NSC3270 / NSC5270
Computational Neuroscience

Tu/Th 9:35-10:50am
Featheringill Hall 129

Professor Thomas Palmeri
Professor Sean Polyn

For Today

Required Readings

Chapter 2 of Churchland, P.S., & Sejnowski, T.J. (2017). *The Computational Brain* (25th Anniversary Edition). MIT Press.

For Tuesday

Required Readings

Chapter 3 (selected pages) of Churchland, P.S., & Sejnowski, T.J. (2017). *The Computational Brain* (25th Anniversary Edition). MIT Press.

links on Brightspace

Modeling the Brain

Creating a Model of the Brain

What is a Model?

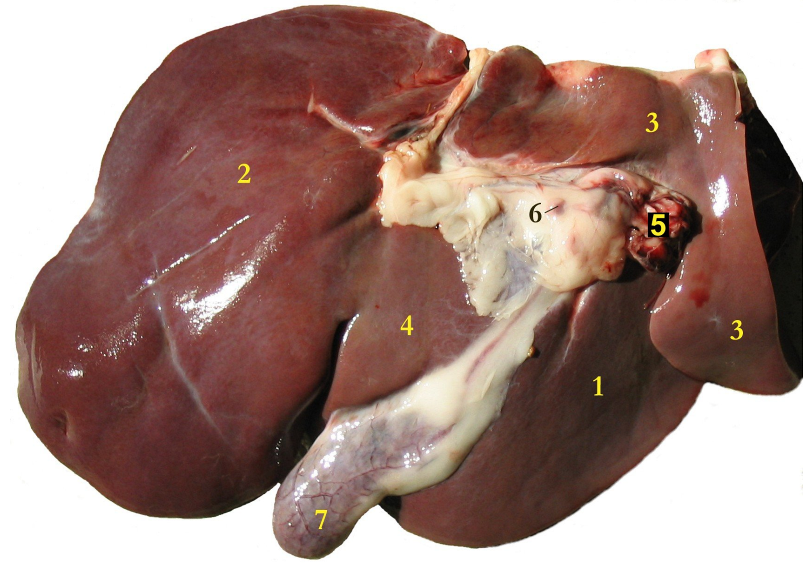
- A mathematical, computational, or physical representation of something in the real world.
- A model embodies our theories and hypotheses of that entity.
- A model allows us to understand, explain, and predict.

Creating a Model of the Brain

Physical Model (for neurosurgery)

- Vanderbilt researchers in engineering aim to develop a model of the brain as a three-dimensional non-rigid piece of tissue, subject to various biomechanical and physical forces.
- Their model embodies biophysical and physical laws that govern how forces act on tissues, allowing precise prediction of the location of healthy and diseased brain tissue during surgery.
- Predicting changes to three-dimensional structure is key. How the brain actually works is often irrelevant.

human brain
100,000,000,000 neurons



human liver
240,000,000,000 cells

What is the difference between the brain and the liver?

Physical Modeling: the same overall approach can be used by by engineers to model tissue deformations during surgery

Mechanistic Modeling: understanding how they work requires completely different approaches

Creating a Model of the Brain

Mechanistic Model (how the brain works)

- Explain and predict how the brain works. How we perceive, remember, think, decide, act, feel, and regulate our bodies.
- These models concern themselves with the three-dimensional structure only to the extent that structure informs our understanding of function.
- Tissue properties and physical forces and biomechanics in the brain are largely irrelevant, to the extent that they do not affect function of the brain (e.g., via trauma).

Creating a Model of the Brain

Generating Predictions of a Model

- **Mathematical Solution**: Some models are simple enough that their behavior can be expressed directly by a mathematical equation (direct solution or numeric solution).
- **Simulation**: Complex models whose behavior (its properties, how it changes, how it responds) can only be understood by "running" it on a computer (or in a physical representation)

Simulation

Simulation is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a **model** be developed; this model represents the key characteristics or behaviors/functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.
-Wikipedia

What is "Computational" in "Computational Neuroscience"?

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Two Senses:

one sense is in using computers as a research tool in modeling and simulating complex systems, in the same sense of "computational astrophysics", "computational fluid dynamics", or "computational chemistry"

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Two Senses:

one sense is in using computers as a research tool in modeling and simulating complex systems, in the same sense of "computational astrophysics", "computational fluid dynamics", or "computational chemistry"

another sense is that "what is being modeled by a computer is itself a kind of computer, albeit one quite unlike the serial, digital machines on which computer science cut its teeth. That is, nervous systems ... are themselves naturally evolved computers - organically constituted, analog in representation, and parallel in their processing architecture."

- Churchland & Sejnowski (2017)

Why Model?

"Formal [mathematical, computational, simulation] theories have a number of advantages that [psychologists and neuroscientists] often overlook. They force the theorist to be explicit, so that assumptions are publicly accessible and the reliability of derivations can be confirmed ... [Furthermore] to have one's hunches about how a simple combination of processes will behave repeatedly dashed by one's own computer program is a humbling experience that no [psychologist or neuroscientist] should miss. Surprises are likely when the model has properties that are inherently difficult to understand, such as variability, parallelism, and nonlinearity [and adaptation and learning] - all, undoubtedly, properties of the brain."

- Hintzman, 1990

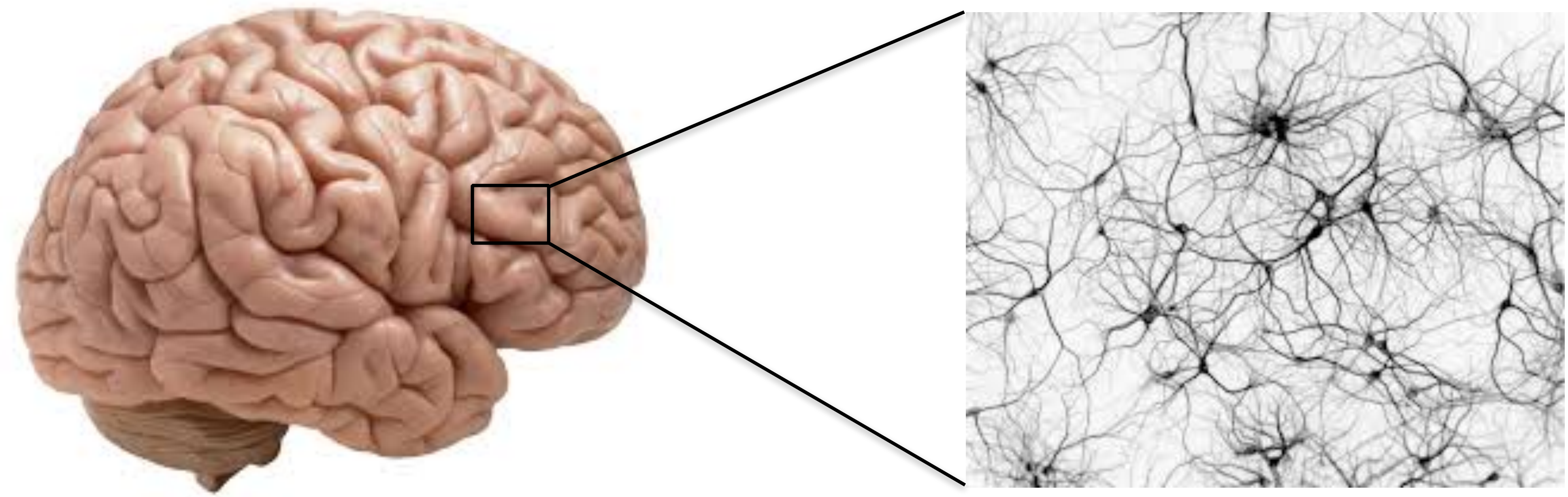
Creating a Model of the Brain

Challenge of Creating a Model of the Brain

- Arguably, the most complex structure in the known universe.

Human Brain:

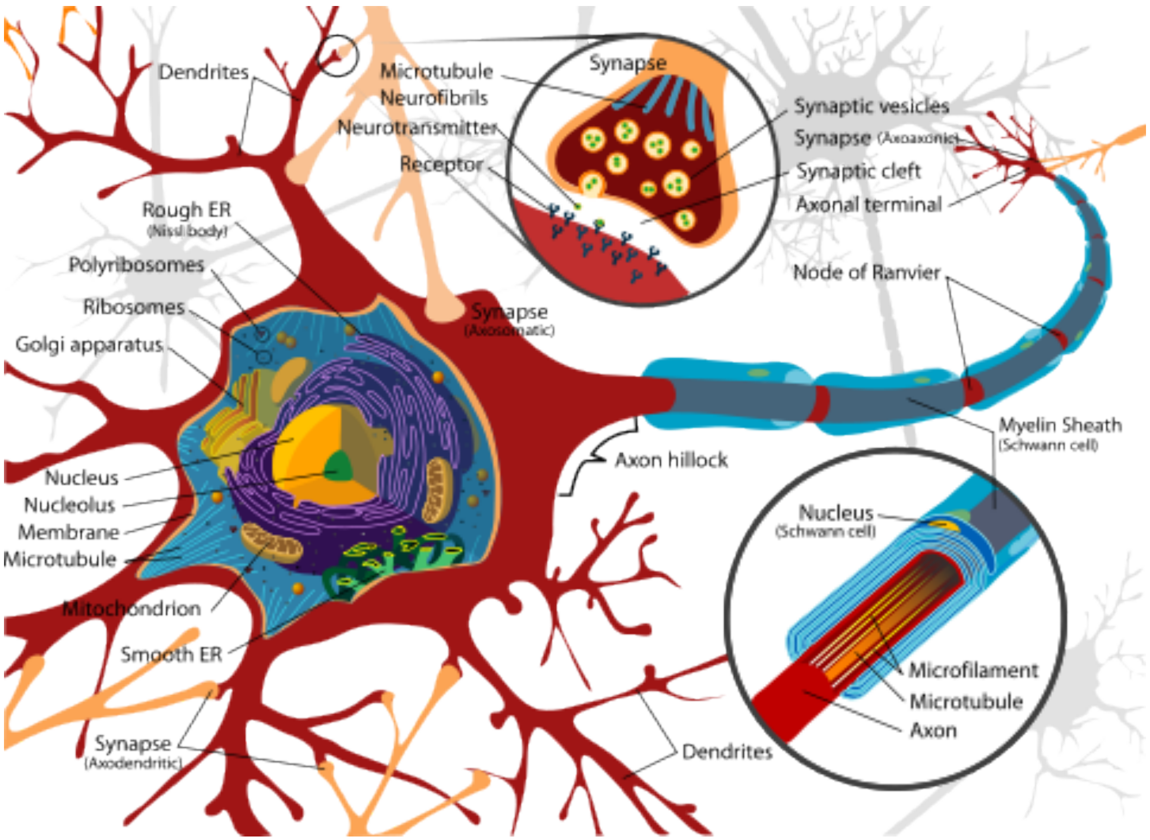
- weighs about 3lbs
- but uses up to 20% of metabolic energy

