Computational Neurodynamics

- Finding common qualities between computer and intelligence

Topic 1
Introduction and Motivation

Pedro Mediano

(Slides: Pedro Mediano & Murray Shanahan)

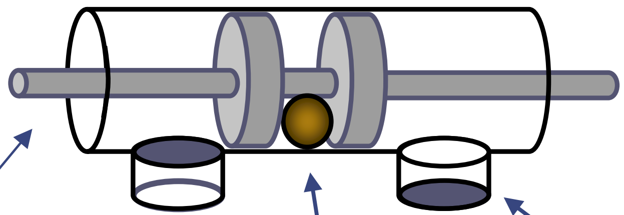
Comparative Cognition

- 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

Zero-shot solution → finding solutions immediately without seeing it before

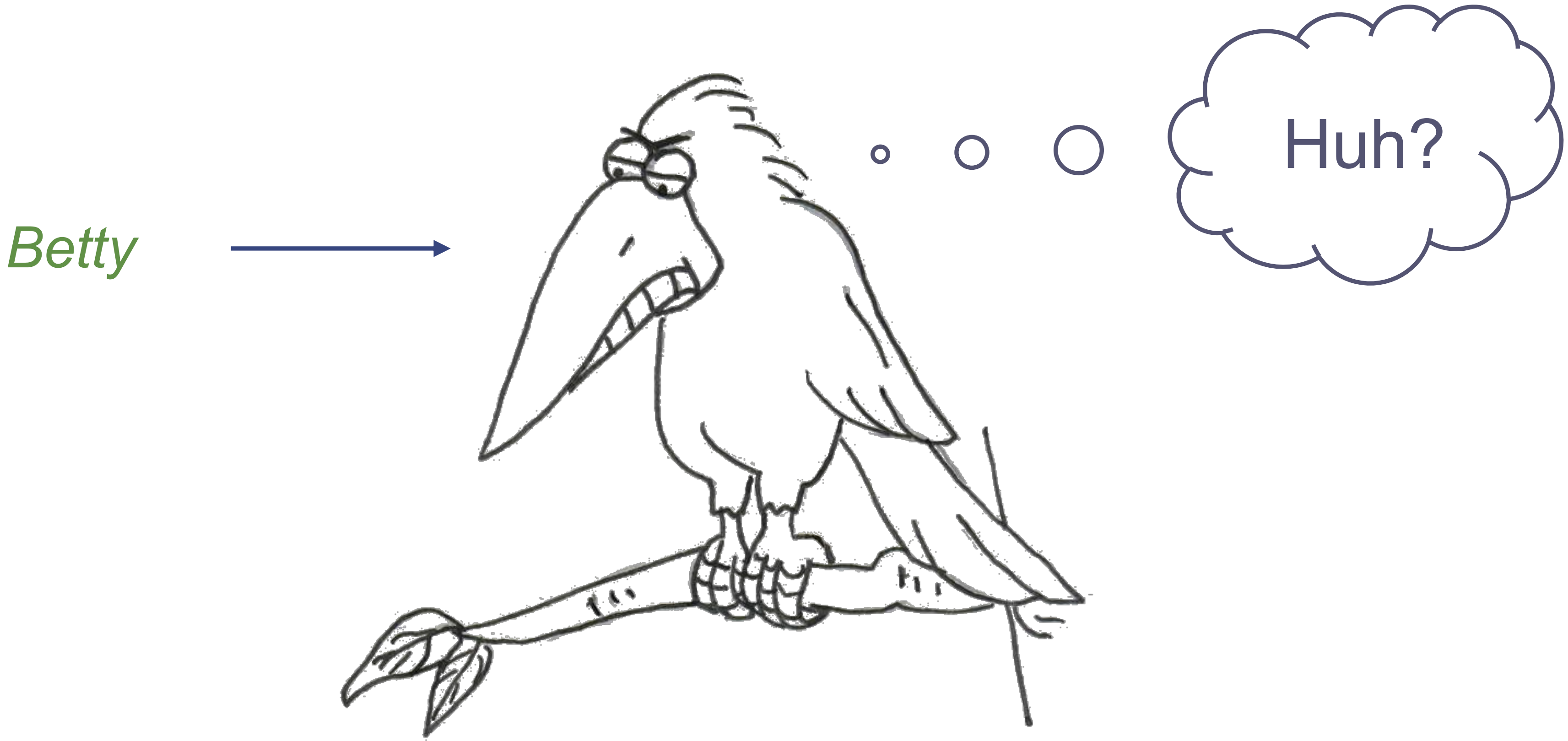
Example: Physical Cognition

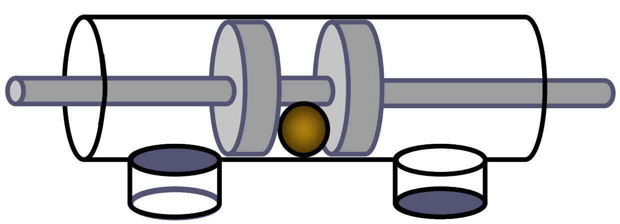
- It has been shown that rooks and crows are capable of solving problems that require an understanding of the physical properties of objects
- One paradigm involves the use of different kinds of *trap-tube*



