Systems Engineering: What can it contribute to Neural Engineering?

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Outline

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Purpose

- Argue the case that systems engineering provides a core framework within which to set about understanding how the brain works
  - Mathematics is the right language to use
  - Signals and systems is the right way to think about processes
  - Biology and neuroscience provides the specialist knowledge
- Argue the case for taking a multi-scale modelling approach to understanding how the brain works
  - Key challenge is to form links between the models at different scales
- Provide some background to the Centre for Neural Engineering

Systems Engineering

- Has different meanings
  - Design and management of complex engineering projects
    - People management
    - Project management
    - Engineering solutions to problems (control theory)
- For this talk, systems engineering refers to the combination of engineering principles and mathematical tools which can be used to model and understand complex systems, such as
  - signals and systems theory
    - control theory
    - information theory
    - signal processing
  - dynamical systems theory
- Generic principles applicable to any "system"
  - Routinely used for stochastic time-varying systems (not just linear time-invariant systems)

Computational Neuroscience

- The study of brain function in terms of the information processing properties of the structures that make up the nervous system
- Interdisciplinary science linking neuroscience, cognitive science, electrical engineering, computer science, physics and mathematics.
- Major topics include:
  - Single-neuron modelling
  - Development, axonal patterning and guidance
  - Sensory processing
  - Memory and synaptic plasticity
  - Behaviours of networks
  - Cognition, discrimination and learning
  - Consciousness (ultimate goal?)
- Coined in 1985 to unite fields such as neural modelling, brain theory and neural networks

Neural Engineering

- A systems engineering approach to
  - understanding how neuronal networks work
  - repairing neuronal networks when they go wrong
    - epilepsy
    - tumours
  - interfacing with neuronal networks
    - medical prostheses (bionic eye)
  - engineering neuronal networks
    - growing neuronal networks to perform a particular task

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How to understand a process?

- Infamous "black box" with an input and an output
  - By playing with input and observing output, can you determine what is inside the box?
  - Need assumptions
    - Very strong assumption would be linear time-invariant
    - Can generally deal with stochastic noise
- Open the box up
  - Inject signals
  - Tamper (break wires; poison ion channels)
  - Take measurements at internal points (observe what is going on)
- Sequential appoximation
  - Formulate hypothesis (gives you working assumptions)
  - Test

How to convey knowledge?

- Need a language
  - Flexible
  - Precise
- For describing nature, mathematics is the universal language of choice
  - Dynamical systems
    - Discrete-time
    - Continuous-time
  - Random events can be handled precisely (probability and measure theory, stochastic process theory, ...)
  - Physics is based on mathematics (Quantum mechanics, ...)

How to think about how something works?

- Engineering and mathematics involves moving between intuition and mathematical theories
    - Intuitively understand why a system might be stable
    - Endeavour to prove that the system is stable
    - Can that intuition be generalised to a larger class of systems?
- Strength comes from having general theories which are widely applicable yet can be understood by simple examples (intuition)
- Ingenuity generally comes from
    - Recognition that an idea in one area is applicable in another
    - Having a novel perspective
- Therefore, seek to map a given problem to a canonical one

Examples of applications of Systems Engineering to Neuroscience

- Dynamical systems and bifurcation theory
  - Normally think of a neuron as a dynamical system and look at the "trajectories"
    - However, the qualitative description of a dynamical system is much simpler
    - There are only four (codimension one) bifurcations possible!
- Information theory
  - Information theory provides bounds on how much information can be sent reliably from X to Y
  - Natural concepts are mutual information, channel capacity, ...
    - Natural because they are universally applicable
    - Therefore, should apply them in neuroscience too
- Control theory
  - The brain is a "controller" in the engineering sense of the word

Mathematics and Physics

- The last century saw an extremely productive symbiosis between mathematics and physics
  - Physicist would "prove" that something was true
  - Mathematicians would exclaim "that is not a proof!" then devise necessary machinery to fix the problem (generalised functions)
  - Physicists realised the correct setting for classical mechanics were manifolds, not Euclidean space
  - Mathematicians developed the theory of differential geometry
  - Physicists then came up with special relativity (which would have been improbable without the ideas of differential geometry in their mind)
- This century will see an analogous symbiosis between the physical sciences and the life sciences
  - Mathematics, engineering and physics will help biology
  - From biology will come new paradigms in the physical sciences

