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On Convex Polygons in Cartesian Products

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Abstract

We study several problems concerning convex polygons whose vertices lie on a grid defined by the Cartesian product of two sets of \( n \) real numbers, using each coordinate at most once. First, we prove that all such grids contain a convex polygon with \( \Omega(\log n) \) vertices and that this bound is asymptotically tight. Second, we present two polynomial-time algorithms that find the largest convex polygon of a restricted type. These algorithms give an approximation of the unrestricted case. It is unknown whether the unrestricted problem can be solved in polynomial time.

1 Introduction

A fast way to generate a random convex polygon, based on a proof by Pavel Valtr [7], first generates two random sets of \( n \) integer coordinates before significantly transforming the \( y \)-coordinates to produce a convex \( n \)-gon with the original \( x \)-coordinates. What happens if we do not transform the \( y \)-coordinates, and instead ask for a convex polygon with the original \( x \)- and \( y \)-coordinates?

Formally, we say that two sets, \( X \) and \( Y \), each containing \( n \) real numbers, form a grid \( X \times Y \). A grid supports a convex polygon \( P \) if for every vertex of \( P \), its \( x \)-coordinate is in \( X \) and its \( y \)-coordinate is in \( Y \), and no two vertices of \( P \) share an \( x \)- or \( y \)-coordinate.

It turns out that not every \( n \times n \) grid supports a convex \( n \)-gon. In fact, this is true already for \( n = 5 \) (see Figure 1). This raises several interesting questions. Can we quickly decide whether a grid supports a convex \( n \)-gon? Or can we find the largest \( k \) such that it supports a convex \( k \)-gon? And what is the largest \( k \) such that any \( n \times n \) grid supports a convex \( k \)-gon? We initiate the study of these questions.

There is a rich history of problems involving convex subsets, including the famous Happy Ending Problem: that any set of five points in the plane in general position contain four
We consider two special types of convex polygons. We classify a convex polygon \( P \) with vertices \( ((x_1, y_1), \ldots, (x_k, y_k)) \) (in clockwise order), as follows:

- **Convex caps** come in four types \( \{\land, \cup, \lor, \lnot\} \). We have
  - \( P \in \land \) if and only if \( (x_i)_{i=1}^k \) is increasing;
  - \( P \in \cup \) if and only if \( (y_i)_{i=1}^k \) is increasing;
  - \( P \in \lor \) if and only if \( (x_i)_{i=1}^k \) is decreasing;
  - \( P \in \lnot \) if and only if \( (y_i)_{i=1}^k \) is decreasing.

- **Convex chains** come in four types \( \{\lnot \land, \land \lor, \lor \land, \lor \land\} \). We have
  \[
  \lnot \land = \land \cap \lor, \quad \land = \land \cap \lor, \quad \lor = \lor \cap \land, \quad \lor = \lor \cap \land.
  \]

Figure 1 illustrates some maximum-size supported convex polygons for various grids. For \( n \times n \) grids with \( n \leq 4 \), the largest supported convex polygon always has size \( n \). For \( n > 4 \), this size can be less than \( n \) (as for \( n = 5 \) in Figure 1). Interestingly, for \( n = 6 \), there always exists a supported convex polygon of size at least 5.

**Lemma 2.1.** Every \( 6 \times 6 \) grid \( X \times Y \) supports a convex polygon of size at least 5.

**Proof.** Let \( X' = X \setminus \{\min(X), \max(X)\} \) and \( Y' = Y \setminus \{\min(Y), \max(Y)\} \). The \( 4 \times 4 \) grid \( X' \times Y' \) supports a convex chain \( P' \) of size 3 between two opposite corners of \( X' \times Y' \). Then one \( x \)-coordinate \( x' \in X' \) and one \( y \)-coordinate \( y' \in Y' \) are not used by \( P' \). Without loss of generality, assume that \( P' = (x', \min(Y)) \) and \( (\max(X), y') \) is a supported convex polygon of size 5 on \( X \times Y \). \(\blacksquare\)
More generally, by Lemma 2.2, every grid supports a convex chain of size $\Omega(\log n)$. We show in Lemma 2.3 that this bound is asymptotically tight: for each $n$, there exists a grid for which the maximum convex chain has size $O(\log n)$. Since every convex cap consists of two convex chains (some of which may be empty), and each convex polygon is composed of two convex caps, the same asymptotic bounds hold for maximum convex caps and polygons.

