Computational Neuroscience

2016

Instructor: Odelia Schwartz

Computational neuroscience

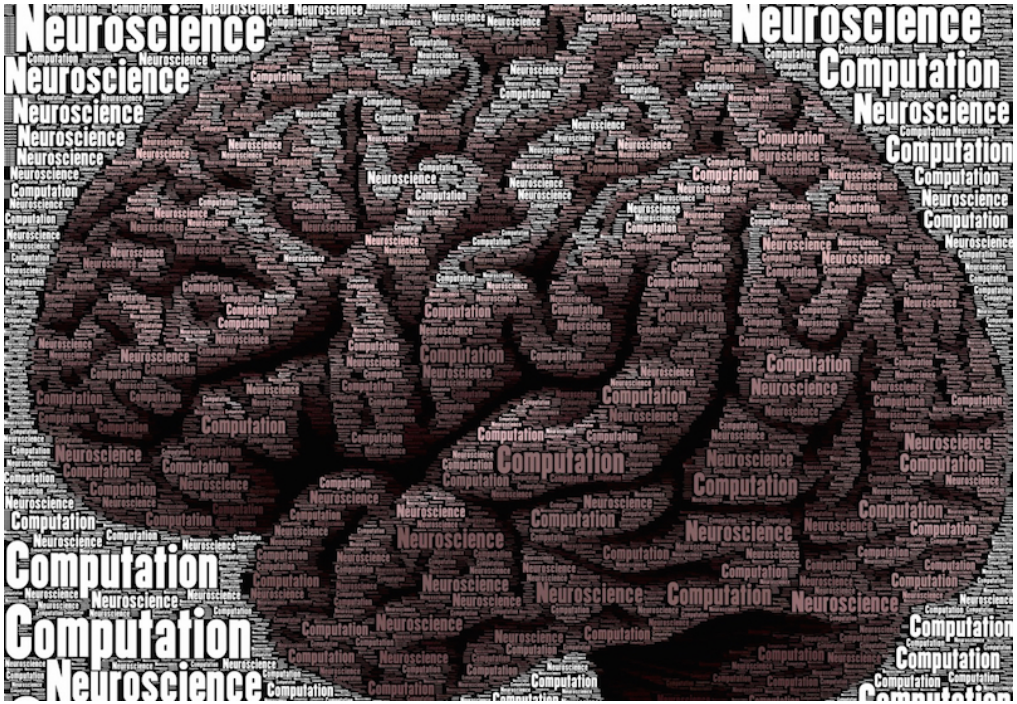
- **Introductions…**

What area are you in / background?

Why Computational Neuroscience?

Computational neuroscience

- **Your goal: Figure out how the brain works!**



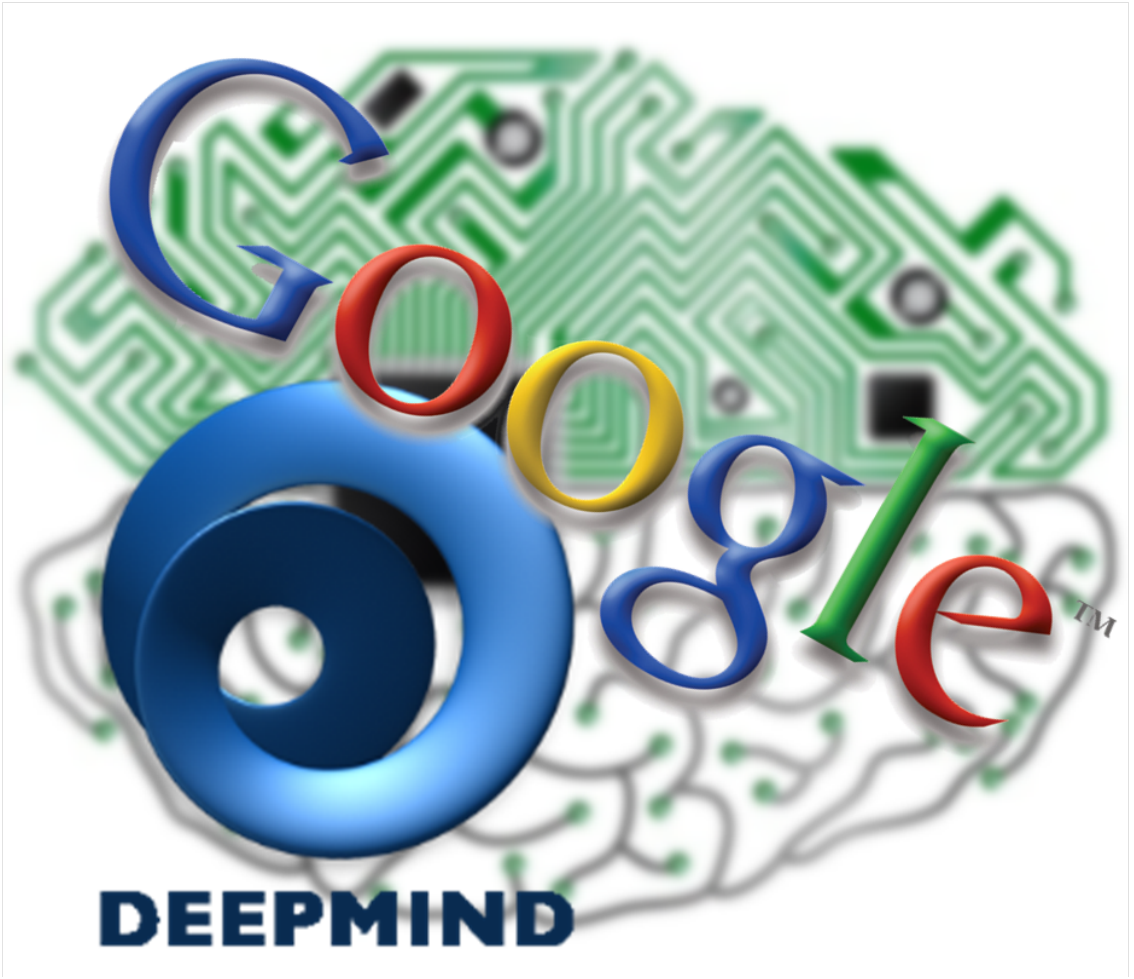
Computational neuroscience

Lots of interest from multiple fields!

