lecture 8

Criticality and Computation

key events coming up

- **Labs: 35% (ISE-483)**
  - Complete 5 (best 4 graded) assignments based on algorithms presented in class
    - Lab 3: **March 31st**
      - Cellular Automata and Boolean Networks (Assignment 3)
        - Delivered by Kaeli Ahn and Erik Fiolkoski
        - Due: **April 7th**
- **SSIE – 583 -Presentation and Discussion: 25%**
  - Present and lead the discussion of an article related to the clas s
    - Enginet students post/send video or join by Zoom
  - April 22, 2025
    - Rik Pardun
      - Conrad, M. [1990]. "The geometry of evolution.“ *Biosystems* **24**: 61-81.
    - Kiet Ngo Tuan
      - Garg, Shivam, Kirankumar Shiragur, Deborah M. Gordon, and Moses Charikar. “Distributed Algorithms from Arboreal Ants for the Shortest Path Problem.”*PNAS* **120**, no. 6 (February 7, 2023): e2207959120.
    - Eric Fiolkoski
      - Schmidt, M. and H. Lipson [2009]. “Distilling Free-Form Natural Laws from Experimental Data". *Science*, **324**: 81-85.

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- Projects
  - **Due by May 7th** in Brightspace, “Final Project 483/583” assignment
    - ALIFE 2025
      - Not necessarily to submit to actual conference due date
        - May 4 full paper, July 4, abstract
      - https://2025.alife.org/
      - Max 8 pages, author guidelines:
      - https://2025.alife.org/calls#paper-call
      - MS Word and Latex/Overleaf templates
    - Preliminary ideas **by March 7**
      - Submit to “Project Idea” assignment in Brightspace.
  - Individual or group
    - With very definite tasks assigned per member of group

ALIFE 2025

Tackle a real problem using bio-inspired algorithms, such as those used in the labs.

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Reusing and expanding labs is highly encouraged.

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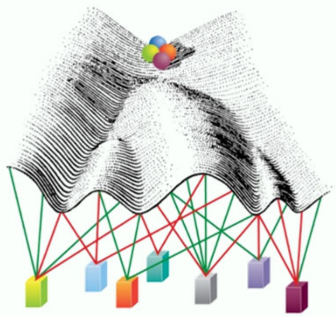
Additional information

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press. Preface, Sections 4.1, 4.2. **Chapter 2.**
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall. Chapter 1, pp. 1-23. Sections **7.1 to 7.4** , Appendix B.3.1. **Chapter 2**, **Sections 8.1, 8.2, 8.3.10**
- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
  - Chapter 4: Self-Organization and Emergent Complex Behavior
    - posted online @ casci.binghamton.edu/academics/i-bic

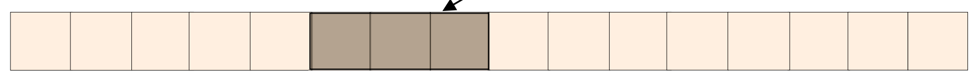


- Papers and other materials
  - Optional
    - Prusinkiewicz and Lindenmeyer [1996] The algorithmic beauty of plants.
      - Chapter 1
    - Flake's [1998], *The Computational Beauty of Life*. MIT Press.
      - Chapters 1, 5, 6 (7-9).
      - Chapters **10, 11, 14**

more formally

D-dimensional lattice *L* with a finite ***automaton*** in each lattice site (cell)

Neighborhood template *N*



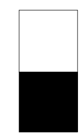
- State-determined system
  - finite number of states Σ: $K = |\Sigma|$
    - E.g. $\Sigma = \{0,1\}$
  - finite input alphabet α
  - transition function $\Delta: \alpha \rightarrow \Sigma$
    - uniquely ascribes state s in Σ to input patterns α

Example (ECA)

$K=2$, $N=3$,

$|\alpha| = 2^3 = 8$

$D = 2^8 = 256$



$$\alpha \in \Sigma^N, |\alpha| = K^N$$

Number of possible neighborhood states

$$D = K^{K^N}$$

Number of possible transition functions

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more formally

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Example (ECA)

$K=2$, $N=3$,

$|\alpha|=2^3=8$

$D = 2^8=256$

Example

$K=8$

$N=5$

$|\alpha|=37{,}768$

$D \approx 10^{30,000}$

$$\alpha \in \Sigma^N, |\alpha| = K^N$$

Number of possible neighborhood states

$$D = K^{K^N}$$

Number of possible transition functions

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Finding the structure of all possible transition functions

- Statistical analysis
  - Identify classes of transition functions with similar behavior
    - Similar dynamics (statistically)
  - Via Higher level statistical observables
    - Like Kauffman
- The Lambda Parameter (similar to bias in BN)
  - Select a subset of D characterized by λ
    - Arbitrary ***quiescent state***: s_q
      - Usually 0
    - A particular function Δ has n transitions to this state and $(K^N\text{-}n)$ transitions to other states s of Σ
    - $(1\text{-}\lambda)$ is the probability of having a s_q *in every position of the rule table*

$$\lambda = \frac{K^N - n}{K^N}$$

λ = $\boxed{\text{0: all transitions lead to } s_q \text{ (n =} K^N)}$

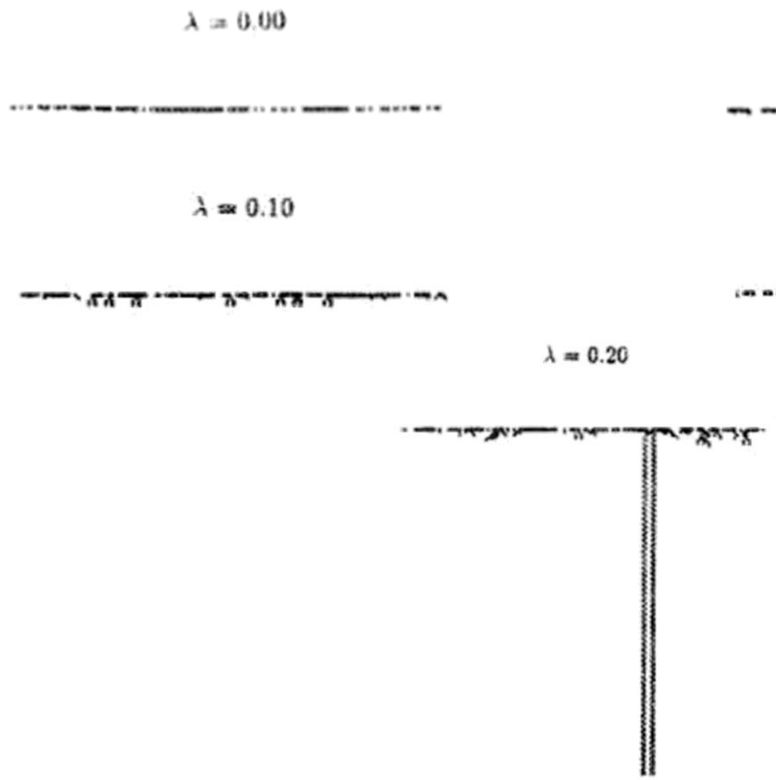
λ = 1: no transitions lead to s_q (n =0)

λ = $\boxed{\text{1-1/K: equally probable states (n=1/K . } K^N)}$

Range: from most homogeneous to most heterogeneous

Langton, C.G. [1990]. "Computation at the edge of chaos: phase transitions and emergent computation". *Artificial Life II*. Addison-Wesley.

- λ only correlates well with dynamic behavior for fairly large values of K and N
  - E.g. K≥4 and N≥5
- Experiments
  - K=4, N=5



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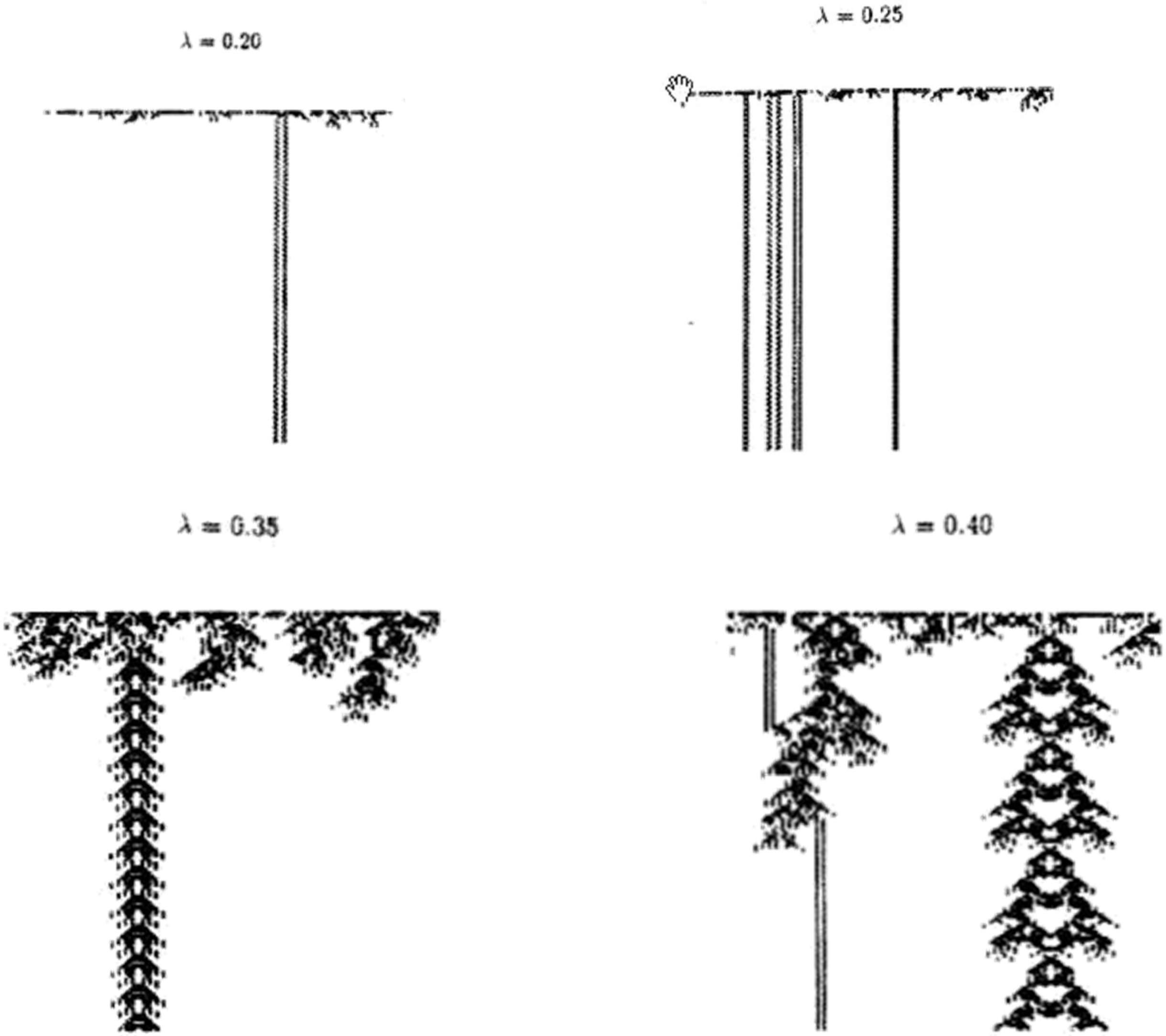
Langton's results



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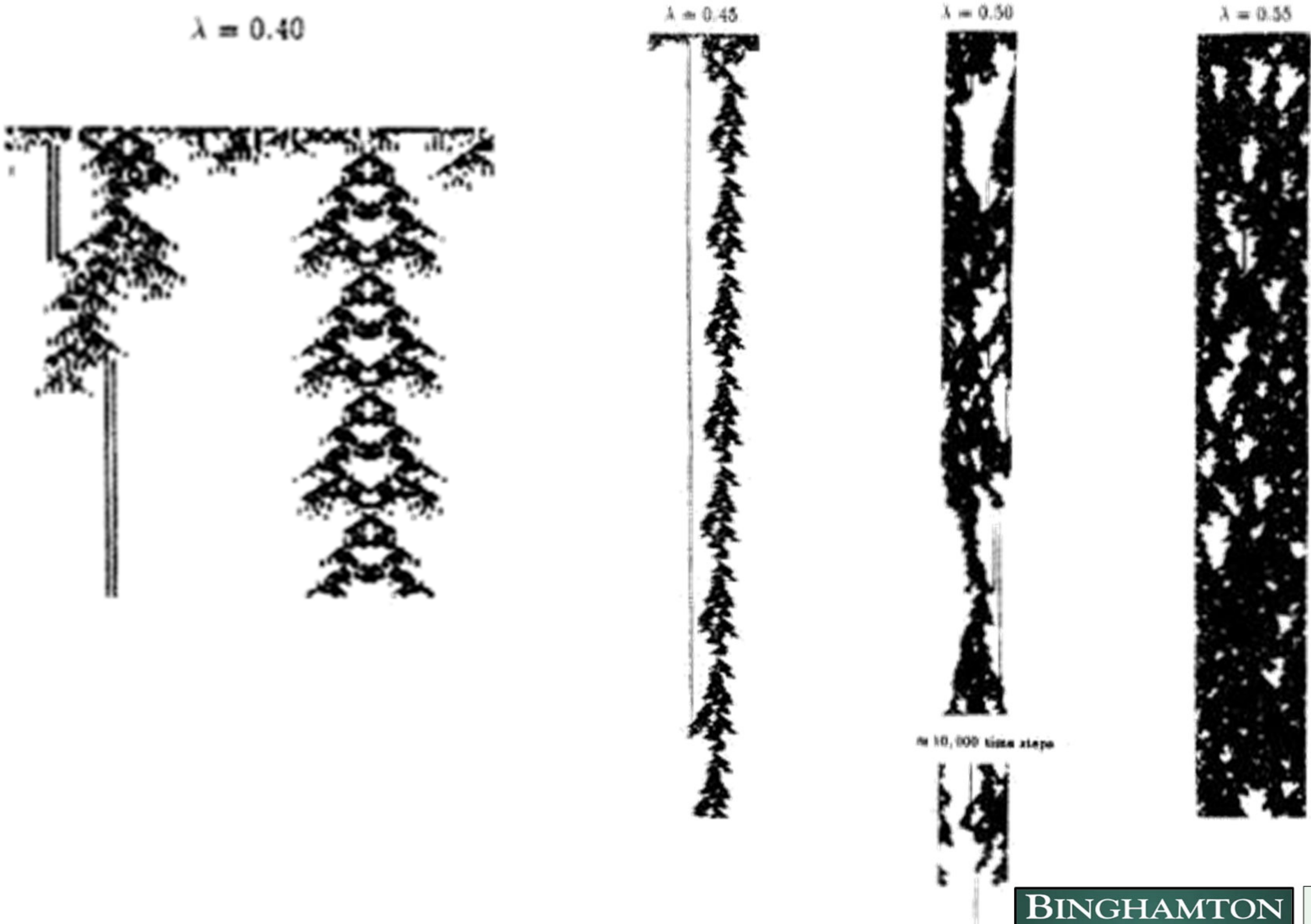

Approximate time when density is within 1% of long-term behavior

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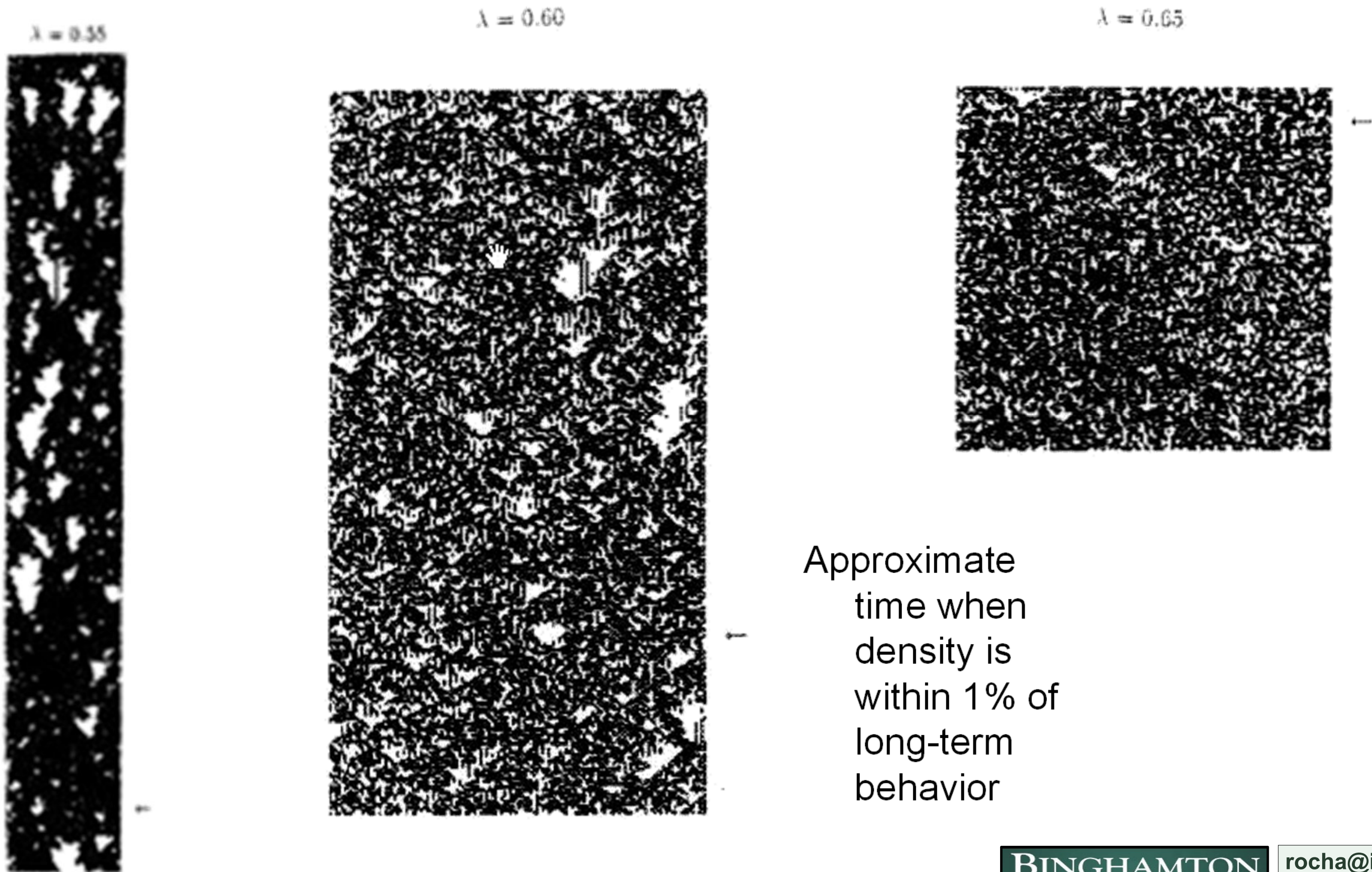
Langton’s results



Approximate time when density is within 1% of long-term behavior

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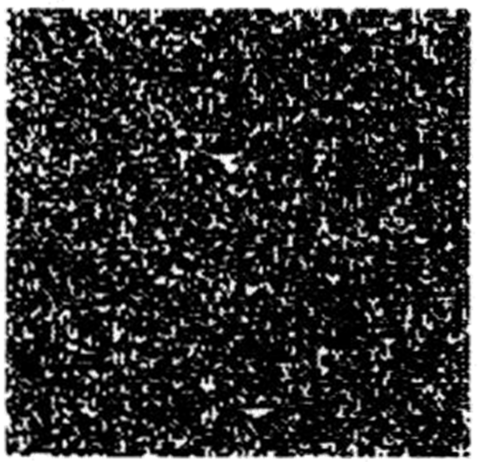
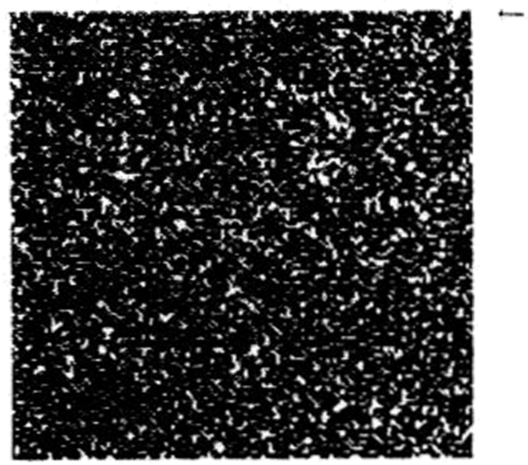
$\lambda = 0.70$



Approximate time when density is within 1% of long-term behavior

$\lambda = 0.75$



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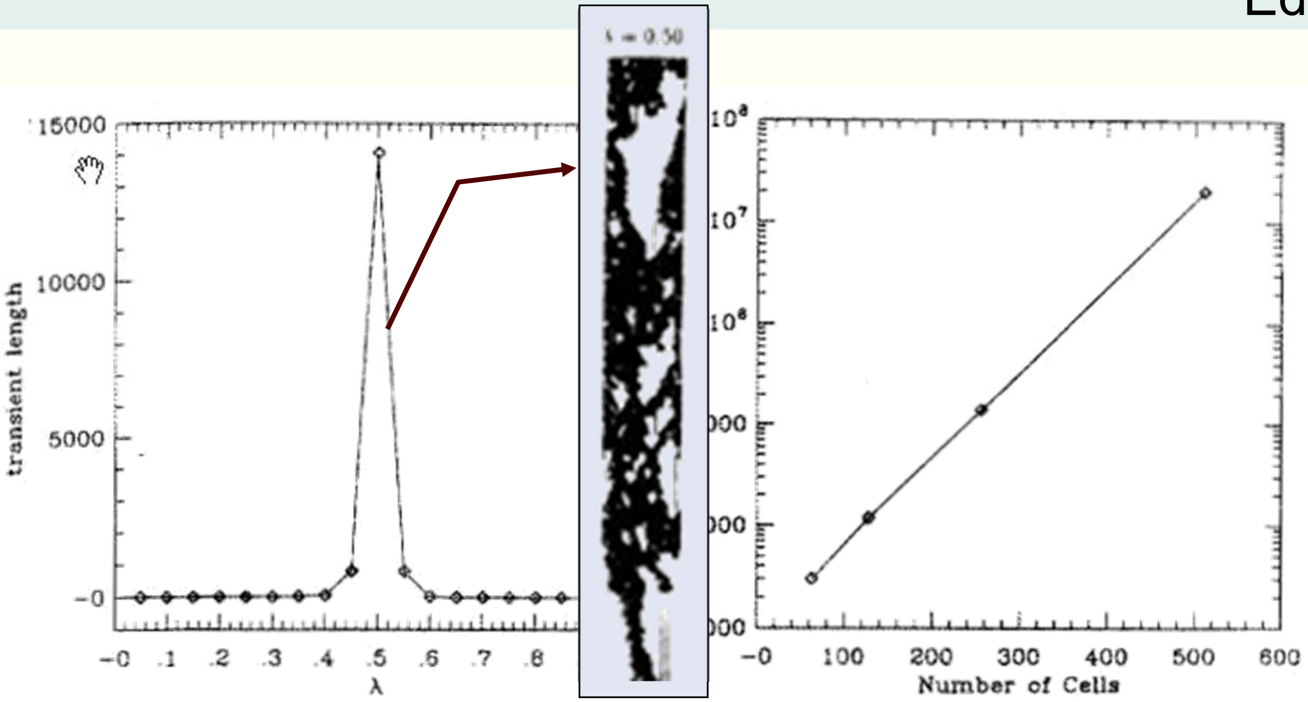
A phase transition?



- Transient growth in the vicinity of phase transitions
  - Length of CA lattice only relevant around phase transition (λ=0.5)
- Conclusion: more complicated behavior found in the phase transition between order and chaos
  - Patterns that move across the lattice

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- Transition region
  - Supports both static and propagating structures
    - λ =0.4+
  - Propagating waves ("signals"?) across the CA lattice
    - Necessary for computation?
    - Signals and storage?
- Computation
  - Requires storage and transmission of information
  - Any dynamical system supporting computation must exhibit long-range signals in space and time
- Wolfram's CA classes
  - I: homogeneous state
    - Steady-state
  - II: periodic state
    - Limit cycles
  - III: chaotic
  - IV: complex patterns of localized structures
    - Long transients
    - Capable of universal computation

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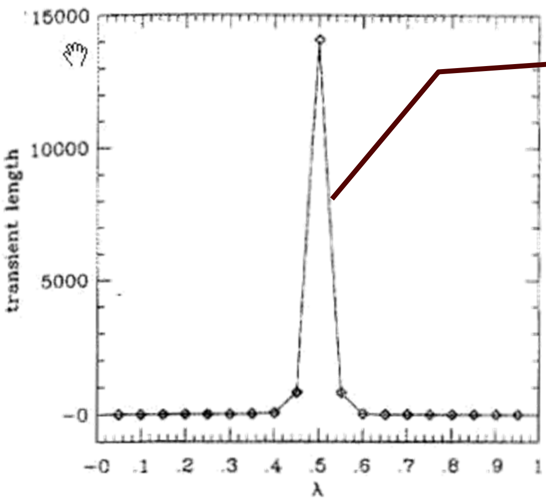
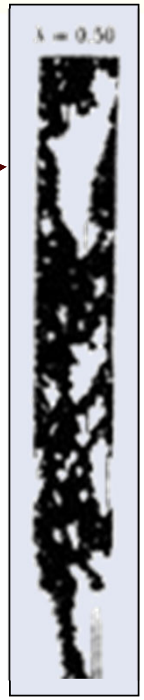
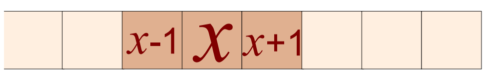
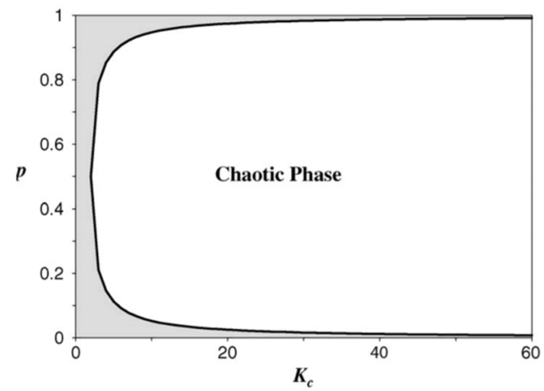
Bias and lambda parameter

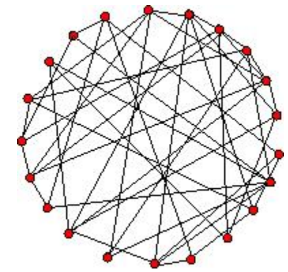


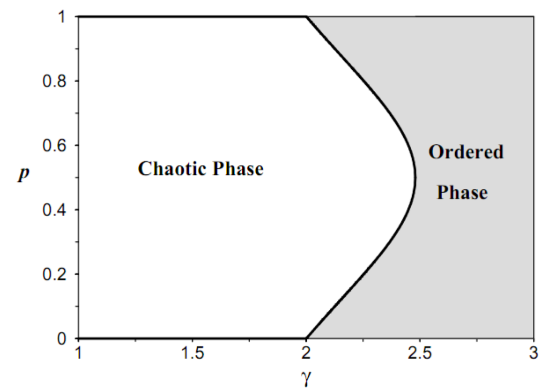


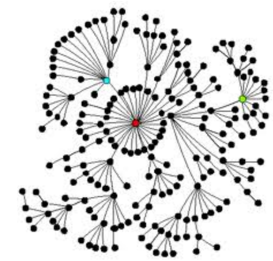
Cellular Automata











Boolean Networks

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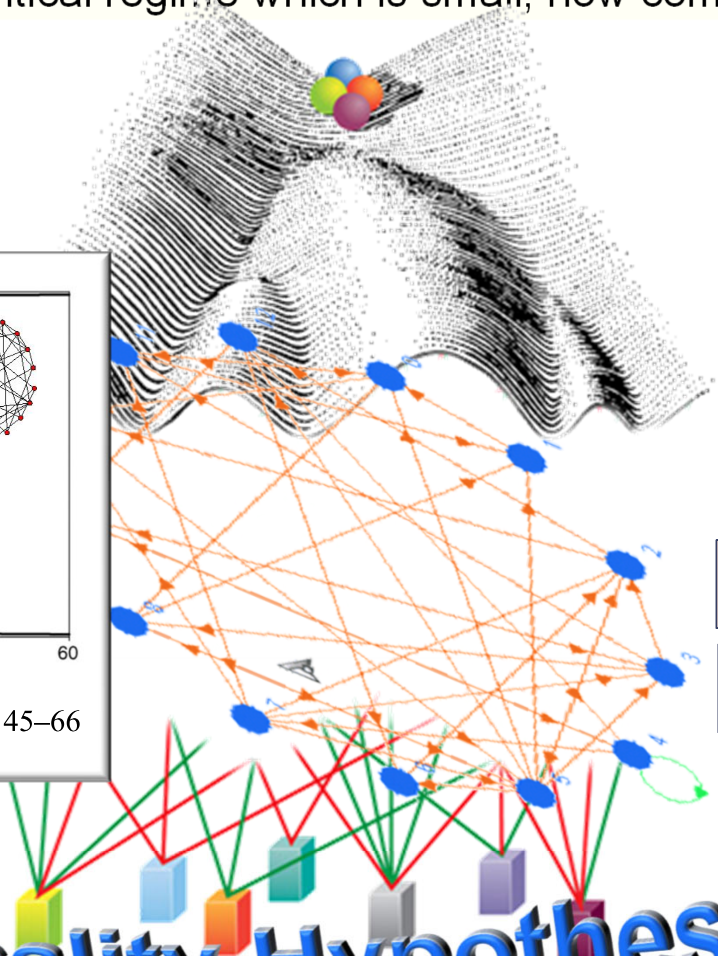
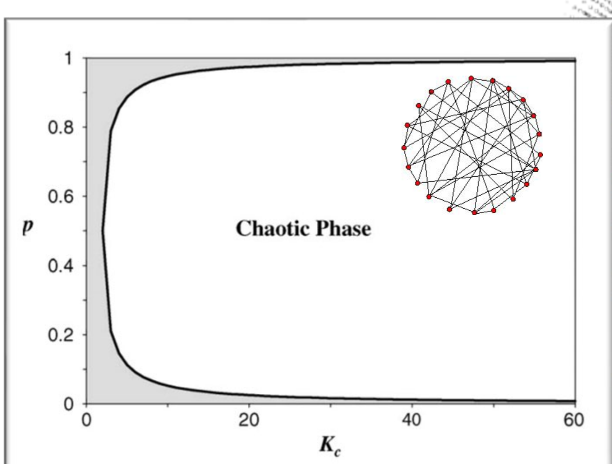
evolution requires life in critical regime which is small, how come life is not chaotic?