\begin{lemma}
Every $n \times n$ grid $X \times Y$ supports a convex polygon of size $\Omega(\log n)$.
\end{lemma}

\begin{proof}
By Payne and Wood [4], every set of $k$ points with at most $\ell$ collinear contains a set of $\Omega(\sqrt{k}/\log \ell)$ points in general position. Here, we have $n^2$ points with at most $n$ collinear, so there is a set of $\Omega(\sqrt{n^2}/\log n) = \Omega(n/\sqrt{\log n})$ points in general position. By Suk [5], every set of $2^{k+o(k)}$ points in general position contains a set of $k$ points in convex position. Hence, we can find a subset of $\Omega(\log(n/\sqrt{\log n})) = \Omega(\log n)$ points in convex position. Eliminating points with the same $x$- or same $y$-coordinate reduces the size by at most 75%, so this asymptotic bound also holds when coordinates in $X$ and $Y$ may be used at most once.
\end{proof}

For the upper bound, we construct a family of grids without any large convex chain. For $n = 8$, this grid is depicted in Figure 2.

\begin{lemma}
For every $n \in \mathbb{N}$, there exists an $n \times n$ grid $X \times Y$ that does not support any convex chain of size greater than $\lceil \log n \rceil + 1$.
\end{lemma}

\begin{proof}
Let $g(n)$ be the maximum value such that for all $X$ and $Y$ of size $n$, the grid $X \times Y$ supports a convex polygon of size $g(n)$; clearly $g(n)$ is nondecreasing. Let $k$ be the minimum integer such that $n \leq 2^k$. We show that $g(2^k) \leq k + 1$ to establish that $g(n) \leq g(2^k) \leq k + 1$.

Without loss of generality, assume that $n = 2^k$, and let $X = \{1, \ldots, n\}$. For a $k$-bit integer $m$, let $m_i$ be the bit at its $i$-th position, such that $m = \sum_{i=0}^{k-1} m_i 2^i$. Let $Y = \{\sum_{i=0}^{k-1} m_i (n^{i+1} - 1) \mid 0 \leq m \leq n - 1\}$. Both $X$ and $Y$ are symmetric: $X = \{\max(X) + 1 - x \mid
Observation 3.1. If a supported convex polygon $P$ is in a set of $\mathcal{R}$, $\mathcal{V}$, $\mathcal{N}$, $\mathcal{G}$, $\mathcal{C}$, or $\mathcal{O}$, then any subsequence of $P$ also lies in that set.

Convex chains. Given a grid $X \times Y$, we provide an algorithm to compute a supported convex chain $P \in \mathcal{V}$ of maximum size. For this, we use a dynamic program to compute for each edge $(p_1, p_2) \in E = (X \times Y)^2$, the maximum size $R(p_1, p_2)$ of a chain of $\mathcal{V}$ with $p_1$ and $p_2$ as first two vertices, or $(p_1)$ if $p_1 = p_2$ (in which case $R(p_1, p_2) = 1$). By Observation 3.1, removing the first vertex from a chain of $\mathcal{V}$ again yields a chain of $\mathcal{V}$.

Observation 3.2. If $A = (a_1, \ldots, a_k) \in \mathcal{V}$ and $B = (b_1, \ldots, b_k) \in \mathcal{V}$ with $k \geq 2$, $\ell \geq 2$ and $a_{k-1} = 1$ and $a_k = 2$, then $(a_1, \ldots, a_{k-2}, b_1, \ldots, b_1)$ also lies in $\mathcal{V}$ and has size $k + \ell - 2$.

Conversely, by Observation 3.2, for a chain $P$ in $\mathcal{V}$, adding a vertex $v$ at the front yields a chain of $\mathcal{V}$ if $(v, p_1, p_2) \in \mathcal{V}$: the $x$- (resp., $y$-) coordinate of $v$ is less (resp., greater) than those of vertices of $P$, so distinctness is maintained. Therefore we can find the maximum size of a chain starting with $p_1$ and $p_2$ based on chains without $p_1$ as follows:

$$R(p_1, p_2) = \begin{cases} -\infty & \text{if } p_1 \neq p_2 \text{ and } (p_1, p_2) \notin \mathcal{V} \\ 1 & \text{if } p_1 = p_2 \\ \max_{(p_1, p_2, v) \in \mathcal{V} \text{ or } v = p_2} R(p_2, v) + 1 & \text{otherwise.} \end{cases}$$

