Maximal spanning time for neighborhood growth on the Hamming plane¹

JANKO GRAVNER
Mathematics Department
University of California
Davis, CA 95616, USA
gravner@math.ucdavis.edu

J.E. PAGUYO Mathematics Department University of California Davis, CA 95616, USA jepaguyo@ucdavis.edu

ERIK SLIVKEN
Mathematics Department
University of California
Davis, CA 95616, USA
erikslivken@math.ucdavis.edu

Abstract

We consider a long-range growth dynamics on the two-dimensional integer lattice, initialized by a finite set of occupied points. Subsequently, a site x becomes occupied if the pair consisting of the counts of occupied sites along the entire horizontal and vertical lines through x lies outside a fixed Young diagram \mathcal{Z} . We study the extremal quantity $\mu(\mathcal{Z})$, the maximal finite time at which the lattice is fully occupied. We give an upper bound on $\mu(\mathcal{Z})$ that is linear in the area of the bounding rectangle of \mathcal{Z} , and a lower bound $\sqrt{s-1}$, where s is the side length of the largest square contained in \mathcal{Z} . We give more precise results for a restricted family of initial sets, and for a simplified version of the dynamics.

1 Introduction

The *Hamming plane* is the Cartesian product of two complete graphs on \mathbb{Z}_+ and so it has vertex set \mathbb{Z}_+^2 with an edge between any pair of points that differ in a single coordinate.

¹Version 1, April 21, 2018

AMS 2000 subject classification. 05D99

Key words and phrases. Hamming plane, growth dynamics, spanning time, Young diagram.

We refer to the points in \mathbb{Z}_+^2 as *sites*. Investigation of percolation and growth models on the Hamming plane and related highly connected graphs is a recent development [Siv, GHPS, BBLN, Sli], and this paper addresses an extremal quantity associated with a growth process introduced in [GSS].

We keep the terminology and notation from [GSS]. For $a, b \in \mathbb{N}$, we let $R_{a,b} = ([0, a-1] \times [0, b-1]) \cap \mathbb{Z}_+^2$ be the discrete $a \times b$ rectangle. A union $\mathcal{Z} = \bigcup_{(a,b)\in\mathcal{I}} R_{a,b}$ of rectangles over some finite set $\mathcal{I} \subseteq \mathbb{N}^2$ is called a *zero-set*. Note that it is possible that $\mathcal{Z} = \emptyset$. Also note that we restrict our consideration to finite zero-sets.

For a site $x \in \mathbb{Z}_+^2$, we denote by $L^h(x) \subset \mathbb{Z}_+^2$ and $L^v(x) \subset \mathbb{Z}_+^2$ the horizontal and vertical lines through x, respectively. The neighborhood of x then is $\mathcal{N}(x) = L^h(x) \cup L^v(x)$. The row and column counts of x in a set $A \subset \mathbb{Z}_+^2$ are given by

$$\operatorname{row}(x,A) = |L^h(x) \cap A| \text{ and } \operatorname{col}(x,A) = |L^v(x) \cap A|.$$

A zero-set \mathcal{Z} determines a neighborhood growth transformation $\mathcal{T}: 2^{\mathbb{Z}_+^2} \to 2^{\mathbb{Z}_+^2}$ as follows. Fix $A \subseteq \mathbb{Z}_+^2$. If $x \in A$, then $x \in \mathcal{T}(A)$. If $x \notin A$, then $x \in \mathcal{T}(A)$ if and only if the pair of row and column counts of x lies outside the zero-set, i.e., $(\mathbf{row}(x, A), \mathbf{col}(x, A)) \notin \mathcal{Z}$. The neighborhood growth dynamics is given by the discrete time trajectory obtained by iteration of \mathcal{T} : $A_t = \mathcal{T}^t(A)$, for $t \geq 0$. We call sites in A_t occupied and sites in A_t^c empty. See Figure 1 for an example of neighborhood growth dynamics.

The simplest example, line growth, introduced as line percolation in [BBLN], is given by a rectangular zero-set $\mathcal{Z} = R_{a,b}$ for some $a,b \in \mathbb{N}$. Another special case, perhaps the most important one, is threshold growth, which is determined by an integer threshold $\theta \geq 1$. This natural growth rule is defined on an arbitrary graph as follows: a site x becomes occupied when the number of already occupied sites among its neighbors is at least θ . This dynamics was first introduced on trees in [CLR] and is typically called bootstrap percolation. The most common setting, with many deep and surprising results, is a graph of the form $[k]^{\ell}$, a Cartesian product of path graphs of k points, and thus with standard nearest neighbor lattice connectivity [AL, GG, Hol, BB, GHM, BBDM]. On the Hamming plane, threshold growth is given by the triangular zero-set $\mathcal{Z} = \{(u, v) : u + v \leq \theta - 1\}$; see [GHPS] and [GSS] for further background.

Define the set of eventually occupied sites by $A_{\infty} = \mathcal{T}^{\infty}(A) = \bigcup_{t \geq 0} A_t$. The set A spans if $A_{\infty} = \mathbb{Z}_+^2$. For a fixed zero-set \mathcal{Z} , we let $\mathcal{A} = \mathcal{A}(\mathcal{Z})$ denote the collection of all finite spanning subsets of \mathbb{Z}_+^2 . It follows from Theorem 2.8 in [GSS] that, for any $A \in \mathcal{A}$, the spanning time

$$\tau(\mathcal{Z}, A) = \min\{t \in \mathbb{N} : \mathcal{T}^t(A) = \mathbb{Z}_+^2\}$$

is finite. Our main focus of attention is the maximal spanning time, the extremal quantity defined by

$$\mu(\mathcal{Z}) = \sup\{\tau(\mathcal{Z}, A) : A \in \mathcal{A}\}.$$

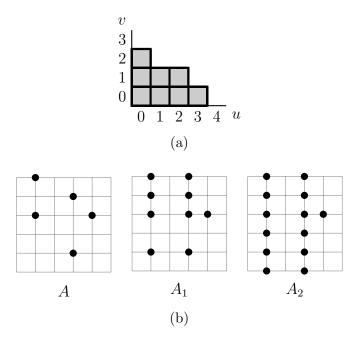


Figure 1: An example of neighborhood growth dynamics with zero-set given in (a) and the initial set in the leftmost panel of (b). The next two panels of (b) depict the subsequent two iterations. Observe that $\mathcal{T}^3(A) = \mathcal{T}^2(A)$, thus A does not span.

Theorem 2.8 in [GSS] shows that $\mu(\mathcal{Z}) < \infty$ by providing a very large upper bound (essentially the product of lengths of all rows of \mathcal{Z} , multiplied by their number). One of our results is a substantial improvement of that bound (see Theorem 1.1 below). Before we give further definitions and state our results, we give a brief review of related results in the literature.

Arguably, the topic that most closely resembles ours is the following classic problem on matrix powers. Let \mathcal{M} be the set of all primitive non-negative $n \times n$ matrices. Then let h = h(n) be the smallest power that makes all elements of the power A^h nonzero for every $A \in \mathcal{M}$. See [HV] for the solution of this problem, and related results for analogous extremal quantities obtained by replacing \mathcal{M} by some natural subsets of \mathcal{M} .

Extremal quantities in growth models have been of substantial interest. Perhaps the most natural one is the smallest cardinality of a spanning set. It is a famous folk theorem that this quantity equals exactly n for the bootstrap percolation on $[n]^2$ with $\theta = 2$. For bootstrap percolation on $[n]^d$ with $\theta = 2$, the smallest spanning sets have size $\lceil d(n-1)/2 \rceil + 1$ [BBM]. Not much was known for thresholds $\theta \geq 3$ in such lattice setting until a recent breakthrough [MN]. Smallest spanning sets have also been studied for bootstrap percolation on trees [Rie] and on hypergraphs [BBMR]. For Hamming graphs, [BBLN] determines the size of the smallest spanning sets for line growth, while [GSS] gives bounds for general neighborhood growth.

