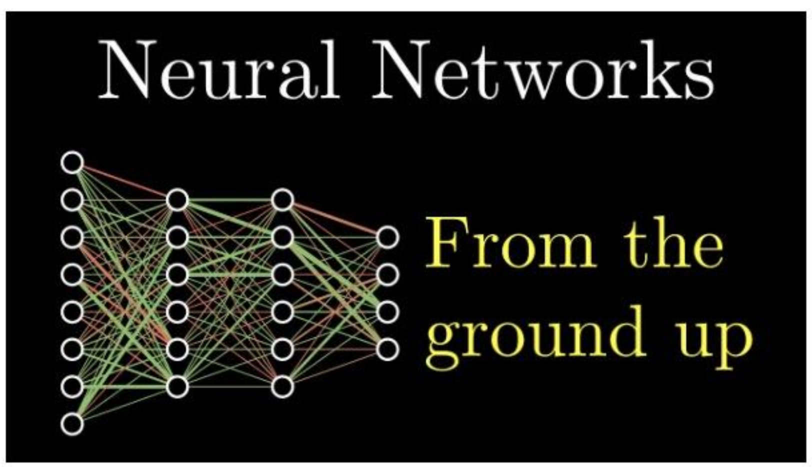
on Brightspace

Readings (on Brightspace)
(for today/Thursday) Chapter 3 (selected pages) of Churchland, P.S., & Sejnowski, T.J. (2017). *The Computational Brain* (25th Anniversary Edition). MIT Press.

Required Video (link on Brightspace)
(for today) *But What *is* a Neural Network?*
by 3blue1brown, Grant Sanderson



Homework 1 (on Brightspace)
Due today

Homework 2 (on Brightspace, in today's slides)
Due Tue Sep 13

on Brightspace

More on Numpy and Numeric Types in Python (on Brightspace)

`MoreNumpyExamples.ipynb`
`NumpyNumericTypes.pdf`

REMINDER: Other Jupyter Notebooks about Python (on Brightspace)

`JupyterNotebooks.ipynb`
`VariablesAndTypes.ipynb`
`ListsAndTuples.ipynb`
`NumpyArrays.ipynb`
`VectorMatrixAlgebra.ipynb`
`ControlFlow.ipynb`
`Functions.ipynb`
`Matplotlib.ipynb`

Homework 2 (due Tue Sep 13)

Homework2.pdf on Brightspace

- using Jupyter notebooks (markdown and code cells)

- basic numpy and matplotlib operations in Python

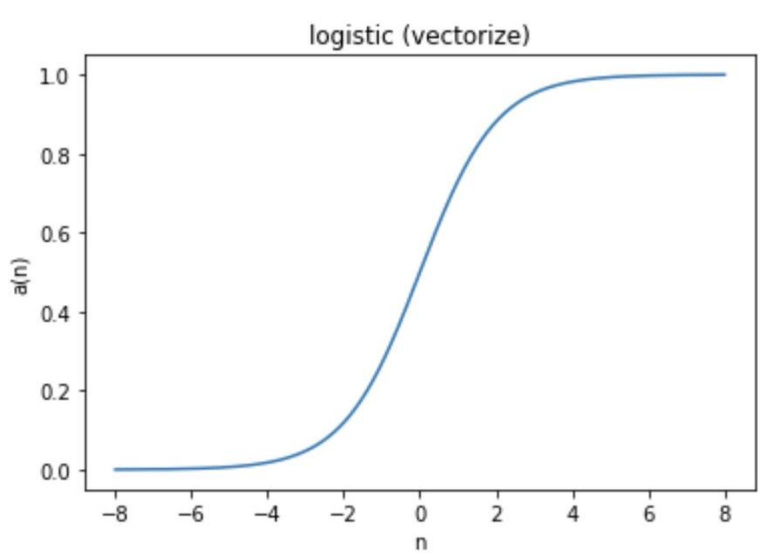
- for loops and "vectorized" calculations with numpy arrays

- basic plotting with matplotlib

- "activation functions" that we will talk about this week (you don't need to know what they are to evaluate them and to plot them)

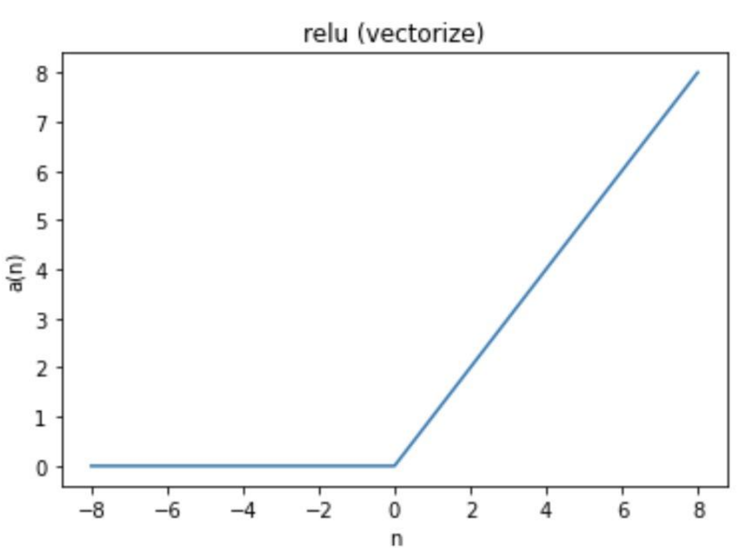
logistic

$$a(n) = \frac{1}{1+\exp(-n)} = \frac{1}{1+e^{-n}}$$



relu (rectified linear unit)

$$a(n) = \begin{cases} n, & n \geq 0 \\ 0, & n < 0 \end{cases}$$



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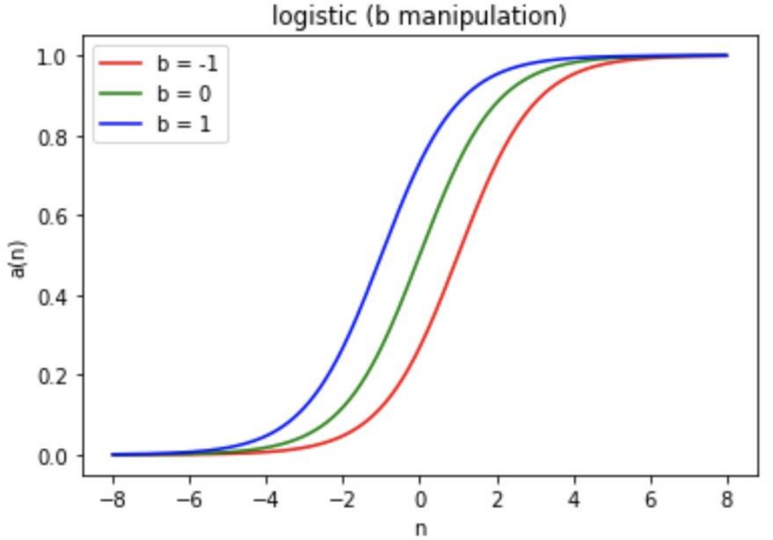
logistic