- 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

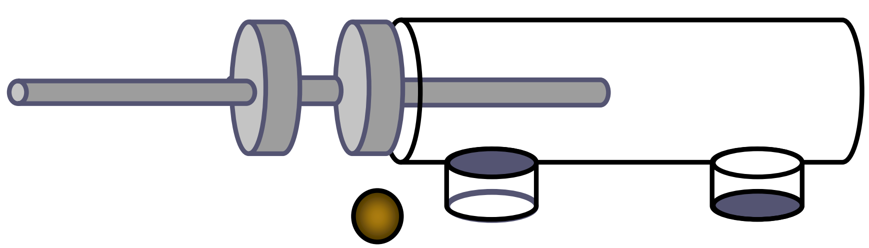
The Initial Problem



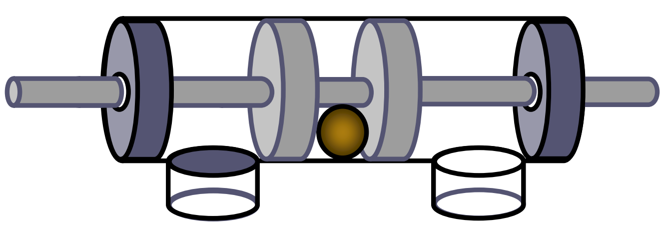


Artwork by Kerry Shanahan

Solved by Trial and Error



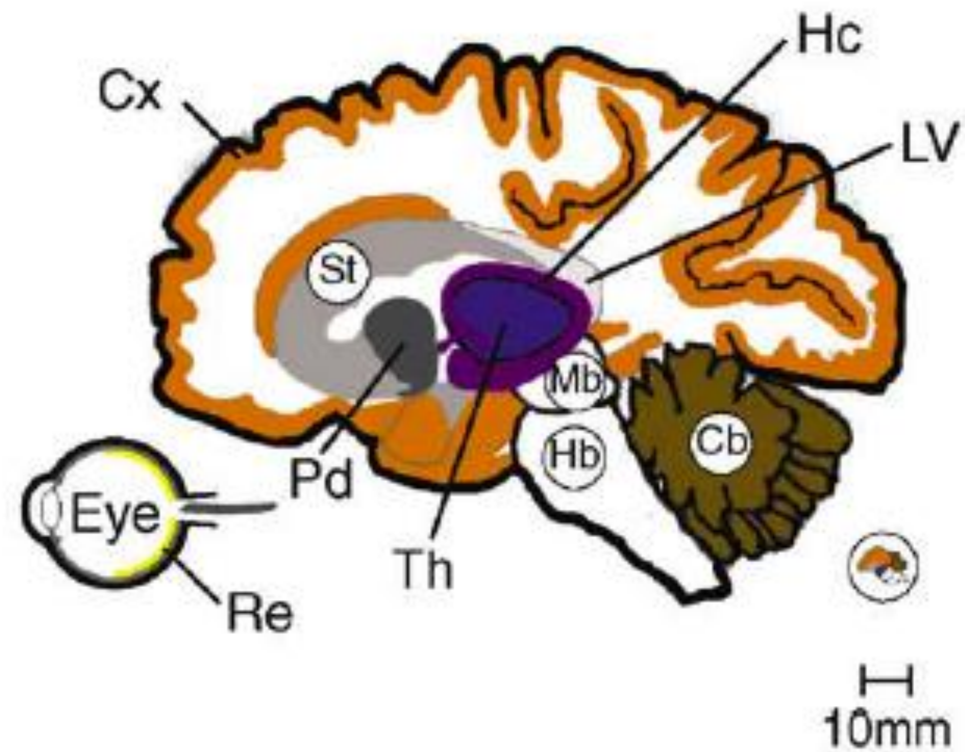
An Unseen Variation



Spontaneously Solved

Mammalian Brains

Human



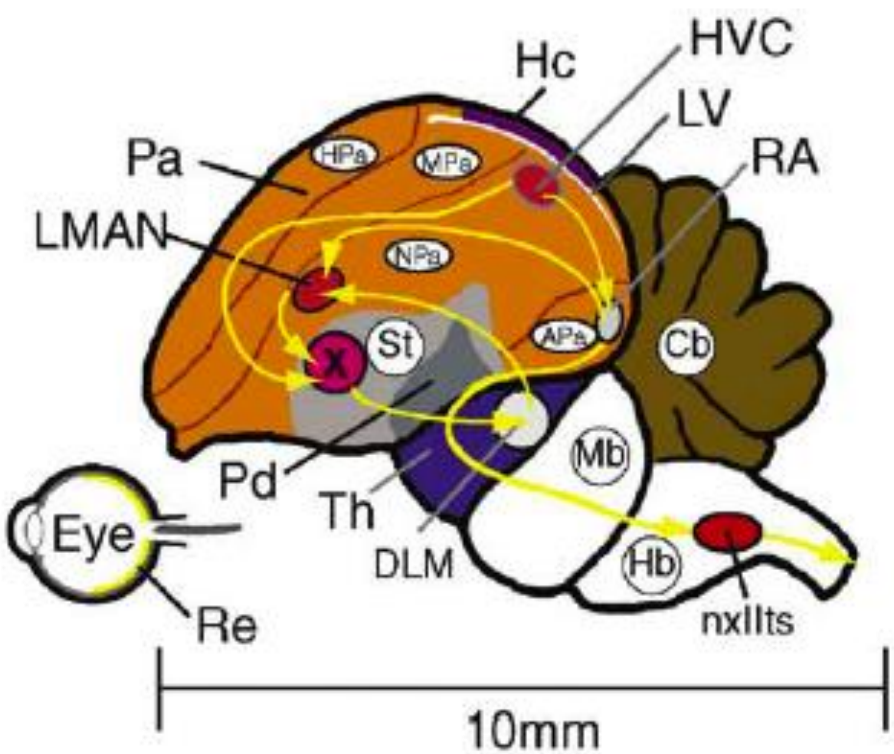
- The anatomy of the human brain is dominated by its large convoluted cerebral *cortex*
- The cerebral cortex is organised into six layers

Cerebral cortex (Cx)
Thalamus (Th)
Hippocampus (Hc)
Striatum (St)
Midbrain (Mb) and hindbrain (Hb)
Cerebellum (CB)

From Edelman & Seth, 2009

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)

