Boundary Influence On The Entropy Of a Problem In Cellular Neural Networks

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1. Introduction

We consider one-dimensional Cellular Neural Networks (CNNs) of the form (e.g., [Ban et al., 2002, 2001; Hsu 2000]).

\[
\frac{dx_i}{dt} = -x_i + z + \alpha f(x_{i-1}) + af(x_i) + \beta f(x_{i+1}), \quad i \in \mathbb{Z},
\]

where \( f(x) \) is a piecewise-linear output function defined by

\[
f(x) = \begin{cases} 
  rx + 1 - r, & \text{if } x \geq 1, \\
  x, & \text{if } |x| \leq 1, \\
  lx + l - 1, & \text{if } x \leq -1.
\end{cases}
\]

(1.1b)

where \( r \) and \( l \) are positive constants. The quantity \( z \) is called threshold or bias term. The constants \( \alpha, a \) and \( \beta \) are the interaction weights between neighboring cells. Such triple pair \( [\alpha, a, \beta] \) of the interaction weights is called the template of the system (1). The complexity of the set of bounded stable (mosaic) stationary solutions of (1.1) has been intensively studied by many authors ([Ban et al., 2002, 2001; Chua, 1998; Chua and Yang 1998a; Hsu 2000; Juang and Lin 2000; Thiran 1997; Thiran et al., 1995]). Those steady-state solutions \( \{x_i\}_{i \in \mathbb{Z}} \), satisfy the equation

\[
f(x_{i+1}) = \frac{1}{\beta} (x_i - z - \alpha f(x_{i-1}) - af(x_i)).
\]

(1.2)

Set \( u_i = f(x_i) \). Then (1.2) becomes

\[
u_{i+1} = \frac{1}{\beta} (-\alpha u_{i-1} - z + f^{-1}(u_i) - au_i),
\]

(1.3a)

or, equivalently,

\[
T(u_{i-1}, u_i) = (u_i, u_{i+1}) = (u_i, \frac{1}{\beta} (-\alpha u_{i-1} - z + f^{-1}(u_i) - au_i)).
\]

(1.3b)

Clearly, (1.3b) such induced is a Lozi-type map \( T \).

\[
(x_{i+1}, y_{i+1}) = T(x_i, y_i) = (y_i, F(y_i) - bx_i).
\]

(1.4a)

Here

\[
b = \frac{\alpha}{\beta},
\]

(1.4b)

and

\[
F(y) = \begin{cases} 
  a_1 y + a_0 - a_1 + \bar{a}_0 := a_1 y + \bar{a}_1, & \text{if } y \geq 1, \\
  a_0 y + \bar{a}_0, & \text{if } |y| \leq 1, \\
  a_{-1} y + a_{-1} - a_0 + \bar{a}_0 := a_{-1} y + \bar{a}_{-1}, & \text{if } y \leq -1.
\end{cases}
\]

(1.4c)
where
\[
a_1 = \frac{1}{\beta} \left( \frac{1}{r} - a \right) > 0, \quad a_0 = \frac{1}{\beta} (1 - a) < 0, \\
a_{-1} = \frac{1}{\beta} \left( \frac{1}{r} - a \right) > 0, \quad \bar{a}_0 = -\frac{z}{\beta}.
\]

Any bounded trajectory \((x_{j+1}, y_{j+1}) = T(x_j, y_j)\) corresponds to a bounded steady-state solution of system (1.1).

Inspired by the open problems raised in [Arnold 1993], and [Afraimovich and Hsu 2003], respectively, we are led to consider the following problems. Define the line \(\ell_{m,k}\) as
\[
\ell_{m,k} = \{(x, y) : y = mx + k\}. \quad (1.5a)
\]
Here \(\ell_{\infty,k}\) is interpreted as \(\{(x, y) : x = k\}\). \quad (1.5b)

Denote by \(N(n, \ell_{m_1,k_1}, \ell_{m_2,k_2}, T)\) the number of points on the intersection of \(T^n\ell_{m_1,k_1} \cap \ell_{m_2,k_2}\). Should no ambiguity arise, we will write \(\ell_{m_i,k_i}\) as \(\ell_i\).