Sept 2014: "The Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative is part of a new Presidential focus aimed at revolutionizing our understanding of the human brain. By accelerating the development and application of innovative technologies, researchers will be able to produce a revolutionary new dynamic picture of the brain"

Computational neuroscience

Lots of interest from multiple fields!



Brain machine interfaces

Lots of interest from multiple fields!

L.R. Hochberg et al., Nature 2012

Computational neuroscience

Lots of interest from multiple fields!

Computer Science
Math
Engineering
Physics

Biology
Cognitive Science
Psychology

Computational neuroscience

Lots of interest from multiple fields!

Computer Science
Math
Engineering
Physics

Biology
Cognitive Science
Psychology

Computational principles
Algorithms
Computer simulations …

Experiments
Data …

Computational neuroscience

- But what does it mean to understand how the brain works?

(discussion)

Computational neuroscience

Levels of investigation

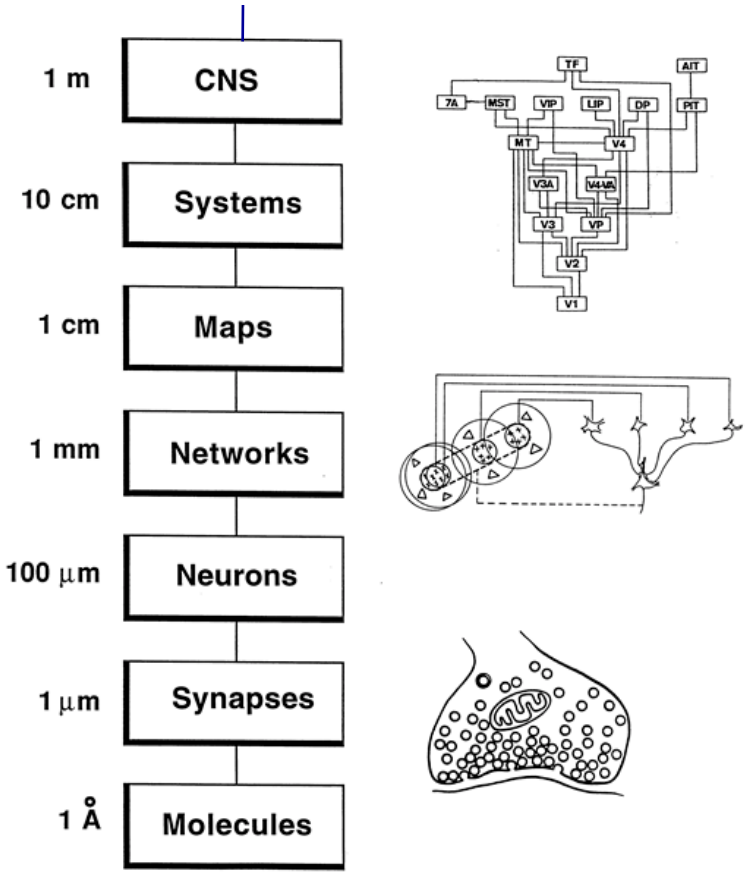
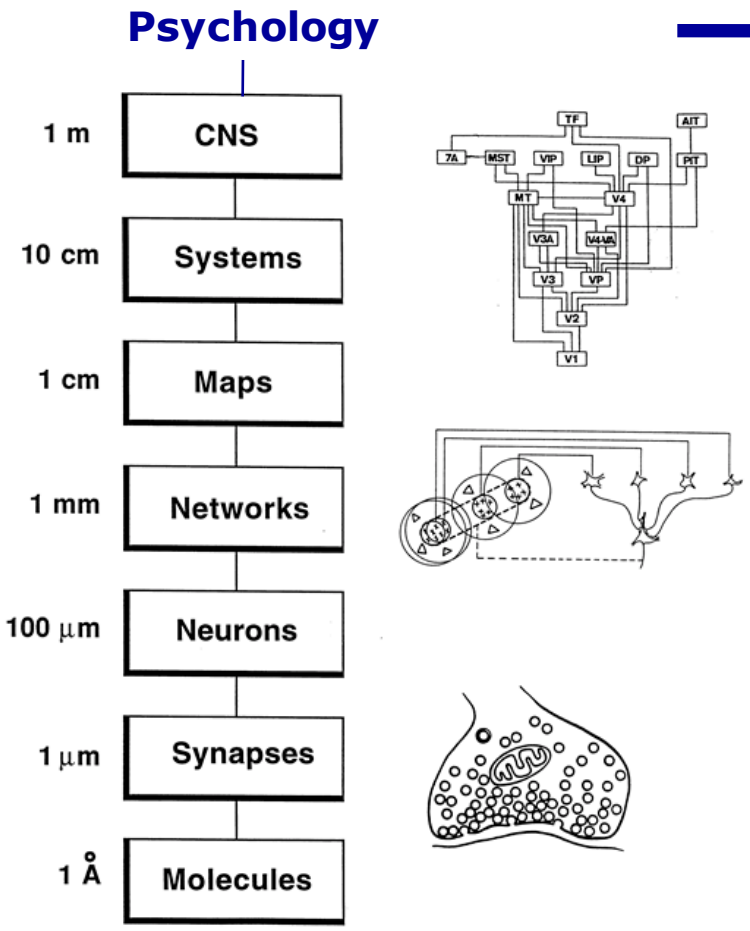


