

Dynamical systems

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Block I

Definitions

1. One-dimensional discrete dynamical systems
Dynamical system

Let:

- M manifold
- T monoid
- $\phi : M \times T \rightarrow M$

Then, (M, T, ϕ) is a dynamical system if:

- $\forall x \in X:$

$$\phi(x, 0) = x$$

$$\forall t_1, t_2 \in T:$$

$$\phi(\phi(x, t_1), t_2) = \phi(x, t_1 + t_2)$$

Dimension

Let:

- (M, T, ϕ) dynamical system

We name dimension of (M, T, ϕ) to:

- $\dim(M)$

We denote:

- $\dim(M) = n : (M, T, \phi)$ n-D dynamical system

Discrete & Continuous

Let:

· (M, T, ϕ) dynamical system

Then, (M, T, ϕ) is discrete if:

· $T \lesssim \mathbb{N}$

Then, (M, T, ϕ) is continuous if:

· $T \subset \mathbb{R}$ T open

Defined by a function

Let:

· (M, T, ϕ) dynamical system

· $f : M \rightarrow M$

Then, (M, T, ϕ) is a dynamical system defined by f if:

· $T = \mathbb{N}$

·
$$\begin{array}{ccc} \phi : M \times \mathbb{N} & \longrightarrow & M \\ (x, n) & \longmapsto & f^n(x) \end{array}$$

We denote:

· (M, T, ϕ) dynamical system defined by $f : (M, \mathbb{N}, f)$

Orbit

Let:

$\cdot (M, \mathbb{N}, f)$ functional dynamical system

$\cdot x \in M$

We name orbit of x to:

$\cdot \{f^n(x)\}_{n \in \mathbb{N}}$

We denote:

$\cdot o(x)$

n-periodic point

Let:

· (M, \mathbb{N}, f) functional dynamical system

· $x \in M$

· $n \in \mathbb{N}$

Then, x is a n-periodic point if:

· $f^n(x) = x$

· $\forall n' \in \mathbb{N} \quad n' < n:$

$$f^{n'}(x) \neq x$$

We denote:

· $n = 1 : x$ fixed point

Attractive & Repulsive

Let:

- (M, \mathbb{N}, f) metrical dynamical system
- $x \in M$ m-periodic point

Then, x is attractive if:

- $\exists \mathcal{U} \subset M$ open :

$$\forall y \in \mathcal{U}:$$

$$\exists N \in \mathbb{N}:$$

$$\forall n \in \mathbb{N} \quad n \geq N:$$

$$f^{nm}(y) \in \mathcal{U}$$

Then, x is repulsive if:

- $\forall \mathcal{U} \subset M \quad x \in \mathcal{U}:$

$$\forall y \in \mathcal{U}:$$

$$\exists N \in \mathbb{N}:$$

$$\forall n \in \mathbb{N} \quad n \geq N:$$

$$f^{nm}(x) \notin \mathcal{U}$$

Attraction set

Let:

- (M, \mathbb{N}, f) dynamical system
- $x \in M$ attractive m-periodic point
- $o(x)$ orbit of x

We name attraction set of x to:

$$\cdot \{y \in M \mid \exists x' \in o(x) : f^{nm}(y) \xrightarrow{n} x'\}$$

We denote:

$$\cdot A(x)$$

Neutral point

Let:

- (M, \mathbb{N}, f) differentiable dynamical system
- $x \in M$

Then, x is a neutral point if:

$$\cdot f'(x) \in \{-1, 1\}$$

Feeble attractive & repulsive points

Let:

· $(M, \mathbb{N}, f) \mathcal{C}^3$ dynamical system

· $x \in M$

Then, x is feeble attractive point if:

· $f'(x) = 1$

· $f''(x) = 0$

· $f'''(x) > 0$

Then, x is feeble repulsive point if:

· $f'(x) = 1$

· $f''(x) = 0$

· $f'''(x) < 0$

Multiplier

Let:

· $(M, \mathbb{N}, f) \mathcal{C}^1$ dynamical system

· $x \in M$

We name multiplier of x to:

· $f'(x)$

Logistic

Let:

$$\cdot f : \mathbb{R} \rightarrow \mathbb{R}$$

$$\cdot (M, T, \phi) \text{ dynamical system defined by } f$$

Then, (M, T, ϕ) is a logistic dynamical system if:

$$\cdot \exists a \in \mathbb{R}:$$

$$\begin{array}{ccc} f : \mathbb{R} & \longrightarrow & \mathbb{R} \\ x & \longmapsto & ax(1-x) \end{array}$$

Chaos

Let:

$$\cdot f : \mathbb{R} \rightarrow \mathbb{R}$$

$$\cdot (M, T, \phi) \text{ dynamical system defined by } f$$

Then, (M, T, ϕ) is chaotic if:

$$\cdot \text{Fix}(f) \text{ dense in } \mathbb{R}$$

$$\cdot \exists x \in \mathbb{R}:$$

$$o(x) \text{ dense in } \mathbb{R}$$

$$\cdot f \text{ sensibility of } x_0$$

Sarkovskii's order

We name Sarkovskii's order to:

