Bifurcation structure of robust chaos in 2D piecewise-linear maps

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Border-collision normal form

- Piecewise-linear maps arise when modeling systems with switches, thresholds and other abrupt events.
- In our project, we study the two-dimensional *border-collision normal form* [H.E. Nusse and J.A. Yorke, 1992], given by

$$f_\xi(x,y) = \begin{cases} \begin{bmatrix} \tau_L & 1 \\ -\delta_L & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}, & x \le 0, \\ \begin{bmatrix} \tau_R & 1 \\ -\delta_R & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}, & x \ge 0. \end{cases}$$

- Here $(x,y) \in \mathbb{R}^2$, and $\xi = (\tau_L, \delta_L, \tau_R, \delta_R) \in \mathbb{R}^4$ are the parameters.

Banerjee-Yorke-Grebogi region in parameter space

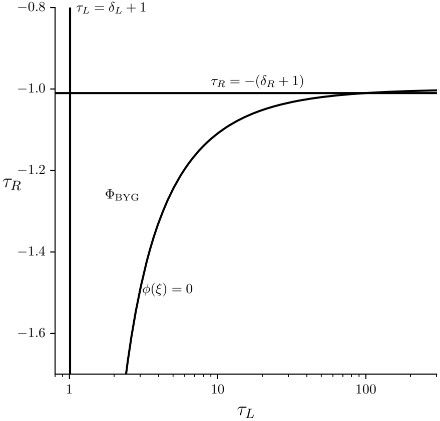


Figure: Sketch of the parameter region $\Phi_{\mathrm{BYG}} \subset \mathbb{R}^4$ [S. Banerjee, J.A. Yorke, and C. Grebogi. Robust chaos. *Phys. Rev. Lett.*, 80(14):3049– 3052, 1998.], with $\delta_L = \delta_R = 0.01$.

Phase portrait of a chaotic attractor

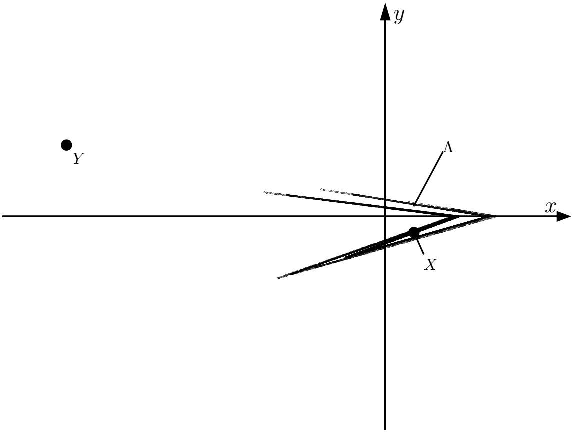


Figure: A sketch of the phase portrait of f_ξ with $\xi \in \Phi_{\mathrm{BYG}}$.

Renormalisation operator I

- Renormalisation involves showing that, for some member of a family of maps, a higher iterate or induced map is conjugate to different member of this family of maps.
- Although the second iterate f_ξ^2 has four pieces, relevant dynamics arise in only two of these. We have

$$f_\xi^2(x,y) = \begin{cases} \begin{bmatrix} \tau_L\tau_R - \delta_L & \tau_R \\ -\delta_R\tau_L & -\delta_R \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \tau_R + 1 \\ -\delta_R \end{bmatrix}, & x \le 0, \\ \begin{bmatrix} \tau_R^2 - \delta_R & \tau_R \\ -\delta_R\tau_R & -\delta_R \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \tau_R + 1 \\ -\delta_R \end{bmatrix}, & x \ge 0. \end{cases}$$

Renormalisation operator II

- Now f_ξ^2 can be transformed to $f_{g(\xi)}$, where g is the *renormalisation operator* [I. Ghosh, and D.J.W. Simpson, 2022] $g : \mathbb{R}^4 \to \mathbb{R}^4$, given by

$$\begin{aligned} \tilde{\tau}_L &= \tau_R^2 - 2\delta_R, \\ \tilde{\delta}_L &= \delta_R^2, \\ \tilde{\tau}_R &= \tau_L \tau_R - \delta_L - \delta_R, \\ \tilde{\delta}_R &= \delta_L \delta_R. \end{aligned}$$