Since the $x$-coordinate of the first vertex of a $\mathcal{V}$ chain is less than those of subsequent vertices, this formula is well defined. For sequences of constant size, membership in $\mathcal{V}$
can be checked in constant time. So the running time to compute \( R(e) \) for all edges is \( O(|E| \cdot |X \times Y|) = O(n^8) \), and the space complexity is \( O(|E|) = O(n^3) \). This algorithm can easily be adapted to find the maximum size convex chains in \{\( \tau \), \( \gamma \), \( \rho \), \( \chi \)\} with the same time and space complexity. We thus conclude the following:

\textbf{Lemma 3.3.} For a given \( n \times n \) grid, we can compute a maximum size convex chain in \( O(n^6) \) time and \( O(n^4) \) space.

\textbf{Convex caps.} To compute the maximum size of a convex cap in \( \rho \), we compute the maximum size of two convex chains that use distinct \( y \)-coordinates. Specifically, for two edges \( l = (l_1, l_2) \) and \( r = (r_1, r_2) \), we compute the maximum total size \( C(l, r) \) of a pair of chains \( A \in \tau \) and \( B \in \rho \) such that their vertices use distinct \( y \)-coordinates and such that \( A \) ends with vertices \( l_1 \) and \( l_2 \) (or \( A = (l_1) \) if \( l_1 = l_2 \)), and \( B \) starts with vertices \( r_1 \) and \( r_2 \) (or \( B = (r_1) \) if \( r_1 = r_2 \)). To compute \( C(l, r) \), we reuse the algorithm of Lemma 3.3 to compute \( L(p_1, p_2) \) (resp., \( R(p_1, p_2) \)), the size of a largest convex chain \( P \) in \( \tau \) (resp., \( \rho \)), ending (resp., starting) in vertices \( p_1 \) and \( p_2 \), or \( P = (p_1) \) if \( p_1 = p_2 \).

The desired quantity \( C(l, r) \) can now be computed using a dynamic program. The main idea is that we can always safely eliminate the highest vertex of the two chains, to find a smaller subproblem, as this vertex cannot be (implicitly) part of the optimal solution to a subproblem. In particular, if \( l \) is a single vertex and it is highest, we can simply use the value of \( R(r_1, r_2) \), incrementing it by one for the one vertex of \( l \). Analogously, we handle the case if \( r \) is or both \( l \) and \( r \) are a single vertex. The interesting case is when both chains end in an edge. Here, we observe that we can easily check whether \( l \) and \( r \) use unique coordinates. If not, then this subproblem is invalid; otherwise, we may find a smaller subproblem by eliminating the highest vertex and checking all possible subchains that could lead to it.

With the reasoning above, we obtain the recurrence below. The first case eliminates invalid edges and combinations that use a coordinate more than once or that do not give a cap. After the first, it holds that \( l \in \tau \), \( r \in \rho \) and that \( l \) and \( r \) use unique coordinates.

\[
C(l, r) = \begin{cases} 
-\infty & \text{if } l_1 \neq l_2 \text{ and } l \notin \tau, \text{ or } \ r_1 \neq r_2 \text{ and } r \notin \rho, \text{ or } \ \{l_1.y, l_2.y\} \cap \{r_1.y, r_2.y\} \neq \emptyset \\
2 & \text{otherwise, if } l_1 = l_2 \text{ and } r_1 = r_2 \\
L(l_1, l_2) + 1 & \text{otherwise, if } r_1 = r_2 \text{ and } l_2.y < r_1.y \\
R(r_1, r_2) + 1 & \text{otherwise, if } l_1 = l_2 \text{ and } l_2.y > r_1.y \\
\max_{(v, l_1, l_2) \in \tau \text{ or } v = l_1} C(\{v, l_1\}, r) + 1 & \text{otherwise, } l_2.y < r_1.y \\
\max_{(r_1, r_2, v) \in \rho \text{ or } v = r_1} C(l, \{r_2, v\}) + 1 & \text{otherwise, } l_2.y < r_1.y \end{cases}
\]

We can compute \( C(l, r) \) for all \( l \) and \( r \) in \( O(|E|^2 |X \times Y|) = O(n^{10}) \) time and \( O(|E|^2) = O(n^8) \) space. With \( C(l, r) \), we can easily find the size of a maximum size cap \( P \) in \( \rho \), using the observation below, and analogous observations for the special case \( k = 1 \) and/or \( \ell = 1 \).

