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Chaos: An Introduction to Dynamical Systems

March 7, 2021

Problem in discrete-time system

1 One-Dimension Maps

Definition 1.1 *n-order differentiable function, Smooth function, Map*

Consider an open set E and $n \in \mathbb{N}$, called

$$C^n(E) = \{f \in C(E) | \forall \alpha \text{ s.t. } |\alpha| \leq n, D^\alpha f \in C(E)\}$$

is *n-order differentiable function set of E*, where $C(E)$ is continuous function on E .

If f on domain E have infinity-order derivative, or $f \in C^\infty(E)$, then called f **smooth function**.

If the function f have same domain and range, then called f is a **map**.

The function in this book will be a smooth function if we not emphasize.

Definition 1.2 *Orbit, initial value, fixed point*

Consider a map $f : X \rightarrow X$, x is a point in X then

Called **orbit** of x is a set of point

$$\text{Orbit}(X) = \{x, f(x), f^2(x), \dots, f^n(x), \dots\}$$

, where $f^n(x) = f(f(\dots f(x))) = (f \circ f \circ f \circ \dots \circ f)(x)$.

The starting point of x for a orbit called the **initial value**.

If the point p s.t. $f(p) = p$, then called p as **fixed point**.

OK, and now we consider two dynamical systems, with a input x , the system will always return to $f(x) = 2x$ and $g(x) = 2x(1 - x)$. And then the output will become the input value and etc. During this looping, it is simple to find the orbit of a certain initial value.

Table 1: Comparison of exponential growth and logistic growth

f	init	1	2	3	4	5	6	7	8	9
$f(x)$	0.01	0.02	0.04	0.08	0.16	0.32	0.64	1.28	2.56	5.12
$f(x)$	0.01	0.0198	0.0388	0.0746	0.138	0.268	0.362	0.462	0.497	0.499
$g(x)$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$g(x)$	0.8	0.32	0.435	0.492	0.499	0.5	0.5	0.5	0.5	0.5
$g(x)$	1.2	-0.48	-1.42	-6.87	-108.4	-23716.9	-1125030476	-inf	-inf	-inf

We found that in the model of f , the result is growth as exponential function and we called that exponential growth. Also, when initial value $x \in [0, 1]$, with iteration, the result have limitation of 0.5 and we called these model as logistic growth.

In this section, we will mainly focus on these kind of dynamical system, obviously, the iteration processing of model are discrete, we also called these dynamical system models as **maps**.

1.1 Cobweb plot, stability

To analysis a maps, the basic method is based on cobweb plot. Fig 1 showed a method to analysis a dynamical system with a certain iteration principle.

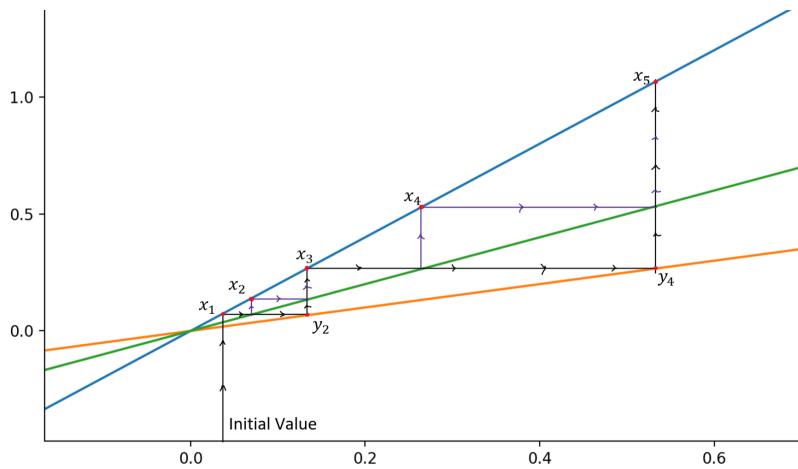


Figure 1: An example of cobweb plot and basic principle

In every iteration, the independent and dependent variable exchanged their location and we can found a group of $\{x_1, y_2, x_3, y_4, \dots\}$ as orbit of initial value. Or, with the symmetric line $y = x$, it is simple to symmetric all black line to purple line and we can build a cobweb plot with origin image and $y = x$ to find a group of $\{x_1, x_2, \dots\}$ as orbit from the initial value.

Before we discuss the different of fixed point, it is necessary to review some basic definitions.

Definition 1.3 ε Neighbourhood

In a metric space X , an ε neighbourhood $N_\varepsilon(p)$ of point p is defined

$$N_\varepsilon(p) = \{x \in X | d(x, p) < \varepsilon\}$$

where $d(x, p)$ is the distance bewteen point p and x . Also, in a R^1 space, the ε Neighbourhood is give by

$$N_\varepsilon(p) = \{x \in R | |x - p| < \varepsilon\}$$

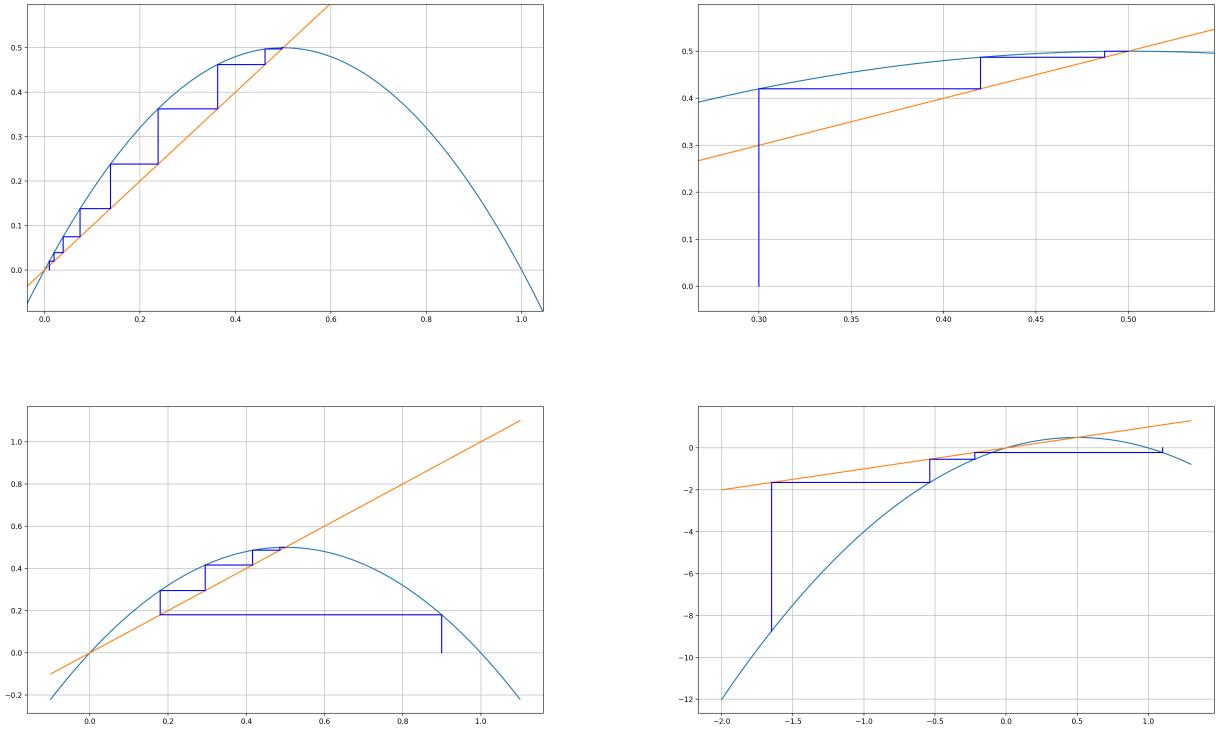


Figure 2: Cobweb plot in different initial value

It is simple to find that for all initial value $x \in (0, 1)$, with iteration, the output have limitation in 0.5. On the other hand, to solve the equation $x = 2x(1 - x)$ we found $x_1 = 0, x_2 = 1, x_3 = 0.5$ as three fixed point. So we have two kinds of fixed point, the one is limitation point and the other is not.

Definition 1.4 *Sink, Source (Attracting and Repelling Fixed Point)*

Consider a map $f : R \rightarrow R$ and point p s.t. $f(p) = p$, then

If for evert points sufficiently to p are attracted to p , then called p as **sink**, or **attracting fixed point**. Or

For an $\varepsilon > 0$, $\forall x \in N_\varepsilon(p)$, $\lim_{k \rightarrow \infty} f^k(x) = p$ then called p as **sink**.

If for every points sufficiently to p are repelled to p , then called p as **source**, or **repelling fixed point**.

For an $\varepsilon > 0$, $\forall x \in N_\varepsilon(p)$, $x \neq p$, $\lim_{k \rightarrow \infty} f^k(x) \notin N_\varepsilon(x)$ then called p as **source**.

Theorem 1.1 Let f is a map on R , assume p is a fixed point of f , then

- [i] If $|f'(p)| < 1$, then p is a sink;
- [ii] If $|f'(p)| > 1$, then p is a source.

PROOF 1.1 [i] Based on definition of derivative, we have

$$\lim_{x \rightarrow p} \frac{|f(x) - f(p)|}{|x - p|} = |f'(p)|$$

Now, let $a \in (\min(|f'(p)|, 1), \max(|f'(p)|, 1))$ (e.g. $a = \frac{1}{2}(1 + |f'(p)|)$), then

$$\forall a \in (\min(|f'(p)|, 1), \max(|f'(p)|, 1)), \exists \varepsilon_0 > 0 \text{ s.t. } \forall \varepsilon \in (0, \varepsilon_0], \forall x \in N_\varepsilon(p), \frac{|f(x) - f(p)|}{|x - p|} < a$$

That means, $f(x)$ is closer to p than x (or distant between curve $y = f(x)$ and $y = x$), but at least a factor of a and we have the conclusion

$$\forall x \in N_\varepsilon(p), f(x) \in N_\varepsilon(p)$$

During the iteration processing it is simple to find that all orbit $\{f(x), f^2(x), \dots, f^n(x), \dots\} \subset N_\varepsilon(p)$, so now we can consider another conclusion in follow.

[ii] We try to prove the inequality $\forall x \in N_\varepsilon(p), |f^k(x) - p|$

[ii-1] Obvious, if $k = 1$, then $|f(x) - p| = |f(x) - f(p)| < a|x - p|$ (p is fixed point so $f(p) = p$)

[ii-2] If $k = 2$, Based on the conclusion in [i], $x_1 = f(x) \in N_\varepsilon(p)$ and $|f(x_1) - p| < a|x_1 - p| < a^2|x - p|$

...

[ii-k+1] (Assume the inequality is established in k), then

$$|f^{k+1}(x) - p| < a|f^k(x) - p| < a \cdot a^k|x - p| = a^{k+1}|x - p|$$

In summary, for all $k \in N$, the inequality is established.

[iii-1] Now we consider the equality condition, if $|f'(p)| < 1$ then $a < 1$ and

$$\lim_{k \rightarrow \infty} |f^k(x) - p| < |x - p| \lim_{k \rightarrow \infty} a^k = 0 \text{ (Because } a \in (0, 1))$$

So we have the conclusion,

$$\forall x \in N_\varepsilon(p), \lim_{k \rightarrow \infty} f^k(x) = p$$

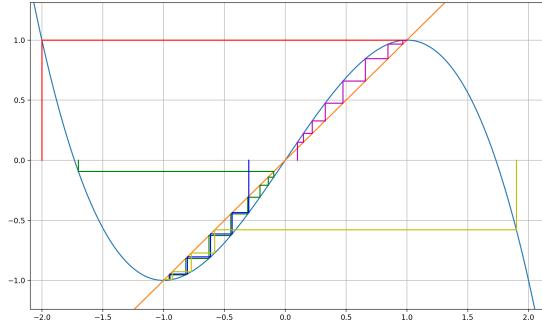
[iii-2] Also, if $|f'(p)| > 1$ then $a^k \rightarrow \infty$, that means, with the iteration, the maps will eventually outside the condition, or the domain interval. ■

* We will discuss what happened while $f'(p) = 1$ laterly.

** Obviously, this theorem expressed a kind of convergence, as the speed of the convergence is based on the a in exponent function, we called this convergence as **Exponential Convergence**.

Now we consider another map as example.

E x a m p l e 1.1 Solved the fixed point of $\varphi(x) = (3x - x^2)/2$, find every sink and source point with Theo. 1.1



SOLUTION 1.1 It is simple to find the fixed point with $x = (3x - x^2)/2$ and $x_1 = 1, x_2 = 0, x_3 = -1$. Based on the image, we can found that 1 and -1 are sink and 0 is source. On the other hand

$$\varphi'(x) = \frac{3}{2}(1 - x^2), \varphi'(-1) = 0 < 1, \varphi'(0) = \frac{3}{2} > 1, \varphi'(1) = 0 < 1$$

and we proved the conclusion we found on figure before. ■

Another way to confirm a point is sink or source is based on the formula identity and algebra. For instance, we consider the distance bewteen $g(x) = 2x(1 - x)$ and fixed point $1/2$, then

$$|g(x) - 1/2| = |2x(1 - x) - 1/2| = 2|x - 1/2||x - 1/2|$$

and $\forall x \in (0, 1), |x - 1/2| < 1 \Rightarrow |g(x) - 1/2| < 1$, that means the distance bewteen $g(x)$ and p is decreasing during time iteration and we can confirm that $1/2$ is a sink point rather than source point.

Next, we will focus on a logistic model with different parameter.

1.2 Periodic points, family of logistic maps

E x a m p l e 1.2 Find the fixed point of $g(x) = 3.3x(1 - x)$, $x \in [0, 1]$.

SOLUTION 1.2 It is simple to find the fixed point with $x = 3.3x(1 - x)$ and $x_1 = 0, x_2 = 23/33, x_3 = 1$. Obviously, both 0 and 1 are source. And

$$g'(x) = 3.3 - 6.6x, |g'(23/33)| = 1.3 > 1$$

So all these three fixed point are source, and it is simple to find the conclusion with cobweb plot. ■

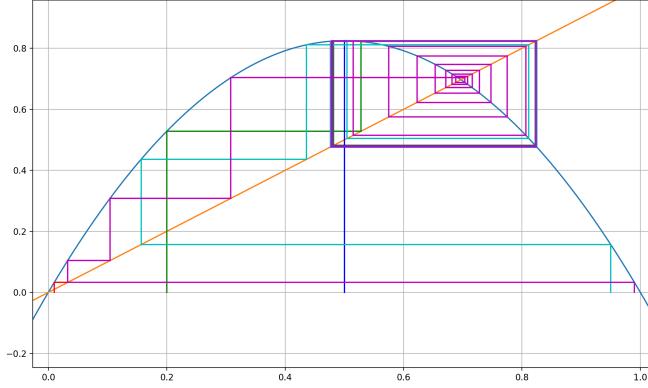


Figure 3: An example of periodic point

Hold on a second, something strange! Even we cannot find a sink fixed point, all of initial value are sank into a group of points!

Definition 1.5 *Period-k point, Period-k orbit*

Let f be a map on R , and p is a point in domain, if $f^k(p) = p$, and k is the smallest such positive integer, then called p as **periodic point of period k** , or **period- k point**;

Called orbit with initial point p as **periodic orbit of period k** , or **period- k orbit**;

Definition 1.6 *Sink and Source in Period point*

Let f be a map and p is a period- k point

If p is a sink, then called this period- k orbit as **periodic sink**;

If p is a source, then called this period- k orbit as **periodic source**.

Obviously, based on the chain rule, we have $(fg)'(x) = f'(g(x))g'(x)$, let $f = g, x = p_1$, then

$$g^2(p_1) = g'(g(p_1))g'(p_1) = g'(p_2)g'(p_1)$$

Summary this formula, we have

Theorem 1.2 For every map f and period- k orbit $\{p_1, p_2, \dots, p_k\}$,

$$(f^k)'(p_1) = (f^k)'(p_2) = \dots = (f^k)'(p_k) = \prod_{i=1}^k f'(p_i)$$

PROOF 1.2 Theo. 1.2

$$(f^k)(p_1) = (f(f^{k-1}))'(p_1) = f'(f^{k-1}(p_1))(f^{k-1})'(p_1) = \dots = \prod_{i=1}^k f'(p_i) = (f^k)(p_i) (\forall i = 1, 2, \dots, k) \blacksquare$$

Same as Theo. 1.1, we have stability test for periodic orbits.

Theorem 1.3 *Stability test for periodic orbits*

Let f is a map and period- k orbit $\{p_1, p_2, \dots, p_k\}$,

If $|\prod_{i=1}^k f'(p_i)| < 1$ then called this periodic orbit is a sink;

If $|\prod_{i=1}^k f'(p_i)| > 1$ then called this periodic orbit is a source;

PROOF 1.3 *Theo. 1.1*

Consider a new map $g(x) = f^k(x)$, where f be a map and p is a period- k point, then p is a fixed point of g . Based on Theo. 1.1, $|g(p)| < 1$ if p is sink and $|g(p)| > 1$ if p is a source. On the other hand, $g(p) = f^k(p) = \prod_{i=1}^k f'(p_i)$ ■

Now we consider another problem.

E x a m p l e 1.3 Find the fixed point or periodic orbit of $g_{3.5}(x) = 3.5x(1 - x)$, $g_{3.86}(x) = 3.86x(1 - x)$, $x \in [0, 1]$.

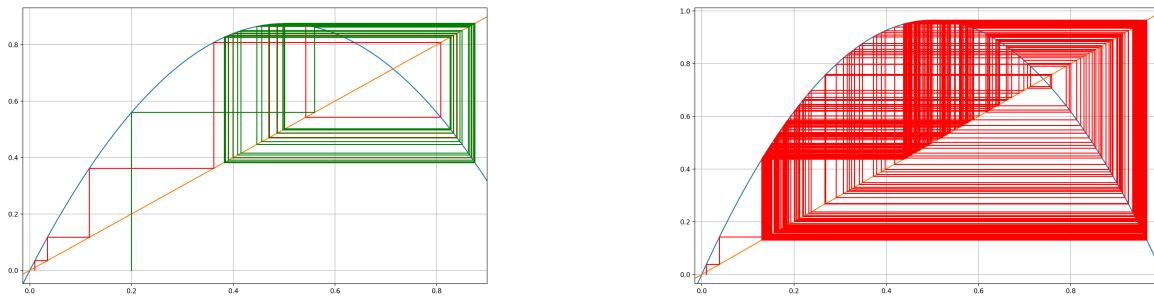


Figure 4: Logistic maps in $a = 3.5$ and $a = 3.86$

We found in $a = 3.5$, even the periodic orbit is difficult to find, the iteration still have a boundary. If we consider every $a \in [1, 4]$, we can plot a figure between parameter a and orbits x , and this **bifurcation diagram** was made by following repeating:

- [i] Choose a value a , starting with $a = 1$.
- [ii] Choose a value $x \in [0, 1]$ randomly.
- [iii] Calculate the orbit of x under $g_a(x)$ in a certain iteration times t_{max} .
- [iv] Ignore the first t_0 iterates and plot the orbit.

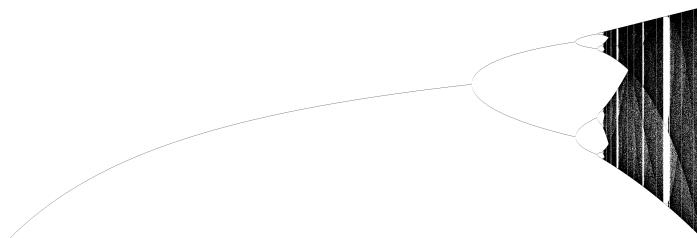


Figure 5: Logistic model stability interval ($a \in [1, 4]$)

D I S C U S S I O N 1.1 Now we will discuss the family of logistic maps with Fig. ??

[i] Periodic-3 window

We found periodic-1 orbits (or point) and periodic-2 orbits, based on the image above, it seem we also have periodic-3 orbits. And now we focus on the interval of parameter a rather than domain of function, we found there is a interval of a inside the $[3.83, 3.86]$ and we called these kind of interval as “periodic window”. For instance, next figure showed the periodic-3 window of a .

