Situated, Embodied, and Dynamical Approaches to Behavior and Cognition: A Progress Report

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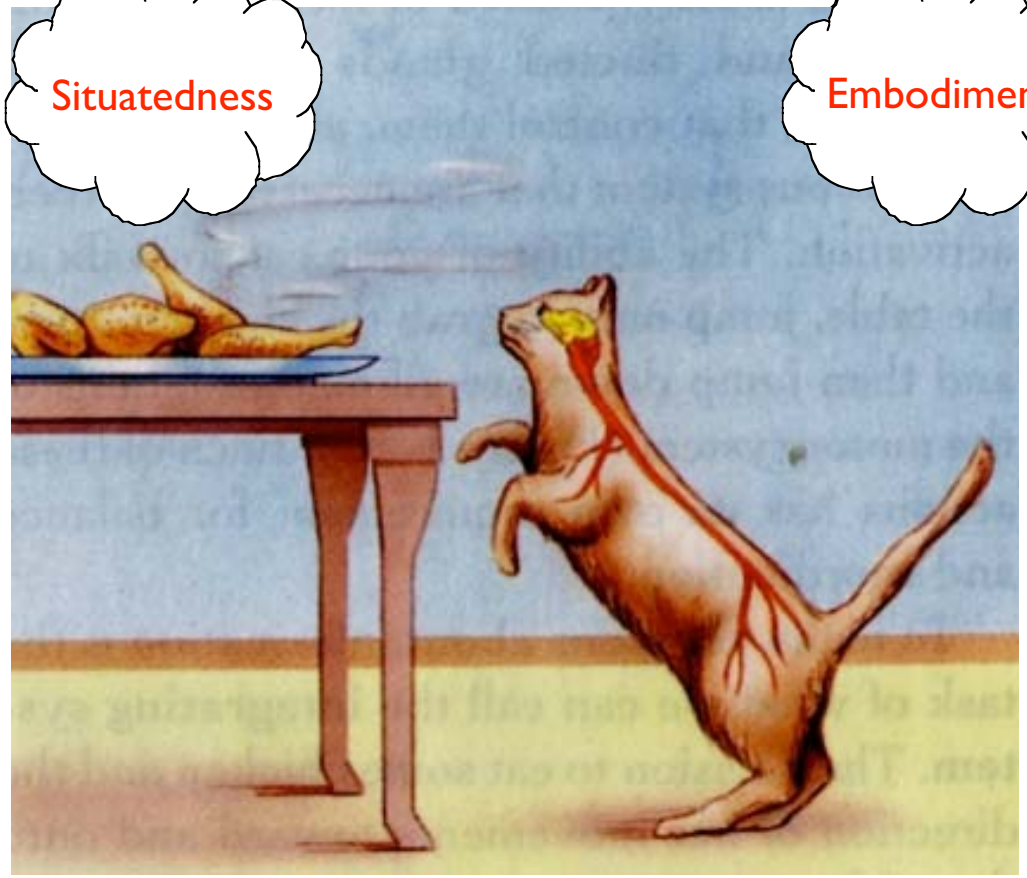
Approach

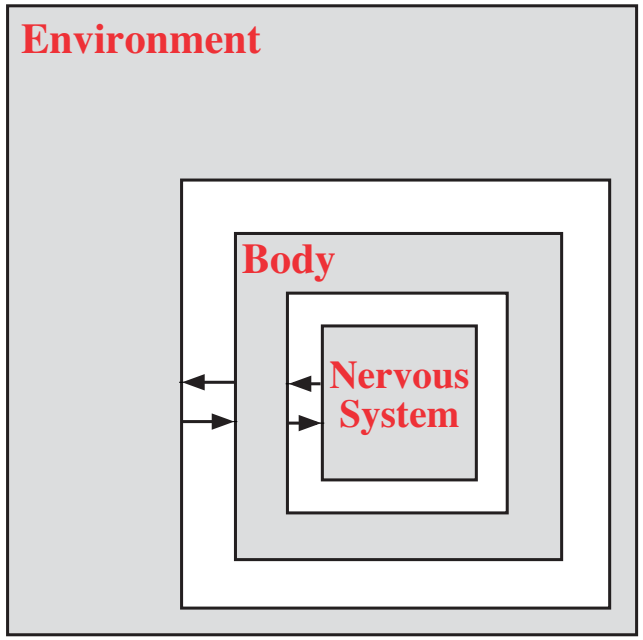
A Situated, Embodied, Dynamical Perspective

Situatedness

Embodiment

Dynamics



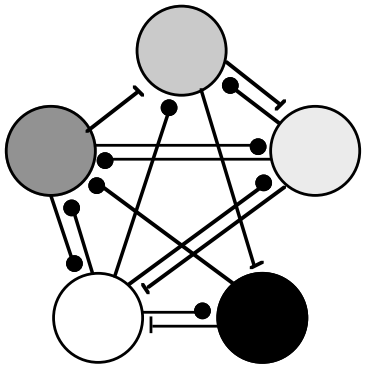


Behavior and **Cognition** are properties of the entire brain-body-environment system, not of any individual component

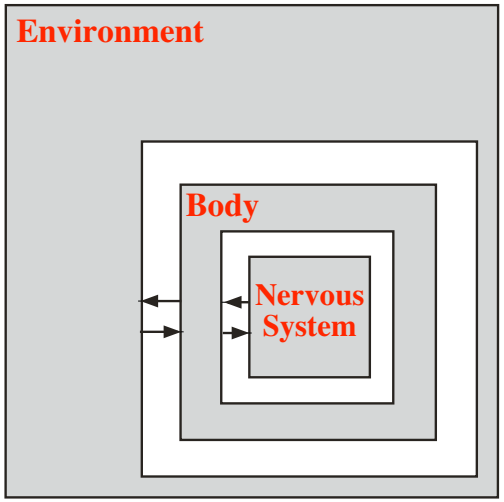
They can only be understood properly in this broader context

Theoretical Challenges

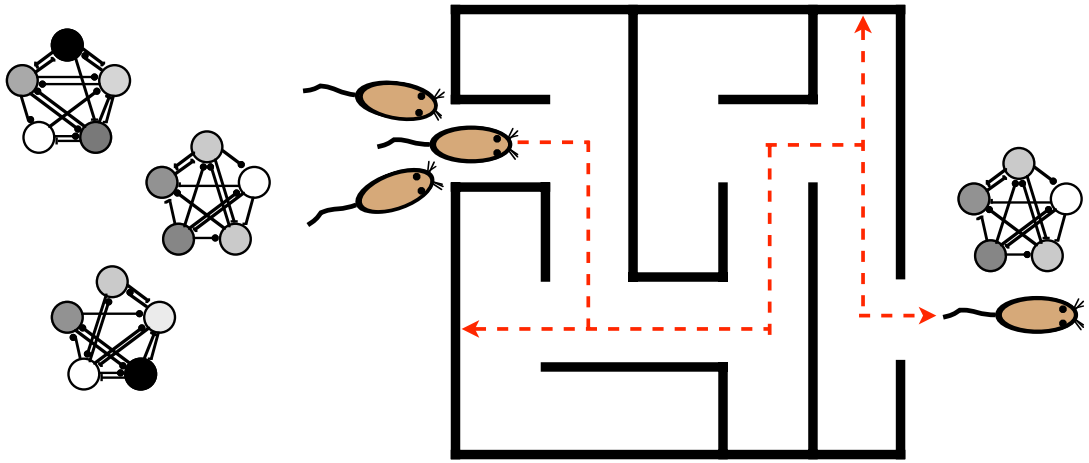
Nervous systems are complex networks of heterogeneous nonlinear elements