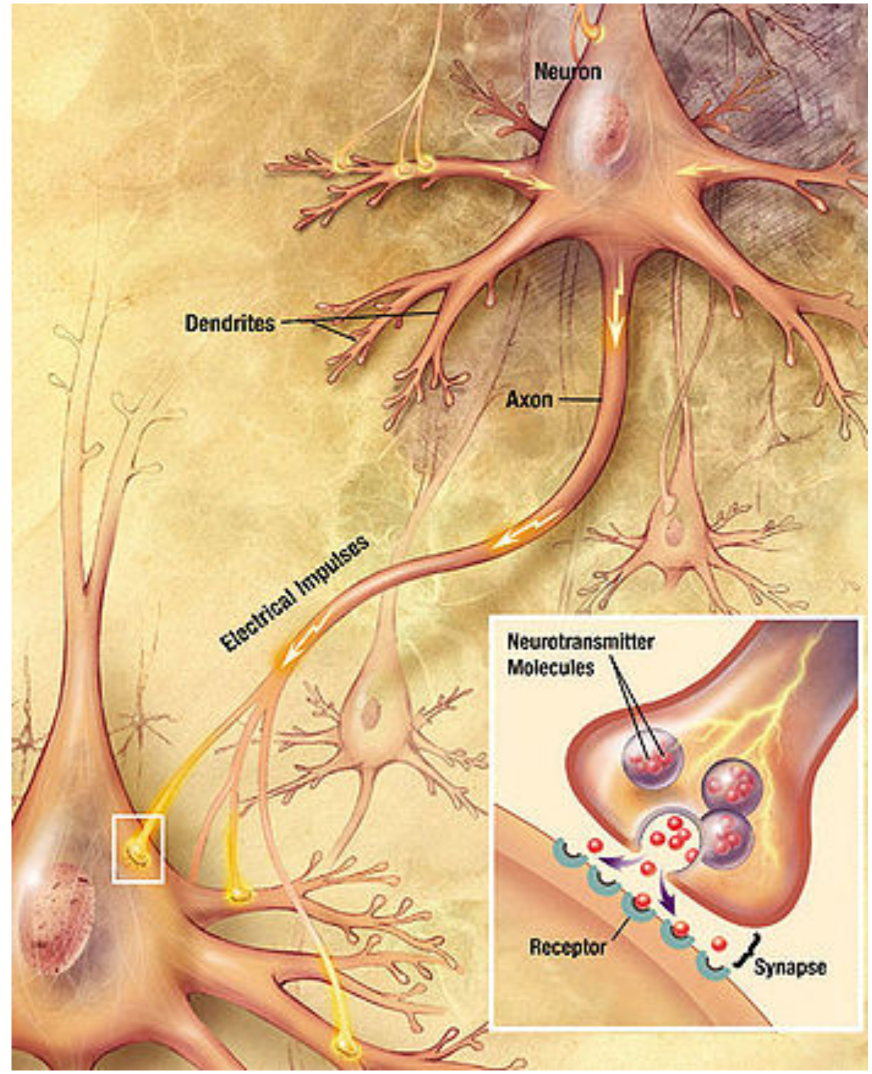


Human Brain:

- estimated between 50-100 billion neurons
- around the same number of non-neuronal glial cells
- each neuron can have thousands or even tens of thousands of connections with other neurons
- each individual connection is complex and nonlinear
- neurons and neural networks are far more complex
- the brain is nonstationary, it continually learns and adapts

The Neuron





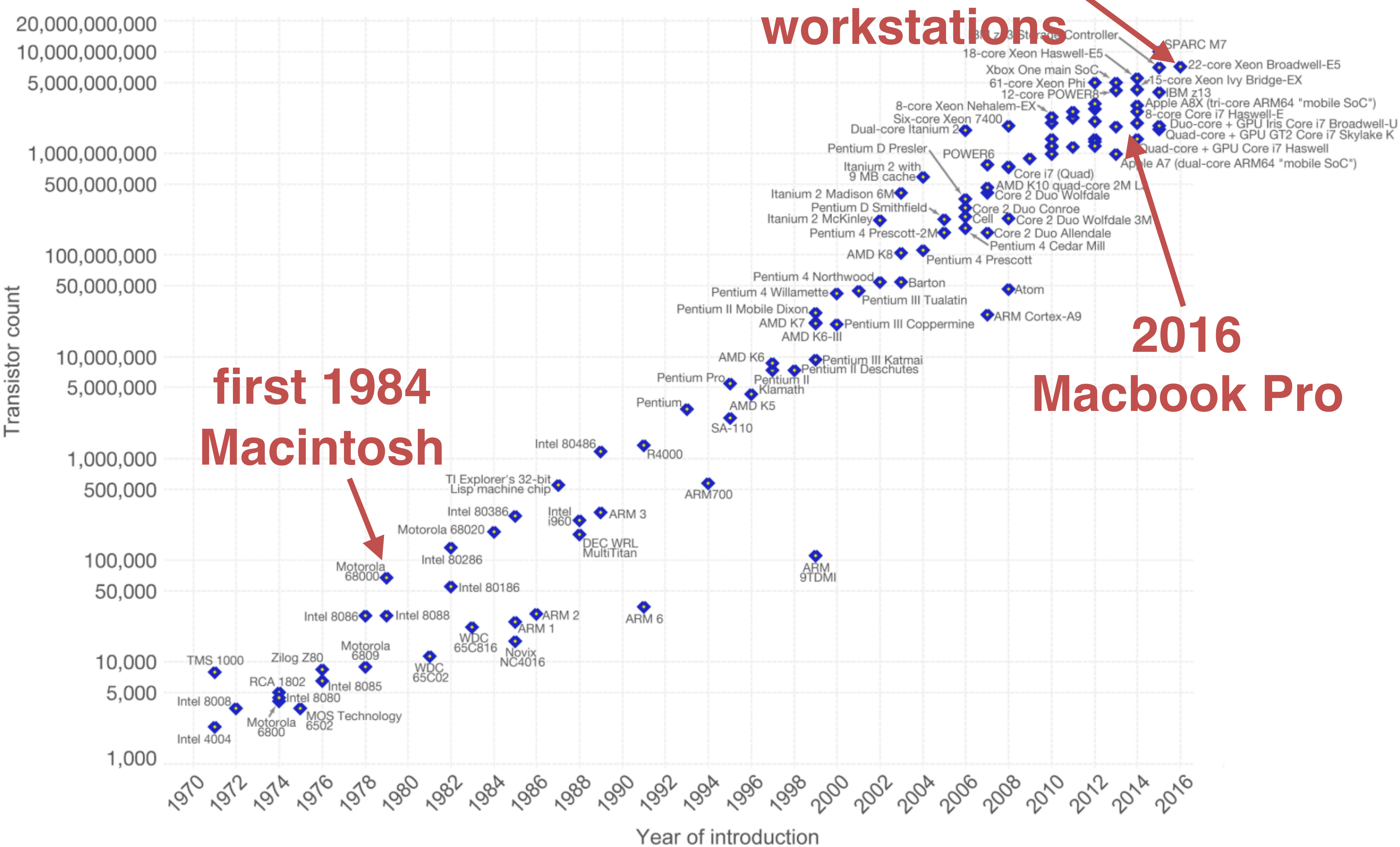
1,000-10,000 synapses per neuron

(Purkinje cells in cerebellum may have 100,000 synapses per neuron)

Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.



