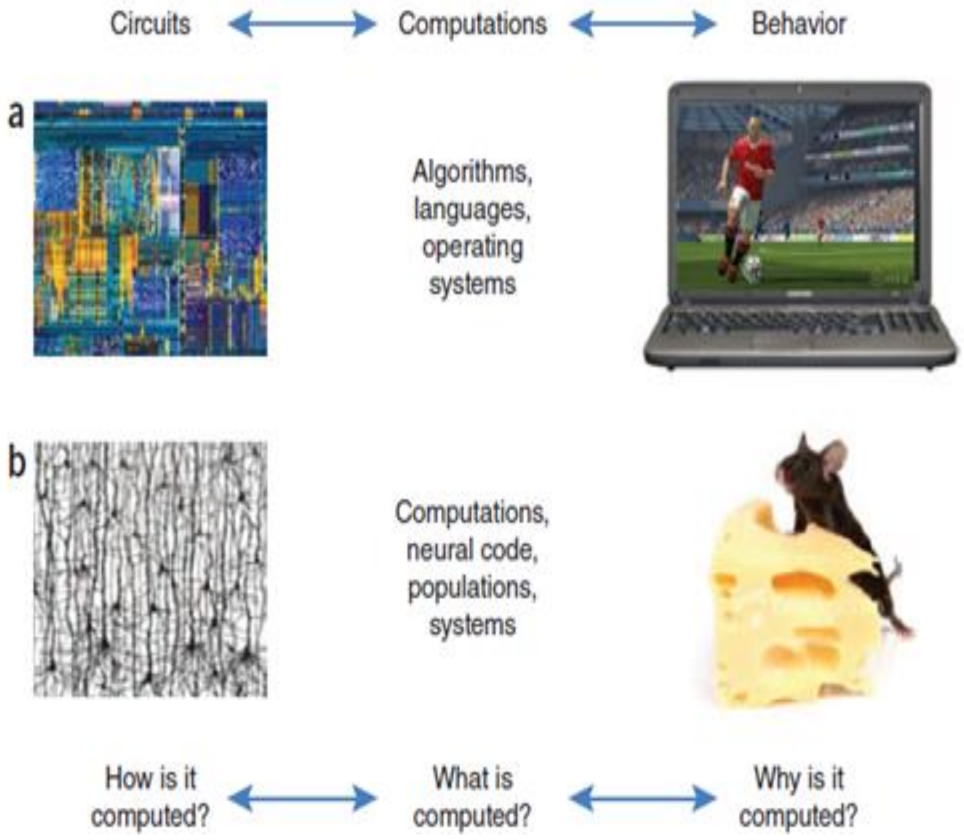
Lecture 1

Computation: Bridge between Neural Circuits and Behavior



- Neuroscience seeks to understand circuits lead to perception, thought, and behavior
- Currently, the gap between circuits and behavior is too wide.
- Neural **computations** occur in individual and populations of neurons.
- This offers an intermediate level to bridge the gap
- Computation supplies common language for neural and cognitive researchers
- Computation is Church-Turing Thesis in broad sense
- Here refers to computations that are relevant to cognition: level above hardware and below end-to-end functionality

From circuits to behavior: a bridge too far?
Matteo Carandini   nature neuroscience volume 15 | number 4 | APRIL 2012

Neural computations (Carandini)

- Impossible to understand a computer operation without layering – hardware, system software, application software.
- Computations in brain could be like instructions in computer:
- An instruction set can be composed in an infinite number of ways to write programs ~ cognitive level behaviors.
- Unlike typical computer, the same instruction (computation) might appear in multiple brain regions implemented in different ways

Alternatives to This Approach

- Obtain full **diagram of the circuits of the brain**, the “connectome”.
    - This diagram will be useful to understand how circuits give rise to computations
    - For instance, a connection map was obtained for a piece of retina (a circuit) and it answered a longstanding question about **direction selectivity (a computation**).
    - **However, this approach will do little to explain how various computations are used together to produce behavior.**
    - Also need **information about connection strength**.
        - For instance, we have long known the full connectome for the worm *C. elegans*, detailing the more than 7,000 connections between its 302 neurons25,
        - yet we are hardly in a position to predict its behavior, let alone the way that this behavior is modified by learning.
    - So we need higher level descriptions, e.g., programming manual for computer