· *naming*

·

We denote:

· *property : notation*

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Block II

Propositions

1. One-dimensional discrete dynamical systems
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introduction

Fixed points theorem

Let:

- $I \subset \mathbb{R}$ open
- $f : I \rightarrow I$ differentiable
- $x \in I$

Then, holds:

- $|f'(x)| < 1 \rightarrow x$ attractive
- $|f'(x)| > 1 \rightarrow x$ repulsive

Demonstration:

demonstration

Attractiveness of periodic points does not involve the chosen point

Let:

- (M, \mathbb{N}, f) functional dynamical system
- $x \in M$ n-periodic point
- $\{x_i\}_{i=1}^r$ orbit of x

Then, holds:

- x attractive $\leftrightarrow \forall x' \in o(x)$:
- x' attractive

Demonstration:

$$\forall x' \in o(x):$$

$$f^{n'}(x') = \prod_{i=1}^r f'(x_i) = f^{n'}(x)$$

Partition of attraction set

Let:

- (M, \mathbb{N}, f) functional dynamical system
- x n-periodic point
- $o(x)$ orbit of x

Then, holds:

- $\forall x' \in o(x):$

$\exists \mathcal{U} \subset M$ open :

$\forall y \in \mathcal{U}:$

$$f^n(y) \xrightarrow{n} x'$$

Demonstration:

demonstration

Homeomorphisms are monotonous

Let:

$\cdot f : \mathbb{R} \rightarrow \mathbb{R}$ homeomorphism

Then, holds:

$\cdot f$ monotonous

Demonstration:

no demonstration

Homeomorphisms and n-periodic points

Let:

· $f : \mathbb{R} \rightarrow \mathbb{R}$ homeomorphism (M, T, ϕ) dynamical system defined by f

Then, holds:

· $\forall n \in \mathbb{N}$:

$\exists x \in M$ „ x n-periodic point

Demonstration:

graphically

Sarkovskii's theorem

Let:

$$\cdot f : I \rightarrow I$$

$$\cdot (M, T, \phi) \text{ dynamical system}$$

Then, holds:

$$\cdot \exists x \in M:$$

$$o(x) \text{ k-period}$$

$$\cdot \rightarrow \forall l \in \mathbb{N} \quad \text{" } l > k:$$

$$\exists x' \in M:$$

$$x' \text{ l-period}$$

Block III

Examples

1. One-dimensional discrete dynamical systems
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Examples of what are and what are not one-dimensional dynamical systems

Analysis of logistic dynamical systems

Let:

· (M, T, ϕ) logistical dynamical system defined by f

Then, holds:

$$\cdot \text{Fix}(f) = \{0, \frac{a-1}{a}\}$$

$$\cdot \text{Per}_2(f) =$$

Demonstration:

demonstration

Block IV

Problems

MODELS I SISTEMES DINÀMICS

Llista 1: Aplicacions unidimensionals

B.1. Trobeu els punts fixos i les òrbites de període 2 de les següents funcions. En el cas que apareixin paràmetres, feu-ho en funció d'aquests.

- | | |
|--|---|
| (a) $* f(x) = 2x(1-x)$, on $x \in \mathbb{R}$. | (c) $f(x) = x^2 + 1$, on $x \in \mathbb{R}$. |
| (b) $* f_c(x) = x^2 + c$, on $x, c \in \mathbb{R}$ (només punts fixos). | (d) $f_{a,b}(x) = ax + b$, on $a, b, x \in \mathbb{R}$. |
| | (e) $f(x) = 2x^2 - 5x$, on $x \in \mathbb{R}$. |

B.2. Fent servir anàlisi gràfic, dibuixeu el retrat de fases de

- | | |
|--|--|
| (a) $f(x) = x^2$, $x \in \mathbb{R}$. | (c) $f_a(x) = ax$, $x \in \mathbb{R}$, pels diferents valors de $a \in \mathbb{R}$. |
| (b) $f(x) = x(1-x)$, $x \in \mathbb{R}$. | |

B.3. * Trobeu els punts fixos atractors i les seves conques d'atracció per a la funció $f(x) = \frac{3x-x^3}{2}$, per $|x| \leq \sqrt{3}$.

B.4. Per a la funció logística $f_a(x) = ax(1-x)$, calculeu els punts fixos i els cicles de període 2 en funció del paràmetre, i determineu-ne l'estabilitat.

1. Estudieu el comportament asimptòtic de la successió $\{x_n\}_{n \in \mathbb{N}}$, pels diferents valors de x_0 indicats.

- | | |
|---|--|
| (a) $* x_{n+1} = \frac{\sqrt{x_n}}{2}$, $x_0 \geq 0$. | (b) $x_{n+1} = \frac{x_n}{2} + \frac{2}{x_n}$, $x_0 \geq 2$. |
|---|--|

2. Donada la successió $x_{n+1} = \frac{x_n+2}{x_n+1}$,

- (a) Trobeu el límit $L = \lim_{n \rightarrow \infty} x_n$ per a $x_0 \geq 0$.
- (b) Descriu el conjunt dels $x_0 < 0$ pels quals el límit $\lim_{n \rightarrow \infty} x_n$ existeix i no és igual a L , o bé no existeix. (Per exemple $x_0 = -1$).