$$n = wx+b$$



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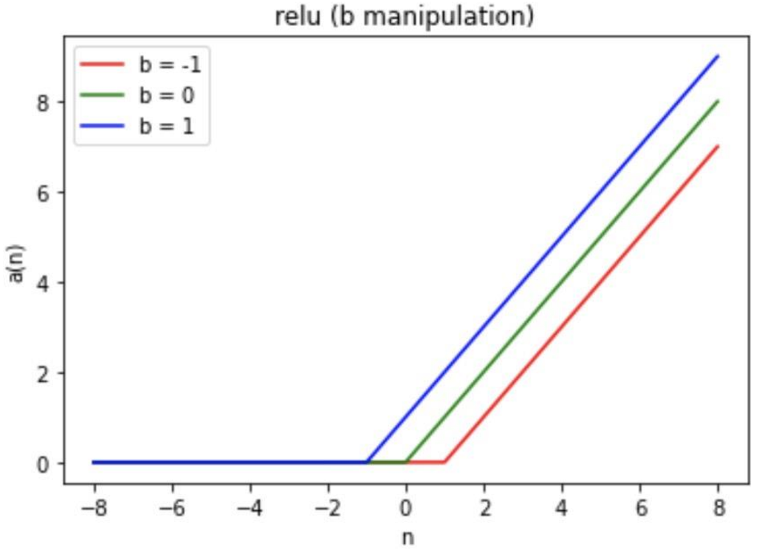


Homework 2 (due Tue Sep 13)

Homework2.pdf on Brightspace

- for loops and "vectorized" calculations with numpy arrays

from Week2a.ipynb

<u>with for loops</u>

```
x = np.linspace(-5.0, 5.0, 1000)
p = np.zeros(len(x))
for i in range(len(x)):
    p[i] = (1/np.sqrt(2*np.pi*(s**2))) * np.exp(-((x[i]-m)**2)/(2*(s**2)))
```

<u>"vectorized" (without for loops)</u>

```
x = np.linspace(-5.0, 5.0, 1000)
p = (1/np.sqrt(2*np.pi*(s**2))) * np.exp(-((x-m)**2)/(2*(s**2)))
```

make sure you review these Jupyter Notebooks:

`NumpyArrays.ipynb`

`Matplotlib.ipynb`

and play around with coding yourself until you understand

Modeling the Brain

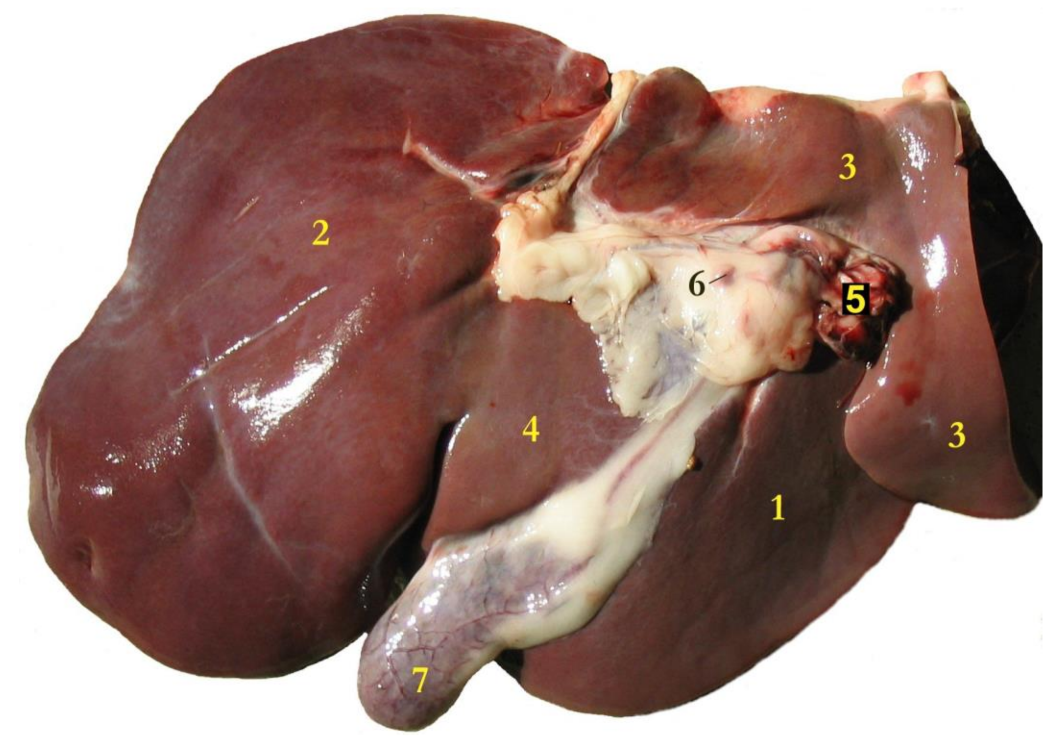
Creating a Model of the Brain

figures from Ploch et al. (2016) - Stanford Mechanical Engineering

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 3D structure only to the extent that structure informs function (e.g., how physical distance might impact connectivity between brain areas).
- 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 predictions can be expressed directly by a mathematical equation (direct solution or numeric solution).
- **Simulation**: Complex models whose predictions (its properties, how it changes, how it responds) can only be understood by "running" it on a computer (or in a physical representation) - described mathematically and computationally, but predictions (its solution, how it operates) can only be simulated.

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 [often expressed in terms of mathematics, logic, or computations]; 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"?

Two Senses:

one sense is in using computers as a research tool in modeling and simulating complex systems, in the same sense of "computational economics", "computational humanities", "computational mechanics", "computational fluid dynamics", "computational chemistry", or "computational physics" (all of which are courses at Vanderbilt)

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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?