Aldana, M. [2003]. *Physica D.* **185**: 45–66

Kauffman, S. A. (1984). *Phys. D Nonlinear Phen.* **10**,145–156.

Waddington CH (1942). *Nature*. **150** (3811):563–565

robustness of phenotypes is the result of a ***buffering*** of the developmental process.

dynamics of gene networks provides buffering (***self-organization***). But still easily chaotic.

The Criticality Hypothesis

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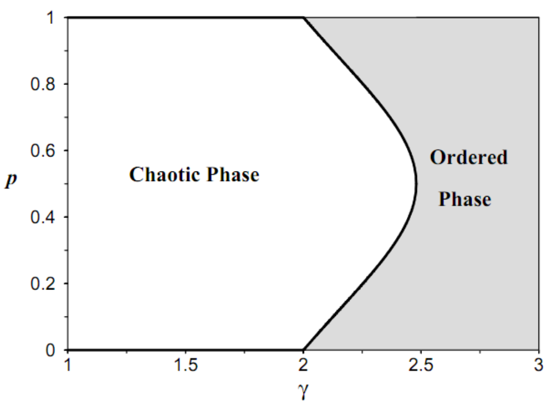

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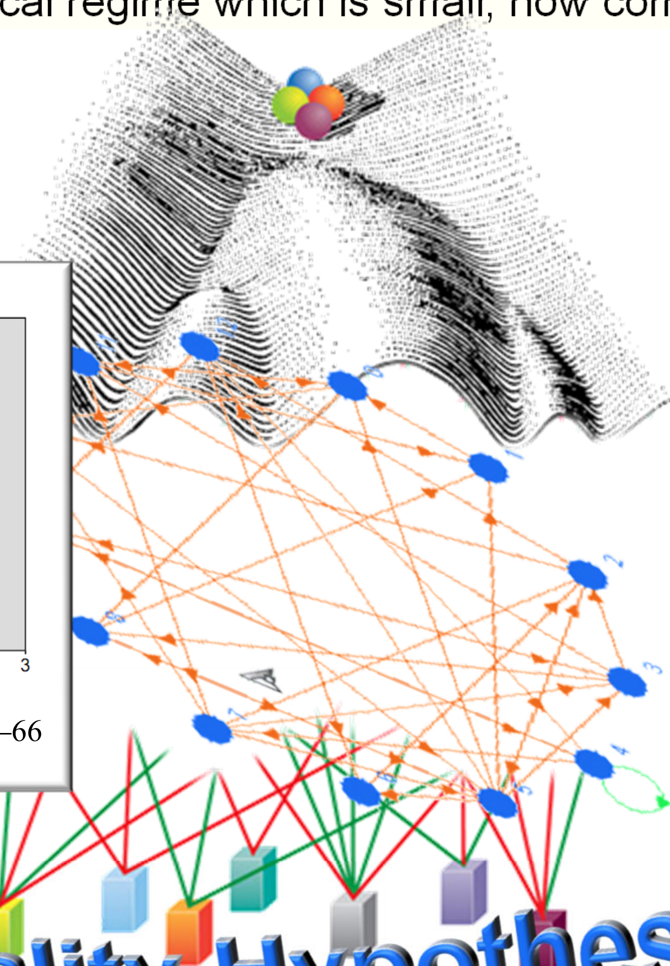

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Structure (***topological organization***), can provide larger stable or critical universe, but still easily chaotic.

The Criticality Hypothesis

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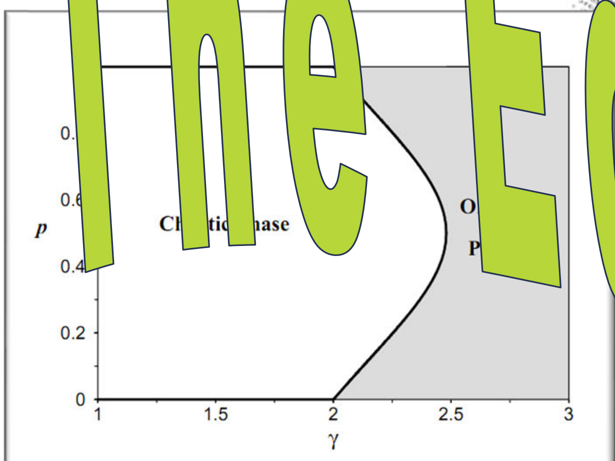
evolution requires life in critical regime which is small, how come life is not chaotic?

The Edge of Chaos?



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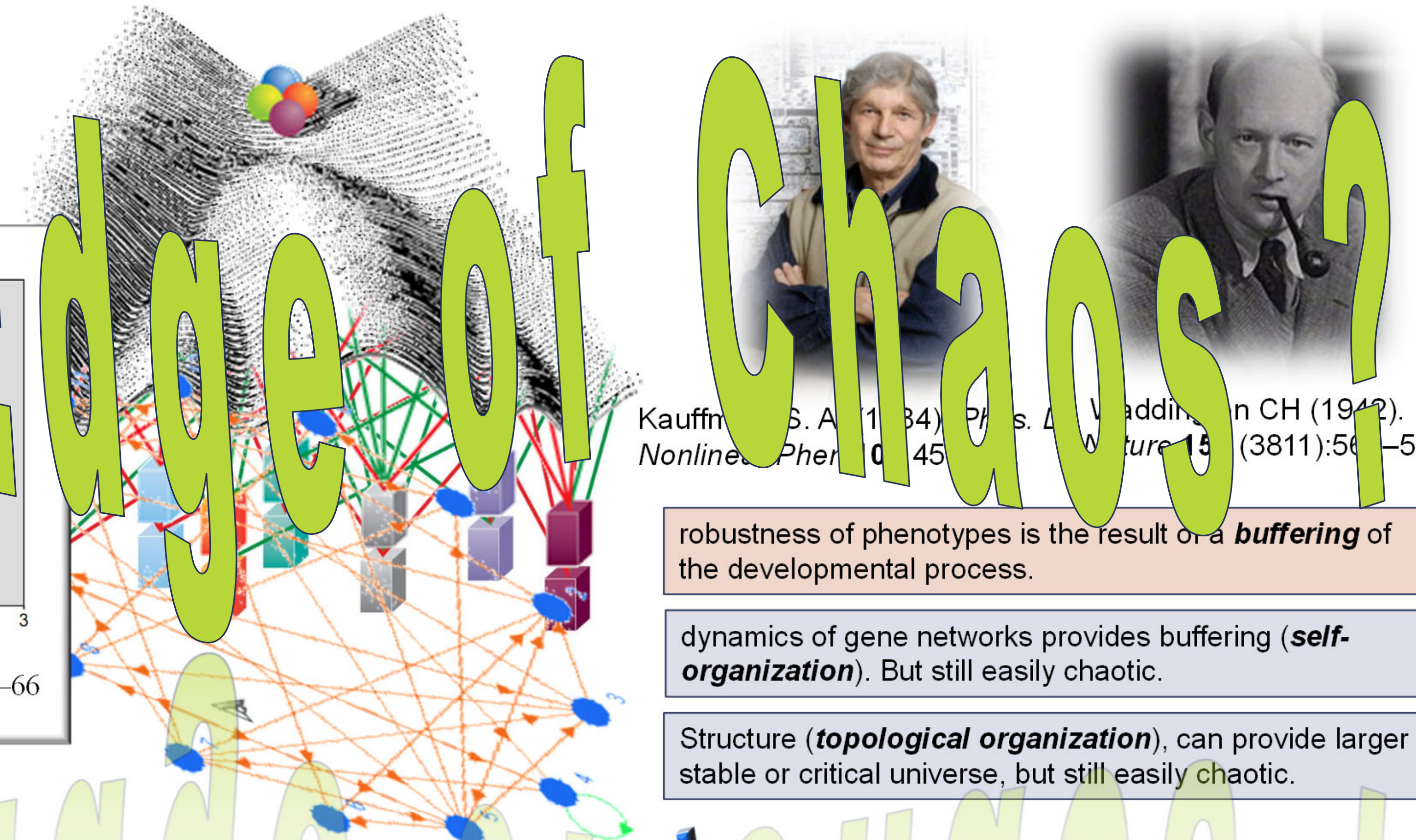

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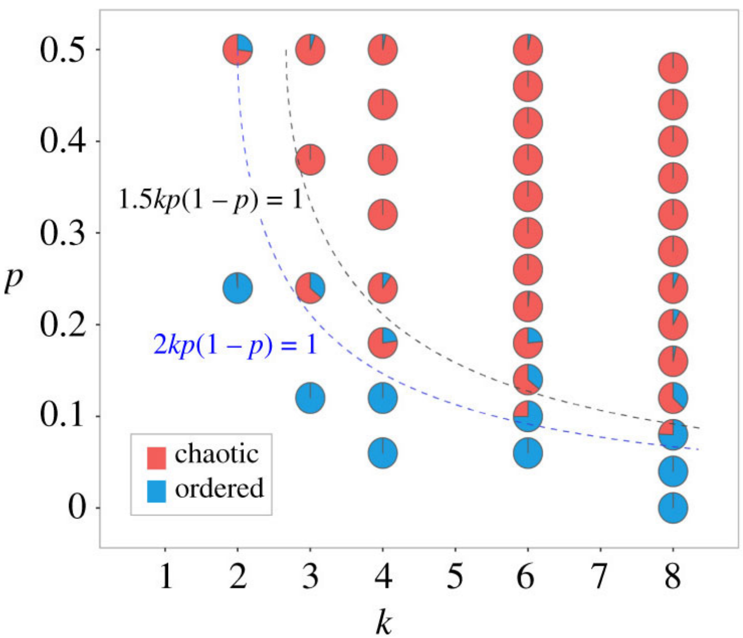
The Criticality Hypothesis

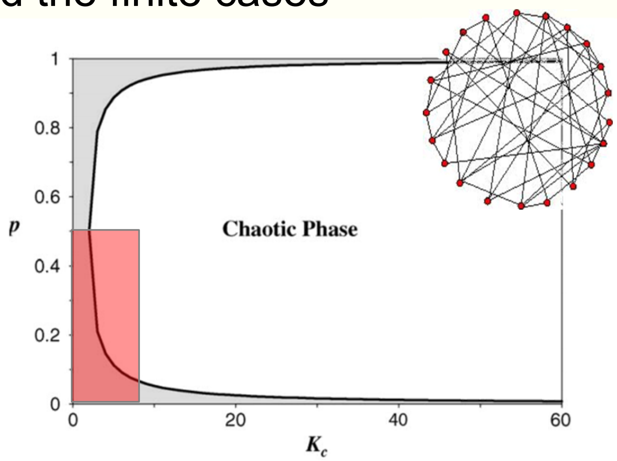
current theory for random networks and the finite cases

homogeneous networks



$$2.k.p(1-p) = 1$$

Derrida & Pomeau. [1986] *EPL* . **1.2**: 45.



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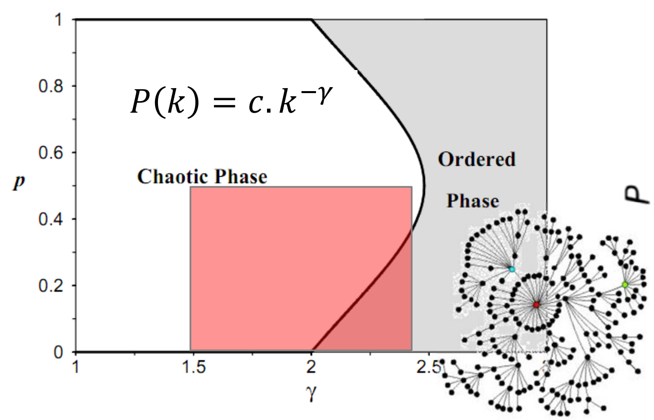
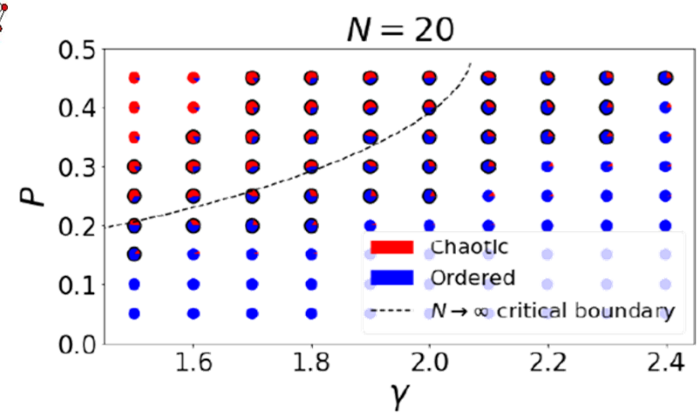
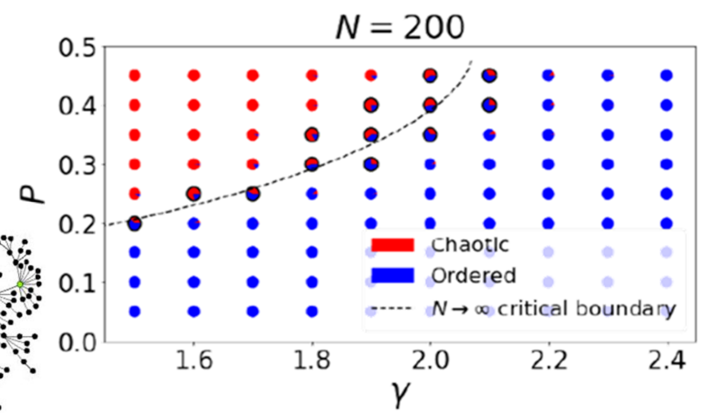


heterogenous networks

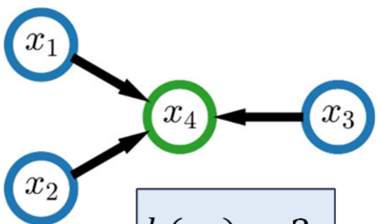




Manicka, Marques-Pita, & Rocha, [2022]. *J. Royal Society Interface*. **19**(186):20210659.
Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.

effective graph: nonlinear measure of effective connectivity

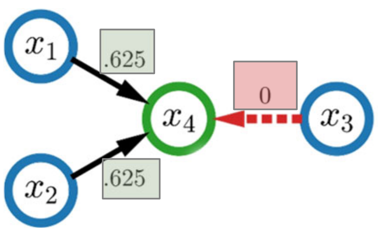
Measuring dynamical ***redundancy*** and its dual ***effectiveness***

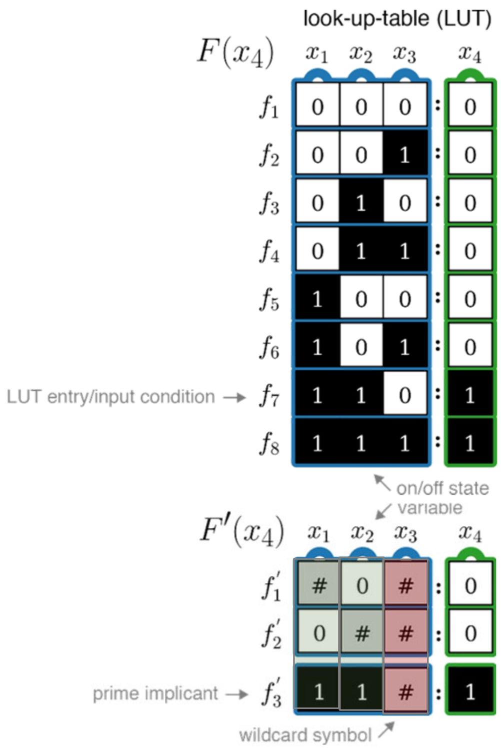


$k(x_4) = 3$

$x_4 = x_1 \wedge x_2$

$k_e(x_4) = 1.25$





Prime Implicants (Quine-McCluskey)

github.com/CASCI-lab/CANA

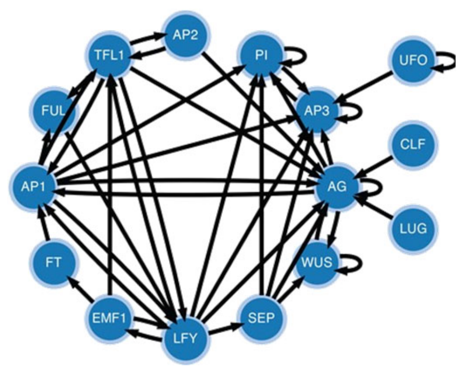
input redundancy:
$k_r(x)$ = mean number of "#" in LUT

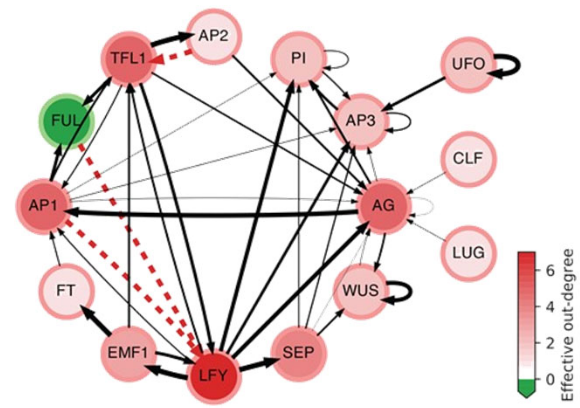
$k_r(x_4) = 1.75$

effective connectivity:
$k_e(x) = k(x) - k_r(x)$

$p(x) = 2/8 = 0.25$

p: bias, ratio of "1's" in output





Correia, Gates, Wang & Rocha [2018]. *Frontiers in Physyology* **9:** 1046.
Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
Marques-Pita & Rocha, [2013]. *PLoS ONE*, **8**(3): e55946.

Chaos et al [2006]. *J. of Plant Growth Regulation*. **25**(4): 278-289.

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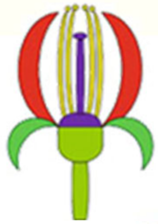
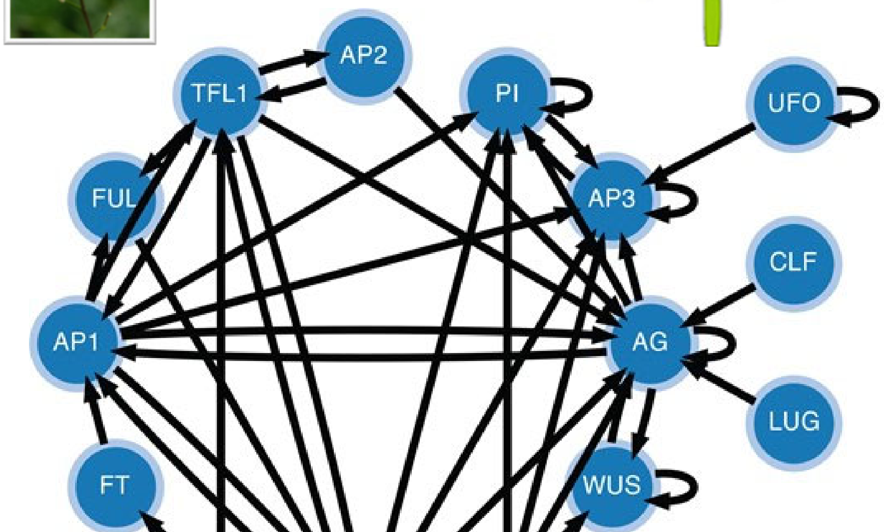
arabidopsis thaliana network

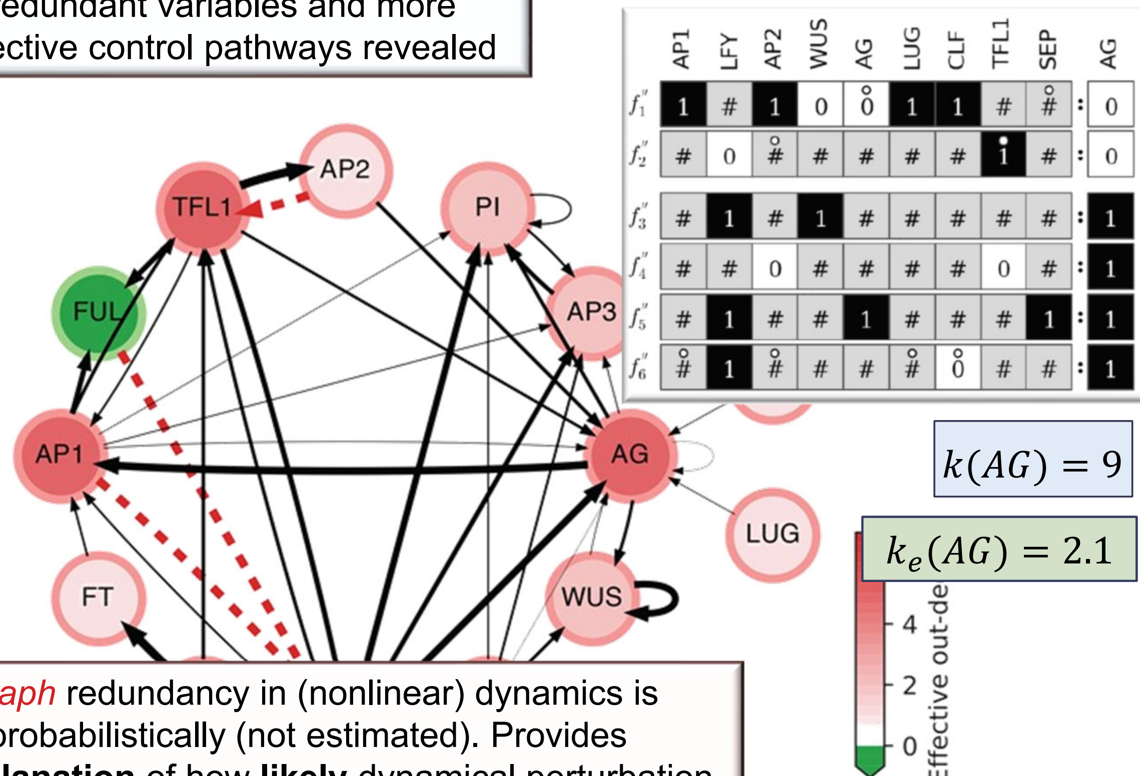
Chaos et al [2006]. *J. of Plant Growth Regulation*. **25**(4): 278-289.



redundant variables and more effective control pathways revealed



Interaction graph obtained from pairwise estimation of interaction. No dynamics represented in graph; many dynamics fit same structure.



$k(AG) = 9$

$k_e(AG) = 2.1$

Effective graph redundancy in (nonlinear) dynamics is integrated probabilistically (not estimated). Provides **causal explanation** of how **likely** dynamical perturbation and control signals propagate in biochemical pathways.

github.com/CASCI-lab/CANA

Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
Gates & Rocha [2016]. *Scientific Reports* **6**, 24456.
Marques-Pita & Rocha, [2013]. *PLoS ONE*, **8**(3): e55946.

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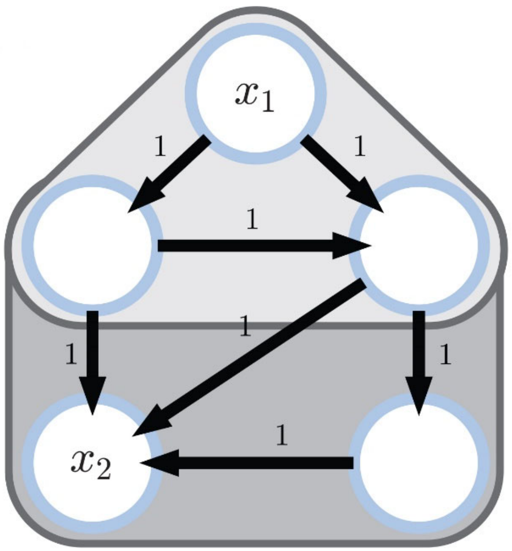
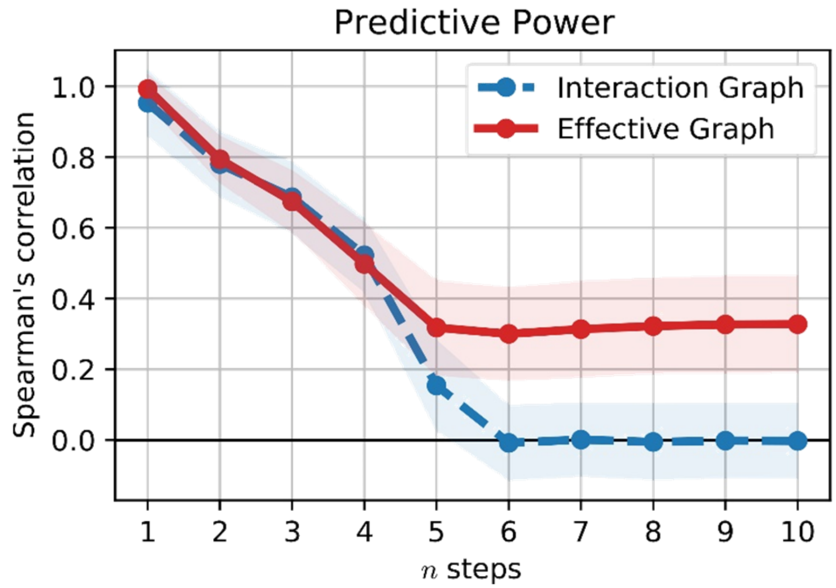
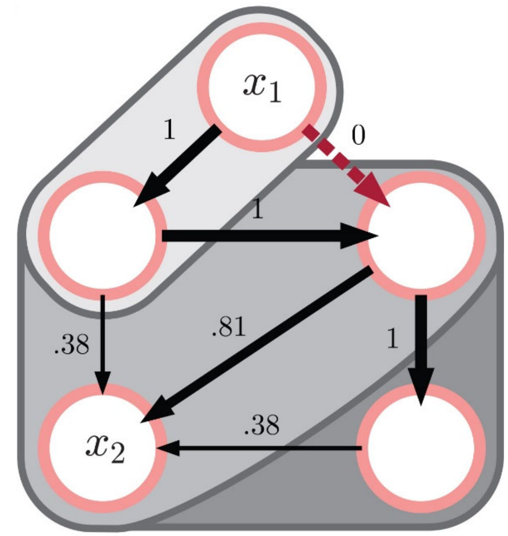
probabilistic and precise characterization of causal (nonlinear) dynamics



$p_3(x_1, x_2) = 1 \times 1 = 1$





$p_3(x_1, x_2) = 1 \times 1 \times 0.81 = 0.81$

Interaction graph typically obtained from (qualitative) pairwise estimation of interaction. No dynamics represented in graph; many dynamics fit same structure.

Effective graph redundancy in dynamics is integrated probabilistically (not estimated). Reveals network of nonlinear interactions that escapes pairwise estimation. Provides **causal explanation** of how dynamical perturbation and control signals propagate in biochemical pathways.

Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.

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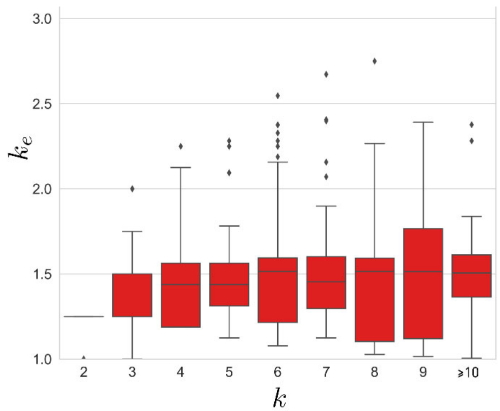
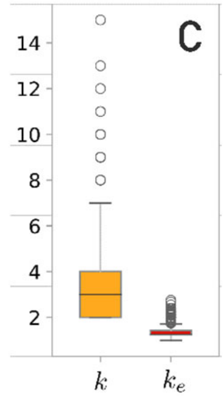
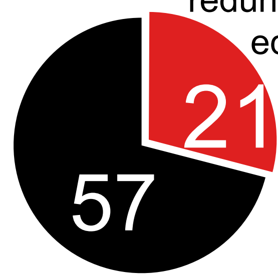
redundant pathways are ubiquitous in biochemical regulation

node-level

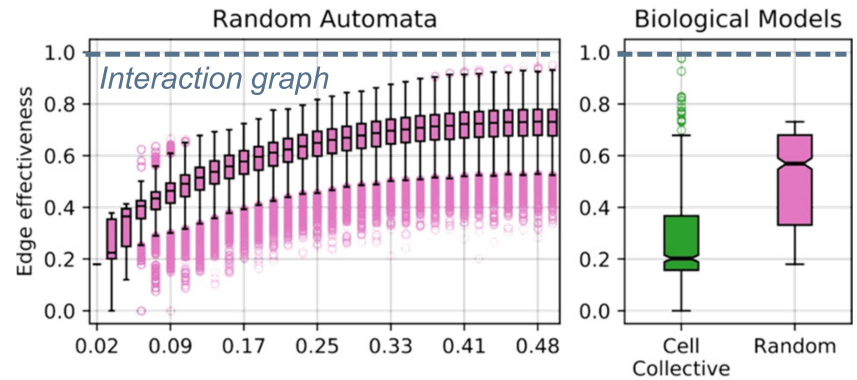




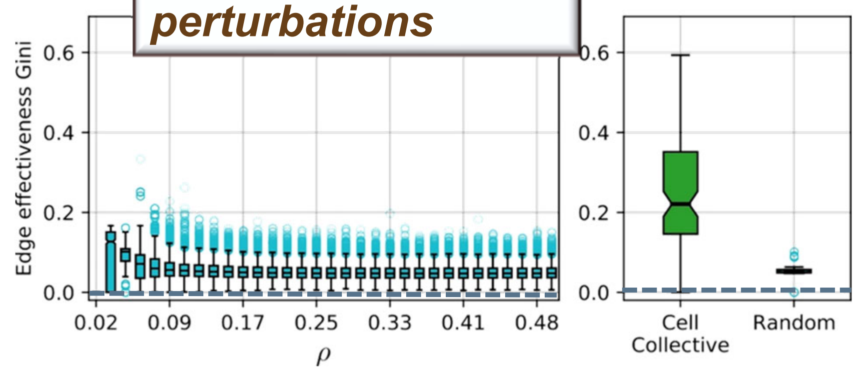
Contain fully redundant edges



edge-level



robustness to most perturbations



dynamical redundancy is pervasive in systems biology models of regulation and signaling: biochemical variables are <u>controlled by substantially fewer inputs</u> than interaction graph suggests.

effectiveness is heterogenous: only few inputs are very effective, most are ineffective or redundant.