Maximal spanning time results are comparatively scarce. In [**BP2**], it is shown that the maximal spanning time for bootstrap percolation on $[n]^2$ with $\theta = 2$ is $13n^2/18 + O(n)$ (see also [**BP1**]). For bootstrap percolation on the hypercube $[2]^n$, the maximal spanning time is $\lfloor n^2/3 \rfloor$ when $\theta = 2$ [**Prz**] and $n^{-1+o(1)}2^n$ when $\theta \geq 3$ [**Har**]. A related clique-completion process is studied from this perspective in [**BPRS**]. It appears that in general the maximal spanning time is considerably more complex than the smallest size of a spanning set. In our case, a major difficulty is non-monotonicity of μ : if $\mathcal{Z} \subseteq \mathcal{Z}'$, then $\mathcal{A}(\mathcal{Z}') \subseteq \mathcal{A}(\mathcal{Z})$ but $\tau(A, \mathcal{Z}) \leq \tau(A, \mathcal{Z}')$ for all $A \in \mathcal{A}(\mathcal{Z}')$, thus it is not clear how $\mu(\mathcal{Z})$ and $\mu(\mathcal{Z}')$ compare. As announced, our first result is an improved upper bound from [**GSS**] on the maximal spanning time.

Theorem 1.1. For any $m, n \in \mathbb{N}$ and zero-set $\mathcal{Z} \subseteq R_{m,n}$,

$$\mu(\mathcal{Z}) \le 2mn + 5.$$

We are able to obtain a better upper bound for a special class of initial sets, which will also provide a lower bound for $\mu(\mathcal{Z})$.

A finite set $A \subseteq \mathbb{Z}_+^2$ is thin if, for every site $x \in A$, either row(x, A) = 1 or col(x, A) = 1. That is, any point $x \in A$ has no other points of A either on the horizontal line or on the vertical line through x. We define \mathcal{A}_{th} to be the set of all spanning thin sets, and let

$$\mu_{\text{th}}(\mathcal{Z}) = \max\{\tau(A, \mathcal{Z}) : A \in \mathcal{A}_{\text{th}}\}.$$

Arguably, thin sets are the simplest general family of initial sets and are for this reason used in [GHPS, GSS] and in Section 3. In certain circumstances, thin set constructions are close to optimal [GSS]; in the present context, the extent to which $\mu(\mathcal{Z})$ and $\mu_{\text{th}}(\mathcal{Z})$ are comparable remains unclear (see open problem 3 in Section 7). The utility of thin sets in part comes from their connection to a simplified growth dynamics, which we now introduce.

The row and column enhancements $\vec{r} = (r_0, r_1, \ldots) \in \mathbb{Z}_+^{\infty}$ and $\vec{c} = (c_0, c_1, \ldots) \in \mathbb{Z}_+^{\infty}$ are two weakly decreasing sequences of non-negative integers which increase row and column counts by fixed values. To be precise, the enhanced neighborhood growth dynamics [GSS] is given by the triple $(\mathcal{Z}, \vec{r}, \vec{c})$, which defines a growth transformation $\mathcal{T}_{en} : 2^{\mathbb{Z}_+^2} \to 2^{\mathbb{Z}_+^2}$ as follows:

$$\mathcal{T}_{\mathrm{en}}(A) = A \cup \{(i,j) \in \mathbb{Z}_+^2 : (\mathsf{row}((i,j),A) + r_j, \mathsf{col}((i,j),A) + c_i) \notin \mathcal{Z}\}.$$

By default, we initialize the enhanced growth by the empty set, and we say that the pair of enhancements (\vec{r}, \vec{c}) spans for \mathcal{Z} if $\bigcup_{t\geq 0} \mathcal{T}_{\mathrm{en}}^t(\emptyset) = \mathbb{Z}_+^2$. We let $\mathcal{A}_{\mathrm{en}}$ be the set of all pairs of enhancements (\vec{r}, \vec{c}) that have finite support and span for \mathcal{Z} . Next, we introduce the enhanced spanning time

$$\tau_{\mathrm{en}}(\mathcal{Z}, \vec{r}, \vec{c}) = \inf\{t \in \mathbb{N} : \mathcal{T}_{\mathrm{en}}^t(\emptyset) = \mathbb{Z}_+^2\},$$

and finally define the corresponding maximal quantity

$$\mu_{\rm en}(\mathcal{Z}) = \max\{\tau_{\rm en}(\mathcal{Z}, \vec{r}, \vec{c}) : (\vec{r}, \vec{c}) \in \mathcal{A}_{en}\}.$$

We next state a comparison result between $\mu_{\rm th}$ and $\mu_{\rm en}$.

Theorem 1.2. For all zero-sets \mathcal{Z} ,

$$\mu_{\rm en}(\mathcal{Z}) - 2 \le \mu_{\rm th}(\mathcal{Z}) \le 2\mu_{\rm en}(\mathcal{Z}).$$

For a zero-set \mathcal{Z} , we let $s = s(\mathcal{Z})$ to be the side of the largest square included in \mathcal{Z} , that is, the integer $s \geq 0$ such that $R_{s,s} \subseteq \mathcal{Z}$ but $R_{s+1,s+1} \not\subseteq \mathcal{Z}$. The upper bound we obtain for μ_{en} and μ_{th} is linear in s, and is in this sense the best possible.

Theorem 1.3. For any zero-set \mathcal{Z} ,

$$\mu_{\rm en}(\mathcal{Z}) \le 4s + 1,$$

 $\mu_{\rm th}(\mathcal{Z}) \le 8s + 2.$

Moreover,

$$\sup_{\mathcal{Z}\neq\emptyset} \mu_{\rm en}(\mathcal{Z})/s(\mathcal{Z}) \in (0,\infty),$$

$$\sup_{\mathcal{Z}\neq\emptyset} \mu_{\rm th}(\mathcal{Z})/s(\mathcal{Z}) \in (0,\infty).$$

Finally, we give the lower bounds on the maximal spanning times. We do not know whether these are in any sense optimal (see open problem 2 in Section 7).

Theorem 1.4. For any zero-set $\mathcal{Z} \neq \emptyset$,

$$\mu_{\rm en}(\mathcal{Z}) \ge s^{1/2}$$

and

$$\mu(\mathcal{Z}) \ge \mu_{\text{th}}(\mathcal{Z}) \ge (s-1)^{1/2}.$$

The paper is organized as follows. In Section 2 we introduce additional notation and definitions, and prove preliminary results. In Section 3, we address special cases of neighborhood growth. We prove Theorem 1.2 in Section 4, Theorems 1.1 and 1.3 in Section 5, and Theorem 1.4 in Section 6. Finally we conclude with a selection of open questions in Section 7.

2 Preliminaries

2.1 Notation and Terminology

We define the partial order \leq on \mathbb{Z}^2_+ as follows. For two sites z=(i,j) and z'=(i',j'), $z \leq z'$ if and only if $i \leq i'$ and $j \leq j'$.

A Young diagram is then a set of sites $X \subseteq \mathbb{Z}_+^2$ such that $z' \in X$ and $z \leq z'$ implies $z \in X$ for all sites $z, z' \in \mathbb{Z}_+^2$. Observe that any zero-set is a Young diagram.

For $A \subseteq \mathbb{Z}_+^2$, we denote the respective projections of A onto the x-axis and y-axis by $\pi_x(A)$ and $\pi_y(A)$.

Consider a vector $\vec{r} = (r_0, r_1, \ldots) \in \mathbb{Z}_+^{\infty}$ with weakly decreasing entries. The size of \vec{r} is $|\vec{r}| = \sum_i r_i$. The support of \vec{r} is the smallest interval [0, N-1] such that $r_i = 0$ for $i \geq N$. We will often write \vec{r} as a finite vector, omitting its zero coordinates.

We say a set $B \subseteq \mathbb{Z}_+^2$ is *covered* at time t by either regular or enhanced growth dynamics if every site of B is occupied at time t by the respective dynamics.

A line in \mathbb{Z}^2_+ is either $L^h(x)$ (also called a row) or $L^v(x)$ (also called a column) for some $x \in \mathbb{Z}^2_+$.