Diagram: Terrence Sejnowski

Computational neuroscience

Levels of investigation



Perception, behavior, cognition

Diagram: Terrence Sejnowski

Computational neuroscience

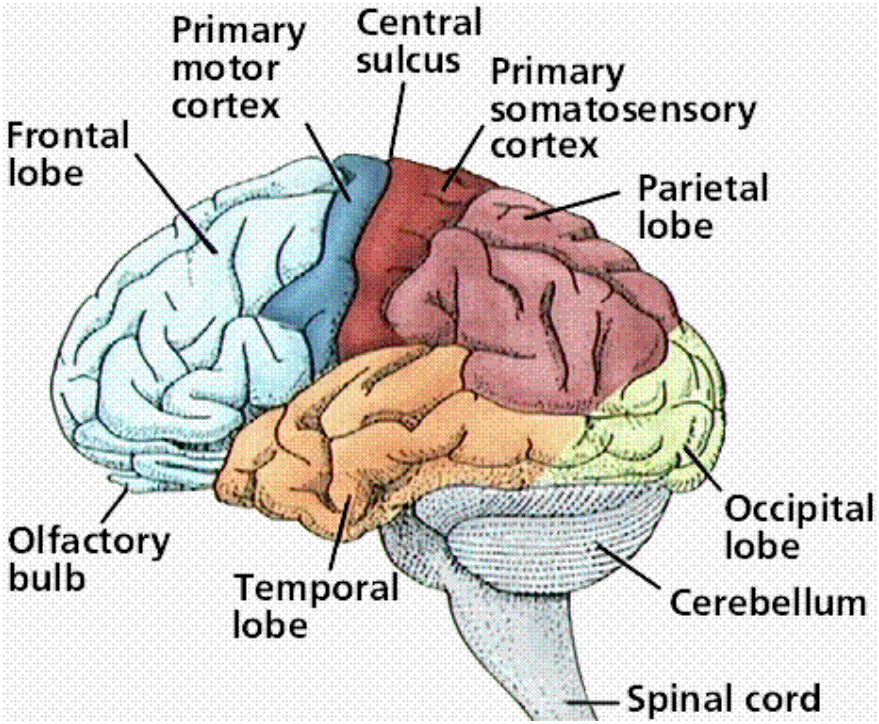
Types of quantitative tools

- Machine learning;
- Statistics / probability
- Information theory;
- Optimization;
- Control theory;
- Signal Processing;
- Dynamical systems;
- Statistical physics;
- Biophysics