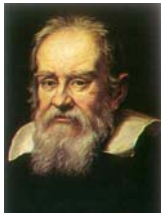
Nervous systems co-evolved with the bodies and environments in which they are embedded



Nervous systems were evolved, not designed

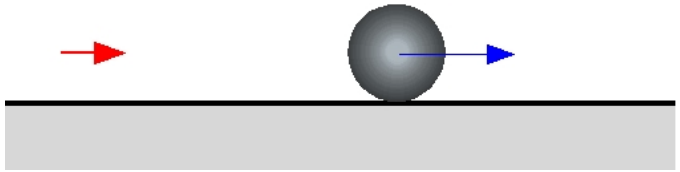


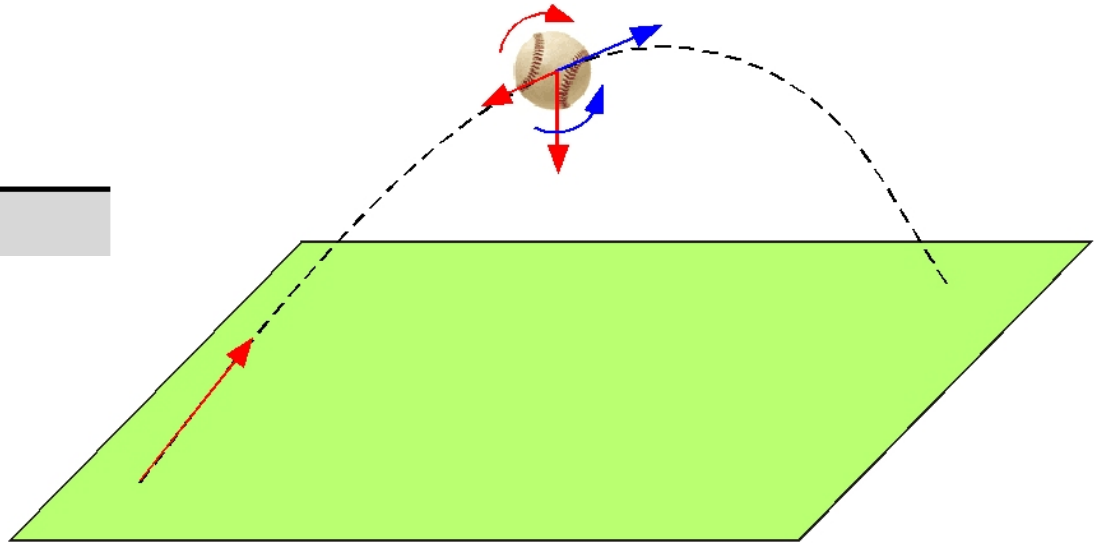
Frictionless Planes



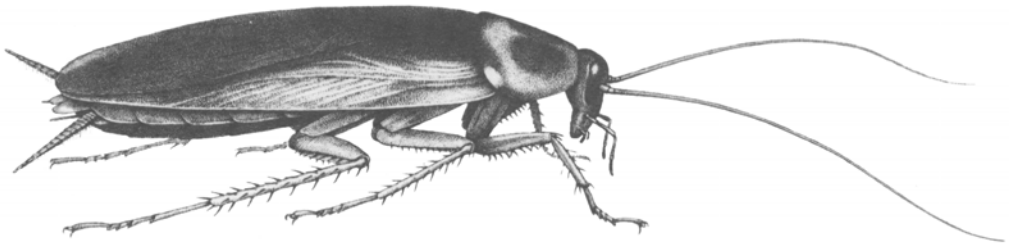
"I mentally conceive of some movable projected on a horizontal plane all impediments being put aside. Now it is evident ... that the equable motion on this plane would be perpetual if the plane were of infinite extent..."

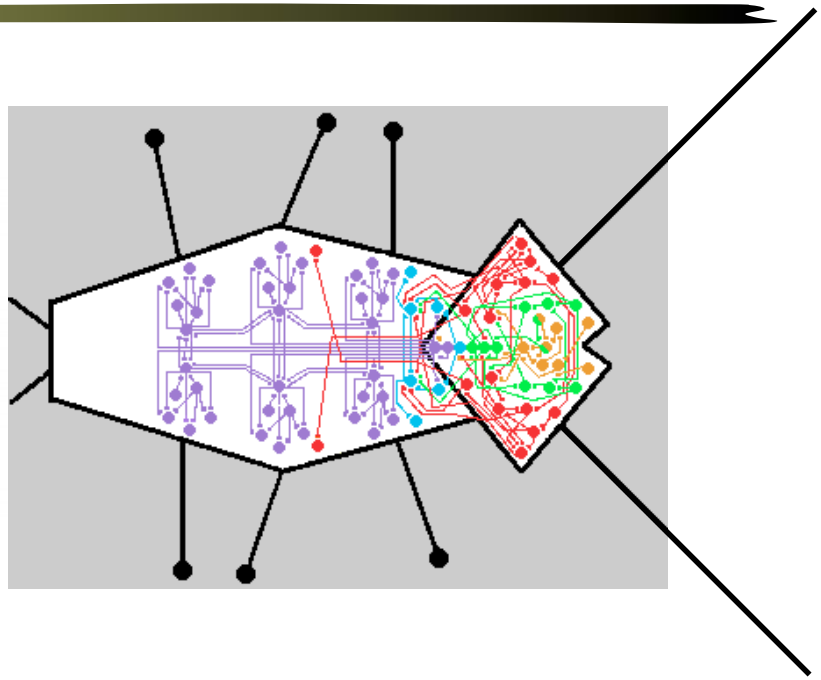
Galileo, Two New Sciences (1638)