**Definition 1.1.** The entropy \(h_{\ell_1,\ell_2}(T)\) of \(T\) with respect to lines \(\ell_1\) and \(\ell_2\) is defined as the limit
\[
h_{\ell_1,\ell_2}(T) = \lim_{n \to \infty} \frac{\ln N(n, \ell_1, \ell_2, T)}{n}. \quad (1.6)
\]

In case that the growth rate of \(N(n, \ell_1, \ell_2, T)\) is super exponential, \(h_{\ell_1,\ell_2}(T)\) is defined to be \(\infty\). For a local holomorphic mapping, preserving the origin, and two lines \(\ell_1\) and \(\ell_2\) passing the origin. Suppose all the images \(T^n\ell_1\) are smooth [15] or that everything is algebraic (see [11], [16]). Then \(h_{\ell_1,\ell_2}(T)\) exists and is finite. In our case, \(N(n, \ell_1, \ell_2, T) \leq 3^n\). We next recall the definition of the spatial entropy of system (1.1).

Now, set \(\Gamma_{n,k}(T)\) to be the number of elements in the solution set \(S_{n,k}, S_{n,k} = \{(u_i)_{i=-\infty}^{n+k-1} : \{u_i\}_{i=-\infty}^{\infty}\}^n_{i=-\infty} \text{ is a bounded steady-state solution of (1.1)}\}. \) Here \(k \in \mathbb{Z}\).

Since the template of system (1.1) is space invariant, the steady-state solutions of (1.1) are also space invariant. That is to say if \(\{u_i\}_{i=-\infty}^{\infty}\) is a steady state solution of (1), so is \(\{u_{i+k}\}_{i=-\infty}^{\infty}\) for any \(k \in \mathbb{Z}\). Hence, \(\Gamma_{n,k}(T)\) is independent of the choice of \(k\). Thus, we set \(\Gamma_{n,k}(T) = \Gamma_n(T)\).

**Definition 1.2.** The spatial entropy \(h(T)\) of the system (1.1) is defined as the limit
\[
h(T) = \lim_{n \to \infty} \frac{\ln \Gamma_n(T)}{n}. \quad (1.7)
\]
We next consider how the behavior of solutions of a large but finite lattice is related to the behavior of steady-state solutions of (1.1). Let \( \{u_i\}_{i=-\infty}^{\infty} \) be an orbit sequence generated by \( T \) as given in (1.3b). The number of distinct orbit sequences \( \{u_i\}_{i=-\infty}^{\infty} \) of \( T \) satisfying
\[
\begin{align*}
  u_2 &= m_1 u_1 + k_1 \text{ (or equivalently } y_1 = m_1 x_1 + k_1), \quad (1.7a) \\
  u_{n+1} &= m_2 u_n + k_2 \text{ (or equivalently } y_n = m_2 x_n + k_2), \quad (1.7b)
\end{align*}
\]
be denoted by \( \Gamma_n(n, m_1, k_1, m_2, k_2, T) \).

**Remark 1.1.**

1. It is easy to see that \( \Gamma_n(n, m_1, k_1, m_2, k_2, T) = N(n-1, \ell_1, \ell_2, T) \), where \( \ell_1 = \ell_{m_1, k_1} \) and \( \ell_2 = \ell_{m_2, k_2} \).
2. When \((m_1, k_1) = (\infty, 0)\) and \((m_2, k_2) = (0, 0)\) (resp., \((m_1, k_1) = (m_2, k_2) = (1, 0)\)), \( h_{\ell_1, \ell_2}(T) \) is the so-called the spatial entropy of system (1.1) with Dirichlet (resp., Neumann) boundary conditions. We write such entropy as \( h_D(T) \) (resp., \( h_N(T) \)).
3. For other choices of \( \ell_1 \) and \( \ell_2 \), \( h_{\ell_1, \ell_2}(T) \) is called the spatial entropy of system (1.1) with Robbin’s boundary conditions.

In [Afraimovich and Hsu, 2003], the following open problems were raised.

**P1:** Is it true that, in general, \( h(T) = h_D(T) = h_N(T) = h_{\ell_1, \ell_2}(T) \)?

**P2:** If it is not true, then which parameters \( m_i \) and \( k_i, i = 1, 2 \), are responsible for the values of \( h(T) \). What kind of bifurcations occurs if the lines \( \ell_{m,k} \) move?

The purpose of this thesis is to shed some light on those two problems. Specifically, under some mild conditions, we show that for any \( \ell_1 \) and \( n \in \mathbb{N} \), except possibly a few pieces of \( T^n \ell_1 \), \( T^n \ell_1 \) is contained in an \( N \)-shaped tunnel for which its boundary point is an \( \omega \)-limit point of \( \ell_1 \) for \( T \). Moreover, we show under a stronger condition, see (3.3), that the entropy \( h_{\ell_1, \ell_2}(T) \) of \( T \) with respect to \( \ell_1 \) and \( \ell_2 \) is independent of the choice of \( \ell_1 \). It is also shown that \( h(T) = h_D(T) = h_N(T) = \ln 3 \), and that \( h_{\ell_1, \ell_2}(T) = h_{\ell_2}(T) \) takes on two distinct values \( \ln 3 \) and \( 0 \). The necessary and sufficient conditions on \( \ell_2 \) for which \( h_{\ell_2}(T) = \ln 3 \) are also obtained. Those
main results are recorded in Section 3. In Section 2, we study the dynamics of a certain two-dimensional map induced from $T^n\ell_1$. We conclude this introductory section by mentioning some related work. Shih [2000] studied the influence of periodic, Neumann and Dirichlet boundary conditions on a problem also arising in two dimensional CNNs. Since their output function $f$, as given in (1.1b), is flat at infinity, i.e., $r = l = 0$, the formulation of the problem is much different from those in [Afraimovich and Hsu 2003]. Consequently, the techniques used in both situations are also quite different.

