations of \( B \) and \( C \), if \( i \) (resp. \( j \)) denotes the number of interior edges incident to the bottom (resp. top) point, there are exactly \( \binom{i+j+2}{i+1} \) ways to recover a pseudo-triangulation of \( A \) from that data, by shuffling the \( i+1 \) pseudo-triangles of \( T_B \) incident to the bottom and the \( j+1 \) of \( T_C \) incident to the top.

Theorem 6 Let \( V \) and \( W \) be subsets of the top and bottom interior points. For each \( V' \subset V \) and \( W' \subset W \) let \( t^V,W,V= \binom{l-|V'|-m-|W'|-2}{l-|V\cap W'|+1} \). Then:

\[
|PT_{V \cup W}(A)| = \sum_{V'\subset V, W' \subset W} t^{V,W,V} |PT_{V'}(B)||PT_{W'}(C)|.
\]

Proof: The first observation is that the “shuffling” described above preserves pointedness. The second observation is that in the expression

\[
|PT_{V}(B)| = \sum_{V' \subset V} |PT_{V'}(B)|
\]

of Lemma 2, each element of \( PT_{V'}(B) \) corresponds to an element of \( PT_{V}(B) \) with exactly \( l - |V\setminus V'| \) interior edges incident to the bottom point (same for \( C \)).
Corollary 7 If Conjecture 2 holds, then the double chain satisfies Conjecture 1.

We now consider the number of pointed pseudo-triangulations of the double chain. Theorem 6 can be rewritten in this case as:

$$|PT_{A_j}(A)| = \sum_{i=0}^{l} \sum_{j=0}^{m} \binom{i + j + 2}{i + 1} a(l, i) a(m, j),$$

where $a(\cdot, \cdot)$ is as in the previous section. The following triangular array gives these numbers for $l + m \leq 5$.

<p>| | | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42</td>
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</tr>
<tr>
<td>252</td>
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<td>226</td>
<td>252</td>
<td></td>
</tr>
<tr>
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<td>1502</td>
<td>1476</td>
<td>1502</td>
<td>1630</td>
</tr>
<tr>
<td>11048</td>
<td>10618</td>
<td>10604</td>
<td>10604</td>
<td>10618</td>
</tr>
</tbody>
</table>

The sequence for $l = m$ is

$$2, 38, 1476, 81310, 5495276, 424398044, \ldots$$

In order to analyze the asymptotics of this sequence we need the following lemma on the numbers $a(l, i)$:

Lemma 8

$$1 - \frac{i(i-1)}{(4l-2)(l-i+2)} \leq a(l, i) \leq \frac{(l+1)}{C_l} \leq 1$$

Corollary 9 Let $A$ be a double chain with $n$ points and with equal numbers on both sides (that is to say, $l = m = (n - 4)/2$). Then:

$$\Omega(12^n n^{-9/2}) \leq |PT_{A_j}(A)| \leq O(12^n n^{-3/2}).$$

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