Computational neuroscience

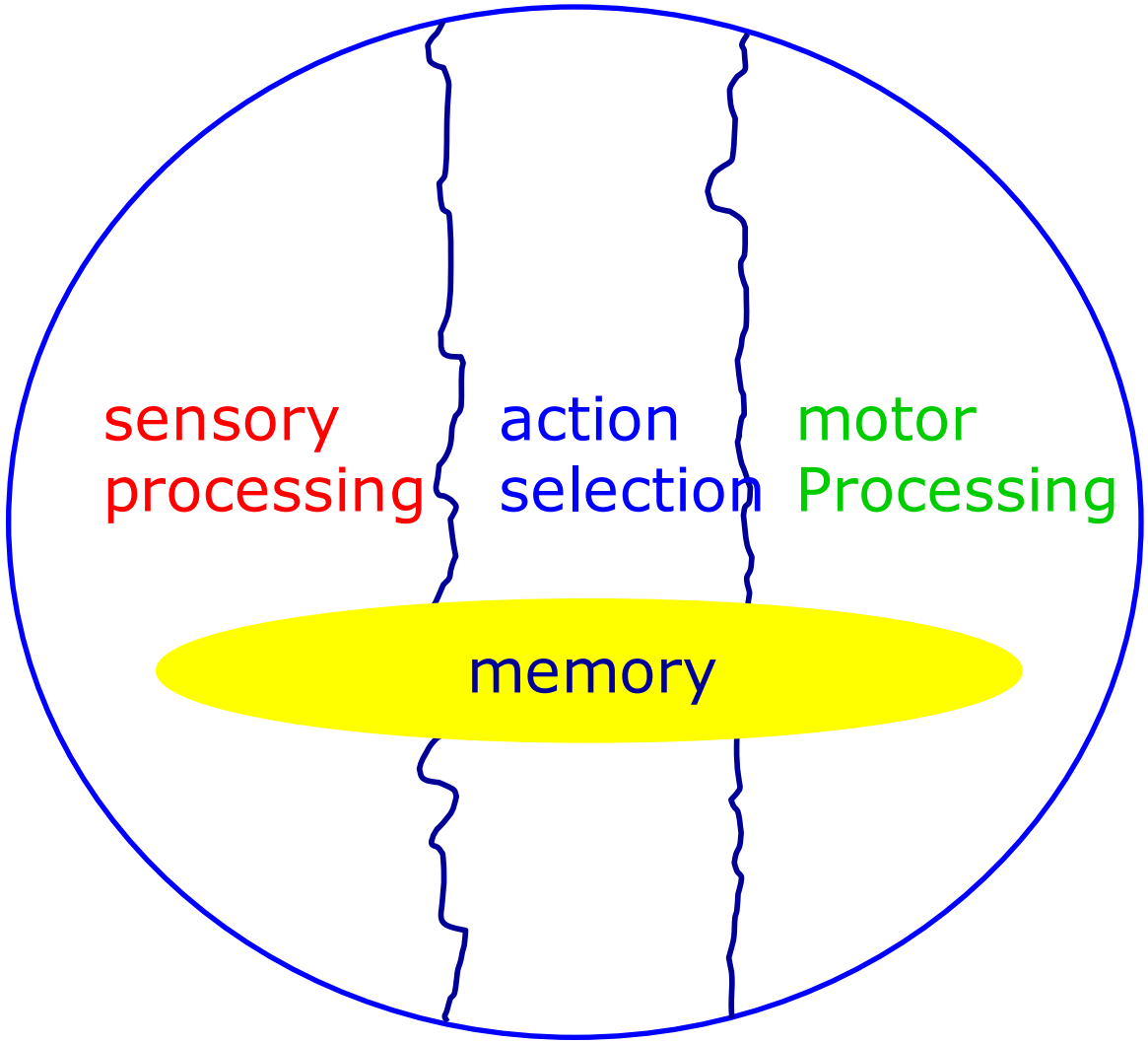
First, a bit about your brain…

Your brain



from Gatsby Computational Neuroscience course

Lots of structure at the macroscopic level



