SYDE 556/750

Simulating Neurobiological Systems
Lecture 1: Introduction

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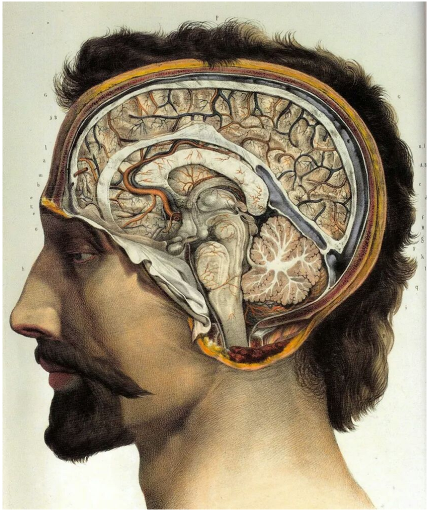
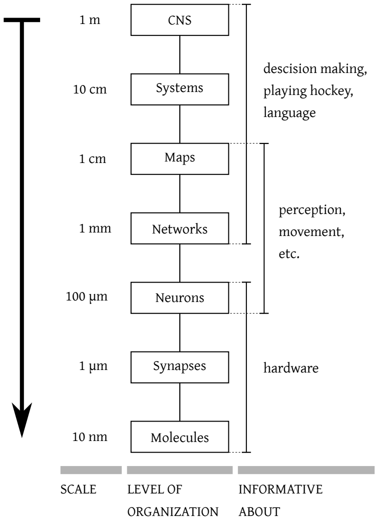


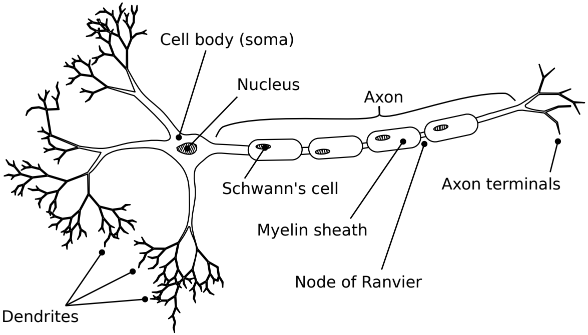
Problems With Current Approaches: Behavioural Models

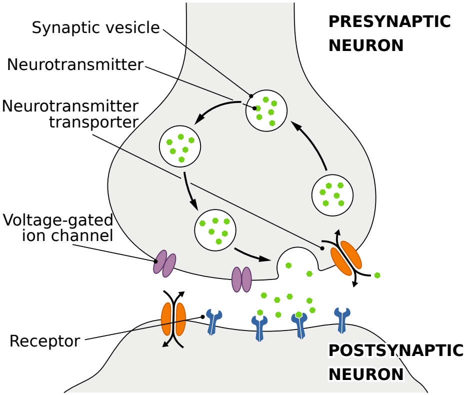
- **Top-down** approach
- **Modeling Frameworks:** ACT-R, SOAR
- **Shortcomings**
  - Can't compare to neural data
  - No "bridging laws"
  - No constraints on the equations

> ⚠ **Maybe these shortcomings are okay.**
>
> Do we understand the brain enough to derive bridging laws and constrain theories?
>
> When understanding a word processor, do we worry about transistors?



Neurons in the Brain





- 100’s or 1000’s of **distinct types** (distinguished by anatomy/physiology)
- Axon length: from 100 μm to 5 m
- Vastly different input/output counts (*convergence* and *divergence*)
- 100’s of different neurotransmitters

Kinds of Data From the Brain – Non-Invasive – EEG

Electroencephalography

Electric activity on top of the scalp

- High time resolution
- Relatively cheap
- Artefacts (eye movement, swallowing)
- Low spatial resolution

Image Sources. Left: Electroencephalogram (image from Wikimedia). Right: EEG cap (image from Wikimedia).

Visual Cortex

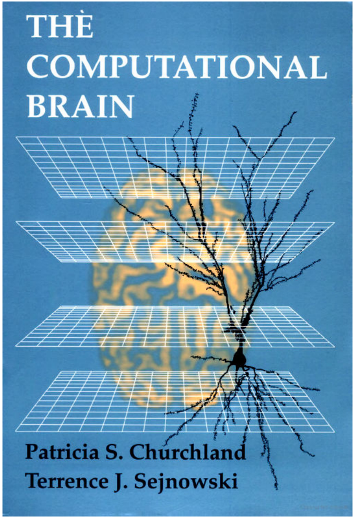
Mapping receptive fields

What do we know so far?

