Chaos for Linear Fractal Transformations of Shifts

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1 Theorem 3

Theorem 3. *Let φ be a LFT with $c \neq 0$ and $|d| > |c|$. The operator $\varphi(B)$ is chaotic if and only if*

$$\big||d|^2 - |c|^2 - |b\bar{d} - a\bar{c}| < |bc - ad|\big|$$

2 Lemma 2

The following result gives a geometrical description of $\varphi(\mathbb{D})$ when the pole of φ lies outside the closed unit disc.

Lemma 2. *Let φ be a linear fractional transformation(LFT) with $c \neq 0$ and $|d| > |c|$. Then $\varphi(\mathbb{D})$ is the disc $P + r\mathbb{D}$ with center P and radius r given by*

$$P = \frac{b\bar{d} - a\bar{c}}{|d|^2 - |c|^2},\ r = \frac{|bc - ad|}{|d|^2 - |c|^2}.$$

Proof. Note that LFTs map circles and lines to circles and lines. Indeed, if f is a LFT and E is a circle or a line in $\mathbb{C}$, the image of E, $f(E)$, is mapped to a line if it passes through the pole. If E avoids the pole, $f(E)$ is a circle.

Observe that $\bar{\mathbb{D}} = \{z : |z| \leq 1\}$ (i.e. the closure of $\mathbb{D}$) is clearly a bounded and convex set. Because we imposed that $|d| > |c|$, we have that $|d/c| > 1$ and so the pole at $z = -d/c$ lies outside of $\bar{\mathbb{D}}$. Since LFTs are conformal at every point except at the pole, $\varphi(\bar{\mathbb{D}})$ must be bounded and convex. Furthermore, $\varphi(\bar{\mathbb{D}})$ is a circle whose boundary is $\varphi(\partial\mathbb{D})$, where $\partial\mathbb{D}$ denotes the boundary of $\mathbb{D}$.

Now, take three distinct points in the unit circle. We choose $z_1 = 1$, $z_2 = -1$, and $z_3 = i$ as they are three very simple points on the unit circle. Since φ is linear, it is also one-to-one. Thus, $A = f(z_1)$, $B = f(z_2)$, and $C = f(z_3)$ are three distinct points. Since z_1, z_2, and z_3 are on the unit circle which is equivalent to $\partial\mathbb{D}$, A, B, and C are in fact three distinct points in the circle $\varphi(\partial\mathbb{D})$. That is, circle circumscribed over A, B, and C coincides with $\varphi(\partial\mathbb{D})$.

To verify that $\varphi(\partial\mathbb{D})$ indeed has center P and radius r, we just need to show that

$$|A - P| = |B - P| = |C - P| = r.$$

For this, we use the equalities $|z|^2 = z\bar{z}$, and $|c + d| = |\bar{c} + \bar{d}|$.

So, we have

$$
\begin{aligned}
|A-P| &= \left|\frac{a+b}{c+d} - \frac{b\bar{d}-a\bar{c}}{|d|^2-|c|^2}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(a+b)(|d|^2-|c|^2)-(b\bar{d}-a\bar{c})(c+d)}{c+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{ad\bar{d}-bc\bar{c}-bc\bar{d}+ad\bar{c}}{c+d}\right|, \text{ by using the first equality} \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(\bar{c}+\bar{d})(bc-ad)}{c+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|\bar{c}+\bar{d}||bc-ad|}{|c+d|}\right) \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|c+d||bc-ad|}{|c+d|}\right), \text{ by using the second equality} \\
&= \frac{bc-ad}{|d|^2-|c|^2} \\
&= r.
\end{aligned}
$$

Showing $|B-P| = r$ is analagous:

$$
\begin{aligned}
|B-P| &= \left|\frac{-a+b}{-c+d} - \frac{b\bar{d}-a\bar{c}}{|d|^2-|c|^2}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(-a+b)(|d|^2-|c|^2)-(b\bar{d}-a\bar{c})(-c+d)}{-c+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{-ad\bar{d}-bc\bar{c}+bc\bar{d}+ad\bar{c}}{-c+d}\right|, \text{ by using the first equality} \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(-\bar{c}+\bar{d})(bc-ad)}{-c+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|-\bar{c}+\bar{d}||bc-ad|}{|-c+d|}\right) \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|-c+d||bc-ad|}{|-c+d|}\right), \text{ by using the second equality} \\
&= \frac{bc-ad}{|d|^2-|c|^2} \\
&= r.
\end{aligned}
$$

