# Neuronal computing or computational neuroscience: brains vs. computers

**Leslie S. Smith, Department of Computing Science and Mathematics, University of Stirling**

**http://www.cs.stir.ac.uk/~lss**

**l.s.smith@cs.stir.ac.uk**


# Acknowledgements


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# Overview

- Which field means what? (briefly!)
  - And why it matters
- Brains and computers:
  - Historical analogies
  - Levels in computers and brains
    - Mixing levels
  - Low-level mechanisms
    - Do they matter
- Towards a project



# Neuronal Computing or Computational Neuroscience?

- Neur(on)al computing
  - Developing systems which use insights from neuroscience to build information processing systems
- Computational Neuroscience
  - Study of both the biophysical and functional aspects of neural systems primarily by model building in order to understand neural systems

- Sometimes similar, but with different aims.

# Neuromorphic Systems

Hodgkin! Huxley! Goldman! Katz!
We build brains for robot rats!

- (Chant of the Neuromorphic Engineers, Telluride, c 1998).
- Hardware oriented: but interested in both neural computing and computational neuroscience



# Building brains

- Has been an aim for some groups for a long time
  - AI’s aim: building intelligent systems
    - But not necessarily thirled to brains
  - Hugo de Garis
    - Building a brain through evolving hardware: StarLab (2000-2001)
  - Blue Brain Project and Artificial Development
    - Detailed biologically accurate modelling using highly parallel computers: Electronic replication of brains
      - (Artificial Development) Ccortex, a “massive spiking neural networks simulation of the human brain”
    - See http://bluebrain.epfl.ch/ and http://www.ad.com
  - Computing Grand Challenges
    - UKCRC GC5: Understanding the architecture of the brain and mind
  - Microelectronic Design Grand Challenges
    - uGC4: Building brains



# Historical analogies

- Ancient Greece
  - Heart as seat of intelligence (Aristotle, Homer)
- Nerves as “pipes” flowing from brain to muscles, producing movement (Descartes)
- *“Early ideas of the brain as a book or blank slate gave way to the 19th-century steam engine, then to the telephone exchange. Most recently the brain has been likened to a computer or the World Wide Web.”* (Wellcome web site)
  - Details: K.L.Kirkland, Perspectives in Biology & Medicine, 45, 2, 212-223, 2002.



# Brain as telephone exchange

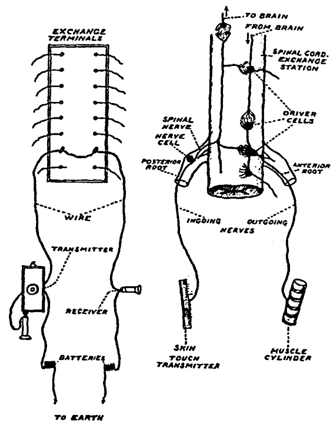



FIGURE 1

*Comparison of the circuitry of a telephone exchange to that of the spinal cord. In this analogy, neurons in the spinal cord relay information either directly to effectors such as muscles or, if additional processing is necessary, to the brain via “spinal cord exchange stations.” Similar exchange stations in the brain were believed to route the information on to the appropriate cognitive centers.*

NOTE: REPRODUCED FROM “THE ENGINES OF THE HUMAN BODY” BY ARTHUR KEITH, 1920 (FIGS. 47A AND B, P. 258). USED BY PERMISSION OF LIPPINCOTT WILLIAMS & WILKINS.

# What *are* brains?

- Brains are multi-cellular organs, connected to other parts of the body
- Brains are made up from a number of types of cells …
  - Neurons, Glia (and many subtypes of each)
- … which are remarkably similar over a very wide range of animals
- The cells themselves are highly interconnected
  - Communicating via spikes, resulting in endo/exocytosis of neurotransmitters and other neurochemicals
- Note that single celled animals survive perfectly well without brains!
  - But their range of behaviour is rather limited



# What are brains *for*?

- Brains exist to enable multi-cellular animals to survive
  - Enabling finding prey, finding mates, avoiding predators
  - Controlling the animal's systems, enabling sensing, enabling control of movement
  - And (for some animals) higher level tasks as well
    - cognition, chess playing, research, lexicography, delivering seminars …