100,000,000,000 neurons

100,000,000,000 neurons

x

1,000 synapses per neuron

————————————

100,000,000,000,000 synapses

100,000,000,000 neurons

x

1,000 synapses per neuron

—————————————

100,000,000,000,000 synapses

x

1000 transistors per synapse

—————————————

100,000,000,000,000,000 transistors

100,000,000,000 neurons

x

1,000 synapses per neuron

——————————————

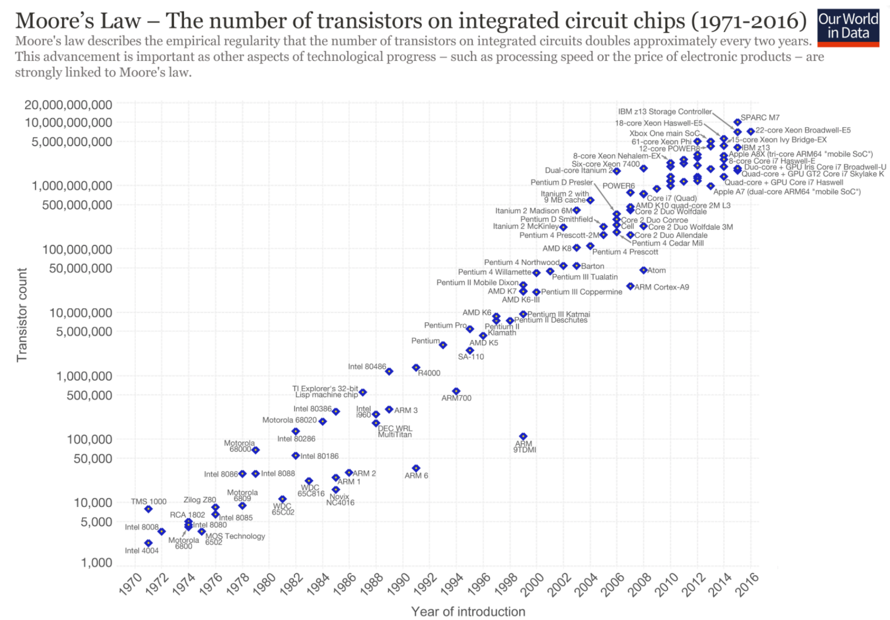
100,000,000,000,000 synapses

x

1000 transistors per synapse

——————————————

100,000,000,000,000,000 transistors



100,000,000,000 neurons

x

1,000 synapses per neuron

——————————————

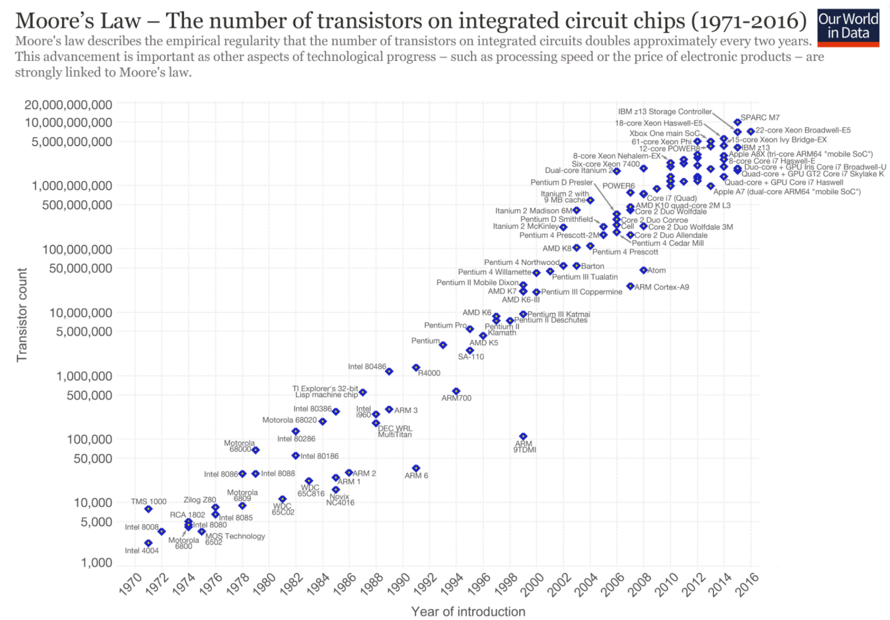
100,000,000,000,000 synapses

x

1000 transistors per synapse

——————————————

100,000,000,000,000,000 transistors



100,000,000,000,000,000 / 10,000,000,000 = 7 orders of magnitude

(about the difference between chips
in the 1970s and chips today)

(brain is also many orders of magnitude
more efficient in its energy consumption)

Titan supercomputer at Oak Ridge (Tennessee)

was most powerful supercomputer in US
(currently seventh most powerful in the world)

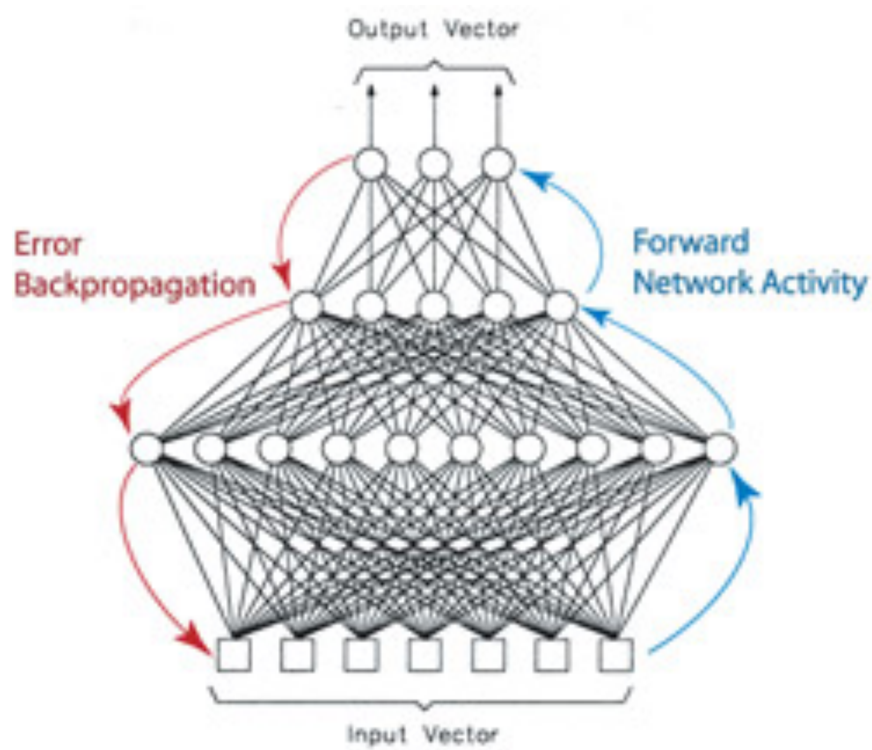
18,688 Titan K20x GPUs
each K20x has 2688 processing cores
each K20x has 7.1B transistors

still several orders of magnitude smaller
than processing in the human brain

autonomous vehicles
(NavLab) circa 1986

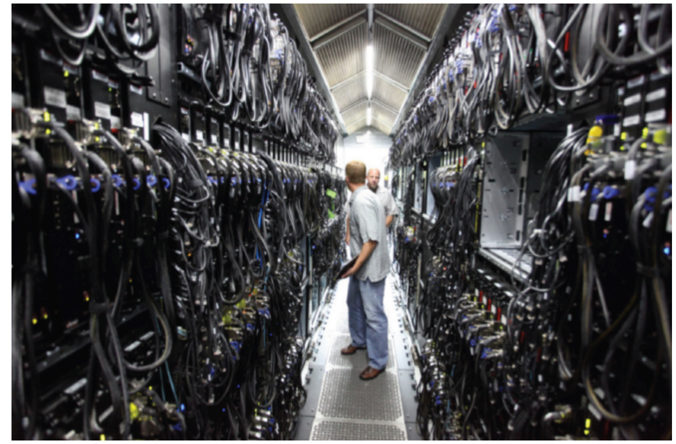
packed with top-end workstations

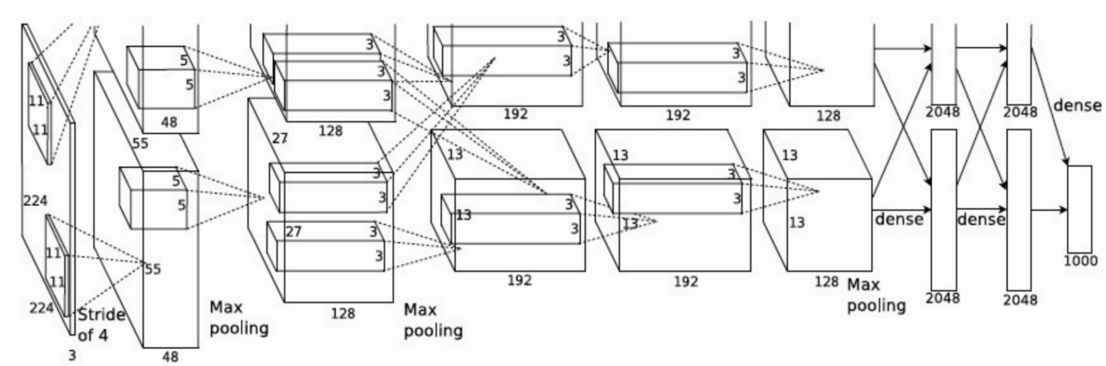
orders of magnitude less processing capacity than an Apple Watch