- **Lots of details**
  - **Data:**
    "The proportion of type A neurons in area X is Y."
  - **Conclusion:**
    "The proportion of type A neurons in area X is Y."
- Hard to get a big picture
  - No good methods for generalizing from data
- Need some way to connect these details

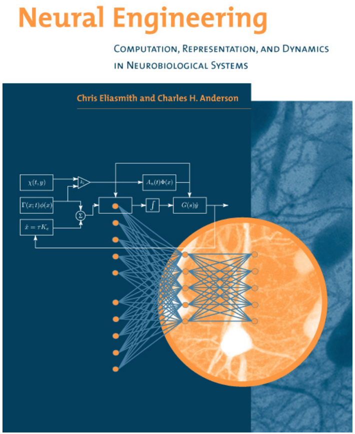
$\Rightarrow$ Need unifying theory

"Neuroscience is data-rich and theory poor"
— Churchland & Sejnowski, 1994



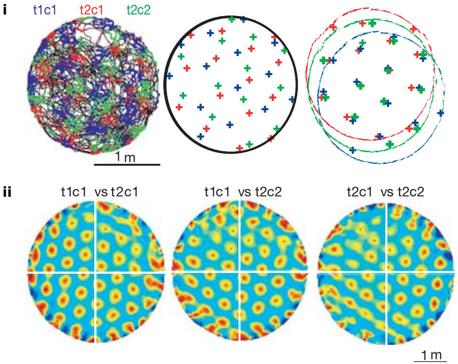
The Neural Engineering Framework

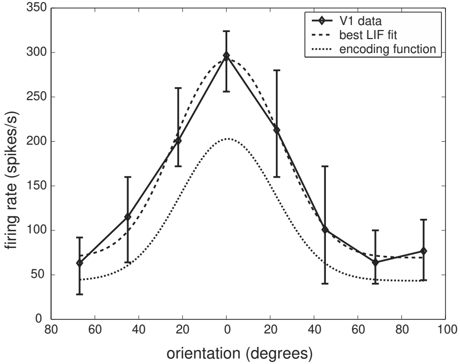
- Our attempt
  - Probably wrong, but got to start somewhere
- **Three principles**
  - Representation
  - Transformation
  - Dynamics
- Building **behaviour** out of **detailed low-level components**



Representation

- How do neurons represent information? (What is the neural code?)

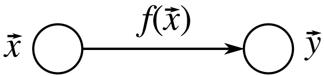




- What is the mapping between a value and the activity of a group of neurons?
- Every group of neurons can be thought of as **representing a vector**

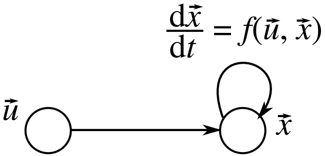
Image Sources. Left: Grid cells, from Hafting et al., *Microstructure of a Spatial Map in the Entorhinal Cortex* Nature (2005), fig. 3. Right: Example of visual orientation tuning in primary visual cortex, from "Neural Engineering", fig. 3.1.

Transformation



- **Connections compute functions** on those vectors
- One group of neurons may represent $\mathbf{x} \in \mathbb{R}^m$, another group a vector $\mathbf{y} \in \mathbb{R}^n$
- Connection determines $f : \mathbb{R}^m \to \mathbb{R}^n$ with $f(\mathbf{x}) = \mathbf{y}$
- We can systematically find connection weights $\mathbf{W}$ that approximate a certain f
- Can analyse which f can be computed

Dynamics



- Recurrent connections (feedback) implement **dynamical systems**

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x}(t) = f\left(\mathbf{x}(t), \mathbf{u}(t)\right)$$

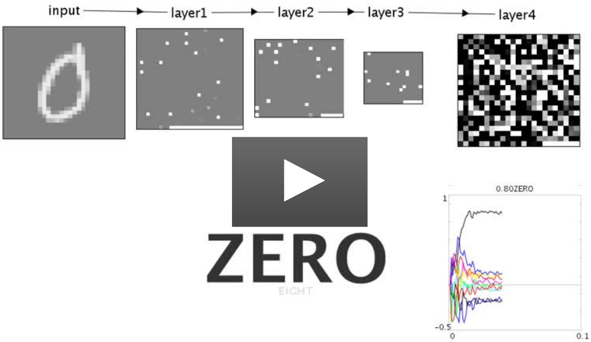
- Great for implementing control theoretical concepts
- Memory as an integrator

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x}(t) = \mathbf{u}(t)$$

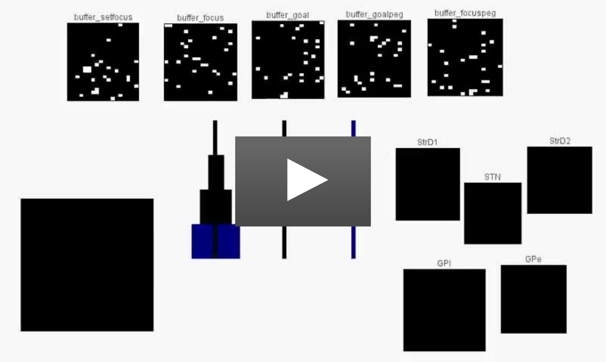
Examples

- This approach gives us a **neural compiler**
- Solve for the connections weights that approximate a **behaviour**
- Works for a wide variety of **neuron models**
- Number of neurons affects **accuracy**
- Neuron properties influence **timing** and computation
- Framework for high-level cognition: **Semantic Pointer Architecture (SPA)**
- World's largest functional brain model: **SPAUN**