- We perform a coordinate change to put f_ξ^2 in the normal form :

$$\begin{bmatrix} \tilde{x}' \\ \tilde{y}' \end{bmatrix} = \begin{cases} \begin{bmatrix} \tilde{\tau}_L & 1 \\ -\tilde{\delta}_L & 0 \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}, & \tilde{x} \le 0, \\ \begin{bmatrix} \tilde{\tau}_R & 1 \\ -\tilde{\delta}_R & 0 \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}, & \tilde{x} \ge 0. \end{cases}$$

Results I

- We consider the parameter region

$$\Phi = \left\{ \xi \in \mathbb{R}^4 \middle| \tau_L > \delta_L + 1, \delta_L > 0, \tau_R < -(\delta_R + 1), \delta_R > 0 \right\}.$$

- The stable and the unstable manifolds of the fixed point Y intersect if and only if $\phi(\xi) \leq 0$.
- Banerjee, Yorke and Grebogi observed that an attractor is often destroyed at $\phi(\xi) = 0$ which is a homoclinic bifurcation, and thus focused their attention on the region

$$\Phi_{\mathrm{BYG}} = \{ \xi \in \Phi | \phi(\xi) > 0 \}.$$

Results II

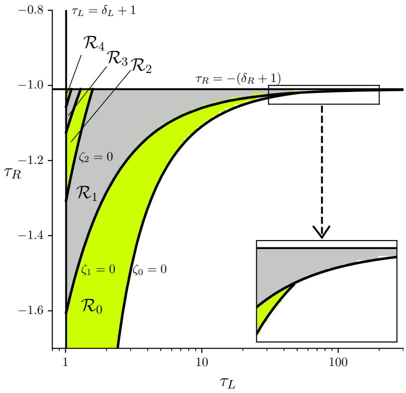


Figure: The sketch of two dimensional cross-section of $\mathcal{R}_n$ when $\delta_L = \delta_R = 0.01$.

Results III

Theorem

The $\mathcal{R}_n$ are non-empty, mutually disjoint, and converge to the fixed point $(1, 0, -1, 0)$ as $n \to \infty$. Moreover,

$$\Phi_{\mathrm{BYG}} \subset \bigcup_{n=0}^{\infty} \mathcal{R}_n.$$

- Let,

$$\Lambda(\xi) = \mathrm{cl}(W^u(X)).$$

Theorem

For the map f_ξ with any $\xi \in \mathcal{R}_0$, $\Lambda(\xi)$ is bounded, connected, and invariant. Moreover, $\Lambda(\xi)$ is chaotic (positive Lyapunov exponent).

Results IV

Theorem

For any $\xi \in \mathcal{R}_n$ *where* $n \geq 0$, $g^n(\xi) \in \mathcal{R}_0$ *and there exist mutually disjoint sets* $S_0, S_1, \ldots, S_{2^n-1} \subset \mathbb{R}^2$ *such that* $f_\xi(S_i) = S_{(i+1) \bmod 2^n}$ *and*

$$f_\xi^{2^n}|_{S_i} \text{ is affinely conjugate to } f_{g^n(\xi)}|_{\Lambda(g^n(\xi))}$$

for each $i \in \{0, 1, \ldots, 2^n - 1\}$. *Moreover,*

$$\bigcup_{i=0}^{2^n-1} S_i = \mathrm{cl}(W^u(\gamma_n)),$$

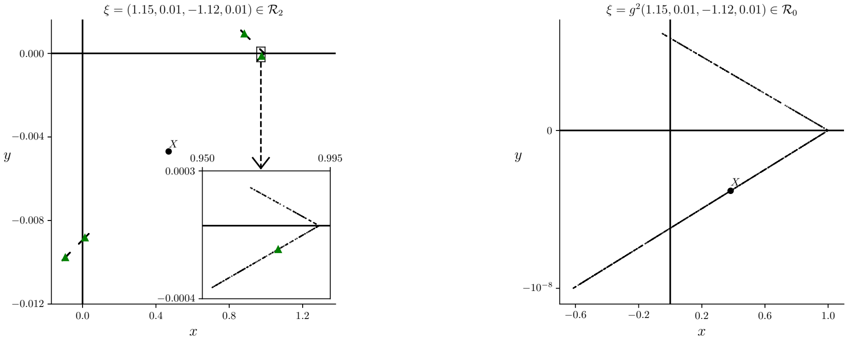
where γ_n *is a saddle-type periodic solution of our map* f_ξ *having the symbolic itinerary* $\mathcal{F}^n(R)$ *given by Table 1.*

Results V

n	$\mathcal{F}^n(\mathcal{W})$
0	R
1	LR
2	$RRLR$
3	$LRLRRRLR$
4	$RRLRRRLRLRLRRRLR$

Table: The first 5 words in the sequence generated by repeatedly applying the substitution rule $(L, R) \mapsto (RR, LR)$ to $\mathcal{W} = R$.