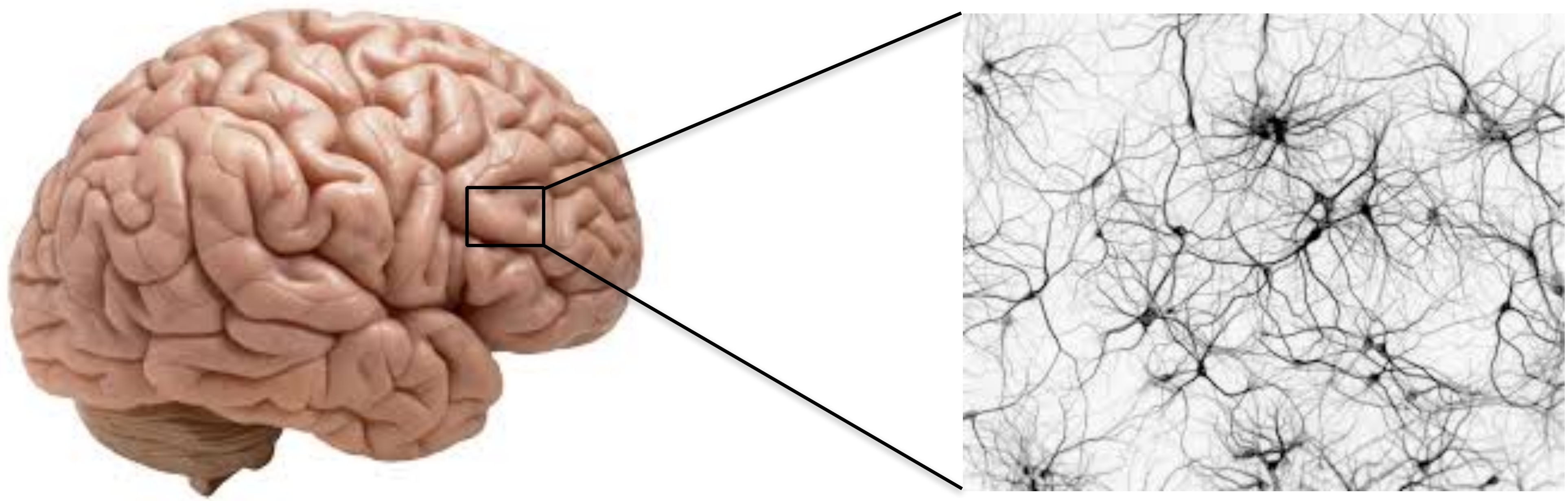
neural network models
circa 1986

Uber self-driving car
circa 2016

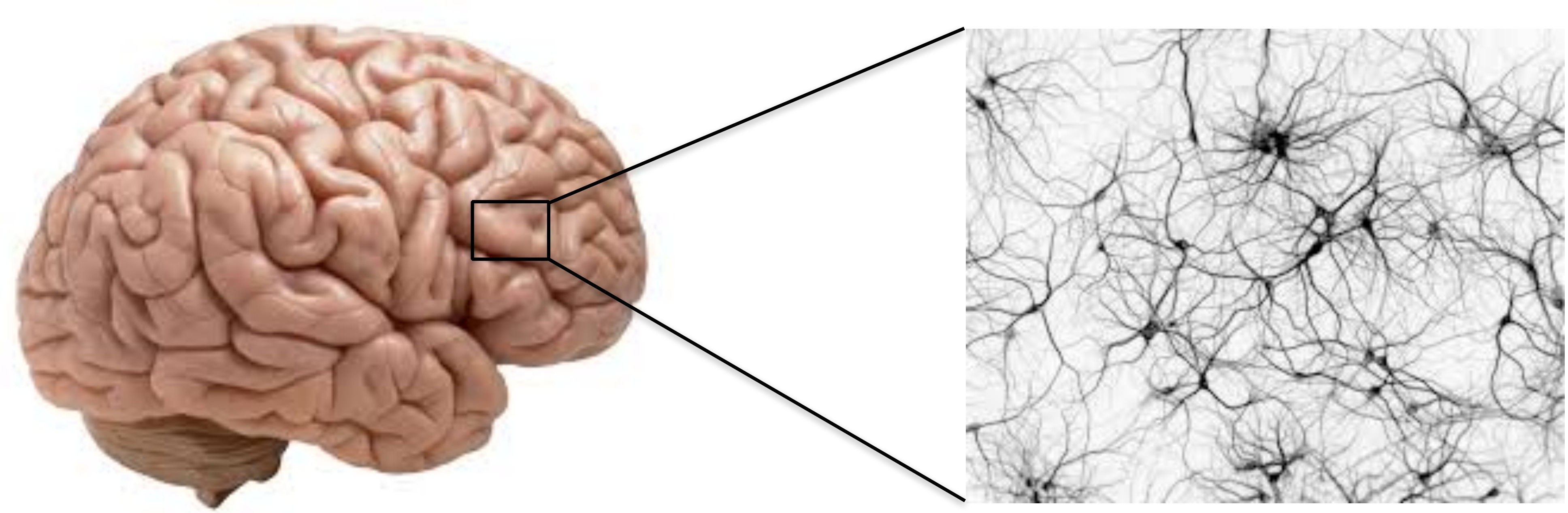




deep learning networks
circa 2016



It is not just the sheer scale (number of neurons, number of synapses) that makes the brain so complex - after all, any large physical model of a material could well have as many elements - it is the complex **connectivity** giving rise to our ability to perceive, remember, think, decide, act, and feel and how this connectivity changes and adapts via **learning** that is only slowly being revealed and understood and that may not be able to be engineered directly.



And even if you could replace every neuron and synapse with its equivalent in electronics and replicate every connection perfectly, creating a perfect simulacrum in silicon, we would not truly understand how the brain works.

It would be a tremendous engineering feat to be sure. But science aims to understand and explain why and how things work.

Given this most complex structure in the known universe, what are some ways that psychologists, biologists, and neuroscientists turn the problem of understanding how the brain works into something tractable?

Divide and Conquer Strategy - The Brain has Parts

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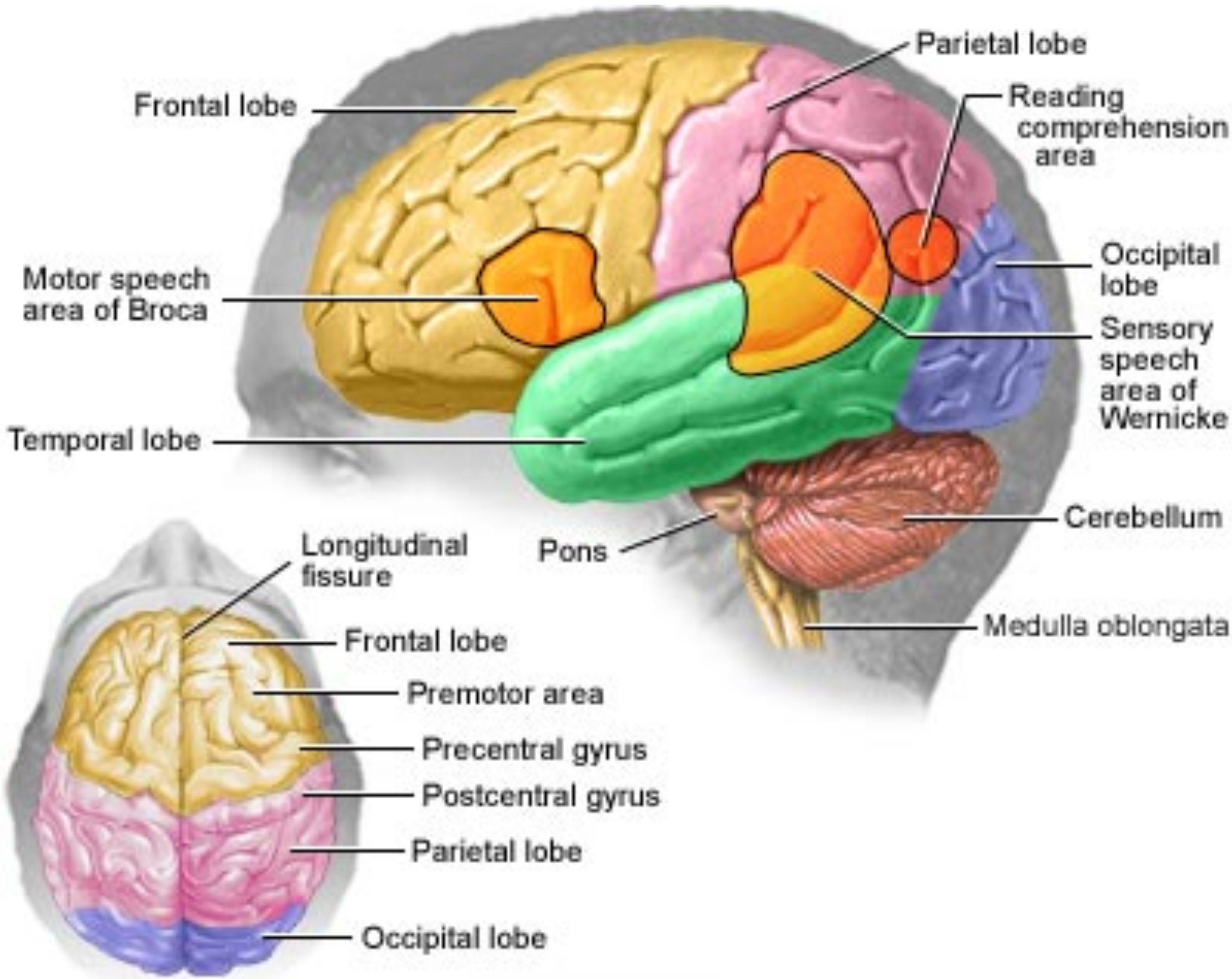
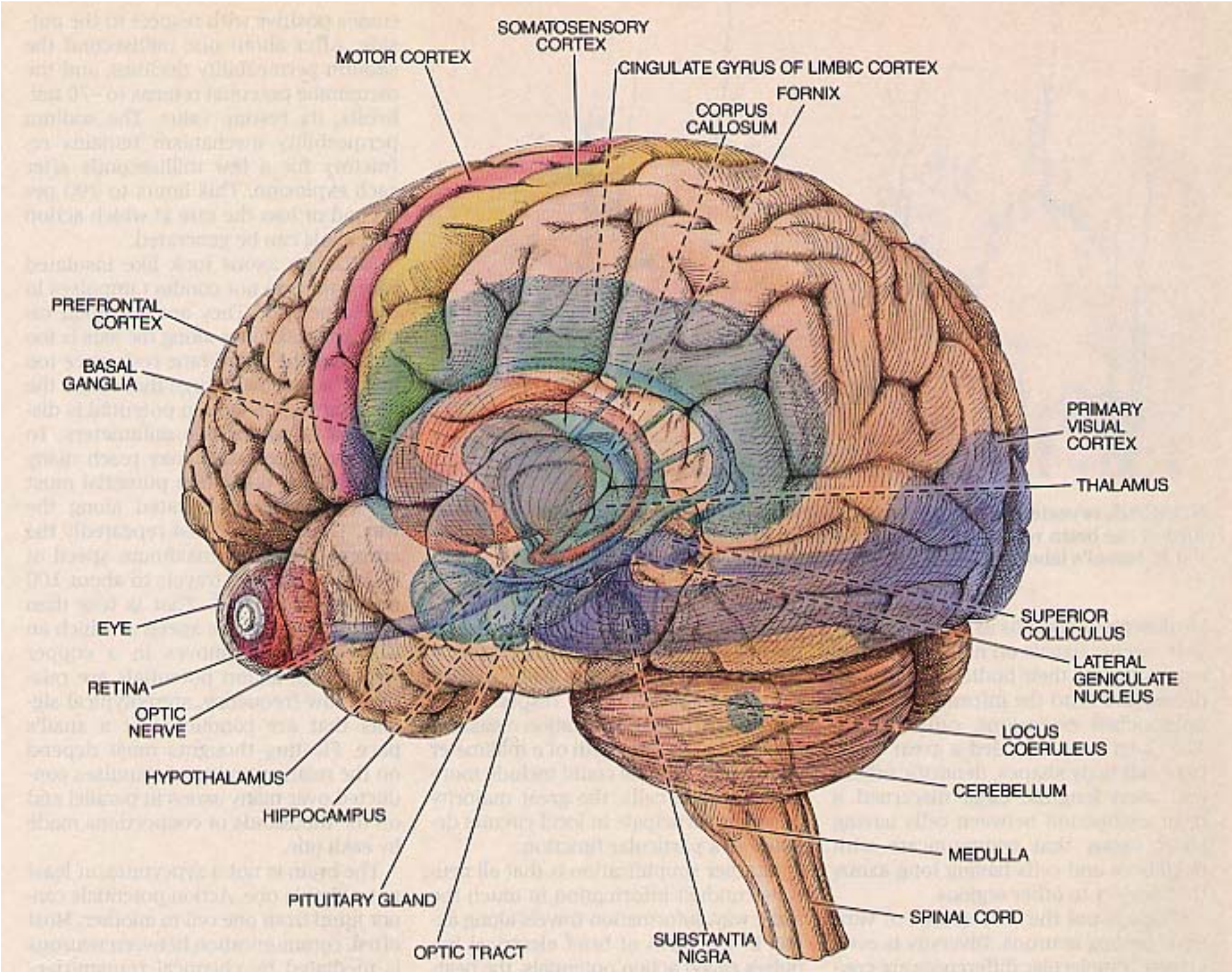


