Computational Neurodynamics

Topic 1
Introduction and Motivation

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Overview

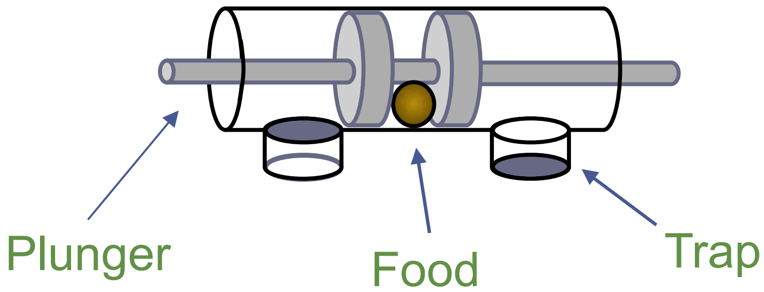
- Comparative cognition
- Animal brains
- The synthetic methodology
- Course overview

Comparative Cognition

- Many animals are capable of impressive cognitive feats despite their lack of language
- Cognitive high-fliers include
  - apes (apart from humans), such as chimpanzees
  - certain birds, especially corvids (rooks, crows, ...)
  - certain cephalopods, notably octopuses
- Cognitive capabilities include
  - Tool use and meta-tool use
  - Tool construction
  - Observational learning
  - Metacognition
  - Episodic-like memory

Example: Physical Cognition

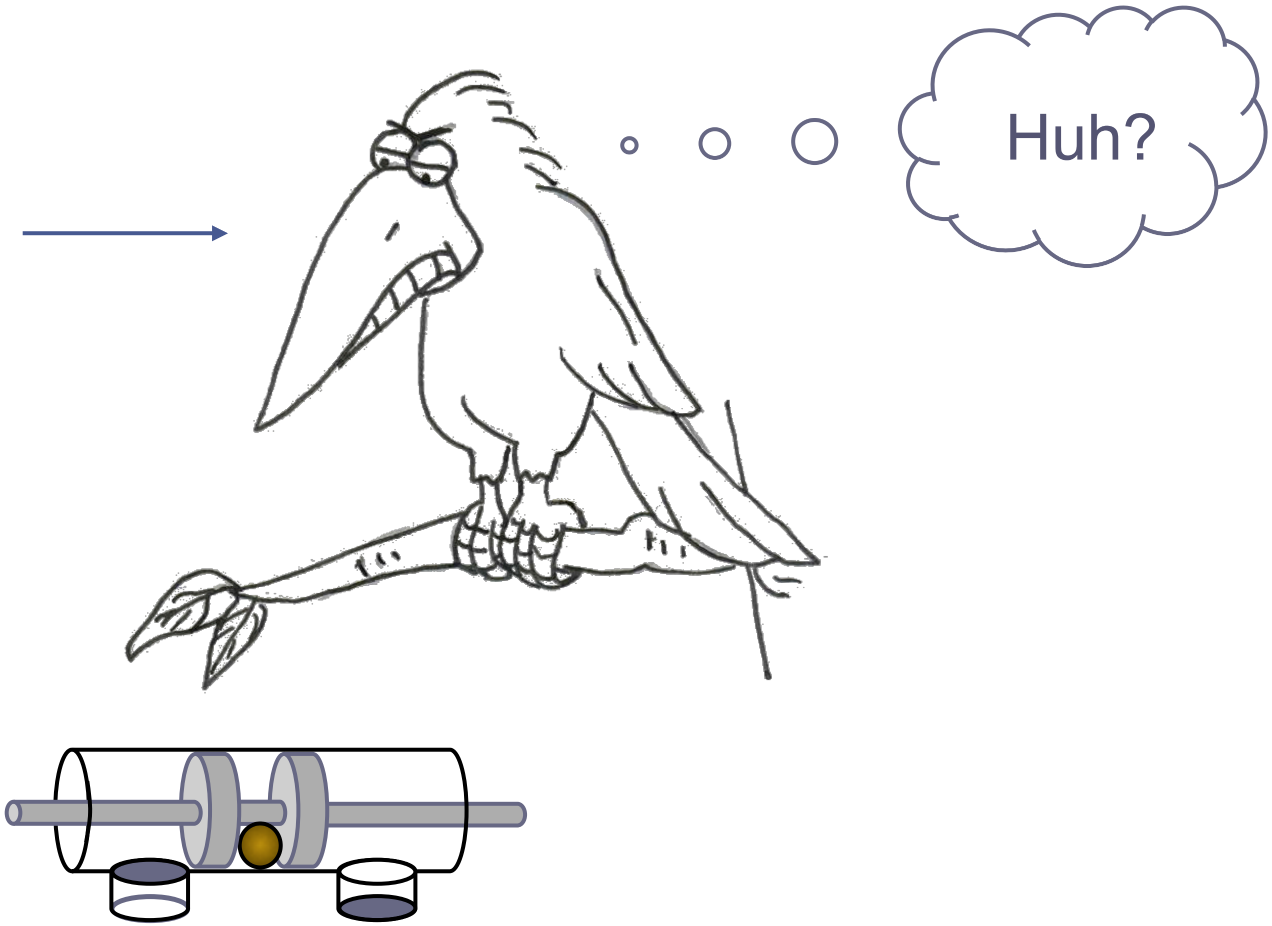
- It has been shown that rooks and crows are capable of solving problems that require an understanding of the physical properties of objects
- One paradigm involves the use of different kinds of *trap-tube*