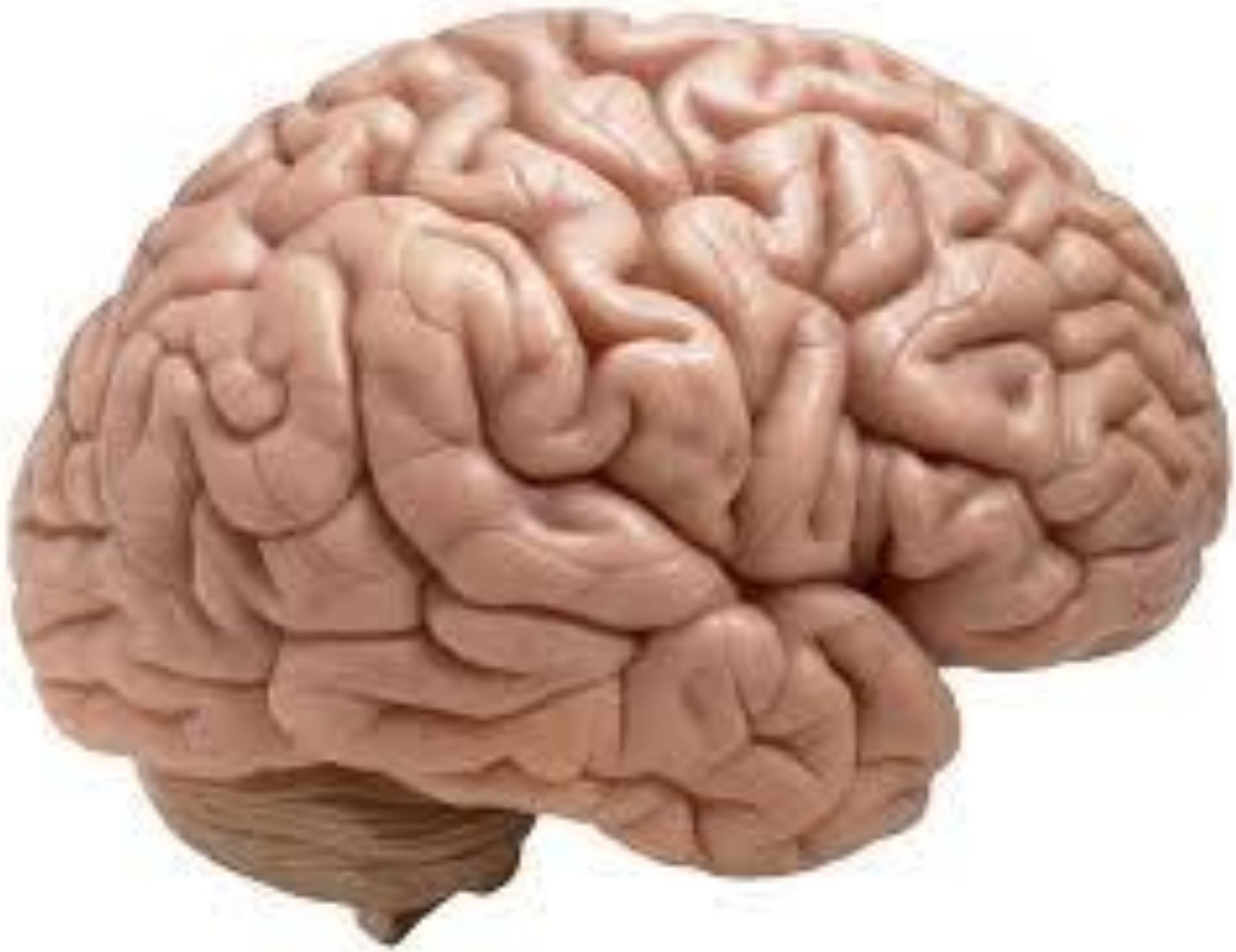
“Formal [mathematical, computational, simulation] theories have a number of advantages [...] They force the theorist to be explicit, so that assumptions are publicly accessible and the reliability of derivations can be confirmed […] [Furthermore] to have one’s hunches about how a simple combination of 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.”

- Doug Hintzman (1990)
(emeritus prof at U. Oregon)

Creating a Model of the Brain

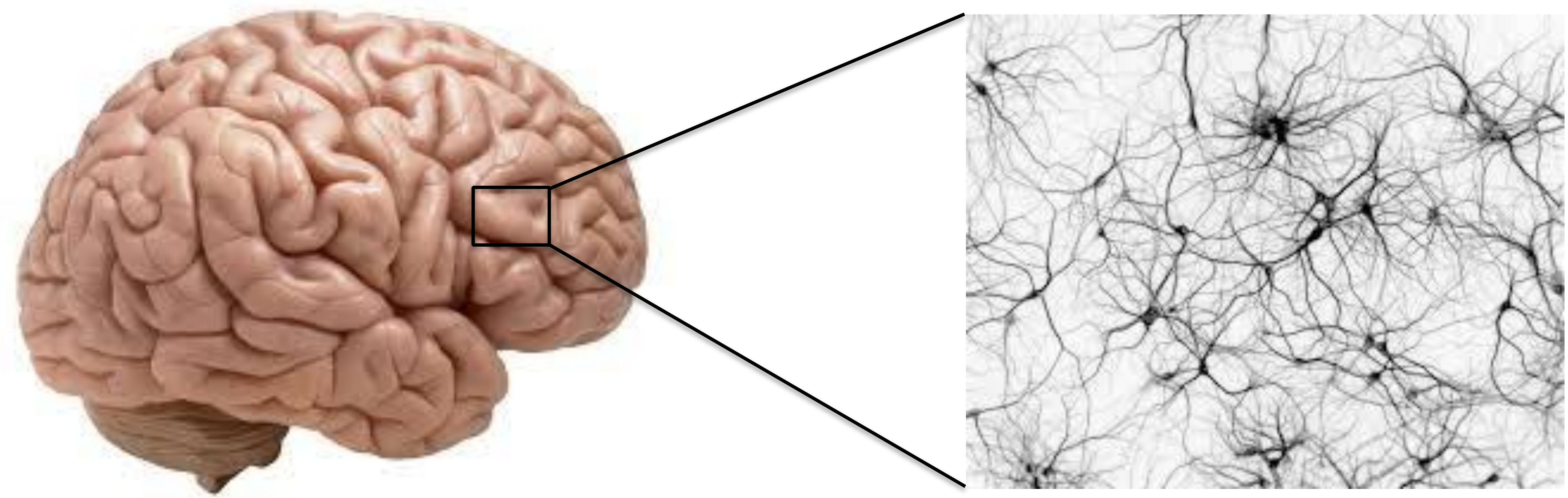
Challenge of Creating a Model of the Brain

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



Human Brain:

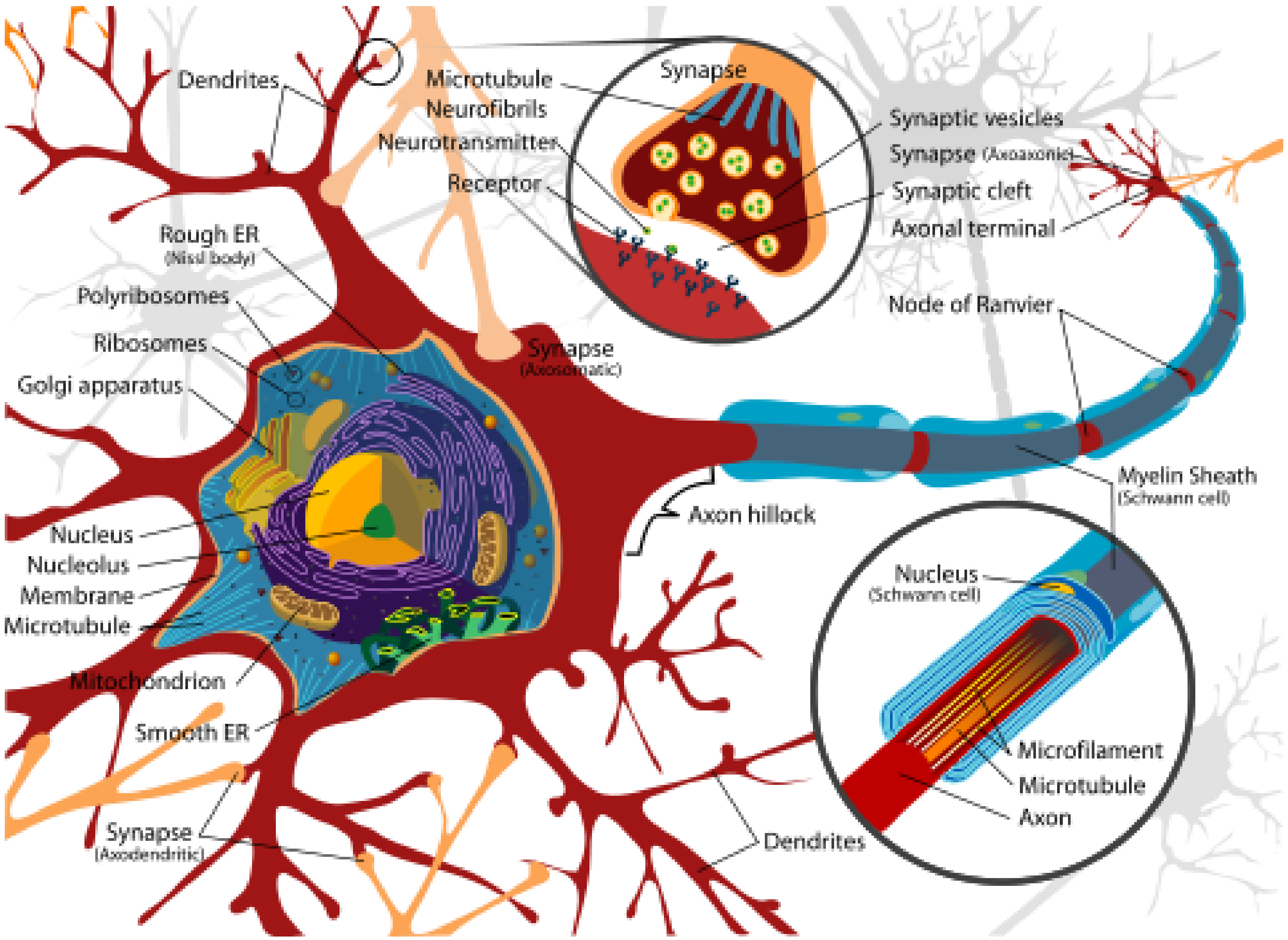
- weighs about 3lbs
- but uses up to 20% of metabolic energy

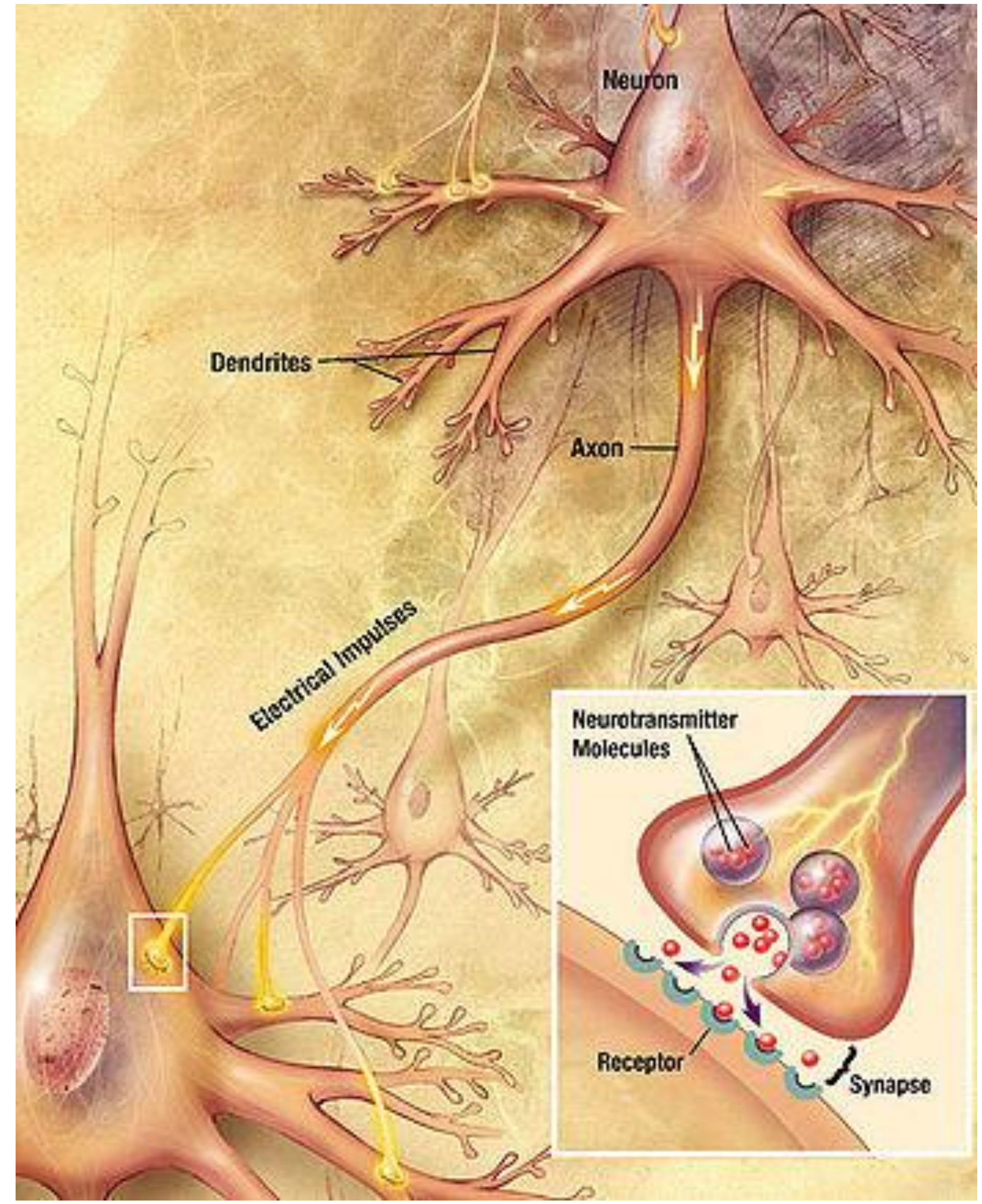


Human Brain:

- estimated between 80-90 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 non-stationary, 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)

What is the scale of brain computations?