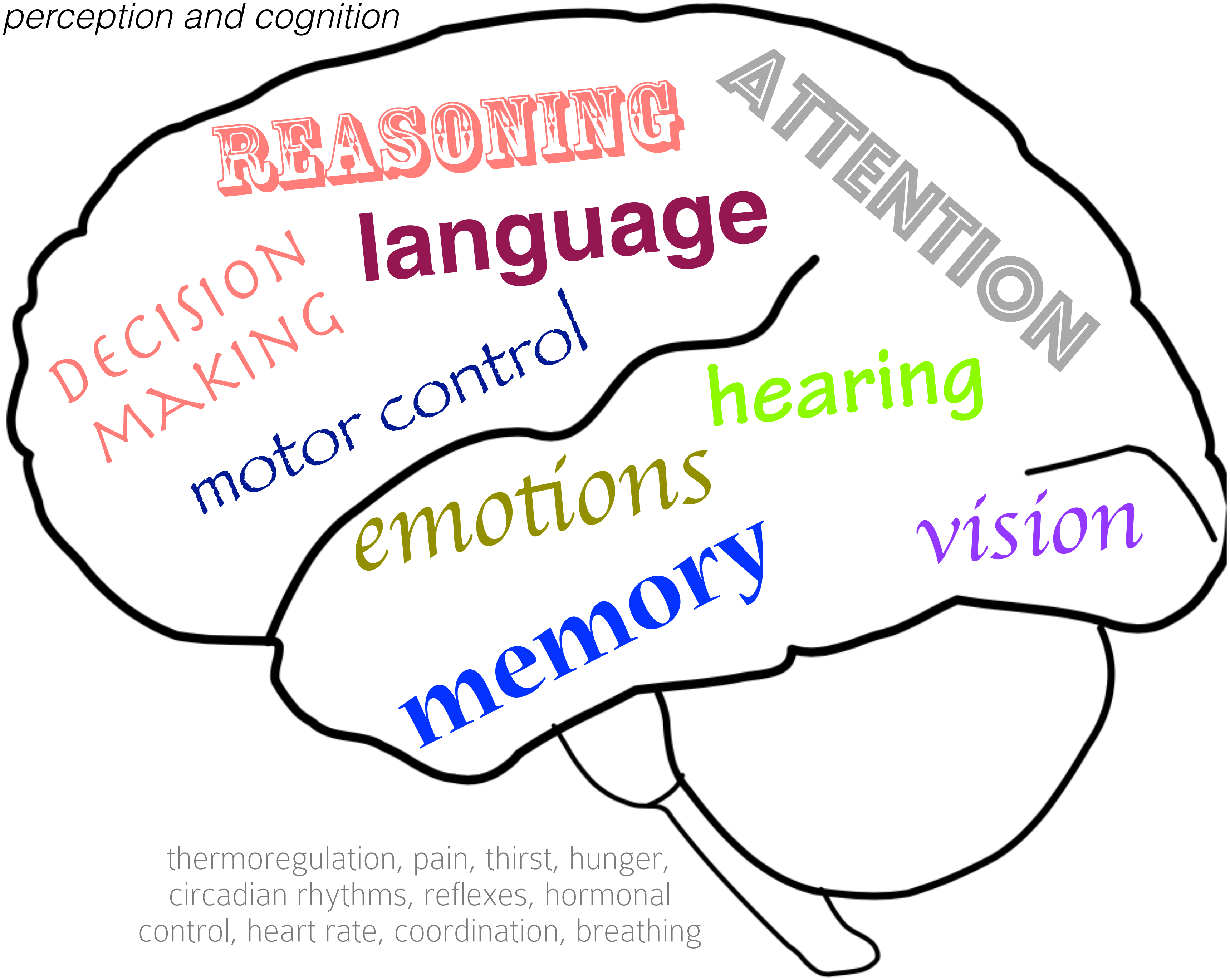
Divide and Conquer Strategy - The Brain has Parts



Divide and Conquer Strategy - Different Aspects of Mental Life

Divide and Conquer Strategy - Different Aspects of Mental Life

in this class, we will focus on examples from perception and cognition



At What Physical Levels of Analysis to Model?

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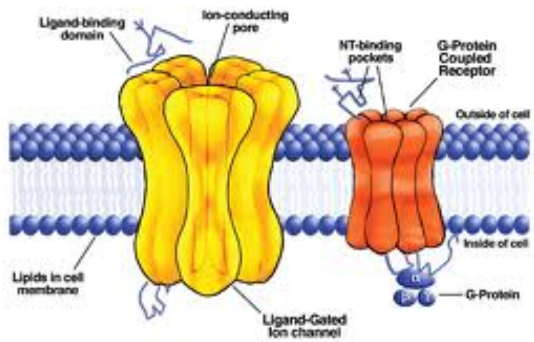
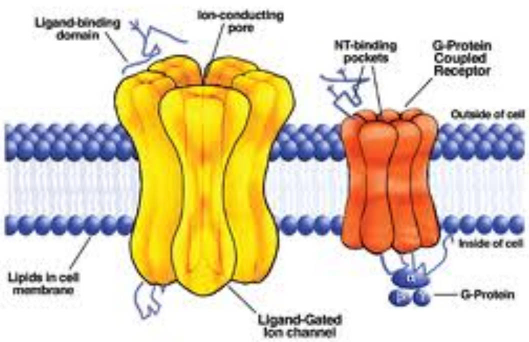


models of ion channels

At What Physical Levels of Analysis to Model?



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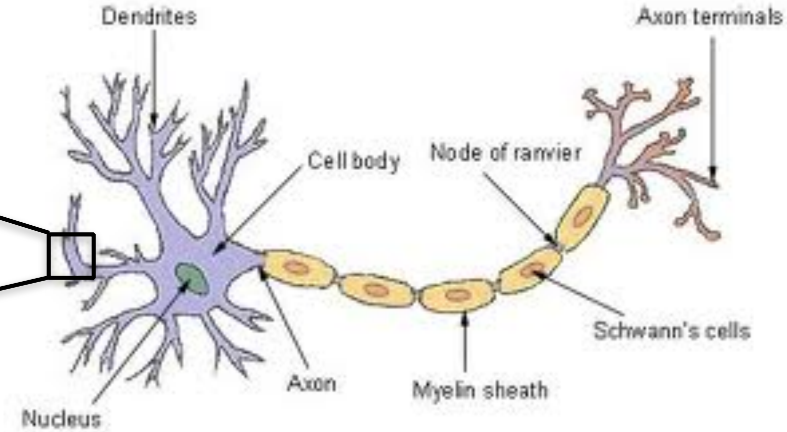

detailed models of a neuron

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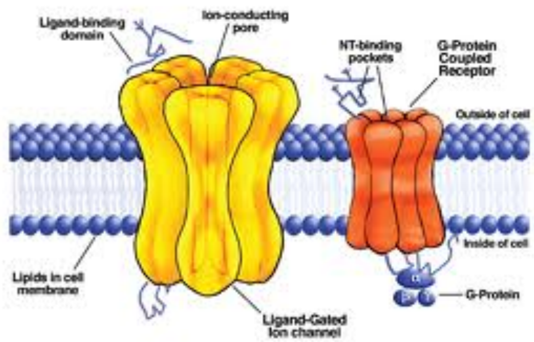

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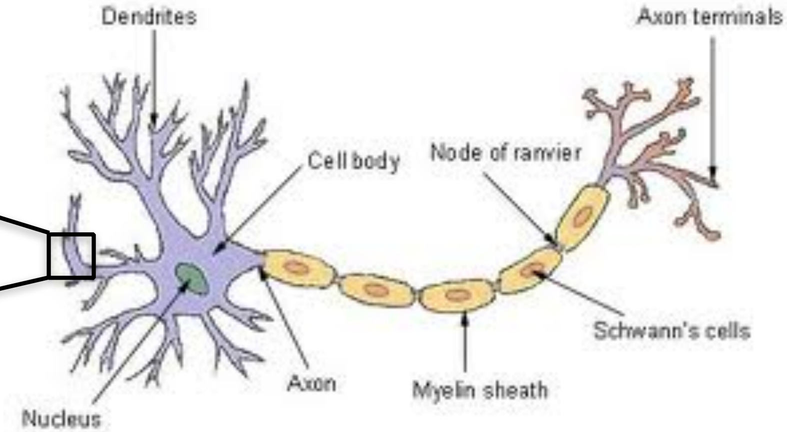