\textbf{Observation 3.4.} If \( A = (a_1, \ldots, a_k) \in \tau \) and \( B = (b_1, \ldots, b_\ell) \in \rho \) with \( k \geq 2 \), \( \ell \geq 2 \) and \( (a_{k-1}, a_k, b_1, b_2) \in \rho \) and \( A \) and \( B \) use distinct \( y \)-coordinates, then \( (a_1, \ldots, a_{k-2}, b_1, \ldots, b_\ell) \) lies in \( \rho \) and has size \( k + \ell \).

\textbf{Lemma 3.5.} For a given \( n \times n \) grid, we can compute a maximum size convex cap in \( O(n^{10}) \) time and \( O(n^8) \) space.

\textbf{Convex \( n \)-chains and \( n \)-caps.} If we are solely interested in deciding whether a convex chain or cap exists that has \( |X| = |Y| = n \) vertices, we can improve upon the previous algorithms
considerably. Let \( X = \{x_1, \ldots, x_n\} \) and \( Y = \{y_1, \ldots, y_n\} \) with \( x_i < x_{i+1} \) and \( y_i < y_{i+1} \). To test whether \( \mathcal{C} \) supports a chain of size \( n \), it suffices to test the chain \( ((x_1, y_1), \ldots, (x_n, y_n)) \), which can be done in linear time.

To test whether \( \mathcal{C} \) supports a convex cap of size \( n \), we adapt the algorithm of Lemma 3.5. Suppose \( P \) is a cap of \( \mathcal{C} \) of size \( n \). For \( k < n \), let \( A_k \) and \( B_k \) be the subchains of \( A_P \) and \( B_P \) obtained after discarding vertices with \( y \)-coordinates greater than \( y_k \). Let \((l_1, l_2)\) be the last edge of \( A_k \) and let \((r_1, r_2)\) be the first edge of \( B_k \). Then \( h, i \) and \( j \) exist such that \( i < j < k \) and \( l_1.x = x_h, l_2.x = x_{h+1}, r_1.x = x_{n-k+h+2}, r_2.x = x_{n-k+h+3} \) and \( \{l_1, y, l_2, y, r_1, y, r_2, y\} = \{y, y_j, y_{k-1}, y_k\} \). Suppose we adapt the formula for \( C(l, r) \) to consider only entries of this form, and adapt the formulas for \( L \) and \( R \) to consider only entries of the form \( ((x_{i-1}, y_{i-1}), (x_i, y_i)) \) and \( ((x_{n-i}, y_{n-i-1}), (x_{n-i+1}, y_i)) \), respectively. We then obtain \( O(|Y|^3|X|) \) possible values for \((l, r)\), and the corresponding values can be computed in \( O(|Y|^4|X|) = O(n^5) \) time and \( O(n^4) \) space. Testing whether \( \mathcal{C} \) supports a cap of size \( n \) can be done within the same time and space bounds.

**Approximation.** Although an efficient algorithm for computing the maximum size of a supported convex polygon is left as an open problem, the algorithms above provide constant-factor approximations. A convex cap \( P \in \mathcal{C} \) is composed of two convex chains \( (A_P \in \rho \) and \( B_P \in \gamma \) as defined before), which are themselves caps in \( \mathcal{C} \), and one of which has at least half the size of \( P \). Hence, the algorithms to compute the maximum size of an \( x \)- and \( y \)-monotone chain provide a factor \( \frac{1}{2} \)-approximation on the size of the largest cap. Similarly, a convex polygon \( P \) is composed of four \( x \)- and \( y \)-monotone convex chains, one of which contains at least a quarter of the vertices of \( P \). Furthermore, \( P \) is composed of a convex cap and a convex cup, one of which contains at least half of the vertices of \( P \). Thus, the algorithms in Lemma 3.3 and Lemma 3.5, respectively, yield factor \( \frac{1}{2} \)- and \( \frac{1}{2} \)-approximations for the maximum size of a convex polygon supported by \( X \times Y \).

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**References**