The dynamics given by the growth transformation \mathcal{T} is sometimes called the *regular dynamics* when it needs to be distinguished from the enhanced version.

2.2 Operations with Young diagrams

Let X be a Young diagram and $k \in \mathbb{N}$. We define reductions of X obtained by removing the k leftmost columns or k bottommost rows of X,

$$X^{\downarrow k} = \{(u, v - k) : (u, v) \in X, v \ge k\},\$$

$$X^{\leftarrow k} = \{(u - k, v) : (u, v) \in X, u \ge k\},\$$

and the diagonal shift of X,

$$X^{\checkmark k} = X^{\leftarrow k \downarrow k}$$
.

Given two Young diagrams X, Y, we define the *infimal sum* of X and Y by

$$X \boxplus Y = (X^c + Y^c)^c$$

where $X^c = \mathbb{Z}_+^2 \setminus X$. See Figure 2 for an example. For a Young diagram X, define its closure $\overline{X} = X \cup (\mathbb{Z}_+^2)^c$ and its height function $\phi_X : \mathbb{R} \to \mathbb{R} \cup \{\infty\}$ so that \overline{X} +

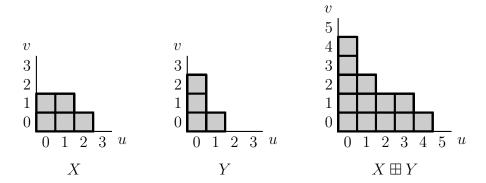


Figure 2: An example of the infimal sum of two Young diagrams.

 $[0,1]^2 = \{(x,y) \in \mathbb{R}^2 : y \leq \phi_X(x)\}$. Then the terminology comes from the fact that $\phi_{X \boxplus Y} = \phi_X \square \phi_Y$, where \square is the infimal convolution (see for example Section 5 of [**Roc**]).

The following lemma in particular establishes that the set of Young diagrams equipped with the operation \boxplus is a commutative monoid. We omit the routine proof.

Lemma 2.1. Let X, Y, Z be Young diagrams. The infinal sum has the following properties:

- 1. $X \boxplus Y$ is a Young diagram.
- 2. $X \boxplus \emptyset = X$.
- 3. $(X \boxplus Y) \boxplus Z = X \boxplus (Y \boxplus Z)$.
- 4. $X \boxplus Y = Y \boxplus X$.
- 5. $(X \boxplus Y) \cap (Z \boxplus Y) = (X \cap Z) \boxplus Y$.
- 6. If $X \subseteq Y$, then $X \boxplus Z \subseteq Y \boxplus Z$.

Assume Y and Z are Young diagrams. Let $\Delta(Z,Y)$ consist of all Young diagrams X such that $Z \subseteq X \boxplus Y$. The *infimal difference* of Z and Y is defined as

$$Z \boxminus Y = \bigcap_{X \in \Delta(Z,Y)} X.$$

Lemma 2.2. Let Y, Z be Young diagrams. The infinal difference has the following properties:

- 1. $Z \boxminus Y \in \Delta(Z, Y)$.
- 2. $Z \boxminus Y \subseteq Z$.

Proof. Property (1) holds since an intersection of Young diagrams is a Young diagram and by Lemma 2.1(5). Property (2) holds since $Z \in \Delta(Z, Y)$ implies $Z \boxminus Y \subseteq Z$.

2.3 Enhanced growth

Given a pair of enhancements (\vec{r}, \vec{c}) , we form a pair of Young diagrams $(\mathcal{R}, \mathcal{C})$ such that the row counts of \mathcal{R} are given by \vec{r} and the column counts of \mathcal{C} are given by \vec{c} . Therefore we use the two pairs interchangeably to describe an enhanced dynamics. The following lemma explains why enhanced growth is simpler than regular growth.

Lemma 2.3. Let $(\mathcal{R}, \mathcal{C})$ be enhancements that span for a zero-set \mathcal{Z} . The set of occupied sites A_t satisfies the following for all $t \geq 0$:

- 1. The set A_t is a Young diagram.
- 2. The concave corners of A_t must grow: if $(i-1,j), (i,j-1) \in \overline{A_t}$, then $(i,j) \in A_{t+1}$ for any $i,j \geq 0$.
- 3. The sites with identical enhancements become occupied simultaneously: if $r_i = r_{i'}$ and $c_i = c_{i'}$, then $(i, j) \in A_t$ if and only if $(i', j') \in A_t$.

Proof. We prove Property (1) by induction. When t = 0, $A_0 = \emptyset$. Now suppose A_t is a Young diagram for some $t \geq 0$. Assume $x = (i, j) \notin A_t$, $x' = (i', j') \notin A_t$, and $x \leq x'$. As A_t is a Young diagram, $row(x, A_t) \geq row(x', A_t)$ and $col(x, A_t) \geq col(x', A_t)$. As $c_i \geq c_{i'}$ and $r_i \geq r_{j'}$, and \mathcal{Z} is a Young diagram, $(row(x, A_t) + r_j, col(x, A_t) + c_i) \notin \mathcal{Z}$ implies $(row(x', A_t) + r_{j'}, col(x', A_t) + c_{i'}) \notin \mathcal{Z}$. Therefore A_{t+1} is also a Young diagram.

To prove Property (2), suppose $x = (i, j) \notin A_{t+1}$. By Property (1), $(i', j') \notin A_{t+1}$ for all $i' \geq i$ and $j' \geq j$. Thus $x' \notin A_s$ for all $s \geq t$ and $x \leq x'$, which contradicts the fact that $(\mathcal{R}, \mathcal{C})$ spans for \mathcal{Z} .

Let x = (i, j) and x' = (i', j'). Then $(\operatorname{row}(x, A_{t-1}) + r_i, \operatorname{col}(x, A_{t-1}) + c_j) \notin \mathcal{Z}$ if and only if $(\operatorname{row}(x', A_{t-1}) + r_{i'}, \operatorname{col}(x', A_{t-1}) + c_{j'}) \notin \mathcal{Z}$. Therefore $(i, j) \in A_t$ if and only if $(i', j') \in A_t$. This proves property (3).

Lemma 2.4. Fix a zero-set \mathcal{Z} and let $(\mathcal{R}, \mathcal{C})$ be enhancements that span for \mathcal{Z} . Let $\{I_i\}_{i=0}^M \subseteq \mathbb{Z}_+$ be maximal intervals of equal column lengths of \mathcal{C} , and similarly let $\{J_i\}_{i=0}^N \subseteq \mathbb{Z}_+$ be maximal intervals of equal row lengths of \mathcal{R} . Then

$$\bigcup_{i+j< t} I_i \times J_j \subseteq A_t$$

for all $t \geq 0$.

Proof. We use induction, beginning with the trivial base case t = 0. The inductive step follows from Lemma 2.3 (2) and (3).

Corollary 2.5. Let \mathcal{R} have M nonzero row counts and \mathcal{C} have N nonzero column counts. If $(\mathcal{R}, \mathcal{C})$ span for \mathcal{Z} , then $\tau_{\text{en}}(\mathcal{Z}, \mathcal{R}, \mathcal{C}) \leq M + N + 1$.

The next lemma provides the key connection between the infimal sum and enhanced growth.

Lemma 2.6. Fix a zero-set \mathcal{Z} . The enhancements $(\mathcal{R},\mathcal{C})$ span for \mathcal{Z} if and only if

$$\mathcal{Z} \subseteq \mathcal{R} \boxplus \mathcal{C}$$
.

Proof. The pair of enhancements $(\mathcal{R}, \mathcal{C})$ does not span if and only if there exists $(i, j) \notin \mathcal{T}_{en}^{\infty}(\emptyset)$ so that (i-1, j) and (i, j-1) are both in $\overline{\mathcal{T}_{en}^{\infty}(\emptyset)}$. For this to happen, we must have $(i+r_j, j+c_i) \in \mathcal{Z}$. But $(i, c_i) \notin \mathcal{C}$ and $(r_j, j) \notin \mathcal{R}$, thus $\mathcal{R}^c + \mathcal{C}^c \not\subseteq \mathcal{Z}^c$, and so $\mathcal{Z} \not\subset \mathcal{R} \boxplus \mathcal{C}$.