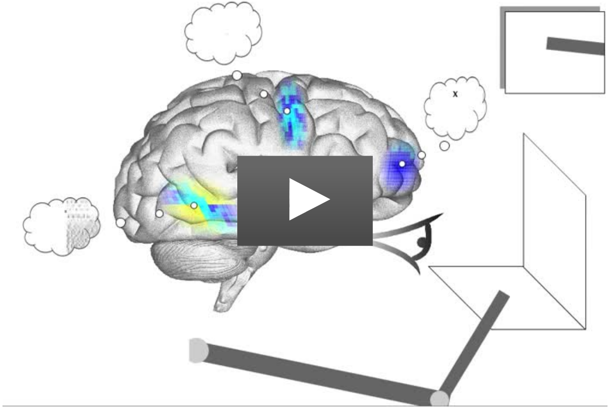
Examples: Recognizing Handwritten Digits



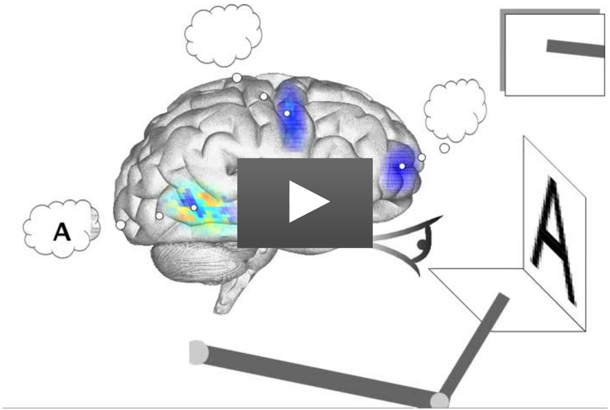
Examples: Playing Towers of Hanoi



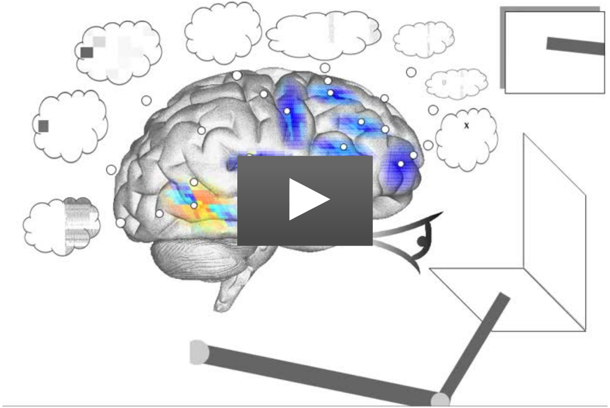
Examples: SPAUN Copy Drawing



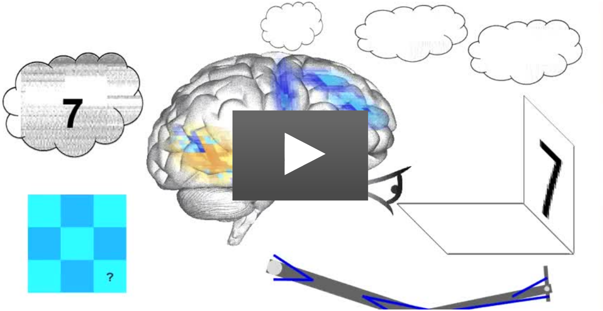
Examples: SPAUN Recognizing Digits



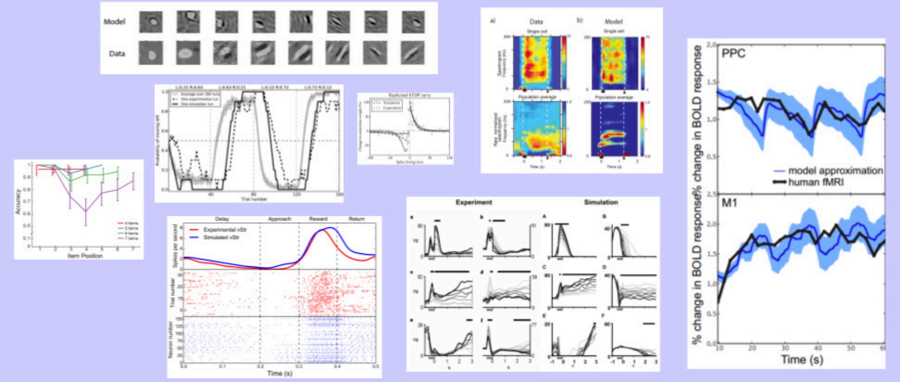
Examples: SPAUN Silent Addition



Examples: SPAUN Pattern Completion



Benefits



- No one else can do this
- New ways to test theories
- Suggests different types of algorithms
- Potential medical applications
- New ways of understanding the mind and who we are