Results VI



$\xi = (1.15, 0.01, -1.12, 0.01) \in \mathcal{R}_2$
0.000
−0.004
−0.008
−0.012
y
X
0.950
0.995
0.0003
−0.0004
0.0
0.4
0.8
1.2
x
$\xi = g^2(1.15, 0.01, -1.12, 0.01) \in \mathcal{R}_0$
0
-10^{-8}
y
X
−0.6
−0.2
0.2
0.6
1.0
x

Generalised parameter region

Now we consider the more generalised parameter region considering the orientation-reversing and non-invertible cases,

$$\Phi = \left\{ \xi \in \mathbb{R}^4 \,\middle|\, -\tau_L - 1 < \delta_L < \tau_L - 1, \tau_R - 1 < \delta_R < -\tau_R - 1 \right\},$$

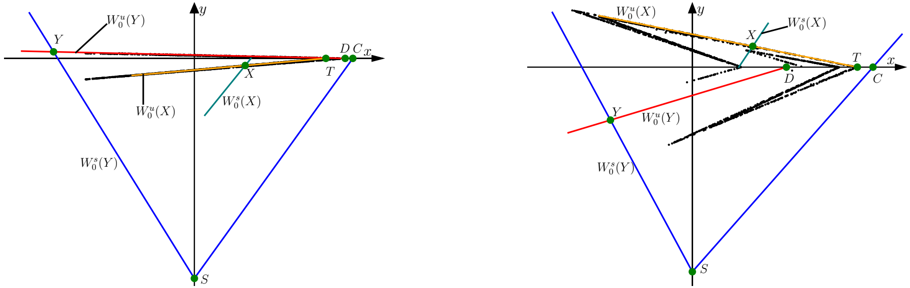
where we define

$$\Phi_{\mathrm{trap}} = \{\xi \in \Phi |\ \phi_i(\xi) > 0, i = 1, \dots, 5\},$$

and

$$\Phi_{\mathrm{cone}} = \{\xi \in \Phi | \theta_i(\xi) \geq 0, i = 1, \dots, 7\}.$$

Typical phase portraits I

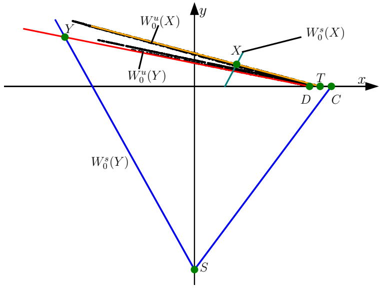


(a) $\delta_L > 0, \delta_R > 0$

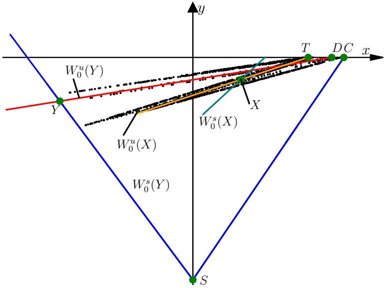
(b) $\delta_L < 0, \delta_R < 0$

Figure: Typical phase portraits of the chaotic attractor for the invertible case ($\delta_L \delta_R > 0$).

Typical phase portraits II



(a) $\delta_L > 0, \delta_R < 0$



(b) $\delta_L < 0, \delta_R > 0$

Figure: Typical phase portraits of the chaotic attractor for the non-invertible case ($\delta_L \delta_R < 0$).