Cell Collective

8,220 interactions (of over 3K automata) in 78 models

Gates & Rocha [2016]. *Scientific Reports* **6**, 24456.
Manicka, Marques-Pita, & Rocha, [2021]. *J. Royal Society Interface*. **19**(186):20210659.
Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.

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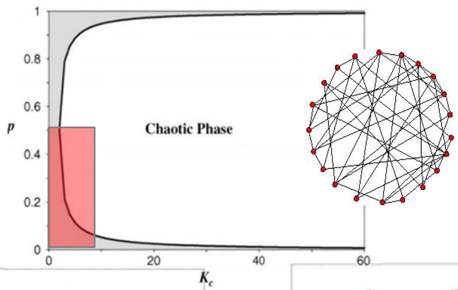
effective connectivity enables greater robustness (random ensembles)

Derrida & Pomeau. [1986] *EPL* . **1.2**: 45.

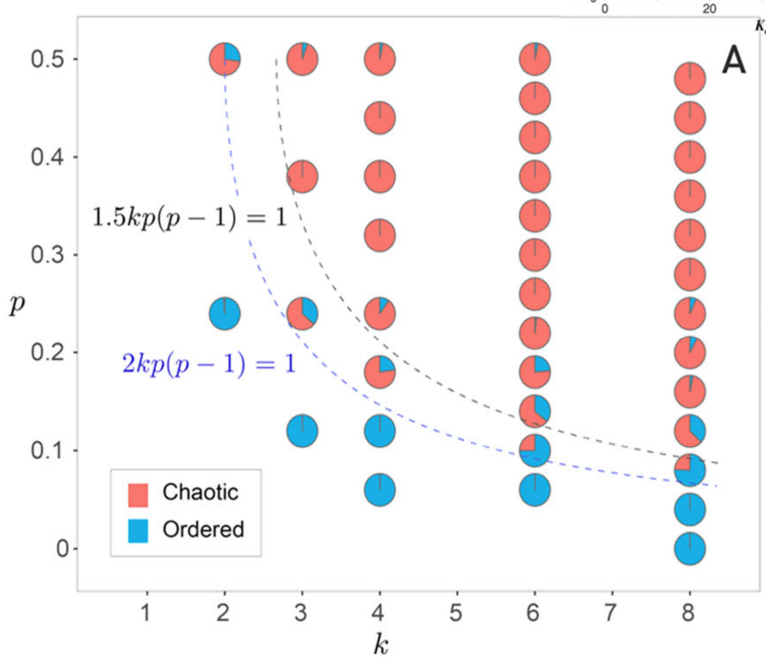
Aldana, M. [2003]. *Physica D.* **185**: 45–66

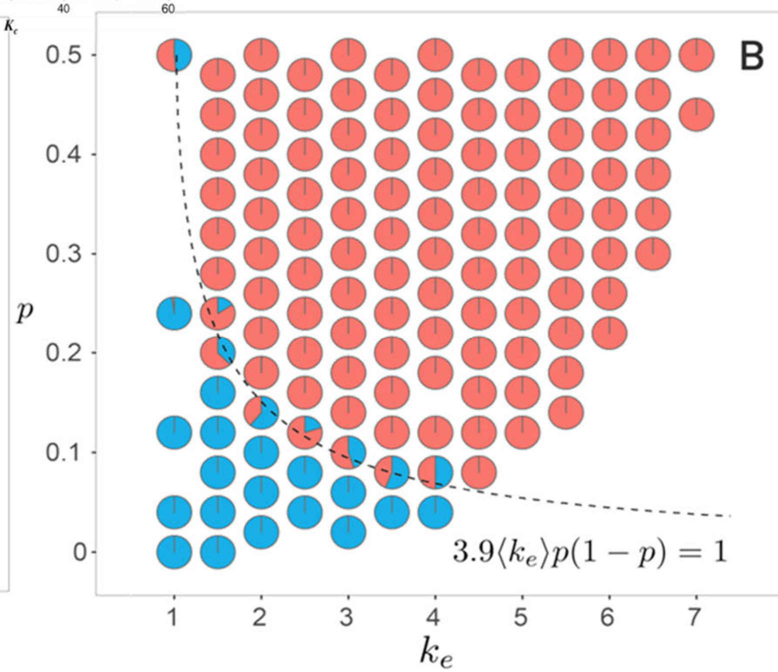
$$\text{c}.\,k.\,p(1-p)=1$$



$$k_e(x)=k(x)-k_r(x)$$

$$\text{c}.\,k_e.\,p(1-p)=1$$





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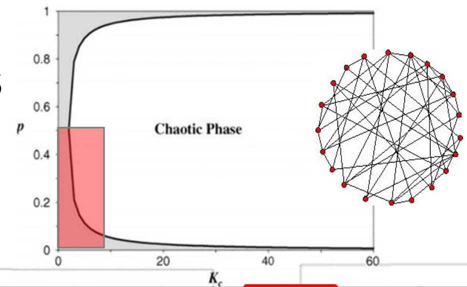
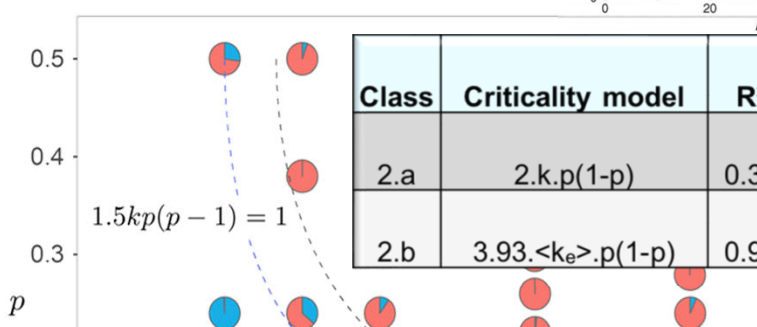
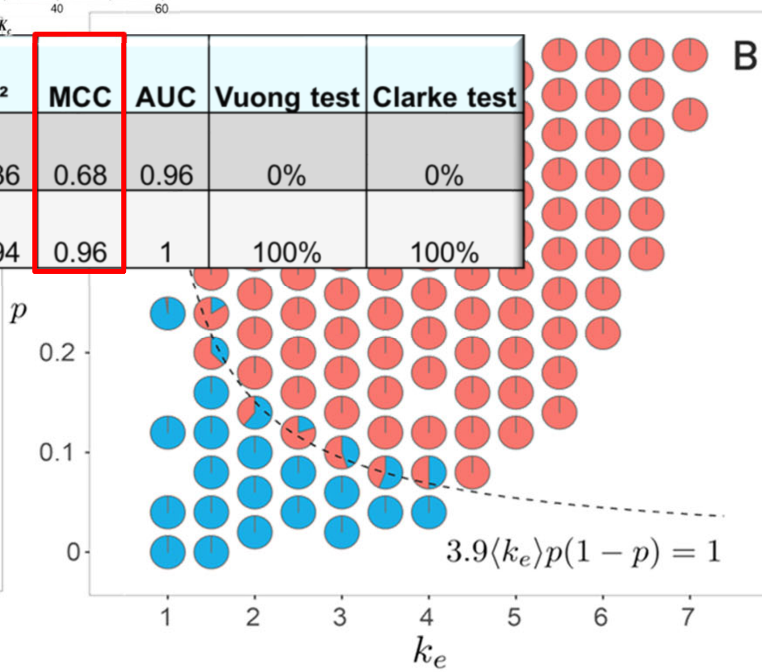


$$k_e(x) = k(x) - k_r(x)$$

$$\mathrm{c}.\,k_e.\,p(1-p) = 1$$



Class	Criticality model	R^2	MCC	AUC	Vuong test	Clarke test
2.a	2.k.p(1-p)	0.36	0.68	0.96	0%	0%
2.b	3.93.<k_e>.p(1-p)	0.94	0.96	1	100%	100%



Stable biochemical networks can exist well into expected chaotic behavior, provided ***canalization*** *is selected for*: dynamics "buffers" underlying interaction structure New theory uses **only dynamical redundancy properties**

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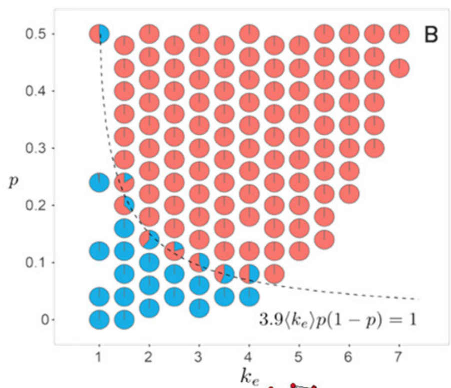
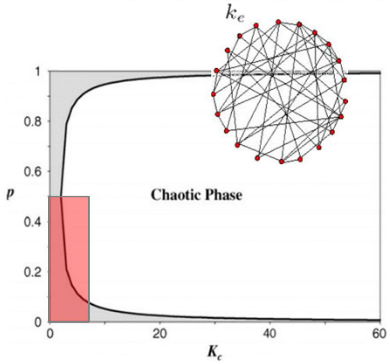
effective connectivity enables greater robustness (random ensembles)

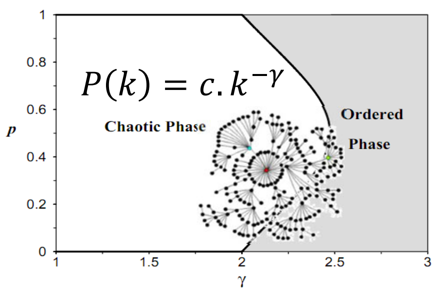
homogeneous networks



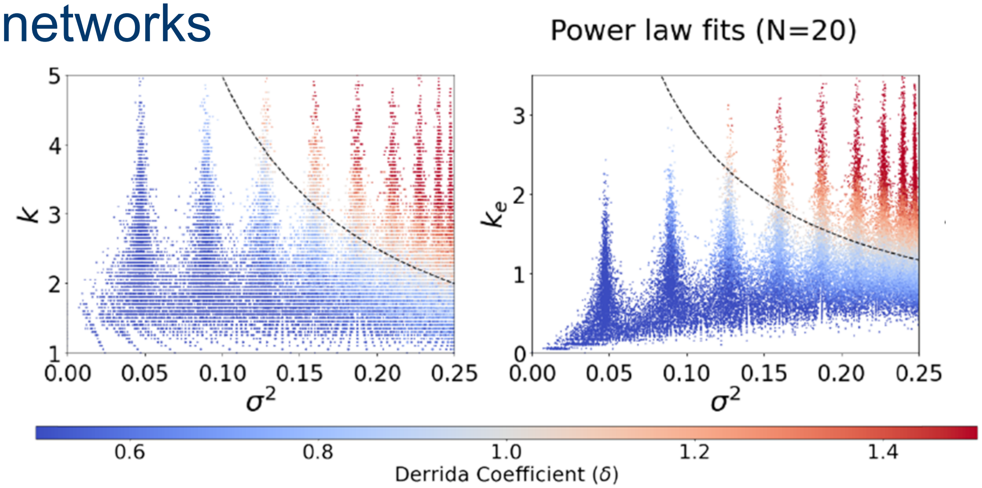


$$c.k_e.p(1-p)=1$$

heterogenous networks



Stable biochemical networks can exist well into expected chaotic behavior, provided ***canalization*** *is selected for*: dynamics “buffers” underlying interaction structure



$$\sigma^2 = p(1-p)$$

N	20	50	100	200
$\sigma^2 k$	93.83	95.04	95.88	96.71
$\sigma^2 k_e$	96.09	96.35	96.53	96.8

Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
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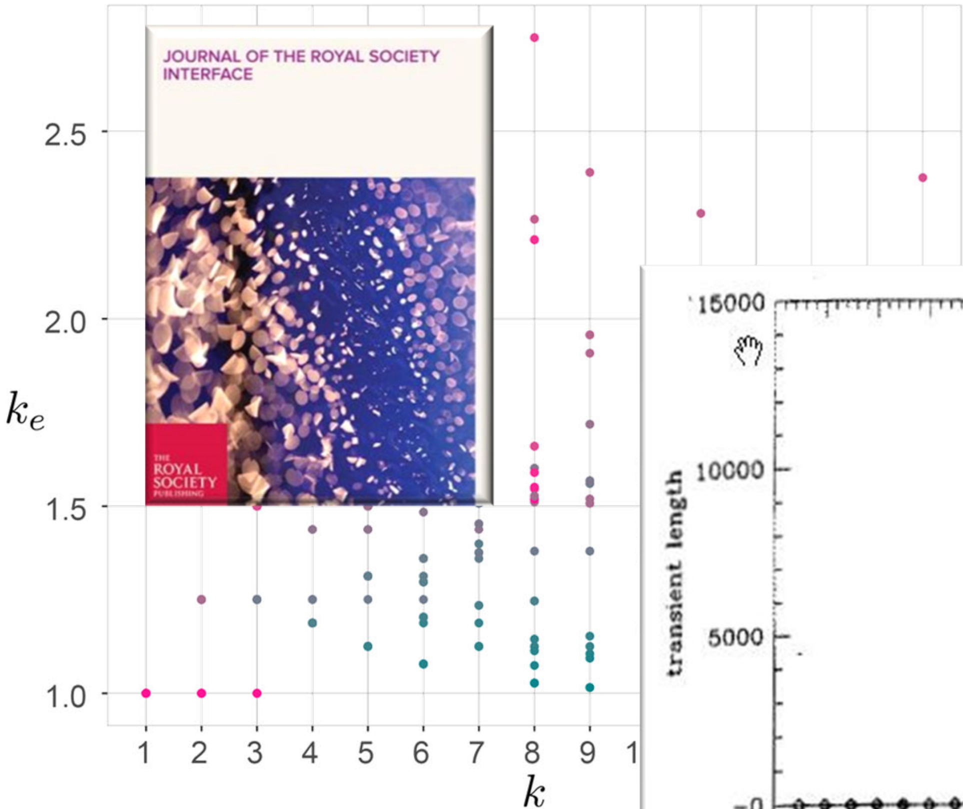
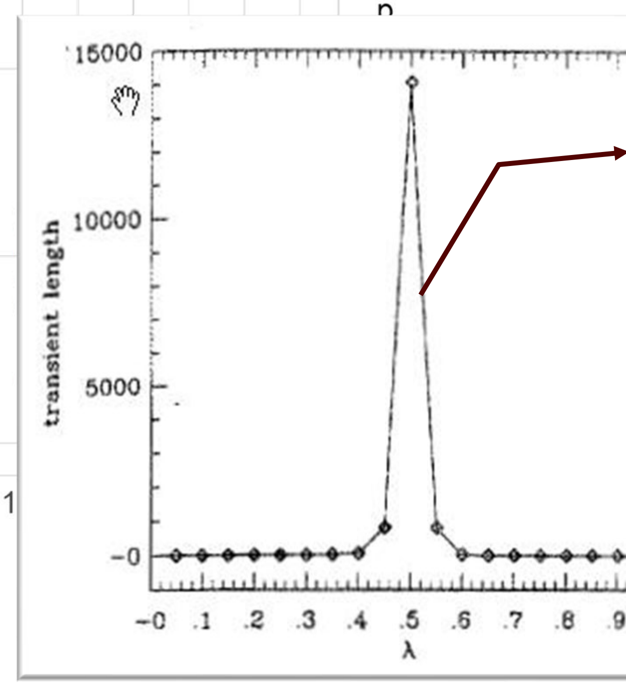
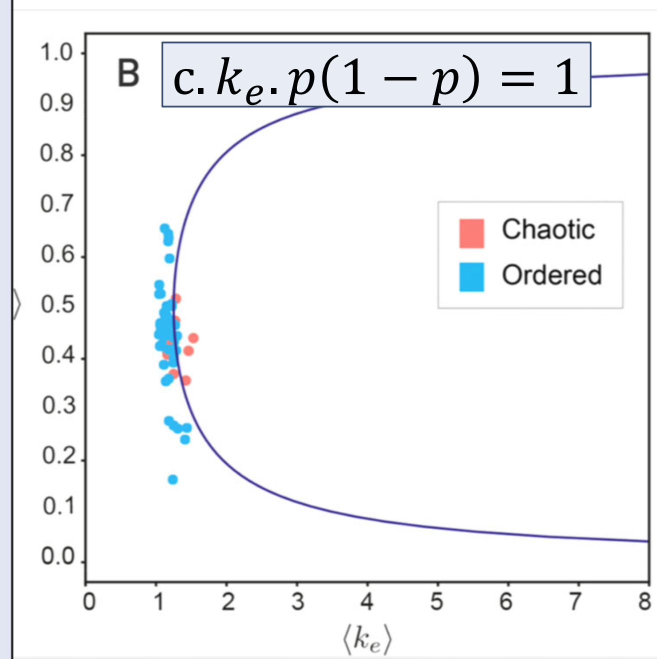
ubiquitous canalization in (experimentally-validated) systems biology models

low effective connectivity leads networks closer to "edge of chaos"



63 Biochemical regulation models with very low effective connectivity despite high connectivity. In new theory networks are near criticality





Cell Collective

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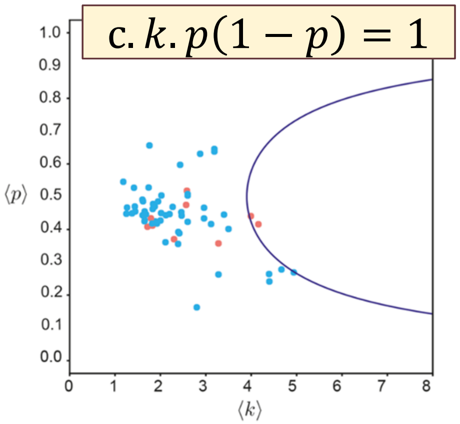
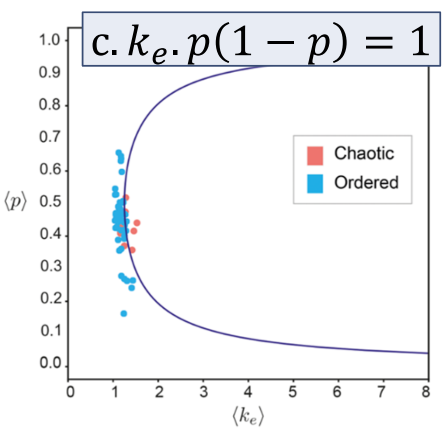
ubiquitous canalization in (experimentally-validated) systems biology models

effective connectivity better predicts critical transition

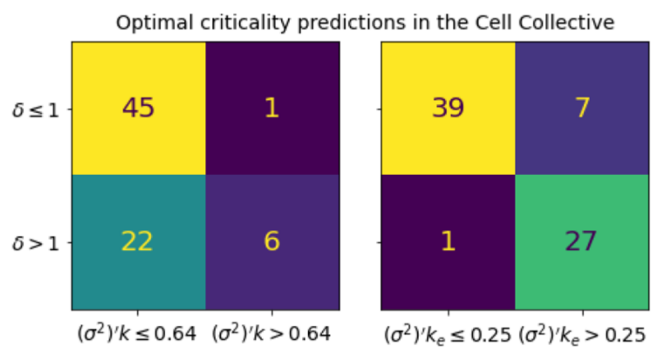
homogeneous networks



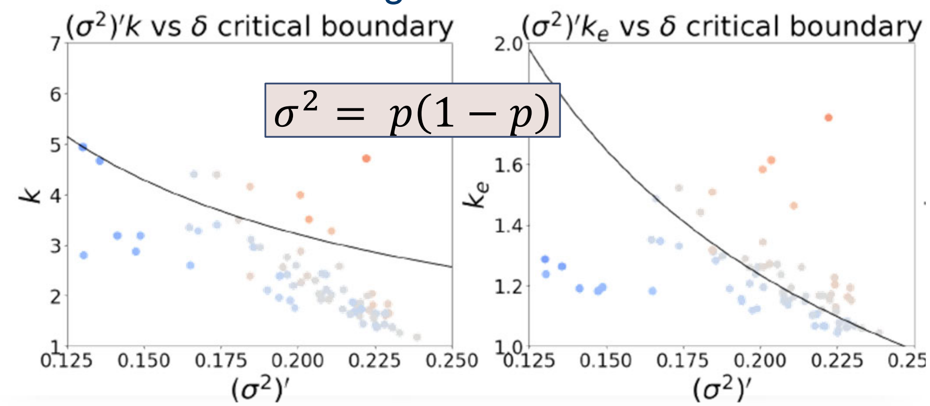


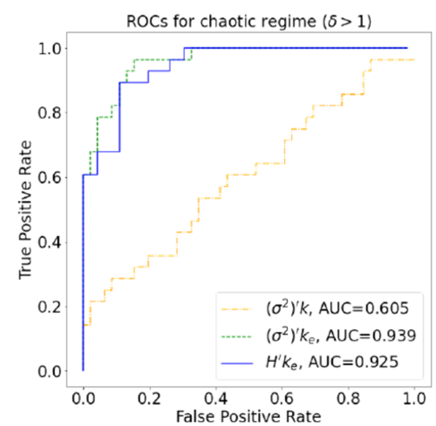
Biochemical regulation models have very low effective connectivity despite high connectivity. Accounting for heterogeneity and canalization better predicts dynamical regime

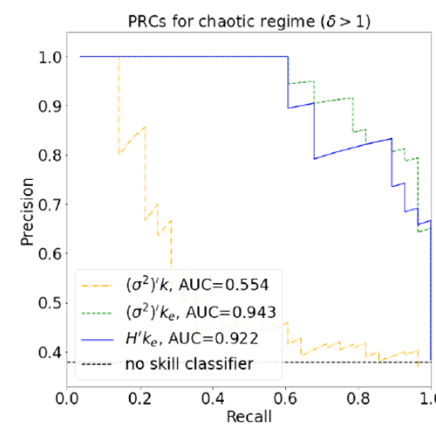
Cell Collective



heterogenous networks







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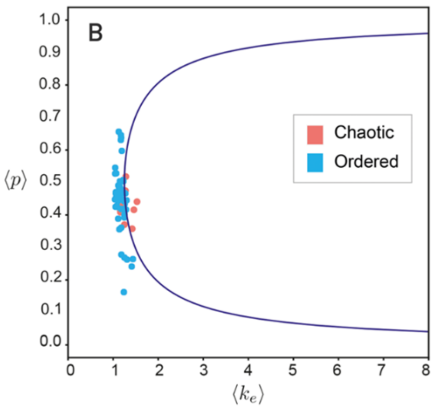
ubiquitous canalization in (experimentally-validated) systems biology models

but is there an edge of chaos boundary?

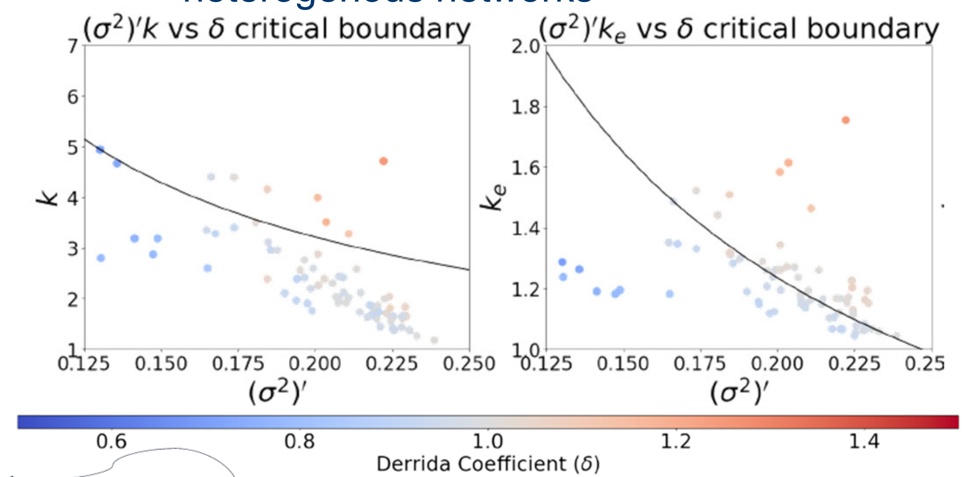
homogeneous networks



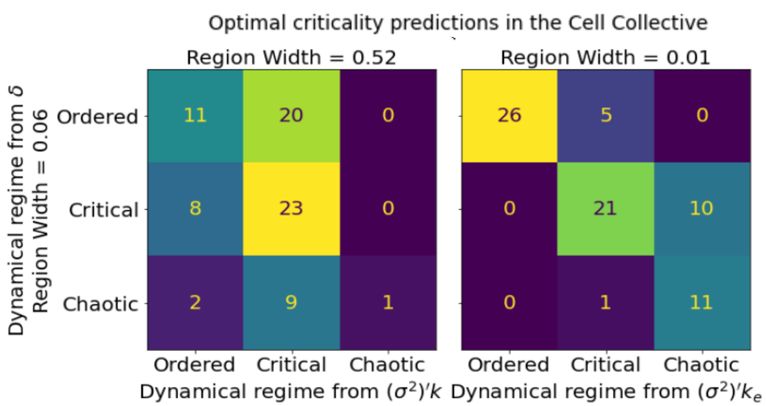
Once canalization (dynamical redundancy) is considered optimal critical region very small and dynamical range is better predicted.