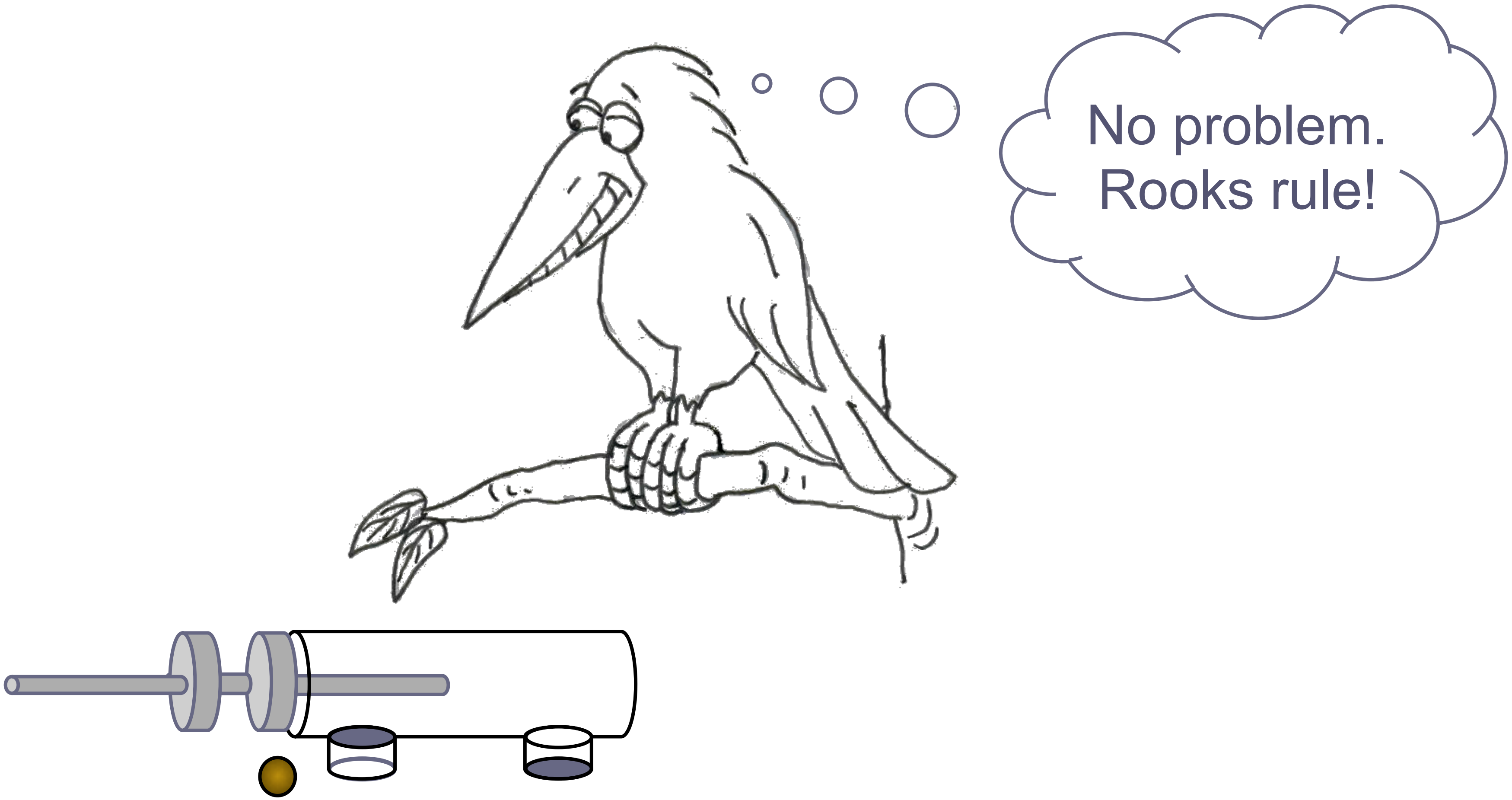
- The birds must pull the plunger in the right direction to obtain the food, or it is lost in the trap
- If a bird spontaneously solves a problem (without trial and error), it is evidence of physical cognition