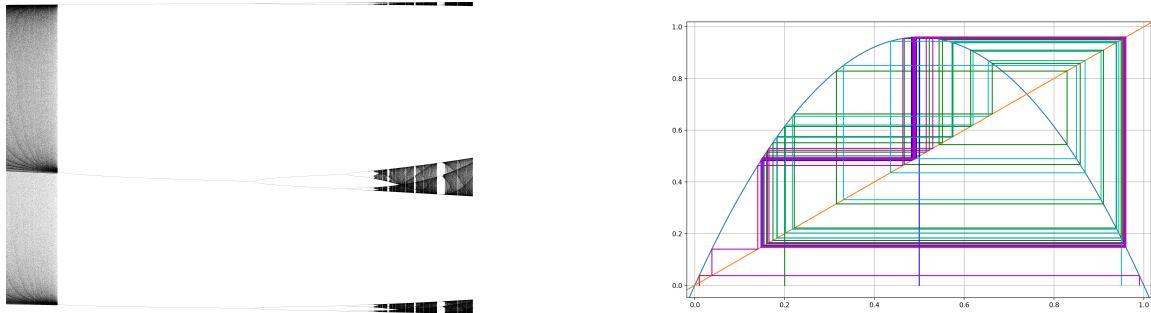


Figure 6: Periodic-3 window and cobweb plot in $a = 3.84$

That's fine, let's check the result by cobweb plot. Ok, hold on a second, something wrong! So we still need more analysis.

Obviously, every periodic-3 orbit of g is a fixed point of g^3 , so we can also analysis g^3 map.

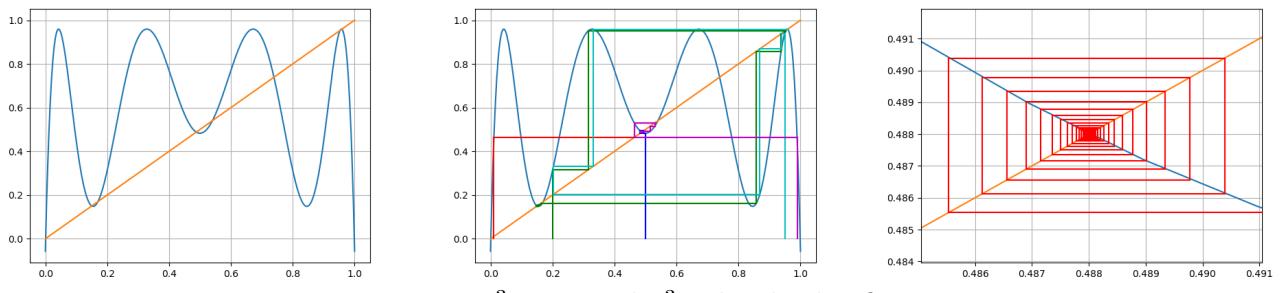


Figure 7: g^3 map and g^3 cobweb plot figure

We found different from periodic-2 orbit, the periodic-3 orbit is nearby(rather than equal) the point and it seems we have periodic-3 orbit. Actually, we will explain all periodic-3 will implies a characteristic we called “chaos”.

[ii] The Logistic Map $G(x) = 4x(1 - x)$

Now we consider another logistic map where $a \equiv 4$.

Firstly, why we are interested in $g_4(x)$, consider a quadratic function

$$g_a(x) = ax(1 - x) = a(-x^2 + x - 1 + 1) = -a(x - \frac{1}{2})^2 + \frac{a}{4}$$

this function have maximum at point $x = 1/2$ and the maximum is $a/4$. As we have the Theo. 1.1, if we consider the sink point set, it is necessary to satisfy $|g_a(x)| < 1$, or $a < 4$. So at the point $a = 4$, this set is empty and this is a critical state. For every $a_{\text{new}} = a - \varepsilon (\varepsilon \rightarrow 0)$, we have the interval of sink. So at this point, some special property has been result and that is why we interested in this map.

We can still find the fixed point of $g_4(x)$ to solve $g_4(x) = x$, and we have $x_{11} = 0, x_{21} = 3/4$. If we consider periodic- k orbit, for instance, we consider periodic-2 orbit, then we have solve the function $g(g(x)) = x$ as

$$\begin{aligned} g(g(x)) &= 4(4x(1 - x))[1 - 4x(1 - x)] = x \Rightarrow (4x^2 - 4x + 1)(x - 1)x + \frac{x}{16} = 0 \\ &\Rightarrow (4x - 3)(16x^2 - 20x + 5)x = 0 \Rightarrow x_{21} = 0, x_{22} = \frac{3}{4}, x_{23,24} = \frac{5 \pm \sqrt{5}}{8} \end{aligned}$$

Also, it is easy to check the periodic- k orbit in the figure.

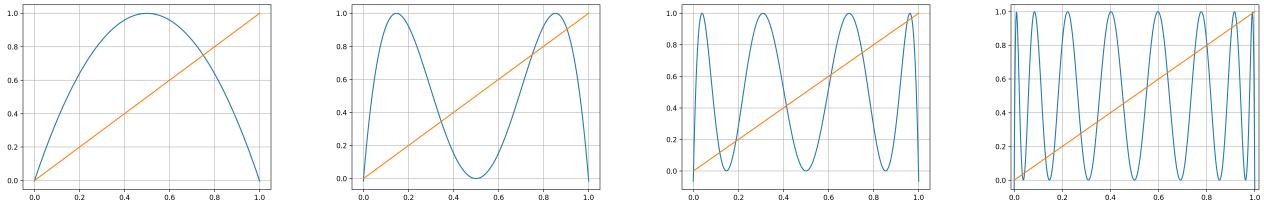


Figure 8: g_4^1, g_4^2, g_4^3 and g_4^4 figure

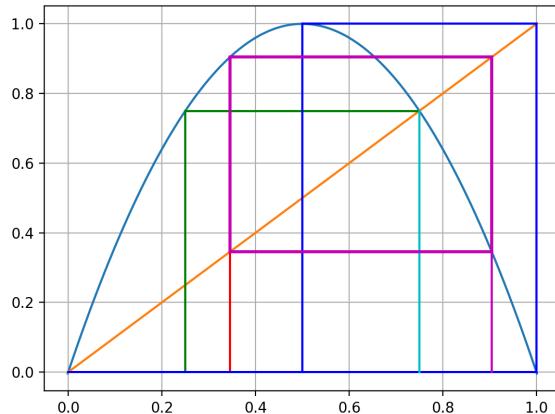


Figure 9: $g_4(x)$ cobweb plot(periodic-1,2 orbits)

We found a conclusion here

CONCLUSION 1.1 For every periodic- k , the model g_4^k have $2^k - 1$ saddle-node bifurcation and 2^k fixed point. And these 2^k points include every fixed point for model g_4^i , $i = 1, 2, \dots, k-1 \wedge k \equiv 0 \pmod{i}$

The number of orbits of the map for each period can be tabulated in the map's periodic table.

Table 2: The periodic table for the logistic4 map

Period k	1	2	3	4	5	6	7
Number of fixed points of g_4^k	2	4	8	16	32	64	128
Orbits of Period k	2	1	2	3	4	5	6
Fixed points due to lower orbits	0	2	2	4	2	4	2
1	/						
2	*	/					
3	*		/				
4	-	*		/			
5	*				/		
6	-	*	*			/	
7	*						/

(*: Greatest common divisor group, -: g^k fixed)

1.3 Chaos

We still focus on $g_4(x)$ map, we try to check the g_4^2 fixed point $\frac{5-\sqrt{5}}{8}$.

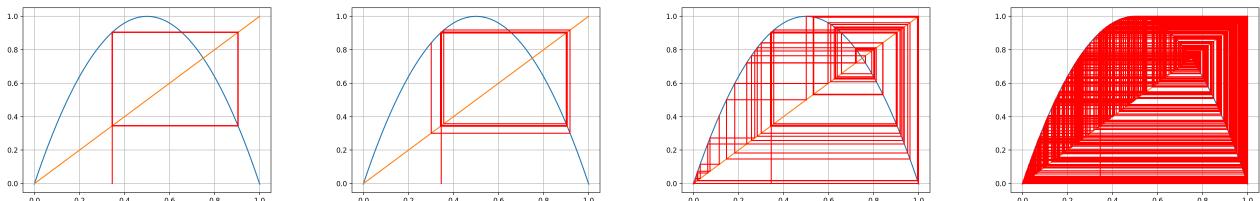


Figure 10: g_4^1, g_4^2, g_4^3 and g_4^4 figure

It seems something wrong. Because we proved that $\frac{5\pm\sqrt{5}}{8}$ is a periodic orbit during the iteration, but once we growth the iteration times, the results filled all the interval.

So what happened? We try to put all of our data into a same image, and we have

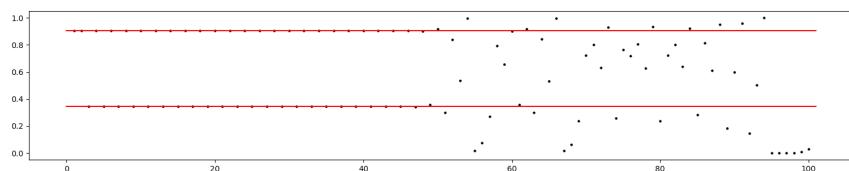


Figure 11: Iteration and “periodic-2 orbit” value

Obviously, in about first 40 times iteration, it was worked for a while, but with the iteration increasing, the error also increased rapidly. Ok, ok, let's check the data for more details.

Table 3: Logistic4 periodic-2 orbit iteration

1-4	0.3454915028125262	0.9045084971874737	0.3454915028125262	0.9045084971874735
5-8	0.34549150281252694	0.9045084971874745	0.3454915028125237	0.9045084971874705
9-12	0.34549150281253665	0.9045084971874865	0.3454915028124849	0.9045084971874225
13-16	0.34549150281269186	0.9045084971876783	0.3454915028118641	0.9045084971866552
17-20	0.3454915028151752	0.9045084971907479	0.34549150280193086	0.9045084971743771
21-24	0.3454915028549078	0.9045084972398602	0.3454915026430002	0.904508496977928
25-27	0.3454915034906304	0.9045084980256565	0.34549150010010987	...

We noticed that during the iteration, the values of periodic-2 orbit are actually changed very small. Then we realized that is because of $\frac{5-\sqrt{5}}{8} \neq 0.3454915028125262$ and this is just a value near the periodic point.(And the computer can only calculate this estimation value rather than real value.) Even these two values are almost nearby, it still have a little difference, and this difference become larger and larger during the iteration.

That is important because we found even two values are almost equal, after iterate, this tiny, tiny difference will become a catastrophe and eventually two orbits move apart.

Definition 1.7 *Sensitive dependence on initial conditions, Sensitive point*

Let f is a map on R , x_0 in domain.

If there is a nonzero distance d s.t. some points arbitrary near x_0 are eventually mapped at least d units from the corresponding image of x_0 , then we called x_0 has **sensitive dependence on initial conditions**;

If for this x_0 , $\exists \varepsilon > 0$ s.t. $\forall x \in N_\varepsilon^o(x_0) = N_\varepsilon(x_0) \setminus \{x_0\}$, $\exists K$ s.t. $\forall k > K$, $\|f^k(x) - f^k(x_0)\| \geq \varepsilon$, then called this point is **sensitive point**.

Definition 1.8 *Eventually periodic*

Let f is a map on R , x_0 in domain. If for some positive integer N , $\forall n > N$, $f^{n+p}(x) = f^n(x)$, then we called x **eventually periodic** with period p , where p is the smallest such positive integer.

Now we consider another model to explain this definition in another way.

E x a m p l e 1.4 Consider a map $f(x) = 3x \pmod{1}$. (e.g. $f(4.33) = 0.33$, $f(-1.98) = 0.02$.)

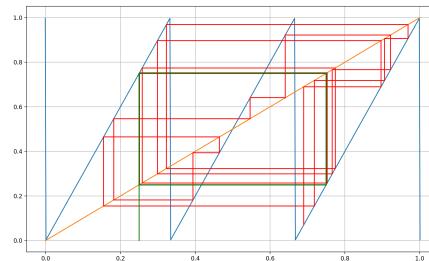


Figure 12: $3x \pmod{1}$ cobweb plot(initial value: 0.25(green), 0.2501(red))

Basically, we have

Theorem 1.4 *For any map f , the source has sensitive dependence on initial conditions.*

PROOF 1.4 *For a certain ε , as p is a source, then $\forall x \in N_\varepsilon^o(p), \lim_{k \rightarrow \infty} f^k(x) \notin N_d^\varepsilon(p) \Rightarrow d(p, x) > \varepsilon$ ■*

Is there any way to investigate this sensitive dependence? Yes, and here we will introduce a method called **itinerary** of an orbit.

SOLUTION 1.3 Itinerary

We still consider the g_4 model. Assign the symbol **L** to the left subinterval $[0, 1/2]$ and **R** to the right subinterval $[1/2, 1]$. Then, for every initial condition x_0 , we can list the itinerary with **L** and **R**.

For instance, the initial point $x_0 = 1/3$ have the itinerary **LRLRLRRLRLLRR**

Table 4: Logistic4 1/3 itinerary

0-2	0.3333333333333333 (L)	0.8888888888888889 (R)	0.39506172839506154 (L)
3-5	0.9559518366102727 (R)	0.16843169076687667(L)	0.5602498252491516 (R)
6-8	0.9854798342297868 (R)	0.05723732222487492 (L)	0.21584484467760304(L)
9-10	0.6770233908148179 (R)	0.874650876417697 (R)	...

And we can list all itinerary with different initial value. ■

Table 5: Logistic4 itinerary with different initial value

Val	1 – 10	11 – 20	21 – 30	31 – 40	...
0.01	LLLRLLLLLR	RRRLRLRLRR	LLRRRLLRRR	RLRRLRLRLR	...
0.25	LRRRRRRRRR	RRRRRRRRRR	RRRRRRRRRR	RRRRRRRRRR	...
1/3	LRLRLRRLR	RLRLLRRRL	LLLRRRLRL	RRRRRRRLRR	...
0.5	RRLLLLLLL	LLLLLLLLL	LLLLLLLLL	LLLLLLLLL	...
1	RLLLLLLLLL	LLLLLLLLL	LLLLLLLLL	LLLLLLLLL	...

Notice that there are some conclusions.

CONCLUSION 1.2 *For every periodic- k point, the itinerary of orbit will repeats **L** or **R** infinitely.*

CONCLUSION 1.3 *For every k iterate, the itinerary have 2^k choice and the sum of their lengths is 1(or the length of the interval).*

Also, we have a conclusion not very obvious.

CONCLUSION 1.4 *Each 2^k itinerary is shorter than $\pi/2^{k+1}$.*

We will prove this conclusion in later sections.

We can also analysis the problem with **transition graph**.

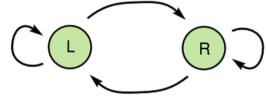


Figure 13: Transition graph

Finally, we focus on the title of this subsection “chaos”, after these analysis, it is simple to summary the definition of chaos.

Definition 1.9 *Chaos*

A chaotic orbit is a bounded, non-periodic orbit that displays sensitive dependence. Chaotic orbits separate exponentially fast from their neighbors as the map iterated.

Theorem 1.5 *The existence of periodic-3 orbit alone implies the existence of a large set of sensitive points, or chaotic orbit.*

We will prove this problem in appendix.

2 Two-Dimension and High-Dimension Maps

In this section, we will mainly discuss a new type of model, called Hénon map which formed

$$f(x, y) = (a - x^2 + by, x)$$

A simple way to analyze this problem is analysis all point in the surface if they are convergence or divergence. In figures following, point in black represent initial conditions whose orbits diverge to infinity and the points in white represent initial values whose orbits converge to the period-2 orbit.

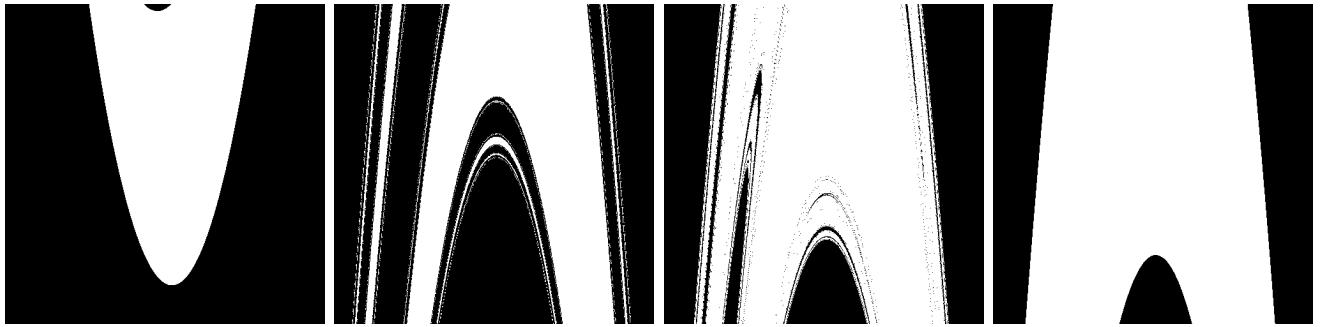


Figure 14: Initial condition square

(Parameter group $(a, b) = (0, 0.4), (2, -0.3), (1.4, -0.3), (1.28, -0.3)$)

2.1 Analysis of Hénon map

Now we focus on Hénon map. Familiar with 1 dim map, it is necessary to define the sink and source as well as saddle.

Definition 2.1 Neighborhood

Consider a R^n space, called every point $x = (x_1, x_2, \dots, x_n)$ is a vector of R^n space,

Define the **Euclidean Length** $|x| = \sqrt{x_1^2 + x_2^2 + \dots + x_n^2}$, which is equal to norm;

And define the distance between two point $d(x, y) = |x - y|$;

Also, the ε -neighborhood is

$\forall \varepsilon > 0$, the ε -neighborhood of point p , $N_\varepsilon(p)$ is $\{x \in R^n \mid |x - p| < \varepsilon\}$, also define $N_\varepsilon^o(p) = N_\varepsilon(p) \setminus \{p\}$

Definition 2.2 Sink and Source in High-dimension Map

Let f is a map on R^n , p is a vector on R^n which is the fixed point and $f(p) = p$ then

If there is an $\varepsilon > 0$ s.t. $\forall x \in N_\varepsilon(p)$, $\lim_{k \rightarrow \infty} f^k(x) = p$, then p is a sink or attracting fixed point.

If $\forall x \in N_\varepsilon^o(p)$, $\exists K$ s.t. $\forall k > K$, $f^k(x) \notin N_\varepsilon(p)$, then called the point p as source.

We will explain these definitions with an example

Example 2.1 Analysis the sink point, source point and saddle of Hénon map with parameter $a = 0, b = 0.4$

SOLUTION 2.1 Obviously, if we consider the function $f(x, y) = (-x^2 + 0.4y, x) = (x, y)$, then

$$-0.2x^2 + 0.4x = x \Rightarrow x_1 = 0, x_2 = -0.6$$

So the fixed points are $(0, 0)$ and $(-0.6, -0.6)$. And now we have a new problem: how to confirm a fixed point is sink or source. Even the definition of sink and source are given above, we still need theory like Theo. 1.1. But here, we can analysis the problem with simulator. ■

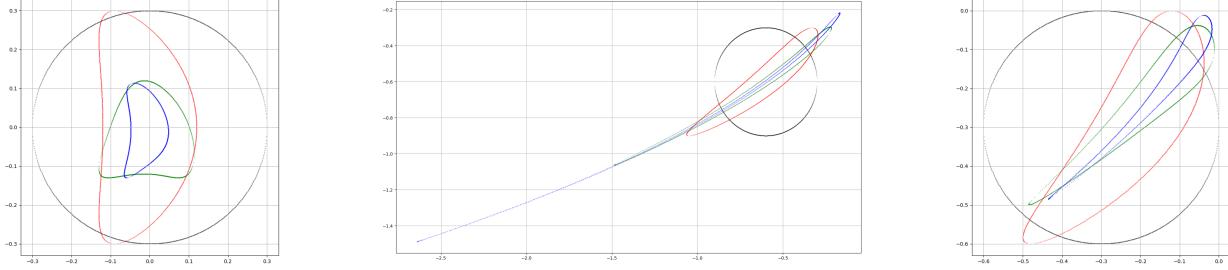


Figure 15: Sink, source and saddle in Hénon map with $a = 0, b = -0.4$

(Order of color: Black(neighborhood), Red (Iter = 1), Green (Iter = 2), Blue (Iter = 3))

To solve the problem we faced in e.g.2.1, we will discuss the simple form of the high dimension maps.