Cell Collective

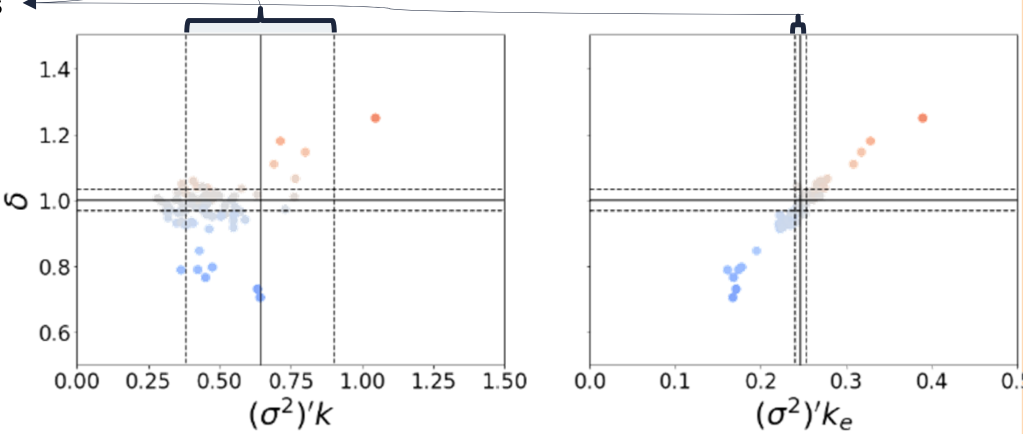
heterogenous networks



Optimal classification thresholds



IQR Of Derrida



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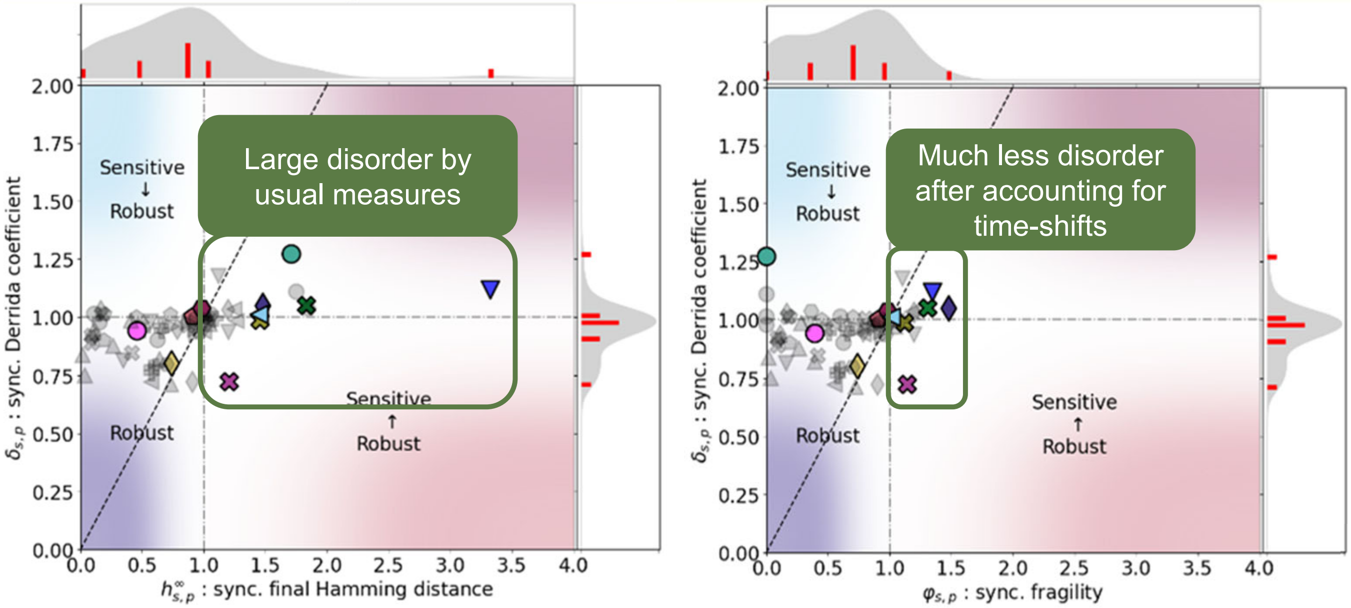
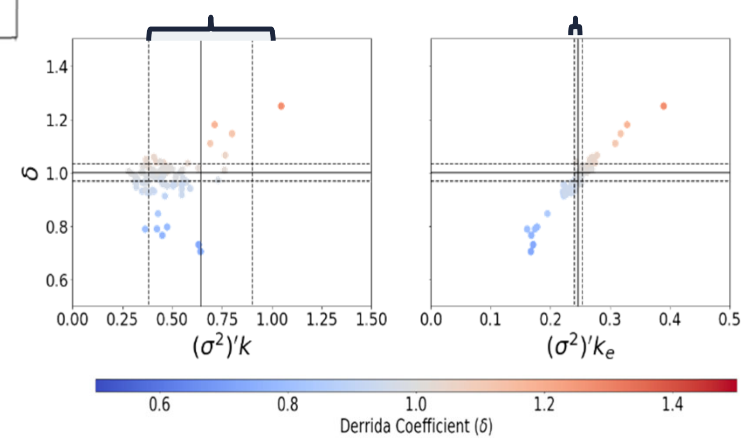


Criticality might arise from interactions of amongst largely stable modules

Cell Collective



More accurate measures of dynamical regime show that experimentally-validated systems biology are far from the edge of chaos

Park, Costa, Rocha, Albert, & Rozum [2023]. *PRX Life*. **1**, 023009.
Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
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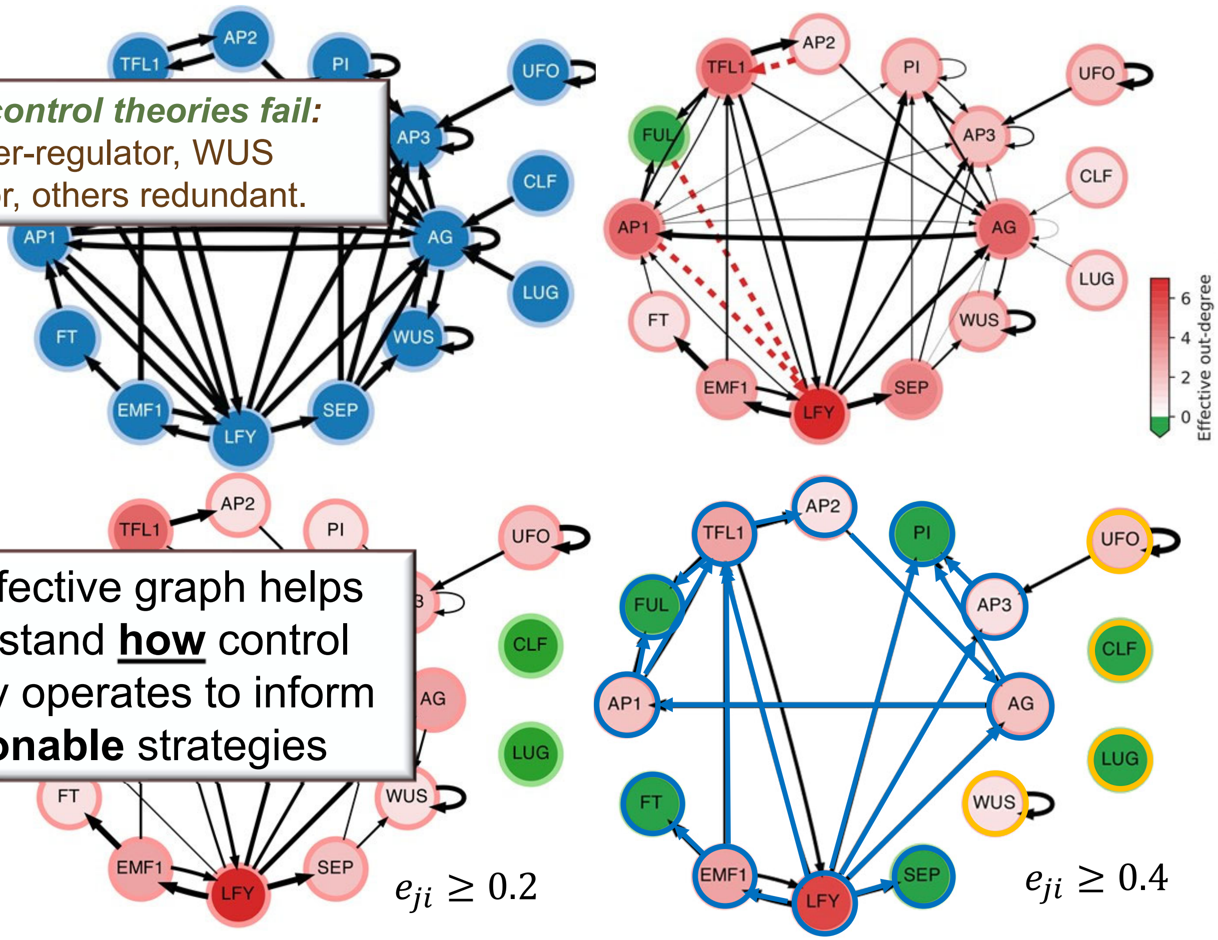
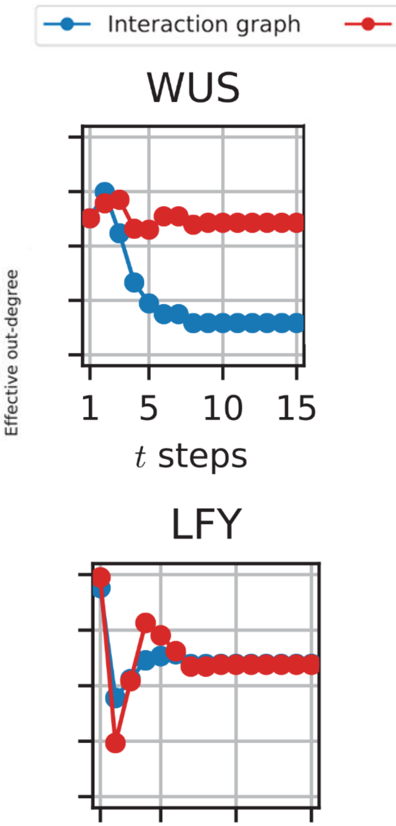
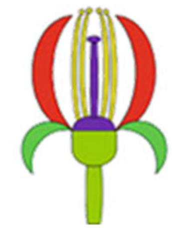
Thaliana control pathways (using structure and dynamics information)



Structural control theories fail:
LFY is master-regulator, WUS autoregulator, others redundant.

The effective graph helps understand **how** control actually operates to inform **actionable** strategies





Chaos et al [2006]. *J. of Plant Growth Regulation*. **25**(4): 278-289.

Gates & Rocha [2016]. *Sci. Rep.* **6**, 24456.
Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.

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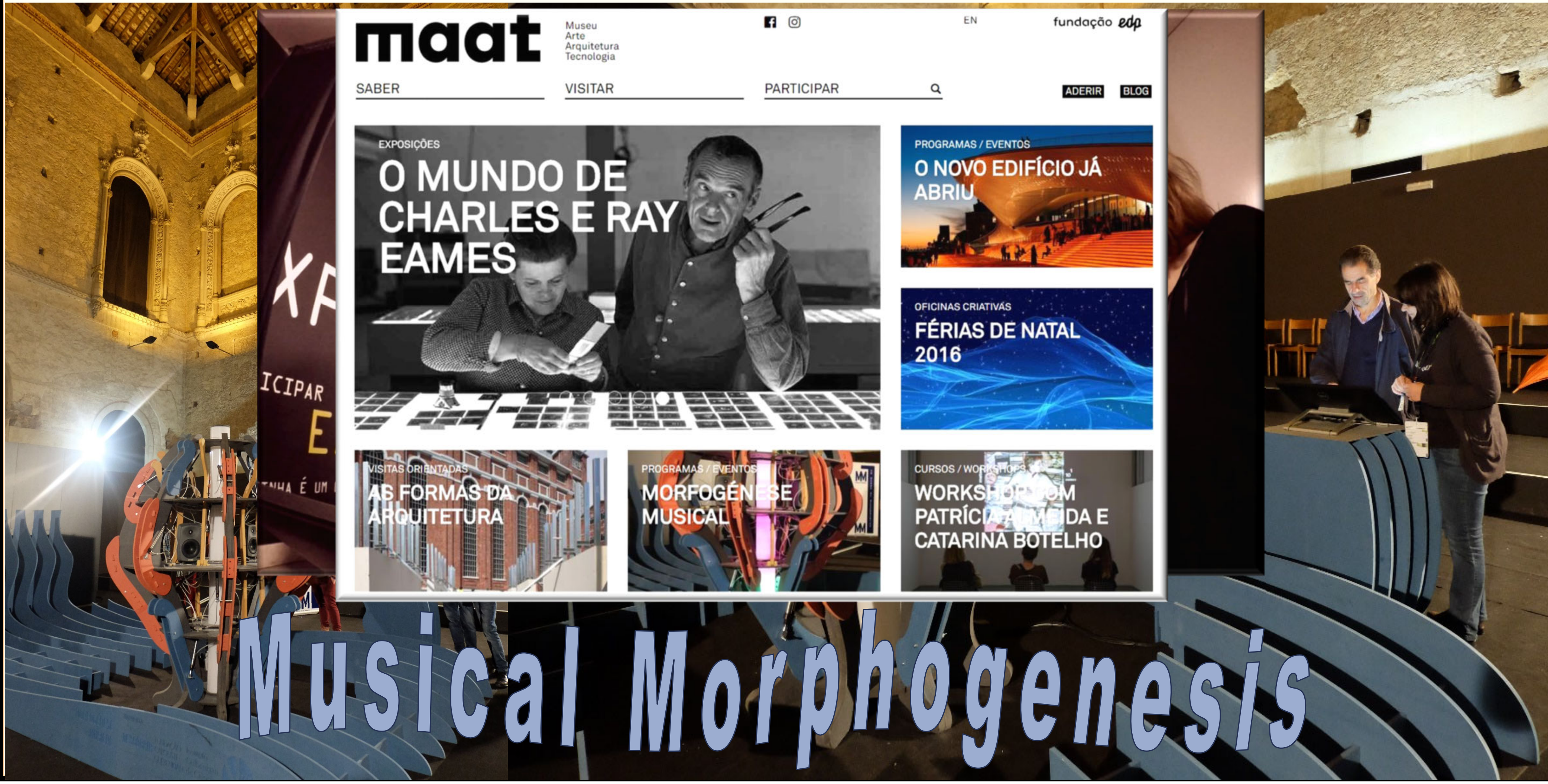
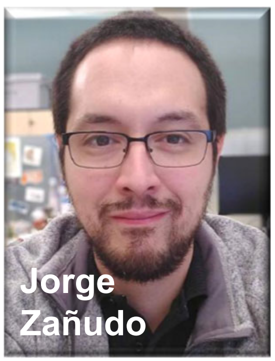
Boolean networks, control, sound, art, and education

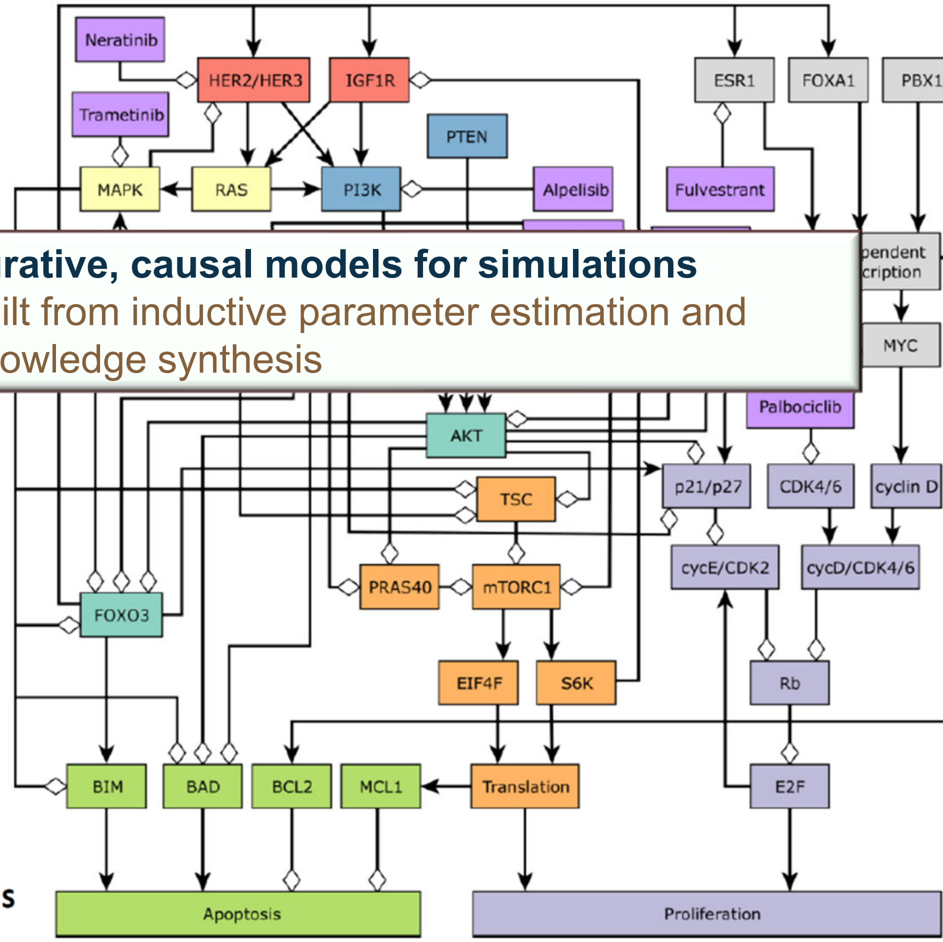
Boolean networks, control, sound, art, and education



predicting drug and therapy targets in causal models

discrete modeling of within-cell **oncogenic signal transduction**, recapitulates known resistance PI3K inhibitors. Suggests novel combinatorial interventions.





Integrative, causal models for simulations

- built from inductive parameter estimation and knowledge synthesis

A network modeling approach to elucidate drug resistance mechanisms and predict combinatorial drug treatments in breast cancer

Jorge G. T. Zañudo[1,2,3,*] and Réka Albert[1,4,&]

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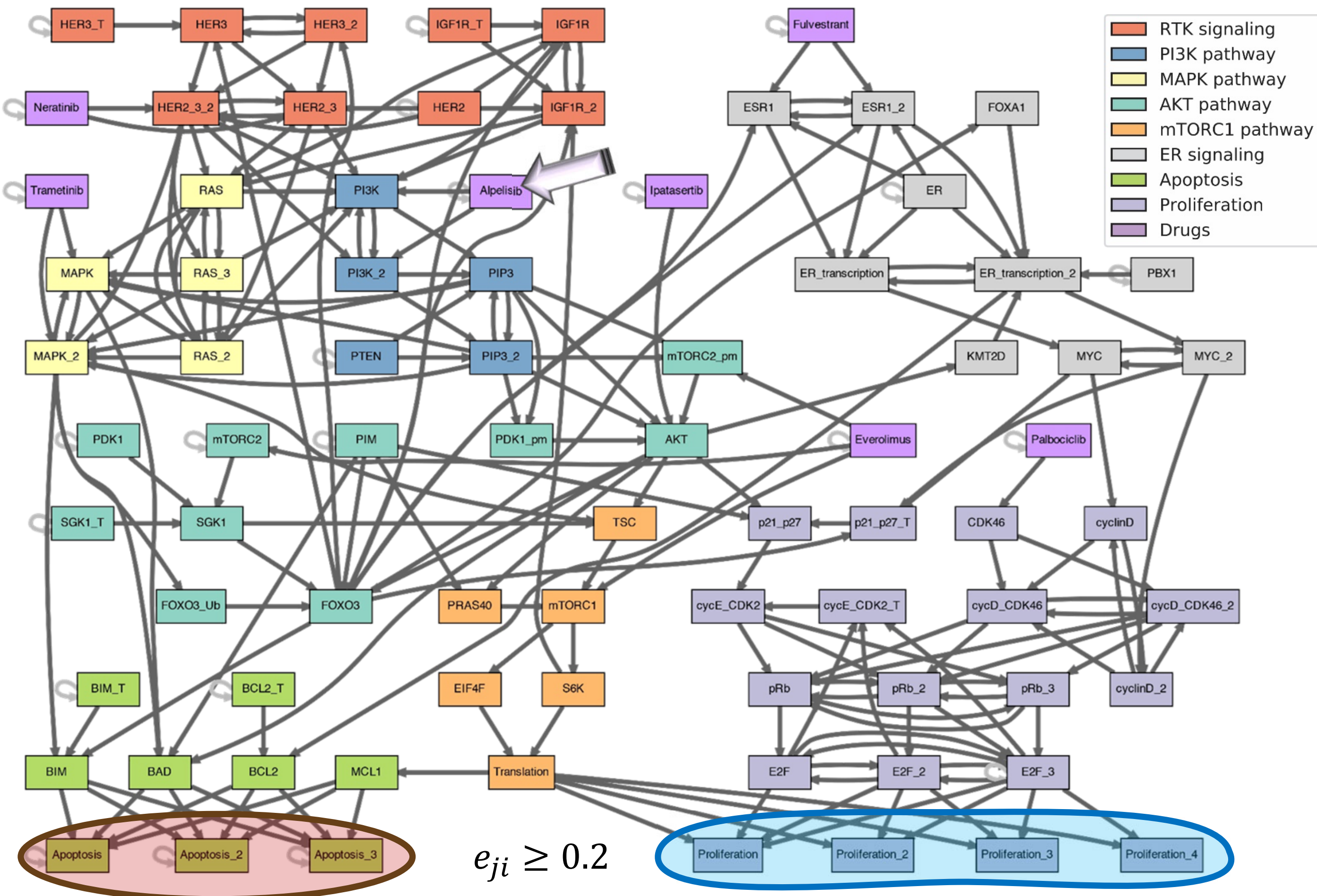
ER+ breast cancer model

uncovering and characterizing control pathways for drug therapy



$e_{ji} \geq 0.2$

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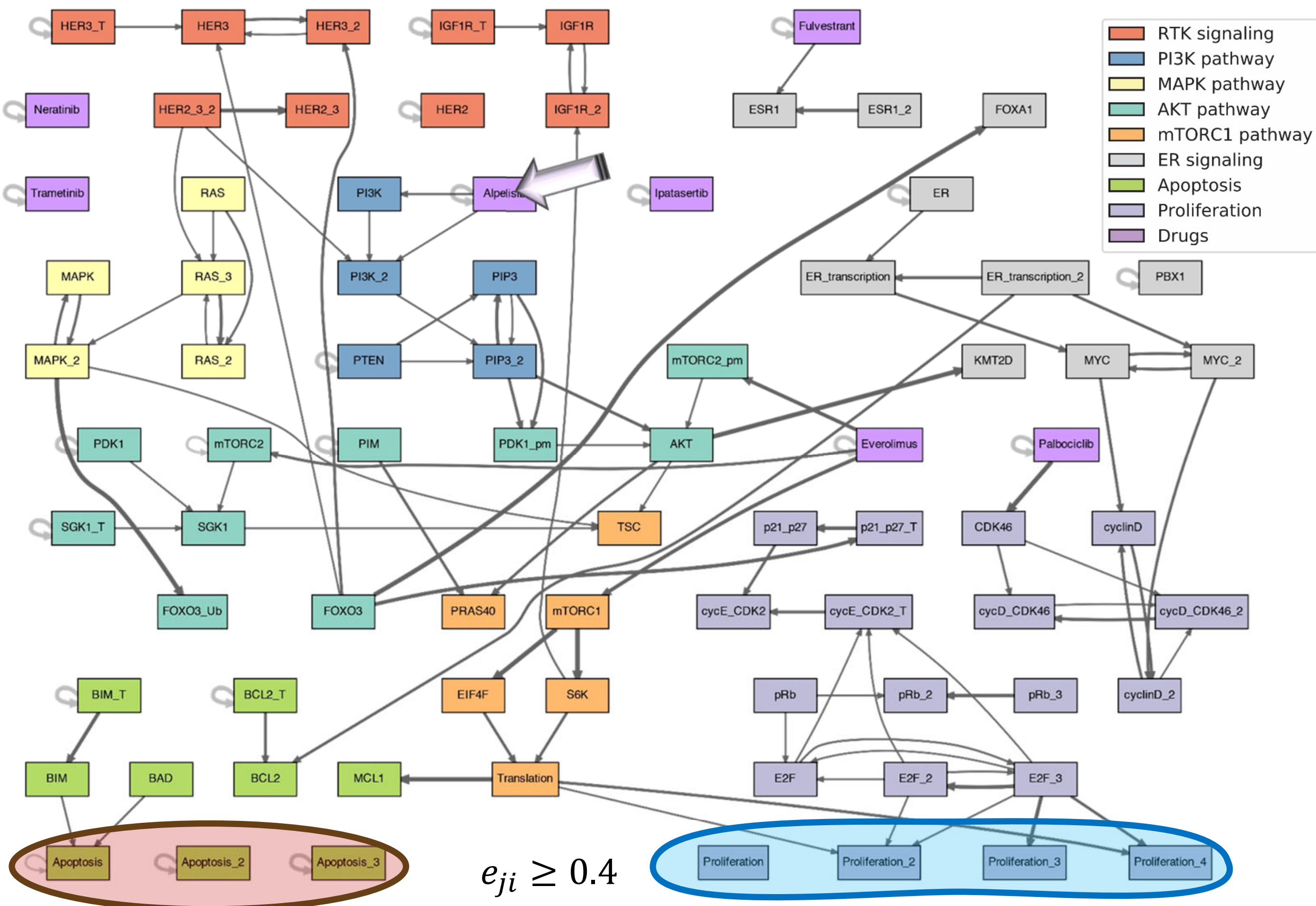
uncovering and characterizing control pathways for drug therapy



$e_{ji} \geq 0.4$

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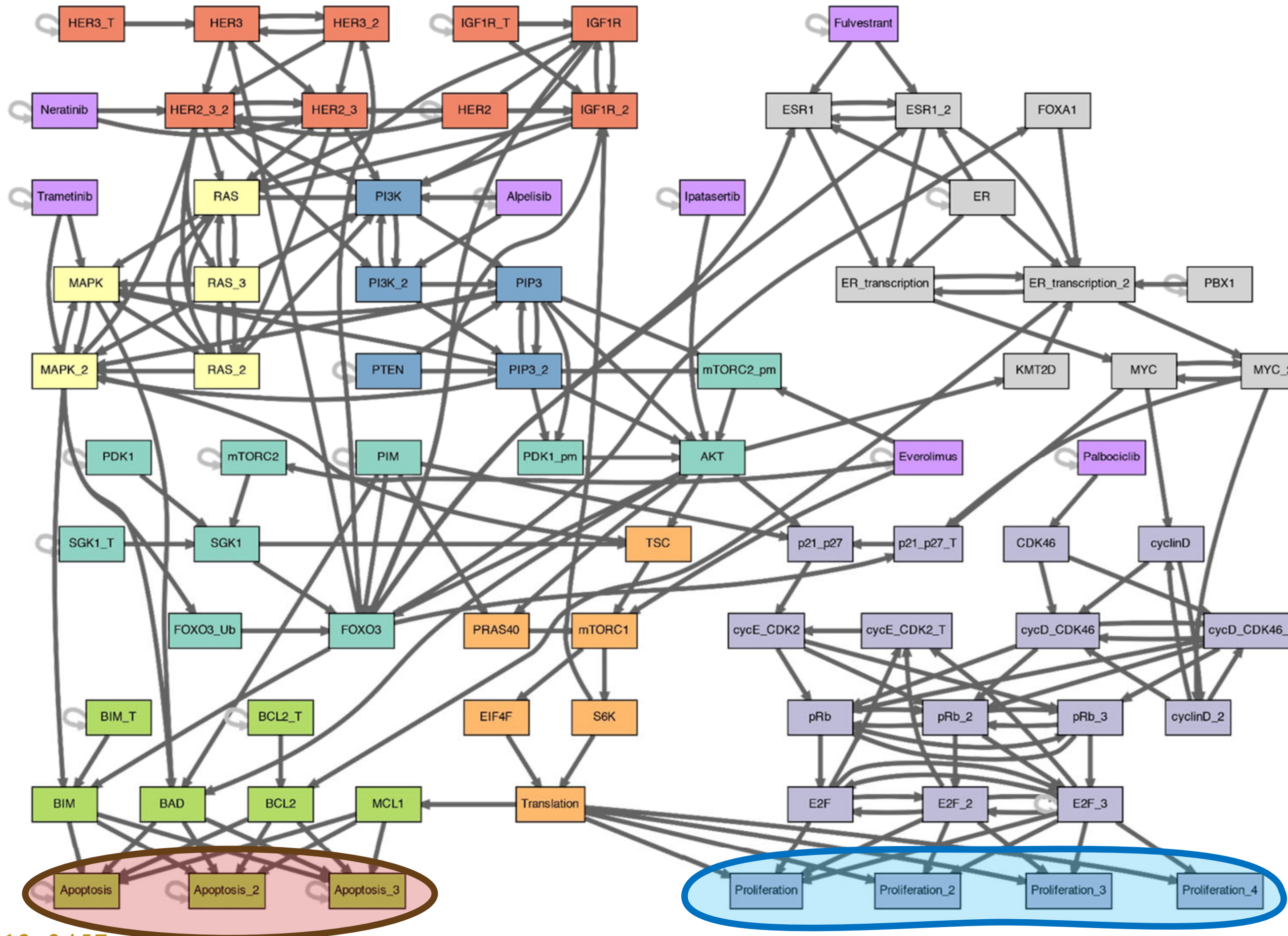
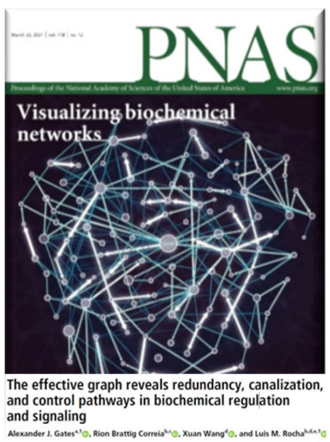
causal (modular) dynamics via conditional effective connectivity





Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
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Rocha L.M. [2022]. *Bioinformatics*. **btac360**.
Parmer, Rocha & Radicchi [2022]. *Nature Communications*. **13**, 3457.
Gates,Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
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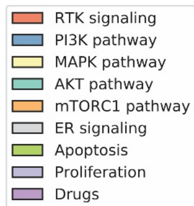

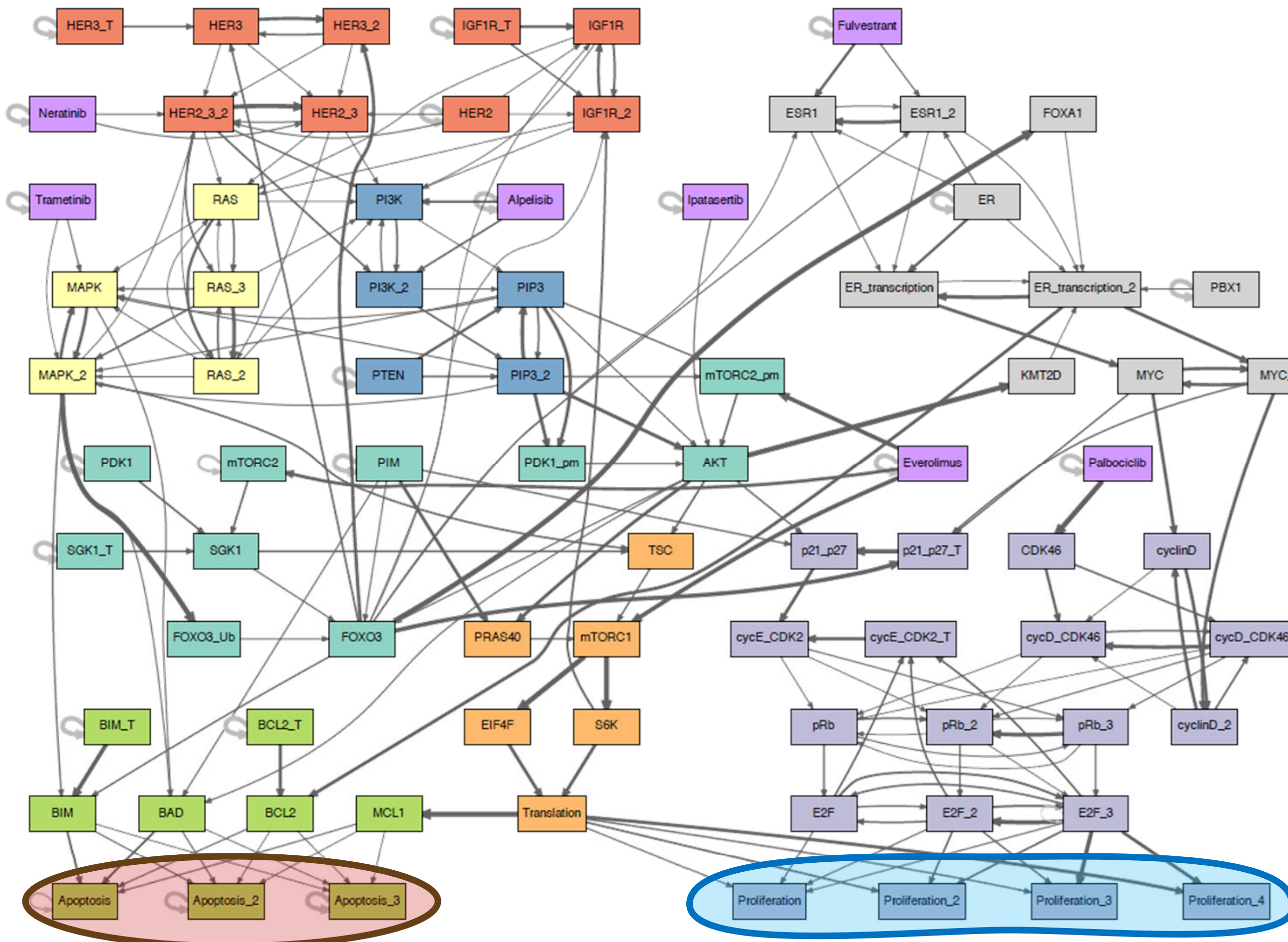

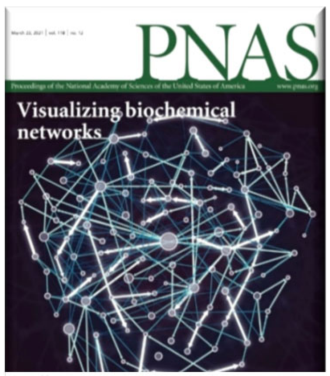

The effective graph reveals redundancy, canalization, and control pathways in biochemical regulation and signaling