The Initial Problem

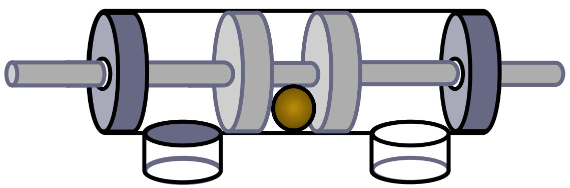
Guillem



Solved by Trial and Error



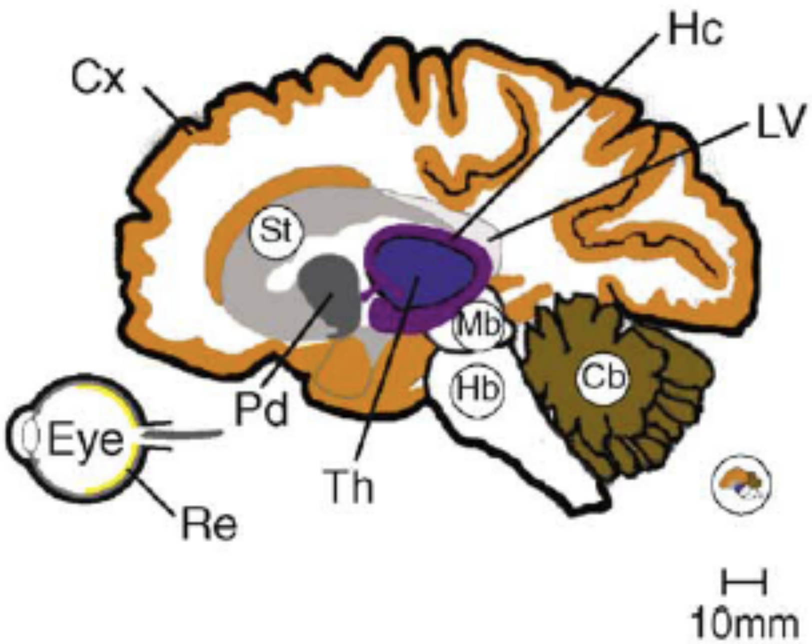
An Unseen Variation



Spontaneously Solved

Mammalian Brains

Human



From Edelman & Seth, 2009

- The anatomy of the human brain is dominated by its large convoluted cerebral *cortex*
- The cerebral cortex is organised into six layers