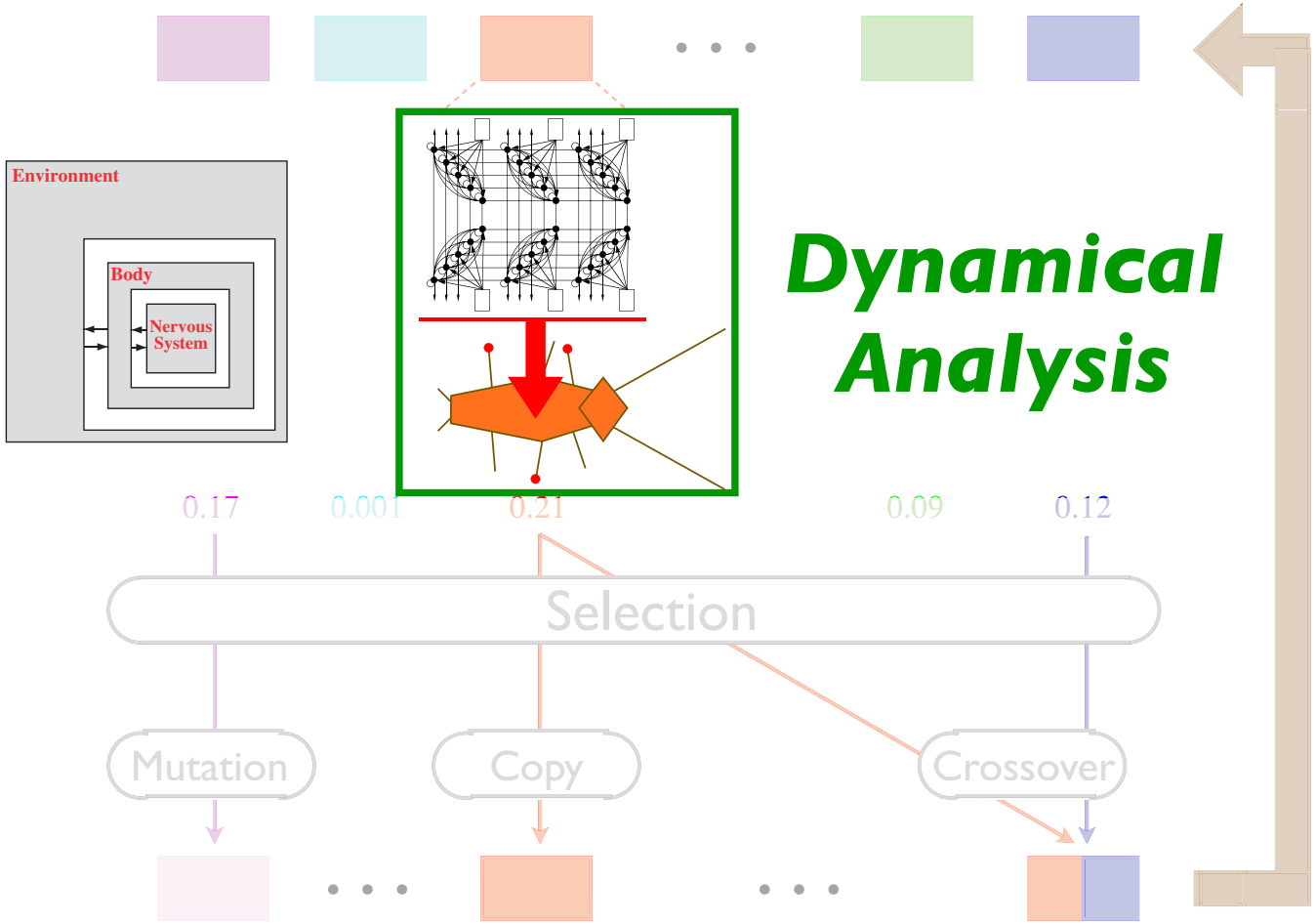
Frictionless Brains





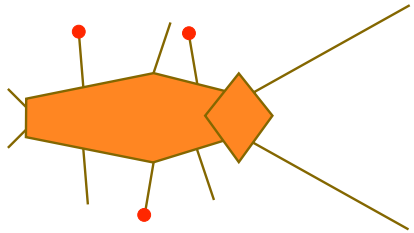
- Frictionless **Brains** (and **Bodies**, and **Environments**)
- Analysis of the simplest model agents that exhibit behavioral capabilities of interest
- Develop the necessary core theoretical principles and tools
- Then systematically complicate
- Mental calisthenics, intellectual warm-up exercises
- Ground conceptual analysis in concrete examples

Evolutionary Robotics and Dynamical Analysis



Accomplishments

Evolution and Analysis of Walking



- Evolving dynamical "nervous systems" for model agents works!
- Intra- and interleg coordination
- Sensor reliability during evolution determines pattern generator organization
- Adaptation to growing legs via entrainment
- Multiple instantiability
- Failure of averaging
- Sensitivity and robustness to parameter variation
- Decomposition and classification of evolved circuits using dynamical modules
- Biomechanical analysis
- Characterizing fitness space structure
- The impact of circuit architecture

with Gallagher, Chiel, Psujek and Ames (1992, 1995, 1999, 2006)

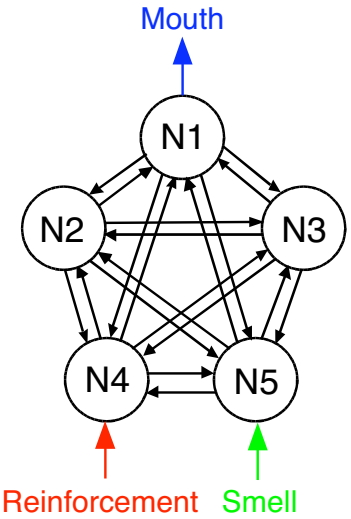
Evolution and Analysis of Learning

Environment A

Smell	Action Before Training	Reinforcement	Action After Training
■	◖	−	◖
	◖	+	
■	◖	+	◖
	◖	−	

Environment B

Smell	Action Before Training	Reinforcement	Action After Training
■	◖	+	◖
	◖	−	
■	◖	−	◖
	◖	+	

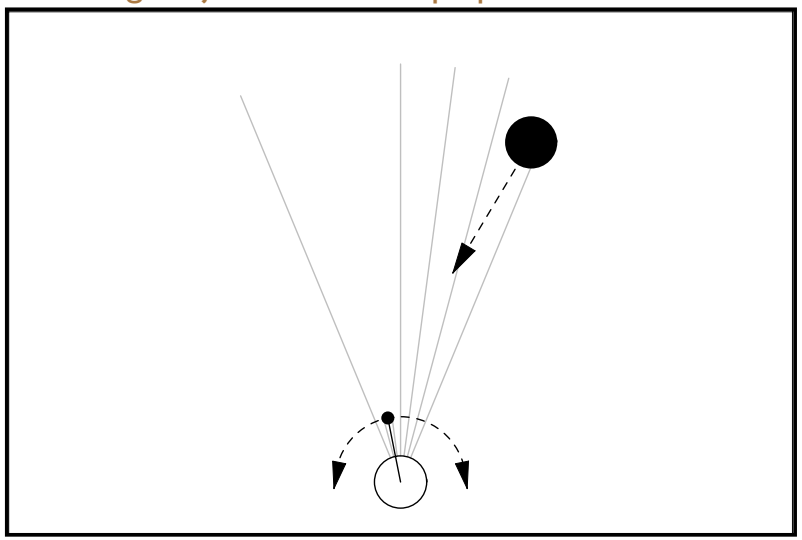


- Behavioral vs. mechanistic definitions of learning
- Learning w/o synaptic plasticity
- Learning in sequential decision-making (Landmark-based navigation)
- Associative learning (Food edibility)
- Analysis of learning dynamics in circuits w/o synaptic plasticity
- Associative learning w/ plastic synapses

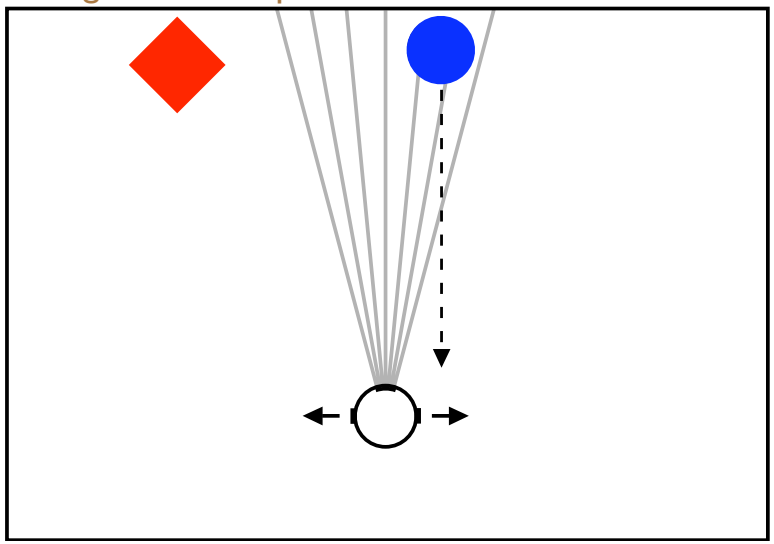
with Yamauchi, Phattanasri and Chiel (1994, 2002, 2006)