We also remark that the problem of the asymptotic behavior of the number of points on the intersection $f_k\ell_1 \cap \ell_2$, where $\ell_1, \ell_2$ are submanifolds of a smooth manifold, and $f$ is a smooth map, is said to be a problem of dynamics of the intersection. These problems arise in various branches of analysis. There are some general results (see, e.g., p.261 of [Arnold 1993]) obtained for such problems. However, no approaches are available to solve specific problems.

2. Dynamics of Certain Maps Induced From $T^m\ell_{m,k}$

We begin with the calculation of $T^m\ell_{m,k}$. Now, for $m \neq 0$,

$$T(x', mx' + k) = (mx' + k, F(mx' + k) - bx').$$

Set $x = mx' + k$, $y = F(mx' + k) - bx'$, we see immediately that

$$y = F(x) - \frac{b(x - k)}{m} = \begin{cases} (a_1 - \frac{b}{m})x + (\bar{a}_1 + \frac{bk}{m}), & \text{if } x \geq 1, \\ (a_0 - \frac{b}{m})x + (\bar{a}_0 + \frac{bk}{m}), & \text{if } |x| \leq 1, \\ (a_{-1} - \frac{b}{m})x + (\bar{a}_{-1} + \frac{bk}{m}), & \text{if } x \leq -1. \end{cases} \quad (2.1)$$

Using (2.1), we define two dimensional maps $G_i(x, y)$, $i = 1, 0, -1$, of the form

$$G_i(x, y) = (a_i - \frac{b}{x}, \bar{a}_i + \frac{b}{x}y) =: (g_{i,1}(x), g_{i,2}(x, y)). \quad (2.2)$$

We call $g_{i,1}(x)$, $i = 1, 0, -1$, the slope maps of $T$. For $g_{i,1}(x)$, $i = 1, 0, -1$, denote, respectively, the slopes of $T\ell_{x,y}$ in the regions.

$$R_1 = \{ (x, y) : x \geq 1 \}, \quad R_0 = \{ (x, y) : |x| \leq 1 \} \quad \text{and} \quad R_{-1} = \{ (x, y) : x \leq -1 \}. \quad (2.3)$$
Moreover, $g_{i,2}(x, y)$ are to be termed the intercept maps. We next consider the dynamics of the slope and intercept maps $g_{i,1}$ and $g_{i,2}$.

**Proposition 2.1.** Let $b > 0$, $a_i > 2\sqrt{b}$, $i = 1, -1$ and $-a_0 > 2\sqrt{b}$. Then (i) $m^\pm_{i,\infty} := \frac{a_i \pm \sqrt{a_i^2 - 4b}}{2}$ are two fixed points of the slope maps $g_{i,1}$. (ii) Moreover, the attracting interval of $m^+_{i,\infty}$, $i = 1, -1$, is $R \setminus \{m^-_{i,\infty}\}$. That is to say if $x \in R \setminus \{m^-_{i,\infty}\}$, then, for $i = 1, -1$, $\lim_{n \to \infty} g^{n}_{i,1}(x) = m^+_{i,\infty}$. (iii) The attracting interval of $m^-_{0,\infty}$ is $R \setminus \{m^+_{0,\infty}\}$. (iv) Suppose $a_i = 2\sqrt{b}$. Then $m^+_{i,\infty} = m^-_{i,\infty}$ is the globally attracting fixed point of $g_{i,1}$, $i = 1, 0, -1$.