Conversely, if $\mathcal{Z} \nsubseteq \mathcal{R} \boxplus \mathcal{C}$, there exist $(i,b) \notin \mathcal{R}$ and $(a,j) \notin \mathcal{C}$, so that $(i+a,j+b) \in \mathcal{Z}$. Then $b \geq c_i$, $a \geq r_j$, and so $(i+r_j,j+c_i) \in \mathcal{Z}$. Thus no point outside of $([0,i-1]\times[0,\infty))\cup([0,\infty)\times[0,j-1])$ becomes occupied, and consequently $(\mathcal{R},\mathcal{C})$ does not span.

2.4 Perturbations of zero-sets

Let $\tau_{\text{line}}(\mathcal{Z}, A)$ be the first time that the regular dynamics given by \mathcal{Z} covers a line in \mathbb{Z}_+^2 . Define

$$\mu_{\text{line}}(\mathcal{Z}) = \max_{A \in \mathcal{A}} \{ \tau_{\text{line}}(\mathcal{Z}, A) \}.$$

We omit the simple proof of the following lemma.

Lemma 2.7. For any zero-set \mathcal{Z} ,

$$\mu(\mathcal{Z}) \le \mu_{\text{line}}(\mathcal{Z}) + \max \left\{ \mu\left(\mathcal{Z}^{\downarrow 1}\right), \mu\left(\mathcal{Z}^{\leftarrow 1}\right) \right\}.$$

As already remarked, μ is not apparently monotone with respect to inclusion. We do however have a weaker form of monotonicity which is the subject of the next lemma.

Lemma 2.8. For any zero-set $\mathcal{Z} \neq \emptyset$,

$$\mu(\mathcal{Z}) \ge \max \left\{ \mu\left(\mathcal{Z}^{\downarrow 1}\right), \mu\left(\mathcal{Z}^{\leftarrow 1}\right) \right\},$$

$$\mu_{en}(\mathcal{Z}) \ge \max \left\{ \mu_{en}\left(\mathcal{Z}^{\downarrow 1}\right), \mu_{en}\left(\mathcal{Z}^{\leftarrow 1}\right) \right\}.$$

Proof. To prove the first inequality, by symmetry we only need to show $\mu(\mathcal{Z}) \geq \mu(\mathcal{Z}^{\leftarrow 1})$. Assume $A \in \mathcal{A}(\mathcal{Z}^{\leftarrow 1})$. Let $A' = A \cup (\{(M,0)\} \times [0,N])$. If M and N are large enough, then $A' \in \mathcal{A}(\mathcal{Z})$ and $\tau(\mathcal{Z}^{\leftarrow 1},A) = \tau(\mathcal{Z},A') \leq \mu(\mathcal{Z})$. Therefore $\mu(\mathcal{Z}^{\leftarrow 1}) \leq \mu(\mathcal{Z})$.

For the second inequality, we again only need to show $\mu_{\text{en}}(\mathcal{Z}) \geq \mu_{\text{en}}(\mathcal{Z}^{\leftarrow 1})$. Assume $(\vec{r}, \vec{c}) \in \mathcal{A}_{\text{en}}(\mathcal{Z}^{\leftarrow 1})$, where $\vec{r} = (r_0, \dots, r_{N_0})$ and $\vec{c} = (c_0, \dots, c_{M_0})$. Let

$$\vec{r}' = (r_0 + 1, \dots, r_{N_0} + 1, 1, \dots, 1, 0, \dots)$$

be row enhancements with finite support [0, N]. For N are large enough, $(\vec{r}', \vec{c}) \in \mathcal{A}_{en}(\mathcal{Z})$, and $\tau_{en}(\mathcal{Z}^{\leftarrow 1}, \vec{r}, \vec{c}) = \tau_{en}(\mathcal{Z}, \vec{r}', \vec{c}) \leq \mu_{en}(\mathcal{Z})$. Thus $\mu(\mathcal{Z}^{\leftarrow 1}) \leq \mu_{en}(\mathcal{Z})$.

The next lemma gives a converse inequality.

Lemma 2.9. For any zero-set \mathcal{Z} ,

$$\mu_{\rm en}(\mathcal{Z}) < \mu_{\rm en}(\mathcal{Z}^{\checkmark 1}) + 2.$$

Proof. Assume that \mathcal{R} and \mathcal{C} , with respective number of rows and columns N_0 and M_0 , span for the zero-set \mathcal{Z} . Then $\mathcal{R}^{\leftarrow 1}$ and $\mathcal{C}^{\downarrow 1}$ span for $\mathcal{Z}^{\checkmark 1}$ and do so in at most $\mu_{\rm en}(\mathcal{Z}^{\checkmark 1})$ steps. The enhanced dynamics given by $(\mathcal{Z}, \mathcal{R}, \mathcal{C})$ and $(\mathcal{Z}^{\checkmark 1}, \mathcal{R}^{\leftarrow 1}, \mathcal{C}^{\downarrow 1})$ agree on the rectangle $[0, M_0 - 1] \times [0, N_0 - 1]$ by Lemma 2.3. Therefore, the dynamics given by $(\mathcal{Z}, \mathcal{R}, \mathcal{C})$ covers this rectangle by time $\mu_{\rm en}(\mathcal{Z}^{\checkmark 1})$, and then needs at most two additional steps to fully occupy \mathbb{Z}^2_+ . The inequality follows.

2.5 Thin sets

As we will see in the next lemma, it is advantageous to permute rows and columns to arrange sites in a thin set in a certain manner reminiscent of convexity (see Figure 3). We formalize this arrangement next.

Two sets $A_1, A_2 \subseteq \mathbb{Z}_+^2$ are *equivalent* if there are permutations of rows and columns of \mathbb{Z}_+^2 that map A_1 to A_2 . It is clear that the spanning times of two equivalent sets are the same.

An equivalence class of thin sets is given by finite (possibly empty) weakly decreasing vectors \vec{r} and \vec{c} with integer entries of at least 2, which specify the number of occupied sites in the rows and columns that contain at least two sites, and a number $w \geq 0$ of isolated occupied sites. We now identify a specific representative of this equivalence class.

We say that a thin set A is in the $standard\ arrangement$ (see Figure 3) if the following hold:

• The row counts row((0, j), A), $j \ge 0$, and column counts col((i, 0), A), $i \ge 0$, are weakly decreasing.

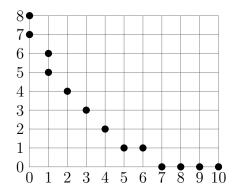


Figure 3: A thin set in the standard arrangement with $\vec{r} = (4, 2)$, $\vec{c} = (2, 2)$, and w = 3.

• If $x, x' \in A$ and $x \leq x'$, then x and x' are on the same line.

To achieve the standard arrangement, let N_0 (resp., M_0) be the number of entries of \vec{r} (resp., \vec{c}), and consider the rectangle $R_{M_0+w+|\vec{r}|,N_0+w+|\vec{c}|}$. The sites in A comprise, in order, the following diagonally adjacent intervals connecting the top left corner of this rectangle with its bottom right corner: vertical intervals of c_i sites, $i = 0, \ldots, N_0 - 1$, followed by w single sites, and followed by horizontal intervals of r_i sites, $i = N_0 - 1, \ldots, 0$ (see Figure 3). It is straightforward to see that the standard arrangement is unique.

Lemma 2.10. Let A be a thin set in the standard arrangement. Assume $Y \subset \mathbb{Z}_+^2$ is a Young diagram. Let $A_0 = A \cup Y$ and $A_1 = \mathcal{T}(A_0)$. Then

- 1. If $x \leq x'$, then for all $t \geq 0$, $row(x, A_0) \geq row(x', A_0)$ and $col(x, A_0) \geq col(x', A_0)$.
- 2. If $x \leq x'$ and $x' \in A_1 \setminus A$, then $x \in A_1$.
- 3. The set A_1 is the union of a Young diagram and A.

Moreover, $A_t = \mathcal{T}^t(A_0)$ is the union of a Young diagram and A for all $t \geq 0$.