Minimally Cognitive Behavior

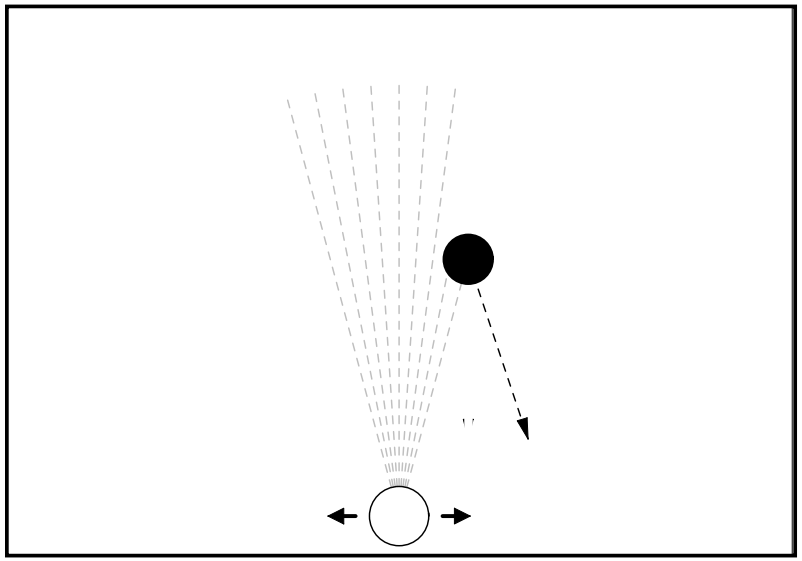
Catching Objects with an Opaque Hand



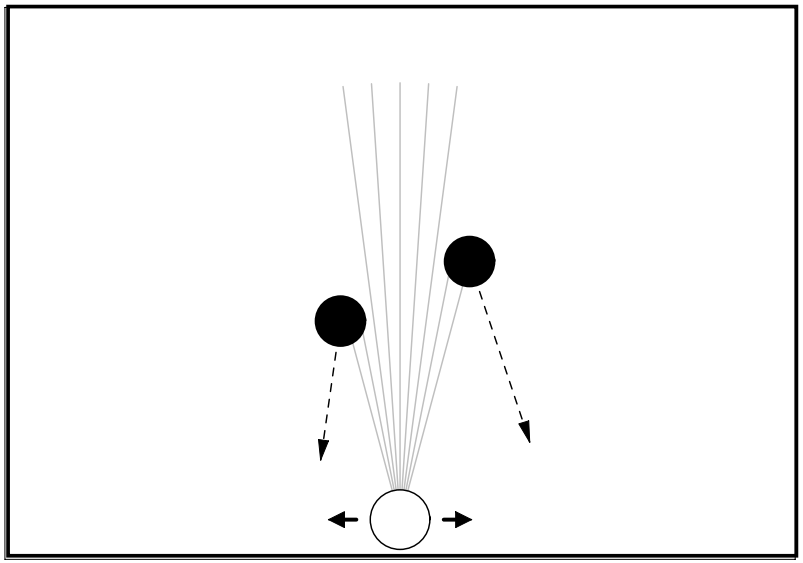
Categorical Perception



Short-Term Memory



Selective Attention



with Gallagher, Downey and Slocum (1996, 1999, 2000, 2003)

The Nature of Dynamical Explanation

Scientific Theories and Mathematics

The World

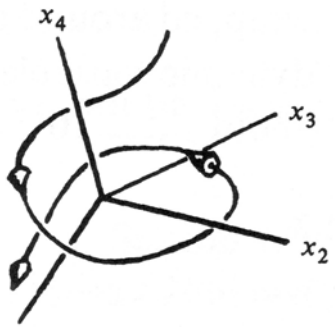
Theories

Mathematics

PREDICTIONS

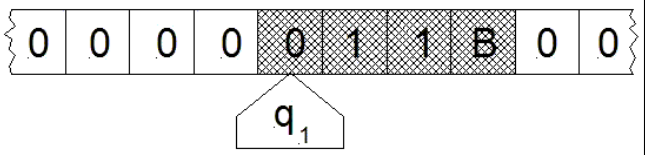
MODELS

$$\frac{dx_k}{dt} = F_K(x_1, \ldots, x_4)$$



Dynamical Systems Theory

Formal Theory of Computation



Theoretical Frameworks

The Roles of Computation in CogSci

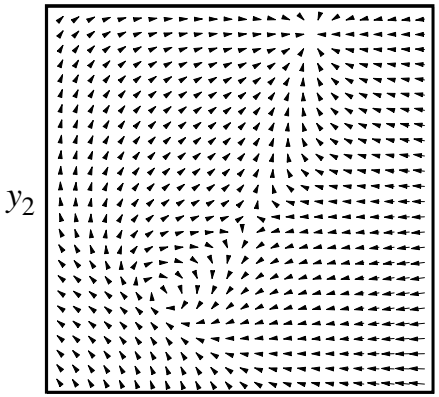
- Computation is a cognitive phenomenon to be explained
  - ➪ Through conscious deliberation, we can compute things
- The formal theory of computation is a body of mathematics
  - ➪ FTC is abstracted from our own computational abilities
- Computers are a modeling technology
  - ➪ A technological instantiation of the mathematical theory
- Computationalism is a theoretical framework for Cognitive Science
  - ➪ The processes underlying cognition are to be understood as computational processes

What is a Dynamical System?

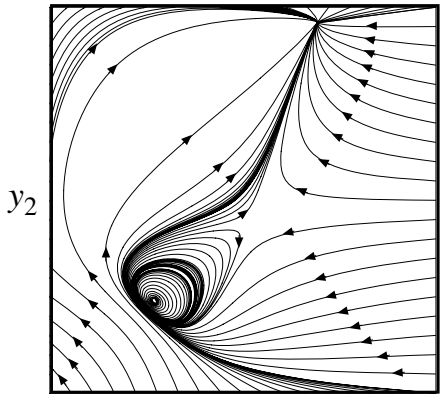
- A state space S
  - May be symbolic or numerical
  - May be discrete or continuous
  - May be any dimension or topology
- An ordered time set T
  - May be discrete or continuous
- An evolution operator $\phi_t(x)$: $S \times T \rightarrow S$
  - May be given explicitly or implicitly
  - May be deterministic or stochastic
- Examples include
  - Sets of differential equations (ordinary, partial, stochastic)
  - Iterated maps
  - Finite state machines, Turing machines
  - Cellular automata