Cerebral cortex (Cx)

Thalamus (Th)

Hippocampus (Hc)

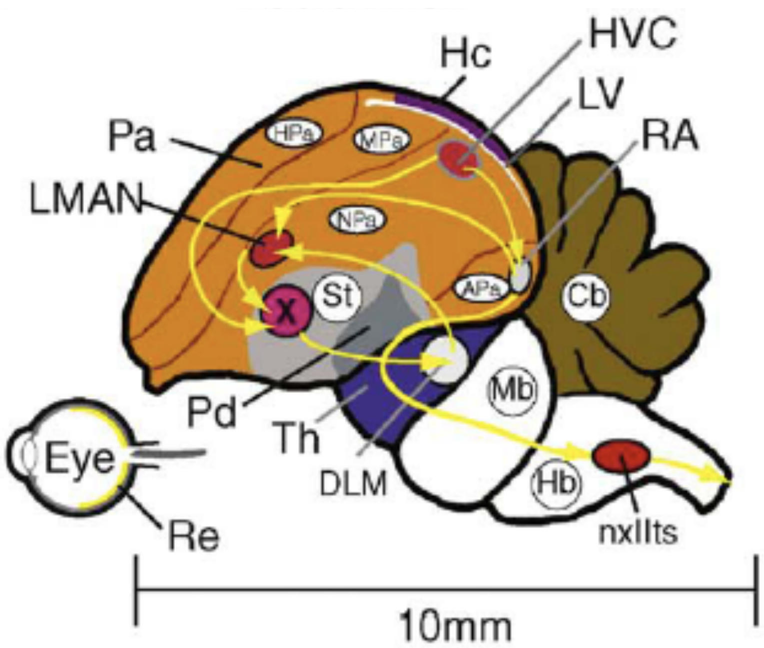
Striatum (St)

Midbrain (Mb) and hindbrain (Hb)

Cerebellum (CB)

Avian Brains

Zebra finch



From Edelman & Seth, 2009

- The homologue of mammalian cortex in a bird’s brain is the *pallium*
- But the pallium is not layered. Rather, it has a nucleated structure

Pallium (Pa)

Thalamus (Th)

Hippocampus (Hc)

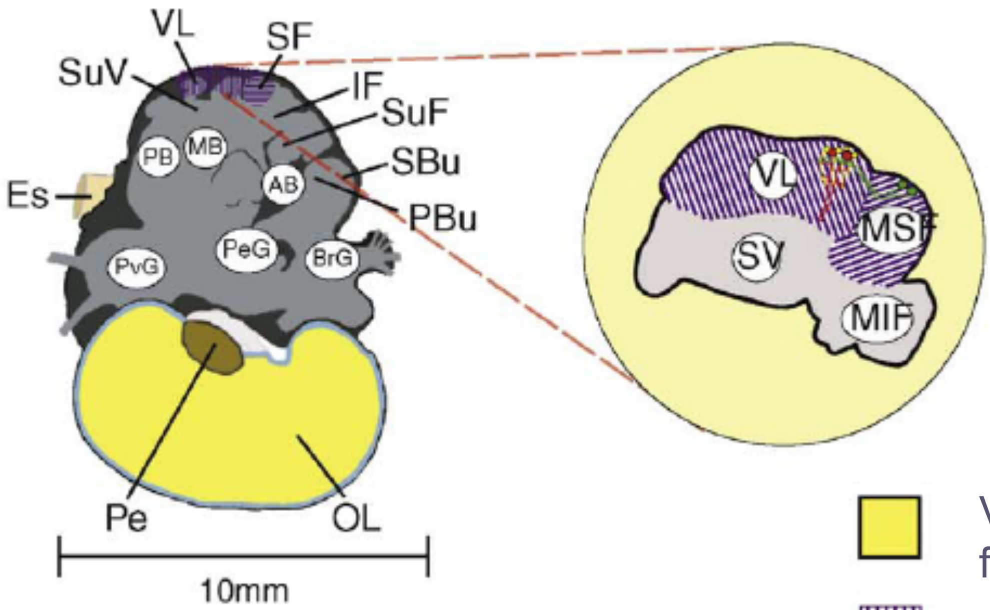
Striatum (St)