Definition 2.3 *High dimension linear map*

A map $A : R^m \rightarrow R^m$ is **linear** if $\forall a, b \in R, \forall x, y \in R^m, f(ax+by) = af(x)+bf(y)$. Equivalently, a linear map $f(x)$ can be represented as multiplication by an $m \times m$ matrix.

Now we consider a system s.t. $f(x) = Ax$, if λ is eigenvalue and \mathbf{v} is eigenvector of A , based on the definition of eigenvalue and eigenvector, we have Let A have eigenvalue λ , based on the definition of eigenvalue, we have

$$A\mathbf{x} = \lambda\mathbf{v}$$

Then, for the initial point \mathbf{v} , we have

$$A(\mathbf{v}) = A\mathbf{v} = \lambda\mathbf{v}$$

let $\mathbf{v}_0 = \mathbf{v}, \mathbf{v}^n = A^n(\mathbf{v})$, then

$$\mathbf{v}_1 = A\mathbf{v}_0 = \lambda\mathbf{v}_0, \mathbf{v}_2 = A\mathbf{v}_1 = \lambda^2\mathbf{v}_1 \dots \mathbf{v}_n = A\mathbf{v}_{n-1} = \lambda^n\mathbf{v}_0$$

Futhermore, if we consider a system in random initial value \mathbf{x}_0 , still define $\mathbf{x}_n = f(\mathbf{x}_{n-1})$, then

$$\mathbf{x}_n = f(\mathbf{x}_{n-1}) = A\mathbf{x}_{n-1} = Af(\mathbf{x}_{n-2}) = \dots = A^n\mathbf{x}_0$$

To analysis this problem, firstly we will review some theorems in algebra.

D I S C U S S I O N 2.1 Eigenvalue, eigenvector and Jordan normal form

* We will consider a square matrix $A_{m \times m}$ s.t. $\text{rank}(A) = m$ in following discussion.

[i] If A have m different Eigenvalue

Based on the discussion above, we know that it is the first step to analysis the A^n to discribe all the linear system. Obviously, if A is a diagonal matrix, then the exponent of the matrix is easy and simple.

Theorem 2.1 Let A is a diagonal matrix s.t. $A = \text{diag}(a_1, a_2, \dots, a_m)$, then $A^n = \text{diag}(a_1^n, a_2^n, \dots, a_m^n)$.

Furthermore, if matrix A have m different eigenvalue $\lambda_1, \lambda_2, \dots, \lambda_m$ and \mathbf{v}_i is the eigenvector of λ_i . Let

$$\Lambda = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_m), V = (\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_m)$$

then we can easily prove that

$$A = V^{-1} \Lambda V$$

And the calculation of A^n is simple.

$$A^n = V^{-1} \Lambda^n V = V^{-1} \text{diag}(\lambda_1^n, \lambda_2^n, \dots, \lambda_m^n) V$$

Now we back to consider the linear system, if $f(\mathbf{x}) = A\mathbf{x}$ and A have m different eigenvalue, then we know that

$$\mathbf{x}_n = A^n \mathbf{x}_0 = V^{-1} \text{diag}(\lambda_1^n, \lambda_2^n, \dots, \lambda_m^n) V \mathbf{x}_0$$

Based on the analysis in the section 1, we still want to analysis the convergence and divergence for ever system.

$$\lim_{n \rightarrow \infty} \mathbf{x}_n = V^{-1} \text{diag}(\lim_{n \rightarrow \infty} \lambda_1^n, \lim_{n \rightarrow \infty} \lambda_2^n, \dots, \lim_{n \rightarrow \infty} \lambda_m^n) V \mathbf{x}_0$$

Obviously, with the knowledge of sequence, if $|\lambda_i| \in [0, 1)$, then $\lim_{n \rightarrow \infty} \lambda_i^n = 0$ and the sequence is convergence. Also, if $|\lambda_i| \in (1, +\infty)$, then $\lim_{n \rightarrow \infty} \lambda_i^n = \infty$ and the sequence is divergence. So we have this conclusion.

Theorem 2.2 Sink, source and saddle in linear system

Consider a linear system $f(\mathbf{x}) = A\mathbf{x}$, where A is a square matrix in m dimension. If the eigenvalue of A are $\lambda_1, \lambda_2, \dots, \lambda_m$ and

[i] $\forall i \in 1, 2, \dots, m, |\lambda_i| < 1$, then the origin point is sink.

[ii] $\forall i \in 1, 2, \dots, m, |\lambda_i| > 1$, then the origin point is source.

[iii] $\{i | |\lambda_i| < 1\} \neq \emptyset \wedge \{j | |\lambda_j| > 1\} \neq \emptyset$, that means, if at least one eigenvalue are absolute smaller than one and at least one is upper than one, then the origin point is saddle.

[ii] If A have at least two equal eigenvalue

We can transfrom the matrix A with Jordan normal form rather than eigenvalue diagonal matrix. Consider the matrix $A_{m \times m}$ and the eigenvalue $\lambda_1, \lambda_2, \dots, \lambda_k$ are r_1, r_2, \dots, r_k multiple root of function $|\lambda I - A| = 0$, which satisfied the definition of eigenvalue, and $k < m$, $\sum_{i=1}^k r_i = m$, $I = \text{diag}(1, 1, 1, \dots, 1)$.

Then for every r_i multiple eigenvalue λ_i , $\exists \mathbf{v}_{i1}, \mathbf{v}_{i2}, \dots, \mathbf{v}_{ir_i}$ s.t.

$$|\lambda I - A| \mathbf{v}_{i1} = 0, |\lambda I - A| \mathbf{v}_{ij+1} = \mathbf{v}_{ij} (j = 1, 2, \dots, r_i - 1)$$

We can still structure the V matrix same as V in [i], and we can also represent the diagonal eigenvalue matrix Λ to the **Jordan normal form matrix** J which satisfied

$$J = \begin{bmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_k \end{bmatrix} = \text{diag}(J_1, J_2, \dots, J_k), \text{ where } J_i = \begin{bmatrix} \lambda_i & 1 & & \\ & \lambda_i & 1 & \\ & & \ddots & \dots \\ & & & \lambda_i & 1 \\ & & & & \lambda_i \end{bmatrix}$$

is r_i dimension square matrix called **Jordan block**

Based on the calculation of block matrix we found that

$$A^n = V^{-1} J^n V = V^{-1} \text{diag}(J_1^n, J_2^n, \dots, J_k^n) V$$

So familiar with the discussion in [i], now it is necessary to discuss the J_i^n . On the other hand, we know that for ever Jordan block, we have

$$J_i^n = \begin{bmatrix} \lambda_i^n & \binom{n}{1} \lambda_i^{n-1} & \binom{n}{2} \lambda_i^{n-2} & \dots & \binom{n}{r_i} \lambda_i^{n-r_i} \\ \lambda_i^n & \binom{n}{1} \lambda_i^{n-1} & \dots & \binom{n}{r_{i-1}} \lambda_i^{n-r_i+1} & \\ \dots & \dots & \dots & \dots & \\ \lambda_i^n & & \binom{n}{1} \lambda_i^{n-1} & & \\ & & & \lambda_i^n & \end{bmatrix}$$

Obviously, for ever element on the diagonal, the Theo. 2.2 still established. To proved that, we will prove the following theorem firstly.

Theorem 2.3 Let J_i is a Jordan block with eigenvalue λ_i .

- [i] If $|\lambda_i| < 1$, then $\lim_{n \rightarrow \infty} J_i^n = 0$
- [ii] If $|\lambda_i| > 1$, then $\lim_{n \rightarrow \infty} J_i^n = \infty$

PROOF 2.1 Consider a element $\binom{n}{k} \lambda_i^{n-k}$ of J_i , then

$$\lim_{n \rightarrow \infty} \binom{n}{k} \lambda_i^{n-k} = \lim_{n \rightarrow \infty} \left(\frac{n(n-1)\dots(n-k)}{1 \cdot 2 \cdot \dots \cdot k} \lambda_i^{n-k} \right)$$

As the $\frac{n(n-1)\dots(n-k)}{1 \cdot 2 \cdot \dots \cdot k}$ is a polynomial of n in k dimension, so $\exists a_1, a_2, \dots, a_k \in R$ s.t.

$$\lim_{n \rightarrow \infty} \binom{n}{k} \lambda_i^{n-k} = \lim_{n \rightarrow \infty} \left(\sum_{p=1}^k a_p n^p \right) \lambda_i^{n-k} = \sum_{p=1}^k \lim_{n \rightarrow \infty} (a_p n^p \lambda_i^{n-k})$$

Finally, we found, if $|\lambda_i| > 1$, then $\lim_{n \rightarrow \infty} \binom{n}{k} \lambda_i^{n-k} = \infty$ and if $|\lambda_i| < 1$, then $\lim_{n \rightarrow \infty} \binom{n}{k} \lambda_i^{n-k} = 0$ and the Theo. 2.3 is established. ■

As for the non-linear problem, a wildly used method is **Jacobian matrix**

Definition 2.4 Jacobian matrix

Let $\mathbf{f} = (f_1, f_2, \dots, f_m)$ be a map on R^m and $\mathbf{p} \in R^m$ is a point on R^m space. The **Jacobian matrix** of \mathbf{f} at \mathbf{p} is the matrix

$$D\mathbf{f}(\mathbf{p}) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}(\mathbf{p}) & \frac{\partial f_1}{\partial x_2}(\mathbf{p}) & \cdots & \frac{\partial f_1}{\partial x_m}(\mathbf{p}) \\ \frac{\partial f_2}{\partial x_1}(\mathbf{p}) & \frac{\partial f_2}{\partial x_2}(\mathbf{p}) & \cdots & \frac{\partial f_2}{\partial x_m}(\mathbf{p}) \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1}(\mathbf{p}) & \frac{\partial f_m}{\partial x_2}(\mathbf{p}) & \cdots & \frac{\partial f_m}{\partial x_m}(\mathbf{p}) \end{bmatrix}$$

Jacobian matrix is a linearization estimation of a non-linear system that we can assume the derivative of the system near the point \mathbf{p} is $D\mathbf{f}(\mathbf{p})$. That means, instead of origin non-linear system, we can analysis the estimated system $\mathbf{f}_1(\mathbf{x}) = D\mathbf{f}(\mathbf{p})\mathbf{x}$ where $\mathbf{x} \in N(\mathbf{p}, \varepsilon)$ and ε is a certain constant. Based on the Theo. 2.2, it is easy to improve the following conclusion.

Theorem 2.4 Sink, source and saddle in non-linear system

Consider a non-linear system $\mathbf{f}(\mathbf{x})$ and a fixed point $\mathbf{p} \in R^m$ s.t. $\mathbf{f}(\mathbf{p}) = \mathbf{p}$. If the Jacobian matrix of \mathbf{f} at \mathbf{p} is $D\mathbf{f}(\mathbf{p})$, and Λ are eigenvalue set of matrix $D\mathbf{f}(\mathbf{p})$

[i] $\forall \lambda_i \in \Lambda | \lambda_i | < 1$, then the \mathbf{p} is a sink point.

[ii] $\forall \lambda_i \in \Lambda | \lambda_i | > 1$, then the \mathbf{p} is a source point.

[iii] $\{ \lambda_i \in \Lambda | |\lambda_i| < 1 \} \neq \emptyset \wedge \{ \lambda_i \in \Lambda | |\lambda_i| > 1 \} \neq \emptyset$, that means, if at least one eigenvalue are absolute smaller than one and at least one is upper than one, then the \mathbf{p} is a saddle point.

Finally, we can analysis the property of fixed point in e.g. 2.1.

SOLUTION 2.2 We can consider the Henon map directly

$$f(x, y) = (a - x^2 + by, x) \Rightarrow Df(x, y) = \begin{bmatrix} -2x & b \\ 1 & 0 \end{bmatrix}$$

Let λ are eigenvalue, then

$$|\lambda I - Df(x, y)| = 0 \Rightarrow \begin{vmatrix} -2x - \lambda & b \\ 1 & -\lambda \end{vmatrix} = 0 \Rightarrow \lambda^2 + 2x\lambda - b = 0 \Rightarrow \lambda_{12} = -x \pm \sqrt{x^2 + b}$$

When $(a, b) = (0, 0.4)$

$$\text{If } (x, y) = (0, 0), \text{ then } |\lambda_{12}| = |-x \pm \sqrt{x^2 + b}| = |\sqrt{0.4}| < 1$$

$$\text{If } (x, y) = (0.6, 0.6), \text{ then } |\lambda_{12}| = |-x \pm \sqrt{x^2 + b}| = |-0.6 \pm \sqrt{0.76}| \Rightarrow |\lambda_1| = 1.472 > 1, |\lambda_2| = 0.272 < 1$$

Finally, we proved that $(0, 0)$ is sink and $(-0.6, -0.6)$ is saddle just as what we found on simulation. ■

2.2 Stability and matrix periodic

We found this conclusion based on the discussion above.

CONCLUSION 2.1 The value of Jacobian matrix of a Henon map is just relevant to variable x and parameter b . That means, if we reduce the dimension of parameter and fixed b as b_0 , then the property of fixed point will be determined only with variable x .

As $y_{n+1} = x_n$, so we can just analysis the bifurcation of $a - x_\infty$ with random initial point.

If we consider the fixed point of system with arbitrary parameter group (a, b) , we found that the fixed point will satisfied

$$x^2 + (1 - b)x - a = 0 \Rightarrow x = \frac{1}{2}(b - 1) \pm \sqrt{(b - 1)^2 + 4a} \quad (1)$$

and the fixed point is $(x, y) = (\frac{1}{2}(b - 1) \pm \sqrt{(b - 1)^2 + 4a}, \frac{1}{2}(b - 1) \pm \sqrt{(b - 1)^2 + 4a})$, so we have the Jacobian matrix at this fixed point as

$$Df(x, y) = \begin{bmatrix} (b - 1) \pm \sqrt{(b - 1)^2 + 4a} & b \\ 1 & 0 \end{bmatrix}, \text{ and the eigenvalue } \lambda_i \text{ satisfied}$$

$$\lambda^2 - [(b - 1) \pm \sqrt{(b - 1)^2 + 4a}] \lambda - b = 0 \quad (2)$$

Then we can found the property of sink and source in every fixed point easily.

Now we focus on periodic-k orbit. Firstly, we still plot the bifurcation diagram of Henon map.

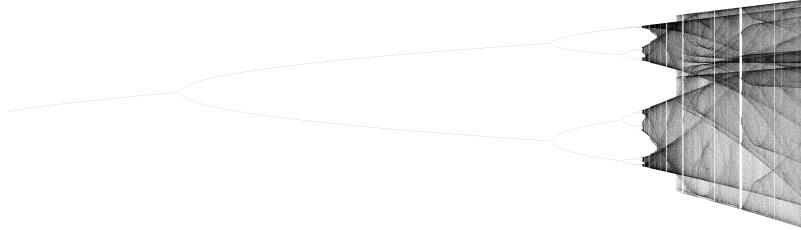


Figure 16: Bifurcation diagram for Hénon map ($b = 0.4$)

That is simple to analysis the influence of parameter. In following plots, $b \equiv 0.4$ and $a = 0.9, 0.988, 1.0, 1.0293, 1.045, 1.2$. We found $a = 0.9$ is a periodic-4 sink, $a = 0.988$ is a periodic-16 sink, $a = 1.0$ is a four-piece attractor, $a = 1.0293$ is a periodic-10 sink, $a = 1.045$ is two-piece attractor and the points of an orbit alternate between the pieces. Finally $a = 1.2$ two pieces have merged to form one-piece attractor.

Definition 2.5 Attractor An attractor is a set of numerical values toward which a system tends to evolve, for a wide variety of starting conditions of the system.

Futuermore, in discrete time, we called the orbit of a system as periodic-k orbit. However in chaotic orbit, the solution set is a continuous (or uncountable) set. And we called this orbit as attractor.

We will discuss the relationship between matrix and periodic-k orbit. But before that, it is necessary to introduce some new definition.

Definition 2.6 A map \mathbf{f} on R^m is **one-to-one** if and only if $\mathbf{f}(\mathbf{v}_1)\mathbf{f}(\mathbf{v}_2) \Leftrightarrow \mathbf{v}_1 = \mathbf{v}_2$

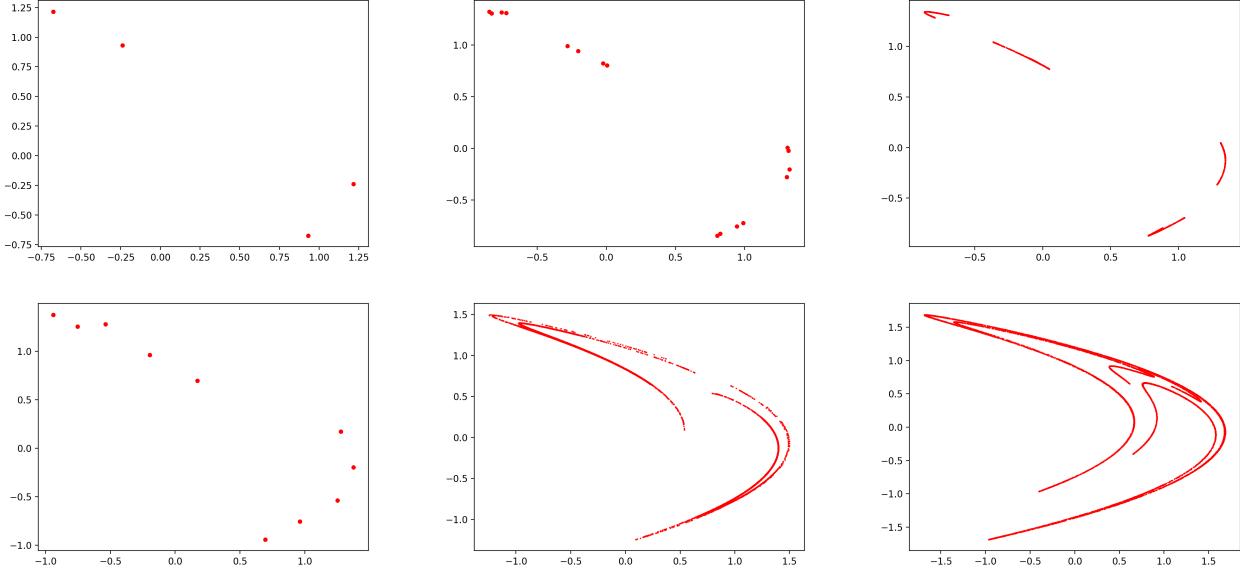


Figure 17: Attractor of Henon map in different parameter

Definition 2.7 *Inverse map*

Consider a one-to-one map \mathbf{f} on R^m . The inverse map \mathbf{f}^{-1} is automatically exists and satisfied $\forall \mathbf{v} \in D \subset R^m, \mathbf{f}(\mathbf{f}^{-1})(\mathbf{v}) = \mathbf{f}^{-1}(\mathbf{f})(\mathbf{v}) = \mathbf{v}$, where D is domain of map.

For instance, a one-to-one map $f(x) = 2x$ have an inverse map $f^{-1} = x/2$. Obviously, for every linear map $\mathbf{f}(\mathbf{x}) = A\mathbf{x}, \exists f^{-1}(\mathbf{x}) = A^{-1}\mathbf{x}$.

Theorem 2.5 For every R^m linear map $\mathbf{f}(\mathbf{x}) = A\mathbf{x}$ and A s.t. $\text{rank}(A) = m$, the inverse map f^{-1} always be existed.