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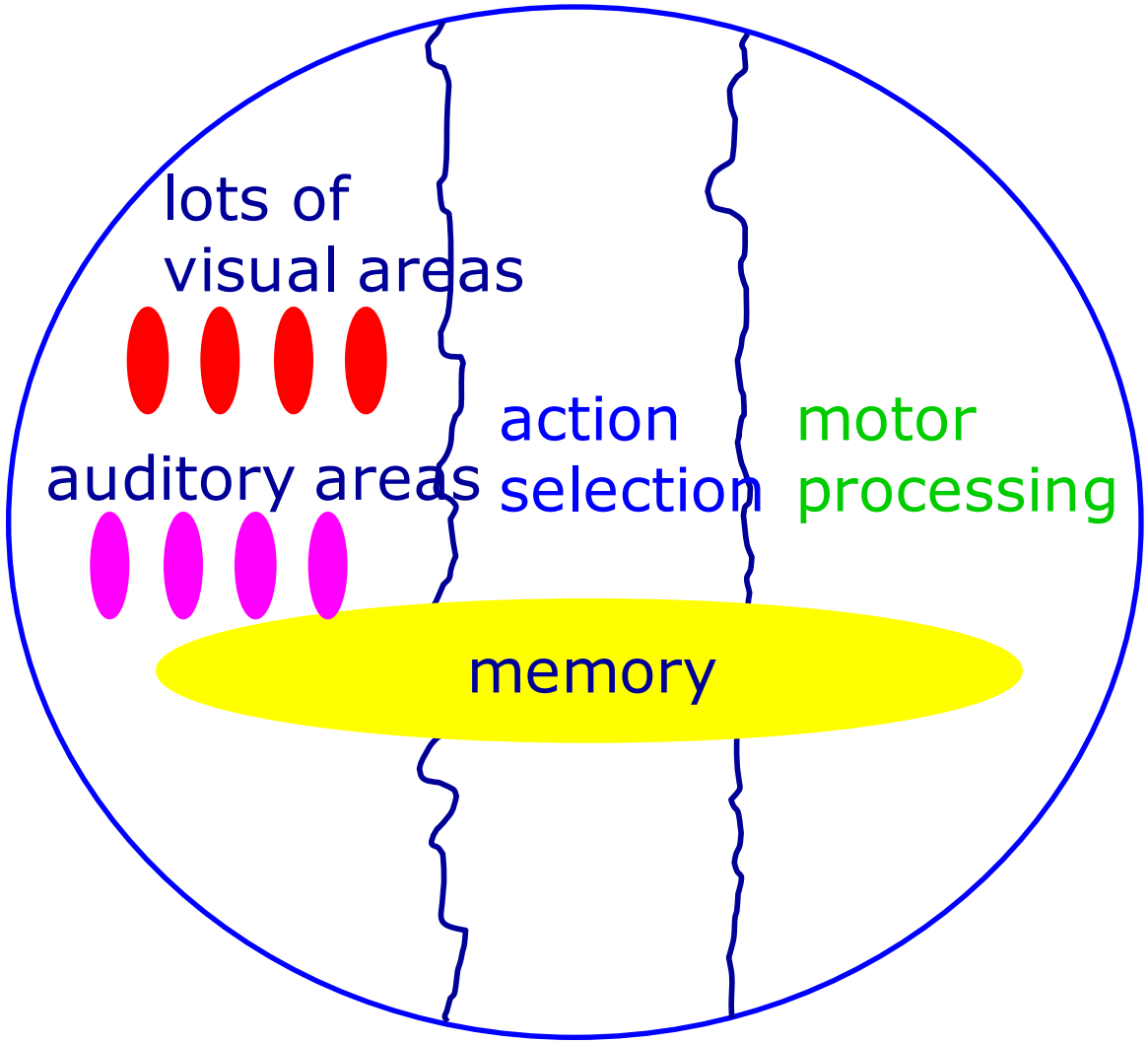
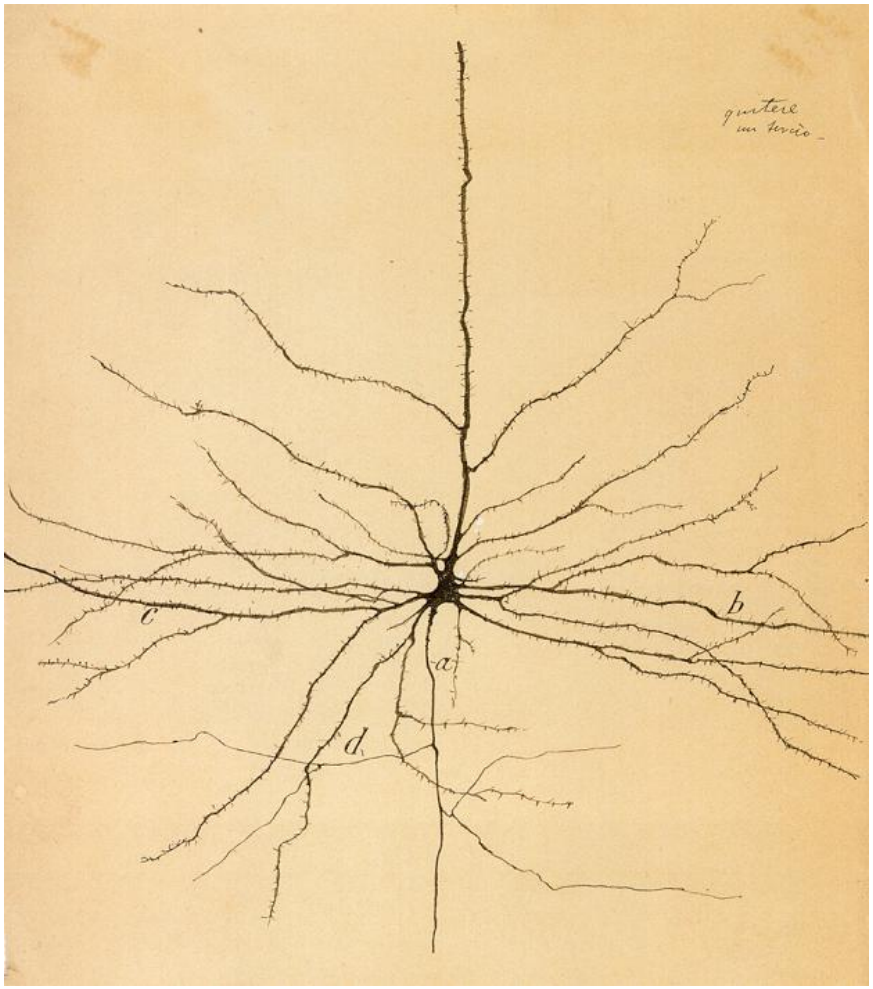
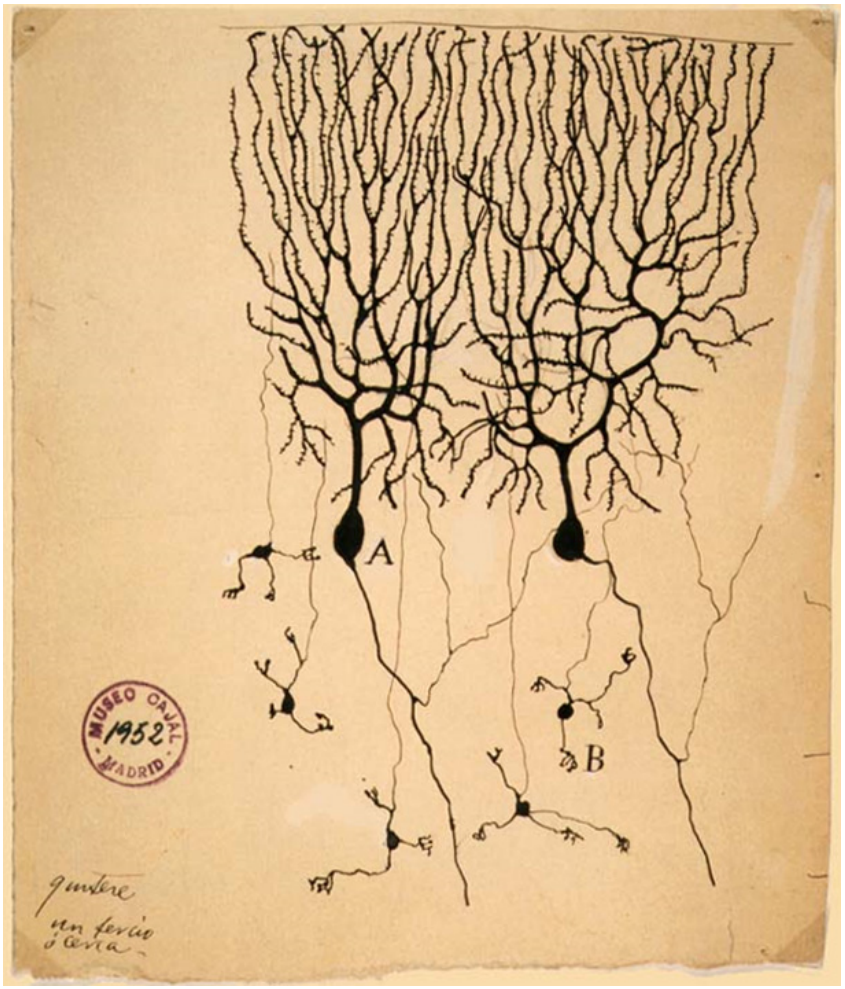
Lots of structure at the macroscopic level