Using a third equality, $|ci+d| = |\bar{c}+\bar{d}i|$, we have

$$\begin{aligned}
|C-P| &= \left|\frac{ai+b}{ci+d} - \frac{b\bar{d}-a\bar{c}}{|d|^2-|c|^2}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(ai+b)(|d|^2-|c|^2)-(b\bar{d}-a\bar{c})(ci+d)}{ci+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{ad\bar{d}i-bc\bar{c}-bc\bar{d}i+ad\bar{c}}{ci+d}\right|, \text{ by using the first equality} \\
&= \frac{1}{|d|^2-|c|^2}\left|\frac{(\bar{c}+\bar{d}i)(ad-bc)}{ci+d}\right| \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|\bar{c}+\bar{d}i||ad-bc|}{|ci+d|}\right) \\
&= \frac{1}{|d|^2-|c|^2}\left(\frac{|ci+d||ad-bc|}{|ci+d|}\right), \text{ by using the third equality} \\
&= \frac{bc-ad}{|d|^2-|c|^2} \\
&= r.
\end{aligned}$$

Hence the circle circumscribed over the points A, B, and C indeed has center P and radius r. Thus $\varphi(\partial\mathbb{D})$ has center P and radius r. Thus $\varphi(\mathbb{D})$ is the disc $P + r\mathbb{D}$. □

3 Definitions

Definition 1. A metric space (X, d) is a set X and a function d(the distance function) which assigns a real number $d(x, y)$ to every pair $(x, y) \in X$, which satisfies the following properties :

1. $d(x, y) \geq 0$
2. $d(x, y) = 0 \Rightarrow x = y$.
3. $d(x, y) = d(y, x)$.
4. $d(x, y) + d(y, z) \geq d(x, z)$. This last property is called the *triangle inequality.*

Definition 2. A function f is topologically transitive iff for all nonempty open subsets U, V of X, there exists $k \in \mathbb{N}$ such that $f^k(U) \cap V$ is nonempty.

Definition 3. Let X be a topological space. A set Q is dense in X if for any point $x \in X$ and for any $\epsilon > 0$, there exists a point in $q \in Q$ such that the distance between x and q is less than ϵ. In other words, a set Q is dense in X if every point in X is either in Q or is a limit point in Q.

Definition 4. A point x is said to be a periodic point of a function f if there exists an integer n such that $f^n(x) = x$. The least positive integer n for which this is true is the period of x.

Definition 5. Let (X, d) be a metric space. A function $f : X \to X$ is said to be chaotic on X if it satisfies the following three conditions:

1. *f is topologically transitive.*
2. *The set of periodic points in f is dense in X.* That is, that every open set in f contains a periodic point.
3. *f has sensitive dependence on initial conditions.* That is, $\exists\delta > 0$ such that for any open set U and for any $x \in U$, there exists a $y \in U$ such that $d(f^{[k]}(x), f^{[k]}(y)) > \delta$ for some k. δ is called a *sensitivity constant.*

Definition 6. A backward shift operator B operates on an element of a sequence to produce the previous element.

e.g. if $X = \{x_1, x_2, \dots\}$, then $B(X) = \{x_2, x_3, \dots\}$.

Definition 7. Let $z \in \mathbb{C}$. That is, let $z = x+yi$, where x and y are real numbers. The absolute value or modulus of z, denoted $|z|$ is given by

$$|z| = \sqrt{x^2 + y^2}.$$

Definition 8. The open unit disc of $\mathbb{C}$, denoted $\mathbb{D}$, is the region in the complex plane defined by

$$\mathbb{D} = \{z \in \mathbb{C} : |z| < 1\}.$$

Definition 9. A mapping T from a vector space V_1 to a vector space V_2, i.e. $T : V_1 \to V_2$, is a linear transformation iff

$$T(c\vec{u} + c\vec{v}) = cT(\vec{u}) + cT(\vec{v}),$$

for all $\vec{u}, \vec{v} \in V_1$, and all $c \in \mathbb{R}$. The transformation is referred to as an operator if the mapping is from a vector space to itself.

Definition 10. Let $U \subset \mathbb{C}$ be open and let $f : U \to \mathbb{C}$. If f is complex differentiable at every point in U, f is said to be holomorphic or on U.

Definition 11. A function f has a pole of order n at z_0 if n is the smallest positive integer for which $(z - z_0)^n f(z)$ is holomorphic at z_0. A function f has a pole at infinity if $\lim_{z\to\infty} f(z) = \infty$.

Definition 12. A Linear Fraction Transformation is a function of the form

$$f(z) = \frac{az + b}{cz + d}$$

where $a, b, c, d \in \mathbb{C}, ad \neq cb$.