PROOF 2.2 [i] If A have m different eigenvalue, then $A = V\Lambda V$ where $\Lambda = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_m)$, $V = (\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_m)$ where λ_i is eigenvalue and \mathbf{v}_1 is eigenvector. Then

$$A^{-1} = (V^{-1}\Lambda V)^{-1} = V\Lambda^{-1}V^{-1} = V\text{diag}\left(\frac{1}{\lambda_1}, \frac{1}{\lambda_2}, \dots, \frac{1}{\lambda_m}\right)V^{-1}$$

[ii] If A have $p < m$ different eigenvalue, based on the Jordan normal form, we still have J, V s.t. $A = V^{-1}JV$ and $J = \text{diag}(J_1, J_2, \dots, J_k)$ where J_i is Jordan block based on the eigenvalue λ_i . And now the problem is prove that for evert Jordan block, the inverse block always be existed.

Obviously, $J_i = \lambda_i I + N$ where

$$N = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 1 \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}$$

And it is simple to found that $N^m = \mathbf{0}_{m \times m}$. Based on the Taylor expansion, we have

$$J_i^{-1} = \lambda_i^{-1}(I + \lambda_i^{-1}N + \lambda_i^{-2}N^2 + \dots + (-\lambda_i)^{-n+1}N^{n-1})$$

Although the inverse of Jordan block is not a Jordan block of $1/\lambda_i$, it is still exists and we proved the theorem. ■

3 Chaos

We discussed the Henon map in last section. However, different from the section 1, Logistic map has been wildly used in application problems, we talked less about why we are interested in this model. So, in this section, we will mainly introduce the motivation.

3.1 Lorenz system, Henon map and Poincare section

D I S C U S S I O N 3.1 *Why are we interested in Henon map?*

First of all, it is necessary to introduce a continuous model. The Lorenz system is a system of ordinary differential equations which notable for having chaotic solutions for certain parameter values and initial conditions. In particular, the Lorenz attractor is a set of chaotic solutions of the Lorenz system.

Problem 3.1 *Lorenz model*

Lorenz model is a system of three ordinary differential equations now known as the Lorenz equations:

$$\begin{aligned}\frac{dx}{dt} &= \sigma(y - x) \\ \frac{dy}{dt} &= x(\rho - z) - y \\ \frac{dz}{dt} &= xy - \beta z\end{aligned}$$

where σ, ρ, β are parameters.

It is continuous problem, however, based on the knowledge in numerical analysis, we can discrete the continuous to discrete problem in several ways.¹

We can reconstruct the Lorenz equation, or a normal continuous dynamical system as

$$\frac{dX_i}{dt} = F_i(X_1, X_2, \dots, X_m), i = 1, 2, \dots, m$$

which is a m -dim dynamical system and t is single independence variable. To simplify this problem, we choose a initial time t_0 and time increment Δt , then let

$$X_{i,n} = X_i(t_0 + n\Delta t)$$

we have several ways to approximate the equations.

SOLUTION 3.1 [i] *Auxiliary approximations* $X_{i,n+1} = X_{i,n} + F_i(P_n)\Delta t$

[ii] *Centered difference procedure* $X_{i,n+1} = X_{i,n-1} + 2F_i(P_n)\Delta t$

[iii] *Double-approximation procedure* $X_{i,n+1} = X_{i,n} + \frac{1}{2}(F_i(P_n) + F_i(P_{n+1}))\Delta t$

¹EDWARD N LORENZ'S 1963 PAPER, "DETERMINISTIC NONPERIODIC FLOW", IN JOURNAL OF THE ATMOSPHERIC SCIENCES, VOL 20, PAGES 130–141

Even solve this group of function directly is difficult, it is not difficult to find the numerical solution.

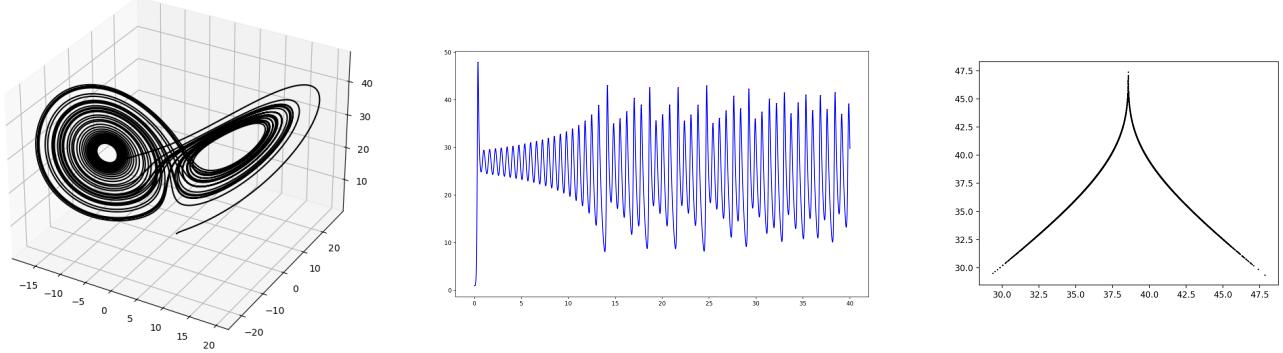


Figure 18: Lorenz system, $z - t$ map and Lorenz map

No we consider the problem in one dimension. In the second part of Fig. 18, we plot the $z - t$ figure of Lorenz model.

Ok, we found that it is still difficult to describe the $z - t$ figure. However, after the discussion of the logistic map $g(x) = 4x(1 - x)$ as well as chaotic orbit, we know in most situation, we just care about the boundary of interval of a map. On the other hand, we found that the $z - t$ figure of Lorenz system is familiar with sine function, it is shaking during the time iteration. So if we just consider the maximum (or the minimum) of this $z - t$ map, we can analysis the problem easier.

Definition 3.1 **Lorenz map**

The function $z_{n+1} = f(z_n)$ satisfied the last of Fig. 18 is called the Lorenz map. The map can be described in following steps.

[i] Find the $z - t$ function in Lorenz model.

[ii] The map $\{z_n\}$ is a point set which is the maxima of $z - t$ function. $z_{n+1} = f(z_n)$ where z_n is a maxima point of $z - t$ function and z_{n+1} is next maxima point of the function with growing of t .

* The graph of Lorenz map is not actually a curve. It does have some thickness because it is not a well-defined function. However thickness is so small and there is so much to be gained by treating the graph as a curve, that we will simplt make this approximation keeping in mind that the sunsequence analysis is plausible.

As Lorenz map have no formula to describe, it is very difficult to research that. However, in Lorenz's paper, he gave a correspondence to analysis the map, called tent map, which we has been introduced in the section 1

$$x_{n+1} = \begin{cases} 2x_n & x_n < 1/2 \\ \text{Undefined} & x_n = 1/2 \\ 2 - 2x_n & x_n > 1/2 \end{cases}$$

At least this is a piecewise continuous funcion with one discontinuous point $x = 1/2$. So we found the property of this map is not good enough to analysis. We hope the function is continuous in all domain. And we found if we try to remove this discontinuous point, then the f' will satisfy $f'^+(1/2) = f'^-(1/2) = 1$. We found it is similar to the Logistic model and it seems we can discuss the property of Logistic map rather than Lorenz map. And we will explain why we can discuss the Logistic map instead of Lorenz map.

On the other hand, we found the Henon map also familiar with Logistic map in Fig. 17. The only different between Henon map and Logistic map is Henon map is fat and Logistic is thin, or a line. However if we change our parameter, like $b \rightarrow 0$, then we found

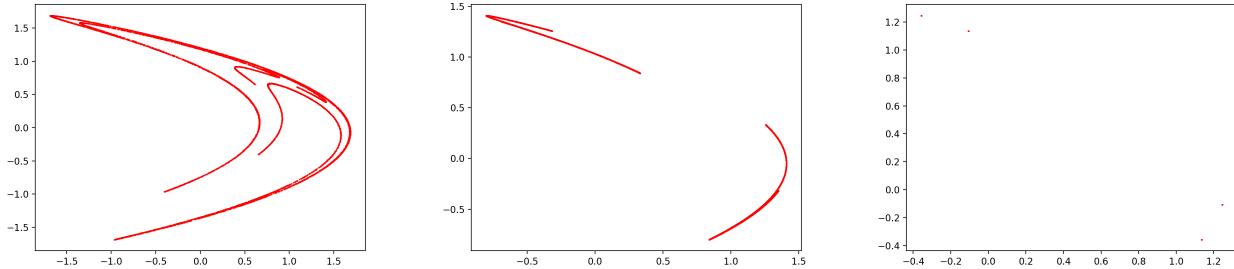


Figure 19: Attractor of Henon map in different $b(0.4, 0.2, 0.05)$

So it **seems** we can analysis the Henon map instead of Lorenz map. But we still need more proof and in this section, we will try to solve these problems.

3.2 Lyapunov exponents and Conjugacy

Definition 3.2 **Asymptotically periodic**

Consider map $f \in C^1(\mathbb{R}^1)$. An orbit $\{x_1, x_2, \dots, x_n, \dots\}$ is called asymptotically periodic if it convergence to a periodic orbit as $n \rightarrow \infty$, that means, $\exists \{y_1, y_2, \dots, y_k, y_1, y_2, \dots, y_k, \dots\}$ is a periodic orbit s.t.

$$\lim_{n \rightarrow \infty} |x_n - y_n| = 0$$

Also, we called these map as **eventually periodic** because their orbit is eventually lands on a periodic orbit.

For instance, the Lorenz map is a eventually periodic map. Because we found in the begining of the iteration, the map shaking in a wild interation (Just as 1-15 iterates in Fig. 18, second image) and after this period, the map become stable and it is convergent to the map in the 3rd image of Fig. 18, which we called that Lorenz map.

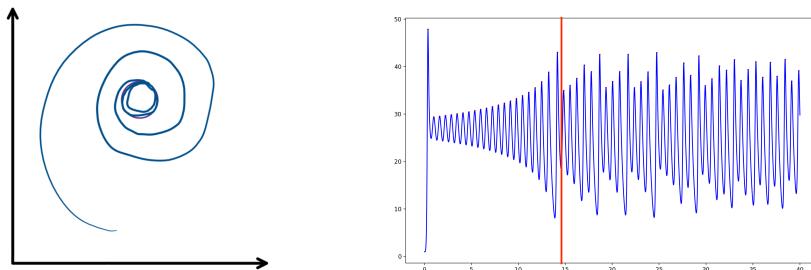


Figure 20: Asymptotically periodic, intro and example in Lorenz map

There are several other maps with this property, for example, in section 1, we introduced the Logistic map $G(x) = 4x(1 - x)$, with the initial condition $x_0 = 1/2$, we found after 2 iterates, is coincides with the fixed point $x = 0$.

Now we try to find a method to judge a map is asymptotically periodic to another periodic map. In the section 1, we introduced the stability test for periodic orbits (Theo. 1.3), we called the limitation of value in Theo. 1.2 as **Lyapunov number**.

Definition 3.3 *Lyapunov number and Lyapunov exponent*

Consider map $f \in C^1(R^1)$. Define **Lyapunov number** $L(x_1)$ as

$$L(x_1) = \lim_{n \rightarrow \infty} \left(\prod_{i=1}^n |f'(x_i)| \right)^{1/n}$$

and based on the logarithm function, we can define the Lyapunov exponent as

$$h_f(x_1) = h(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(f'(x_i)) \right]$$

Notice that h exists if and only if L exists and is nonzero, also $\ln L = h$.

D I S C U S S I O N 3.2 Why are we interested in Lyapunov exponent?

We know that chaos means if two initial values have small different, then after long time iteration, the system showed us very different property with these two initial values. (Just like Fig. 11, the error from computer results very different value, one is periodic and the other is chaos.)

Consider a self map f and a orbit $x_0, x_1, \dots, x_n, \dots$, where $x_{i+1} = f(x_i) = f^i(x_0) (\forall i \in \mathbb{N})$. Now we focus on the point $x_0 + \delta_0$ where δ_0 is small almost near the x_0 point. For other $\delta_i, i \in \mathbb{N}^+$, we define

$$\delta_i = f(x_{i-1} + \delta_{i-1}) - x_i = f^i(x_0 + \delta_0) - f^i(x_0)$$

which described the distant between different initial value in i -iterate.

Based on the definition of **exponentially stable**, we assume

$$|\delta_i| = \exp(\lambda i) |\delta_0|$$

then, for every $i \in \mathbb{N}$ which is positive, the monotony of $\exp(\lambda i) |\delta_0|$ is decided by λ . If $\lambda > 1$, the sequence $\{\delta_i\}$ is disconvergence and if $\lambda < \infty (0, 1)$ the sequence is convergence.

On the other hand, to find property of λ is difficult because we cannot describe the property of λ directly. However, during the iteration, we will find every $x_1, x_2, \dots, x_n, \dots$ as well as $\delta_1, \delta_2, \dots, \delta_n, \dots$, and we know that

$$\lambda = \frac{1}{n} \ln \left| \frac{\delta_n}{\delta_0} \right| = \frac{1}{n} \ln \left| \frac{f^n(x_0 + \delta_0) - f^n(x_0)}{\delta_0} \right|$$

Based on our thought, we need $\delta_0 \rightarrow 0$ and $n \rightarrow \infty$ so

$$\lambda = \lim_{n \rightarrow \infty} \frac{1}{n} \ln \left| \lim_{\delta_0 \rightarrow 0} \left(\frac{f^n(x_0 + \delta_0) - f^n(x_0)}{\delta_0} \right) \right| = \lim_{n \rightarrow \infty} \frac{1}{n} \ln |(f^n)'(x_0)| = \lim_{n \rightarrow \infty} \frac{1}{n} \ln \left| \prod_{i=0}^n f'(x_i) \right|$$

which is the definition of Lyapunov number.

Based on this Lyapunov exponent, we have this theorem.

Theorem 3.1 Consider map $f \in C^1(R^1)$. If orbits $\{x_1, x_2, \dots\}$ of f satisfies $f'(x_i) \neq 0 \forall i \in N$ and it is asymptotically periodic to the periodic orbit y_1, y_2, \dots , then two orbit have identical Lyapunov exponents, assuming both exist.

PROOF 3.1 [i] If we consider a sequence $\{s_i\}$ s.t. $\lim_{i \rightarrow \infty} s_i = s$, then

$$\forall \varepsilon > 0, \exists N_1 \in \mathcal{N} \text{ s.t. } \forall n > N_1, |s_n - s| < \varepsilon$$

Now we consider the average of $\{s_i\}$, we found for this ε ,

$$\begin{aligned} \lim_{N \rightarrow \infty} \frac{1}{N} \left| \sum_{i=1}^N s_i - s \right| &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N |s_i - s| = \lim_{N \rightarrow \infty} \frac{1}{N} \left[\sum_{i=1}^{N_1-1} |s_i - s| + \sum_{i=N_1}^N |s_i - s| \right] \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^{N_1-1} |s_i - s| + \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=N_1}^N |s_i - s| \leq 0 + \lim_{N \rightarrow \infty} \frac{1}{N - N_1} \sum_{i=N_1}^N |s_i - s| < \frac{N_0 N_1}{N - N_1} \varepsilon = \varepsilon \end{aligned}$$

So we have this conclusion

$$\forall \varepsilon > 0, \exists N_1 \in \mathcal{N}, \text{ s.t. } \forall n > N_1, \lim_{N \rightarrow \infty} \frac{1}{N} \left| \sum_{i=1}^N s_i - s \right| < \varepsilon \Rightarrow \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N s_i = s$$

[ii] Let y_1 is the fixed point (that means, x_i asymptotically periodic to a periodic-1 orbit), then $\lim_{n \rightarrow \infty} x_n = y_1$. As $f \in C^1(R^1)$, then f' is exists and f' Riemann integrable (and of course, Lebesgue integrable), so we can exchange the order of integral(or differential of f) and limitation, then we have

$$\lim_{n \rightarrow \infty} f'(x_n) = f'(\lim_{n \rightarrow \infty} x_n) = f'(y_1)$$

On the other hand, as $\ln|x|$ is a continuous, monotony function for $x \in R^+$, then

$$\lim_{n \rightarrow \infty} \ln |f'(x_n)| = \ln \left| \lim_{n \rightarrow \infty} f'(x_n) \right| = \ln |f'(y_1)| \Rightarrow h(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \ln |f'(x_i)| = \ln |f'(y_1)| = h(y_1)$$

[iii] Now we assume $k > 1, k \in \mathcal{N}$, obviously, y_1 is fixed point of f^k , and

$$h_{f^k}(x_1) = \ln |(f^k)'(y_1)| = h_{f^k}(y_1)$$

Now we will prove $h_{f^k}(x_1) = \frac{1}{k} h_f(x_1)$. Based on the definition, we know

$$h_{f^k}(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \ln |(f^k)'(x_i)| = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \ln \left| \frac{1}{k} \prod_{j=i}^{i+k-1} f'(x_j) \right| = \frac{1}{k} \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \sum_{j=i}^{i+k-1} \ln |f'(x_j)| = \frac{1}{k} h_f(x_1)$$

And we proved the theorem. ■

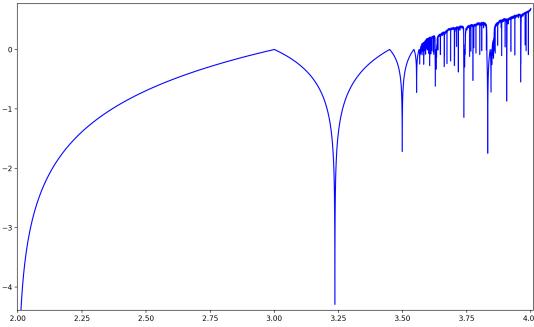


Figure 21: Lyapunov exponent of logistic model in different parameter

Obviously, the chaotic orbit satisfied Def. 1.9 will have no asymptotically periodic and we have this theorem.

Definition 3.4 Consider map $f \in C^1(R^1)$, the orbit is **chaotic** if it satisfied both

- [i] $\{x_1, x_2, \dots\}$ is no asymptotically periodic, and
- [ii] the Lyapunov exponent $h(x_1)$ is **greater** than zero.

Now we will discuss the mod map and the tent map.

The mod map has been introduced in section 1 (Fig. 12) and we will mainly discuss the $f(x) = 2x(\text{mod}1)$ in this discussion. A simple way to analysis the stability of map is itinerary.

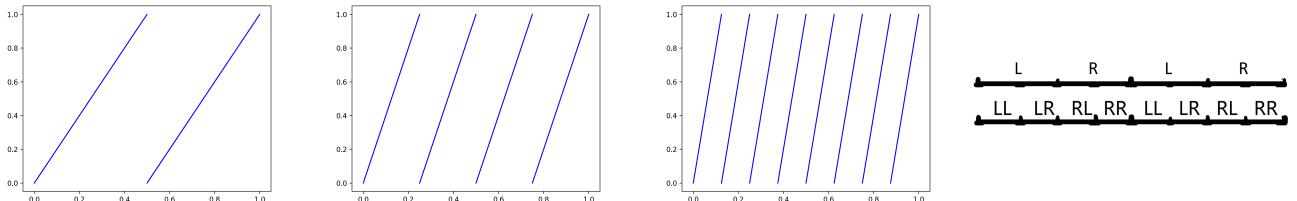


Figure 22: Iterates and itinerary of mod-2 map

[i] Binary and itinerary of mod map

We will focus on the initial value 0.2 of mod-2 map firstly. That is simple to find the itinerary with the code we used in section 1.

Table 6: Logistic4 itinerary with different initial value

Val	1 – 8	9 – 16	17 – 24	25 – 32	...
0.2	LLRRLLRR	LLRRLLRR	LLRRLLRR	LLRRLLRR	...

We found that this point is a periodic-4 point. And now, to analysis the problem simple, we will import a new method based on the binary number. In this problem, we have

$$\frac{1}{5} = 0.\overline{0011}, \quad f\left(\frac{1}{5}\right) = 0.011\overline{0011}, \quad f^2\left(\frac{1}{5}\right) = 0.11\overline{0011}, \quad f^3\left(\frac{1}{5}\right) = 0.1\overline{0011}, \quad f^4\left(\frac{1}{5}\right) = \overline{0011},$$

and obviously $1/5$ point is a periodic-4 orbit. So in summary, we can use binary value to find the period of every point in this map.

Now we consider the Lyapunov exponent of mod map. Obviously, the differential of map is equal to 2 except the discontinuous point $1/2$, so for ever initial value different from the $1/2$, we have

$$h_{mod-2}(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(f'(x_i)) \right] = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(2) \right] = \lim_{n \rightarrow \infty} \left(\frac{1}{n} n \ln(2) \right) = \ln(2) > 0$$

So the conclusion is the orbit of every initial value will result chaotic.