# What are computers for?

- Controlling systems
- Information processing
- Programmed calculation
- Modelling and emulation



# Modelling brains using computers

- Connectionist models of cognitive systems,
- Neural network pattern recognition and classification systems
- Non-algorithmic computing
  - Highly successful for pattern recognition: also helped understand relationship between statistics and some aspects of neural computing

But we have not been successful in creating machines which are truly like brains
  - by what criteria would we judge success?
    - ability to really learn to perform in novel environments,
    - capability of completing the whole sensing/action/performing loop
    - Goal orientation? Motivation? Robust autonomous robotics?

# What's the problem?

- Several possible answers:
  - No conceptual problem at all:
    - we simply haven't been creative enough,
    - or real-time behaviour is critical, and we haven't fast enough machines, or parallel enough computers, or enough memory
    - can't prove or disprove this
      - So let's assume that there is a conceptual problem!
  - Possibility 1: we don't have enough information yet about the morphology/structure/etc. of brains
  - Possibility 2: there is some specific difference between brains and computers that makes it hard to emulate brains on computers



# An aside …

- Modelling computers using brains
  - Basic counting with small integers seems to come naturally
    - Basic logic?
  - But even elementary arithmetic is more difficult to learn
  - Few brains are capable of accurate complex calculation

- Does this mean that we need larger brains (or a better understanding of arithmetic or computers) to make it easier for brains to emulate computers?

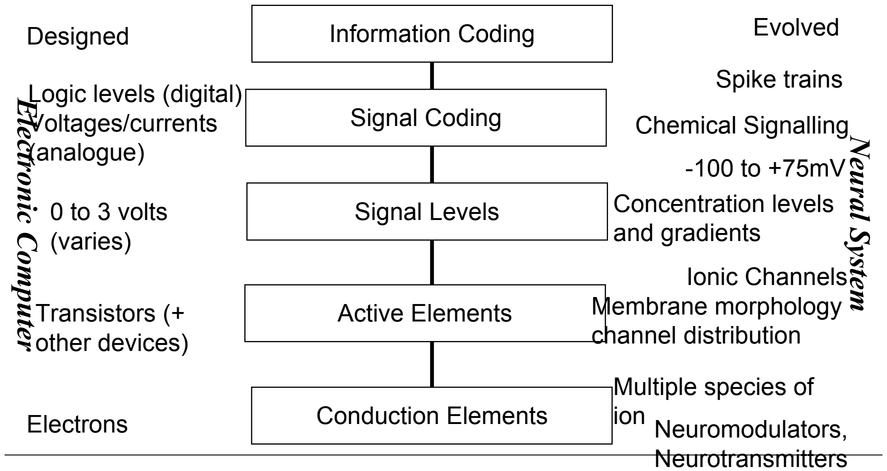


# How do we proceed from here?

- Philosophically?
  - Too difficult for me
- Computationally?
  - Look at computability, and try to see what there might be in the structure of brains that enables them to perform something non computable. See above.
  - Computer modelling: but what sort of model (there's already been an awful lot of them)?
- Neurophysiologically?
  - There is great deal of information about brain structure and organisation.
  - Are there any clues in this that might help us understand the differences between brains and computers?

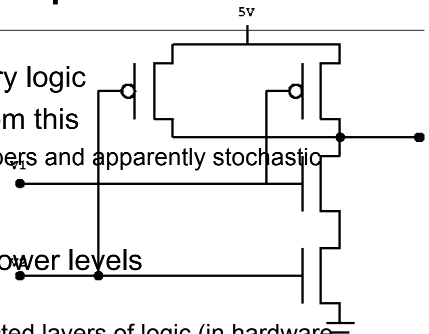


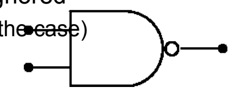
# The differences between brains and computers



# Digital Computers

- Underlying technology: binary logic
- Everything is constructed from this
  - Even apparently random numbers and apparently stochastic noise
- Machine is actually built on lower levels
  - Quantum effects, for example
  - But by using carefully constructed layers of logic (in hardware and software), lower levels can be safely ignored
    - (the construction is designed so that this is the case)