What would it take to instantiate that scale on a computer?

100,000,000,000 neurons

100,000,000,000 neurons

x

1,000 synapses per neuron

—————————————

100,000,000,000,000 synapses

What would it take to instantiate that scale on a computer?

brain computing

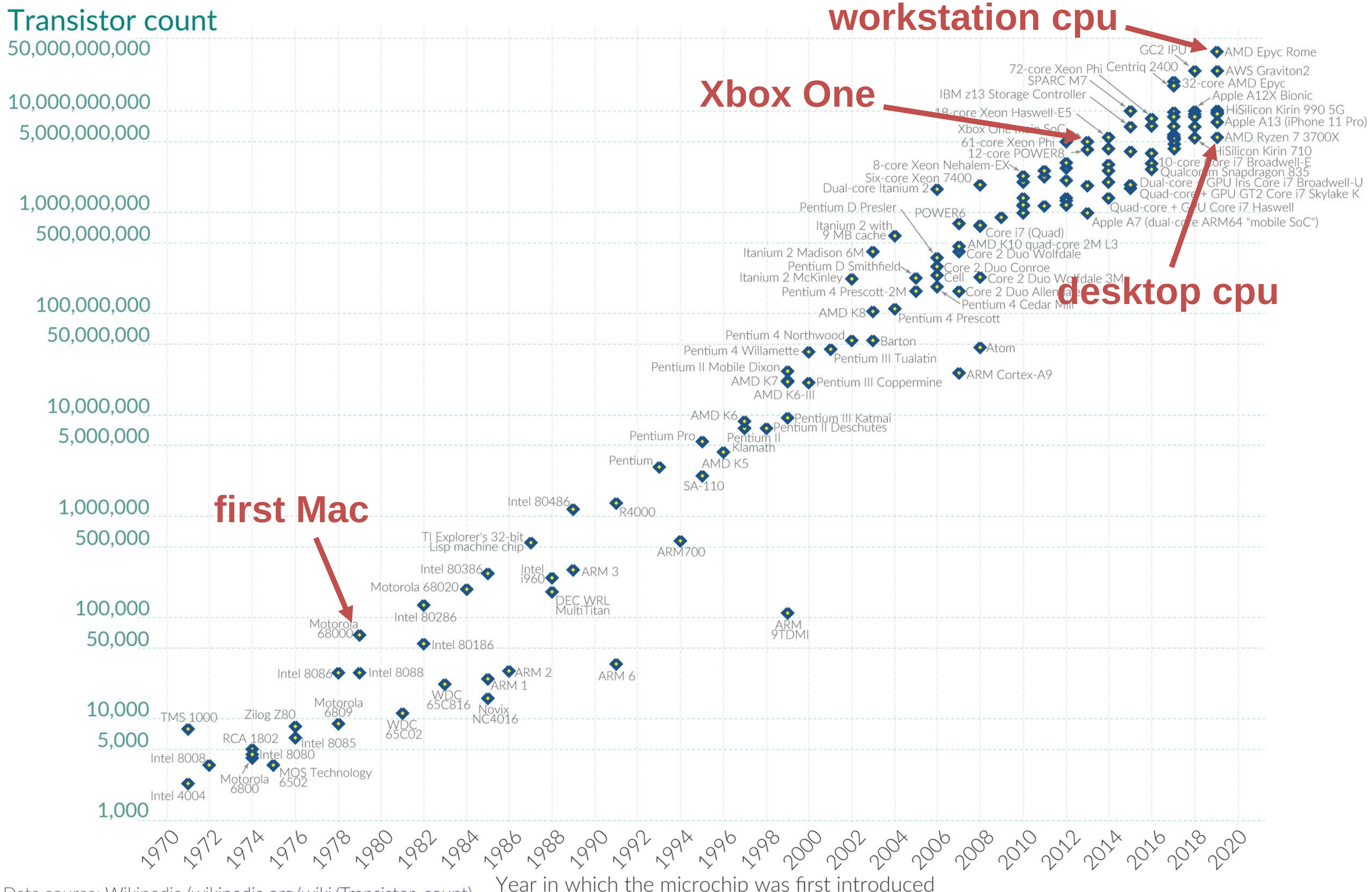
vs.

artificial computing

Moore's Law: The number of transistors on microchips doubles every two years

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 for other aspects of technological progress in computing – such as processing speed or the price of computers.



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

100,000,000,000 neurons

x

1,000 synapses per neuron

—————————————

100,000,000,000,000 synapses

x

1000 transistors per synapse *(back of the envelope underestimate to capture some complexity of synapses)*