3. (**Examen 2011**) Considereu el sistema dinàmic real definit per $x_{n+1} = \frac{x_n}{4} + x_n^3$. Trobeu el comportament asimptòtic de les òrbites per a tota condició inicial $x_0 \in \mathbb{R}$. Justifiqueu rigorosament les vostres afirmacions.

4. Demostreu rigurosament que $f(x) = \sin(x)$ té $x = 0$ com atractor global.

5. Demostreu que si $f : \mathbb{R} \rightarrow \mathbb{R}$ és derivable, x_0 és un punt fix i $|f'(x_0)| > 1$ llavors x_0 és un punt fix repulsor.

6. Signi $f : \mathbb{R} \rightarrow \mathbb{R}$ de classe \mathcal{C}^∞ i sigui x_0 un punt fix tal que $f'(x_0) = 1$. Doneu criteris sobre les derivades d'ordre superior, per determinar el retrat de fase local al voltant de x_0 . Apliqueu-ho a determinar l'estabilitat dels punts fixos de $x^3 - x$.

1. One-dimensional discrete dynamical system

introduction

Decreasing function orbits

Let:

· *declarations*

·

Show that:

· *statements*

·

Demonstration:

f corta en un punto

f decreasing $\rightarrow f^2$ increasing

$f^{2n} \xrightarrow{n}$ fixed point of f

10.

Let:

$$\cdot f : \mathbb{R}^+ \rightarrow \mathbb{R}^+ \in \mathbb{C}^\infty$$

$$\cdot f(0) = 0$$

$$\cdot p \in \mathbb{R}^+ \setminus \{0\} \quad \text{,, } f'(p) \geq 0$$

$$\cdot f' \text{ decreasing}$$

Show that:

$$\cdot \forall p \in \mathbb{R}^+ \setminus \{0\}:$$

$$f^n(x) \xrightarrow{n} p$$

Demonstration:

$$f' \text{ decreasing} \rightarrow f'' < 0 \rightarrow f \text{ concave}$$

$$f \text{ positive} \rightarrow f \text{ has no extrema} \rightarrow f' > 0 \rightarrow f \text{ increasing}$$

$$f \text{ has only one fixed point}$$

$$\text{Suppose 2 fixed points : } p, p'$$

$$IVT \rightarrow \exists c \in (0, p'):$$

$$f'(c) = 1$$

$$f'(p) < 1 \rightarrow p \text{ attractive } IVT \rightarrow \text{dont exist more fixed points}$$

$$\rightarrow f'(c') = 1 \not\leq 1$$

$$\forall x \in (0, p):$$

$$f(x) > x$$

$$\forall x \in \mathbb{R} \quad \text{,, } x > p:$$

$$f(x) < x$$

$$f \text{ increasing} \rightarrow f([0, p]) = [0, p]$$

Block V

Laboratory

1. Fixed points cardinality

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Let:

$$\cdot f : [0, 1] \rightarrow [0, 1] \in \mathcal{C}^2([0, 1])$$

$$\cdot f(1) < 1$$

$$\cdot f'' > 0 \in [0, 1]$$

Show that:

$$\cdot \# \{x \in [0, 1] \mid f(x) = x\} = 1$$

Demonstration:

$$\# \{x \in [0, 1] \mid f(x) = x\} \geq 1:$$

Case $f(0) = 0$:

0 fixed point

Case $f(0) > 0$:

$$\begin{array}{ccc} g : [0, 1] & \longrightarrow & [-1, 1] \\ x & \longmapsto & f(x) - x \end{array} \in \mathcal{C}^2([0, 1])$$

$$g(0) = f(0) - 0 > 0$$

$$g(1) = f(1) - 1 < 0$$

Bolzano's theorem:

$$\exists x \in (0, 1):$$

$$g(x) = 0$$

$$f(x) = x$$

$$\# \{x \in [0, 1] \mid f(x) = x\} \leq 1:$$

$$f'' > 0 \in [0, 1]$$

Rolle's theorem:

$$\# \{x \in (0, 1) \mid f'(x) = 0\} \leq 1$$

$$\# \{x \in (0, 1) \mid f(x) = 0\} \leq 2$$

$$f'' > 0 \in [0, 1]$$

Monotonicity test:

$$f' \text{ increasing in } [0, 1]$$

$$\forall a < b \in [0, 1] \quad f(a) = a, f(b) = b:$$

Mean Value Theorem:

$$\exists c \in (a, b):$$

$$f'(c) = \frac{f(b) - f(a)}{b - a} = 1$$

$$\exists d \in (b, 1):$$

$$f'(d) = \frac{f(1) - f(b)}{1 - b} < 1$$

$$f' \text{ increasing} \rightarrow f'(c) < f'(b) < f'(d)$$

$$1 < f'(b) < 1 \text{ absurd}$$

$$\therefore \# \{x \in [0, 1] \mid f(x) = x\} = 1$$