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Some Big Questions

- How is information coded (the neural code)?
  - more than one code?
- How is information processed?
  - Brain uses only 20W yet outperforms computers on many tasks
  - Perhaps information and coding are intertwined?
- How does the brain evolve?
  - From birth to adulthood, the brain goes through an evolutionary process
    - External stimulus is essential for formation of certain circuits
  - From randomness emerges functional circuitry
- What goes wrong in, say, epilepsy? Treatment?

How much is known?

- One the one hand, an enormous amount of knowledge is known
- On the other, an enormous amount of knowledge remains undiscovered
- Full details of how an individual neuron works still not known
  - Vesicle release and replenishment process
  - Ion channels
- Networks of neurons
  - Some intuition about roles of excitatory and inhibitory connections
  - Conductance-based integrate-and-fire model appears to be simplest model to reproduce background activity of the cortex
  - How does a signal propagate faithfully through a neuronal network?
  - Memory, learning, consciousness. . .

Models in Neuroscience

- Models exist at different levels, for example
  - sub-cellular processes
  - single neurons; micro-circuits
  - auditory and visual pathways
- Models come in different varieties
  - Block diagram
    - The "where" and the "what" pathways
  - Algorithm capturing observed features
    - Hebbian learning as a model of evolution of sound localisation circuitry
  - Differential equations
    - Hodgkin-Huxley model of excitable membrane for action potential generation
- Essentially no linking of models across scales

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Multi-scale Modelling

- It is the field of solving physical problems which have important features at multiple scales, particularly multiple spatial and/or temporal scales
- Traditional monoscale approaches have proven inadequate
    - range of scales; prohibitively large number of variables
- The key is to work out how to link the scales together
    - Aim is to calculate system behaviour on one level using information or models from different levels
    - Particular approach for describing system is used at each level
        - quantum mechanical models; molecular dynamics models; mesoscale or nano level; continuum models; device models
    - Each level addresses a phenomenon over a specific window of space and time
- It allows the prediction of system behaviour based on knowledge of the atomistic structure and properties of elementary processes

Meteorology

- Weather forecasting is an example of multi-scale modelling
- The most challenging task is modelling the interaction between sub-systems of different spatial and temporal scales (linking of scales)
  - A Global Climate Model typically has about a 100km grid size
  - Cloud structure is of the order of 0.5km
- Balance point
  - Computationally feasible
  - Retains enough information to be accurate and precise
- Parameterisation
  - Represent distinct parts by inaccurate or semi-empirical mathematical expressions
  - Simplest form is null parameterisation; ignore the process!
    - Decision to neglect can only be made after a detailed consideration of their importance relative to other processes being modelled

Neuroscience

- Requires a multi-scale modelling approach
  - Mathematical models (not pictures) at all levels
  - Physically-based models (not phenomenological models)
  - Challenge is to link the scales
    - What is the effect of a drug operating at the level of ion channels on the stability of the brain as a whole?
- Must determine beforehand what the purpose of the model is
  - How else to determine what is important and what is not?
  - How else to determine what levels of approximation are appropriate?
- Any modelling of internal processes should therefore be in the context of an end-to-end process
  - from sight or sound to perception
  - from drug to pain relief

Too Difficult?

- Systems Biology
    - Biology is astoundingly complex
    - Structures found by evolution are
        - dependent on historical chance (to some degree)
        - laden with biochemical detail
        - requires special description in every case
    - Despite this, scientists have been able to formulate general laws that apply to biological networks
        - Because it has evolved to perform functions, biological circuitry is far from random or haphazard
        - Although evolution works by random tinkering, it converges again and again onto a defined set of circuit elements that obey general design principles
        - Simplifying principles make biological design understandable to us

What role can computers play?