from Gatsby Computational Neuroscience course

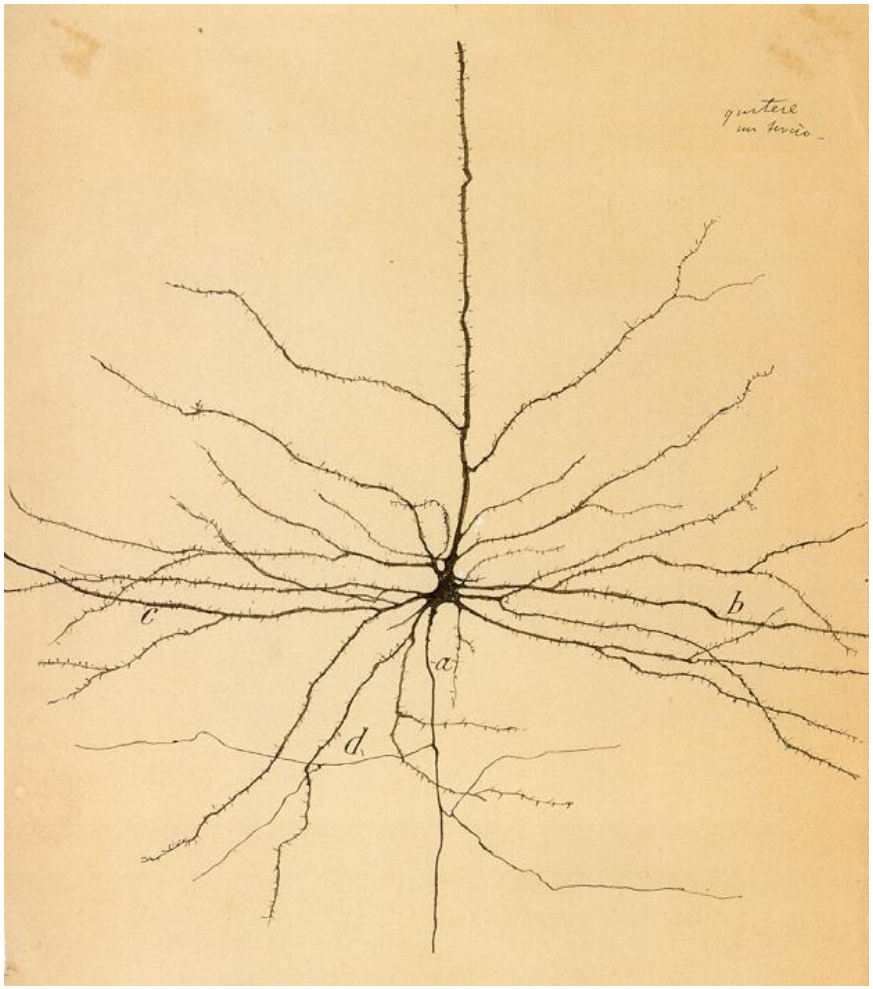
Neurons in the brain

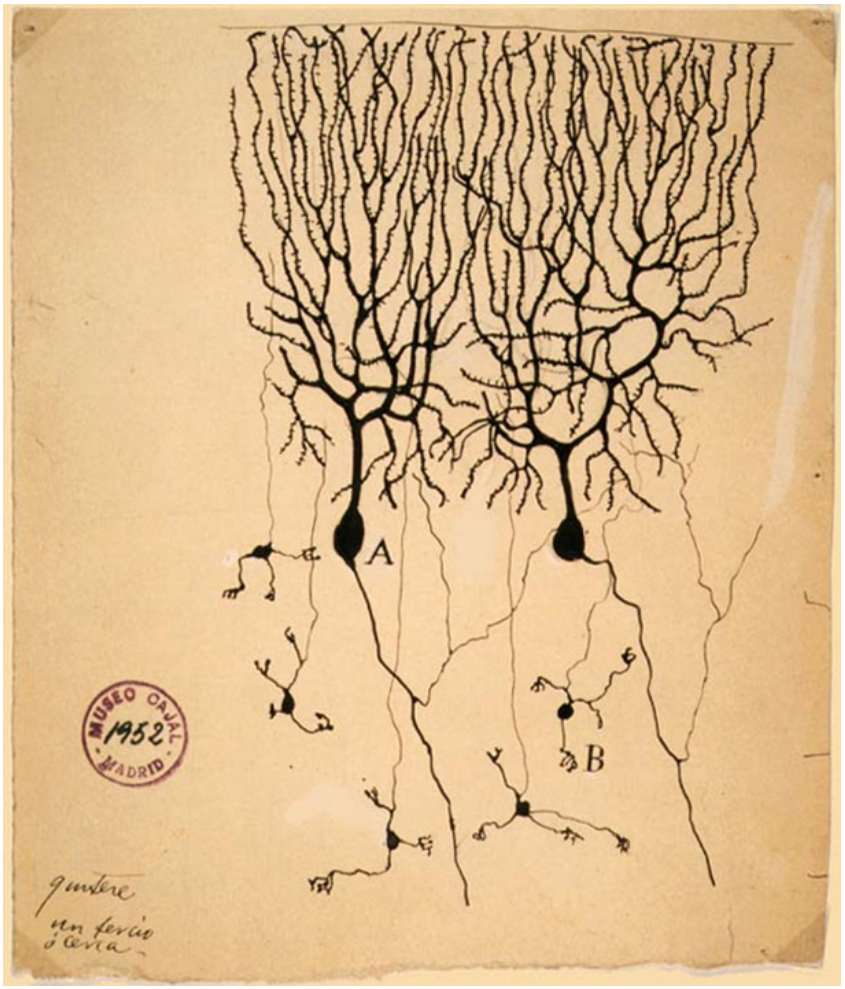




Santiago Ramón y Cajal (drawn 1899)

Neurons in the brain



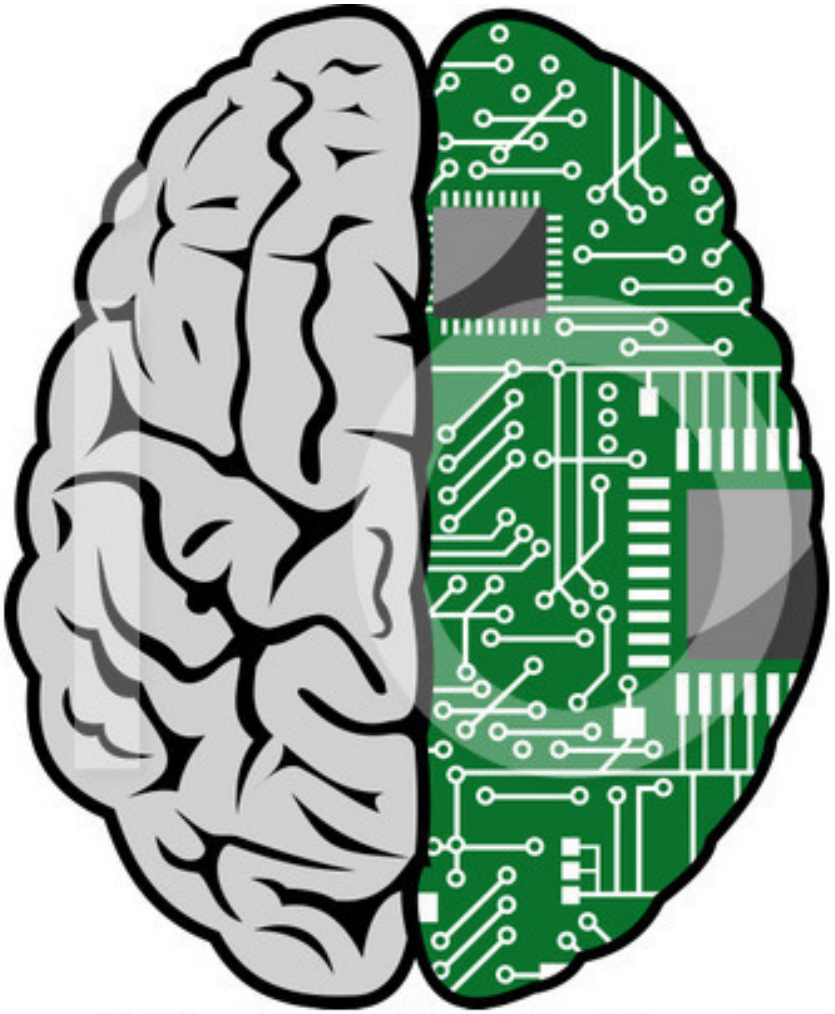


How many neurons in the human brain?

Neurons in the brain

Around 10^{11} neurons in the human brain

Brain versus CPU



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Brain versus CPU

whole brain (2 kg):

10^{11} neurons
10^{14} connections
(1000 connections per neuron)
8 million km of axons

Adapted from Gatsby Computational Neuroscience course

Brain versus CPU

whole brain (2 kg):

10^{11} neurons
10^{14} connections
(1000 connections per neuron)
8 million km of axons

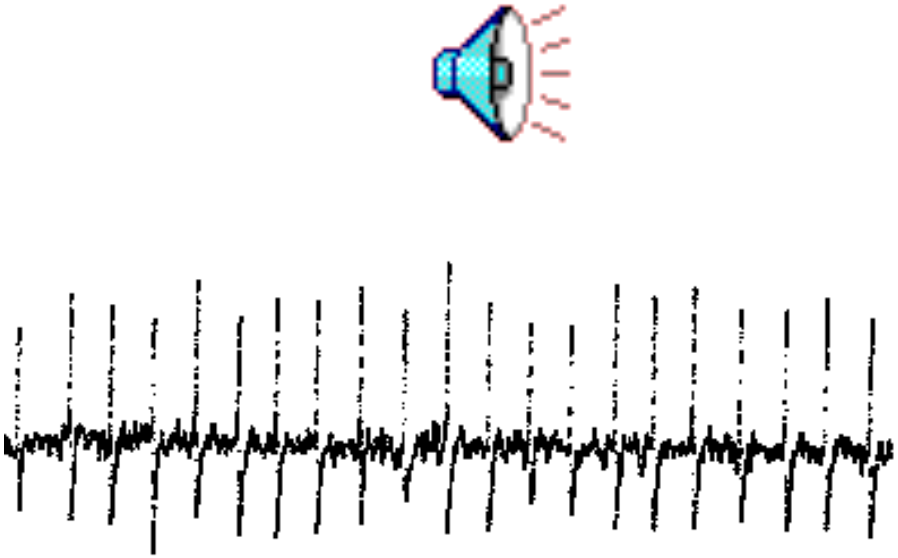
whole CPU:

10^{9} transistors
2×10^{9} connections
(few connections per transistor)
2 km of wire

Adapted from Gatsby Computational Neuroscience course

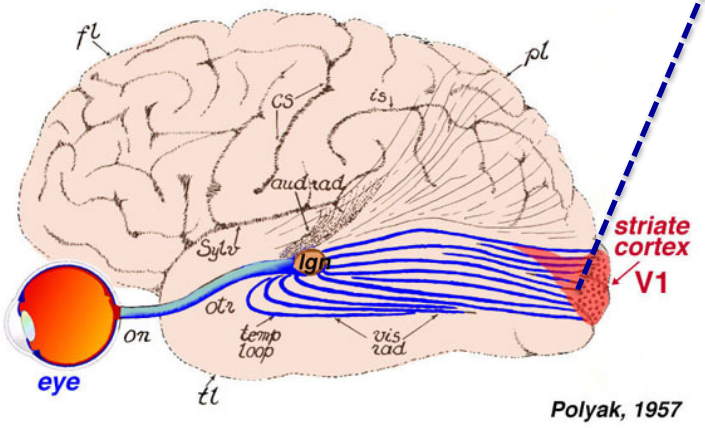
Man versus Machine

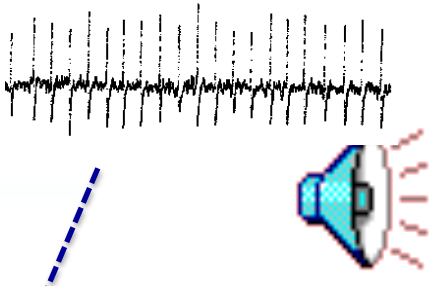
Neural Currency



- Spike (action potential): approximately 100 mV rise in voltage, lasting for approximately 1 msec

Neural processing





- Example: Visual neurons spike in response to features or properties of images

What do we want to know?

- What questions do we want to know? (often not clear in neuroscience!)
- Identifying a question that's both answerable and brings us closer to understanding how the brain works.

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What do we want to know?

Example 1:

how does the brain work?

is not answerable (at least not directly, or any time soon) but it will bring us (a lot!) closer to understanding how the brain works.

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What do we want to know?

Example 2:

what's the activation curve for the Kv1.1 voltage-gated potassium channels?

is answerable, but it will bring us (almost) no closer to understanding how the brain works.

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Computational neuroscience

David Marr, 1982
Levels of modeling

- Computational: What is the goal of the computation?
- Algorithm: What is the strategy or algorithm to achieve the computation?
- Implementation: How is this implemented in the brain? (mechanism in neurons; networks of neurons)

Computational neuroscience

David Marr, 1982
Levels of modeling

Computational theory	Representation and algorithm	Hardware implementation
What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?	How can this computational theory be implemented? In particular, what is the representation for the input and output, and what is the algorithm for the transformation?	How can the representation and algorithm be realized physically?

Figure 1–4. The three levels at which any machine carrying out an information-processing task must be understood.

Computational neuroscience

David Marr, 1982
Levels of modeling, example:

- Computational: What is the goal of the computation?
  example: maximize reward

Computational neuroscience

David Marr, 1982
Levels of modeling

- Computational: What is the goal of the computation?
  example: maximize reward

- Algorithm: What is the strategy or algorithm to achieve the computation?
  reinforcement learning algorithms to minimize prediction error of reward

Computational neuroscience

David Marr, 1982
Levels of modeling

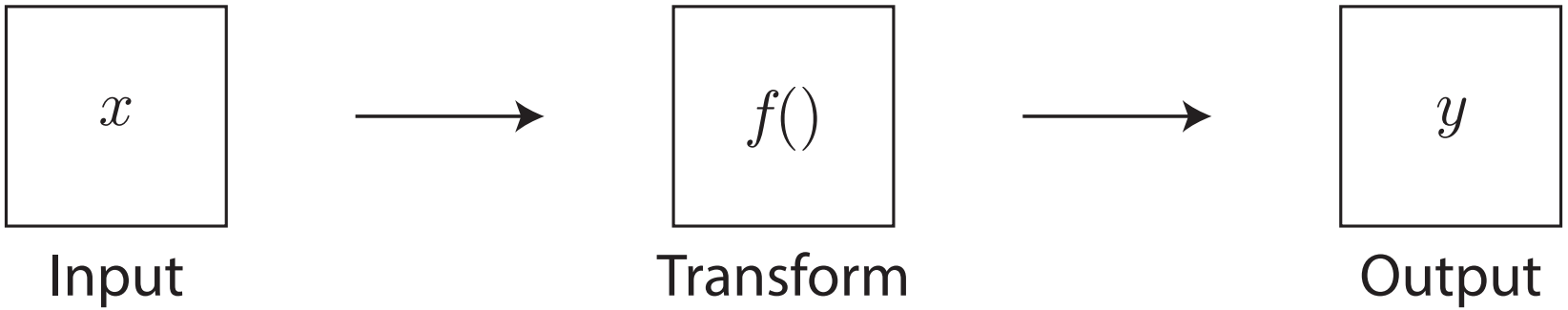
- Computational: What is the goal of the computation?
  example: maximize reward

- Algorithm: What is the strategy or algorithm to achieve the computation?
  reinforcement learning algorithms to minimize prediction error of reward

- Implementation: How is this implemented in the brain?
  dopaminergic neurons?

Computational neuroscience

Another way to parse model types



What? How? Why?