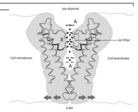


# Analog(ue) Computers

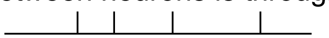
- Underlying technology:
  - currents and voltages, controlled by a small number of types of device (linear and non-linear, FET, Bipolar transistors, diodes, tunnel diodes, etc.)
  - devices interact with each other in a precisely specified fashion
    - and only where connected by wires
  - devices which alter their characteristics do so in response to the outputs of other parts of the circuit in a very predictable way.
- Machine is built on quantum effects
  - But these are abstracted into discrete (integrated) components
  - And these in turn are built into circuits



# Neural Systems



- Underlying technology: ionic concentrations (multiple species), a multitude of ionic channels embedded in the (otherwise insulating) membranes of cells, numerous modulating neurotransmitters, complex enzyme-based interactions.
- Transmission of information between neurons is through action potentials (spikes)



  - And through release of neurotransmitters, some of which diffuse relatively long distances, and last a long time
- Alteration in ion channel protein conformation is critically important
  - alters permeability/conductance of ion channels
  - May be voltage or ion or neuromodulator sensitive



# Major differences

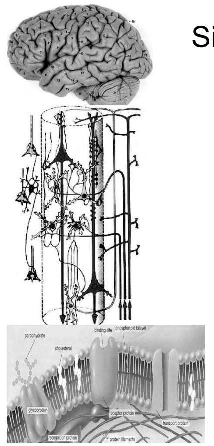
- Levels of operation can interact and influence each other
  - Neural systems are not built hierarchically.
    - Unlike digital and analogue computers
- This can even be the case for genetically programmed computer chips

# Mixing levels

- Concept has been that the molecular/ionic level interactions subserve some higher-level …
  - perhaps neuron based
- … information processing system
  - (in the same way as the conduction mechanism of a FET subserves the operation of a cMOS implemented NAND gate).
- Simulations have generally been at a single level



# Single level models: levels



Single level models can tell only some of the story

- Whole brain level: complete system level.
- Brain region level: subsystem level. But which subsystem?
  - Are they telling the same, or different stories?
- Cortical column level: interacting neurons. Cortical microcircuits
- Neuron level: what sort of neuron are we working with? Asynchronous spiking? Multi-compartment?
- Membrane/ion channel level: complex interactions between ions, ion channels and neuromodulators



# Multi-level models

- Many single level models are justified from lower levels
  - E.g. by deriving parameter values from lower levels
- But this is not the same as permitting higher level aspects to influence lower level operation
  - Or vice versa
- For example,
  - allowing neurotransmitter released due to a spike from one synapse to leak to an adjacent one, or
  - allowing overall depolarisation of a volume to alter diffusion rates of small molecules (like NO).