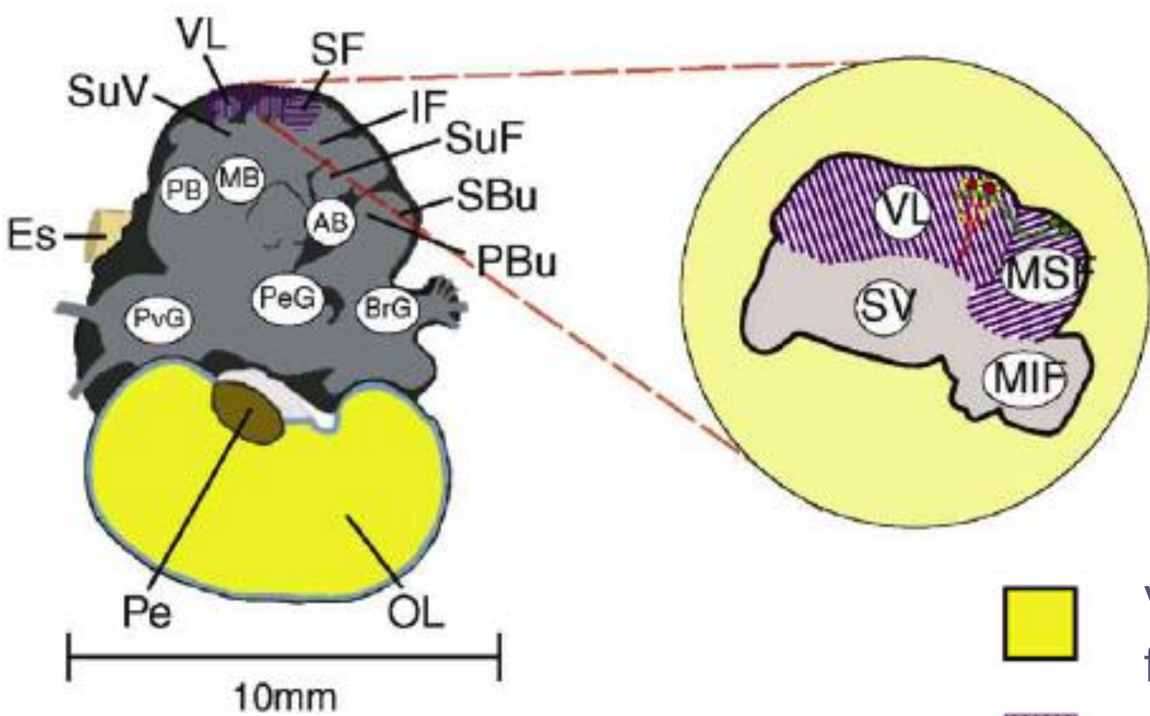
Striatum (St)

Midbrain (Mb) and hindbrain (Hb)

Cerebellum (CB)