—————————————

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

100,000,000,000 neurons

x

1,000 synapses per neuron

—————————————

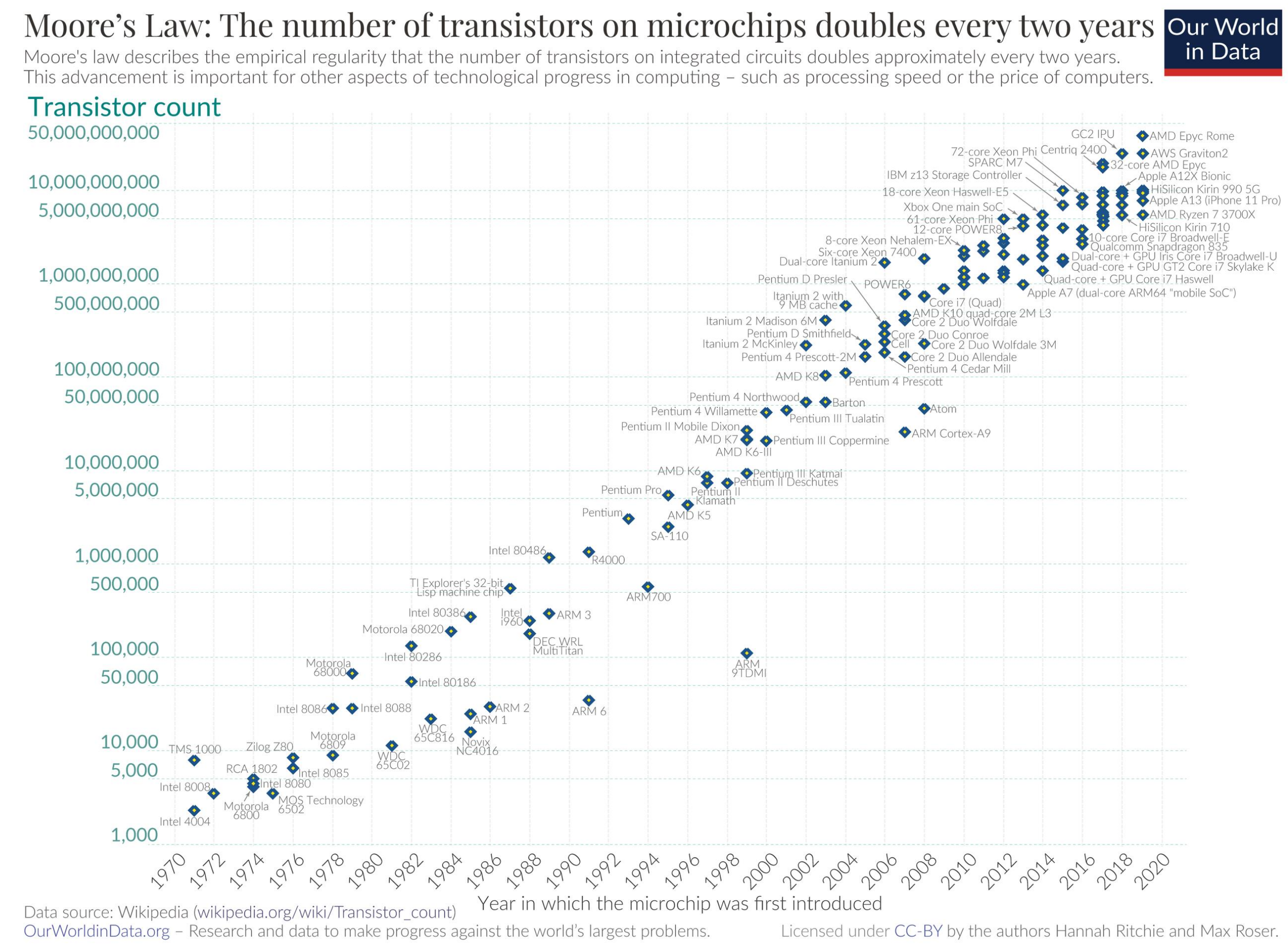
100,000,000,000,000 synapses

x

1000 transistors per synapse

—————————————

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



100,000,000,000,000,000 / 50,000,000,000 = 6-7 orders of magnitude

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

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

Summit supercomputer at Oak Ridge (Tennessee)

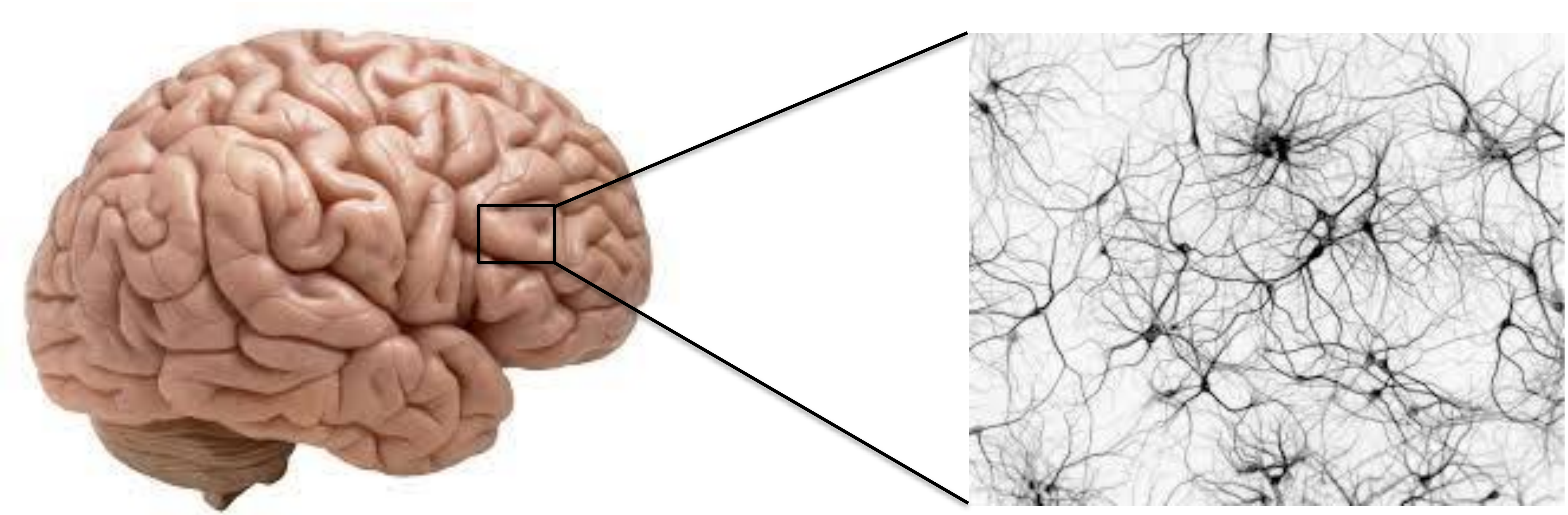
#2 supercomputer in 2021

27,648 NVIDIA V100s GPUs

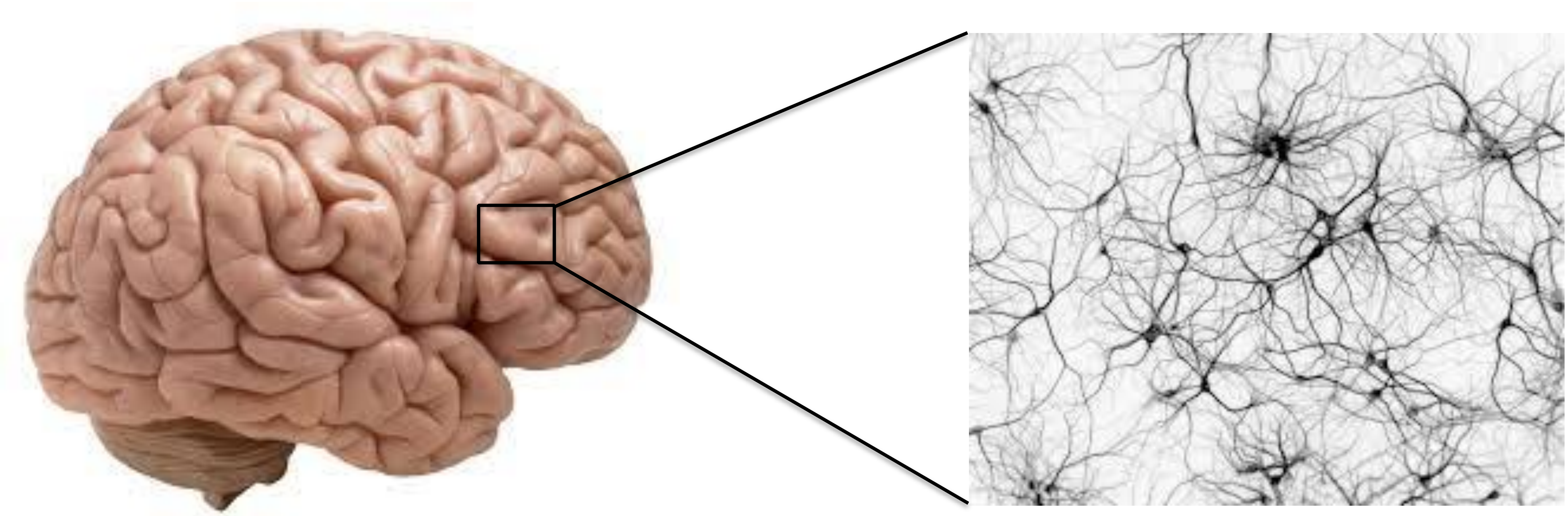
each V100s has 5120 CUDA cores, with 20 billion transistors