Proof. To prove (1), it is, by symmetry, enough to prove the inequality for the row counts. Let x = (i, j) and x' = (i', j'), where $i \le i'$ and $j \le j'$. Let $I' = \{a \in \mathbb{Z}_+ : (a, j') \in Y\}$, $I = \{a \in \mathbb{Z}_+ : (a, j) \in Y\}$, $J' = \{a \in \mathbb{Z}_+ : (a, j') \in A\}$, and $J = \{a \in \mathbb{Z}_+ : (a, j) \in A\}$. As Y is a Young diagram, $I' \subseteq I$. As A is in the standard arrangement, $|J' \setminus I| \le |J \setminus I|$.

Therefore,

$$\begin{split} \operatorname{row}(x',A_0) &= |I' \cup J'| \\ &= |I'| + |(J' \cap I) \setminus I'| + |J' \setminus I| \\ &\leq |I'| + |I \setminus I'| + |J \setminus I| \\ &= |I \cup J| \\ &= \operatorname{row}(x,A_0). \end{split}$$

This establishes (1), which immediately implies (2). Then (3) follows, as $A_1 = A \cup Y_1$, where

$$Y_1 = \bigcup_{x' \in A_1 \setminus A} \{x : x \le x'\}$$

is a Young diagram. Finally, the last claim follows by induction.

3 Special cases

In this section we prove results on $\mu(\mathcal{Z})$ for two special cases of neighborhood growth. First is line growth, where \mathcal{Z} is a single rectangle. The second is L-growth, where \mathcal{Z} is a union of two rectangles: $\mathcal{Z} = R_{a,b} \cup R_{c,d}$, where $a,b,c,d \in \mathbb{N}$ such that a > c and d > b. It turns out that the bounds for L-growth do not depend on the larger numbers a and d.

Lemma 3.1. Let $\mathcal{Z} = R_{m,n}$ and let $A \subseteq \mathbb{Z}_+^2$. If $L^h(x) \subseteq \mathcal{T}^2(A) \setminus \mathcal{T}(A)$, then there exists at least one site $y \in L^h(x)$ such that $L^v(y) \subseteq \mathcal{T}(A) \setminus A$. Similarly, if $L^v(x) \subseteq \mathcal{T}^2(A) \setminus \mathcal{T}(A)$, then there exists at least one site $y \in L^v(x)$ such that $L^h(y) \subseteq \mathcal{T}(A) \setminus A$.

Proof. By symmetry we may assume that $L^h(x) \subseteq \mathcal{T}^2(A) \setminus \mathcal{T}(A)$. Then $row(x, \mathcal{T}(A)) \ge m$ and row(x, A) < m. There exists at least one site $y \in L^h(x)$ such that $y \in \mathcal{T}(A) \setminus A$. Since row(y, A) < m, we must have that $col(y, A) \ge n$. This implies $L^v(y) \subseteq \mathcal{T}(A) \setminus A$.

Proposition 3.2. If $\mathcal{Z} = R_{m,n}$, then with $m \neq n$, then

$$\mu(\mathcal{Z}) = \mu_{\text{th}}(\mathcal{Z}) = \begin{cases} 2\min\{m, n\}, & \text{if } m \neq n, \\ 2n - 1, & \text{if } m = n. \end{cases}$$

Proof. We only address the case when m > n, as the case m = n is similar. Let A be a spanning set for \mathcal{Z} . By Lemma 3.1, there are at least n-1 covered rows and n-1 covered columns at time t = 2n-2. At t = 2n-1, every column containing at least one site that lies outside of the n-1 spanned rows and n-1 spanned columns becomes covered. As A spans, there must be at least m covered columns at t = 2n-1. Therefore $\tau(\mathcal{Z}, A) \leq 2n$.

For the lower bound let A be a thin set in the standard arrangement given by $\vec{r} = (m-1, m-2, \ldots, 2)$, $\vec{c} = (n, n-1, \ldots, 2)$, and w = 2. It is straightforward to check that A spans in 2n steps.

Lemma 3.3. Let $\mathcal{Z} = R_{a,b} \cup R_{c,d}$ and let $A \subseteq \mathbb{Z}_+^2$. In every two time steps, at least one line is covered.

Proof. Suppose $x \in \mathcal{T}^2(A) \setminus \mathcal{T}(A)$. There exists $y \in \mathcal{N}(x)$ such that $y \in \mathcal{T}(A) \setminus A$. Suppose $y \in L^h(x)$. Then either $\operatorname{col}(y, A) \geq d$, or $b \leq \operatorname{col}(y, A) < d$ and $c \leq \operatorname{row}(y, A) < a$.

If $\operatorname{col}(y,A) \geq d$, then column $L^v(y)$ is covered in $\mathcal{T}(A)$. Otherwise, $b \leq \operatorname{col}(y,A) < d$ and $c \leq \operatorname{row}(y,A) = \operatorname{row}(x,A) < a$, and $\operatorname{col}(x,A) < b$. There exists $z \in L^v(x)$ such that $z \in \mathcal{T}(A) \setminus A$. Then $\operatorname{col}(x,A) = \operatorname{col}(z,A) < b$ which implies that $\operatorname{row}(z,A) \geq a$. Thus $\operatorname{row} L^h(z)$ is covered in $\mathcal{T}(A)$.

Proposition 3.4. If $\mathcal{Z} = R_{a,b} \cup R_{c,d}$, then

$$2\min\{b,c\} \le \mu(\mathcal{Z}) \le 2(b+c)$$

Proof. Without loss of generality assume $b \le c$. By Lemma 3.3 at least one row or column is spanned in every two steps, and Lemma 2.7 gives us

$$\mu(\mathcal{Z}) \le 2 + \max \left\{ M\left(\mathcal{Z}^{\leftarrow 1}\right), M\left(\mathcal{Z}^{\downarrow 1}\right) \right\},$$

and the upper bound follows by induction.

For the lower bound, we consider two cases. If d-b>c, then by Lemma 2.8, $\mu(\mathcal{Z}) \geq \mu(\mathcal{Z}^{\downarrow b}) = 2c$. Otherwise $d-b \leq c$. Let $\mathcal{Z}' = \mathcal{Z}^{\leftarrow c-b}$. Let A be a thin set in the standard arrangement given by $\vec{r} = (n-1, n-2, \ldots, 2)$, $\vec{c} = (b, b-1, \ldots, 2)$, and w=2, where $n = \max\{a-c+b, d\}$. One can check that $\tau(\mathcal{Z}', A) = 2b+1$, if $a-c+b \geq d$, and $\tau(\mathcal{Z}', A) = 2b$, otherwise. Therefore by Lemma 2.8, $\mu(\mathcal{Z}) \geq \mu(\mathcal{Z}') \geq 2b$.

4 Enhanced growth vs. growth from thin sets

In this section we prove Theorem 1.2.

Lemma 4.1. For any zero-set \mathcal{Z} ,

$$\mu_{\rm en}\left(\mathcal{Z}^{\checkmark 1}\right) \leq \mu_{\rm th}(\mathcal{Z}).$$

Proof. Let $(\mathcal{R}, \mathcal{C})$ be some enhancements that span for $\mathcal{Z}^{\checkmark 1}$, given respectively by infinite vectors $\vec{r} = (r_0, r_1, \ldots)$ and $\vec{c} = (c_0, c_1, \ldots)$ of respective finite supports $[0, N_0 - 1]$ and $[0, M_0 - 1]$. Form infinite vectors $\vec{r}^+ = (r_i^+ : i \ge 0) = (r_0 + 1, r_1 + 1, \ldots, r_{N_0 - 1} + 1, 1, \ldots)$ and $\vec{c}^+ = (c_i^+ : j \ge 0) = (c_0 + 1, c_1 + 1, \ldots, c_{M_0 - 1} + 1, 1, \ldots)$.