Basic Concepts

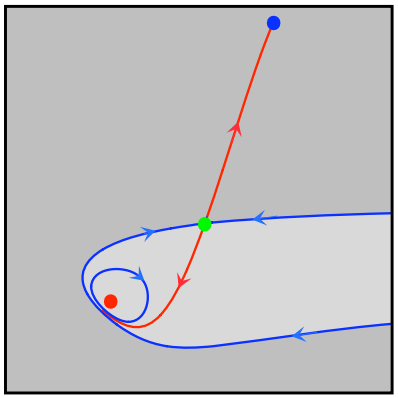
Vector Field



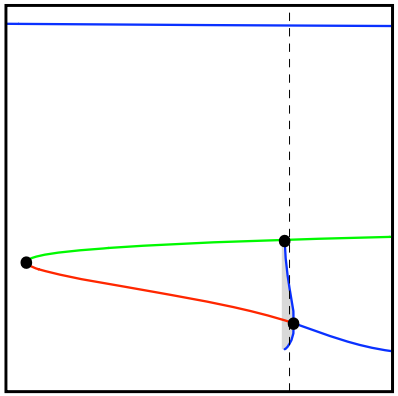
Initial State
Solution Trajectory
Flow



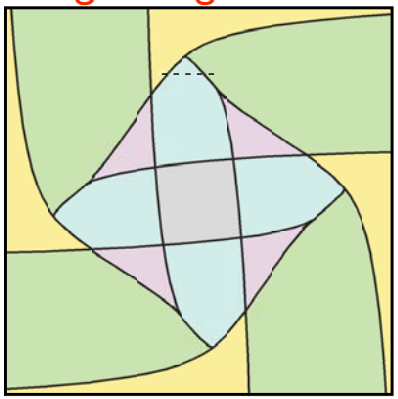
Limit Set
Stability
Phase Portrait



Bifurcation Diagram
Center Manifold
Normal Form

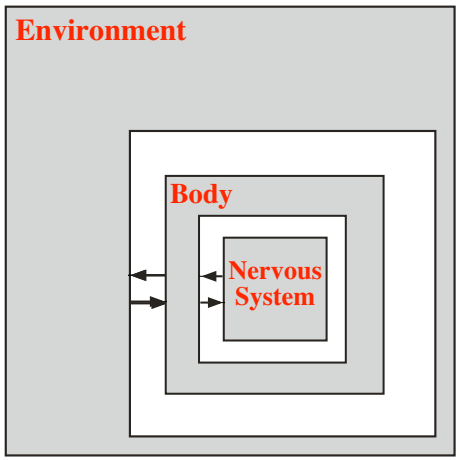


Parameter Chart
Organizing Centers

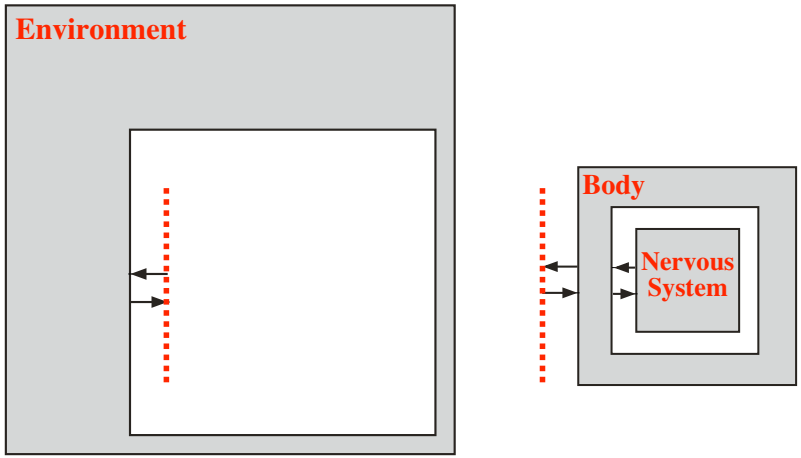


Levels of Dynamical Analysis

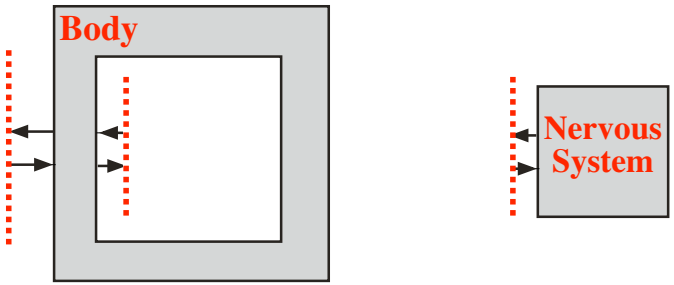
Coupled System Dynamics



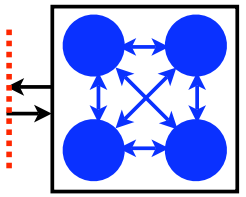
Agent-Environment Interaction Dynamics



Neuromechanical Dynamics

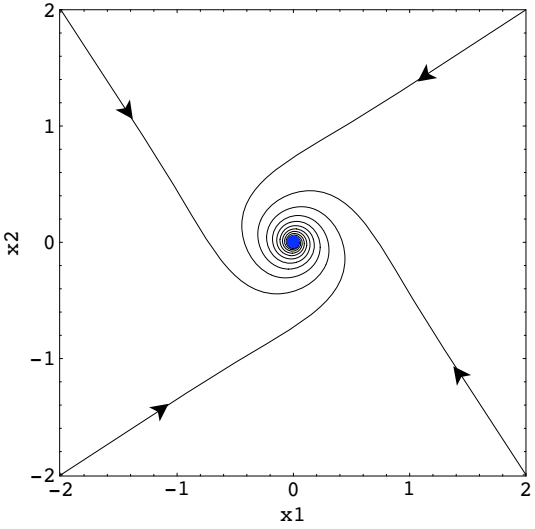


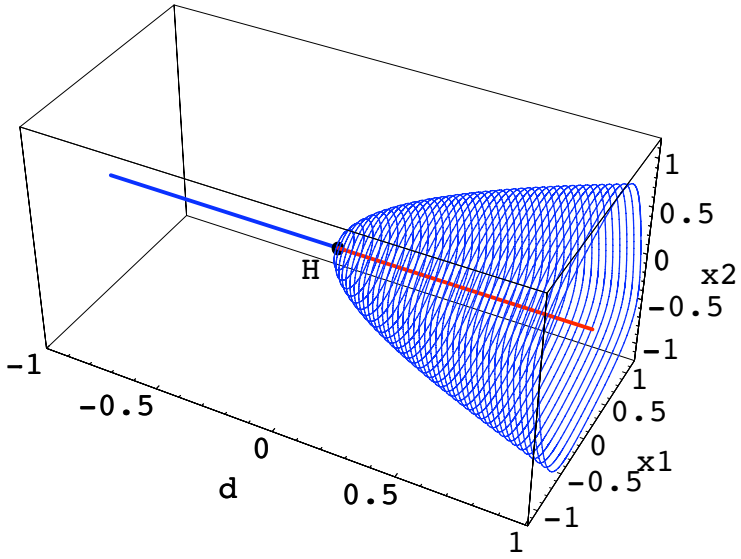
Neuronal Dynamics

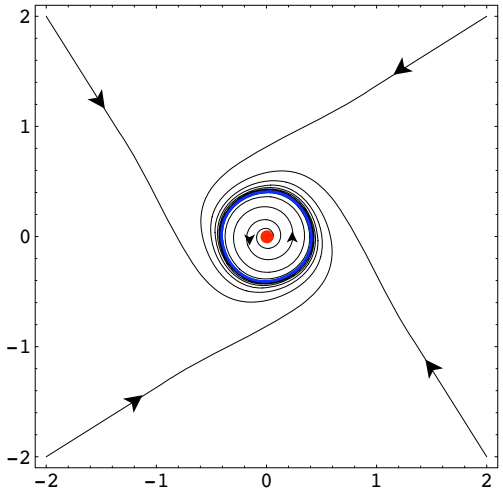


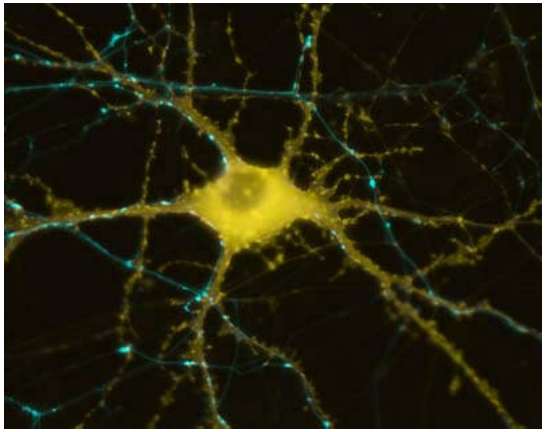
Universal Features of Dynamical Systems

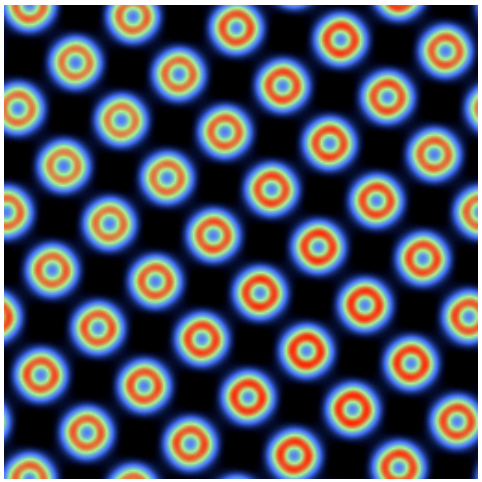
A Hopf Bifurcation











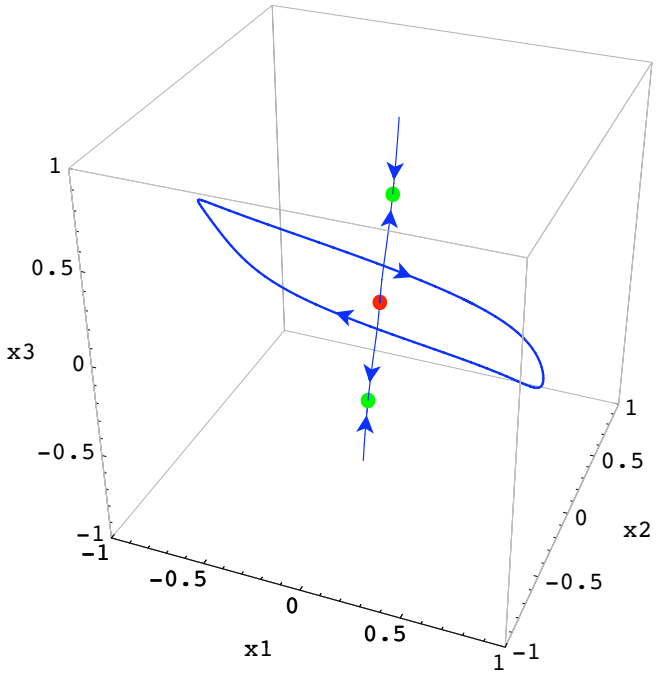
Repetitive Firing in Nerve Cells

Chemical Reactions

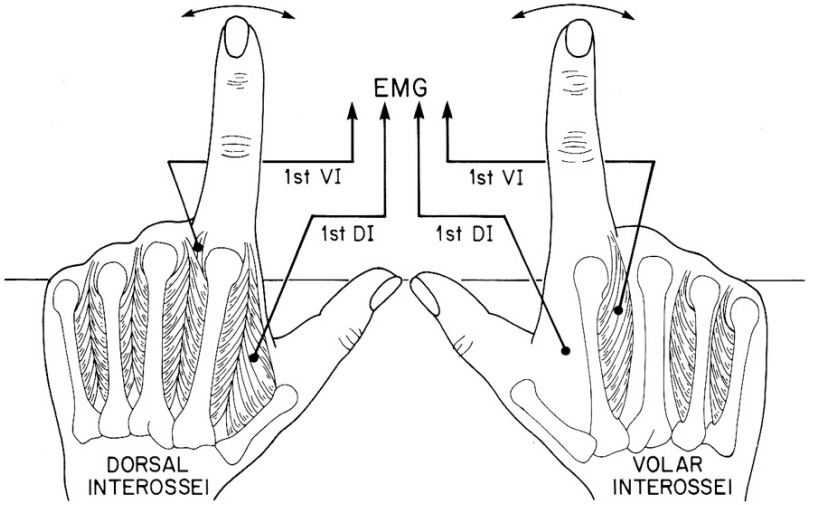
Predator-Prey Interactions

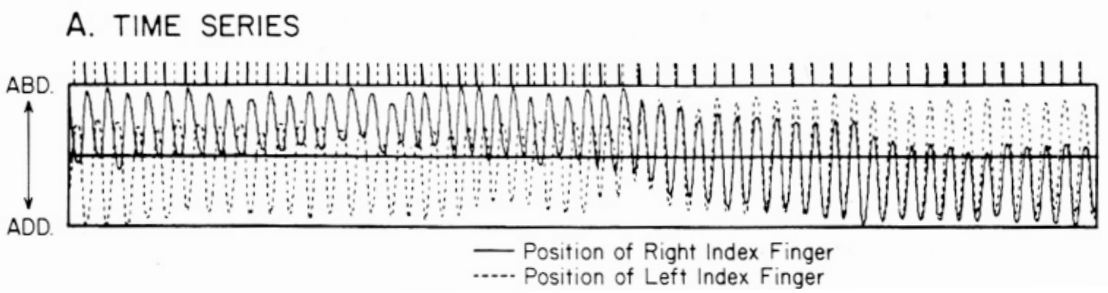