- Model-order reduction
  - Is a simpler model a good approximation to a more complicated model?
- Model validation through prediction
  - Use computer to predict expected outcome, then
  - compare with experimental data
- Data and model analysis and visualisation
- Exploratory tool?
  - Caveat: The key to science is asking the right questions

New Technologies

- History shows that breakthroughs in neuroscience often involve pioneering technologies
  - Low-noise amplifiers
  - Stimulation and recording techniques
- Challenges
  - Ability to stimulate and record from every one of 100,000 neurons simultaneously
    - Optical?
    - Electric field?
    - Magnetic field?
  - Ability to image at high spacial and temporal resolutions
    - Watch movement of vesicles
    - How to overcome fundamental limitations?

CFNE — Background

- Infrastructure funding ($34M)
  - Data Centre ($20M + $3M)
  - Renovations ($6M)
    - Offices
    - PC2 Lab
    - Electronics Workshop
    - Psychophysics Booths
    - Meeting areas (including teleconferencing)
  - Equipment ($5M)
- Research
- Education
- Outreach

A New Biology for the 21st Century

- Report released by National Academies in USA
  - Current state of biological research?
  - How best to capitalise on recent scientific advances
- The challenge of advancing from identifying parts, to defining complex systems, to systems design, manipulation, and prediction:
  - is still well beyond current capabilities; and
  - barriers to advancement are similar at all levels from cell to ecosystems
- Overarching recommendations:
  - Establishment of National New Biology Initiative
  - Priority be given to the development of information technologies and sciences that will be critical to the success of the New Biology
  - Devote resources to interdisciplinary curricula

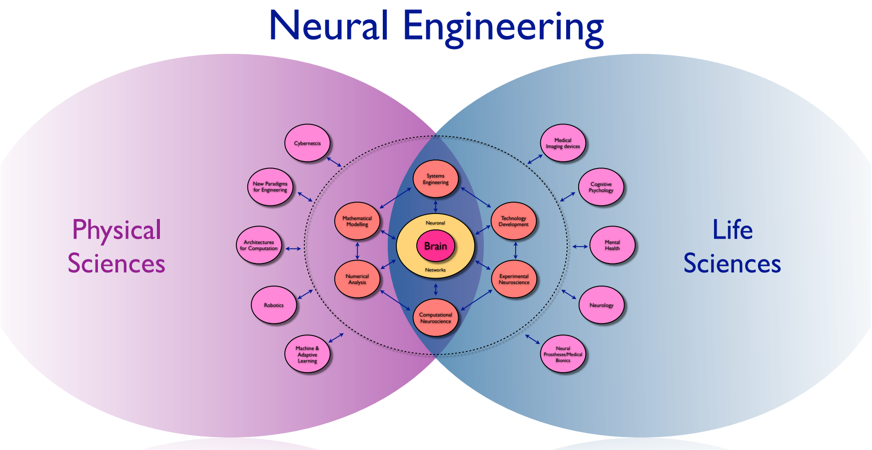
New Biology

- Potential benefits are remarkable and far-reaching
- Approaches which will accelerate progress are those that:
  - integrate a wide range of scientific disciplines
  - draw on the strengths and resources of
    - universities
    - federal agencies
    - private sector
- Best way to capitalise on this opportunity is to focus on
  - accelerating understanding of complex biological systems
  - driving rapid progress in meeting societal challenges
  - advancing fundamental knowledge

Scientists

- New Biology will require the creative drive and deep knowledge base of individual scientists from
  - biology
  - physical, computational and geosciences
  - engineering
- Offers the potential to address questions at a scale and with a focus that cannot be undertaken by any single scientific community, agency or sector
- Providing a framework for different communities to work together will lead to synergies and new approaches that no single community could have achieved alone
- The New Biologist is not a scientist who knows a little bit about all displines, but a scientist with deep knowledge in one discipline and a "working fluency" in several
  - Highly developed quantitative skills will be increasingly important

Convergence of Physical and Life Sciences



Convergence of the physical and life sciences focused on a systems engineering approach for understanding mathematically how biological neurones naturally work

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