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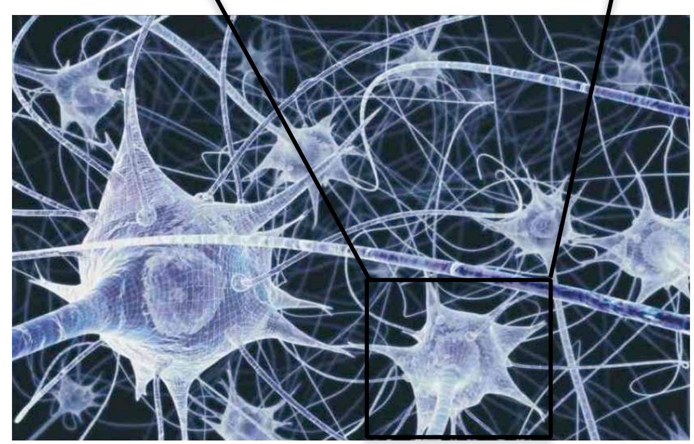

models of neural circuits

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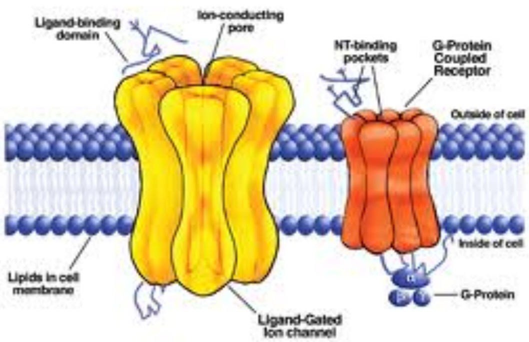
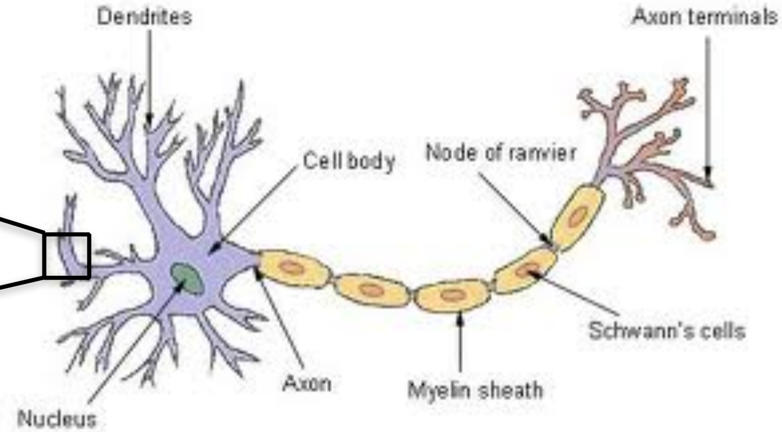
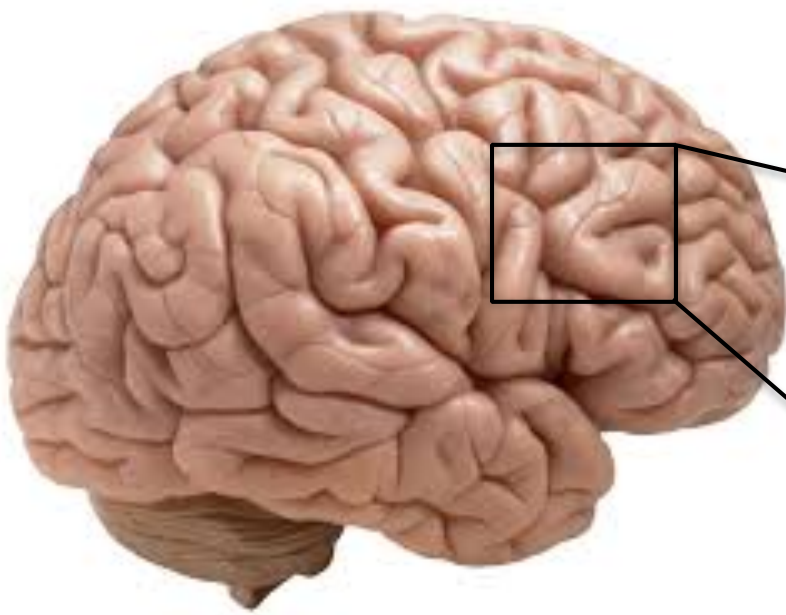
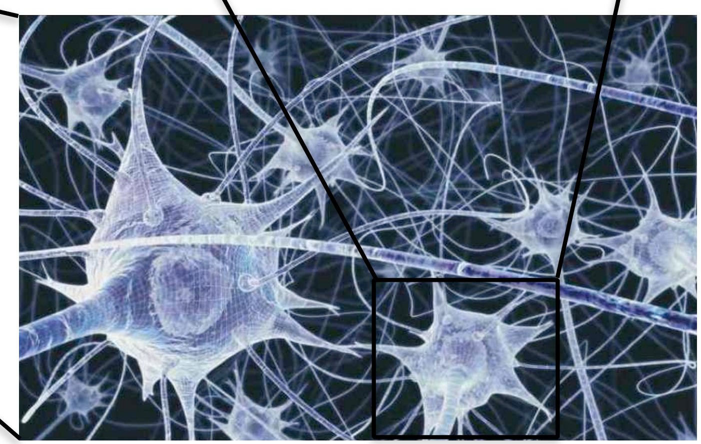




models of ion channels

detailed models of a neuron





models of brain circuits

models of neural circuits

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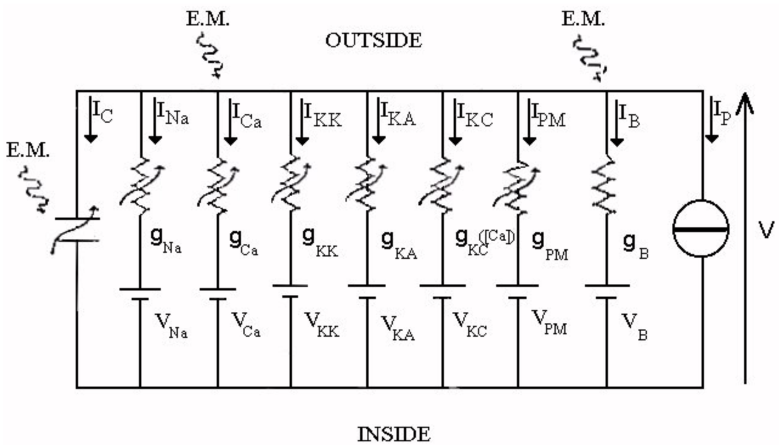
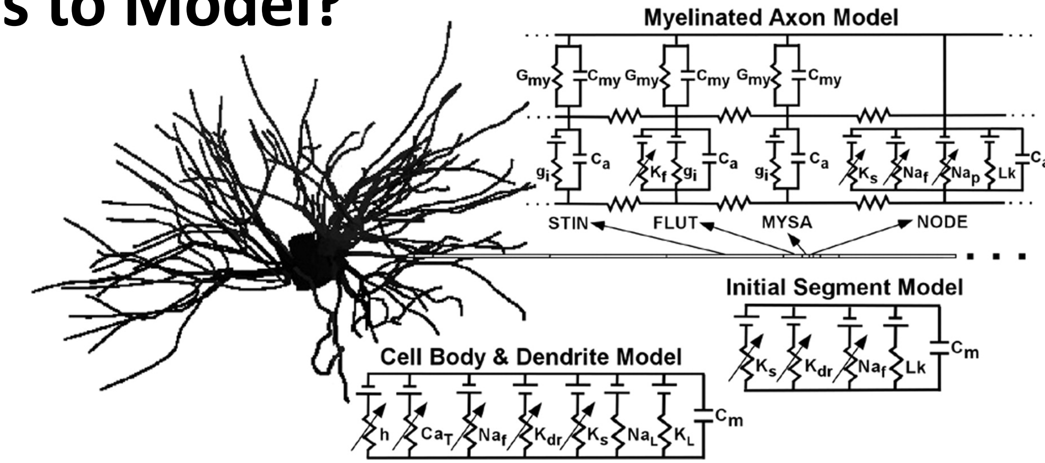
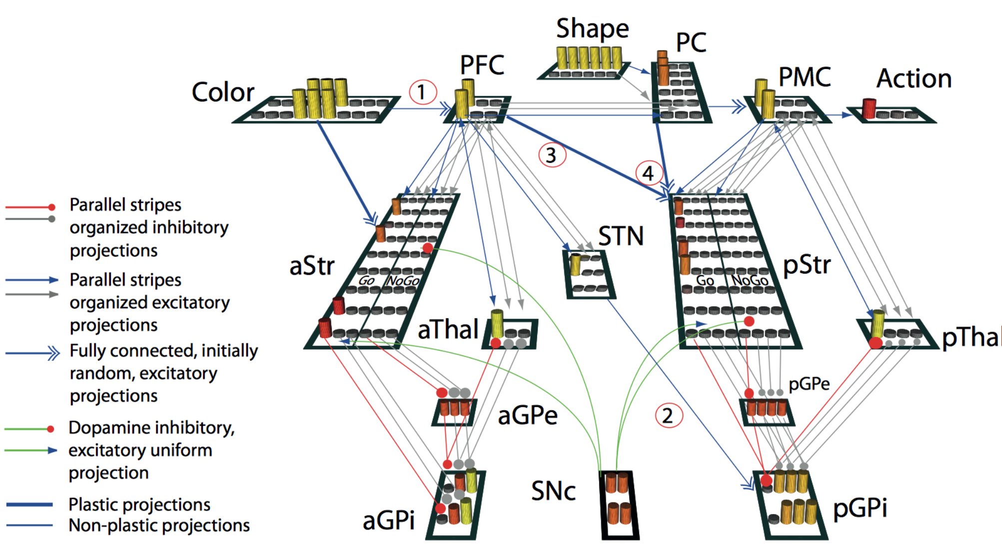