[ii] Mod-Sum model and asymptotically periodic

Now we change the mod model a little bit.

$$f(x) = (x + q)(mod1) \text{ where } q \text{ is a constant.}$$

We will mainly consider the $q \in [0, 1]$, if not, $\exists p \in [0, 1]$ and $p = q(mod1) \wedge \forall x \in [0, 1] f_q(x) = (x + q)(mod1) = f_p(x) = (x + p)(mod1)$.

That is simple to found the discontinuous point of $f_q(x)$ as $1 - q$, futhermore, the differential of model is equal to 1 except this discontinuous point. So we have the Lyapunov exponent as

$$h_{f_q}(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(f'(x_i)) \right] = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(1) \right] = 0$$

And

[iii] Tent map

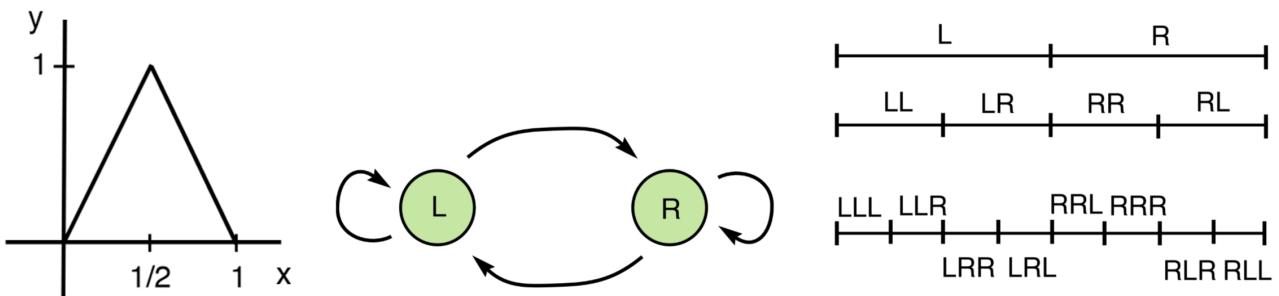


Figure 23: Tent map

We found that tent map have similar property of mod-2 map, that is because of the left side of the tent map is equal to the mod-2 map, and the right side of the tent map is symmetric of mod-2 map. So we can found that the size of interval in itinerary of both mod-2 map and tent map are 2^k and the only different between the mod-2 map and tent map is tent map will exchange the order of the **L** and **R** during iteration.

However, if we consider the topic of asymptotically periodic, we can found this conclusion.

Theorem 3.2 *The tent map T has infinitely many chaotic orbits.*

PROOF 3.2 [i] Consider the set of $[0, 1] \setminus Q$ which is combined with all irrational number in $[0, 1]$. If $x \in [0, 1] \setminus Q$, then

1. If $x < 1/2$, then $x_{new} = 2x \in [0, 1] \setminus Q$
2. If $x > 1/2$, then $x_{new} = 2 - 2x \in [0, 1] \setminus Q$

Now we consider a orbit with irrational begining, obviously, every value of this orbit is based on irrational value. And we know that there are infinity element in $[0, 1] \setminus Q$, so we have infinity irrational based orbits.

On the other hand, we know ever orbits avoid have

$$\forall x_1 \in [0, 1], x_1 \neq \frac{1}{2}, h_f(x_1) = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln |f'(x_i)| \right] = \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln(2) \right] = \ln(2) > 0$$

As $1/2$ is a rational value, so every orbit in [i] will avoid this point. So all of these orbits are chaotic. And in summary we found infinity many chaotic orbits in tent map T . ■

[iv] Conjugacy and Logistic map

First of all, we will list the main property in both logistic-4 map and tent map.

Table 7: Logistic-4 map VS tent map

Property	Logistic-4 map($G(x)$)	Tent map($T(x)$)
Critical point	$1/2 \rightarrow 1 \rightarrow 0$	
Fixed point	$0, 3/4$	$0, 2/3$
Period-2 orbit	$\{(5 - \sqrt{5})/8, (5 + \sqrt{5})/8\}$ (Single) Lies in the same relation, one in $[0, 1/2]$ and the other in $[1/2, 1]$ where $1/2$ is critical point	$\{0.4, 0.8\}$ (Single)

We will check the derivative value for periodic-k orbit in both map.

Periodic-1

[1] Tent map $T'(2/3) = -2$

[2] Logistic map $G'(3/4) = -2$

CONCLUSION: $T'(2/3) = G'(3/4)$

Periodic-2

[1] Tent map $T'(0.4)T'(0.8) = -4$

[2] Logistic map $T'((5 - \sqrt{5})/8)T'((5 + \sqrt{5})/8) = -4$

CONCLUSION: $T'(0.4)T'(0.8) = T'((5 - \sqrt{5})/8)T'((5 + \sqrt{5})/8) = -4 = -2^2$

...

We found some intersted result, but we cannot confirm how long these property still established. To solve, or to prove the similiarity of tent map and logistic map, we will import the definition of conjugate.

Definition 3.5 *The mape f and g are **conjugate** if they are related by a continuous one-to-one change of coordinates, that is, if $C \circ f = g \circ C$.*

Problem 3.2 *Proof:* Map T and G are conjugate, and the C is $C(x) = (1 - \cos(\pi x)) / 2$.

PROOF 3.3 [i] $x \in [0, 1/2]$ $G(C(x)) = 4(C(x))(1 - C(x)) = 1 - \cos^2(\pi x) = \sin^2(\pi x)$

$$C(T(x)) = 1 - \cos(2\pi x)/2 = \sin^2(\pi x) = G(C(x))$$

[ii] $x \in [1/2, 1]$ $G(C(x)) = 4(C(x))(1 - C(x)) = 1 - \cos^2(\pi x) = \sin^2(\pi x)$

$$C(T(x)) = 1 - \cos(\pi(2 - 2x))/2 = 1 - \cos(2\pi x)/2 = \sin^2(\pi x) = G(C(x))$$

In summary we proved the problem. ■

Familiar with matrix exponent, if we consider the G^n map, then

$$G^n = G \circ G \circ G \circ \dots \circ G = CTC^{-1}CTC^{-1}CTC^{-1}CTC^{-1} \dots CTC^{-1} = CT^nC^{-1} \Rightarrow G^nC = CT^n$$

Theorem 3.3 If x is periodic- k point of f , then $C(x)$ is a periodic- k point of g , where f, g are conjugate with C and $Cf = gC$.

PROOF 3.4 With the conclusion above, we have

$$f^k = C^{-1}g^kC, \text{ then } \forall x \text{ is a periodic-}k \text{ point, } f^k(x) = C^{-1}\{g^k[C(x)]\} = x \Rightarrow g^k[C(x)] = C(x) \blacksquare$$

Now we focus on the partial of map, because we want to know if the conclusion like $T'(0.4)T'(0.8) = T'((5 - \sqrt{5})/8)T'((5 + \sqrt{5})/8) = -4$ is established on high dimension or not.

Theorem 3.4 If f and g are conjugate with C and $Cf = gC$ and x is periodic- k point of f (that means $C(x)$ is a periodic- k point of g), then

$$(g^k)'[C(x)] = (f^k)'(x)$$

PROOF 3.5 [1] The chain rule says that

$$C[f(x)] = g[C(x)] \Rightarrow C'[f(x)]f'(x) = g'[C(x)]C'(x)$$

If x is periodic-1 (fixed) point, then $f(x) = x \wedge g(C(x)) = C(x)$, so we have

$$C'(x)f'(x) = g'[C(x)]C'(x) \Rightarrow f'(x) = g'[C(x)]$$

[2] Now if x is periodic-2 point, then $f^2(x) = x, g^2[C(x)] = C(x) \wedge C[f^2(x)] = g^2[C(x)]$ and

$$\frac{dC[f^2(x)]}{dx} = C'[f^2(x)]\frac{df[f(x)]}{dx} = C'[x]\frac{df[f(x)]}{dx} = \frac{dg\{g[C(x)]\}}{dx} = [(g^2)'(C(x))]C'(x)$$

So In summary we have

$$(f^2)'(x) = (g^2)'(C(x))$$

[k] Now we consider arbitrary $k \in \mathcal{N}$, familiar periodic-2, for a periodic- k point x , we have $f^k(x) = x, g^k[C(x)] = C(x) \wedge C[f^k(x)] = g^k[C(x)]$ and

$$\frac{d\{C[f^k(x)]\}}{dx} = C'[f^k(x)](f^k)'(x) = C'(x)(f^k)'(x) = \frac{d\{(g^k)[C(x)]\}}{dx} = (g^k)'[C(x)]C'(x)$$

In summary we proved the conclusion that $\forall k \in \mathcal{N}, (f^k)'(x) = (g^k)'(C(x)) \blacksquare$

Now we can simply found this conclusion:

CONCLUSION 3.1 *If f and g are conjugate with C and $Cf = gC$ and $\{x_1, x_2, \dots, x_k\}$ is periodic- k orbit of f (that means $\{C(x_1), C(x_2), \dots, C(x_k)\}$ is a periodic- k orbit of g), then*

$$\prod_{i=1}^k f'(x_i) = \prod_{i=1}^k g'(C(x_i))$$

PROOF 3.6 *Based on the chain rule, we still have*

$$(f^k)'(x_1) = [f^{k-1}(f)]'(x_1) = (f^{k-1})'(f(x_1))f'(x_1) = (f^{k-1})'(x_2)f'(x_1) = \dots = \prod_{i=1}^k f'(x_i)$$

also this conclusion is established in $(g^k)'(C(x))$ ■

Based on the conjugacy, we can prove these series of conclusions

CONCLUSION 3.2 *All periodic points of logistic map G are source.*

PROOF 3.7 *Firstly, we consider the tent map T , and obviously the point $0, 1/2$ and 1 will now be the periodic points because they result asymptotically periodic. And for ever other point of tent map, we know that $|T'(x)| \equiv 2$. On the other hand, we know that exists C s.t. $GC(x) = CT(x)$, so*

$$\prod_{i=1}^k |G'(x_i)| = \prod_{i=1}^k |T'(C(x_i))| = 2^k > 1$$

(Also, this conclusion told us that $\prod_{i=1}^k |G'(x_i)| = 2^k$ will always be established, which we has beed found in periodic-1 and periodic-2 discussion.)

CONCLUSION 3.3 *Consider a itinerary figure of logistic map G , the length of every k -iterates subinterval is lower than $\frac{\pi}{2^{k+1}}$.*

PROOF 3.8 *Consider a subinterval of itinerary after k -iterates $[x_p, x_q]$ where $\forall x \in [x_p, x_q], T^k(x)$ have symbol $\mathbf{L} \vee T^k(x) \equiv \mathbf{R}$ and $\forall \varepsilon > 0 \forall x \in (N_\varepsilon(x_p) \cup N_\varepsilon(x_q)) \setminus [x_p, x_q], T^k(x)$ have different symbol of $x \in [x_p, x_q]$. Obviously, we know that $\mu([x_p, x_q]) = 2^{-k}$, where μ is lebesgue measure (or the length of the interval), then*

$$\mu_G([x_p, x_q]) = C(x_q) - C(x_p) = \int_{x_p}^{x_q} C'(x) dx = \int_{x_p}^{x_q} \frac{\pi}{2} \sin(\pi x) d\pi \leq \frac{\pi}{2} \int_{x_p}^{x_q} dx = \frac{\pi}{2} (x_q - x_p) = \frac{\pi}{2^{k+1}}$$

Finally, we will use the tools of Lyapunov exponent as well as conjugacy to proof the following theorem.

Theorem 3.5 *The logistic map G has chaotic orbit.*

Lemma 3.1 *If f and g are conjugate with C and $Cf = gC$ $\{x_1, x_2, \dots, x_k, \dots\}$ and $\{C(x_1), C(x_2), \dots, C(x_k), \dots\}$ are orbit of f and g , if C satisfied $\lim_{k \rightarrow \infty} \frac{1}{k} C'(x_k) = 0$ then we have*

$$h_f(x_1) = h_g(C(x_1))$$

PROOF 3.9 *Consider $C[f(x_i)] = g[C(x_i)]$, then the chain rule told us that*

$$\{C[f(x_i)]\}' = C'[f(x_i)]f'(x_i) = C'(x_{i+1})f'(x_i) = \{g[C(x_i)]\}' = g'[C(x_i)]C'(x_i)$$

$$\Rightarrow f'(x_i) = g'[C(x_i)] \frac{C'(x_i)}{C'(x_{i+1})} \Rightarrow \prod_{i=1}^k f'(x_i) = \prod_{i=1}^k g'[C(x_i)] \left(\frac{C'x_1}{C'(x_{k+1})} \right)$$

(This formula obey the conclusion above, if we pay attention to the condition, we know that once x_1 is a periodic- k point, then $x_{k+1} = x_1$ and we have $\prod_{i=1}^k f'(x_i) = \prod_{i=1}^k g'[C(x_i)]$)
Moreover, based on the definition of Lyapunov exponent, there is

$$\ln \left| \prod_{i=1}^k f'(x_i) \right| = \sum_{i=1}^k \ln |f'(x_i)| = \ln \left| \prod_{i=1}^k g'[C(x_i)] \right| + \ln |C'(x_1)| - \ln |C'(x_{k+1})|$$

Note that $C'(x_1)$ is constant so $\lim_{k \rightarrow \infty} \frac{1}{k} (\ln |C'(x_1)|) = 0$. And based on the condition of theorem, we have $\lim_{k \rightarrow \infty} \frac{1}{k} \ln |C'(x_{k+1})| = 0$

So finally

$$\begin{aligned} h_f(x_1) &= \lim_{k \rightarrow \infty} \frac{1}{k} \sum_{i=1}^k \ln |f'(x_i)| \\ &= \lim_{k \rightarrow \infty} \frac{1}{k} \ln \left| \prod_{i=1}^k g'[C(x_i)] \right| + \lim_{k \rightarrow \infty} \frac{1}{k} (\ln |C'(x_1)| - \ln |C'(x_{k+1})|) \\ &= \lim_{k \rightarrow \infty} \frac{1}{k} \ln \left| \prod_{i=1}^k g'[C(x_i)] \right| = h_g(C(x_1)) \end{aligned}$$

In summary the theorem is established. ■

Lemma 3.2 *The periodic point of T map is countable, that is, if P_T is the periodic point of T then $P_T \sim \mathcal{N}$, or exists an one-to-one map R , $\forall x \in P_T, \exists$ only one $y \in \mathcal{N}$ s.t. $R(x) = y$ vice versa.*

PROOF 3.10 *We can write a binary tree to analysis the periodic-k point of tent map.*

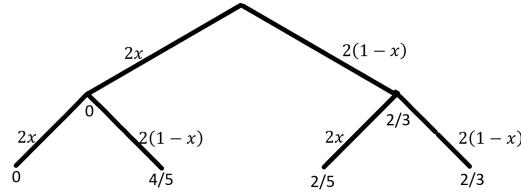


Figure 24: Binary tree of periodic-k point in tent map

We found that in every layer- k , the total of solution is less than 2^k and it is obviously that if we have infinity countable set in total and every set is infinity countable set, then the union of these sets is still countable (which has been introduced in Hilbert's paradox of the Grand Hotel).

On the other hand, in this problem, we have another simple way to build an one-to-one from periodic points P_T to \mathcal{N} . In the solusion binary tree above, we can code the solution from line to line. That means, in the first line, we code 0 to 1 and $2/3$ to 2. Then, in the next line, if we coded the solution, we jump over that node. After this iteration, we will build a one-to-one.

Moreover, actually we can proof that $P_T \subset [0, 1] \cap Q$. It is simple to proof that the solution set $P_T^{(k)}$ of $T^k(x) = x (\forall k \in \mathcal{N})$ is the subset of $P^{(k)}$ and $x \in P^{(k)}$ satisfied $p + q \cdot 2^k x = x$, where $p \in \mathbb{Z}$ and $q = \pm 1$, so $x = \frac{p}{q \cdot 2^k - 1} \in Q \cap [0, 1]$ and we have

$$P_T^{(k)} \subset P^{(k)} \subset Q \cap [0, 1]$$

So we have

$$P_T = \bigcup_{k=1}^{\infty} P_T^{(k)} \subseteq \bigcup_{k=1}^{\infty} P^{(k)} \subseteq Q \cap [0, 1] \subset Q$$

As Q is countable set, then every subset of Q is countable, so P_T is countable. ■

PROOF 3.11 Now we try to proof that G has chaotic orbit. As T and G are conjugacy, so based on one-to-one C , we know that P_G is countable. On the other hand, we proved that every periodic points of G are source, annd therefore no orbits besides periodic orbits - and eventually periodic orbits, another countable set - can be asymptotically periodic. Then any orbits whose responding symbol sequence is not eventually periodic, and which never contains the sequence **LL**, has Lyapunov exponent $\ln 2$ and is chaotic. ■

In the last of this subsection, we will introduce some other definition.

Definition 3.6 If $A \subset B$ called A is **dense** in B if

$$\forall x \in B, \forall \varepsilon > 0, N_{\varepsilon}(x) \cap A \neq \emptyset$$

Also, imitate the linear space, topological space, we can define the **symbol space** to discribe the itinerary of a map.

Definition 3.7 *Symbol space*

The set S of all infinity itineraries of a map is called the **symbol space** for the map. The **shift map** s is defined on the symbol space S as follows

$$s(S_0S_1S_2\dots) = S_1S_2S_3\dots$$

This shift map chops the leftmost symbol, which is the analogue on the itineraries of iterating the map on the point.

3.3 Fixed point theorem

Theorem 3.6 *Fixed point theorem*

Let $f \in C(R^n)$, $I = [a, b]$ s.t. $I \subset f(I)$, Then f has a fixed point in I

Moreover, if I_1, I_2, \dots, I_k are all closed intervals s.t. $\forall i = 1, 2, \dots, k-1, I_{i+1} \subset f(I_i) \wedge I_1 \subset f(I_n)$, then f^n has a fixed point in I_1 , or f has a periodic- k point in I_1 .

PROOF 3.12 Proof: Theo.3.6

$$I \subset f(I) \Rightarrow \forall x \in I, x \in f(I) \Rightarrow a, b \in f(I) \Rightarrow \exists x_1, x_2 \in [a, b] \text{ s.t. } f(x_1) = a, f(x_2) = b$$

$$(0 = f(x_1) - a \leq f(x_1) - x_1) \wedge (0 = f(x_2) - b \geq f(x_2) - x_2)$$

So we found a point x_1 s.t. $f(x) - x \geq 0$ and a point x_2 s.t. $f(x) - x \leq 0$, as the function f is continuous, based on the Intermediate Value Theorem, $\exists x_3$ s.t. $f(x_3) - x_3 = 0$ ■

Definition 3.8 *Partition*

The collection of subintervals that are pairwise disjoint except at the endpoints whose union is I is the **partition** of I .

CONCLUSION 3.4 *Covering rule for transition graphs*

- [i] An arrow is drawn from set A to set B in a transition graphs if and only if $B \subset f(A)$
- [ii] Moreover, assume that $\{S_1, S_2, \dots, S_n\}$ is a partition and the transition graph of f allows a sequence of symbols that returns to the same symbols s.t. $S_1S_2\dots S_kS_1$, then $S_1 \subset f^k(S_1)$
- [iii] Generally, if $S_1S_2\dots S_kS_1$ is a path in the transition graph of a map f , then the subinterval denoted by $S_1S_2\dots S_kS_1$ contains a fixed point of f^k .