still orders of magnitude smaller than number of synapses in the brain

at one order of magnitude increase per decade, it would be 30-40 years before computers reach human "computing" (assuming current technology)

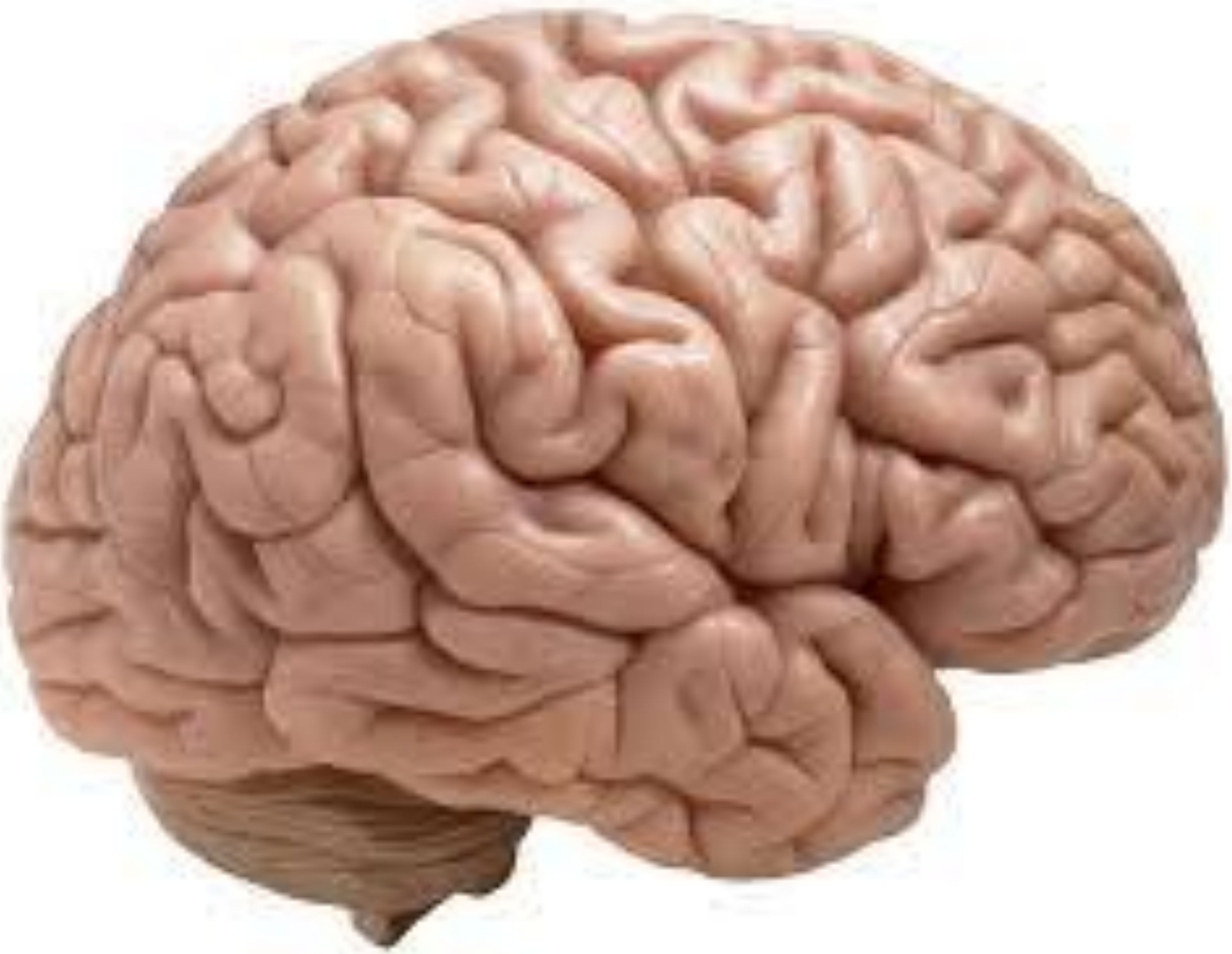


It is not just the sheer scale (number of neurons, number of synapses) that makes the brain so complex - after all, any large physical model of a material could well have as many elements - it is the complex **connectivity** giving rise to our ability to perceive, remember, think, decide, act, and feel 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.