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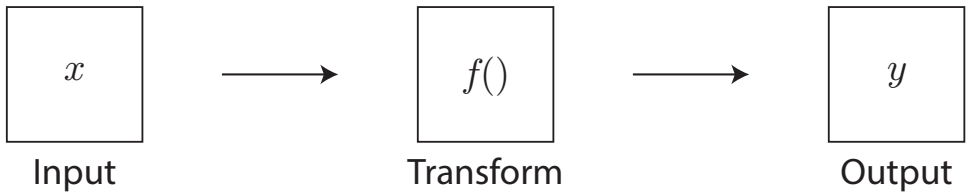
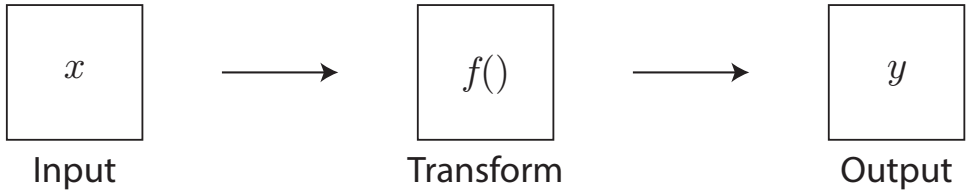
Answer three kinds of questions about the brain



- Descriptive (what)
- Mechanistic (how)
- Interpretive/normative (why)

Computational neuroscience

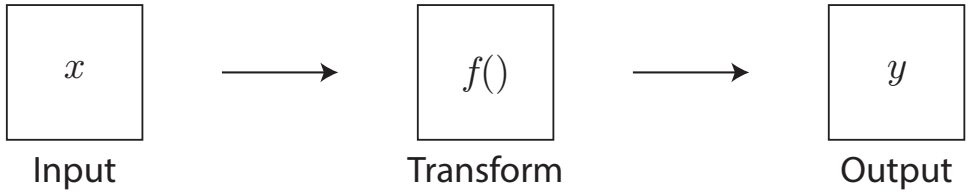
Answer three kinds of questions about the brain



- Descriptive (what): What is the transform between input and output?

Computational neuroscience

Answer three kinds of questions about the brain

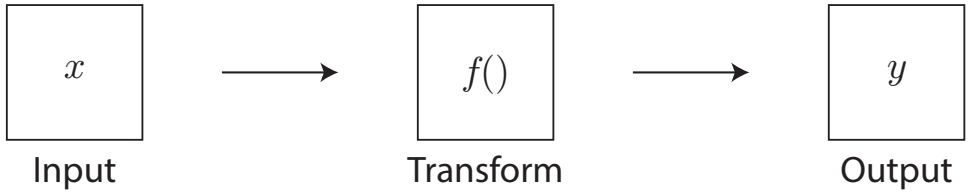


- Descriptive (what): What is the transform between input and output?

- Mechanistic (how): How does the system transform the input into the output?

Computational neuroscience

Answer three kinds of questions about the brain



- Descriptive (what): What is the transform between input and output?
- Mechanistic (how): How does the system transform the input into the output?
- Interpretive/normative (why): Why does the system transform the input into the output?

Computational neuroscience

Answer three kinds of questions about the brain

- Descriptive (what)
  examples: addition or division between neural units, receptive field models

- Mechanistic (how)
  examples: ionic channels, synaptic depression, network mechanisms

- Interpretive/normative (why)
  examples: efficient coding, optimal estimation or decision, wiring length, metabolic cost

Computational neuroscience

Answer three kinds of questions about the brain

So what level do we want to study??

Computational neuroscience

Answers three kinds of questions about the brain

- descriptive (what)
- mechanistic (how)

} Interpretive/normative models (why)

Computational neuroscience

- Barlow 1961: “A wing would be a most mystifying structure if one did not know that birds flew”

Computational neuroscience

Interaction with experiments

- Fit existing data

Computational neuroscience

Interaction with experiments

- Fit existing data
- Make predictions…

Computational neuroscience

Interaction with experiments

- Fit existing data

- Make predictions…
  about other data
  new experiments
  other neurons
  behavior
  generalization

This class

- Lectures
- Matlab computer tutorials and labs – some Thursdays
- Several paper discussions that cover recent progress in the field, or classical papers. You will be asked to do a presentation of a paper or research topic in groups
- No exams

This class

- Focus on tools
- Questions in the field
- Different levels of modeling
- Systems

This class

Topics include…

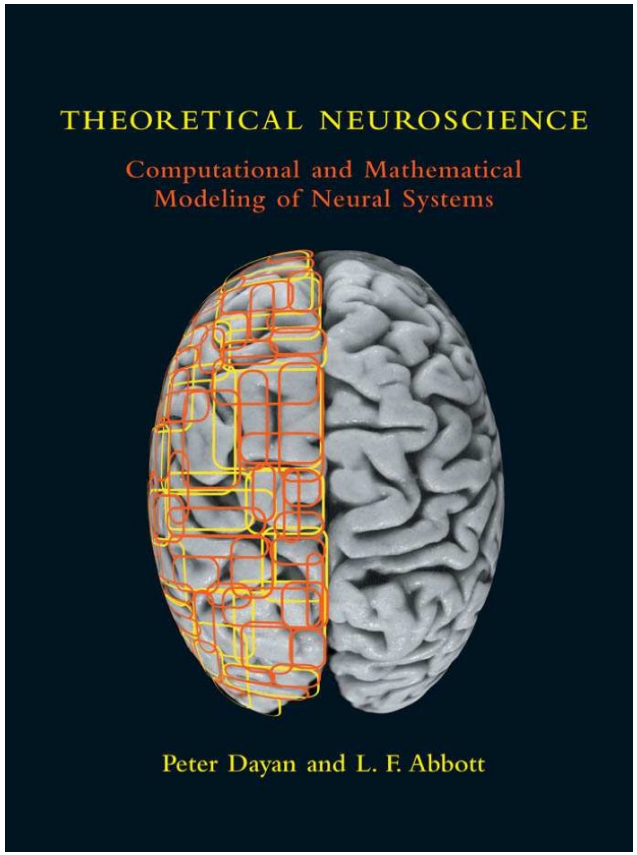
- The problem of neural coding
- Neural population Coding
- Brain Machine Interfaces
- Information theory and neural coding
- Example neural system: The visual system
- Other example neural systems…
- Estimating descriptive neural models from data
- Spike Train models
- Neural circuit models
- Neural processing of natural stimuli
- Finding correlations and higher order dependencies
- Bayesian models
- Relation to recent advances in machine learning and deep learning

This class

http://www.cs.miami.edu/home/odelia/teaching/compneuro2016/index.html

This class

- Suggested textbook: Theoretical Neuroscience: Computational and Mathematical Modeling of Neural Systems, by Peter Dayan and L.F. Abbott.



This class

- Suggested textbook on
  visual processing and scene statistics:
  Aapo Hyvarinen, Jarmo Hurri, Patrik O. Hoyer:
  Natural Image Statistics: A probabilistic approach
  to early computational vision.

  (particularly introduction chapters to the visual
  system and Interpretive (why) models)