**Proof.** We illustrate only $i = 1$. Clearly, two fixed points of $g_{1,1}$ are $m^+_{1,\infty}$. The attracting interval of $g_{1,1}$ can be easily concluded by using graphical analysis on Figure 2.1. □

**Proposition 2.2.** Suppose

$$b > 0, \; a_i > 1 + b, \; i = 1, -1 \text{ and } -a_0 > 1 + b. \quad (2.4)$$

(i) For fixed $x = m^+_{i,\infty}$, $i = 1, -1$, then $k_{i,\infty} := \frac{m^+_{i,\infty}{a_i}}{m^+_{i,\infty} - b}$ is a globally attracting fixed point of the intercept maps $g_{i,2}(m^+_{i,\infty}, y)$. Moreover, (ii) for fixed $x = m^-_{0,\infty}$, $k_{0,\infty} = \frac{m^-_{0,\infty}{a_0}}{m^-_{0,\infty} - b}$ is also a globally attracting fixed point of $g_{0,2}(m^-_{0,\infty}, y)$.

**Proof.** It suffices to show that $0 < \frac{b}{m^+_{i,\infty}} < 1$, $i = 1, -1$, and $-1 < \frac{b}{m^-_{0,\infty}} < 0$. 

**Figure 2.1**
successively the double limits of $g$ for all sufficiently small $\varepsilon > 0$. Suppose (2.4) holds.

**Theorem 2.1.** Suppose (2.4) holds. (i) The two dimensional map $G_i$, as defined in (2.2), $i = 1, 0, -1$, have two fixed points $(m_{1,\infty}^+, m_{1,\infty}^-) =: (A_{1,1}^+, A_{1,2}^+)$, and $m_{0,\infty}^+$, are, respectively, $\mathbb{R}^2 - \{(x, y) : x = A_{1,1}^-\}$, $i = 1, -1, 0$, and $\mathbb{R}^2 - \{(x, y) : x = A_{0,1}^-\}$. That is to say, for any $(m, k) \in \mathbb{R} - \{(x, y) : x = A_{1,1}^-\}$, $i = 1, -1, 0$, (resp., $(m, k) \in \mathbb{R}^2 - \{(x, y) : x = A_{0,1}^-\}$),

$$\lim_{n \to \infty} G^n_i(m, k) = (A_{1,1}^+, A_{1,2}^+), \quad i = 1, -1, 0, \quad \lim_{n \to \infty} G^n_0(m, k) = (A_{0,1}^-, A_{0,2}^-).$$

**Proof.** We only illustrate $i = 1$. The cases for $i = 0, -1$ are similar. Define $g_{1,1}^n(m) = m_{1,n}$ and $G^n_i(m, k) = (m_{1,n}, k_{1,n})$. If $m \neq m_{1,\infty}$, then given $\varepsilon > 0$, there exists an $N_\varepsilon \in \mathbb{N}$ such that for every $n \geq N_\varepsilon$, we have

$$m_{1,\infty}^- - \varepsilon < m_{1,n} < m_{1,\infty}^+ + \varepsilon. \quad (2.6)$$

It follows from (2.6) that for any $k \in \mathbb{R}$, and $n$ sufficiently large,

$$\min\{a_1 + \frac{bk}{m_{1,\infty} - \varepsilon}, a_1 + \frac{bk}{m_{1,\infty} + \varepsilon}\} < \bar{a}_1 + \frac{bk}{m_{1,n}} < \max\{a_1 + \frac{bk}{m_{1,\infty} - \varepsilon}, a_1 + \frac{bk}{m_{1,\infty} + \varepsilon}\}. \quad (2.7)$$

It follows from (2.5) and Proposition 2.2 that for sufficiently small $\varepsilon > 0$,

$$\lim_{n \to \infty} g^n_{1,2}(m_{1,\infty}^+ \pm \varepsilon, k) \text{ exist and that}$$

$$\lim_{n \to \infty} g^n_{1,2}(m_{1,\infty}^+ \pm \varepsilon, k) = \frac{\bar{a}_1(m_{1,\infty}^+ \pm \varepsilon)}{m_{1,\infty}^+ - \varepsilon - b} =: k_{1,\pm\varepsilon}.$$

Using (2.7), we see inductively that

$$\min\{g^n_{1,2}(m_{1,\infty}^+ \pm \varepsilon, k), g^n_{1,2}(m_{1,\infty}^- \pm \varepsilon, k)\} < g^n_{1,2}(m_{1,n}, k)$$

$$< \max\{g^n_{1,2}(m_{1,\infty}^+ \pm \varepsilon, k), g^n_{1,2}(m_{1,\infty}^- \pm \varepsilon, k)\}.$$
limit of \( g^n_{1,2}(m_1, n, k) \) exists. Moreover, for each \( \varepsilon > 0 \) the limit \( \lim_{n \to \infty} g^n_{1,2}(m_1, n, k) \) exists. So the iterated limit \( \lim_{n \to \infty} g^n_{1,2}(m_1, n, k) \) exists and is equal to \( \frac{m_{1,\infty} + \bar{a}_1}{m_{1,\infty} - b} \). It is then easy to see that, for \( (m, k) \in \mathbb{R}^2 - \{A^+ \} \),

\[
\lim_{n \to \infty} G^n_1(m, k) = (m_{1,\infty} + \bar{a}_1, \infty - b).
\]