Microdynamical vs. Macrodynamical

$$\dot{x}_1 = f_1(x_1, x_2, x_3)$$
$$\dot{x}_2 = f_2(x_1, x_2, x_3)$$
$$\dot{x}_3 = f_3(x_1, x_2, x_3)$$



$$\dot{\theta} = g(\theta)$$





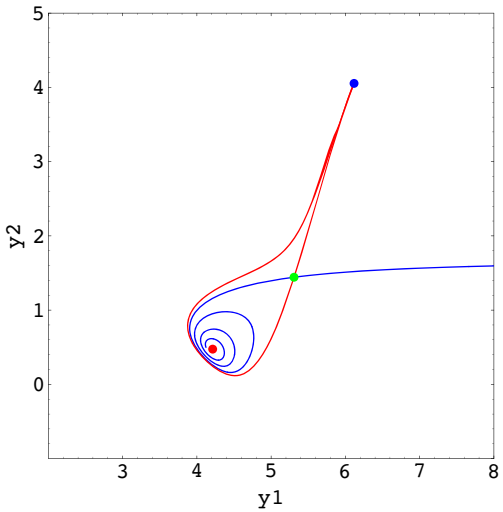
$$\dot{\phi} = -a\sin\phi - 2b\sin 2\phi$$

Dynamics and Mechanism

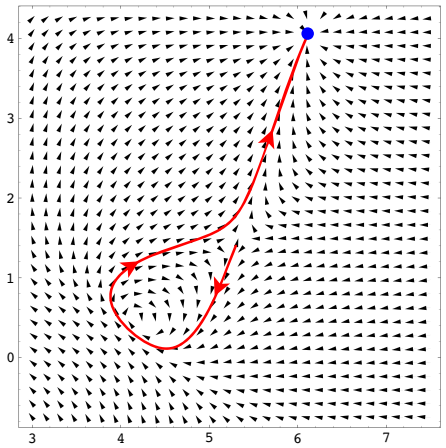
- Dynamics concerns patterns of change that transcend particular instantiations
- Connectionism and Dynamicism overlap but are not equivalent
  - ➪ Connectionist Dynamicism may provide a path to Neuroscience
  - ➪ Dynamical Connectionism may provide a path to higher cognition
- Continuous-Time Recurrent Neural Networks
  - ➪ Neurobiological interpretations
    - ☑ Mean firing rate
    - ☑ Nonspiking neurons with nonlinear synaptic interactions
  - ➪ Neurobiological implications
    - ☑ Multiple instantiability
    - ☑ Failure of averaging
    - ☑ Sensitivity and robustness to parameter variation
- CTRNNs are universal approximators of smooth dynamics
- CTRNNs can be interpreted in two different ways
  - ➪ As a simple model of nervous systems
  - ➪ As a convenient basis dynamics