Alexander J. Gates, Rion Brattig Correia, Xuan Wang, and Luis M. Rocha

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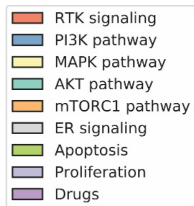

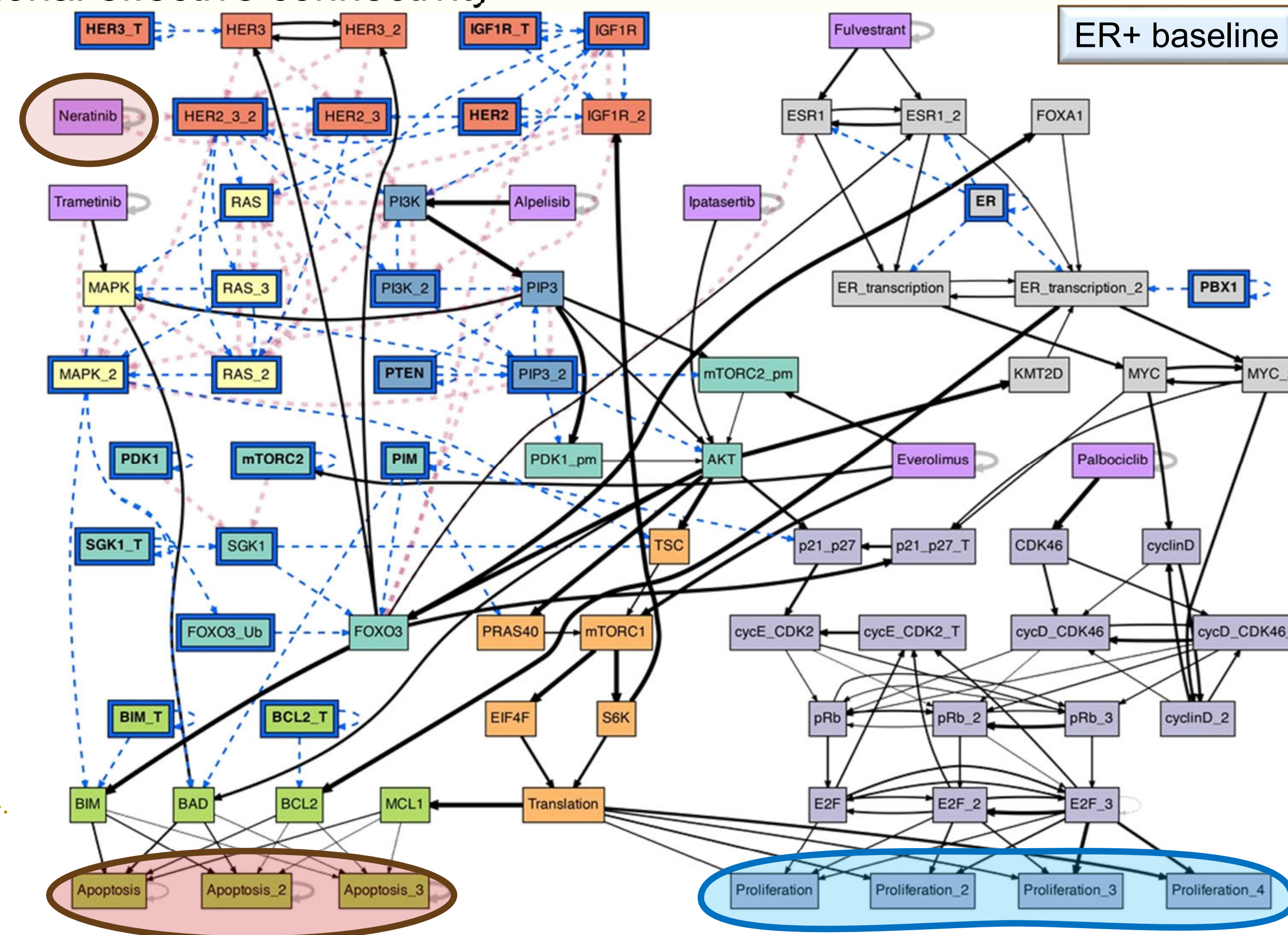

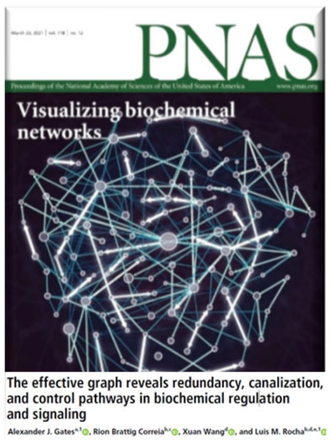

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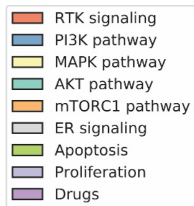

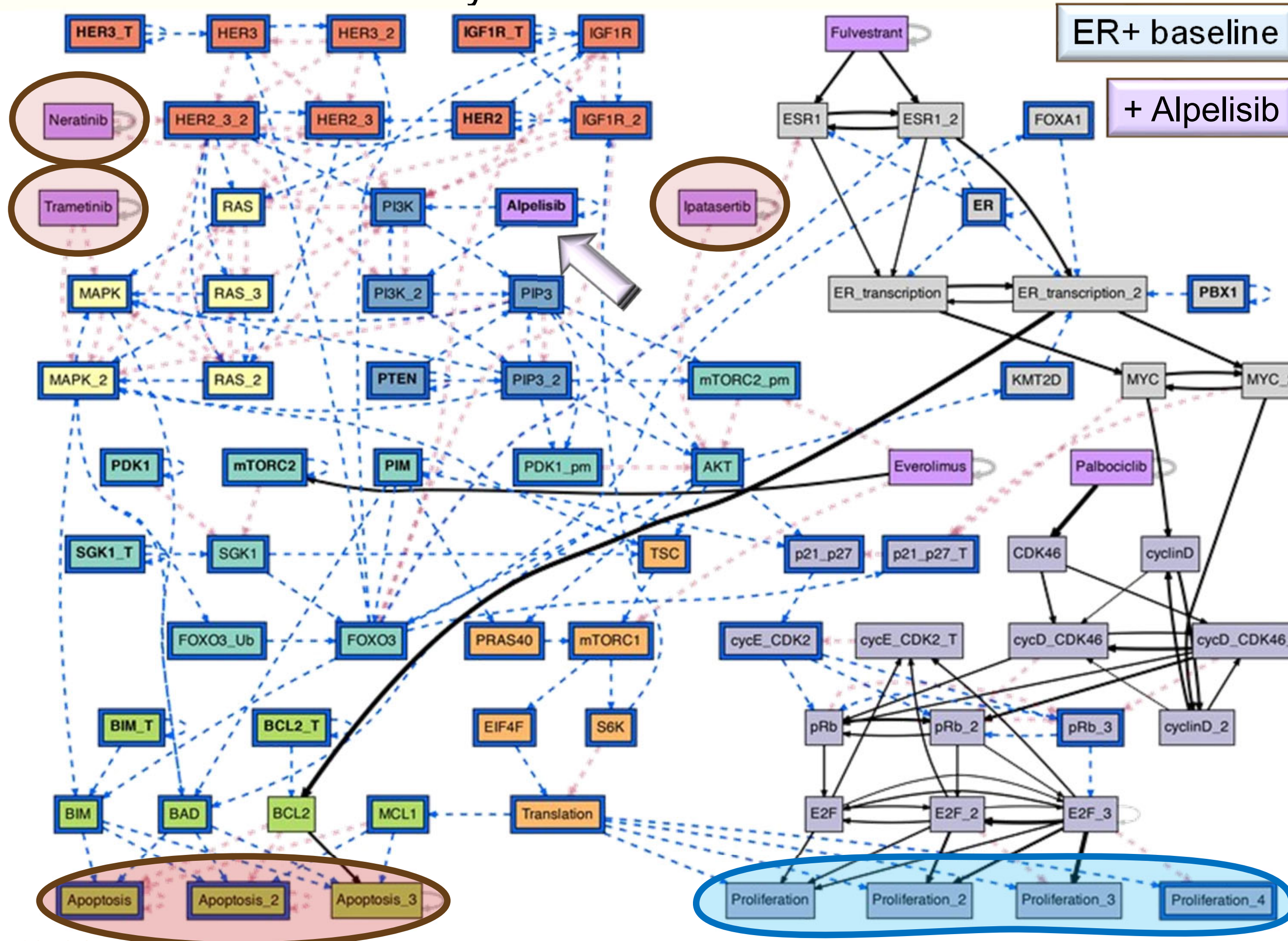

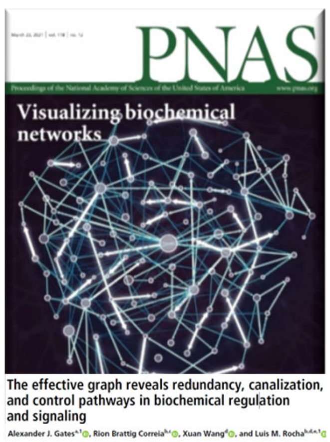

Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
Manicka, Marques-Pita, & Rocha, [2022]. *J. Royal Society Interface*. **19**(186):20210659.
Rocha L.M. [2022]. *Bioinformatics*. **btac360**.
Parmer, Rocha & Radicchi [2022]. *Nature Communications*. **13**, 3457.
Gates,Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
Gates & Rocha [2016]. *Scientific Reports* **6**, 24456.

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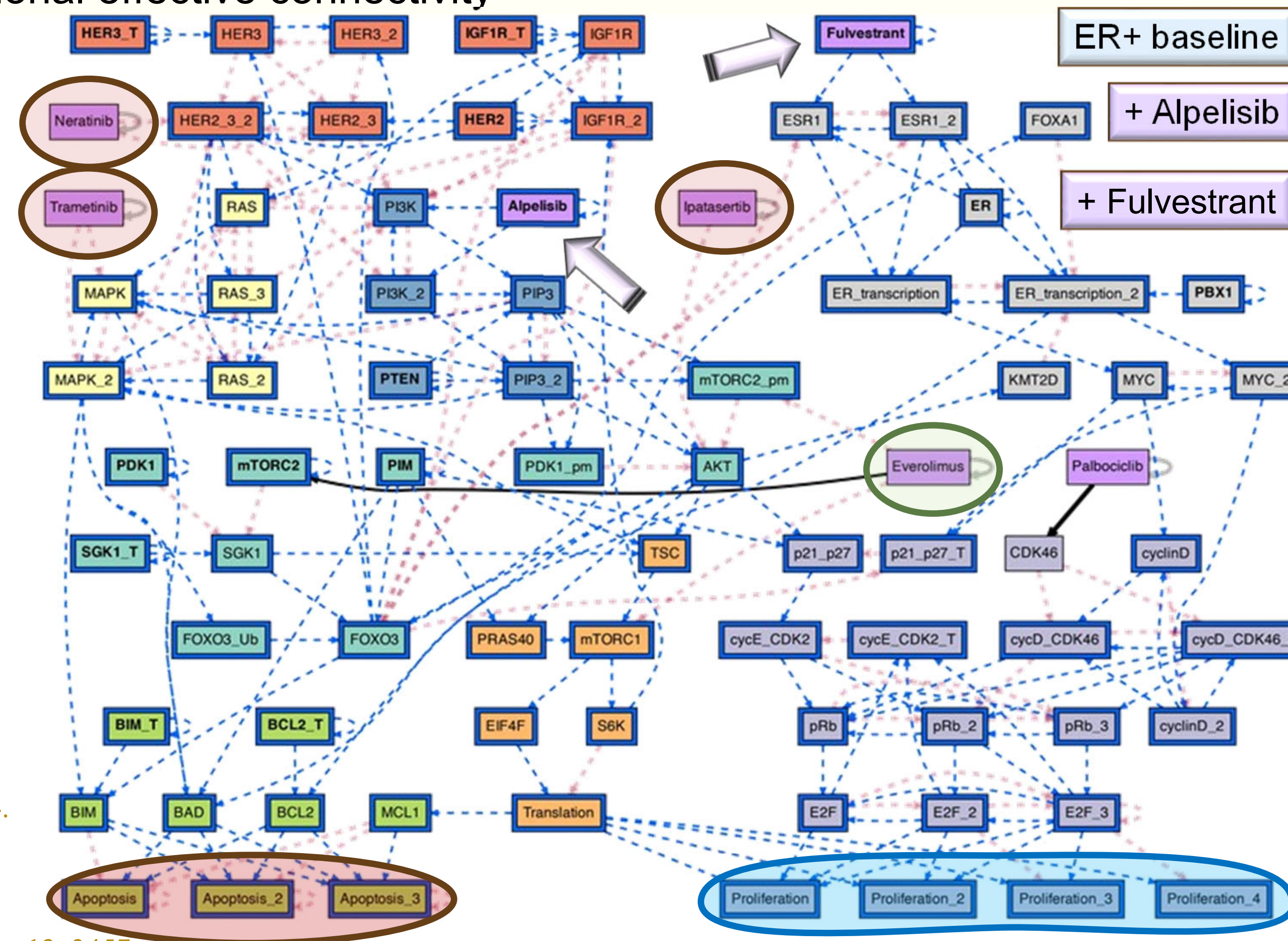
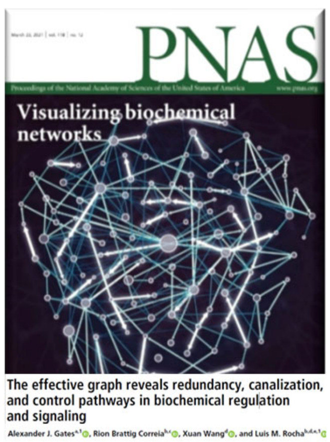
causal (modular) dynamics via conditional effective connectivity





Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
Manicka, Marques-Pita, & Rocha, [2022]. *J. Royal Society Interface*. **19**(186):20210659.
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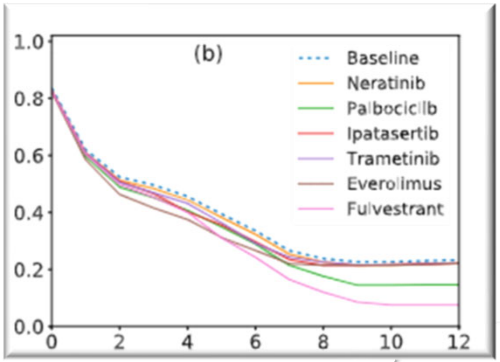

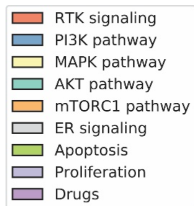

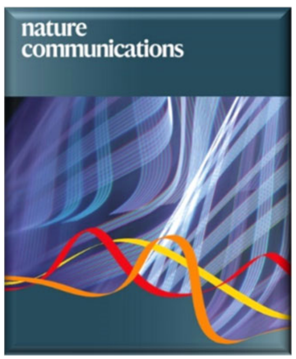

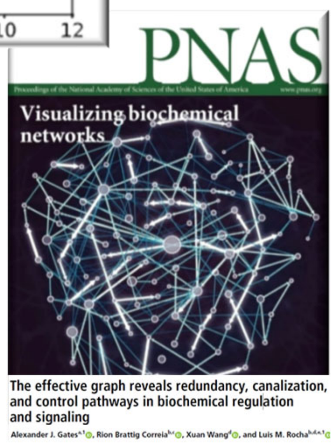

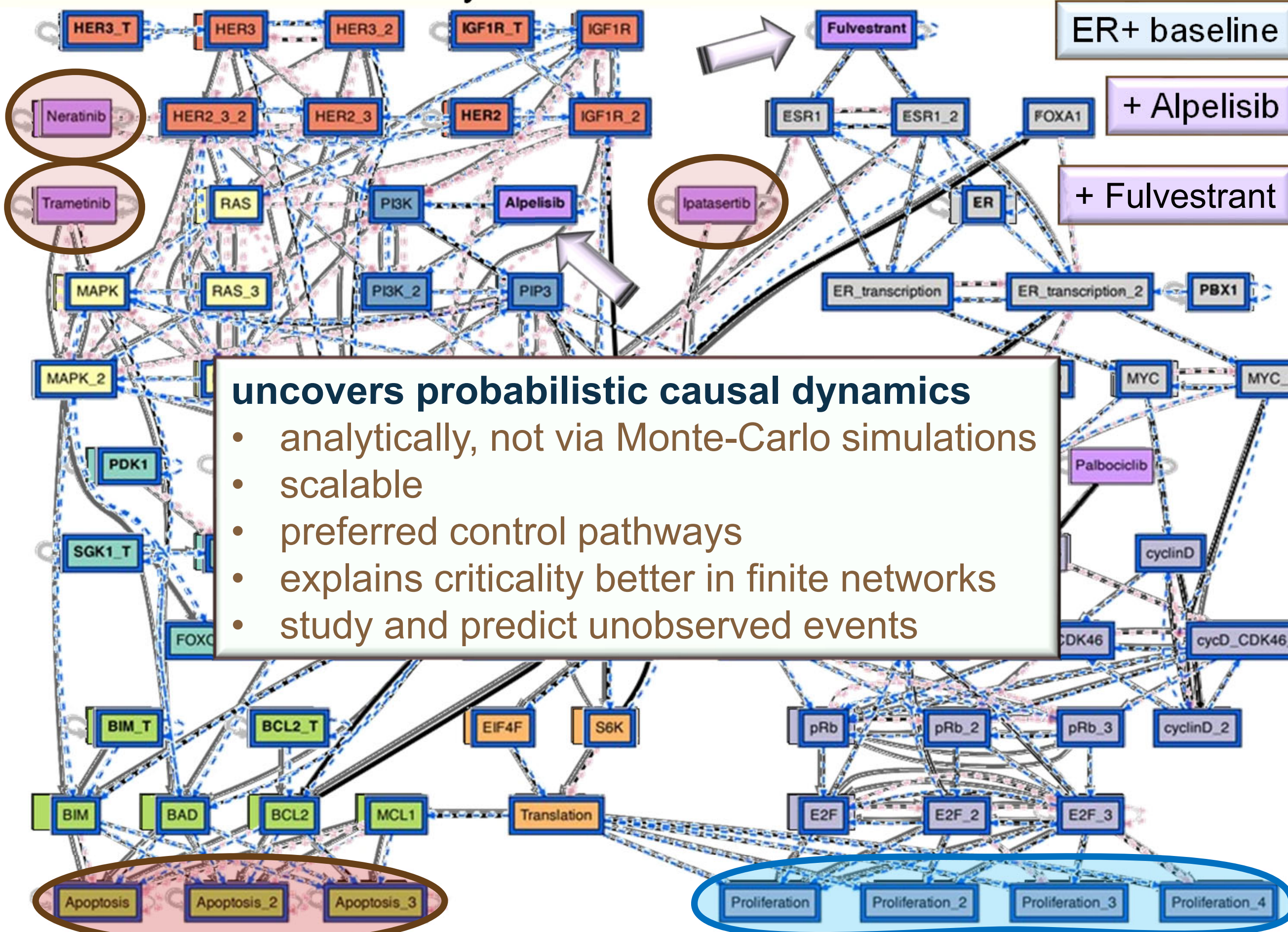

uncovers probabilistic causal dynamics

- analytically, not via Monte-Carlo simulations
- scalable
- preferred control pathways
- explains criticality better in finite networks
- study and predict unobserved events

Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
Manicka, Marques-Pita, & Rocha, [2022]. *J. Royal Society Interface*. **19**(186):20210659.
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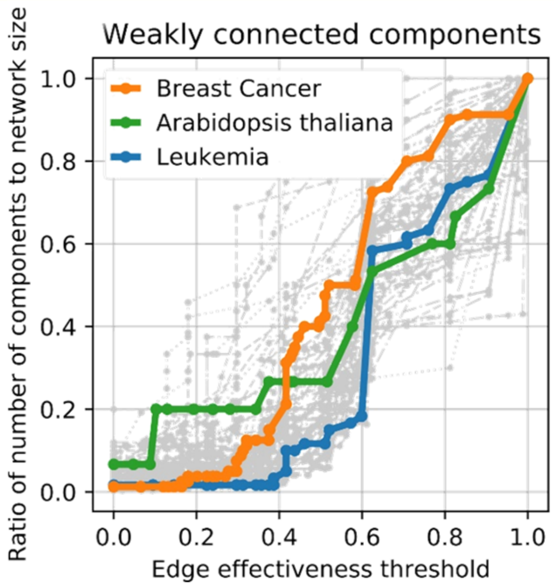
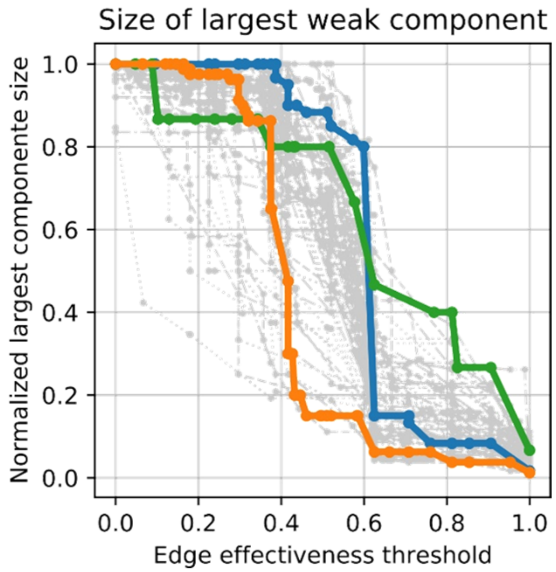
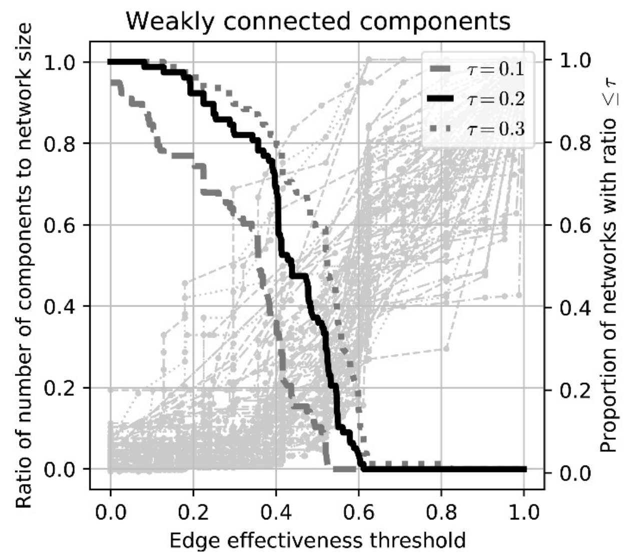
dynamically-decoupled modules







Most networks preserve a large weakly connected component up to edge effectiveness ≤ 0.4.

Cell Collective

Allows comparisons between networks regarding the ability to effectively propagate signals.

But most break into dynamically-decoupled modules for edge effectiveness > [0.4, 0.6].

Experimentally-validated models suggest biochemical regulation highly ***modular*** with low effectiveness interactions between modules granting robustness to perturbations.

Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
Manicka, Marques-Pita, & Rocha, [2022]. *J. Royal Society Interface*. **19**(186):20210659.
Costa, Rozum, Marcus, & Rocha[2023]. *Entropy*. **25**(2):374.
Park, Costa, Rocha, Albert, & Rozum [2023]. *PRX Life*. **1**, 023009.

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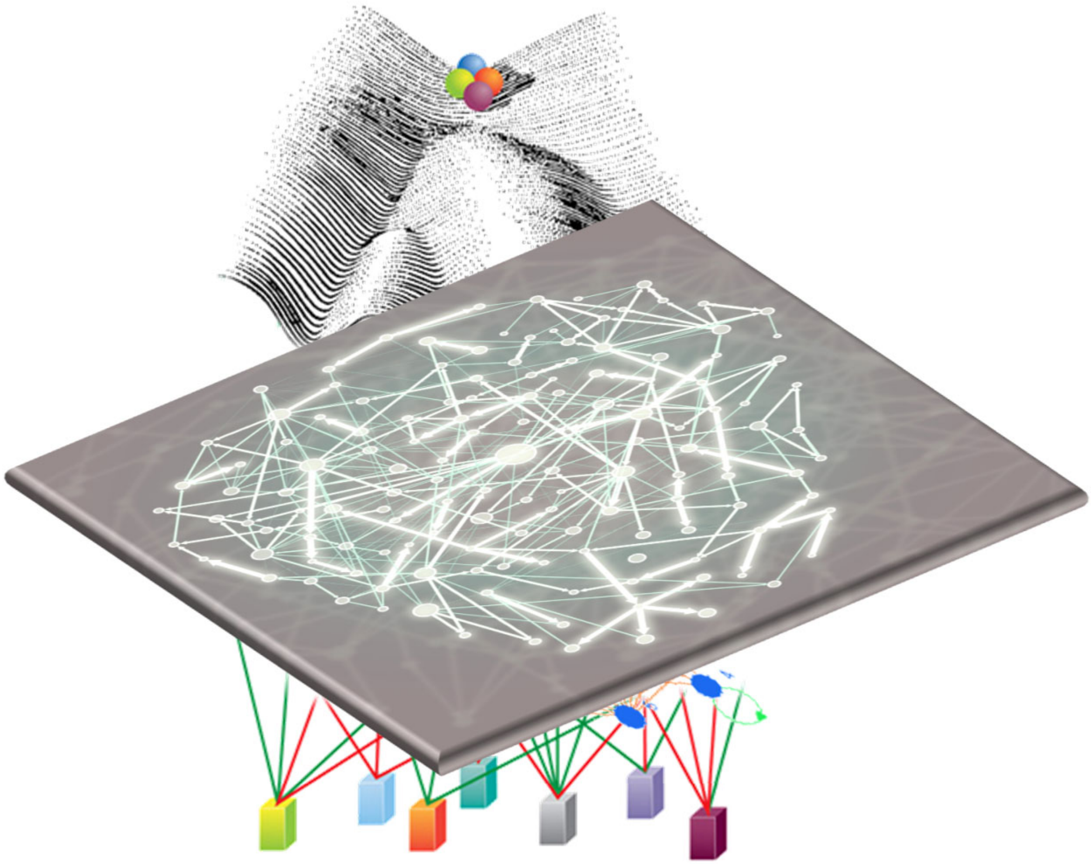
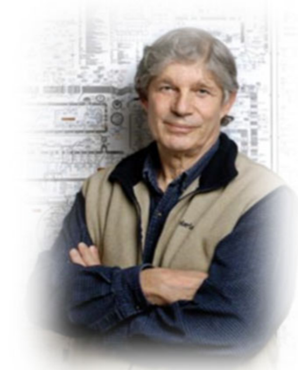
canalization as a key mechanism for resilience

from evolutionary robustness to network and dynamical redundancy





Kauffman, S. A. (1984). *Phys. D Nonlinear Phen.***10**,145–156.

Waddington CH (1942). *Nature*.**150** (3811):563–565

robustness of phenotypes is the result of a ***buffering*** of the developmental process.

dynamics of gene networks provides buffering (***self-organization***). But still easily chaotic.