We then complete the proof of theorem. \( \square \)

We are now in a position to study \( T^n \ell_{m,k} \). To this end, we consider the lines \( \ell_{i,\infty}, i = 1, 0, -1, \) defined as follows. The \((m, k)\)-pairs of \( \ell_{i,\infty} \) are, respectively, \((m_{i,\infty}^{+}, m_{i,\infty}^{+}, \bar{a}_i)\), for \( i = 1, -1 \), and \((m_{0,\infty}^{+}, m_{0,\infty}^{+}, \bar{a}_0)\) for \( i = 0 \).

From here on, to same notations, we write \( \ell_{i,\infty}, i = 1, 0, -1, \) as \( \ell_{i,\infty} \cap R_i \).

Here \( R_i \) are given as in (2.3). For any line or line segment \( \ell \), we also use the following notation

\[
T \ell = \begin{cases} 
\ell_1, & \text{if } y \geq 1, \\
\ell_0, & \text{if } |y| \leq 1, \\
\ell_{-1}, & \text{if } y \leq -1.
\end{cases}
\]

In case \( \ell \) is a line segment or \( \ell \) is a horizontal line, \( \ell_i, i = 1, 0, -1 \), could be empty depending on the range of \( y \) in \( \ell \). Likewise, we may define \( T(\ell_{i_1,i_2,\ldots,i_{n-1}}) \) inductively as follows.

\[
T(\ell_{i_1,i_2,\ldots,i_{n-1}}) = \begin{cases} 
\ell_{i_1,i_2,\ldots,i_{n-1},1}, & \text{if } y \geq 1, \\
\ell_{i_1,i_2,\ldots,i_{n-1},0}, & \text{if } |y| \leq 1, \\
\ell_{i_1,i_2,\ldots,i_{n-1},-1}, & \text{if } y \leq -1.
\end{cases}
\]

3. Main Results-Boundary Influence on the Spatial Entropy

The following lemma is very useful in determining how we number and order the line segments and half-lines of \( T^n \ell_{m,k} \). The proof is trivial and, thus, skipped.

**Lemma 3.1.** For fixed \( y \), if \( x_1 \geq x_2 \), then the \( y \)-coordinate of \( T(x_1, y) \) is no greater than that of \( T(x_2, y) \).

Using lemma 3.1 and the fact that \( T \) is one-to-one, we have the following principle.
Proposition 3.1. Let $\ell$ and $k$ be lines or line segments, and $\ell \cap k = \emptyset$. If $k$ is to the right of $\ell$. Then so are $k_i$ to $\ell_i$, $i = 1, -1$. However, $\ell_0$ is to the right of $k_0$. Here $k_i$, $\ell_i$, $i = 1, 0, -1$ are defined in (2.8).

Note that the reverse of the ordering in $k_0$ and $\ell_0$ is due to the fact that, in $R_0$, $F(y)$ has a negative slope.

It follows from Proposition 3.1 that the construction of the $N$-shaped figure with boundaries indicated as in Figure 3.1 makes sense. We shall call the region bounded by two $N$-shaped lines the $N$-shaped tunnel of $T$.

The intersection of the lines/line segments $\ell$ and $k$ will be denoted by

$$\ell \cap k.$$ (3.1)

Lemma 3.2. Suppose $\bar{a}_0$ and $b > 0$ are sufficiently small, and $a_i > 1 + b$, $i = 1, -1$, and $-a_0 > 1 + b$. Then the $y$-coordinate $(\ell_{-1_{\infty},0} \cap \ell_{-1_{\infty},1})_y$ of $(\ell_{-1_{\infty},0} \cap \ell_{-1_{\infty},1})$ is less than $-1$, and $(\ell_{1_{\infty},-1} \cap \ell_{1_{\infty},0})_y > 1$.

