Frictionless Brains: Evolution and Analysis of Brain-Body-Environment Systems

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How can we understand the neural mechanisms underlying animal behavior?

How can we design artificial systems with the flexibility and robustness of animals?
The Artificial Insect

Beer (1989)
Research Overview

Biology

Robotics

Theoretical Challenges
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
Behavior is a property of the entire brain-body-environment system, not of any individual component.

*It can only be understood properly in this broader context*
Evolutionary Robotics

Dynamical Analysis

Environment
Body
Nervous System

Selection
Mutation
Copy
Crossover
CTRNN Dynamics
Continuous-Time Recurrent Neural Networks

\[ \dot{y}_i = \frac{1}{\tau_i} \left( -y_i + \sum_{j=1}^{N} w_{ji} \sigma(y_j + \theta_j) + I_i \right) \]

- Simplest nonlinear continuous-time dynamical neural model
- Biological interpretations
  - Mean firing rate model
  - Model of nonspiking neuron with input nonlinearities
- Computationally and analytically tractable
- (Continuous) Hopfield networks, but
  - Connections need not be symmetric
  - Self-connections allowed
- Universal approximator of smooth dynamics
- Model neurons or convenient basis dynamics?
CTRNN Dynamics

Phase Portraits

Bifurcation Diagrams

Parameter Charts

Beer (1995)
What is the structure of the \((N^2+2N)\)-dimensional space \(C_{\text{CTRNN}}(N)\)?
CTRNN Parameter Space Structure

Varying a self-weight

Varying a cross-weight

Beer (2006)
CTRNN Design & aVLSI Implementation

R. Kier and R. Harrison
University of Utah

with Kier, Ames and Harrison (2006)
Walking
Legged Locomotion

with Gallagher (1992)
Multiple Instantiability

Differ by less than 2% in performance

with Chiel and Gallagher (1999)
Failure of Averaging

with Chiel and Gallagher (1999)
Sensitivity and Robustness

6% change in 1 parameter

Nominal

129-467% coordinated change in 3 parameters

with Chiel and Gallagher (1999)
Walking:
Neuromechanical Analysis
Biomechanical Analysis

\[ V^* = \frac{D^*}{T^*} \approx 0.627 \]

Stance

\[ \pi/6 \]

Power

\[ \pi/6 \]

Foot

\[ 20 \]

Up

Swing

\[ \pi/6 \]

Down

\[ \pi/6 \]

\[ D^* \]

\[ T^* \]

with Chiel and Gallagher (1999)
Explaining Motor Pattern Variability

with Chiel and Gallagher (1999)
Walking:
Fitness Space Structure
CPG Fitness Space Structure

Beer (2002)
RPG Fitness Space Structure

Beer (2002)
The Impact of Circuit Architecture

~2.2 million experiments!

with Psujek and Ames (2006)
Fitness Classes

3-Neuron

Class 1

Class 2

Class 3

4-Neuron

5-Neuron

with Psujek and Ames (2006)
Evolvability

with Psujek and Ames (2006)
Learning
Associative Learning

Environment A

<table>
<thead>
<tr>
<th>Smell</th>
<th>Action Before Training</th>
<th>Reinforcement</th>
<th>Action After Training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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Environment B

<table>
<thead>
<tr>
<th>Smell</th>
<th>Action Before Training</th>
<th>Reinforcement</th>
<th>Action After Training</th>
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<tbody>
<tr>
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with Phattanasri and Chiel (2002)
Circuit Behavior

Environment A  Environment B  Environment A

with Phattanasri and Chiel (2002)
The Dynamics of a Trial
Circuit Dynamics

Environment A

Environment B
Minimally-Cognitive Behavior
Visually-Guided Behavior

Catching Objects

Perception of Body-Scaled Affordances

Short-Term Memory

Selective Attention
An Object Discrimination Task
Evolution of Genetic Regulatory Networks
Model

Regulatory Region

- ZZZZ
- WWX
- yzXX

Coded Protein → 6

Coding Region

- wxxzyy
- wzwxxxywxwzw
- ZZWZZZ

Bind x y z x

Start codon
Promotor
Enhancer
Repressor
Domain Function
Data Segment

with Drennan (2004, 2006)
## The Repressilator


<table>
<thead>
<tr>
<th>Repressors</th>
<th>Binding Sequence</th>
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<tbody>
<tr>
<td>wzw</td>
<td>xxx yww wzw wzw</td>
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<tr>
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<td>zzx zzz</td>
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<tr>
<td>wzw</td>
<td>wzw xxx yww wzw</td>
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<td>zzw zzz</td>
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<tr>
<td>wzw</td>
<td>wzw wzw xxx xxx</td>
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<tr>
<td></td>
<td>zzx zzz</td>
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Evolving a Repressilator

with Drennan (2004, 2006)
Interplay of Development Bias and Evolution
Model Gene

![Diagram of a model gene with regulatory and coding sections, showing various sequences and protein types.]

**Coding section sequences**

1. **i)** \( \text{CC}xxx \) \( \text{CCCC}xx \) - Intra-cellular signal/TF (Int)
2. **ii)** \( \text{CA}xxx \) \( \text{CCCC}xx \) - Extra-cellular signal/TF (Ext)
3. **iii)** \( \text{AC}xxx \) \( \text{CCCC}xx \) - Pre-synaptic marker (Pre)
4. **iv)** \( \text{AA}xxx \) \( \text{CCCC}xx \) - Post-synaptic marker (Post)

**Protein types**

1. Intra-cellular signal/TF (Int)
2. Extra-cellular signal/TF (Ext)
3. Pre-synaptic marker (Pre)
4. Post-synaptic marker (Post)

**Protein shapes**

- Intra-cellular signal/TF: Ellipse
- Extra-cellular signal/TF: Rectangle
- Pre-synaptic marker: Triangle
- Post-synaptic marker: Square

*with Psujek (2006)*
with Psujek (2006)
Developmental Bias

Global Bias

Local Bias

with Psujek (2006)
Summary

- **Research Program**: Dynamics of brain-body-environment systems
- **Methodology**: Evolution and analysis of model agents
- **Results**
  - Dynamics of neural circuits
  - Evolution and analysis of sensorimotor control
  - Evolution and analysis of learning
  - Evolution and analysis of minimally cognitive behavior
- "Frictionless Brains" (and Bodies and Environments)
- Theoretical/Computational Biology