Observe that the enhancements \vec{r}^+, \vec{c}^+ span for \mathcal{Z} . In fact, the enhanced dynamics with zero-set $\mathcal{Z}^{\checkmark 1}$ and enhancements \vec{r}, \vec{c} and the enhanced dynamics with zero-set \mathcal{Z} and enhancements \vec{r}^+, \vec{c}^+ have the same occupied set B_t^+ at any time $t \geq 0$. It is important to note that when B_t^+ covers the rectangle R_{M_0+1,N_0+1} , it in fact fully occupies \mathbb{Z}_+^2 .

Choose N large enough so that the square $S = R_{N,N}$ satisfies $R_{M_0+1,N_0+1} \subseteq S$ and $\mathcal{Z} \subseteq S$. For i < N let $r'_i = r^+_i$ and $c'_i = c^+_i$, and for $i \geq N$ let $r'_i = c'_i = 0$. Let B_t be the set of occupied sites at time t under the enhanced dynamics given by $(\mathcal{Z}, \vec{r}', \vec{c}')$. By Lemma 2.3, $B_t \cap S = B_t^+ \cap S$ for all $t \geq 0$ and therefore the enhancements \vec{r}', \vec{c}' span for \mathcal{Z} .

Define a thin set A in the standard arrangement given by the row vector $(r'_0, \ldots, r'_{N_0-1})$, the column vector $(c'_0, \ldots, c'_{M_0-1})$, and $w = N - N_0 + N - M_0 \ge 2$. Observe that $S \cap A = \emptyset$. Let A_t be the set of occupied sites at time t starting from A under the regular dynamics given by \mathcal{Z} .

We claim that $A_t \cap S = B_t \cap S$ for all $t \geq 0$. We use induction to prove this claim, which clearly holds at t = 0. Assume that the claim holds for some $t \geq 0$. Let $x \in S \setminus A_t = S \setminus B_t$. By Lemma 2.10, $\mathcal{N}(x) \cap A_t \cap A^c = \mathcal{N}(x) \cap (A_t \cap S)$ and again by Lemma 2.3, $\mathcal{N}(x) \cap B_t = \mathcal{N}(x) \cap (B_t \cap S)$. Therefore $x \in A_{t+1}$ if and only if $x \in B_{t+1}$ which proves the induction step.

When the enhanced dynamics given by $(\mathcal{Z}, \vec{r}', \vec{c}')$ covers S, the enhanced dynamics given by $(\mathcal{Z}, \vec{r}^+, \vec{c}^+)$ also covers S, and thus fully occupies \mathbb{Z}^2_+ . Therefore, by the claim in the previous paragraph, $\tau_{\rm en}(\mathcal{Z}, \vec{r}^+, \vec{c}^+) \leq \tau(\mathcal{Z}, A) \leq \mu_{\rm th}(\mathcal{Z})$, and then $\tau_{\rm en}(\mathcal{Z}^{\checkmark 1}, \vec{r}, \vec{c}) = \tau_{\rm en}(\mathcal{Z}, \vec{r}^+, \vec{c}^+) \leq \mu_{\rm th}(\mathcal{Z})$. As \vec{r} and \vec{c} are arbitrary enhancements that span for $\mathcal{Z}^{\checkmark 1}$, the proof is concluded.

Lemma 4.2. For any Young diagram $Y \in \mathcal{A}$, $\tau(\mathcal{Z}, Y) \leq \mu_{en}(\mathcal{Z})$.

Proof. The enhanced spanning time for the pair of enhancements (\mathcal{Z}, \emptyset) is given by the number of distinct row counts (including 0) in \mathcal{Z} . We also have $\tau(\mathcal{Z}, \mathcal{Z}) \leq \mathcal{T}_{en}(\mathcal{Z}, \mathcal{Z}, \emptyset) \leq \mu_{en}(\mathcal{Z})$. By Lemma 3.1 in [GSS], the Young diagram $Y \in \mathcal{A}$ if and only if $\mathcal{Z} \subseteq Y$. Therefore by monotonicity $\tau(\mathcal{Z}, Y) \leq \tau(\mathcal{Z}, \mathcal{Z}) \leq \mu_{en}(\mathcal{Z})$

Lemma 4.3. For any \mathcal{Z} , $\mu_{th}(\mathcal{Z}) \leq 2\mu_{en}(\mathcal{Z})$.

Proof. Let $A \in \mathcal{A}$ be a thin set in the standard arrangement. Let X be the set of points $x \in \mathbb{Z}_+^2 \setminus A$ such that $x \leq x'$ for some $x' \in A$, that is, X is the set of points strictly below A (see Figure 4). Let $\ell = \inf\{t \geq 0 : X \subseteq A_t\}$ be the first time at which the regular dynamics starting from A covers X.

In order to obtain an upper bound on ℓ we consider enhanced growth with enhancements \mathcal{R} and \mathcal{C} that are given by the row and column counts of A. Thus, for any $x = (i, j) \in \mathbb{Z}_+^2$ the row and column enhancements for x are given by $r_j = \operatorname{row}(x, A)$ and

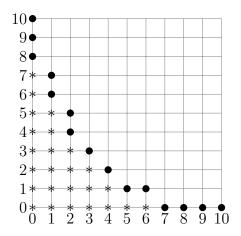


Figure 4: Illustration of the proof of Lemma 4.3. The thin set A is marked by solid circles, and the set X by asterisks.

 $c_i = \text{col}(x, A)$. The pair $(\mathcal{R}, \mathcal{C})$ spans for \mathcal{Z} under the enhanced dynamics as the proof for the two-Y construction in Lemma 3.3 of [GSS] applies.

For $t \geq 0$, let B_t denote the set of occupied sites under enhanced growth given by $(\mathcal{Z}, \mathcal{R}, \mathcal{C})$. First we claim that, for $t \geq 0$, $A_t \cap X = B_t \cap X$. We proceed by induction. The claim is true for t = 0 as $A_0 \cap X = \emptyset = B_0 \cap X$. Suppose the claim is true for some $t \geq 0$. By Lemma 2.3 (1) and Lemma 2.10 (3), for $x \in X \setminus A_t = X \setminus B_t$,

$$\mathcal{N}(x) \cap A_t \cap A^c = \mathcal{N}(x) \cap B_t.$$

Therefore $row(x, A_t) = row(x, B_t) + row(x, A)$ and the analogous equality holds for the column counts. It follows that $A_{t+1} \cap X = B_{t+1} \cap X$, which establishes the inductive claim.

By the inductive claim $\ell \leq \mu_{\text{en}}(\mathcal{Z})$. Now, $A \cup X$ is a Young diagram that includes A, and therefore spans, and is also covered by A_{ℓ} . By Lemma 4.2, $\tau(\mathcal{Z}, A_{\ell}) \leq \mu_{\text{en}}(\mathcal{Z})$ and therefore $\tau(\mathcal{Z}, A) \leq \ell + \mu_{\text{en}}(\mathcal{Z}) \leq 2\mu_{\text{en}}(\mathcal{Z})$.

Proof of Theorem 1.2. The upper bound on $\mu_{\rm th}$ follows from Lemma 4.3, and the lower bound follows from Lemmas 2.9 and 4.1.

5 Upper bounds

In this section we prove Theorem 1.1 and Theorem 1.3.

Lemma 5.1. Let A be an initial set of occupied points and A_t the resulting set of occupied points at time t in the regular dynamics with zero-set \mathcal{Z} . Assume that $x \in A_t \setminus A$ and $y \in A_t \setminus A$ are not neighbors. Let w be the sole element of $L^h(x) \cap L^v(y)$ and z the sole element of $L^v(x) \cap L^h(y)$. Then either $w \in A_t$ or $z \in A_t$.

Proof. Let (u_x, v_x) and (u_y, v_y) denote the row and column counts of x and y, respectively, in A_{t-1} . Since x and y are both occupied by time t, $(u_x, v_x) \notin \mathcal{Z}$ and $(u_y, v_y) \notin \mathcal{Z}$. The pair of row and column counts of w (resp., z) in A_{t-1} is given by (u_x, v_y) (resp., (u_y, v_x)).