Cephalopod Brains

Octopus



From Edelman & Seth, 2009

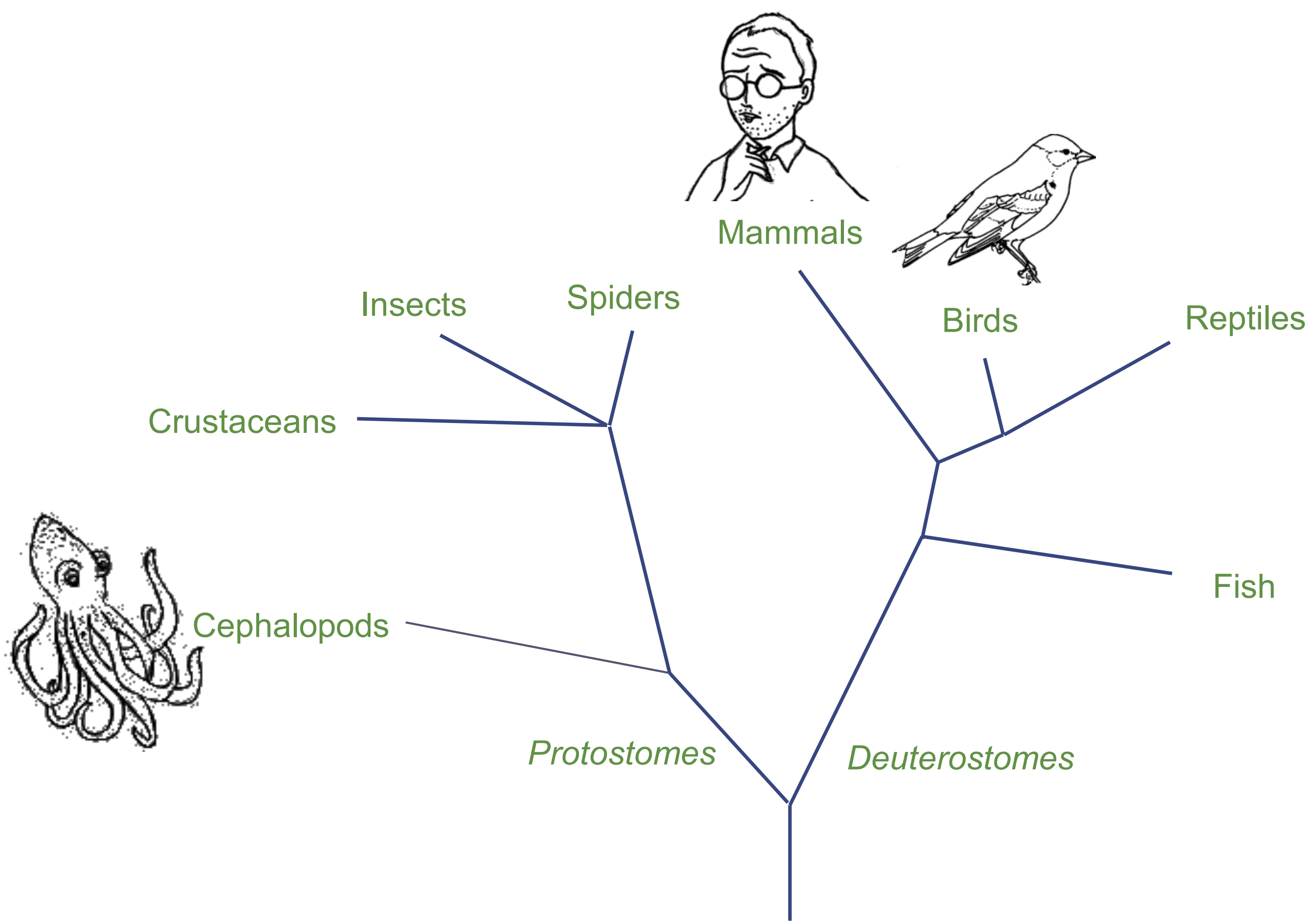
- The octopus brain has almost no structures that are homologous to those of the vertebrate brain
- And as well as its central nervous system, it has eight mini-brains (or *ganglia*), one per tentacle

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

— First, AI research went top-down (logic, etc.), now bottom-up (neurons)

Towards a Deep Theory 2

How do we know that the complexity of neurons satisfies intelligence capabilities?

- What form would such a theory take?
- It must sit at a level above the “lowest common denominator” in the evolution of animal cognition

it is only preconditio

- 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*

→ they don't have to be biological neurons, it can be any substance

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* — ⇒ we can easily formulate neuron-behaviour, not network-behaviour
  - 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

2, this is what we do with people as well in labs

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
  - Information theory
  - Criticality
- Oscillations and synchrony
- Plasticity
  - STDP
  - Reward-modulated STDP
- Consciousness

Logistics

- In-person sessions:
  - Monday 9am, Huxley 311 (lecture)
  - Thursday 11am, Huxley 144 (lab – bring your laptop!)
- Assessment:
  - 20% programming coursework (deadline Nov 18th)
  - 80% exam
- Teaching assistants: Hanna Tolle, Alex Proca
- Materials in Scientia, discussions on EdStem

Projects available

- Explaining brain organisation through spatially embedded deep neural networks.
- Leveraging ML to innovate optimization frameworks for brain simulations.
- Building and interpreting models for electronic health records during cannabis therapy.
- Analysing the computational role of complex representations in RNNs.
- An optimisation perspective on multivariate information theory for neural computation.

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.