Simulate brain circuits in full complexity

- Approach was championed with the neural simulator Genesis, in the bluebrain project and the Human Brain Project.
- Central hypothesis is that an **“understanding of the way nervous systems compute will be very closely dependent on understanding the full details of their structure**”.
- According to this hypothesis, one should seek “computer simulations that are very closely linked to the detailed anatomical and physiological structure” of the brain, in hopes of “ generating unanticipated functional insights based on emergent properties of neuronal structure”
- Disappointment: have not discovered much by putting together highly detailed simulations of vast neural systems.
- Have succeeded when they have concentrated on a more microscopic scale

Extend decomposition to subcellular level

- Put all of the **subcellular** details into a simulation of a vast circuit
- Not likely to shed light on the underlying computations
- Most details are not known
- May not be needed if the level of the subcellular and the level of the network are strongly decoupled.
- Very similar patterns of cellular and network responses (and therefore very similar computations) can be obtained with wide differences in biophysical details.
- Conversely, small changes in biophysical details can lead to wide differences in cellular properties (and therefore in computations).

Computation as the Intermediate Layer

- Intermediate between detailed mechanism (too much reductionism) and overall function (too much holism).
- The known neural computations were discovered by
  - Measuring the responses of single neurons and neuronal populations and
  - Relating these responses quantitatively to known factors (e.g., sensory inputs, perceptual responses, cognitive states or motor outputs).
- Currently, can record from **hundreds** of neurons: New technology will soon grow this to **thousands**.
- Models are needed to
  - Provide concepts for the concerted activity of large neuronal populations
  - Drive experiments for validation and refinement
- Marr : "any particular biological neuron or network should be thought of as just one implementation of a more general computational algorithm"
- Brain relies on a core set of standard (canonical) neural computations:
  - Combined and repeated across brain regions and modalities
  - Apply similar operations to different problems.

Examples of generic computation: linear filtering, divisive normalization

- **Linear filtering** is a widespread computation in sensory systems, in which neurons operate on sensory inputs by weighted summation in linear receptive fields.
  - It is performed, at least approximately, at various stages in the visual system6, in the auditory system7 and in the somatosensory system.
  - It may also be involved in motor systems, where neural activity can specify force fields obeying linear superposition.
- **Divisive normalization** an operation in which neuronal responses are divided by a common factor, the summed activity of a pool of neurons.
  - Normalization was developed to explain responses in primary visual cortex and is now thought to operate throughout the visual system and in multiple other sensory modalities and brain regions.
  - Underlies representation of odors, visual attention, the encoding of value and the integration of multisensory information.
- Other examples: detection of time differences between two sets of inputs (sound localization), thresholding and exponentiation, recurrent amplification, associative learning rules, cognitive spatial maps, coincidence detection, gain changes resulting from input history and cognitive demands, population vectors, and constrained trajectories in dynamical systems.

Approach For This Seminar

- Focus on some neuron-inspired components that are abstractions “with some resemblance” to biological neurons
- Ask how they could do some computations for some cognitive level behaviors.
- Express the layering of circuits-computation-behavior more formally and precisely
- Computations in neuronal systems may require a variety of different types of component behaviors,
  - Some of which are recognized as biologically plausible models (e.g., Leaky integrator neurons)
  - Many of which seem to require simple behaviors that have not been so identified.
- Show how a dynamic systems modeling framework using discrete events in a well-defined manner
- Provide an appropriate means for characterizing and investigating the building blocks for the computations that link circuits to behavior.
- Are capabilities to do computations different at single and population levels?
- Simulating large networks is hard: How to derive lumped model mechanisms and parameters from base model populations of neuron components to predict/guide simulation results?

Overview of Neuron Modeling: System Abstraction, Composition, and Search

Activity-based Learning

Combined

Fast Discrete Event Nets

Markov Neuron Populations

Component Alternatives Search

Thorpe One-spike-per-neuron

Markov Stochastic Neurons

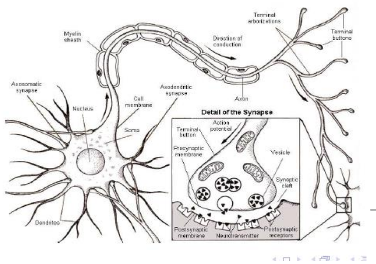
McCullough Pitts: Logic

Leaky Integrate & Fire

System Composition

Hodgkin-Huxley Model

System Abstraction



A lot is left out – hopefully the right stuff is retained

“right” means “for the intended purpose”