Proof. We illustrate only $(\ell_{1_{\infty},-1} \cap \ell_{1_{\infty},0})_y > 1$. The other assertion is similarly obtained. Note that the equation of the line $\ell_{1_{\infty}}$ is $y = m_{1,\infty}^+ x + k_{1,\infty}$. Letting $y = -1$, we see $x = -\frac{k_{1,\infty}}{m_{1,\infty}}$. Clearly, $(\ell_{1_{\infty},-1} \cap \ell_{1_{\infty},0})_y$ is the $y$-coordinate of
whenever $a_0$ and $b$ are sufficiently small.

\[ T\left(\frac{-k_{1,\infty} - 1}{m_{1,\infty}}, -1\right) = -a_0 + \bar{a}_0 + \frac{b(k_{1,\infty} + 1)}{m_{1,\infty}} =: t > 1, \quad (3.2) \]

Lemma 3.3. Suppose

\[ a_i > 3, \quad i = 1, -1, \quad -a_0 > 3 \text{ and } \bar{a}_0 \text{ and } b > 0 \text{ are sufficiently small.} \quad (3.3) \]

Let $A$ be any point in the line segment for which its both endpoints are $\ell_{-1,\infty} \cap \ell_{1,-1,0}$ and $\ell_{1,-1} \cap \ell_{1,0}$. Then the limit of both coordinates of $T^n(A)$ approaches to $+\infty$.

**Proof.** We first note that $T$ has a fixed point $B = \left(\frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b}, \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b}\right)$ for which its stable (resp., unstable) direction is $\left(1, \frac{a_1 - \sqrt{a_1^2 - 4b}}{2}\right)$ (resp., $\left(1, \frac{a_1 + \sqrt{a_1^2 - 4b}}{2}\right)$). Since $(\ell_{-1,\infty} \cap \ell_{1,-1,0})_y > (\ell_{1,\infty} \cap \ell_{1,0})_y > 1$, as showed in (3.2), it suffices to show that $T^n(\ell_{1,\infty} \cap \ell_{1,0}) \to (+\infty, +\infty)$ as $n \to \infty$. To this end, we need to show that $T(\ell_{1,\infty} \cap \ell_{1,0}) = T(-1, t)$ as given in (3.2), lies on the upper half of the stable line

\[ \left( y - \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b} \right) = m_{1,\infty}(x - \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b}), \]

or, equivalently,

\[ F(t) + b - \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b} - m_{1,\infty}t + m_{1,\infty} \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b} =: h(b, \bar{a}_0) > 0. \]

Now,

\[ h(0, 0) = \frac{-a_0a_1^2 + 2a_0a_1 - a_1^2}{a_1 - 1} = \frac{a_1[(-a_0 - 1)(a_1 - 2)]}{a_1 - 1} > 0. \]

We thus complete the proof of the lemma. \[ \square \]

For any non horizontal line $\ell_{m,k}$, $m \neq 0$, we have that $T\ell_{m,k} = \ell_{-1} \cup \ell_0 \cup \ell_1$, see Figure 3.2 and (2.9), is an $N$-shaped graph with $(\ell_1 \cap \ell_0)_y < -1$ and $(\ell_0 \cap \ell_{-1})_y > 1$ provided $T$ satisfies the assumptions in Lemma 3.2.

Moreover, $T^2\ell_{m,k} \cap R_1 = \ell_{-1,1} \cup \ell_{0,1} \cup \ell_{1,1}$. Note that $\ell_{i,1}$, $i = 1, 0, -1$, are obtained by applying the action of $T$ on the portion of $\ell_i$ for which their $y$ coordinates are greater or equal than 1. By Proposition 3.1, we see that the ordering of $\ell_{i,1}$, $i = 1, 0, -1$, going from left to right, is $\ell_{-1,1}, \ell_{0,1}$ and $\ell_{1,1}$. 

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Likewise, we define $\ell_{i,j}$, $i = 1, 0, -1$, $j = 0, -1$, accordingly so that

$$T^2 \ell_{m,k} \cap R_0 = \ell_{1,0} \cup \ell_{0,0} \cup \ell_{-1,0},$$

and

$$T^2 \ell_{m,k} \cap R_{-1} = \ell_{-1,-1} \cup \ell_{0,-1} \cup \ell_{1,-1}.$$  

Note that the ordering of $\ell_{i,0}$ (resp., $\ell_{i,-1}$), $i = 1, 0, -1$, going from left to right is $\ell_{1,0}$, $\ell_{0,0}$ and $\ell_{-1,0}$ (resp., $\ell_{-1,-1}$, $\ell_{0,-1}$ and $\ell_{1,-1}$).

In general, $T^n \ell_{m,k}$ consists of $3^n$ line segments/half lines that can be labelled as $\ell_{i_1, i_2, \ldots, i_n}$, $i_j = 1, 0, -1$, $j = 1, 2, \ldots, n$. See Figure 3.3.

Our first main result is to characterize how $T^n \ell_1$ behaves for all $n$.

**Theorem 3.1.** Suppose (3.3) holds. Then for any $n$, all $\ell_{i_1, i_2, \ldots, i_n}$ lie in the $N$-shaped tunnel of $T$ except possibly $\ell_{1,1,\ldots,1}$, $\ell_{-1,-1,\ldots,-1}$, $\ell_{1,1,\ldots,0}$ and $\ell_{1,1,\ldots,-1,0}$.