3.4 Basins of attraction

Definition 3.9 Basin of attraction

Let f be a map on R^n and p be an attracting fixed point or periodic point of f , then the **basin of attraction** of p , or just **basin** of p is the set of point s.t.

$$\lim_{k \rightarrow \infty} |f^k(x) - f^k(p)| = 0$$

Theorem 3.7 Let f is a continuous map on R^1 , then

- [i] if $f(b) = b \wedge (\forall x \in [a, b], x < f(x) < b)$, then $a \rightarrow b, f^k(a) \rightarrow b$
- [ii] if $f(b) = b \wedge (\forall x \in [b, c], b < f(x) < x)$, then $c \rightarrow b, f^k(c) \rightarrow b$

PROOF 3.13 We just need to proof [i] because it is simple to proof [ii] in the same method. Let $x_0 = a, x_{i+1} = f(x_i) \forall i \in \mathbb{N}^*$, obviously, $a \leq x < f(x) < b$, thus all $x_i \in [a, b] \wedge a = x_0 < x_1 < x_2 < \dots < x_\infty < b$ which is strictly increasing and bounded above by b . Since increasing bounded sequence must convergence, $\exists x_*$ s.t. $x_i \rightarrow x_*$ and

$$x_* = \lim_{i \rightarrow \infty} x_{i+1} = \lim_{i \rightarrow \infty} f(x_i) = f(x_*)$$

and x_* is a fixed point ■

Definition 3.10 Schwarzian derivative, negative Schwarzian

Let $f \in C^\infty(R^1)$, then the **Schwarzian derivative** of f is

$$S(f)(x) = \frac{f'''(x)}{f'(x)} - \frac{3}{2} \left(\frac{f''(x)}{f'(x)} \right)^2$$

If $\forall x$ s.t. $f'(x) \neq 0, S(f)(x) < 0$, then called the map has negative Schwarzian.

Theorem 3.8 If f, g are negative Schwarzian, then fg has negative Schwarzian. Moreover, if f has negative Schwarzian, then f^k has negative Schwarzian.

Theorem 3.9 If map f on R^1 has negative Schwarzian, and p is a fixed point or periodic point of f , then either

- [i] p has an infinity basin; or
- [ii] there is a critical point of f in the basin of p ; or
- [iii] p is a source.

PROOF 3.14 Proof: Theo. 3.8

If f, g are negative Schwarzian, then

$$\forall x \in D \cap \{x | f'(x) \neq 0\} \cup \{x | g'(x) \neq 0\} \subset R^1, (S(f)(x) < 0) \wedge (S(g)(x) < 0)$$

On the other hand, we have

$$S(f \circ g)(x) = \frac{(f \circ g)'''}{(f \circ g)'} - \frac{3}{2} \left(\frac{(f \circ g)''}{(f \circ g)'} \right)^2$$

and

$$(f \circ g)' = g' \cdot f'(g) \quad (f \circ g)'' = g'' \cdot f'(g) + (g')^2 \cdot f''(g)$$

$$(f \circ g)''' = g''' \cdot f'(g) + g'g'' \cdot f'(g) + 2g'g''f'' \cdot (g) + (g')^3 f''' \cdot (g)$$

so we have

$$\frac{(f \circ g)'''}{(f \circ g)'} = \frac{g''' \cdot f'(g) + g'g'' \cdot f'(g) + 2g'g''f'' \cdot (g) + (g')^3 f''' \cdot (g)}{g' \cdot f'(g)} = \frac{g'''}{g'} + \frac{g''}{g'} + 2 \frac{g'' \cdot f''(g)}{f'(g)} + \frac{(g')^2 \cdot f'''(g)}{f'(g)}$$

$$\left(\frac{(f \circ g)''}{(f \circ g)'} \right)^2 = \left(\frac{g'' \cdot f'(g) + (g')^2 \cdot f''(g)}{g' \cdot f'(g)} \right)^2 = \left(\frac{g''}{g'} + \frac{g' \cdot f''(g)}{f'} \right)^2 = \left(\frac{g''}{g'} \right)^2 + 2 \frac{g'' \cdot f''(g)}{f'(g)} + \left(\frac{g' \cdot f''(g)}{f'(g)} \right)^2$$

and finally

$$S(f \circ g)(x) = \frac{g'''}{g'} + \frac{g''}{g'} + 2 \frac{g'' \cdot f''(g)}{f'(g)} + \frac{(g')^2 \cdot f'''(g)}{f'(g)} - \frac{3}{2} \left(\frac{g''}{g'} \right)^2 - 3 \frac{g'' \cdot f''}{f'(g)} - \frac{3}{2} \left(\frac{g' \cdot f''}{f'} \right)^2$$

$$= S(g)(x) + (g')^2 S(f)(x) + g'' \left(\frac{1}{g'} - \frac{f''(g)}{f'(g)} \right) = (Sf)(g(x)) \cdot (g'(x))^2 < 0 \quad \blacksquare$$

Example 3.1 [1] $f(x) = ax$ on R^1 and $|a| < 1$, zero is a fixed point sink whose basin is the entire real line.

[1.1] A linear map on R^n whose matrix representation has distinct eigenvalues that are less than one in magnitude, then the origin is a fixed sink whose basin is R^n .

[2] $f(x) = 4/\pi \arg \tan(x)$ on R^1 has 3 fixed points ± 1 and 0 where ± 1 are sink and 0 is source. The basin of 1 is positive and the basin of -1 is negative.

[3.1] $g(x) = ax(1-x)$, $a \in (0, 1)$, the fixed point is 0 all R^1 is basin of this point.

* We can prove that $((a-1)/a, 1]$ lies in the basin of $x = 0$ with Theo. 3.7. From graphical representation orbits, it is clear that in addition, the interval $[1, 1/a]$, $(-\infty, (a-1)/a)$ and $(1/a, \infty)$ are basin of 0.

[3.2] $g(x) = ax(1-x)$, $a \in (1, 2)$, the sink fixed point is $(a-1)/a$, the basin is $(0, 1)$.

[4] $f(r, \theta) = (r^2, \theta - \sin \theta)$, $r \in R^+$, $\theta \in [0, 2\pi]$ which used the polar coordinates. The fixed points are $(0, 0)$, $(1, 0)$, $(1, \pi)$, the attractors are $(0, 0)$ and (∞, ∞) . The basin of $(0, 0)$ is the points inside the unit circle and the points outside the unit circle are basin of (∞, ∞) .

[5] $g(x) = ax(1-x)$ has Schwarzian derivative formed

$$S(g)(x) = -\frac{3}{2} \left(\frac{-2a}{a-2ax} \right)^2$$

and therefore has negative Schwarzian.

CONCLUSION 3.5 The logistic map $g(x) = ax(1-x)$ ($a \in [1, 4]$) has at most one periodic sink.

PROOF 3.15 $g'(x) = a - 2ax$, $g''(x) = -2a$, $g'''(x) = 0$ and

$$S(g)(x) = -\frac{3}{2} \left(\frac{-2a}{1-2ax} \right)^2 < 0$$

[i] Consider a point $p \in [0, 1]$, as every point in $R \setminus [0, 1]$ will tend to $-\infty$ so no point in $[0, 1]$ have infinity basin.

[ii] Since the only critical point of g is $1/2$, there can be at most one attracting periodic orbit. ■

3.5 Density function and Ulam-von Neumann transformations

We found the relationship between the tent map, the logistic map(l-4), and the mod map. Now we try to explain the Henon map and the tent map.² ³

Consider a Henon map formed

$$H_{(a,b)}(x, y) = (1 - ax^2 + by, y)$$

when $a = 2$ and $b \rightarrow 0$, the map is

$$H_{(2,0)}(x, y) = (1 - 2x^2, y) \Rightarrow q(x) = 1 - 2x^2$$

which is a 1-dim nonlinear map. Obviously, there is exists a one-to-one map from tent map to the map follows

$$\tau(x) = \begin{cases} 2x + 1 & x \in [-1, 0] \\ -2x + 1 & x \in [0, 1] \end{cases} \Rightarrow \tau(x) = 1 - 2|x|, x \in [-1, 1]$$

So the problem is how to find a one-to-one between the $\tau(x)$ and $q(x)$. Even in the introduction of conjugacy in the last section, we just given the map between the tent map and logistic map and never discuss how to find these kind of map. Here, we will used the definition of probability density function (PDF, or invariable density in dynamic system) to analysis this problem.

Definition 3.11 *Density Function*

Consider a map $f \in C^1([0, 1])$ and a group of initial stats $x_1^{(0)}, x_2^{(0)}, \dots, x_N^{(0)}$, then define the $x_i^{(1)}, x_i^{(2)}, \dots, x_i^{(m)}$ sequence with

$$x_i^{(p)} = f(x_i^{(p-1)}) = f^p(x_i^{(0)}), i = 1, 2, \dots, N$$

And a **density function** of a $x_i^{(p)}$ sequence will satisfy, for every interval $\Delta_0 \subset [0, 1]$

$$\int_{\Delta_0} f_0(u) du \simeq \frac{1}{N} \sum_{k=1}^N 1_{\Delta_0}(x_k^{(0)})$$

where $1_{\Delta}(x)$ is **indicator function** s.t.

$$1_{\Delta}(x) = \begin{cases} 1 & x \in \Delta \\ 0 & x \notin \Delta \end{cases}$$

In most situation, we cannot find the density function directly with the formula of map. We can only statistic the value of map and hope we can find a distribution to evaluate it. However, in logistic-4 map $G(x)$, we have a certain distribution.

$$\rho_q = \frac{1}{\pi \sqrt{1 - x^2}}$$

On the other hand, based on the bifurcation diagram, we found that in ever parameter in $[1, 4]$, there are some continuous line in the image. We can guess that in a normal situation, the

²Reference: Jiang, Y., 1995. On Ulam von Neumann transformations.

³Reference: Lasota, A. and Mackey, M., n.d. Chaos, Fractals, and Noise.

density function is a mixture model based on the ρ_q just like Gaussian Mixture Model(GMM) in probability.

$$\rho_{(g_a)}(x) = \sum_{i=1}^K \frac{p_i}{\pi \sqrt{1 - (x - q_i)^2}}, \text{ where } \sum_{i=1}^K p_i = 1$$

Moreover, as we know the statistic data $x_i^{(p)}$ sequence, it is easy to get the numerical solution of parameter in the model above. For instance, with the machine learning method like Expectation–maximization(EM) algorithm we can find a mixture model.

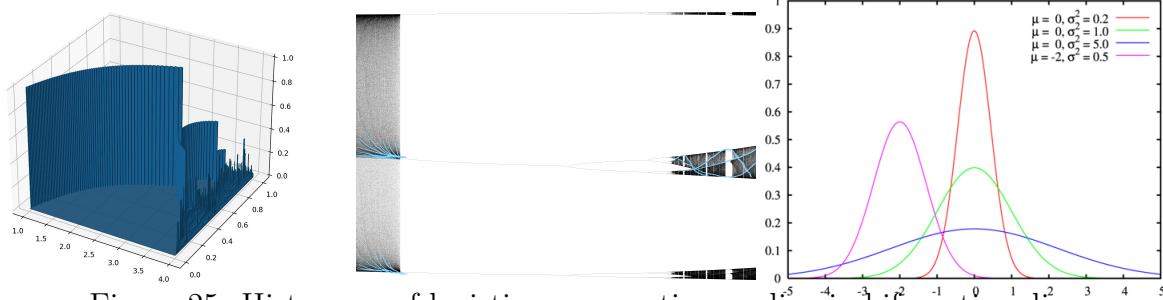


Figure 25: Histogram of logistic map, continuous line in bifurcation diagram

We found the density function of $q(x)$ is $\rho_q = \frac{1}{\pi \sqrt{1-x^2}}$, and the reflection between q and τ will satisfy

$$dy = \frac{2dx}{\pi \sqrt{1-x^2}} \Rightarrow y = h(x) = \frac{2}{\pi} \arg \sin(x) \text{ and } h^{-1}(x) = \sin\left(\frac{\pi x}{2}\right)$$

And we have

$$\begin{aligned} \bar{q}(x) &= h\{q[h^{-1}(x)]\} = h\left\{1 - 2 \sin^2\left(\frac{\pi x}{2}\right)\right\} = \frac{2}{\pi} \arg \sin\left[1 - 2 \sin^2\left(\frac{\pi x}{2}\right)\right] = \frac{2}{\pi} \arg \sin[\cos(\pi x)] \\ &\Rightarrow \sin\left(\frac{\pi \bar{q}}{2}\right) = \cos(\pi x) \Rightarrow \cos\left(\frac{\pi}{2} - \frac{\pi \bar{q}}{2}\right) = \cos(\pi x) \Rightarrow 1 - \bar{q} = 2|x| \Rightarrow \bar{q} = 1 - 2|x| = \tau(x) \blacksquare \end{aligned}$$

Based on this density function, we can find the one-to-one between most non-linear map with certain condition and τ map, or tent map. Obviously, both τ map and tent map have certain Lyapunov exponent, and this makes the analysis of chaotic in non-linear system become easier.

Definition 3.12 *Ulam-von Neumann transformation*

A map f is a Ulam-von Neumann transformation if it satisfied

- [i] f is a piecewise C^1 self mapping of $[-1, 1]$ with a unique power law singular point 0;
- [ii] $f|_{[-1,0]}$ is C^1 and increasing, and $f|_{[0,1]}$ is C^1 and decreasing;
- [iii] $f(0) = 1, f(-1) = f(1) = 1$
- [iv] $f|_{[-1,0]}$ and $f|_{[0,1]}$ are $C^{1+\alpha}$ for some $\alpha \in (0, 1]$ and the restrictions of $r_f(x) = f'(x)/|x|^{\gamma-1}$ to $[-1, 0)$ and to $(0, 1]$ are β -Bolder continuous for some $\beta \in (0, 1]$
- [v] the sequence $\{\eta_n\}_{n=0}^\infty$ of nested partitions by f decreases exponentially.

Theorem 3.10 Any two Ulam-von neumann transformations f and g are topologically conjugate.

Theorem 3.11 The Lorenz map is a Ulam-von Neumann transformation.

Typically, we can describe the Ulam-von Neumann transformations with properties follows: It is either linear or non-linear curve like a mountain from point $(-1, -1)$ increase to $(0, 1)$ and finally decrease to $(1, -1)$, the only singular point is 0 which may discontinuous. Also, there are some properties in differential of the function.

It is difficult to proof these theorem strickly because we need tools of manifold as well as real analysis. So here we just introduce these definition and conclusions.



Figure 26: CHAOS

4 Fractal

4.1 General tent map, Cantor set and self-similar attractor

In this section, we will mainly focus on the general tent map

$$T_a(x) = \begin{cases} ax & x \leq 1/2 \\ a(1-x) & x \geq 1/2 \end{cases}$$

There are several properties of this map

Property 4.1 General tent map - fixed point

$a \in (0, 1)$: single fixed point 0, all initial conditions are attracted to 0;

$a \in (1, \infty)$: both 0 and $\frac{1}{1+a}$ are fixed point.

In last section, we know that if $a = 2$, then $T_2(x)$ is mapped onto itself and we have

Property 4.2 Point leave the interval

$a \in (0, 2]$: points stay within I ;

$a \in (2, \infty)$: a.e. points eventually leave the interval and never return, where a.e. means almost everywhere, that means, without a measure zero subset, all set will satisfied this property.

We will try to proof the second property.

PROOF 4.1 [i] Obviously, based on the definition of tent map, if $x < 0$, then $f(x) < 0$, if we let $x_1 = f(x) < 0$, then $f(x_1) < 0$ etc. So we have this conclusion: if $f^p(x) < 0$, then $\forall q > p, f^q(x) < 0$ where $p, q \in \mathbb{N}$.

Moreover, if $x > 1$, then $f(x) < 0$ and $\forall n \in \mathbb{N}^+, f^n(x) < 0$.

Define the set L s.t.

$$L = \{x \in [0, 1] | f^n(x) < 0\}$$

where $n \in \mathbb{N}$ is a certain value.

[ii] If $a \in (0, 2)$, then $f([0, 1]) = [0, a/2] \subset [0, 1]$. On the other hand, as $\forall x \in [0, 1], f(x) \geq 0$, so $L = \emptyset$.

[iii] We will proof that if $a > 2$, then $\mu(L) = 1$ where μ is (lebesgue) measure. Firstly, we consider the interval $L_1 = (1/a, (a-1)/a)$ s.t. $\forall x \in L_1, f(x) > 0 \Rightarrow f^2(x) < 0$.

Now we consider the subset $L_0 = (0, 1/a)$, we found that $f((0, 1/a)) = (0, 1)$, so we can apart the interval $(0, 1/a)$ again, where

$$L_{00} = (0, 1/a^2), L_{01} = (1/a^2, (a-1)/a^2), L_{02} = ((a-1)/a^2, 1/a)$$

We found that $\forall x \in L_{01}, f^2(x) > 1 \Rightarrow f^3(x) < 0$

If we consider the subset $L_2 = ((a-1)/a^2, 1)$, we found that is symmetric of $(0, 1/a)$, that means we can also apart L_2 as L_{20}, L_{21}, L_{22} , where L_{21} have same property with L_{01} . We found the structure of this set is familiar with **Cantor set** especially when $a = 3$.

Definition 4.1 Cantor Set

Let set G s.t.

$$G = \bigcup_{n=0}^{\infty} \bigcup_{k=0}^{3^{n-1}} \left(\frac{3k+1}{3^{n+1}}, \frac{3k+2}{3^{n+1}} \right)$$

then called $C = [0, 1] \setminus G = [0, 1] \cap G^c$ as Cantor set.

Based on the knowledge in real analysis, we know that

Property 4.3 $\mu(C) = 0, \mu(G) = 1$ where μ is measure of set.

The proof of this property is simple because we know that for a certain interval (a, b) , the measure $\mu((a, b)) = b - a$ which also be called as **Borel measure**. And we can just calculate the measure of G with limitation.

Now we come back to the problem above

If $a = 3$, then $L = G$ and we proved the problem. If $a > 2, a \neq 3$, we can found a one-to-one map from $T_a(x)$ to $T_3(x)$ and the attractor will express same property as $a = 3$. So we finally proved that $\forall a > 2, x \in [0, 1]$ a.e. s.t. $\exists N, \forall n > N, f^n(x) < 0$ ■

Now we come back to the title of this section, so that means “fractal”? We know that for every subset of Cantor set, or attractor of $T_a(a > 2)$ map, these subset showed us same property of the original set and we called this **self-similar** set as **fractal**.

Here are some example of fractal set.

Definition 4.2 Iterated function system.

Consider a group of map on R^m s.t. $f = \{f_1, f_2, \dots, f_r\}$ and for every maps, exists a positive number p_1, p_2, \dots, p_r s.t. $\sum_{i=1}^r p_i = 1$ (probabilities). Then we called this group of f_i is iterated function system.

Example 4.1 (A simple iterated function system)

0 Roll a point x_0 randomly in $[0, 1]$

[i] flip a coin,

[i-1] if coin comes up heads, then move the point x_{i-1} to $x_i = \frac{1}{3}x_{i-1}$

[i-2] if coin comes up tails, then move the point x_{i-1} to $x_i = \frac{1}{3}(2 + x_{i-1})$

We can simulate this example with code, if we statistic the point, or find the density figure of map, we found that .

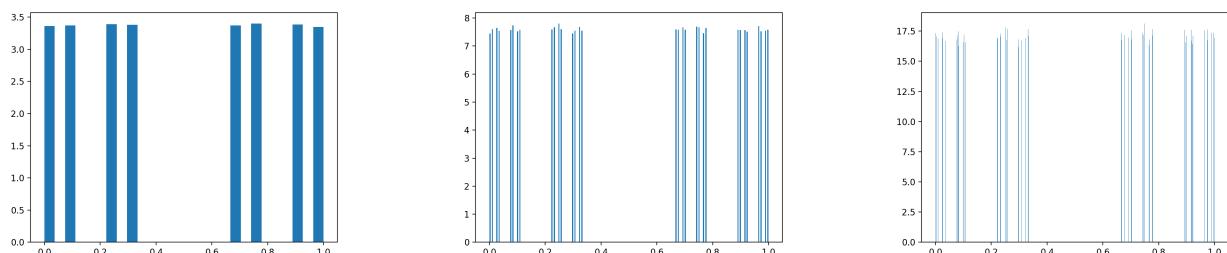


Figure 27: Simulation of Simple Iterated Function System

which showed us the property of Cantor set, and we can guess that the Cantor set is the attractor of the probabilistic constructions.

Here is another example of self-similar map.

E x a m p l e 4.2 *Sierpinski carpet* .