Midbrain (Mb) and hindbrain (Hb)

Cerebellum (CB)

Cephalopod Brains

Octopus



From Edelman & Seth, 2009

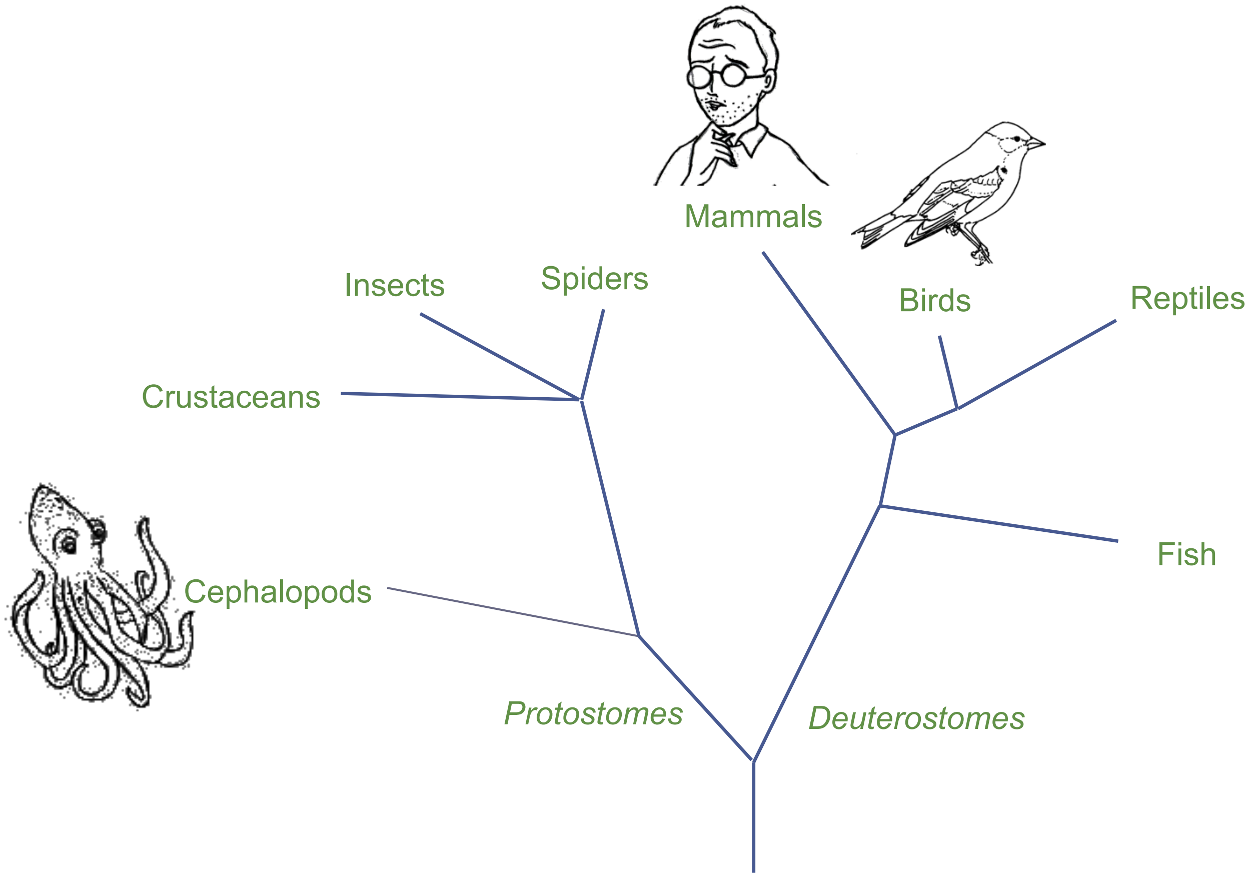
- The octopus brain has almost no structures that are homologous to those of the vertebrate brain
- And as well as its central nervous system, it has eight mini-brains (or *ganglia*), one per tentacle