Attractors and Transients

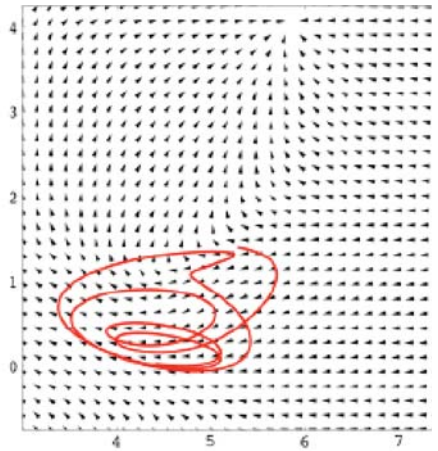
Autonomous Dynamics



Transient Dynamics



Nonautonomous Dynamics

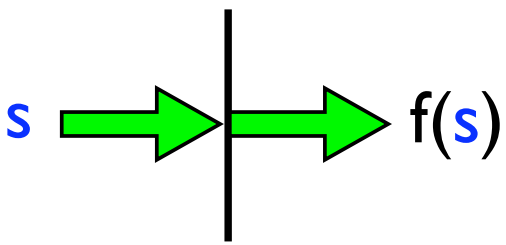


Stalking the Wily Representation

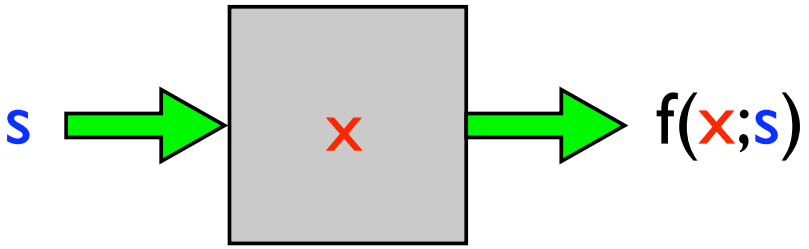
Representational Skepticism

- Internal state plays an essential role in dynamical agents
- But is it a re-presentational role?
- **Not** being antirepresentational to ask this question
- The concept of representation is absolutely fundamental to cognitive science
- Yet this concept is largely taken for granted
- It would be scientifically irresponsible **not** to critically examine this concept
- Representational skepticism

The Significance of Internal State



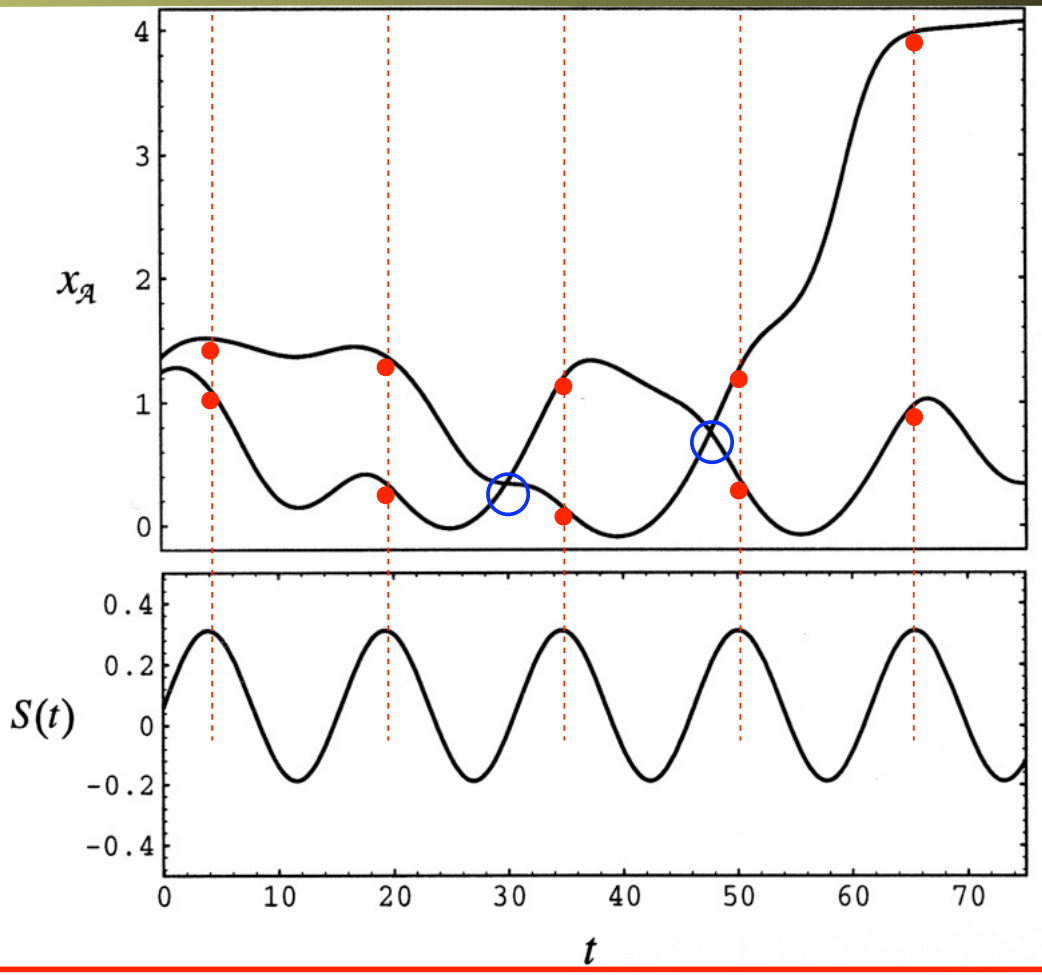
A Reactive Agent



A Dynamical Agent

- A reactive agent is at the mercy of its environment
- A dynamical agent can
  - Initiate behavior independently of its immediate sensations
  - Respond differently to identical sensory stimuli at different times
  - Organize its behavior in anticipation of future events
  - Modify its future behavior based on its history of interactions

Internal State ≠ Representation

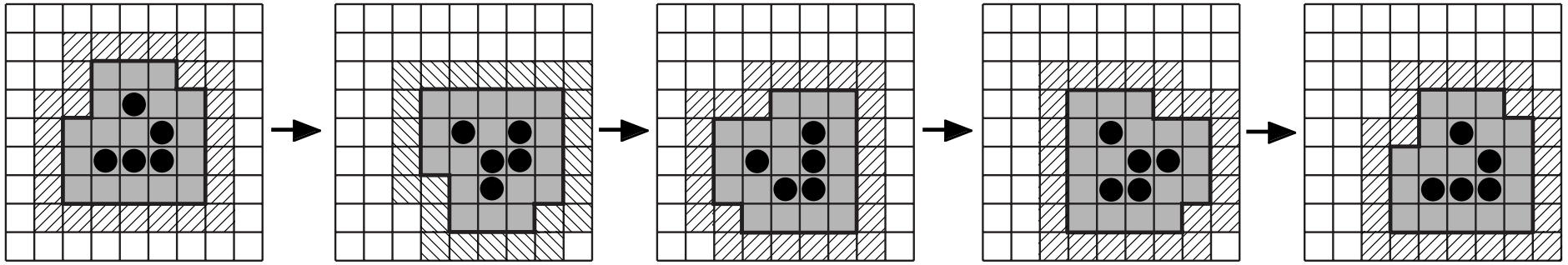


Internal state sets a context for the response of a dynamical agent to subsequent perturbation