*Nature/evolution is not bound by engineering design laws!*



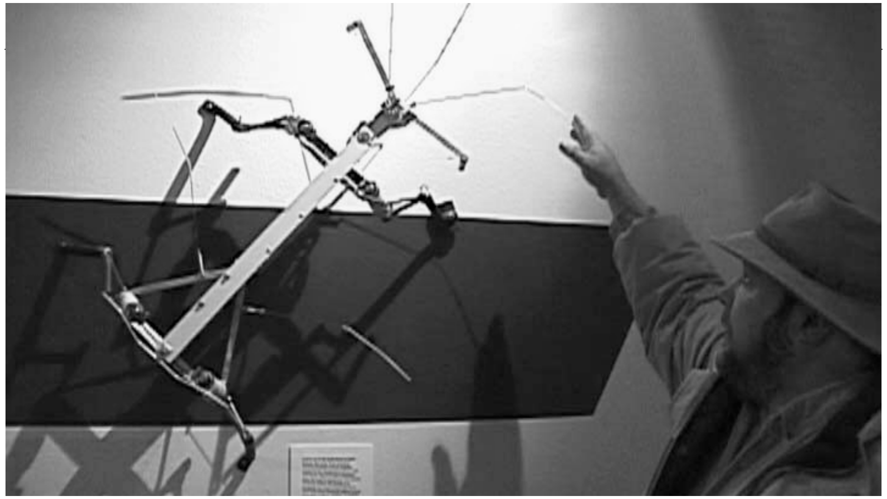
# Examples of multi-level systems

- Adrian Thompson’s GA optimised FPGA systems.
  - Thompson’s systems were Xilinx FPGAs programmed using Gas to optimise the programs
  - The fitness functions were tested on real FPGA’s (not simulations)
  - They solved the problems posed
    - But if one took the solution and simulated it, this would not solve the problem
    - Systems took advantage of “undocumented” interactions between adjacent cells
    - Many of the solutions found were highly efficient.

# Another example

- Mark Tilden is a roboticist who worked at Santa Fe
- He designs robots in which the whole robot is the controller
  - As opposed to designing systems in which there is a separate identifiable brain
  - There is direct interaction between the moving elements and the processing elements
    - Leads to rapidly reacting systems, tied into the appropriate time-scale of their physical components
- Tao Geng's Runbot uses time constants from the mechanical legs as inputs to a simple neural network controller to achieve fast running.







# Building multi-level models

Issues:

- Where does one stop?
  - Membrane patches? Ion channels? Protein configuration due to local static charges (like Mg++ ions blocking NMDA channels)? Quantum levels?
- Speed of simulation (even in parallel implementations)
  - Important if one wants to interact with a real environment
- Difficulty in understanding what's really going on
  - Even in Thompson's genetically programmed FPGA the mechanism of solving the problem was entirely unclear
    - And that's in an engineered system where one can examine the precise architecture!



# Thesis 1

- Mixing levels enables building systems which are more brain-like.
  - It can provide direct (and therefore fast) interaction between different aspects of the brain processing, permitting rapid reconfiguration.
  - But: it might also cause inappropriate crosstalk (which is why it is normally carefully avoided in engineered systems).
- Provides a different way for integrating the knowledge that we have about brains and systems

# Underlying mechanisms

- Digital electronics is based on 2-valued logic
  - (whether implemented in valves, relays, DTL, TTL, ECL, nMOS, CMOS, etc.)
  - And this remains visible through multiple layers of hardware and software.
- What are the underlying mechanisms of brains?
  - Excitable cells
    - Ion channels (proteins embedded in bilipid membrane of cell, allowing charged ion transport)
      - Many different types: often voltage and/or neurochemical sensitive
    - Complex reaction cascades (systems biology) at synapses



# Do these differences matter?

- Answer 1: No.
  - Computers are universal emulation machines, and can therefore emulate anything, including ionic channels, reaction kinetics etc.
- Answer 2: Yes
  - The truly enormous computational load of simulating these low-level and highly concurrent events makes digital computer simulation essentially impossible

I suggest the second answer is more relevant here.



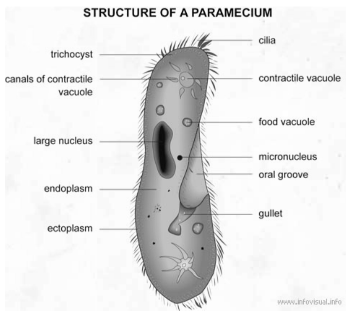
# How do these differences matter?

- Ion channels
  - Ion channels are proteins with multiple possible configurations
  - The channels alter their configurations frequently (and sometimes stochastically) in response to voltage changes, or presence of other ions or neuromodulators
- Many neural processes act through the action (relatively) small enzymes catalysing reactions
  - However the reactive area on each molecule is relatively small, and they need to match up for the reaction to occur (F.T. Hong)
    - Affects reaction timing and likelihood
- Both the above suggest that variations in behaviour will occur at the microscopic level



# Single cell behaviour

- Consider a single celled organism
  - E.g. Paramecium, a single celled organism with no neural system, but which eats, digests, and moves successfully.
    - All of these are predicated on transfer of material across the cell membrane
      - exocytosis and endocytosis
    - or on molecular motors (driving cilia) on the surface
      - Essentially all based on ion channels
  - Wide variety of behaviour in a single cell



# Can we model cellular behaviour?

- One interpretation of the effects of nondeterminstic reactions etc. is that they are simply noise
  – Can we simply add noise to the digital simulation?
  – Or perhaps use noisy components
    - Such a (very) deep sub micron MOS transistors
- Is the form of the noise important?
  – Or is the precise nature of the stochasticity important?