Structure (***topological organization***), can provide larger stable or critical universe, but still easily chaotic.

canalized genetic **control** ignores some inputs (***redundancy***) to attain necessary resilience (tradeoff stability/evolvability)

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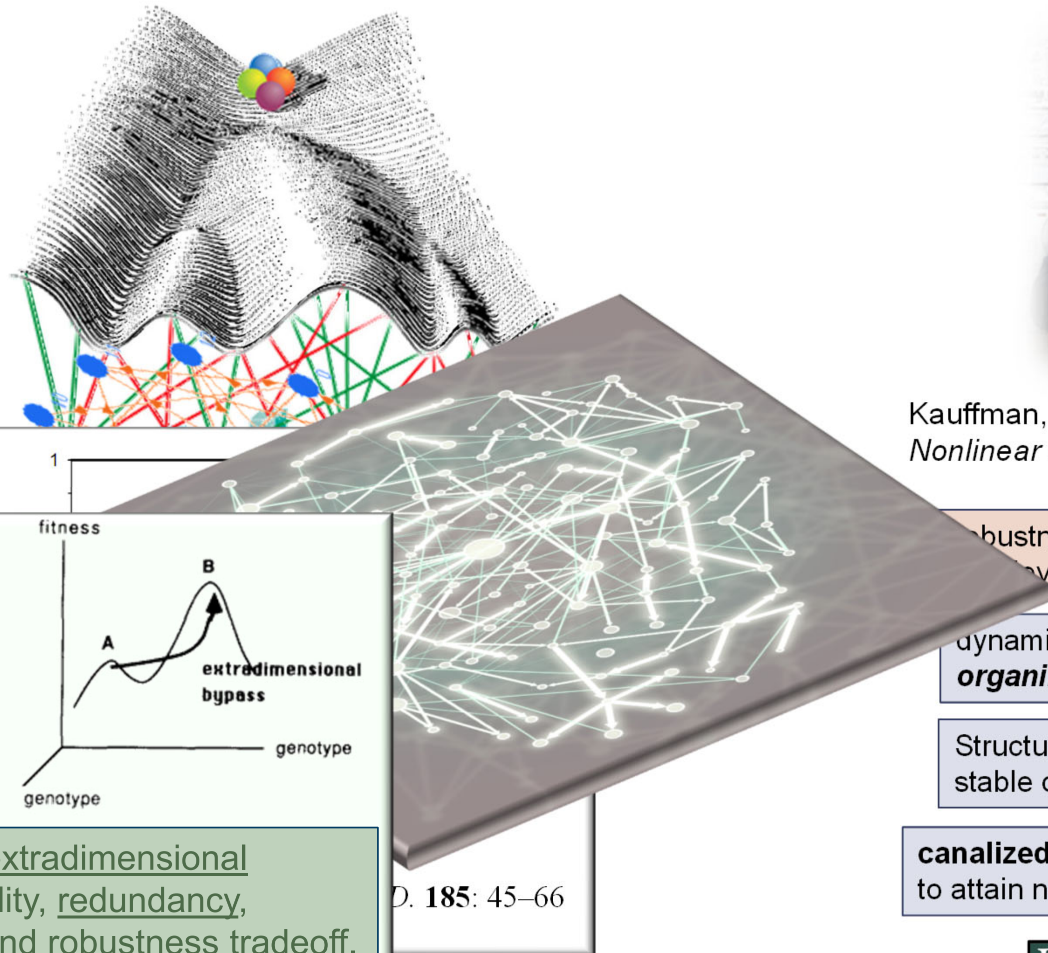

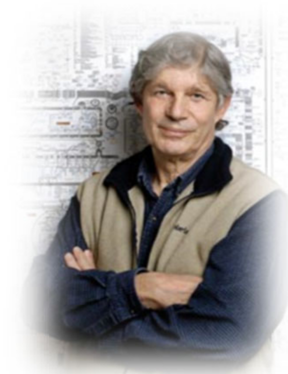

Kauffman, S. A. (1984). *Phys. D Nonlinear Phen.***10**,145–156.

Waddington CH (1942). *Nature*.**150** (3811):563–565

Michael Conrad

Evolvability: extradimensional bypass, neutrality, redundancy, controllability and robustness tradeoff.

…bustness of phenotypes is the result of a ***buffering*** of …velopmental process.

…dynamics of gene networks provides buffering (***self-organization***). But still easily chaotic.

Structure (***topological organization***), can provide larger stable or critical universe, but still easily chaotic.

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Alan Turing (1912-1954)

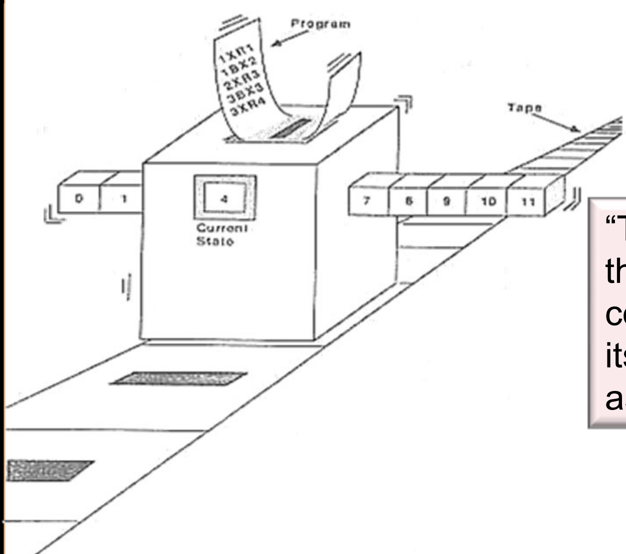
key contributions (most relevant to biocomplexity)

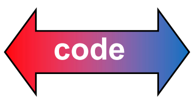
- “The chemical basis of morphogenesis”
  - Turing, A. M. *Phil. Trans. R. Soc. Lond. B* **237**, 37–72 (1952).
    - Reaction-diffusion systems
- “Computing machinery and intelligence”
  - Turing, A. M. *Mind* **49**, 433–460 (1950).
    - The “Turing Test”
- “On computable numbers with an application to the *Entscheidungsproblem*”
  - Turing, A. M. *Proc. Lond. Math. Soc.* **s2–42**, 230–265 (1936–37).
    - Turing machine, universal computation, decision problem

Brenner, Sydney. [2012]. “Life’s code script.” *Nature* **482** (7386): 461-461.

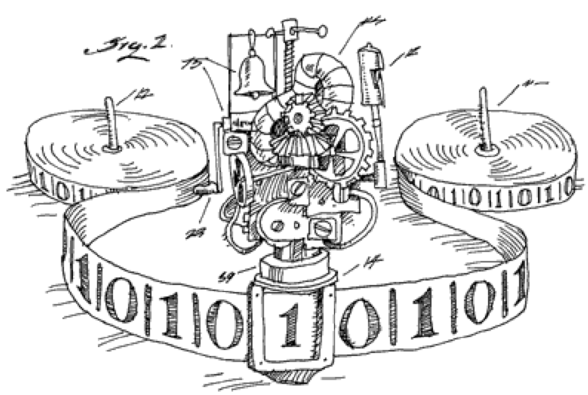
A fundamental principle of computation

- "On computable numbers with an application to the *Entscheidungsproblem*"
  - Turing, A. M. *Proc. Lond. Math. Soc.* **s2–42**, 230–265 (1936–37).
    - **Turing machine**, universal computation, decision problem
  - **Machine**'s *state* is *controlled* by a *program*, while *data* for program is on limitless **external tape**
    - every machine can be described as a **number** that can be stored on the tape (for itself or another machine)
      - Including a Universal machine
    - **distinction** between *numbers that mean things* (data) and *numbers that do things* (program)

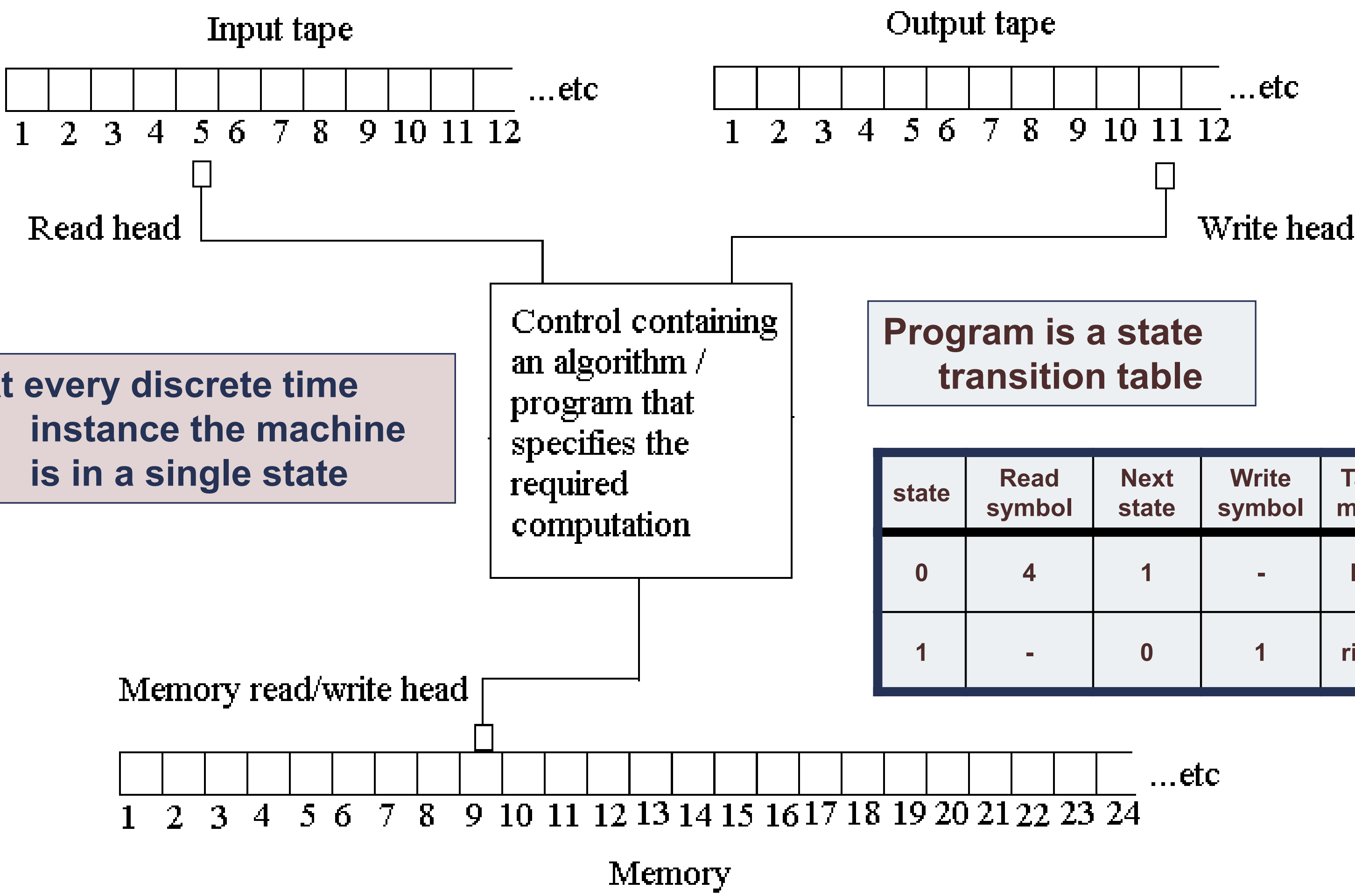




"The fundamental, indivisible unit of information is the bit. The fundamental, indivisible unit of digital computation is the transformation of a bit between its two possible forms of existence: as [memory] or as [code]. George Dyson, 2012.



A Turing Machine



At every discrete time instance the machine is in a single state

Program is a state transition table

state	Read symbol	Next state	Write symbol	Tape move
0	4	1	-	left
1	-	0	1	right

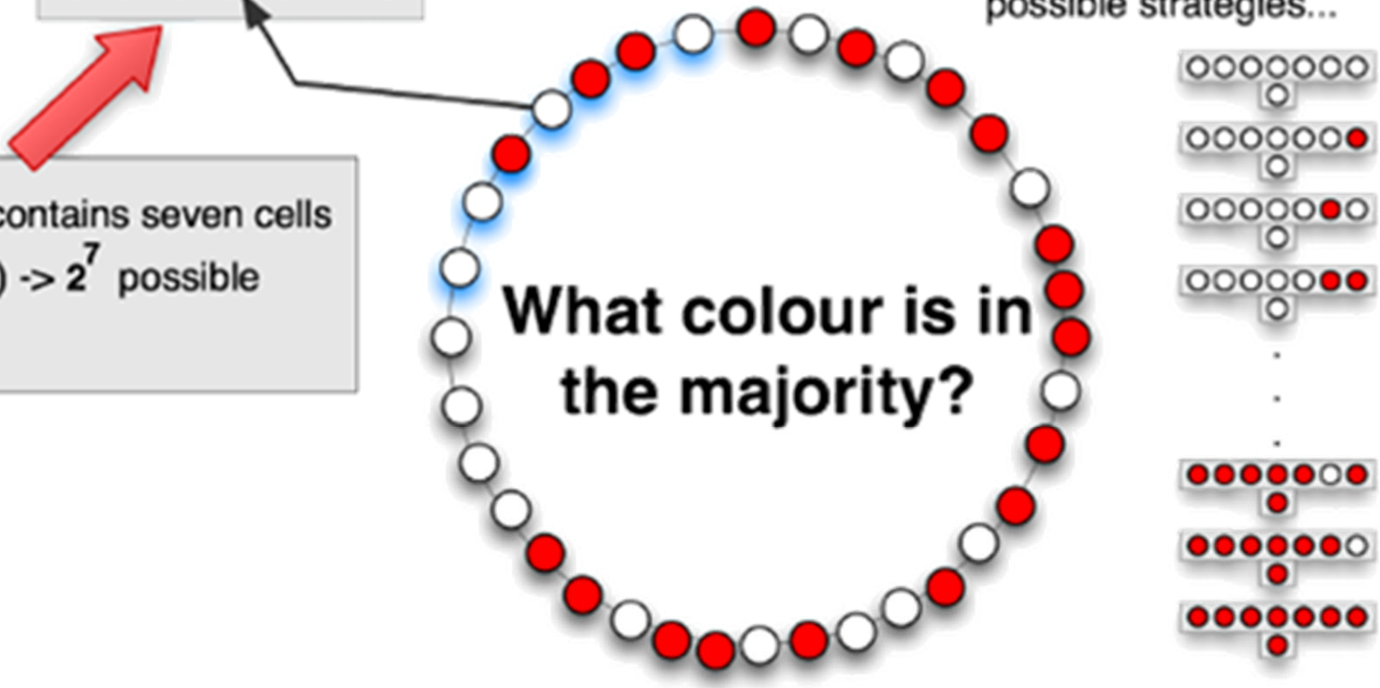
quorum sensing or what decision to take? (Density Classification)

$$K^{|N|} = 2^7 = 128$$

Each cell only has access to LOCAL information

local **neighbourhood** (**LNC**) contains seven cells two allowed states (red or white) -> $\mathbf{2^7}$ possible **LNCs**

A possible strategy, out of $\mathbf{2^{2^7}}$ possible strategies...



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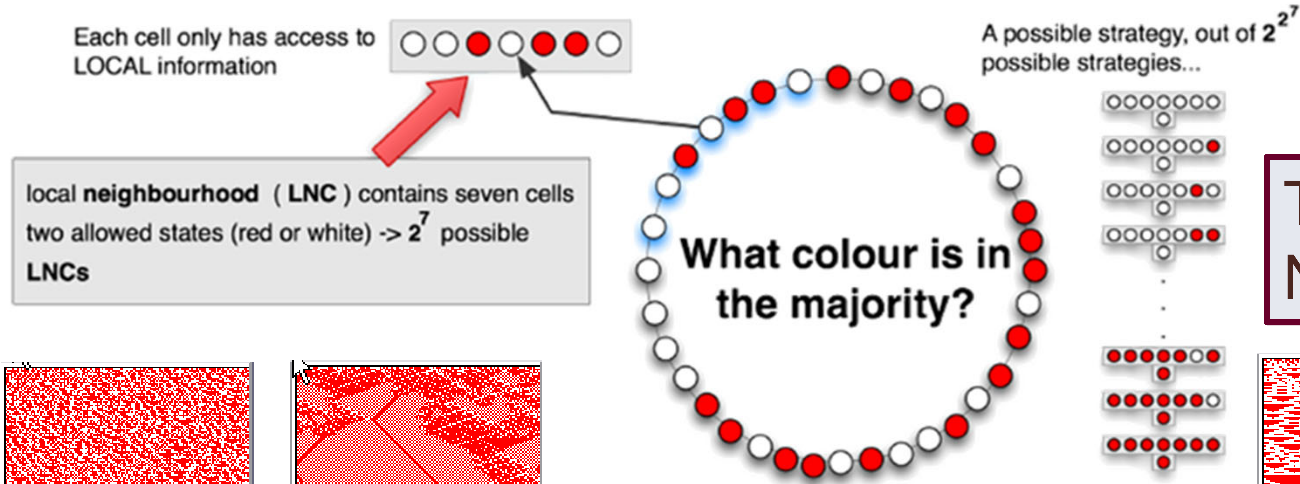
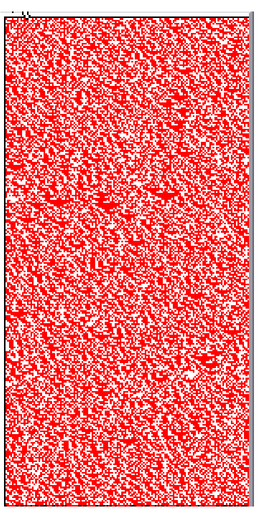
random strategies

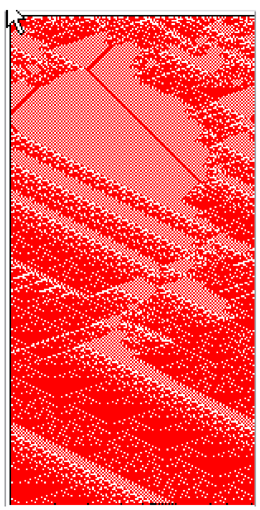
density classification task



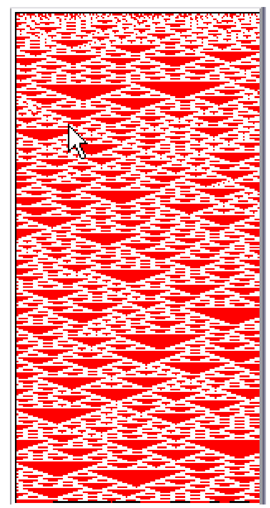
$$K^{|N|} = 2^7 = 128$$

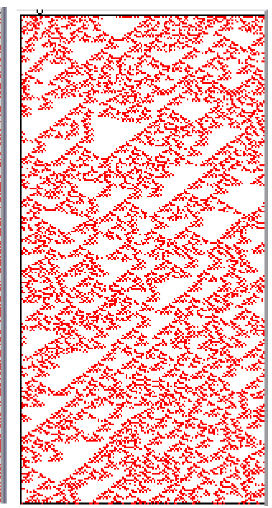
Typically chaotic behavior
No convergence

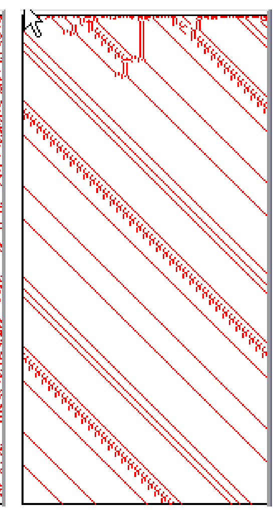




$$\mathcal{P} = 0$$







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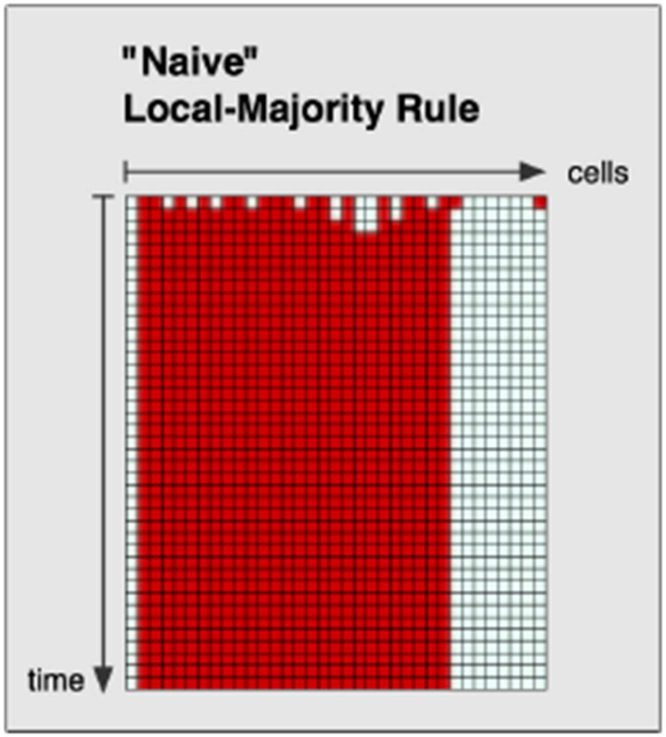
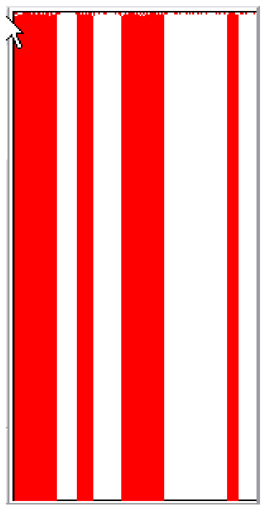
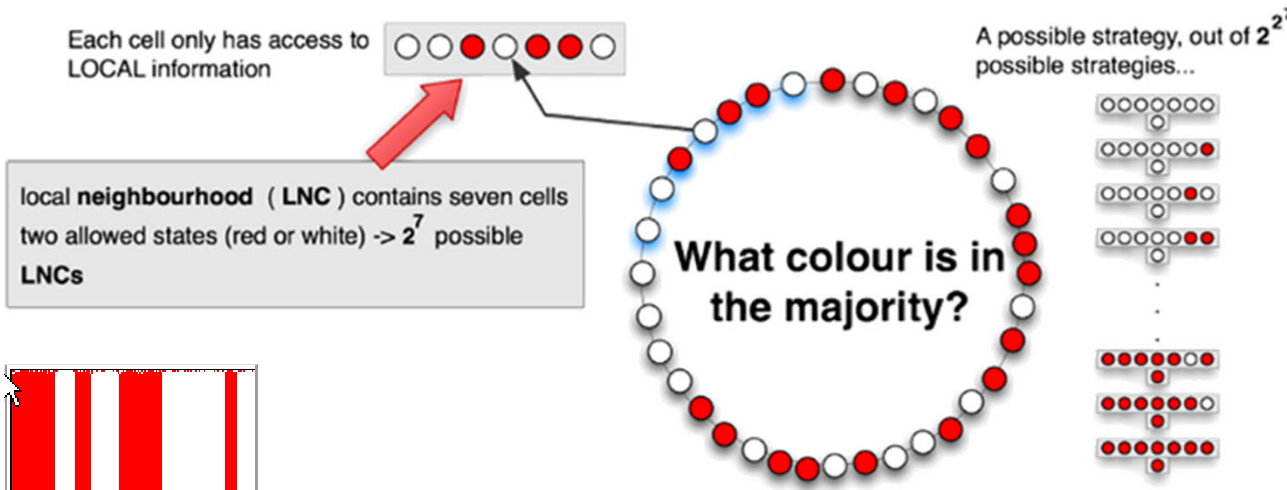
local strategy: majority rule

density classification task

$$K^{|N|} = 2^7 = 128$$







$$\mathscr{P} = 0$$

Isolated groups
No information transmission

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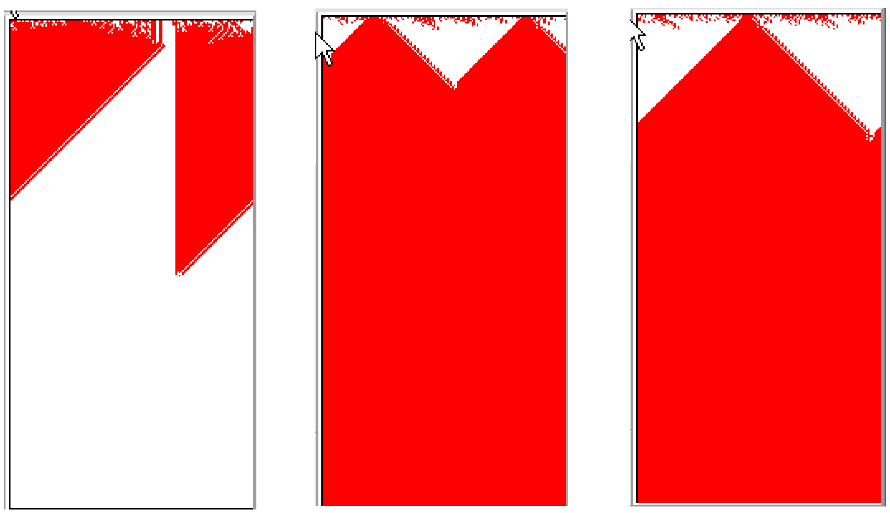
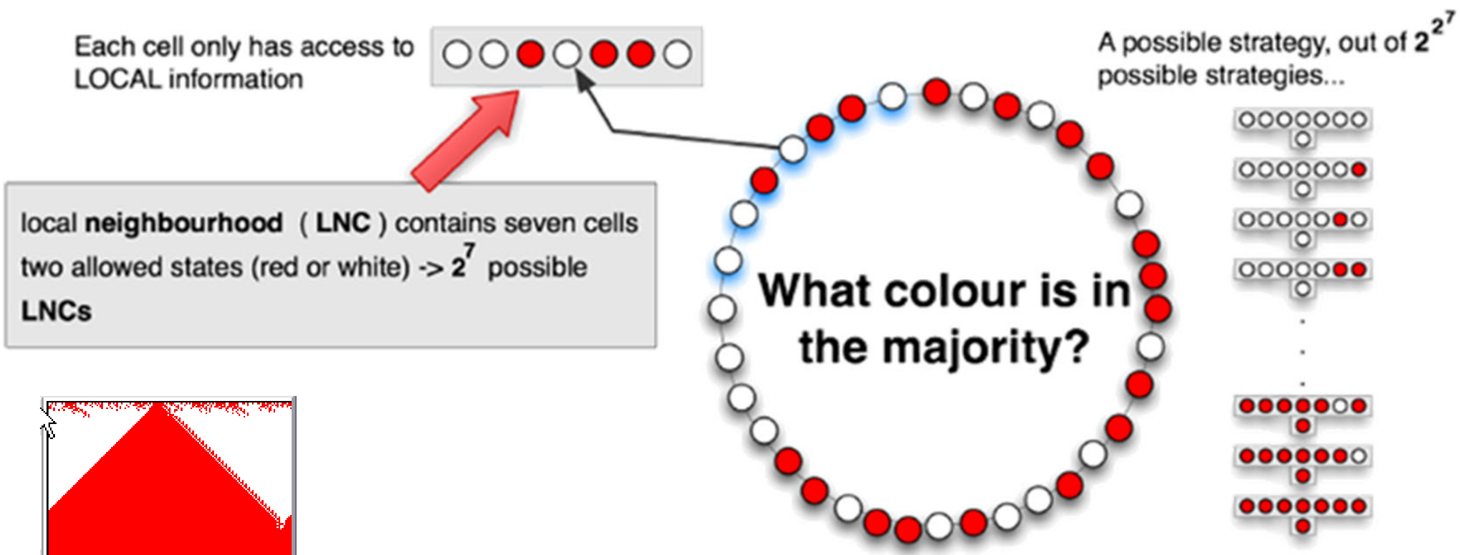
density classification task

$$K^{|N|} = 2^7 = 128$$

$$\mathscr{P} \in [53\%, 60\%]$$



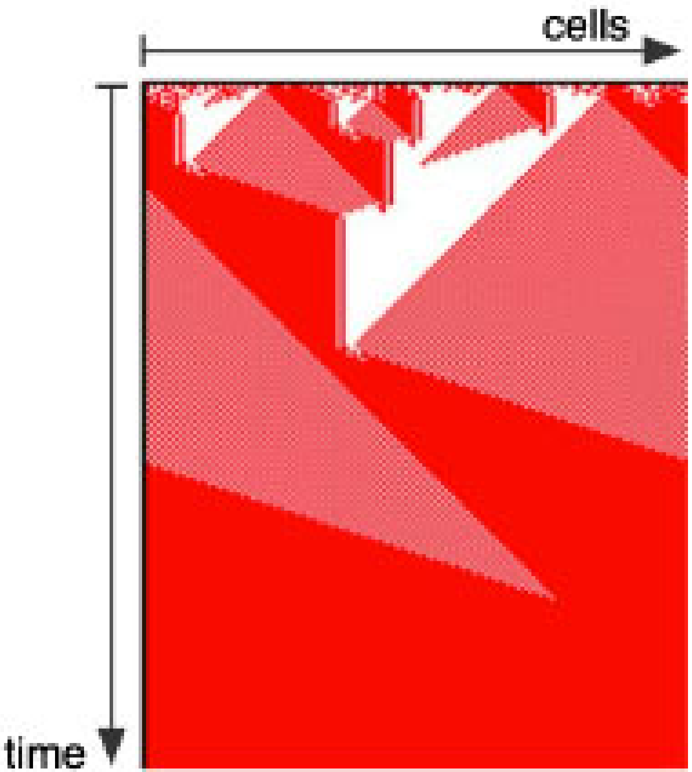


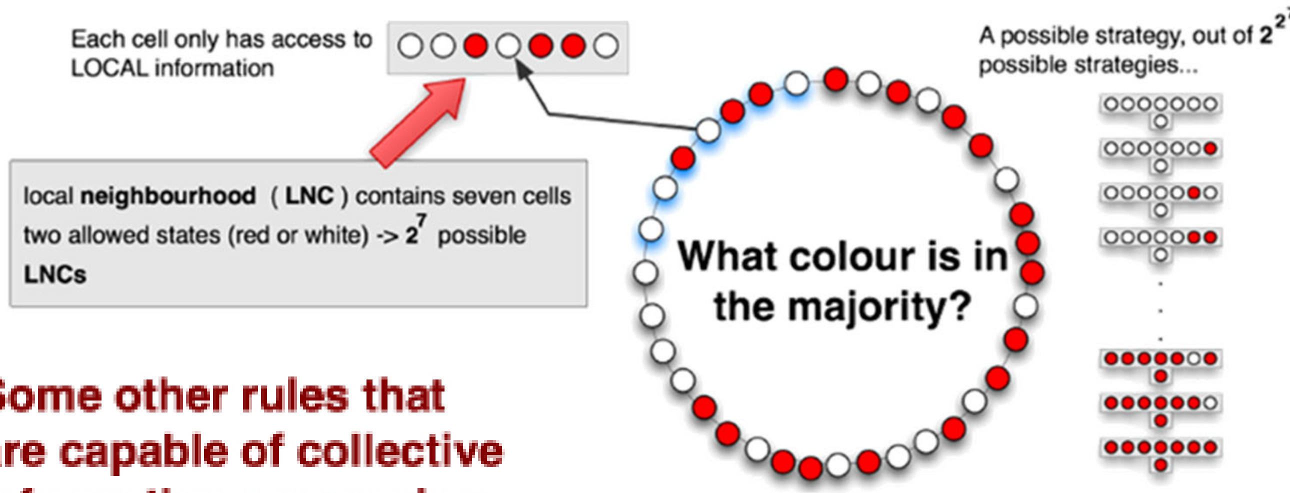
GA to evolve rules for DCT [1994]