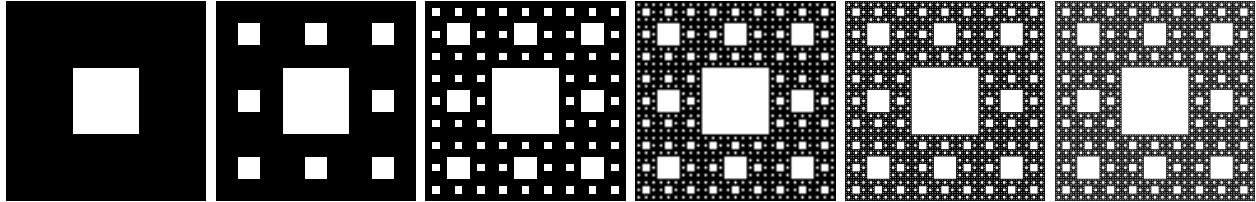


Figure 28: Sierpinski carpet

Of course, Henon's map also have this fractal property.

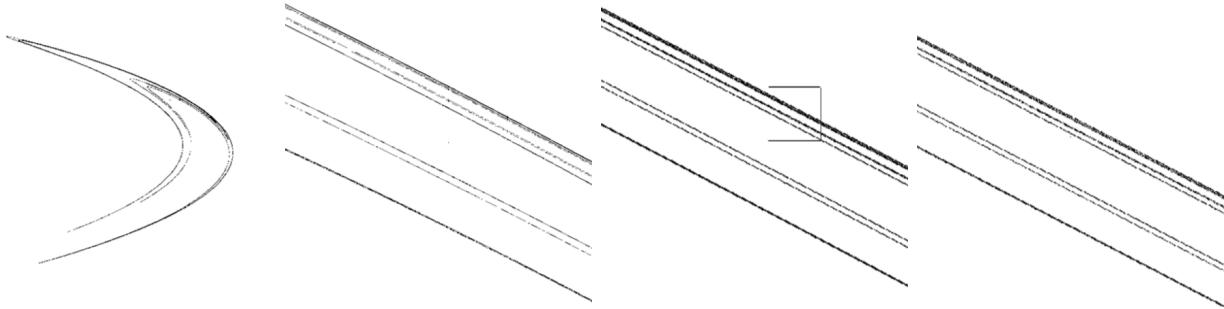


Figure 29: Fractal in Henon's map

Moreover, we can also discuss this fractal property in basin.

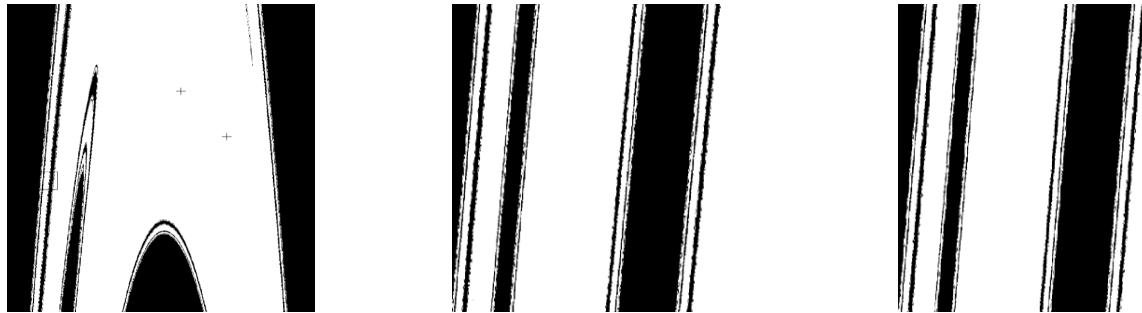


Figure 30: Fractal in basin of Henon's map

E x a m p l e 4.3 *Julia set, Mandelbrot set*

Now we consider a map in complex values

$$P_c(z) = z^2 + c$$

where z, c are complex number s.t. $\exists x, y, c_x, c_y \in \mathcal{R}, z = x + yi, c = c_x + c_yi$ and $i = \sqrt{-1}$. Based on the calculation rules of complex number, we know

$$P_c(z) = (x + yi)^2 + (c_x + c_yi) = x^2 + 2xyi - y^2 + c_x + c_yi = (x^2 - y^2 + c_x) + i(2xy + c_y)$$

so we have

$$f(x, y) = (Re[P_c(z)], Im[P_c(z)]) = (x^2 - y^2 + c_x) + i(2xy + c_y) \Rightarrow \begin{cases} x_{n+1} = x_n^2 - y_n^2 + c_x \\ y_{n+1} = 2x_n y_n + c_y \end{cases}$$

where $n \in \mathcal{N}$, $x_n, y_n, c_x, c_y \in \mathcal{R}$ are c_x, c_y is constant.

We know that if we consider a map formed $f(x, y) = x^2 + y^2$, then the unit circle is important, for ever point inside the unit circle, the are all sink to zero point and for every point outside the unit circle, they will go to infinity after enough iteration.

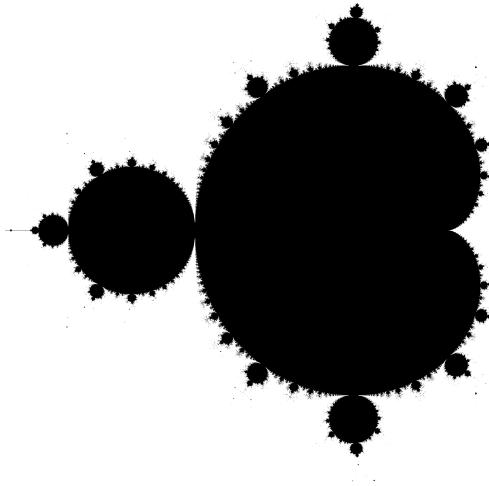


Figure 31: Mandelbrot set

We called the Black area in the image above as Mandelbrot set, more mathematically, the **Mandelbrot set** is

$$M = \{c : 0 \text{ is not in the basin of infinity for the map } P_c(z) = z^2 + c\}$$

We can analysis the convergence and disconvergence of this complex map too. For a certain c , now we consider the convergence and disconvergence for every point in the space. We called this set as Julia set.

Definition 4.3 Julia set

Consider a map $f : \mathcal{R}^n \rightarrow \mathcal{R}^n$

$$J(f) = \{x | x \in R^n, \forall \varepsilon > 0, \exists x_1, x_2 \in N(x, \varepsilon) \text{ s.t. } \left(\lim_{n \rightarrow \infty} f^n(x_1) < \infty \wedge \lim_{n \rightarrow \infty} f^n(x_2) = \infty \right)\}$$

which is the boundary points between convergence area and disconvergence area.

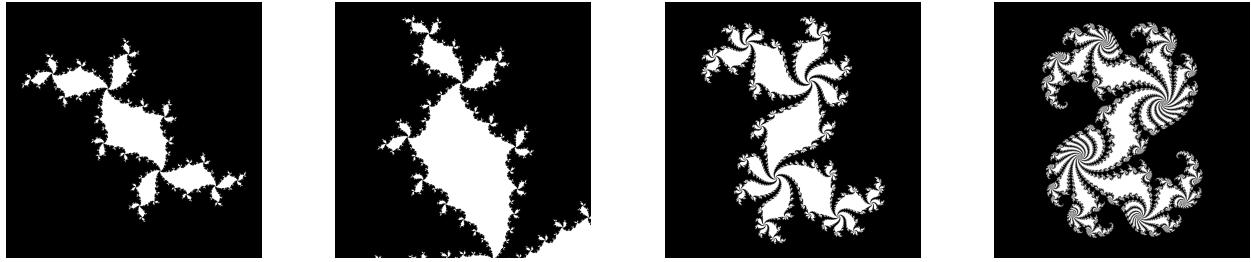


Figure 32: Julia set

(parameter $c_1 = c_2 = -0.17 + 0.78i, c_3 = 0.38 + 0.32i, c_4 = 0.32 + 0.043i$)

Table 8: Interval

img	x	y	img	x	y
1	[-1.5, 1.5]	[-1.5, 1.5]	2	[-0.19, 0.01]	[0.89, 1.09]
3	[-1.3, 1.3]	[-1.3, 1.3]	4	[-1.3, 1.3]	[-1.3, 1.3]

4.2 Fractal dimension

Finally, we try to analysis the calculation of these fractal. In analysis we know that **measure** is a describe of area, also we define the Lebesgue outer measure in follow

Definition 4.4 *Eculidean rectangle Neighbourhood*

1. Opened box $I = \{x = (x_1, x_2, \dots, x_n) | a_i < x_i < b_i, i \in N\}$, where a_i, b_i are constant;

2. Closed box $I = \{x = (x_1, x_2, \dots, x_n) | a_i \leq x_i \leq b_i, i \in N\}$, where a_i, b_i are constant;

Called the $b_i - a_i$ is side length of a box. If $|b_1 - a_1| = |b_2 - a_2| = \dots = |b_n - a_n|$, then called this box as cube.

Definition 4.5 *Lebesuge outer measure*

$$\mu^*E = \inf \left\{ \sum_{i=1}^{\infty} |I_i| : E \subset \bigcup_{i=1}^{\infty} I_i, I_i \text{ is an opened box} \right\}$$

Also, we can define the outer measure with ε (Familiar with Cauchy's limitation)

$$\forall \varepsilon > 0, \exists \{I_i\} \text{ open cover s.t. } E \subset \bigcup_{i=1}^{\infty} I_i \wedge \mu^*E \leq \sum_{i=1}^{\infty} |I_i| + \varepsilon$$

In this subsection, we mainly focus on the area based on the cube.

Definition 4.6 *C(1/ε) cube*

Now we consider a special type of cover.

[i] Firstly, for a interval $I_1 = [a_1, b_1]$, let the side length of boxes is ε , then we have $N = \text{int}(C/\varepsilon) + 1$ subintervals to cover the original interval. (e.g. $[a_1 + (p-1)C/\varepsilon, a_1 + pC/\varepsilon], p = 1, 2, \dots, N$)

[ii] Now we consider a surface in R^n space, let the projection on x_i axis is $I_i = [a_i, b_i]$, and $C = \max\{\mu(I_i)\}, i = 1, 2, \dots, n$, then we have a group of cube total $N(\varepsilon) = (C\varepsilon)^n$ and

$$d = \frac{\ln N(\varepsilon) - \ln C}{\ln(1/\varepsilon)}$$

Definition 4.7 *C($1/\varepsilon$) cube*

A bounded set $S \subset R^n$ has box-counting dimension

$$bd(S) = \lim_{\varepsilon \rightarrow 0} \frac{\ln(N(\varepsilon))}{\ln(1/\varepsilon)}$$

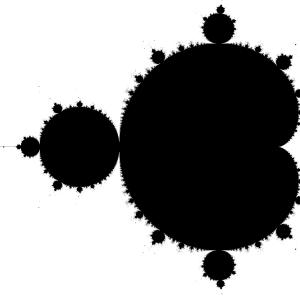
when the limit exists.

CONCLUSION 4.1 Based on the Bolzano–Weierstrass theorem, we know that if we have a sequence $\{b_n\}$ s.t. $\lim_{n \rightarrow \infty} b_n = 0$, if b_n is ε then $\lim_{n \rightarrow \infty} \frac{\ln b_{n+1}}{\ln b_n} = 1$

CONCLUSION 4.2 We still consider the sequence above, then

$$\frac{N(b_n)}{4} \leq N(b_n) \leq 4N(b_{n+1})$$

and the proof is simple with figure follows



Theorem 4.1 If $\{b_n\}$ is monotony, or assume $b_1 > b_2 > \dots > b_n > \dots > b_\infty = 0$ If

$$\lim_{n \rightarrow \infty} \left(\frac{\ln b_{n+1}}{\ln b_n} \right) = 1 \wedge \lim_{n \rightarrow \infty} \left(\frac{\ln N(b_n)}{\ln(1/b_n)} \right) = d =$$

then $\lim_{\varepsilon \rightarrow 0} \frac{\ln N(\varepsilon)}{\ln(1/\varepsilon)} = d$ and therefore the box-counting dimension is d .

Theorem 4.2 If $S \subset R^n$ is bounded and $bd(S) = d < n$, then $\mu(S) = 0$

Another way to calculate the measure of a area is based on the statistic,

Definition 4.8 *Correlation dimension* Let $S = \{v_0, v_1, \dots\}$ be an orbit of the map $f : \mathcal{R}^n \rightarrow \mathcal{R}^n$, then for ever $r > 0$, define $C(r)$ s.t.

$$C(r) = \lim_{N \rightarrow \infty} \frac{|\{(p, q) | p, q \in S, |p - q| < r\}|}{|\{(p, q) | p, q \in S\}|}$$

Moreover, if $C(r) \approx r^d$, then

$$d \approx cd(S) = \lim_{r \rightarrow 0} \frac{\ln C(r)}{\ln(r)}$$

And here we found another way to calculation the area of attractor.

5 Chaos in high dimension map

5.1 Lyapunov Spectrum

In the section 3, we mainly discussed the judgement of chaos in 1 dimension. Here we focus on the Lyapunov exponent in high dimension. Obviously, in high dimension, the δ_n function which we used in Discussion 3.2 will be a m dimension vector δ_n and we mainly focus on the length(or norm) of this vector.

$$||\delta_t|| = \exp(\lambda t) ||\delta_0||$$

$$t \rightarrow \infty, ||\delta_t|| = \exp(\lambda t) ||\delta_0|| \Rightarrow \lambda = \lim_{t \rightarrow \infty} \frac{1}{t} \ln \frac{||\delta_t||}{||\delta_0||} = \lim_{t \rightarrow \infty} \ln \left[\frac{||\delta_t||}{||\delta_0||} \right]^{\frac{1}{t}}$$

However, in high dimension problem, it is different from 1-dim because during the iteration, some direct of vector increase and the others decrease. Fig. 33 showed us an example of this evolution.

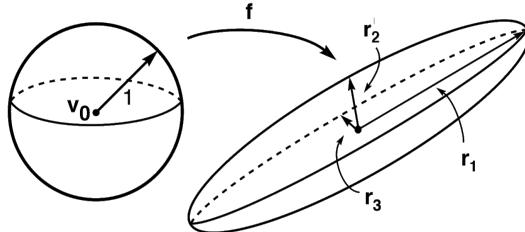


Figure 33: Evolution of unit vector in 3d

To solve this problem, we should consider the evolution of every direct in the space.

Let $\omega_0^{(1)}, \omega_0^{(2)}, \dots, \omega_0^{(m)}$ is a group of orthogonal basis in \mathcal{R}^m space which satisfied $\forall i, j = 1, 2, \dots, m, i \neq j$, the inner production $\langle \omega_0^{(i)}, \omega_0^{(j)} \rangle = 0$, then for every direction, we have a λ value based on the formula above, that means

$$\forall i = 1, 2, \dots, m, \lambda_i = \lim_{t \rightarrow \infty} \frac{1}{t} \ln \frac{||\omega_t^{(i)}||}{||\omega_0^{(i)}||}$$

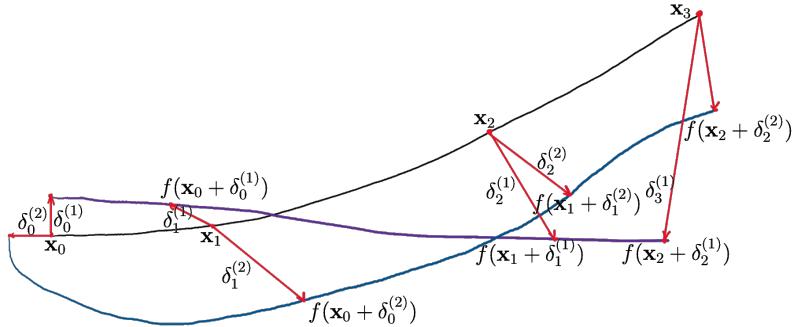


Figure 34: Analysis in two dimension problem

Basically, a simple basis in \mathcal{R}^m space is $\omega_0^{(1)} = (1, 0, \dots, 0)^T, \omega_0^{(2)} = (0, 1, \dots, 0)^T, \dots, \omega_0^{(m)} = (0, 0, \dots, 1)^T$ and

$$\Omega_0 = (\omega_0^{(1)}, \omega_0^{(2)}, \dots, \omega_0^{(m)}) = I$$

In this situation, $\|\omega_0^{(i)}\| = 1 (i = 1, 2, \dots, m)$, let

$$\Lambda = (\lambda_1, \lambda_2, \dots, \lambda_m) = \lim_{t \rightarrow \infty} \frac{1}{t} \left(\ln \|\omega_t^{(1)}\|, \ln \|\omega_t^{(2)}\|, \dots, \ln \|\omega_t^{(m)}\| \right)$$

Let p_1, p_2, \dots, p_m s.t. $\{p_1, p_2, \dots, p_m\} = \{1, 2, \dots, m\} \wedge \forall i, j = 1, 2, \dots, m, i \neq j, p_i \neq p_j$ and

$$\ln \|\omega_t^{(i_1)}\| \geq \ln \|\omega_t^{(i_2)}\| \geq \dots \geq \ln \|\omega_t^{(i_m)}\|$$

In the discrete time processing, we know that $t = 0, 1, 2, \dots$ so $r_t^{(k)} = r_n^{(k)}$ where $n \in \mathcal{N}$.

Let $r_n^{(k)} = \ln \|\omega_n^{(i_1)}\|$ be the length of the k th longest orthogonal axis after n time iterate for an initial point $\omega_0^{(i_1)}$. Obviously, these $r_n^{(k)}$ sequence (with k , not n) measured the expansion of initial vectors, so we can define the Lyapunov exponent in follows.

Definition 5.1 Lyapunov number, Lyapunov exponent in high dimension problem
Let $f \in C^\infty(\mathcal{R}^m)$, $J_n = Df^n(\mathbf{x}_0)$, $r_n^{(k)}$ be the length of the k th longest orthogonal axis which defined by the explanation above. Then the k th Lyapunov number of \mathbf{x}_0 is defined by

$$L_k = \lim_{n \rightarrow \infty} (r_n^{(k)})^{\frac{1}{n}}, \text{ and the Lyapunov exponent } h_k = \ln L_k$$

Obviously,

$$(L_1 \geq L_2 \geq \dots \geq L_m) \wedge (h_1 \geq h_2 \geq \dots \geq h_m)$$

For every single $r_n^{(k)}$ we know that is familiar with λ in 1-dim Lyapunov exponent, so we have
The orbit is **chaotic** if it satisfied both

- [i] $\{\mathbf{x}_1, \mathbf{x}_2, \dots\}$ is no asymptotically periodic, and
- [ii] the Lyapunov exponent h_k is **greater** than zero.

As $h_1 \geq h_2 \geq \dots \geq h_m$, so if $h_1 < 0$, then every Lyapunov exponent is less than zero, that means, we can simplify the definition and only care about h_1

Definition 5.2 Orbit chaotic in high dimension

let f be a map of \mathcal{R}^m , and $\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, \dots$ be a bounded orbit of f , if

- [i] orbit is not asymptotically periodic; and
- [ii] $\forall i = 1, 2, \dots, m, h_m \neq 0$ and $h_1 > 0$ then the orbit is **chaotic**.

Now we consider how to calculate this Lyapunov exponent in normal problem.

- [i] f is linear map

If f is a linear map, then $\exists P$ s.t. $f(\mathbf{x}) = P\mathbf{x}$ and

$$\forall i = 1, 2, \dots, m, \omega_n^{(i)} = f(\mathbf{x}_{n-1} + \omega_{n-1}^{(i)}) - f(\mathbf{x}_{n-1}) = P(\mathbf{x}_{n-1} + \omega_{n-1}^{(i)}) - P\mathbf{x}_{n-1} = P\omega_{n-1}^{(i)} = P^n\omega_0^{(i)}$$

So we have

$$\Lambda = \lim_{n \rightarrow \infty} \frac{1}{n} (\ln \|\omega_n^{(1)}\|, \ln \|\omega_n^{(2)}\|, \dots, \ln \|\omega_n^{(m)}\|) = \lim_{n \rightarrow \infty} \frac{1}{n} \ln \left(\|P^n\omega_0^{(1)}\|, \|P^n\omega_0^{(2)}\|, \dots, \|P^n\omega_0^{(m)}\| \right)$$

Define the vector norm function $\xi_p(X)$, where $X = (\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n)$ s.t.

$$\xi_p(X) = (\|\mathbf{x}_1\|_p, \|\mathbf{x}_2\|_p, \dots, \|\mathbf{x}_n\|_p)$$

is the p -norm of every vector in the matrix. Then we have

$$\Lambda = \lim_{n \rightarrow \infty} \frac{1}{n} \ln (\xi(P^n \Omega_0))$$

We know that Ω_0 is a normal orthogonal basis, and we said the most useful and simple orthogonal basis is I , so here we let $\Omega_0 = I$ then

$$\Lambda = \lim_{n \rightarrow \infty} \frac{1}{n} \ln (\xi(P^n))$$

And now, the problem is how to calculate this P^n , we know that if the eigenvector and eigenvalue of P is V and E , then $P^n = V^{-1}E^nV$, that means, if there is a eigenvalue of P absolute greater than 1, then some element in P^n will satisfy $n \rightarrow \infty, p_{i,j} \rightarrow \infty$. So now we will try to put the $1/n$ into the ξ function.