# Thesis 2

- The nature of the variation in the ion channel and neurochemical reactions in neural systems matters
  – Simply adding noise is not the same
  – Diversity in response lies at the root of successful adaptivity
    - by responding differently to identical events, and then rewarding responses which have the best outcomes by making them more likely to occur in future, an organism can adapt to its environment rapidly and effectively.



# Synthesis

Recall

- Possibility 1: we don't have enough information yet about the morphology/structure/etc. of brains
- Possibility 2: there is some specific difference between brains and computers that makes it hard to emulate brains on computers

- Is there a “Possibility 1.5” that is made possible by the two theses here?

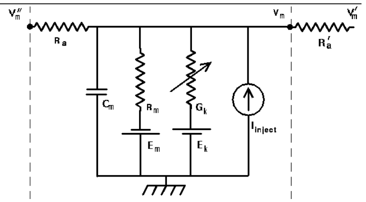


# Possibility 1:

- part of problem is that we attempt to explain “higher level” behaviour directly and purely in terms of “lower level” effects
  – E.g. spiking neurons result from synapses and activation levels
    - and we ignore these once we know when the spikes occur.
- Could we use the knowledge that we have differently by mixing levels?

# Possibility 2:

- There is something about neural / living tissue:
  - It's based on multiple different sets of active (nonlinear) elements which interact through electrical, ionic, neurotransmitter movements all concurrently
    - Unlike existing simulations
      - E.g. compartmental models in which the interaction between compartments is restricted to current flow
- Can we model neural tissue in a more realistic way?





# Possibility 1.5:

- Consider neural tissue differently:
  - Model it as a whole
    - Including interaction across levels
      - Difficult: requires a highly concurrent approach
      - Impossible? Presumably not
  - Model it using appropriate stochastic systems
    - Which communicate directly and continuously
    - Investigate whether the noise characteristics matter



# Towards a project

- Aims:
  - ability to learn to perform in novel environments,
  - capability of completing the whole sensing/action/performing loop robustly
  - Goal orientation? Motivation? Robust autonomous robotics?

  - And perhaps understanding neural tissue at the same time



# Towards a programme of work

- Existing approaches:
  - Giant machines: the Blue Brain/Artificial Development approach
    - Highly parallel huge simulations which incorporate multiple intercommunicating levels
  - Evolutionary systems: the de Garis / Thompson approach
    - Adaptive evolutionary simulations in a "real" environment
      - Able to react across levels
      - Not designed, but evolved
- Suggest something closer to de Garis, but with non-determinism (based on protein/enzyme interactions) at its base

## From single to multi-cellular animals

- In a single celled animal, sensing and action are about directly opening/closing ion channels
  - Directly resulting in eating and movement (as in Paramecium)
- To sensing causing ion channel alterations
    - As in photoreceptors, mechanoreceptors, etc.
    - (often mediated by exo and endo-cytosis)
  - which in turn affect other cells
  - whose activity causes changes in yet other cells
  - which results in action or movement.

Evolution took a long time to discover these possibilities.



## From single to multi-cellular animats

- Could we replicate this in an Alife scenario?
  - Not just controller evolution, but evolution of a complete multi-level Alife critter
- Needs a relatively rich Alife environment
  - One in which sensing and action start off very closely related
    - Reactive system, no neural control
  - But in which the (single-celled-animal like) critter can grow
    - To produce a more complex, multi-level system
- Implies an expandable genetic system
  - And probably a lot of (parallel) computing time too



## Summary

- We are suggesting that
  - the interaction between levels

  and
  - the low-level mechanisms

have an effect on the nature of processing which differentiates neural systems from computer systems.

- And proposing a project which might help illustrate this difference.