"blind" spreading of local information
No information integration
Not much better than random choice

density classification task

$$K^{|N|} = 2^7 = 128$$





Some other rules that are capable of collective information processing over time and space can solve this task with a range of performances where

$P_{149}^{10^5} > 80\ \%$

Integration and transmission of information across population

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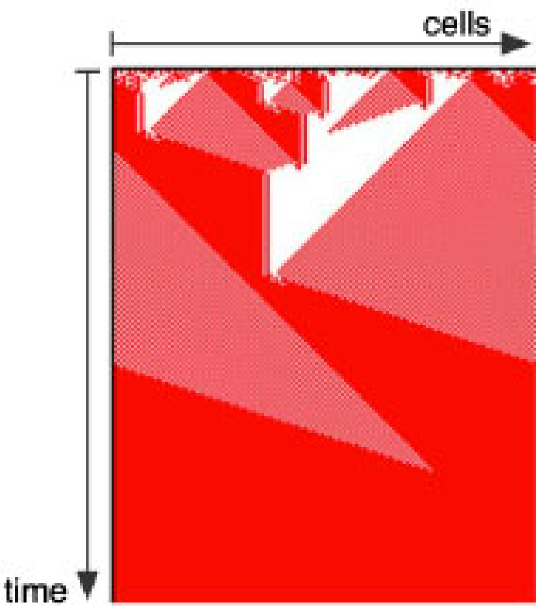
for DST



Some other rules that are capable of collective information processing over time and space can solve this task with a range of performances where $P_{149}^{10^5} > 80\ \%$

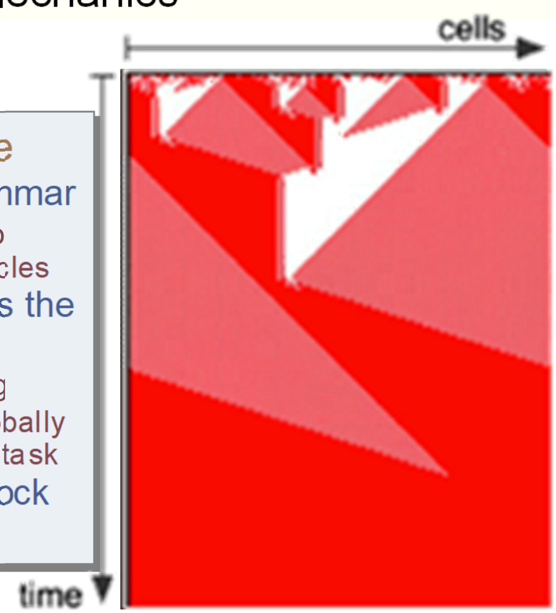
Rule	Hexadecimal Representation	$\mathcal{P}_{149}^{10^5}$	Produced by	Source
Φ_{GKL}	5f005f005f005f005fff5f005fff5f	0.8143	HE	Gacs et al., 1978
$\Phi_{Davis95}$	2f035f001fcf1f002ffc5f001fff1f	0.8188	HE	Andre et al., 1996
Φ_{Das95}	70007ff0f000fff0f0007ff0f310fff	0.8215	HE	Andre et al., 1996
Φ_{GP1995}	500550505005505555ff55ff55ff55ff	0.8212	GP	Andre et al., 1996
Φ_{DMC}	504058705000f77037755837bffb77f	0.7784	GA	Das et al., 1994
Φ_{COE1}	11430d7110f395705b4ff17f13df957	0.8498	CE	Juillè and Pollack, 1998
Φ_{COE2}	1451305c0050ce5f1711ff5f0f53cf5f	0.8601	CE	Juillè and Pollack, 1998
Φ_{GEP1}	50005ff050005ff05ff05ff05ff05ff	0.8119	GEP	Ferreira, 2001
Φ_{GEP2}	55007700550077 0f550f77ff55ff77	0.8250	GEP	Ferreira, 2001

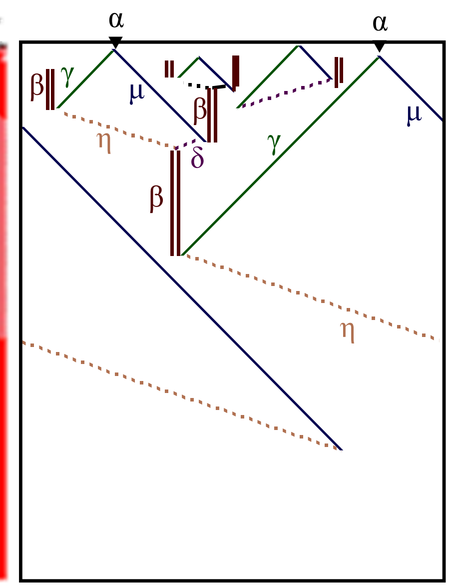
Integration and transmission of information across population

collective (emergent) computation via computational mechanics

GA to evolve rules for DCT [1994]

- Particle interaction scheme
  - Rules like a production grammar
    - the presence (collision) of two particles produces other particles
  - Transfer information accross the lattice
    - Loci of information processing
    - integrate local information globally to solve the nontrivial density task
  - Higher performance than block expansion





Crutchfield & Mitchell [1995]. *PNAS* **92**: 10742-10746

Das, Mitchell & Crutchfield [1994]. In: *Parallel Problem Solving from Nature-III*: 344-353.

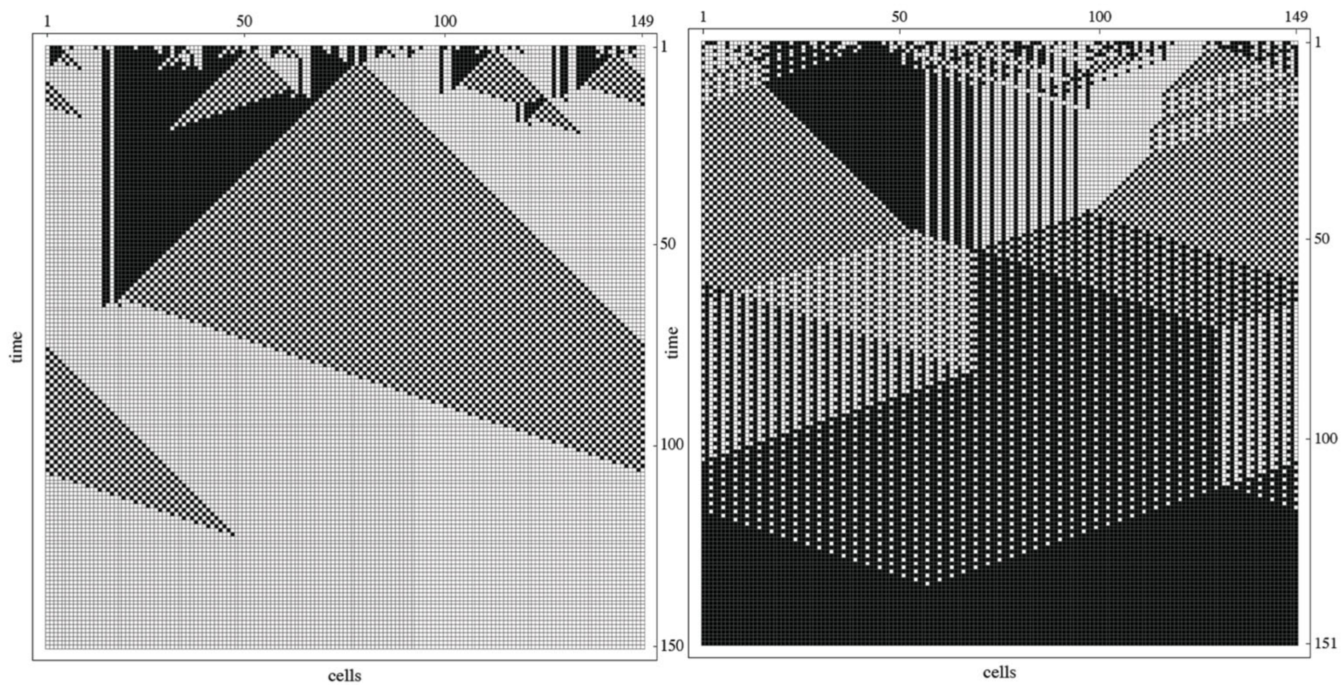
Table I: Catalog of regular domains, particles and particle interactions for rule ϕ_{DMC}

Regular Domains	$\Lambda^0 = \{0+\}$, $\Lambda^1 = \{1+\}$, $\Lambda^2 = \{(01)+\}$	
Particles (velocities)	$\alpha \sim \Lambda^0\Lambda^1$ (–), $\beta \sim \Lambda^1\Lambda^0$ (0), $\gamma \sim \Lambda^0\Lambda^2$ (-1), $\mu \sim \Lambda^2\Lambda^1$ (1), $\delta \sim \Lambda^2\Lambda^0$ (-3), $\eta \sim \Lambda^1\Lambda^2$ (3)	
Observed Interactions	**decay**	$\alpha \to \gamma + \mu$
	react	$\beta + \gamma \to \eta$, $\mu + \beta \to \delta$, $\eta + \delta \to \beta$
	annihilate	$\eta + \mu \to \Lambda^1$, $\gamma + \delta \to \Lambda^0$

Hanson,J.E., Crutchfield,J.P., [1992]. *Journal of Statistical Physics*. **66** (5/6), 1415-1462.

Crutchfield,J.P., Hanson,J.E., [1993]. *Physica D*. **69**, 279-301.

comparison of different automata

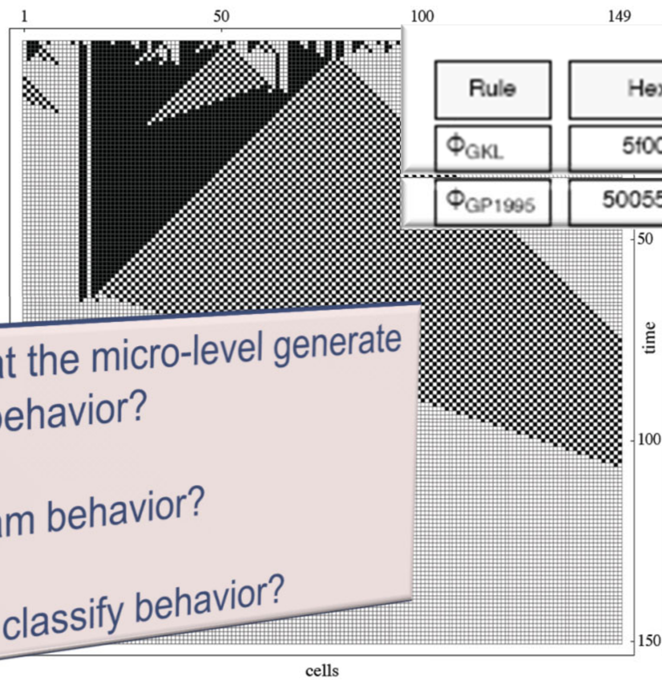


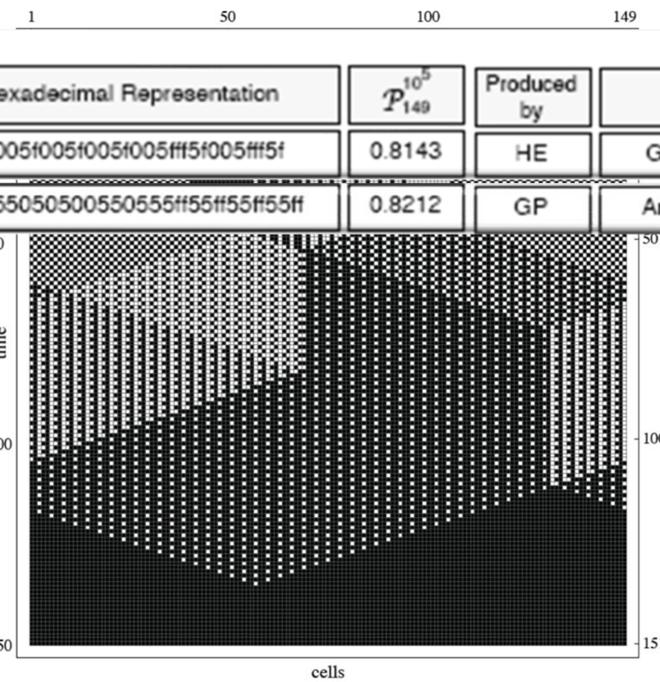
GKL Rule
- 3 domains
- 6 particles

$$p = \frac{d!}{(d-2)!}$$

GP Rule
- > 10 domains
- > 90 particles!!!

comparison of different automata





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Φ_{GP1995}	5005505050055055fff55fff55fff55ff	0.8212	GP	Andre et al., 1996

How do interactions at the micro-level generate desired macro-level behavior?

How to control/program behavior?

How to compare and classify behavior?

GKL Rule
- 3 domains
- 6 particles

$$p = \frac{d!}{(d-2)!}$$

GP Rule
- > 10 domains
- > 90 particles!!!

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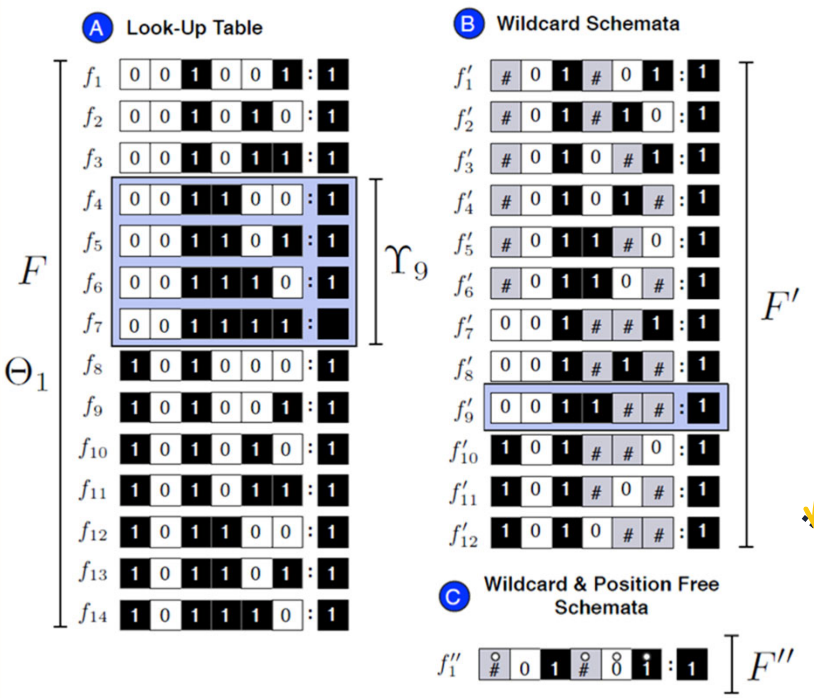
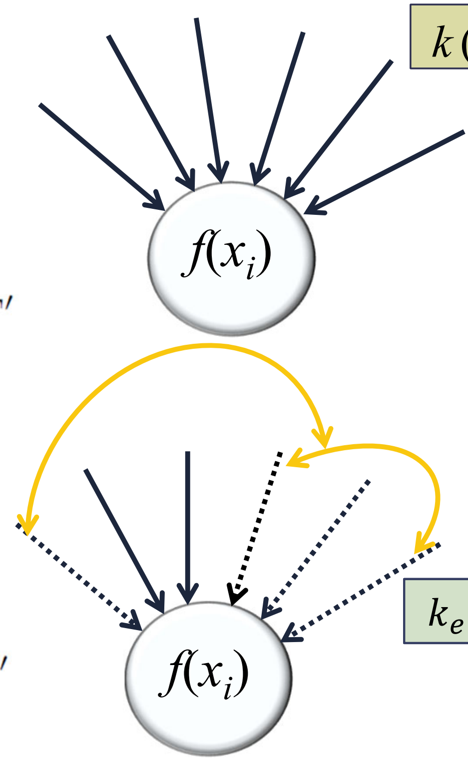
canalization (beyond pairwise interaction)

effective connectivity/input redundancy + input symmetry





$k(x) = 6$

$p(x) = 14/64 \approx 0.22$

p: bias, ratio of "1's" in output

Measuring dynamical ***redundancy***, its dual ***effectiveness***, and ***symmetry***

input redundancy:

$k_r(x)$ = mean number of "#" in LUT

$k_r(x) = 2$

effective connectivity:

$k_e(x) = k(x) - k_r(x)$

$k_e(x) = 6 - 2 = 4$

$k_s(x) = 4$

$k_s(x)$ = mean number of "○" in LUT

Prime Implicants (Quine-McCluskey) plus **group invariance**

minimal transition control: set of wildcard schemata is **DNF** of prime implicants (Blake Canonical Form)

github.com/CASCI-lab/CANA

Correia, Gates, Wang & Rocha [2018]. *Frontiers in Physyology* **9:** 1046.
Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.
Marques-Pita & Rocha, [2013]. *PLoS ONE*, **8**(3): e55946.

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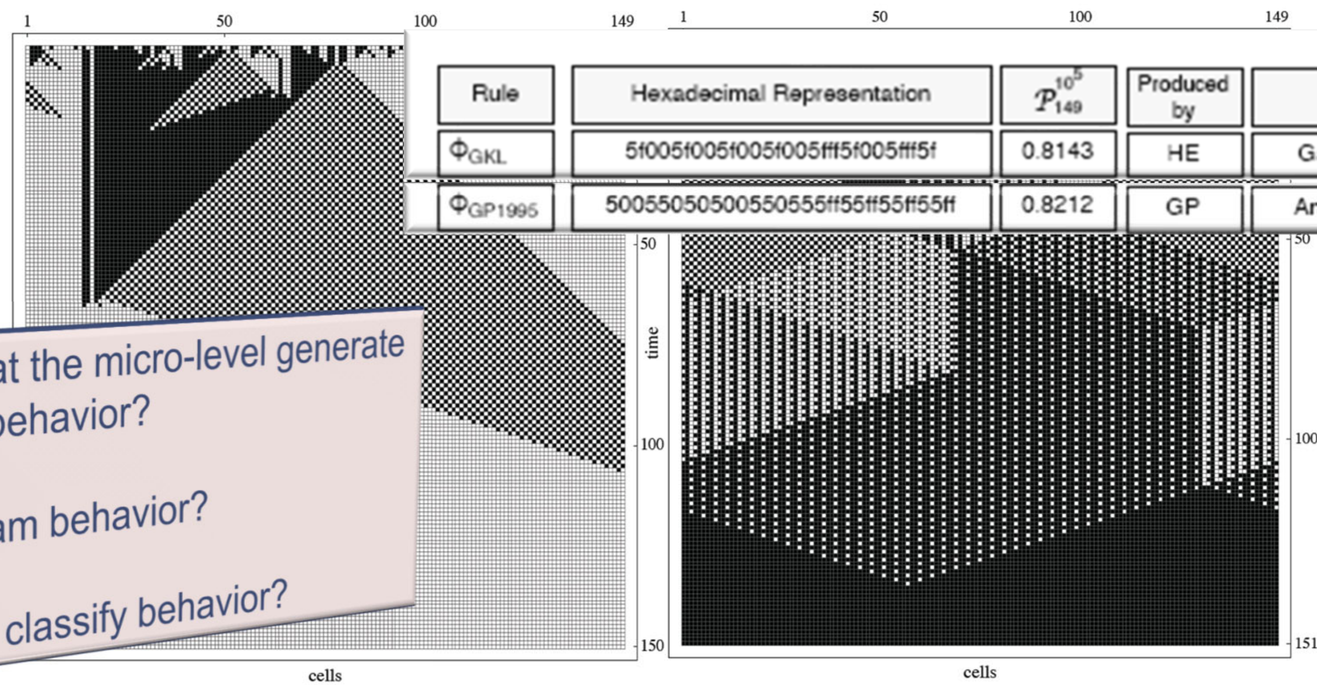
comparison of different automata



Rule	Hexadecimal Representation	$\mathcal{P}_{149}^{10^5}$	Produced by	Source
Φ_{GKL}	5f005f005f005f005fff5f005fff5f	0.8143	HE	Gacs et al., 1978
Φ_{GP1995}	005505005005505555ff55ff55ff55ff	0.8212	GP	Andre et al., 1996

How do interactions at the micro-level generate desired macro-level behavior?

How to control/program behavior?

How to compare and classify behavior?

GKL Rule
- 3 domains
- 6 particles

$$p = \frac{d!}{(d-2)!}$$

GP Rule
- > 10 domains
- > 90 particles!!!

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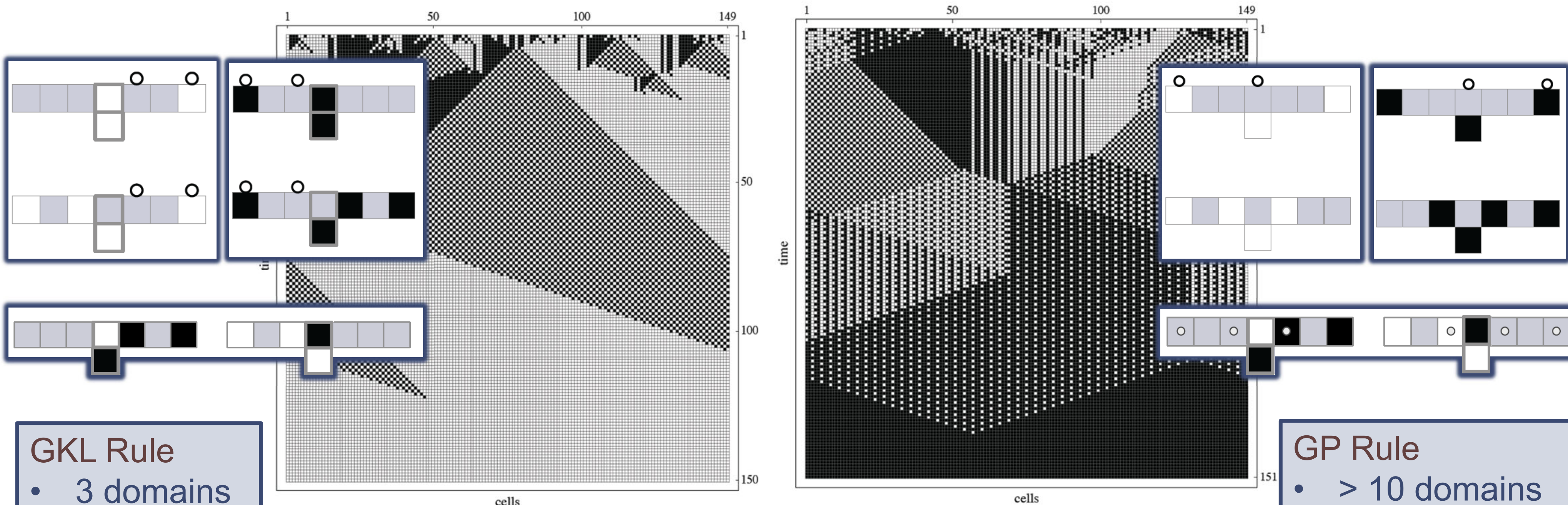
ignoring most incoming information

- Solving by schemata
  - Each automaton ignores most inputs, avoiding chaos



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Marques-Pita & Rocha, [2011]. *IEEE Alife*: 233-240.

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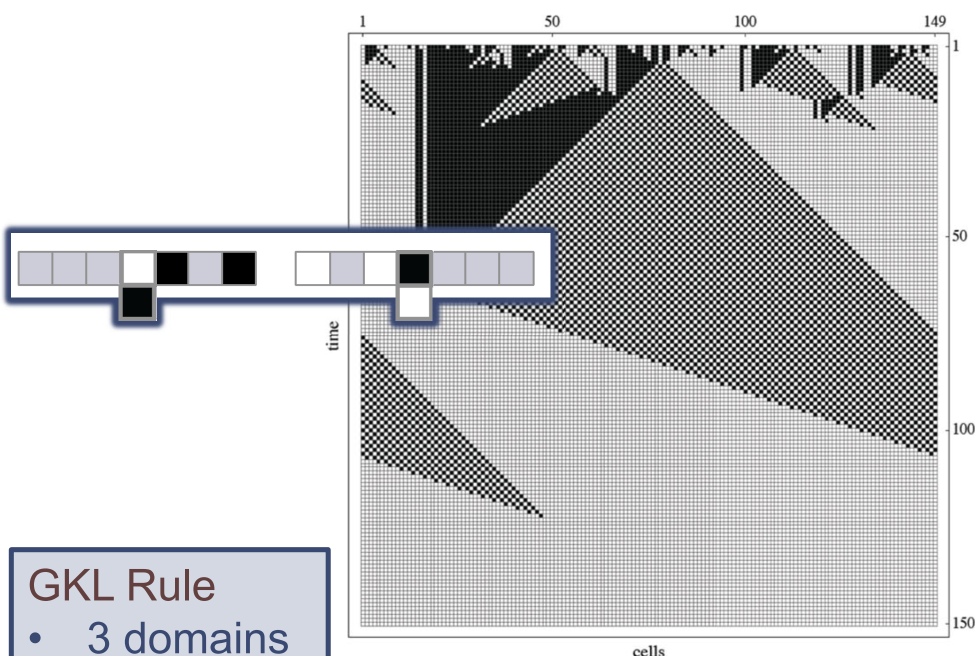
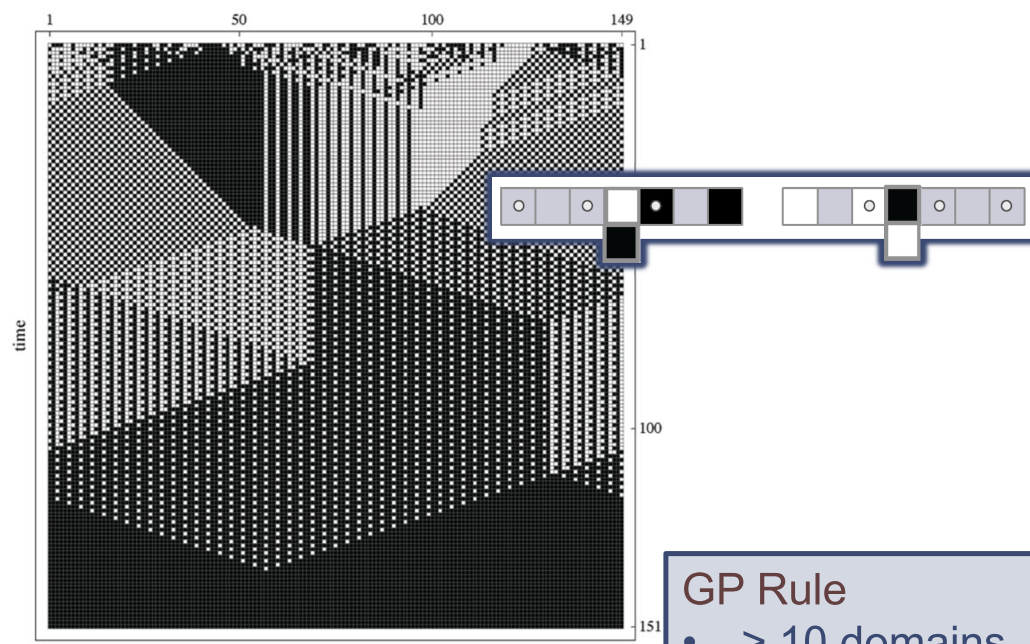
it takes redundancy to solve

ignoring most incoming information

- **Solving by schemata**
  - Each automaton ignores most inputs, avoiding chaos





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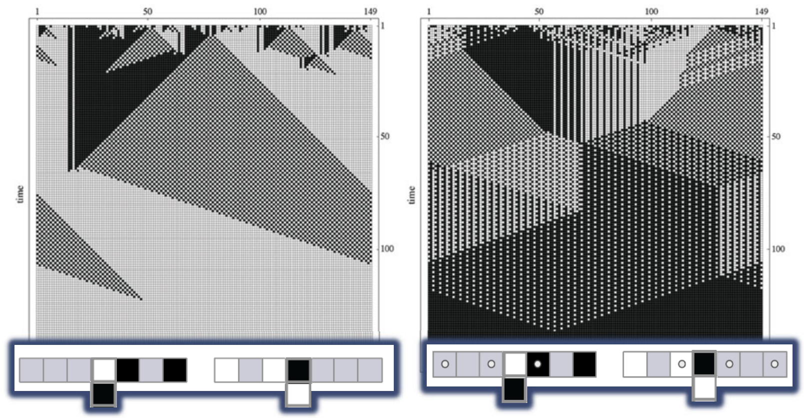
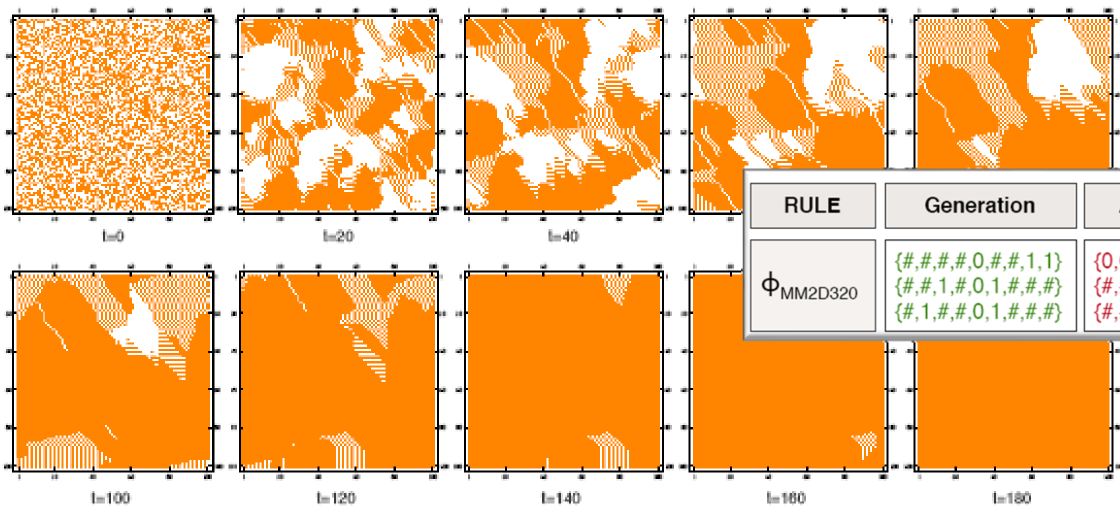
canalization (redundancy) improves evolutionary search

- Created much smoother search space
  - Allows more focused search of rules
    - Canalization, neutrality, robustness?
  - Second best rule in 1-D CA (best-known PS rule)
    - Best split-performance
  - Best rule in 2-D CA
- reason about emergent computation in new ways
  - Process-symmetry



Marques-Pita & Rocha. [2008]. *ALIFE XI.* MIT Press: 390-397.