Vetical lobe (VL) and median superior frontal lobe (MSF)

Retina-like optic lobe (OL)

Peduncle (Pe)

Brain Evolution



- The octopus lies on a branch of the evolutionary tree that diverged from the branch that includes mammals long before the basic blueprint of the vertebrate brain was settled
- Its brain is made of the same neurons, but its architecture is completely different

Towards a Deep Theory 1

- A deep theory of how cognition (and consciousness) is realised in the biological brain must rest on principles that apply not only to mammals, but also to birds, and to cephalopods
  - Here's a good question to ask a neuroscientist: "Does your work help to explain the cognitive capabilities of the octopus?"
- Even more generally, it should describe the *space of possible minds*
  - In principle, it should account for cognition as it might evolve elsewhere in the Universe
  - And it should allow for the construction of forms of artificial cognition

Towards a Deep Theory 2

- What form would such a theory take?
- It must sit at a level above the “lowest common denominator” in the evolution of animal cognition
- The basic electrical and chemical properties of the neuron have been conserved since before the split into protostomes and deuterostomes
- All animal cognition is the product of the dynamics that emerges when large networks of such neurons are connected together
- So this is our object of study: *the dynamics of large networks of spiking neurons and their role in producing behaviour*

Methodology

- How should we study the dynamics of large networks of neurons?
- The analytical method
  - One approach is to build mathematical models of such networks
  - The ideal mathematical model can predict, or at least characterise formally, the behaviour of such networks over time
- Complexity
  - The problem for the analytical method is that it has difficulty with *complex systems*
  - Complex systems comprise large numbers of interacting components, whose individual behaviour is easy to describe mathematically, but whose collective behaviour is not

The Synthetic Method

- Brains are complex systems *par excellence*
- To complement analytical methods for studying the brain, we can use a synthetic methodology
- In a nutshell, we *simulate* the relevant complex system using computers
- We still need mathematical models of the components (ie: the neurons)
- And we still need mathematical methods to understand the complex behaviour that our simulations produces
- But computer simulation is our main tool

Course Overview 1

- Neurons
  - Real neurons
  - The Hodgkin-Huxley model
- Numerical integration
  - The Euler method
  - The Runge-Kutta method
- Simple neuron models
  - Integrate-and-fire neurons
  - Izhikevich neurons
- Connecting neurons
  - Braitenberg vehicles

Course Overview 2

- Competition
- Small-world networks
  - Brain networks
  - The Watts-Strogatz procedure
  - Small-world index
  - Efficiency
- Modular networks
  - Modularity index
  - Spatial embedding
  - Hub nodes
  - Hierarchical modularity

Course Overview 3

- Dynamical complexity
  - Neural complexity
  - Causal density
  - Criticality
- Oscillations and synchrony
- Plasticity
  - STDP
  - Reward-modulated STDP
- Consciousness

Related Reading

Edelman, D.B. & Seth, A.K. (2009). Animal Consciousness: A Synthetic Approach. *Trends in Neurosciences* 32 (9), 476–484.

Seed, A.M. & Byrne, R. (2011). Animal Tool-Use. *Current Biology* 20, R1032–R1039.

Shanahan, M.P. (2010). *Embodiment and the Inner Life: Cognition and Consciousness in the Space of Possible Minds*. Oxford University Press.