Results I

Theorem

Suppose $\xi \in \Phi_{\mathrm{trap}} \cap \Phi_{\mathrm{cone}}$, *then* f_ξ *has a topological attractor with the property that it is chaotic in sense of positive maximal Lyapunov exponent on each point on the attractor.*

- Our construction of a trapping region requires

$$\begin{aligned}
\phi_1(\xi) &= \delta_R - \tau_R \lambda_L^u, \\
\phi_2(\xi) &= \delta_R(\lambda_L^s + 1) - \lambda_L^u(\tau_R + (\delta_R + \tau_R)\lambda_L^s), \\
\phi_3(\xi) &= \delta_R - (\delta_R + \tau_R - (\tau_R + 1)\lambda_L^u)\lambda_L^u, \\
\phi_4(\xi) &= \delta_R - (\tau_R + \delta_L + \delta_R - (1 + \tau_R)\lambda_L^u)\lambda_L^u, \\
\phi_5(\xi) &= \delta_R - (\delta_R + \tau_R - (1 + \lambda_R^u)\lambda_L^u)\lambda_L^u.
\end{aligned}$$

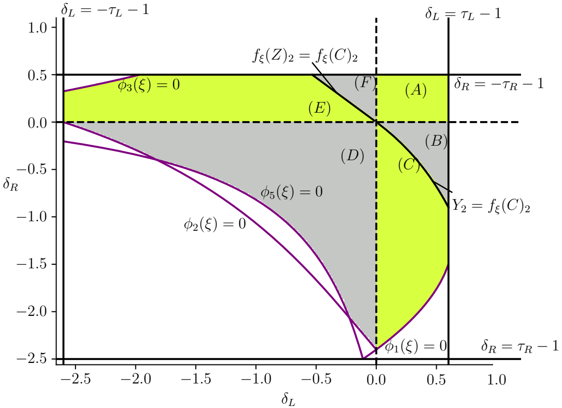


Figure: A 2D slice of $\Phi_{\mathrm{trap}} \subset \mathbb{R}^4$.

- The construction of an invariant expanding cone requires

$$\theta_1(\xi) = (\delta_R - \delta_L - \tau_L\tau_R)^2 - 4\delta_L\tau_R\tau_L,$$

$$\theta_2(\xi) = \min\left(-\frac{\tau_L}{2}\left(1 - \sqrt{1 - \frac{4\delta_L}{\tau_L^2}}\right), -\frac{\delta_R}{\tau_R}\right) - \frac{1 - \delta_L^2 - \tau_L^2}{2\tau_L},$$

$$\theta_3(\xi) = \tau_L^2 - \frac{4\delta_R\tau_L^2}{\tau_R\tau_L + \delta_R - \delta_L - \sqrt{\theta_1(\xi)}} + \delta_L^2 - 1,$$

$$\theta_4(\xi) = \tau_R^2 + \frac{\tau_R}{\tau_L}\left((\delta_R - \delta_L - \tau_L\tau_R) - \sqrt{\theta_1(\xi)}\right) + \delta_R^2 - 1,$$

$$\theta_5(\xi) = -\max\left(-\frac{\tau_R}{2}\left(1 - \sqrt{1 - \frac{4\delta_R}{\tau_R^2}}\right), -\frac{\delta_L}{\tau_L}\right) + \frac{1 - \delta_R^2 - \tau_R^2}{2\tau_R},$$

$$\theta_6(\xi) = \tau_R^2 + \delta_R^2 - 1,$$

$$\theta_7(\xi) = \tau_L^2 + \delta_L^2 - 1.$$

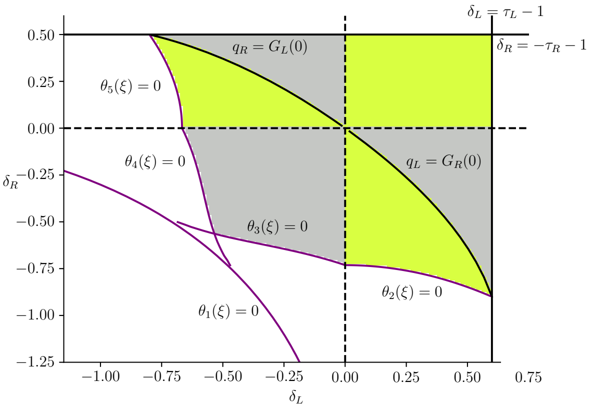


Figure: A 2D slice of $\Phi_{\text{cone}} \subset \mathbb{R}^4$.

Summary

- We have used renormalization to explain how the parameter space Φ_{BYG} is divided into regions according to the number of connected components of an attractor.
- We have further shown how the robust chaos extends more broadly to orientation-reversing and non-invertible piecewise-linear maps.
- It remains to apply similar renormalization technique in a more generalized parameter setting and determine the analogue of the existence of robust chaos in higher dimensional maps.

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The End

Thank you! Questions?