**Proof.** Since $T$ takes a horizontal line into a vertical line, we may assume that $\ell_{m,k}$ is a non horizontal line. Set $T \ell_{m,k} = \ell_{-1} \cup \ell_0 \cup \ell_1$, see Figure 3.2. It is clear that $\ell_{-1}$ and $\ell_0$ are to the left of $\ell_1$ and $\ell_0$ and $\ell_1$ are to the right of $\ell_{-1}$. Using proposition 3.1 inductively, we conclude that all $\ell_{i_1, i_2, \ldots, i_{n-1}, 1}$ (resp., $\ell_{i_1, i_2, \ldots, i_{n-1}, -1}$) except possibly $\ell_{1,1,\ldots,1}$ (resp., $\ell_{1,1,\ldots,-1,1}$) must lie in the region bounded by $\ell_{-1,1,\ldots,1}$, $\ell_{1,1,\ldots,1}$ and $x = 1$ (resp., $\ell_{-1,1,\ldots,1}$ and $x = -1$). Since the above are true for all $n$, we see immediately, via Proposition 3.1, that all $\ell_{i_1, i_2, \ldots, i_{n-1}, 0}$ except possibly $\ell_{1,1,\ldots,1,0}$ and $\ell_{1,1,\ldots,-1,0}$, must lie in the region bounded by $x = -1$, $x = 1$, $\ell_{1,1,\ldots,0}$ and $\ell_{1,1,\ldots,-1,0}$. 

\[\square\]
We note that the boundary points of the N-shaped tunnel are ω-limit points ω(ℓ1; T) of ℓ1 for T. That is if y ∈ ω(ℓ1; T), then there exists a x ∈ ℓ1, and a sequence {nk}k=1, nk ∈ N, such that Tnk(x) → y as k → ∞.

The second main results are stated in the following.

**Theorem 3.2.** Suppose (3.3) holds. (i) Then hℓ1,ℓ2(T) is independent of the choice of ℓ1. We then write hℓ1,ℓ2(T) as hℓ2(T). (ii) If a1 > a−1, (resp., a1 < a−1), let ℓ2 be a line passing through ℓ1∞ ∩ ℓ1∞,0 (resp., ℓ−1∞ ∩ ℓ−1∞,0) with slope m satisfying a−1 ≤ m ≤ a1 (resp., a1 ≤ m ≤ a−1), then hℓ2(T) = 0; otherwise, hℓ2(T) = ln 3.

(iii) If a1 = a−1, let ℓ2 be a line with slope m = a1 and y-intercept k satisfying k ≥ k−1,∞ or k ≤ k1,∞, then hℓ2(T) = 0; otherwise, hℓ2(T) = ln 3.

**Proof.** Let ℓ2 = k be a line in between ℓ−1,1 and ℓ1,∞. Denote by ky (resp., (ℓ1,∞)y) the y-coordinate of k ∩ {x = 1} (resp., ℓ1,∞ ∩ {x = 1}). Since ℓ0,1,∞ = ℓ1,∞, there exists an N such that

\[ ky > (T^nℓ1,∞,0)y > (ℓ1,∞)y \text{ whenever } n \geq N. \tag{3.4} \]

Using Theorem 3.1, we have that all

\[ ℓ_{i_1,i_2,\ldots,i_{N−1}}, \text{ where } i_1, i_2, \ldots, i_{N−2} \in \{1,0,−1\}, \text{ and } i_{N−1} = 0, \tag{3.5} \]
lie in between \( \ell_{1,0} \) and \( \ell_{-1,0} \). It then follows from (3.4) and Proposition 3.1 that for \( n \geq N \)

\[
k_y > (T^n_{\ell_{1,0}})_y > (\ell_{i_1, i_2, \cdots, i_{n-1}, 1})_y > (\ell_{1,0})_y,
\]

where \( i_1, i_2, \cdots, i_{N-1} \) satisfy (3.5). Consequently, \( k \) must intersect \( \ell_{i_1, i_2, \cdots, i_{n-1}, 0} \), where \( i_1, i_2, \cdots, i_{N-1} \) satisfy (3.5). See Figure 3.4.