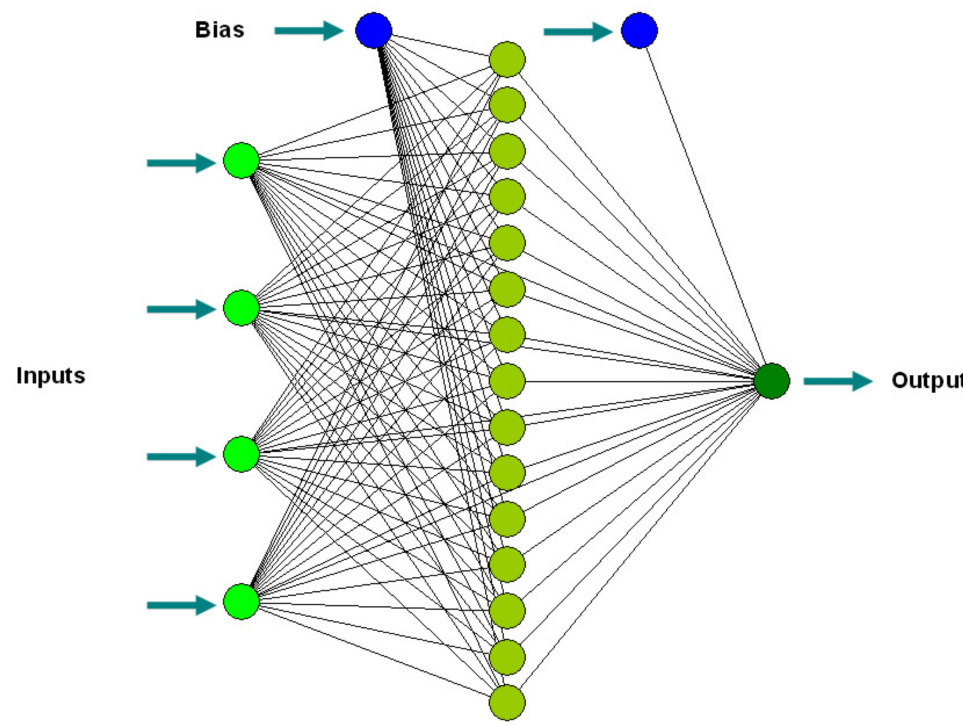
models of ion channels



detailed models of a neuron



models of brain circuits



models of neural circuits

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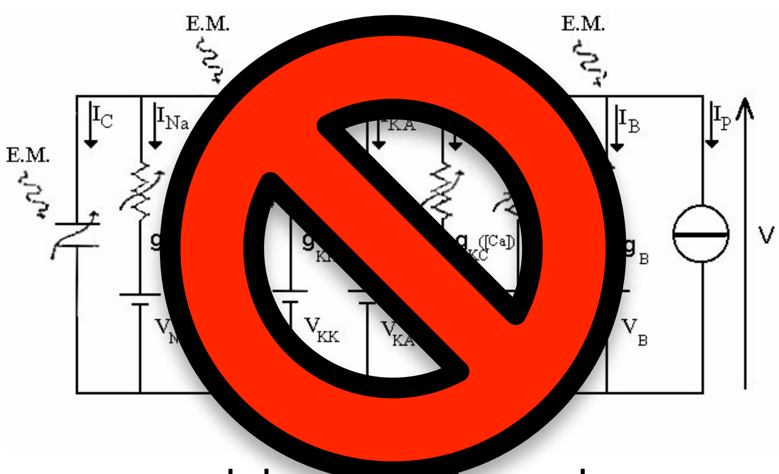

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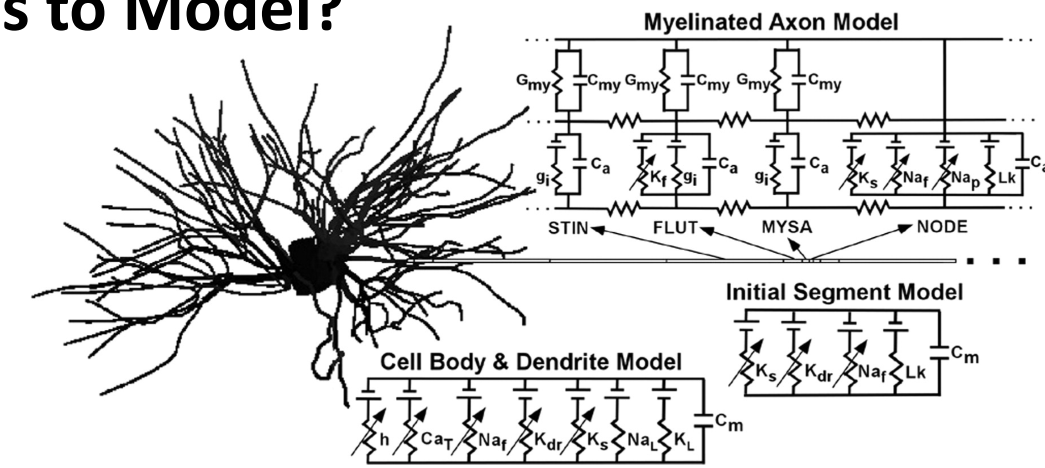

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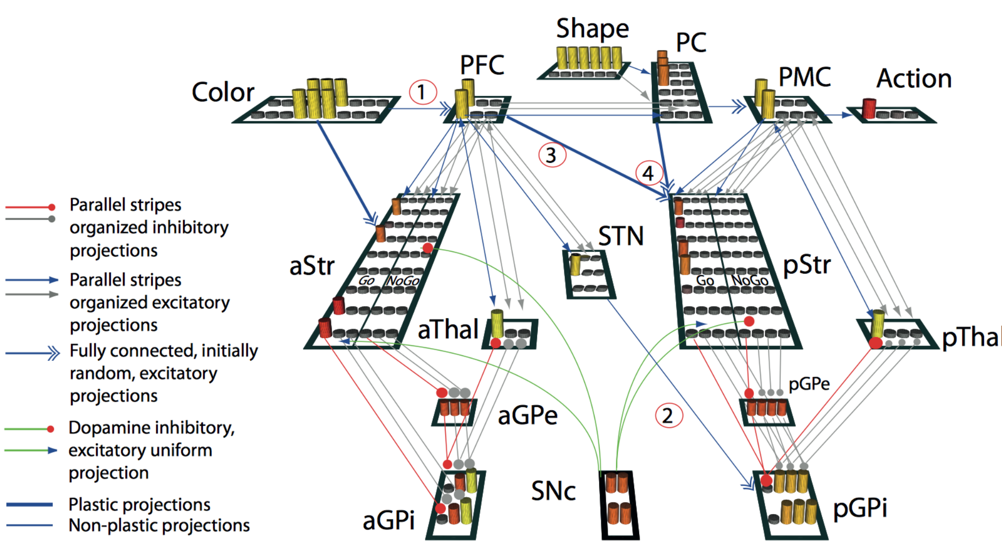
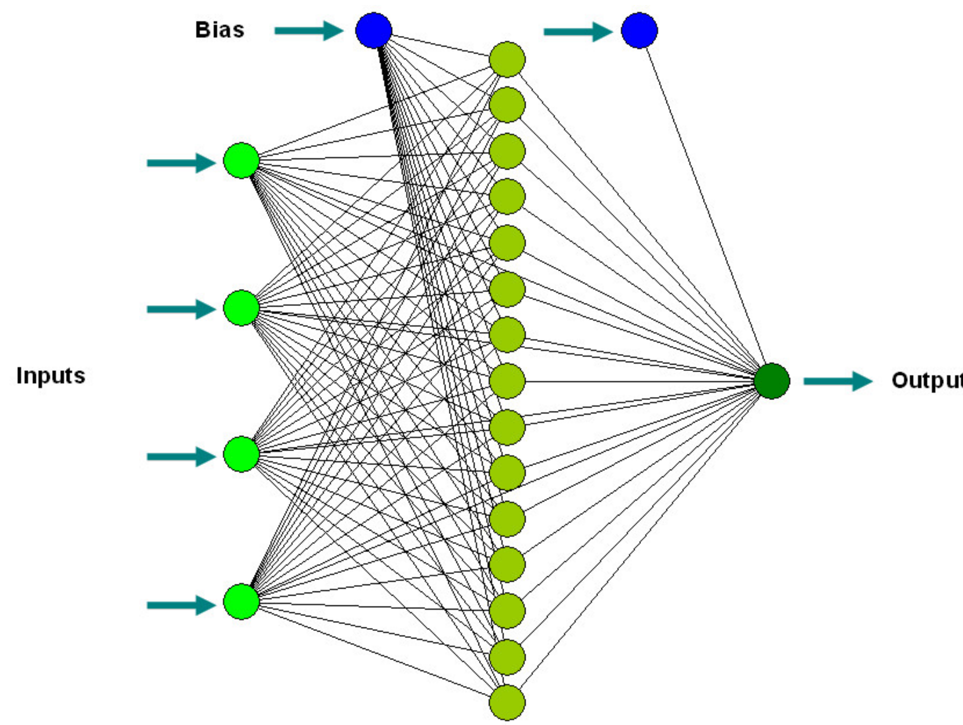


models of brain circuits



models of neural circuits

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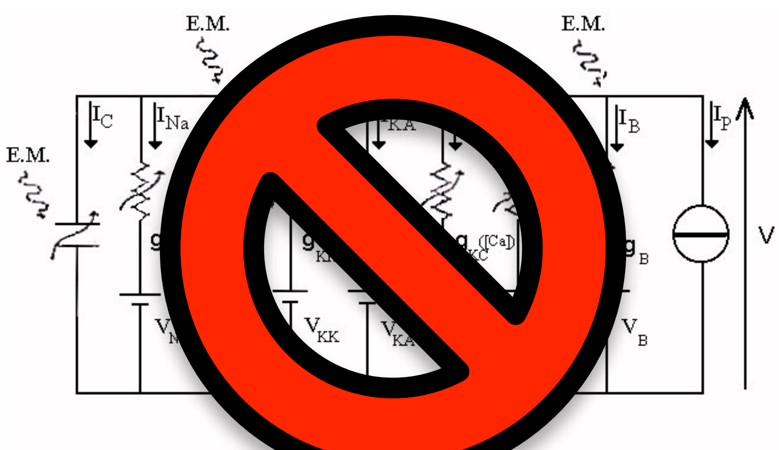
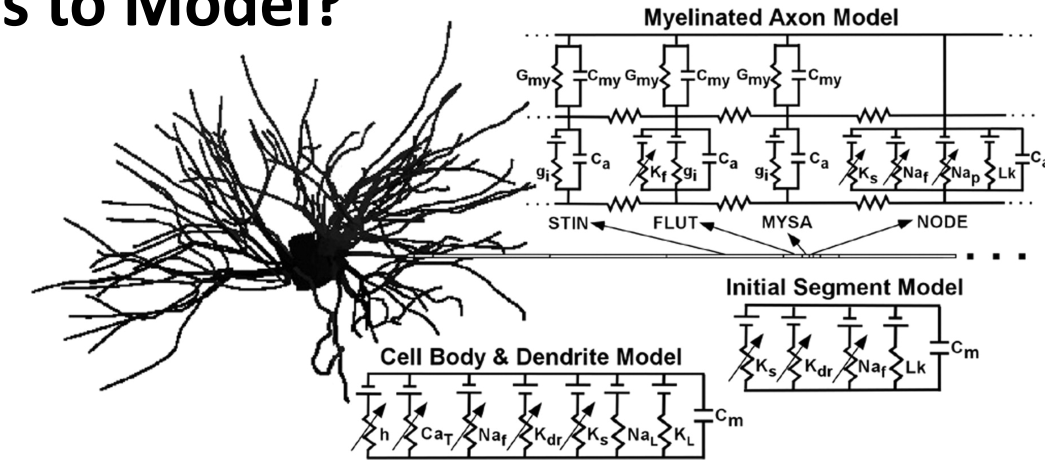
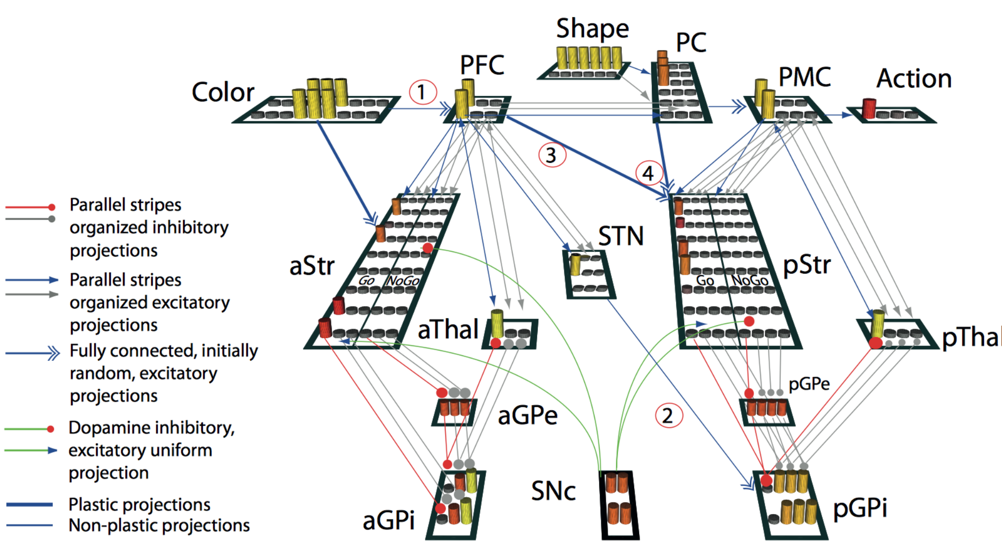