We know that in the begining of the discussion, Λ satisfied

$$\begin{aligned} \Lambda &= \lim_{n \rightarrow \infty} \frac{1}{n} \left[\ln \left(\frac{\|\omega_n^{(1)}\|}{\|\omega_{n-1}^{(1)}\|} \frac{\|\omega_{n-1}^{(1)}\|}{\|\omega_{n-2}^{(1)}\|} \cdots \frac{\|\omega_1^{(1)}\|}{\|\omega_0^{(1)}\|} \right), \ln \left(\frac{\|\omega_n^{(2)}\|}{\|\omega_{n-1}^{(2)}\|} \frac{\|\omega_{n-1}^{(2)}\|}{\|\omega_{n-2}^{(2)}\|} \cdots \frac{\|\omega_1^{(2)}\|}{\|\omega_0^{(2)}\|} \right), \dots \right. \\ &\quad \left. \ln \left(\frac{\|\omega_n^{(m)}\|}{\|\omega_{n-1}^{(m)}\|} \frac{\|\omega_{n-1}^{(m)}\|}{\|\omega_{n-2}^{(m)}\|} \cdots \frac{\|\omega_1^{(m)}\|}{\|\omega_0^{(m)}\|} \right), \right] \\ &= \lim_{n \rightarrow \infty} \frac{1}{n} \left[\sum_{i=1}^n \ln \left(\frac{\|\omega_i^{(1)}\|}{\|\omega_{i-1}^{(1)}\|} \right), \sum_{i=1}^n \ln \left(\frac{\|\omega_i^{(2)}\|}{\|\omega_{i-1}^{(2)}\|} \right), \dots \sum_{i=1}^n \ln \left(\frac{\|\omega_i^{(m)}\|}{\|\omega_{i-1}^{(m)}\|} \right), \right] \\ &= \lim_{n \rightarrow \infty} \frac{1}{n} \left\{ \sum_{i=1}^n \left[\ln \left(\frac{\|\omega_i^{(1)}\|}{\|\omega_{i-1}^{(1)}\|} \right), \ln \left(\frac{\|\omega_i^{(2)}\|}{\|\omega_{i-1}^{(2)}\|} \right), \dots, \ln \left(\frac{\|\omega_i^{(m)}\|}{\|\omega_{i-1}^{(m)}\|} \right) \right] \right\} \end{aligned}$$

Notice for every $\omega_{i-1}^{(j)}, j = 1, 2, \dots, m$ we can find a normal orthogonal basis of \mathcal{R}^m space based on the **Gram Schmidt Processing**

Algorithm 1 Gram-Schmidt process in orthogonal decomposition

INPUT: A n-dimension Euclidean space, a basis $\{\alpha_1, \alpha_2, \dots, \alpha_n\}$ of the space.

```

procedure GRAM-SCHMIDT PROCESS
  for  $i = 1, i \leq n, i + \text{do}$ 
     $\beta_i = - \sum_{j=1}^{i-1} \frac{\langle \beta_j, \alpha_i \rangle}{\langle \beta_j, \beta_j \rangle} \beta_j + \alpha_i$ 
     $\beta_i = \text{normalization}(\beta_i) = \frac{\beta_i}{\|\beta_i\|}$ 
  end for
  return Normal orthogonal basis  $\{\beta\}$ 
end procedure

```

Let the basis of $\omega_{i-1}^{(j)}$ is $B_{i-1} = (\beta_{i-1}^{(1)}, \beta_{i-1}^{(2)}, \dots, \beta_{i-1}^{(m)})$, and $Q_{i-1} = (q_{i-1}^{(1)}, q_{i-1}^{(2)}, \dots, q_{i-1}^{(m)})$ s.t.

$$\begin{aligned} \forall j = 1, 2, \dots, m, \omega_{i-1}^{(j)} &= B_{i-1} q_{i-1}^{(j)} \wedge \|q_{i-1}^{(j)}\| = 1 \\ &\left[\ln \left(\frac{\|\omega_i^{(1)}\|}{\|\omega_{i-1}^{(1)}\|} \right), \ln \left(\frac{\|\omega_i^{(2)}\|}{\|\omega_{i-1}^{(2)}\|} \right), \dots, \ln \left(\frac{\|\omega_i^{(m)}\|}{\|\omega_{i-1}^{(m)}\|} \right) \right] \\ &= \left[\ln \left(\frac{\|PB_{i-1}q_{i-1}^{(1)}\|}{\|B_{i-1}q_{i-1}^{(1)}\|} \right), \ln \left(\frac{\|PB_{i-1}q_{i-1}^{(2)}\|}{\|B_{i-1}q_{i-1}^{(2)}\|} \right), \dots, \ln \left(\frac{\|PB_{i-1}q_{i-1}^{(m)}\|}{\|B_{i-1}q_{i-1}^{(m)}\|} \right) \right] = \xi(P) \quad (*) \end{aligned}$$

And finally, we have

$$\Lambda = \lim_{n \rightarrow \infty} \frac{1}{n} \left\{ \sum_{i=1}^n [\xi(P)] \right\} = \xi(P)$$

[ii] f is non-linear map

Now we focus on the problem that f is not a linear map. Typically, we will use Jacobian matrix to linearize the problem and for a sequence x_i we have

$$\mathbf{x}_{i+1} = f(\mathbf{x}_i) = P_i \mathbf{x}_i$$

where P_i is Jacobian matrix near the point x_i , so we just need to change the P matrix to P_i matrix in non-linear problems. We found in formula $(*)$ we have

$$\begin{aligned} &\left[\ln \left(\frac{\|\omega_i^{(1)}\|}{\|\omega_{i-1}^{(1)}\|} \right), \ln \left(\frac{\|\omega_i^{(2)}\|}{\|\omega_{i-1}^{(2)}\|} \right), \dots, \ln \left(\frac{\|\omega_i^{(m)}\|}{\|\omega_{i-1}^{(m)}\|} \right) \right] \\ &= \left[\ln \left(\frac{\|P_{i-1}B_{i-1}q_{i-1}^{(1)}\|}{\|B_{i-1}q_{i-1}^{(1)}\|} \right), \ln \left(\frac{\|P_{i-1}B_{i-1}q_{i-1}^{(2)}\|}{\|B_{i-1}q_{i-1}^{(2)}\|} \right), \dots, \ln \left(\frac{\|P_{i-1}B_{i-1}q_{i-1}^{(m)}\|}{\|B_{i-1}q_{i-1}^{(m)}\|} \right) \right] = \xi(P_{i-1}) \quad (*) \end{aligned}$$

then, we have

$$\Lambda = \lim_{n \rightarrow \infty} \frac{1}{n} \left\{ \sum_{i=1}^n [\xi(P_{i-1})] \right\}$$

Finally, we can summary this processing in algorithm follows

Algorithm 2 Calculation of Lyapunov spectrum

INPUT: Values of system: x_0, x_1, \dots, x_N ;

```
procedure GRAMSCHMIDT(matrix);           ▷ Return the Gram-Schmidt orthogonal matrix.  
end procedure  
  
procedure JACOBIAN(value);                ▷ Return the Jacobian matrix at input value  
end procedure  
  
procedure VECNORM(matrix);                ▷ Return the norm of every vector in the matrix  
end procedure  
  
procedure LYASPEC  
    float P = I;  
    list Lyaspec;  
    for i = 1, i ≤ N, i ++ do  
        P = Jacobian( $x_i$ ) · P  
        Lyaspec = Lyaspec + (ln VecNorm(P));  
        P = VecNorm(P)  
    end for  
    Lyaspec = Lyaspec/N  
    return Lyaspec  
end procedure
```

Now we will apply the method with several example.

Example 5.1 *Lyapunov spectrum in Henon's map*

Firstly we consider the Henon's map

$$\begin{cases} x = 1 - ax^2 + by \\ y = x \end{cases} \quad \text{and the Jacobian matrix is } J(x, y) = \begin{bmatrix} -2ax & b \\ 1 & 0 \end{bmatrix}$$

Based on the Algo. 2, we can calculate the Lyapunov spectrum numerically.

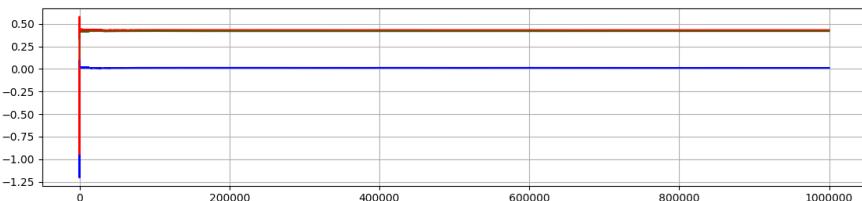


Figure 35: Lyapunov spectrum in Henon's map ($a = 2, b = 0.3$)

Lyapunov spectrum = (0.42040807, 0.01305949), sum = 0.4334675666638811

We can check the conclusion with the column of the map.

Theorem 5.1 *Column of the map*

Consider a map $f = (f_1, f_2, \dots, f_m)$ in \mathcal{R}^m the column of the map can be defined in follows

$$V = \sum_{i=1}^m \frac{\partial \dot{f}_m}{\partial x_m}$$

and the sum of the Lyapunov spectrum is equal to the column V .

Now we consider a continuous system s.t. $\dot{x} = f(x)$, $x(0) = x_0$ where x_0 is a constant vector at initial time t_0 . With Ronge-kutta method, we can find a group of value to simulate the system. So we can change the system to a map formed

$$x_{n+1} = g(x_n, t_n), x_0 = x(0), t_{n+1} = t_n + \Delta t$$

where g is based on the Ronge-kutta method.

Here we don't care about the formula g , we just consider for a certain n , if we still find a Jacobian matrix J_n , then $x_{n+1} = J_n x_n$.

On the other hand, we know that

$$\dot{x} = \frac{x(t_0 + (n+1)\Delta t) - x(t_0 + n\Delta t)}{\Delta t} = \frac{x_{n+1} - x_n}{\Delta t} = f(x_n)$$

In a certain model, we know the formula of f as well as parameter Δt . Let $\bar{J}(x)$ is Jacobian matrix of $f(x)$, then

$$x_{n+1} - x_n = \Delta t \bar{J}(x_n) x_n = (J_n - I_n) x_n \Rightarrow J_n = \Delta t \bar{J}(x_n) + I_n$$

Example 5.2 *Lyapunov spectrum in Lorenz system*

Now we consider the Lorenz system:

$$\begin{cases} \dot{x} = \sigma(y - x) \\ \dot{y} = x(\rho - z) - y \\ \dot{z} = xy - \beta z \end{cases} \quad \text{and the Jacobian matrix of } f \text{ is } \bar{J}(x, y, z) = \begin{bmatrix} -\sigma & \sigma & 0 \\ (\rho - z) & -1 & -x \\ y & x & -\beta \end{bmatrix}$$

So the Jacobian matrix of the discrete maps is

$$J(x, y, z) = \Delta t \bar{J}(x, y, z) + I = \begin{bmatrix} 1 - \sigma \Delta t & \sigma \Delta t & 0 \\ (\rho - z) \Delta t & 1 - \Delta t & -x \Delta t \\ y \Delta t & x \Delta t & 1 - \beta \Delta t \end{bmatrix}$$

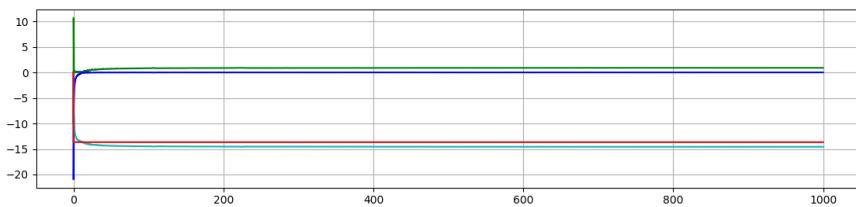


Figure 36: Lyapunov spectrum in Lorenz system($(\sigma, \rho, \beta, \Delta t) = (28, 10, 8/3, 0.0001)$)

Lyapunov spectrum = (0.903833632, 0.00483117315 – 14.5749841), *sum* = -13.666319315391025

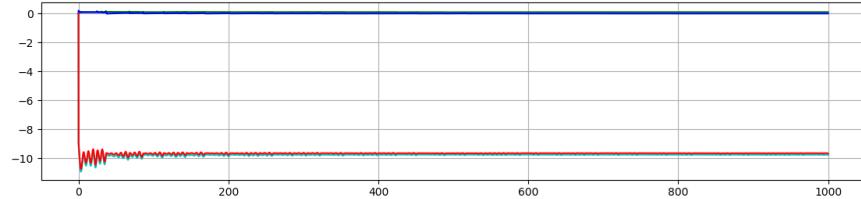


Figure 37: Lyapunov spectrum in Lorenz system($(\sigma, \rho, \beta, \Delta t) = (45.92, 4, 10, 0.0001)$)

Lyapunov spectrum = (0.104081796, 0.00285865072 – 9.75901813), *sum* = -9.652077679944226

E x a m p l e 5.3 *Lyapunov spectrum in Rossler system*

Now we consider the Rossler system:

$$\begin{cases} \dot{x} = -y - z \\ \dot{y} = x + ay \\ \dot{z} = b + z(x - c) \end{cases} \quad \text{and the Jacobian matrix of } f \text{ is } \bar{J}(x, y, z) = \begin{bmatrix} 0 & -1 & -1 \\ 1 & a & 0 \\ z & 0 & x - c \end{bmatrix}$$

So the Jacobian matrix of the discrete maps is

$$J(x, y, z) = \Delta t \bar{J}(x, y, z) + I = \begin{bmatrix} 1 & -\Delta t & -\Delta t \\ \Delta t & a\Delta t + 1 & 0 \\ z\Delta t & 0 & (x - c)\Delta t + 1 \end{bmatrix}$$

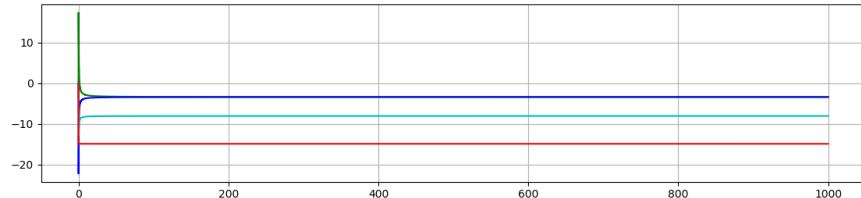


Figure 38: Lyapunov spectrum in Rossler system($(a, b, c, \Delta t) = (0.2, 0.3, 9, 0.001)$)

Lyapunov spectrum = (0.104081796, 0.00285865072, -9.75901813), *sum* = -9.629091584454333

E x a m p l e 5.4 *Lyapunov spectrum in Duffing system*

Now we consider the Duffing equation:

$$\ddot{x} + \delta \dot{x} + \alpha x + \beta x^3 = \gamma \cos(\omega t)$$

Let $y = \dot{x}$, then

$$\dot{y} = \ddot{x} = \gamma \cos(\omega t) - \delta \dot{x} - \alpha x - \beta x^3 = \gamma \cos(\omega t) - \delta y - \alpha x - \beta x^3$$

So we have

$$\begin{cases} \dot{x} = y \\ \dot{y} = \gamma \cos(\omega t) - \alpha x - \beta x^3 - \delta y \end{cases} \quad \text{and the Jacobian matrix of } f \text{ is } \bar{J}(x, y) = \begin{bmatrix} 0 & 1 \\ -\alpha - 3\beta x^2 & \delta \end{bmatrix}$$

So the Jacobian matrix of the discrete maps is

$$J(x, y, z) = \Delta t \bar{J}(x, y) + I = \begin{bmatrix} 1 & \Delta t \\ (-\alpha - 3\beta x^2)\Delta t & \delta \Delta t + 1 \end{bmatrix}$$

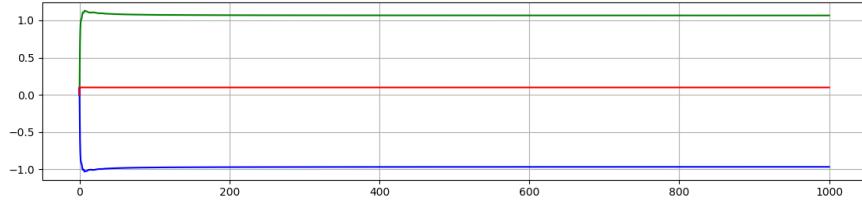


Figure 39: Lyapunov spectrum in Duffing equation($(\alpha, \beta, \gamma, \delta, \omega, \Delta t) = (1, 0.04, 1, 0.1, \pi/2, 0.001)$)

Lyapunov spectrum = $(1.06601852, -0.96612192)$, sum = 0.09989660859631133

E x a m p l e 5.5 *Lyapunov spectrum in Duffing system*

In the last of this part, we consider a 4-dim dynamic system:

$$\begin{cases} \dot{x} = -y - z \\ \dot{y} = x + 0.25y + w \\ \dot{z} = 3 + xz \\ \dot{w} = -0.5z + 0.05w \end{cases} \quad \text{and the Jacobian matrix of } f \text{ is } \bar{J}(x, y, z, w) = \begin{bmatrix} 0 & -1 & -1 & 0 \\ 1 & 0.25 & 0 & 1 \\ z & 0 & x & 0 \\ 0 & 0 & -0.5 & 0.05 \end{bmatrix}$$

So the Jacobian matrix of the discrete maps is

$$J(x, y, z, w) = \Delta t \bar{J}(x, y, z, w) + I = \begin{bmatrix} 1 & -\Delta t & -\Delta t & 0 \\ \Delta t & 1 + 0.25\Delta t & 0 & \Delta t \\ z\Delta t & 0 & 1 + x\Delta t & 0 \\ 0 & 0 & -0.5\Delta t & 1 + 0.05\Delta t \end{bmatrix}$$

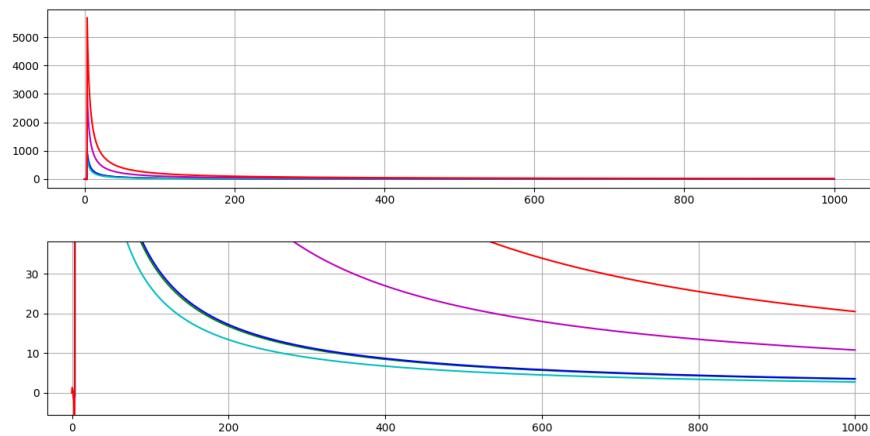


Figure 40: Lyapunov spectrum in this 4-dim equation

Lyapunov spectrum = (3.44750533, 3.53053891, 2.70980462, 10.76963212), *sum* = 20.457480973829277