Assume $u_x \leq u_y$ and $v_x \leq v_y$. Then $(u_x, v_y) \notin \mathcal{Z}$ and $(u_y, v_x) \notin \mathcal{Z}$, and consequently w and z are both occupied at time t. The same conclusion holds if $u_y \leq u_x$ and $v_y \leq v_x$. Otherwise suppose without loss of generality that $u_x \leq u_y$ and $v_y \leq v_x$. Then we claim $(u_y, v_x) \notin \mathcal{Z}$. If not, then $(u_x, v_x) \in \mathcal{Z}$ and $(u_y, v_y) \in \mathcal{Z}$, a contradiction. Thus $z \in A_t$. \square

Proof of Theorem 1.1. Suppose that $\mathcal{Z} \subseteq R_{m,n}$. Fix a set A of initially occupied sites that spans. Also fix a time k > 0 to be specified later. Suppose that $A_k \setminus A_{k-1} \neq \emptyset$ so that $\mu(\mathcal{Z}) \geq k$.

For i > 0, let $B_i = A_i \setminus A_{i-1}$ be the set of sites that become occupied at time i. A horizontal line with at least m sites in A_i or a vertical line with at least n sites in A_i is said to be *saturated* at time i. Let I denote the set of times $i \in [1, k]$ such that no line becomes saturated or covered at time i. We claim that $|[1, k] \setminus I| \leq 2m + 2n - 1$.

To prove the claim, we make a few observations. If a horizontal or a vertical line is saturated at time i, then it becomes covered by time i+1. Once n+m-1 lines become saturated (resp., covered), at least n horizontal lines or at least m vertical lines will be saturated (resp., covered). If at least n+m-1 lines are saturated at time i, then at least n+m-1 lines are covered by time i+1 and all of \mathbb{Z}^2_+ is occupied by time i+2. At time k-1, \mathbb{Z}^2_+ is not covered, so there are at most 2(n+m-2) times in [1,k-3] in which a line becomes either saturated or covered, which implies the claim.

Let $B = \bigcup_{i \in I} B_i$. If follows from the claim that

$$|B| \ge |I| \ge k - 2m - 2n + 1.$$
 (1)

On any given horizontal (resp., vertical) line, there are less than m (resp., n) sites in B; otherwise, that line would become saturated by the last point added. Fix a $z \in B$ and suppose neither $L^h(z)$ nor $L^v(z)$ is saturated by time k. Define the sets

$$B_h = (L^h(z) \cap B) \bigcup \{z' \in B \setminus \mathcal{N}(z) : L^h(z) \cap L^v(z') \in A_k\}$$

and

$$B_v = B \backslash B_h$$
.

The set B_v consists of sites z' that satisfy one of the following two properties: either $z' \in L^v(z) \setminus \{z\}$; or both $z' \in B \setminus \mathcal{N}(z)$ and $L^h(z) \cap L^v(z') \notin A_k$, in which case by Lemma 5.1, $L^v(z) \cap L^h(z') \in A_k$. Therefore $|\pi_x(B_h)| \leq |L^h(z) \cap A_k|$ and $|\pi_y(B_v)| \leq |L^v(z) \cap A_k|$.

For any subset $B' \subseteq B$, we have

$$|B'| \le (n-1)|\pi_x(B')|, \qquad |B'| \le (m-1)|\pi_y(B')|.$$

Therefore, the inequalities

$$|\pi_x(B_h)| \le \frac{k - 2m - 2n}{2(n-1)}, \qquad |\pi_y(B_v)| \le \frac{k - 2m - 2n}{2(m-1)}$$
 (2)

cannot both be satisfied, as otherwise

$$|B| = |B_h| + |B_v| \le (n-1)|\pi_x(B_h)| + (m-1)|\pi_y(B_v)| \le k - 2m - 2n.$$

Assume $k \geq 2(m-1)(n-1) + 2m + 2n$. For any $z \in B$, we claim a line through z is covered at time k+1. If either $L^h(z)$ or $L^v(z)$ is saturated the claim is true. Otherwise one of the inequalities in (2) is not satisfied, and then either $|\pi_x(B_h)| \geq m$ or $|\pi_y(B_v)| \geq n$. In the former case $|L^h(z) \cap A_k| \geq |\pi_x(B_h)| \geq m$ and $L^h(z)$ is covered by time k+1. In the latter case $|L^v(z) \cap A_k| \geq |\pi_y(B_v)| \geq n$ and $L^v(z)$ is covered by time k+1.

Let H (resp., V) be the set of all $z \in B$ such that $L^h(z)$ (resp., $L^v(z)$) is covered at time k+1. By the previous paragraph, $B = H \cup V$. Let k = 2(m-1)(n-1)+2m+2n+1 = 2mn+3. For this choice of k, $|B| \geq 2(m-1)(n-1)+2$ by (1), and therefore either $|H| \geq (m-1)(n-1)+1$ or $|V| \geq (m-1)(n-1)+1$. As a horizontal line can contain at most m-1 sites in H, $|H| \geq (m-1)(n-1)+1$ implies that there are at least n horizontal lines with sites in H which are covered by time k+1. Similarly, as a vertical line can contain at most n-1 sites in V, $|V| \geq (m-1)(n-1)+1$ implies that there are at least m vertical lines with sites in V which are covered by time k+1. In either case, \mathbb{Z}_+^2 is fully occupied by time k+2=2mn+5.

We now proceed to prove the better upper bound for enhanced growth. Let $\widetilde{\mathcal{A}}_{en}$ consist of pairs $(\mathcal{R}, \mathcal{C}) \in \mathcal{A}_{en}$ such that $\mathcal{R} \subseteq \mathcal{Z}$ and $\mathcal{C} \subseteq \mathcal{Z}$.

Lemma 5.2. For any zero-set \mathcal{Z} ,

$$\mu_{\rm en}(\mathcal{Z}) = \sup \{ \tau_{\rm en}(\mathcal{Z}, \mathcal{R}, \mathcal{C}) : (\mathcal{R}, \mathcal{C}) \in \widetilde{\mathcal{A}}_{\rm en} \}.$$

Proof. Fix $(\mathcal{R}, \mathcal{C}) \in \mathcal{A}$ and let $\mathcal{R}' = \mathcal{Z} \boxminus \mathcal{C}$ and $\mathcal{C}' = \mathcal{Z} \boxminus \mathcal{R}'$. By Lemma 2.2, $(\mathcal{R}', \mathcal{C}')$ span for \mathcal{Z} , and $(\mathcal{R}', \mathcal{C}') \in \widetilde{\mathcal{A}}_{en}$. Moreover, $\mathcal{R}' \subseteq \mathcal{R}$ and $\mathcal{C}' \subseteq \mathcal{C}$, and so $\tau_{en}(\mathcal{Z}, \mathcal{R}', \mathcal{C}') \geq \tau_{en}(\mathcal{Z}, \mathcal{R}, \mathcal{C})$. This shows that $\mu_{en}(\mathcal{Z}) \leq \sup\{\tau_{en}(\mathcal{Z}, \mathcal{R}, \mathcal{C}) : (\mathcal{R}, \mathcal{C}) \in \widetilde{\mathcal{A}}_{en}\}$, and the other inequality is trivial.

Proof of Theorem 1.3. The zero-set \mathcal{Z} contains at most s rows and s columns that are longer than s, so the number of distinct non-zero row counts of \mathcal{Z} is at most 2s, and the same upper bound holds for the column counts of \mathcal{Z} . For every $(\mathcal{R}, \mathcal{C}) \in \widetilde{\mathcal{A}}_{en}$, $\mathcal{R} \subseteq \mathcal{Z}$ and $\mathcal{C} \subseteq \mathcal{Z}$ and so the number of distinct row counts of \mathcal{R} , including zero, is at most 2s+1, and again the same upper bound holds for the number of distinct nonzero column counts of \mathcal{C} . By Corollary 2.5, $A_{2s+2s+1} = \mathbb{Z}_+^2$. Thus, for every $(\mathcal{R}, \mathcal{C}) \in \widetilde{\mathcal{A}}_{en}$, $\tau_{en}(\mathcal{Z}, \mathcal{R}, \mathcal{C}) \leq 2s+2s+1=4s+1$ and therefore by Lemma 5.2, $\mu_{en}(\mathcal{Z}) \leq 4s+1$. The upper bound on μ_{th} follows from Theorem 1.2. The two statements on the suprema over \mathcal{Z} now follow from Proposition 3.2.