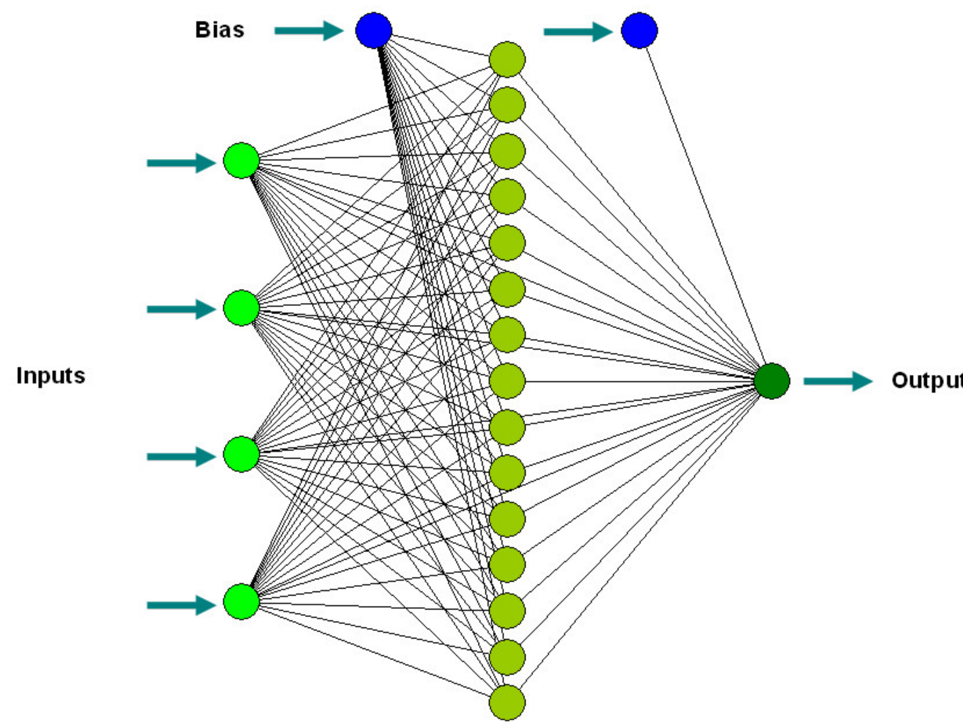
models of ion channels



detailed models of a neuron



models of brain circuits



models of neural circuits

At What Conceptual Levels of Analysis to Model?

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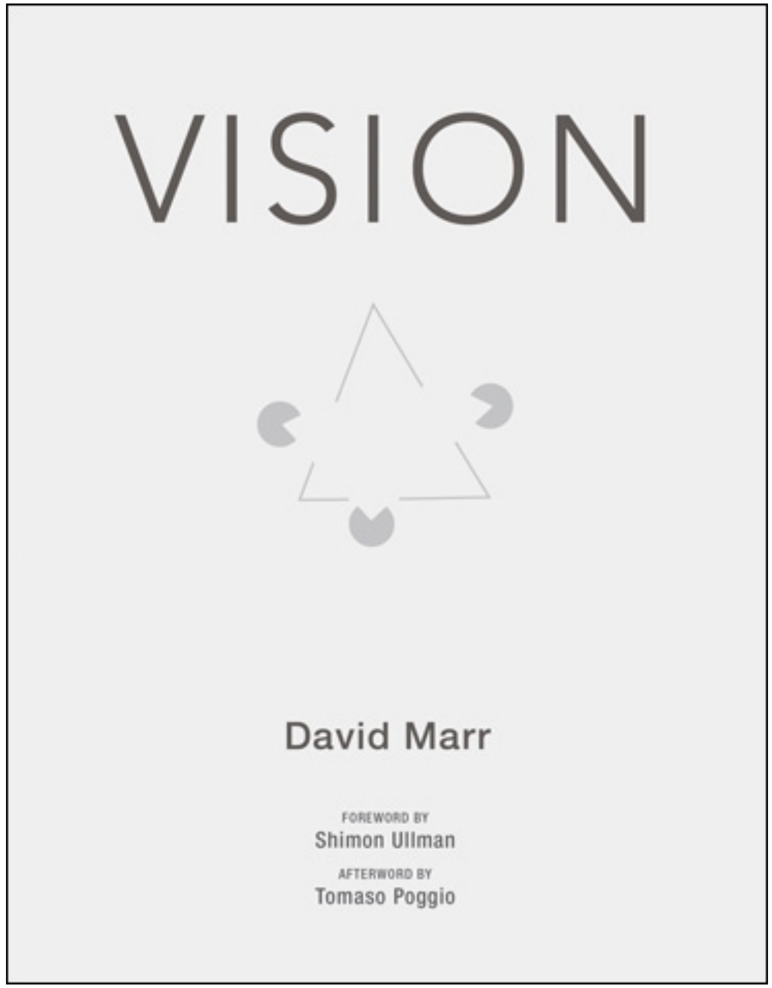


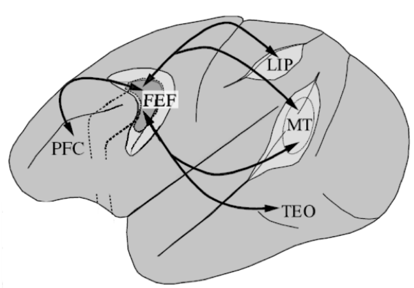
Vision: A Computational Investigation into the Human Representation and Processing of Visual Information
By David Marr
1980, MIT Press

At What Conceptual Levels of Analysis to Model?

(yet another sense of "computational")

Computational Level

Algorithmic/ Representational Level



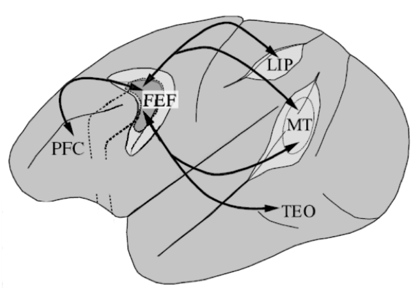
Implementation/ Biophysical Level

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level

Marr's Three Levels of Analysis

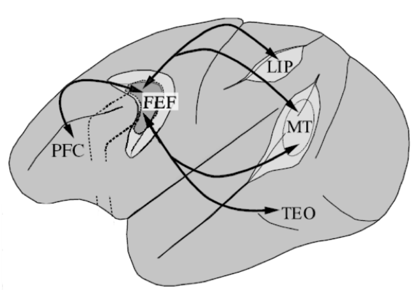


Implementation/ Biophysical Level

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level



Implementation/ Biophysical Level

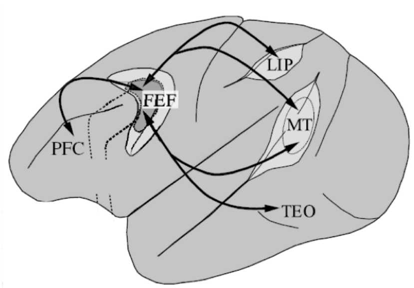
how mechanisms are physically realized within a biological substrate (neurons and their connections)

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level

what kinds of representations and computations are performed



Implementation/ Biophysical Level

how mechanisms are physically realized within a biological substrate (neurons and their connections)

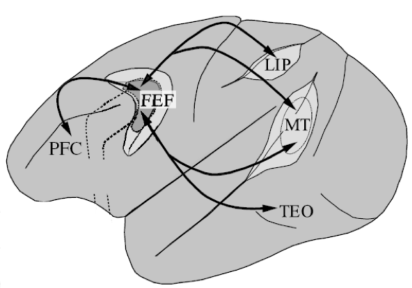
At What Conceptual Levels of Analysis to Model?

Computational Level

what are the goals of the organism
what is optimal for survival

Algorithmic/ Representational Level

what kinds of representations and computations are performed



Implementation/ Biophysical Level

how mechanisms are physically realized within a biological substrate (neurons and their connections)

At What Conceptual Levels of Analysis to Model?

Computational Level

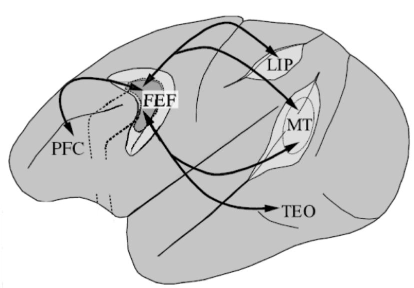
NORMATIVE

what are the goals of the organism
what is optimal for survival

Algorithmic/ Representational Level

SOFTWARE

what kinds of representations and computations are performed



Implementation/ Biophysical Level

HARDWARE

how mechanisms are physically realized within a biological substrate (neurons and their connections)