RULE	Generation	Annihilation
ϕ_{MM0802}	{1, 0, 1, 0, #, #, #}	{0, 0, 1, 1, 1, 1, #}
	{1, 0, #, 0, #, 1, 1}	{0, 0, #, 1, #, 1, 0}
	{1, 1, #, 0, 1, #, #}	{0, 1, 0, 1, 1, #, #}
	{1, #, 1, 0, 1, #, #}	{0, #, 0, 1, #, #, 0}
	{1, #, 1, 0, #, 0, #}	{1, #, 0, 1, #, 0, #}
	{1, #, #, 0, 1, 1, #}	{#, 0, 0, 1, #, #, 0}
	{1, #, #, 0, 1, #, 1}	{#, 1, 0, 1, #, 0, #}
	{#, 0, 0, 0, 0, 1, 1}	{#, 1, #, 1, 0, #, 0}
	{#, 1, 0, 0, 1, #, #}	{#, #, 0, 1, 0, #, 0}
	{#, 1, #, 0, 1, 0, #}	{#, #, 0, 1, 1, 0, #}
	{#, 1, #, 0, 1, #, 0}	{#, #, 0, 1, #, 0, 0}
	{#, #, 0, 0, 1, 0, 1}	{#, #, #, 1, 0, 1, 0}



RULE	Generation	Annihilation
$\phi_{MM2D320}$	{#,#,#,#,0,#,#,1,1}	{0,0,#,#,1,#,#,#,#}
	{#,#,1,#,0,1,#,#,#}	{#,#,#,0,1,#,0,#,#}
	{#,1,#,#,0,1,#,#,#}	{#,#,#,0,1,#,#,0,#}

Marques-Pita , Mitchell & Rocha. [2008]. *UC08.* LNCS. **5146**-163. 204:

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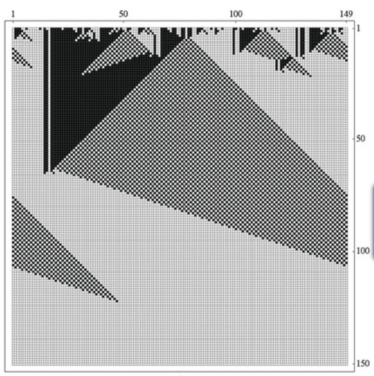
linking local and global/collective behavior

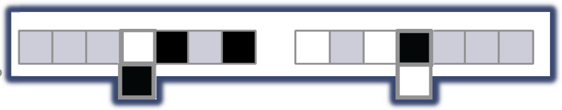
- Are emergent patterns good for explanation?
  - Do stripes or spots explain the “system”?
- Canalization (dynamical redundancy) is a powerful idea
  - Capture loci of control and building blocks of information transmission

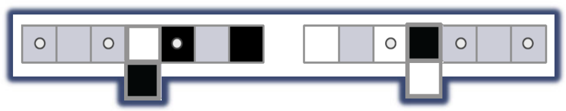


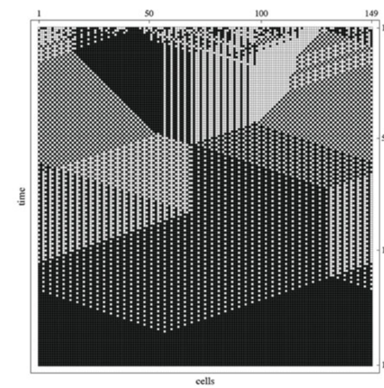
GKL Rule
- 3 do
- 6 pa

GP Rule
- > 10 domains
- es!!!

(mechanistic) reductionism vs emergence:
what is the best explanation?







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- Does canalization help?
  - Studying the effect of noise on the density classification task

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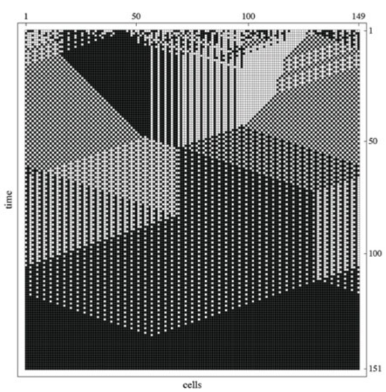

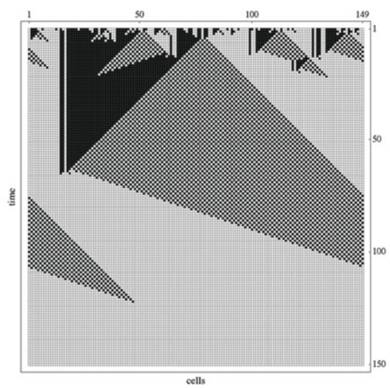

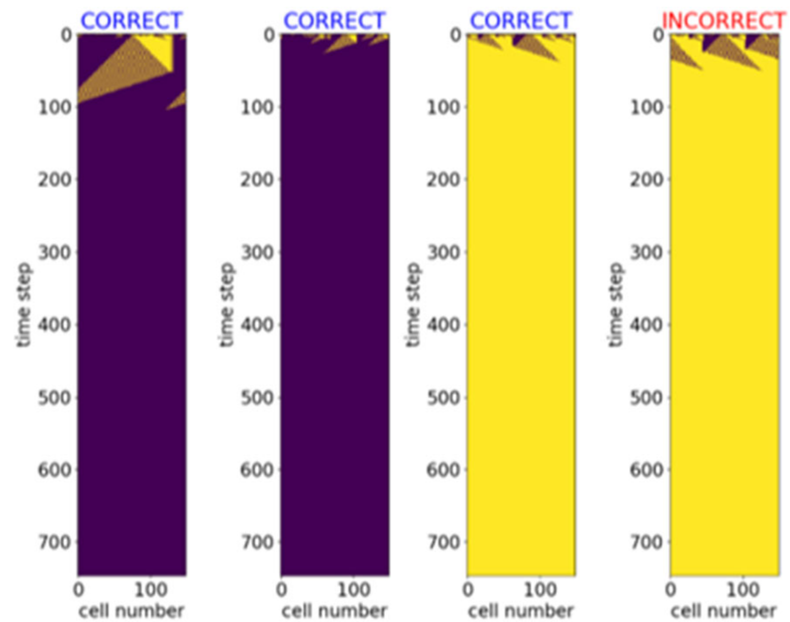

Challa, Hao, Rozum, & Rocha.[2024]. *ALIFE 2024*. MIT Press. pp. 83. DOI: 10.1162/isal_a_00823.
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realistic emergent/collective computation

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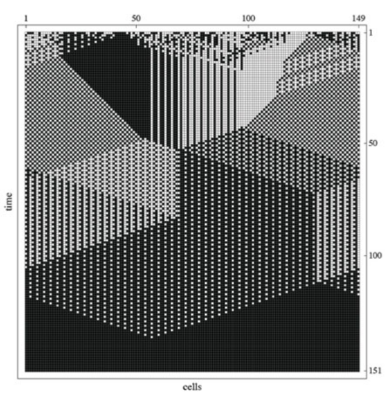

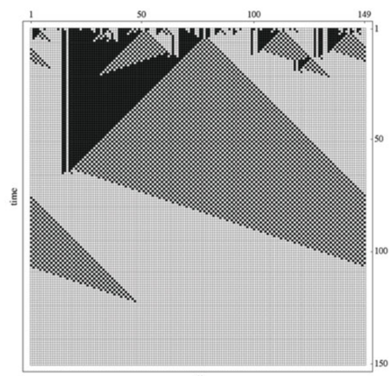

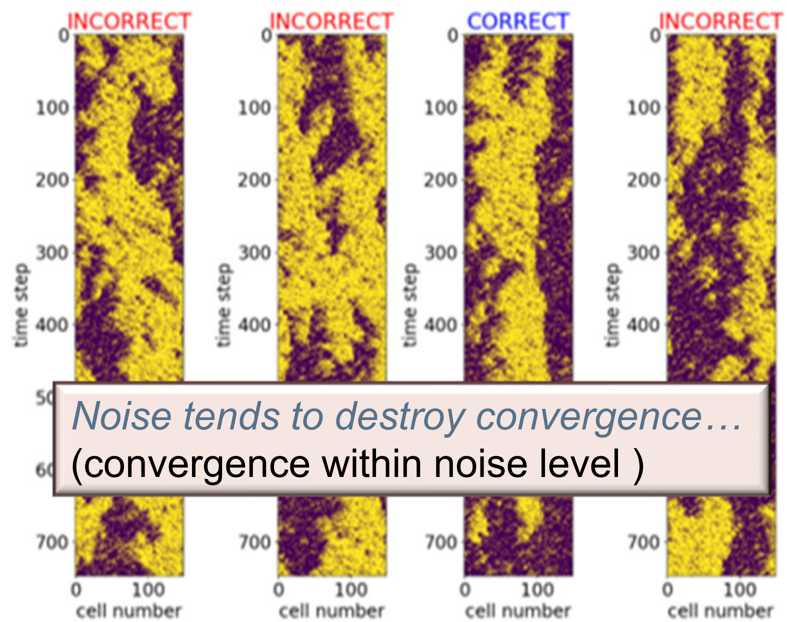

Noise tends to destroy convergence…
(convergence within noise level)

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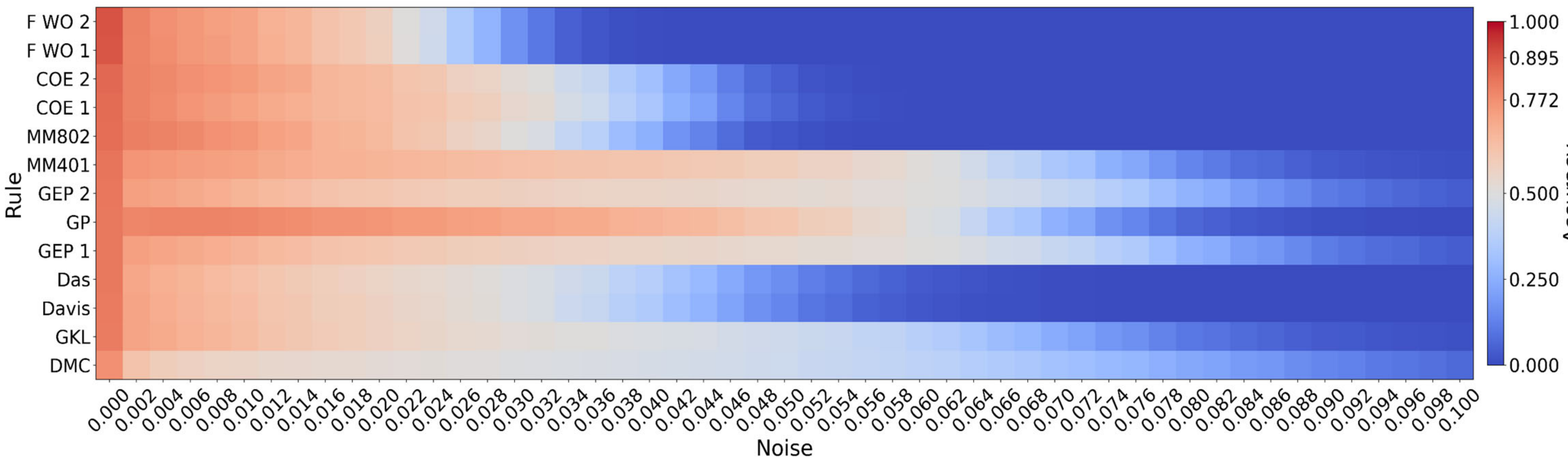

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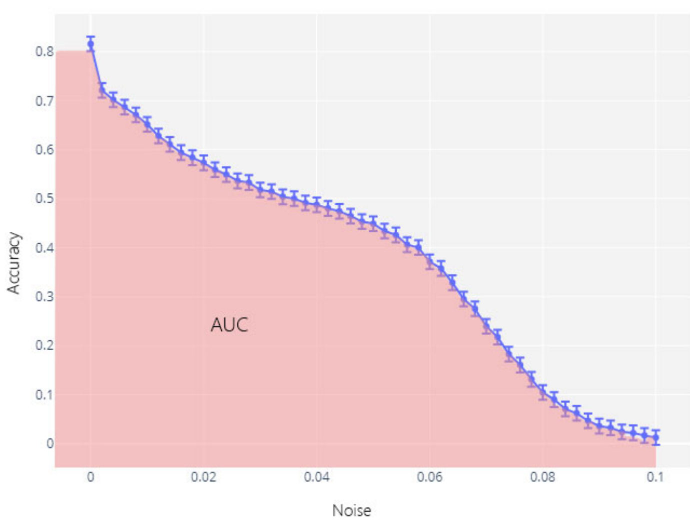

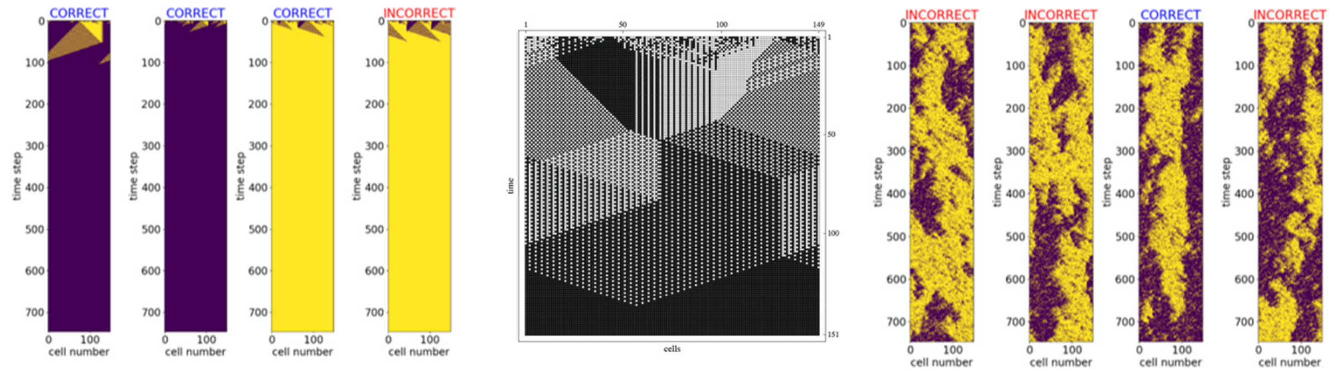

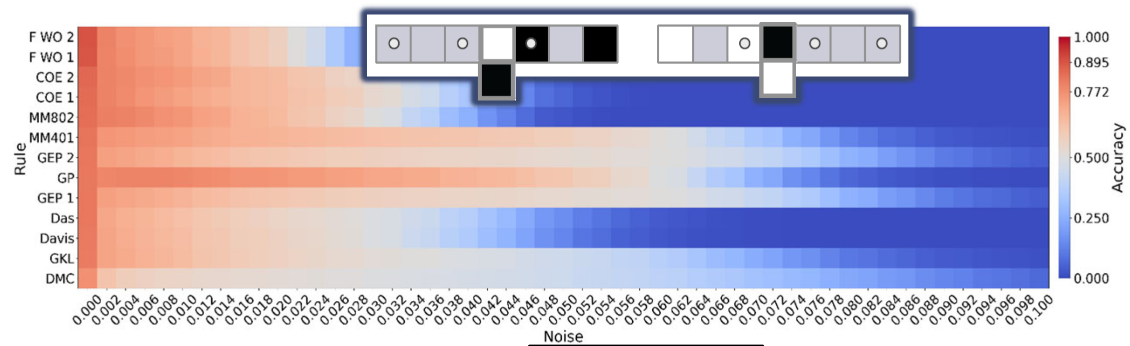

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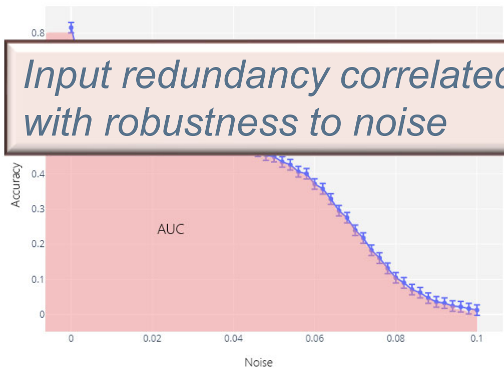
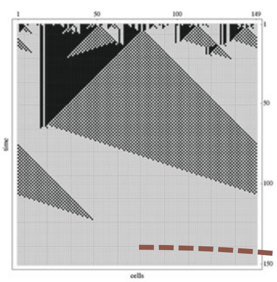
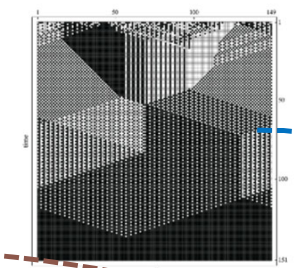
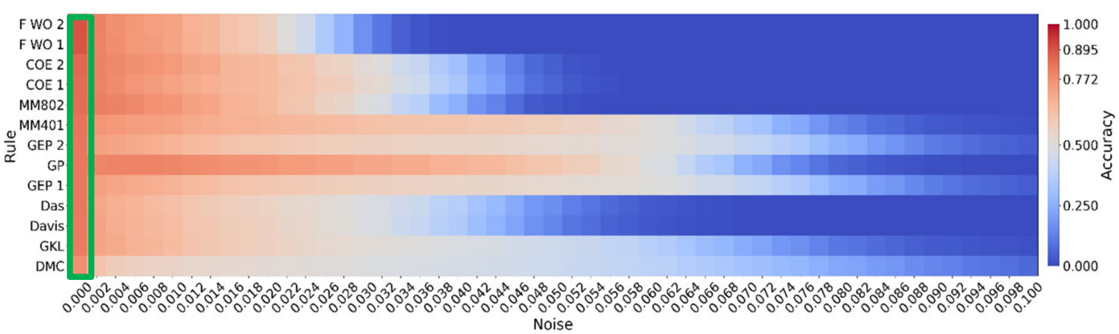
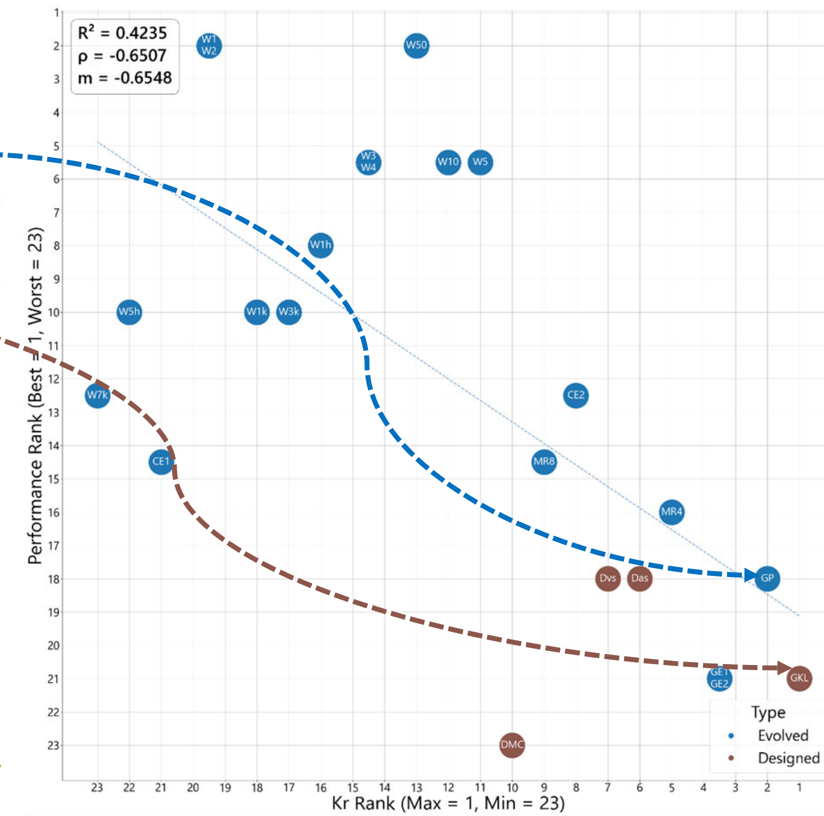


Input redundancy correlated with robustness to noise









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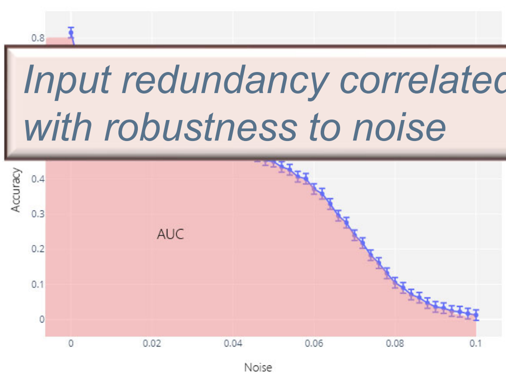

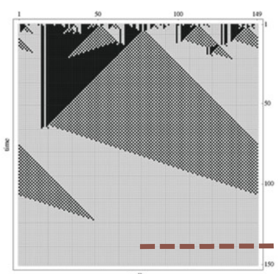

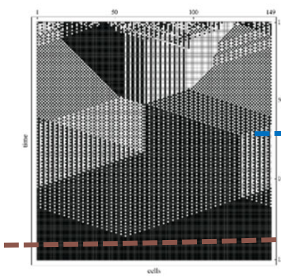

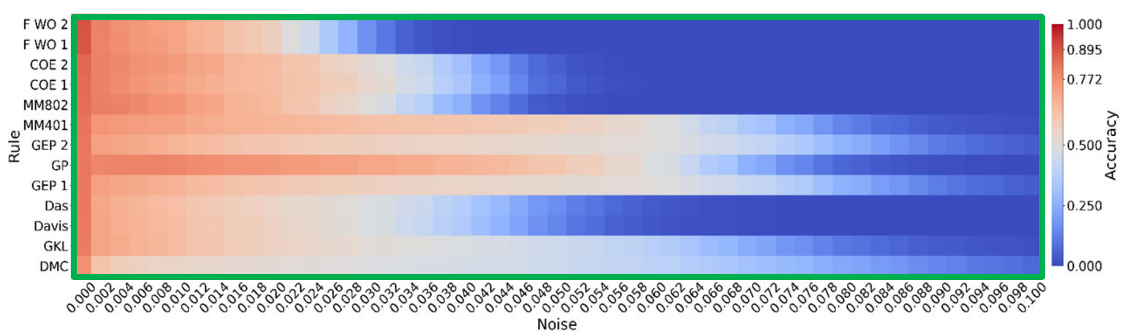

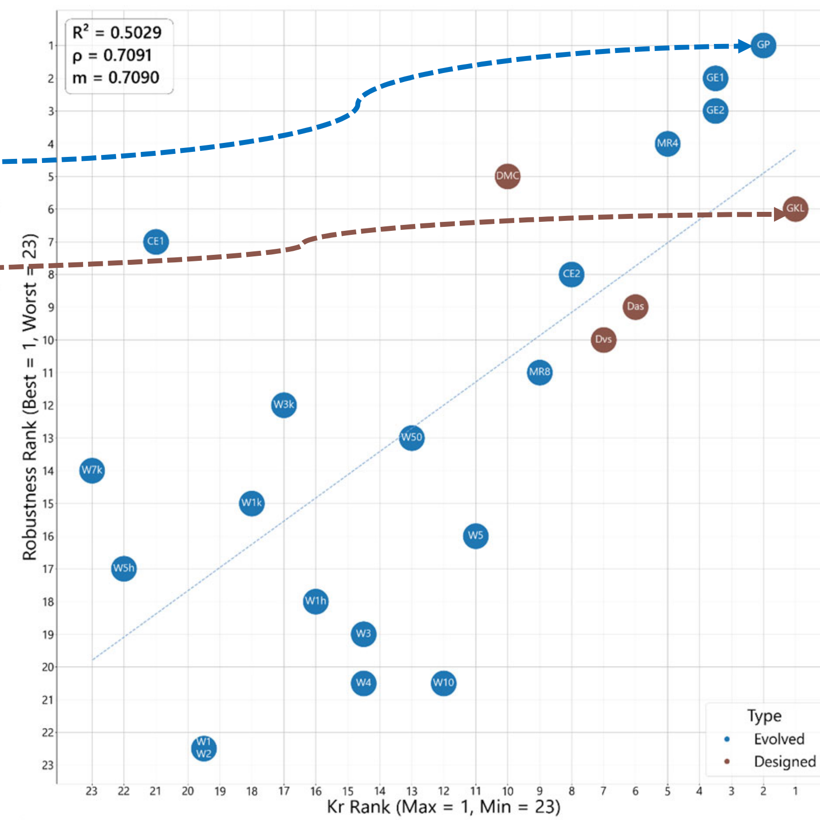

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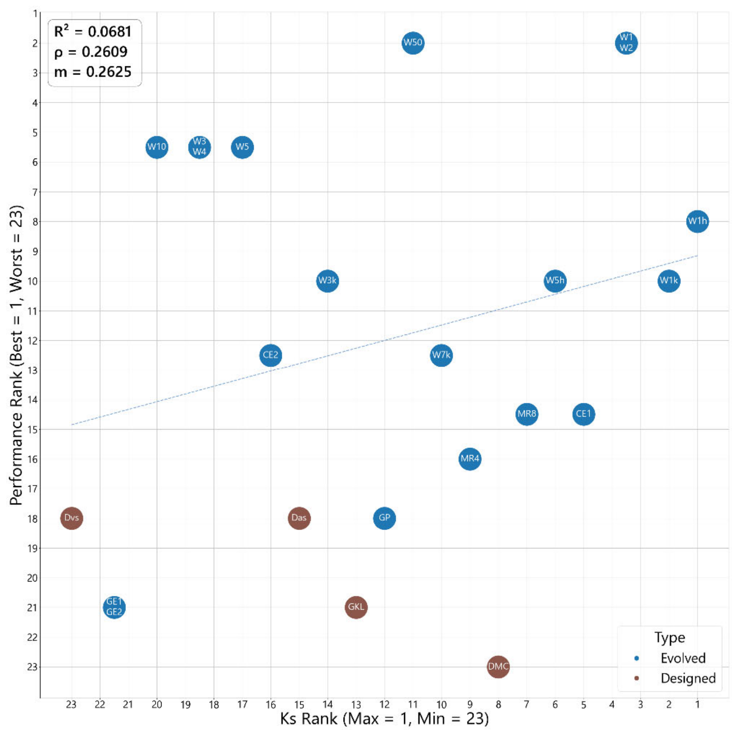
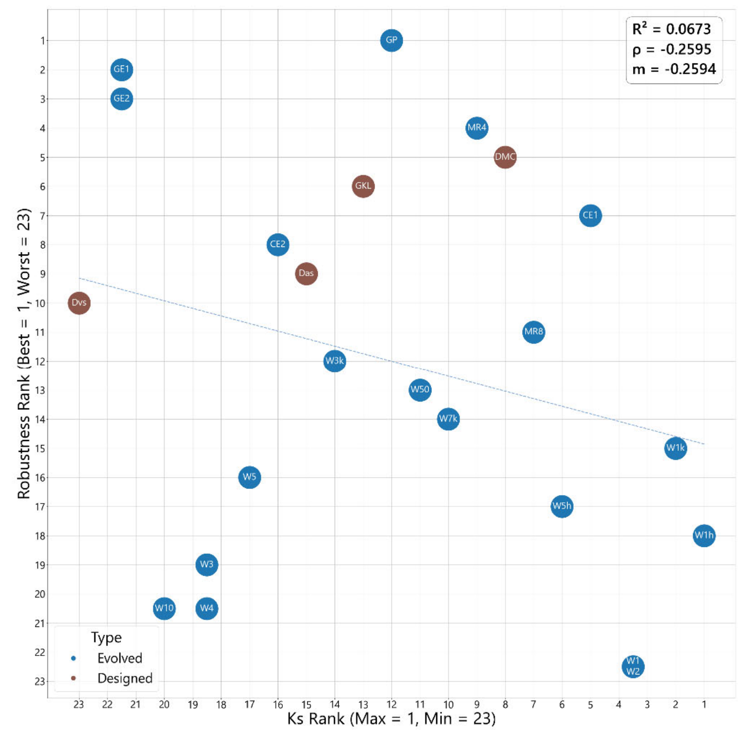
- What about symmetry?
  - Not so much, at least for existing (non-noise) CA rules….





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readings

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press.
    - **Chapter 2**.
- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
  - Chapter 4: Self-Organization and Emergent Complex Behavior
    - posted online @ http://informatics.indiana.edu/rocha/i-bic
- Papers and other materials
  - Optional
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall.
      - Chapter 2, all sections
      - Chapter 7, sections 7.3 – Cellular Automata
      - Chapter 8, sections 8.1, 8.2, 8.3.10
    - Flake's [1998], *The Computational Beauty of Life*. MIT Press.
      - Chapters 10, 11, 14 – Dynamics, Attractors and chaos