6 Lower bounds

In this section we prove Theorem 1.4.

For $a, b, k \in \mathbb{N}$, define the (a, b)-staircase of size k as the following union of rectangles:

$$S_{a,b,k} = \bigcup_{i=1}^{k} R_{bj,a(k+1-j)} = \left\{ (i,j) : \left\lfloor \frac{i}{b} \right\rfloor + \left\lfloor \frac{j}{a} \right\rfloor \le k-1 \right\}.$$

This Young diagram has row counts of length $b, 2b, \dots, kb$, each with multiplicity a, and column counts $a, 2a, \dots, ka$ each with multiplicity b.

Lemma 6.1. Fix $a, b \in \mathbb{N}$. For any $k \geq 1$, $S_{a,b,k}$ lies strictly below the line ax + by = (k+1)ab and contains the set of sites $\{(i,j) : ai + bj < kab\}$ Furthermore, if $k_1, k_2 \in \mathbb{N}$,

$$S_{a,b,k_1} \coprod S_{a,b,k_2} = S_{a,b,k_1+k_2}. \tag{3}$$

Proof. This is a straightforward verification.

The next lemma provides a general method for establishing lower bounds; see Figure 5 for an illustration.

Lemma 6.2. Fix a zero-set \mathcal{Z} and two positive integers a and b. Let k be the smallest positive integer such that ai + bj < kab for all $(i, j) \in \mathcal{Z}$. Let $(i_0, j_0) \in \mathcal{Z}$ be a point that satisfies $(k-1)ab \leq ai_0 + bj_0$. Then

$$\mu_{\text{en}}(\mathcal{Z}) \ge \min\left(\left\lceil \frac{i_0+1}{b}\right\rceil, \left\lceil \frac{j_0+1}{a}\right\rceil\right).$$

Proof. By Lemma 6.1, $\mathcal{Z} \subseteq S_{a,b,k}$. Assume $k_1, k_2 \in \mathbb{N}$ such that $k_1 + k_2 \geq k$. By (3) and Lemma 2.6, the row and column enhancements $\mathcal{R} = S_{a,b,k_1}$ and $\mathcal{C} = S_{a,b,k_2}$ span for \mathcal{Z} .

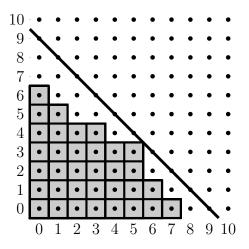


Figure 5: Illustration of Lemma 6.2, with a = b = 1, k = 9, and $(i_0, j_0) = (5, 3)$.

Let $m = i_0 + 1$ and $n = j_0 + 1$. Then $R_{m,n} \subseteq \mathcal{Z}$. Moreover, $k_1 = \lceil \frac{m}{b} \rceil$ and $k_2 = \lceil \frac{n}{a} \rceil$ satisfy $k_1 + k_2 \ge k$.

In this paragraph we consider the dynamics with zero-set $R_{m,n}$. As $R_{m,n} \subseteq \mathcal{Z}$, \mathcal{R} and \mathcal{C} span for $R_{m,n}$. Let $\ell = \min(k_1, k_2)$. At any time $t \leq \ell$, exactly a new rows and b new columns become covered. Therefore, \mathbb{Z}_+^2 does not become occupied by time ℓ .

By monotonicity,
$$\tau_{\text{en}}(\mathcal{Z}, \mathcal{R}, \mathcal{C}) \geq \tau_{\text{en}}(R_{m,n}, \mathcal{R}, \mathcal{C})$$
, and therefore $\mu_{\text{en}}(\mathcal{Z}) \geq \ell$.

Proof of Theorem 1.4. Let k_r (resp., k_c) denote the largest number of rows (resp., columns) in \mathcal{Z} that are all of the same length and are of length at least s. If $k_r < s^{1/2}$, then there are at least $s^{1/2}$ rows of different lengths in \mathcal{Z} . Let $(\mathcal{R}, \mathcal{C})$ be enhancements such that $\mathcal{R} = \mathcal{Z}$ and $\mathcal{C} = \emptyset$. Then rows with different lengths are spanned at different times, which gives a spanning time of at least $s^{1/2}$. Similarly, if $k_c < s^{1/2}$, $\mathcal{R} = \emptyset$ and $\mathcal{C} = \mathcal{Z}$ induce a spanning time of at least $s^{1/2}$.

Otherwise, $k_r \geq s^{1/2}$ and $k_c \geq s^{1/2}$. Let d_c be the number of columns with length strictly larger than the common length of the k_c columns. Analogously let d_r be the number of rows with length strictly larger than that of the k_r rows. Define $\mathcal{Z}' = \mathcal{Z}^{\leftarrow d_c \downarrow d_r}$. We use Lemma 6.2 with a = b = 1 and zero-set \mathcal{Z}' . There exists $(i_0, j_0) \in \mathcal{Z}'$ such that $i_0 + 1 \geq k_c$, $j_0 + 1 \geq k_r$ and the line with slope -1 through $(i_0 + 1, j_0 + 1)$ does not intersect \mathcal{Z}' . By Lemma 6.2 $\mu_{\rm en}(\mathcal{Z}') \geq \min\{i_0 + 1, j_0 + 1\} \geq \min(k_c, k_r) \geq s^{1/2}$. By Lemma 2.8, $\mu_{\rm en}(\mathcal{Z}') \leq \mu_{\rm en}(\mathcal{Z})$, so $\mu_{\rm en}(\mathcal{Z}) \geq s^{1/2}$. This proves the inequality for $\mu_{\rm en}$.

The remainder of the theorem follows from Lemma 4.1 and the observation that if $R_{s,s} \subseteq \mathcal{Z}$, then $R_{s-1,s-1} \subseteq \mathcal{Z}^{\checkmark 1}$.

7 Open questions

- 1. Is there an explicit formula for $\mu(\mathcal{Z})$ or for $\mu_{\text{en}}(\mathcal{Z})$ for threshold growth $\mathcal{Z} = \{(u, v) : u + v \leq \theta 1\}$? We know that $\theta + 1 \leq \mu(\mathcal{Z}) \leq 2\theta^2 + 5$.
- 2. Let α_c^{\min} be the infimum of the set of exponents $\alpha > 0$ for which

$$\inf_{\mathcal{Z}} \frac{\mu_{\rm en}(\mathcal{Z})}{s^{\alpha}} = 0.$$

What is the value of α_c^{\min} ? We suspect that the answer is 1/2 and know that $1/2 \leq \alpha_c^{\min} \leq \alpha_c^{\max} = 1$ (from Theorems 1.3 and 1.4). Here, α_c^{\max} is defined to be the supremum of the exponents $\alpha > 0$ for which

$$\sup_{\mathcal{Z}} \frac{\mu_{\rm en}(\mathcal{Z})}{s^{\alpha}} = \infty.$$

3. Is there a finite exponent $\alpha > 0$ so that

$$\sup_{\mathcal{Z}} \frac{\mu(\mathcal{Z})}{s^{\alpha}} < \infty?$$

4. Call a set $A \subseteq \mathbb{Z}_+^2$ k-thin if, for every $x \in A$, either $row(x, A) \le k$ or $col(x, A) \le k$. Observe that 1-thin sets are exactly the thin ones. Let $\mu_{th}^k(\mathcal{Z})$ be the maximal finite spanning time of a k-thin set. Do there exist finite constants $c_k, C_k > 0$ such that

$$c_k \mu_{\text{th}}(\mathcal{Z}) \leq \mu_{\text{th}}^k(\mathcal{Z}) \leq C_k \mu_{\text{th}}(\mathcal{Z})$$
?

Acknowledgements

Janko Gravner was partially supported by the NSF grant DMS-1513340, Simons Foundation Award #281309, and the Republic of Slovenia's Ministry of Science program P1-285. J.E. Paguyo was partially supported by the same NSF grant and the UC Davis REU program.

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