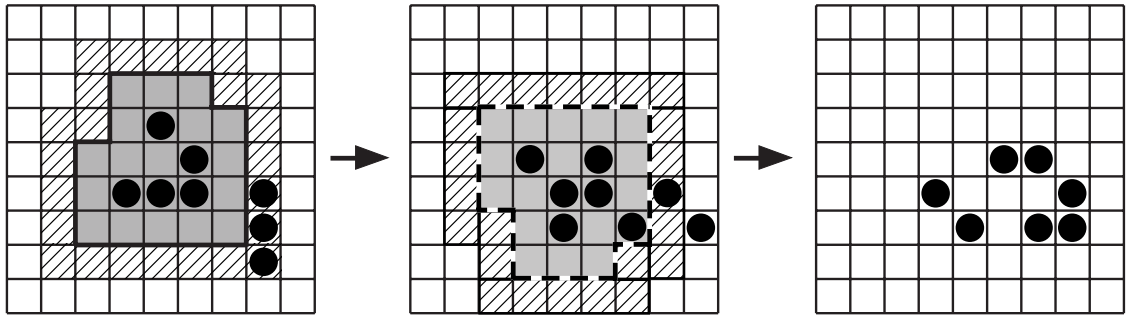
A broader theoretical playing field

Autopoiesis and Cognition in the Game of Life

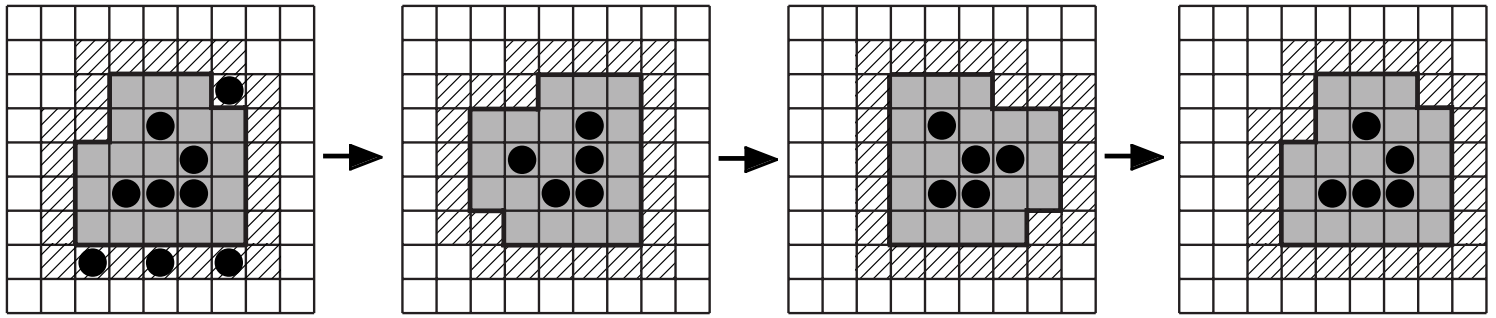
A Glider



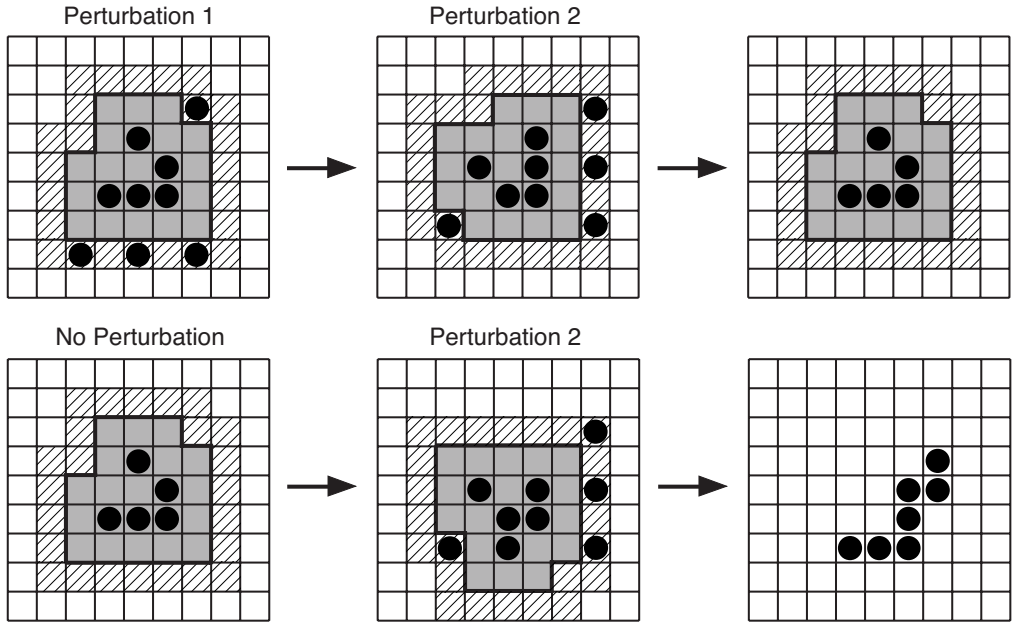
Destructive Perturbation



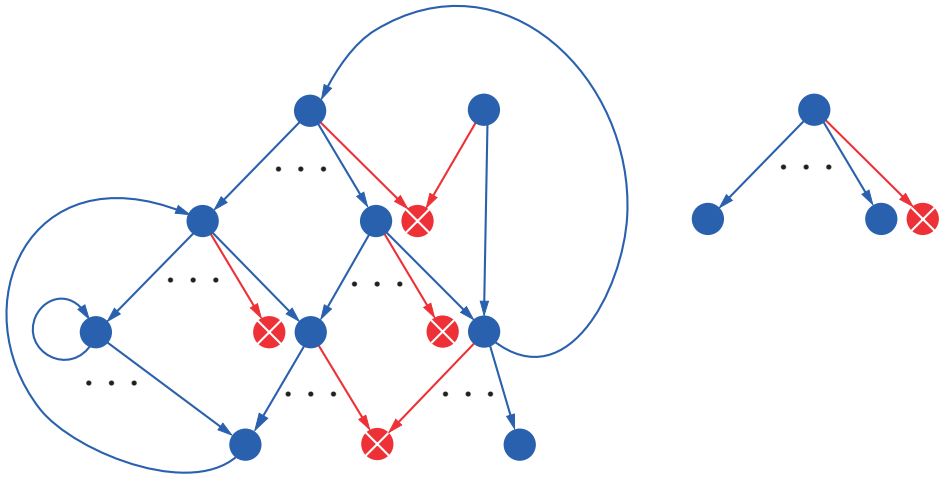
Nondestructive Perturbation



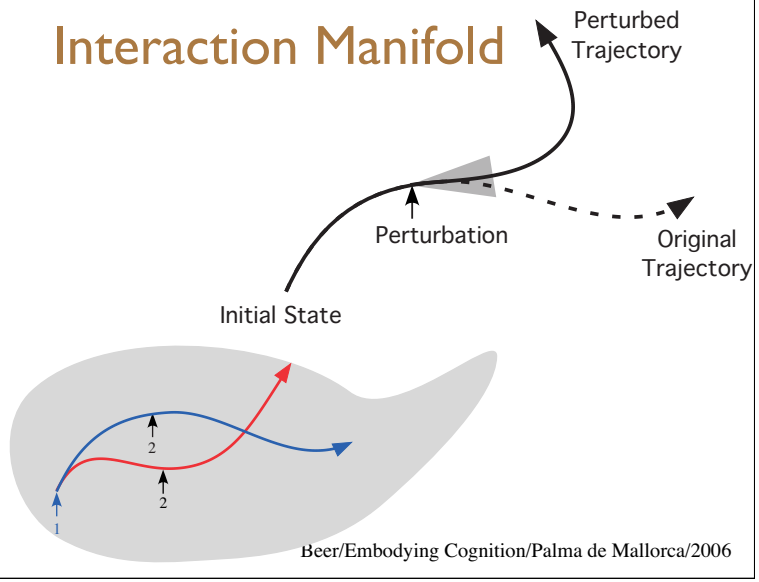
State-Dependent Sensitivity to Perturbation



Interaction Graph



Interaction Manifold



Challenges

- Methodological challenges
  - Scaling of evolutionary robotics
  - Better software tools for dynamical analysis
- Technical challenges
  - Managing complexity
  - Analysis of transient and nonautonomous dynamics
- Theoretical challenges
  - Scaling dynamical explanation
  - State-dependent sensitivity to perturbation
- Educational challenges