Hence, for \( n \geq N \), the number \( N(n, \ell_1, k, T) \) of intersections of \( T^n \cap k \) satisfies

\[
3^{n-N} \leq N(n, \ell_1, k, T) \leq 3^n
\]

Thus \( h_{\ell_1, \ell_2}(T) = \ln 3 \). The cases that \( k \) lies between \( \ell_{-1,0} \) and \( \ell_{1,0} \) or \( \ell_{-1,-1} \) and \( \ell_{1,-1} \) are similar. The other remaining nontrivial case is \( k = \{(x, y) : y = d, \ |d| \text{ is large}\} \). However, using Lemma 3.3, we see similarly that there exists an \( M \in \mathbb{N} \), for all \( n \) sufficiently large, we have

\[
3^{n-M} \leq N(n, \ell_1, k, T) \leq 3^n
\]

Hence, \( h_{\ell_1, \ell_2}(T) = \ln 3 \). The remaining part of the theorem is trivial and thus omitted. \( \square \)
Figure 3.5. Here we denote by $K_1 = T(K)$. We use similar notations to denote points under the first iteration of $T$.

**Proposition 3.2.** Suppose (3.3) holds. Then there exists a $p > 1$ such that the following holds.

\[
F(p) - bp > p, \quad (3.6a)
\]
\[
F(1) + bp < -p, \quad (3.6b)
\]
\[
F(-1) - bp > p, \quad (3.6c)
\]

and

\[
F(-p) + bp < -p. \quad (3.6d)
\]

**Proof.** Equations (3.6) are equivalent to

\[
\min\left\{ \frac{-a_0 + \bar{a}_0}{1 + b}, \frac{-a_0 - \bar{a}_0}{1 + b} \right\} > p > \max\left\{ \frac{a_1 - a_0 - \bar{a}_0}{a_1 - 1 - b}, \frac{a_{-1} - a_0 + \bar{a}_0}{a_{-1} - 1 - b} \right\}. \quad (3.7)
\]

Letting $b = \bar{a}_0 = 0$, (3.7) reduces to

\[
-a_0 > p > \max\left\{ \frac{a_1 - a_0}{a_1 - 1}, \frac{a_{-1} - a_0}{a_{-1} - 1} \right\}. \quad (3.8)
\]

However, under condition (3.3), (3.8) holds and $\frac{a_i - a_0}{a_i - 1} > 1$, $i = 1, -1$. We thus complete the proof of proposition. \qed
Let $S$ be a square defined as

$$S = \{(x, y) \in \mathbb{R}^2 : |x| \leq p, |y| \leq p\},$$

where $p$ satisfies (3.6). Then $T(S) \cap S = S_3 \cup S_2 \cup S_1$. See Figure 3.5.

Inductively, we see that $T^n(S) \cap S$ consists of $3^n$ nested pieces of $S_{i_1,i_2,\ldots,i_n}$, $i_j = 1, 0, -1, j = 1, 2, \cdots, n$. Likewise, backward iterations: $T^{-n}(S) \cap S$ will produce $3^n$ nested pieces of $\bar{S}_{i_1,i_2,\ldots,i_n}$, $i_j = 1, 0, -1, j = 1, 2, \cdots, n$ with each piece $\bar{S}_{i_1,i_2,\ldots,i_n}$ cross the east and west side of the rectangle $S$. Using Theorem 2.1, we see that the size of $\bar{S}_{i_1,i_2,\ldots,i_n}$ and $S_{i_1,i_2,\ldots,i_n}$ shrinks to zero as $n \to \infty$. Thus,

$$\bigcap_{n=-\infty}^{\infty} T^n(S) \cap S =: \Lambda$$

is a cantor set of infinite points. Using standard argument in symbolic dynamics, one shows that the dynamics of $T$ on the invariant set $\Lambda$ is conjugate to the shift map with three symbols. Thus, any trajectory of $T$ in $\Lambda$ is a bounded steady state of (2). Hence, we have the following theorem.

**Theorem 3.3.** Suppose (3.3) holds. Then $h(T) = \ln 3 = h_D(T) = h_N(T)$.

We conclude this thesis with the following remarks.

1. We have shown that Dirichlet and Neuman boundary conditions have no effect on the entropy of $T$ under the circumstances and that certain Robbin’s boundary conditions do influence the entropy of $T$.

2. In the language of CNNs, condition (3.3) means that the slopes $r$ and $l$ of the output function $f$ are small and so is the bias term $z$. The self-interaction weight $a$ has to be strong. However, the right-side (forward) interaction weight $\beta$ has to be much stronger than that of the left-side (backward) interaction weight $\alpha$.

3. The cases when $1 \leq a_1, -a_0, a_{-1} \leq 3$ are complicated as well as interesting.

4. It is also of interest to see if our techniques developed here can be applied to the cases when $F(y)$ is a cubic polynomial, such as those in p.163 of Afraimovich and Hsu [2003] or a quadratic map for which the resulting $T$ is a Henon map.
References