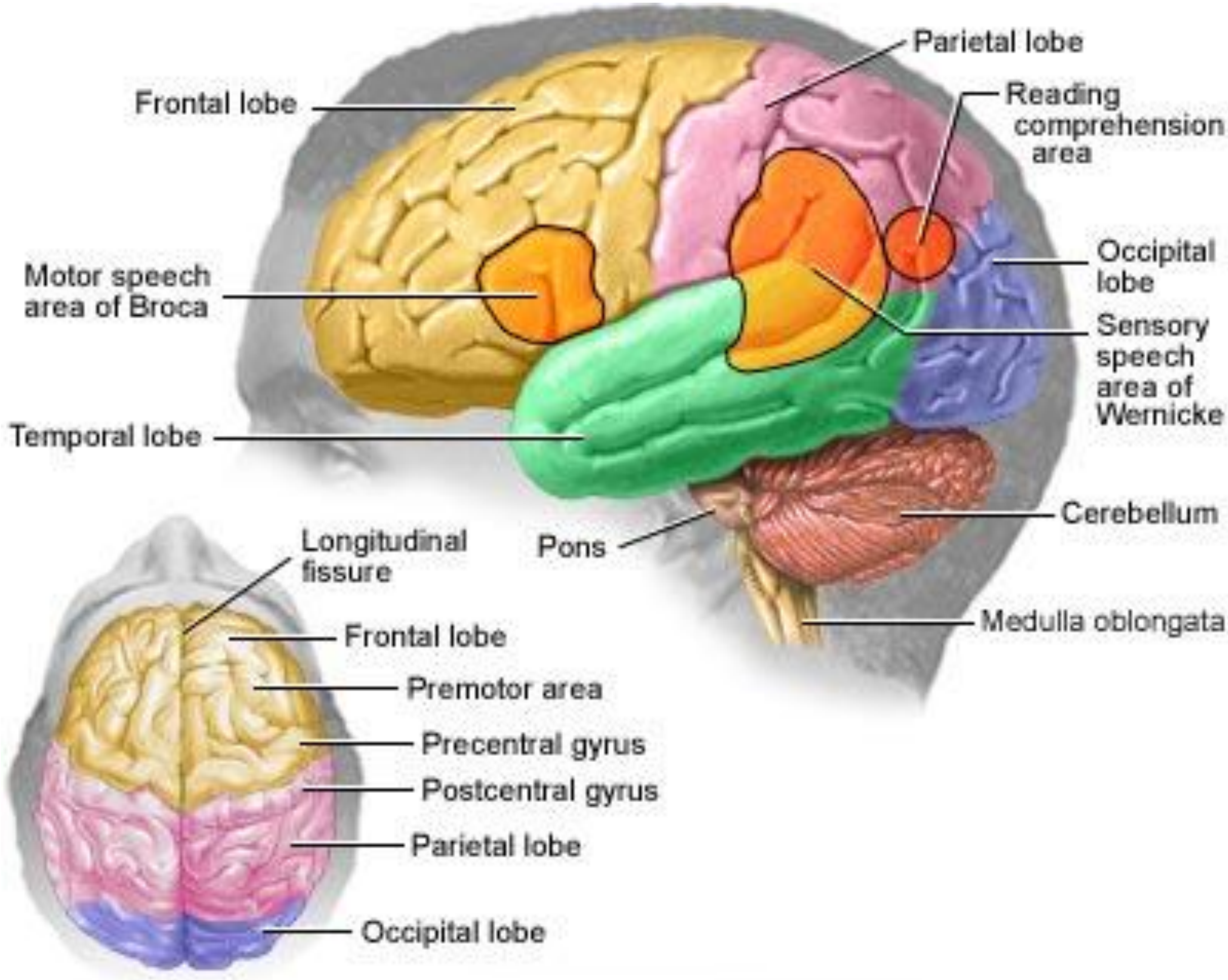
It would be a tremendous engineering feat to be sure. But science aims to understand and explain why and how things work.



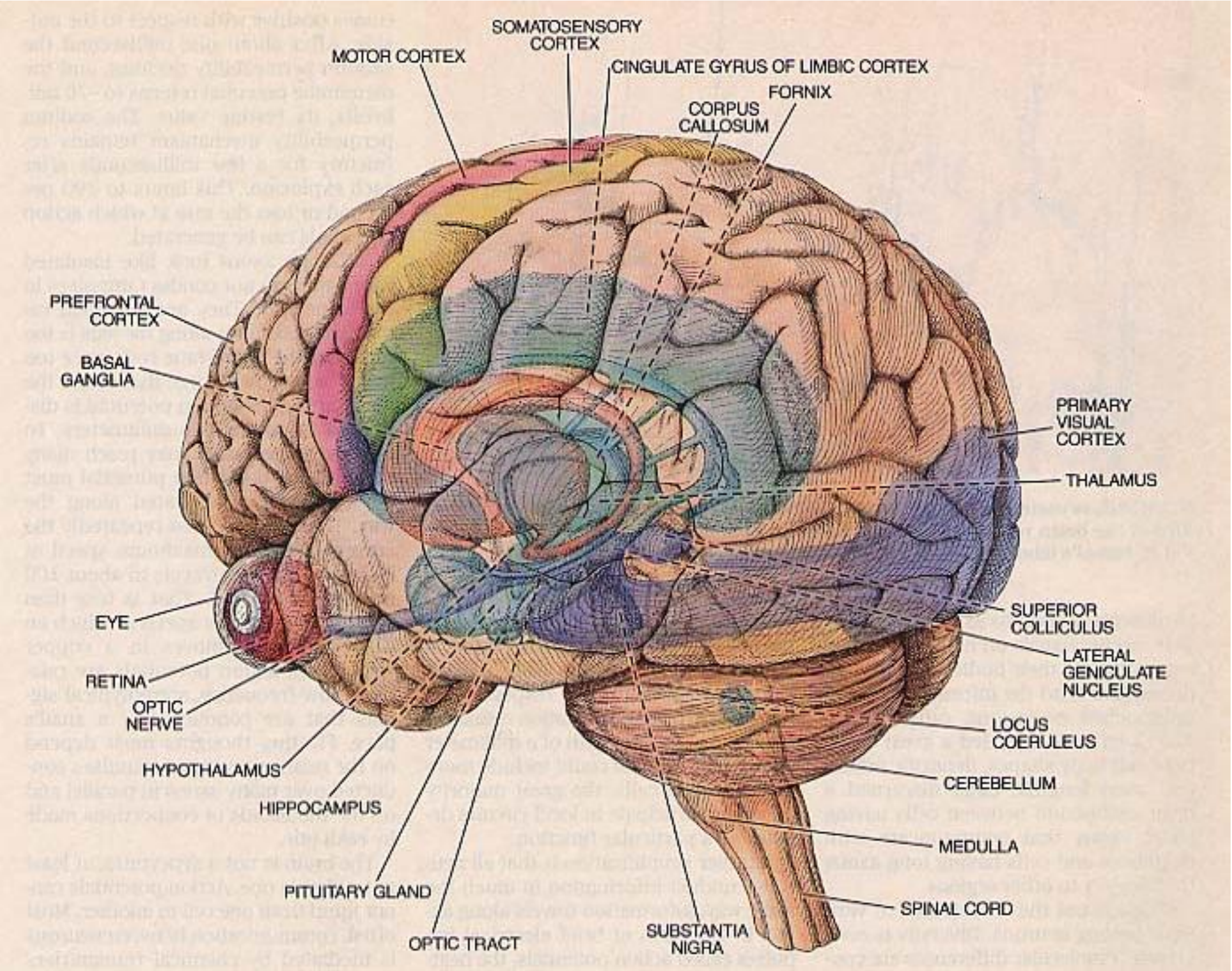
Given this most complex structure in the known universe, what are some ways that psychologists, biologists, and neuroscientists turn the problem of understanding how the brain works into something tractable?

Divide and Conquer Strategy - The Brain has Parts

Divide and Conquer Strategy - The Brain has Parts



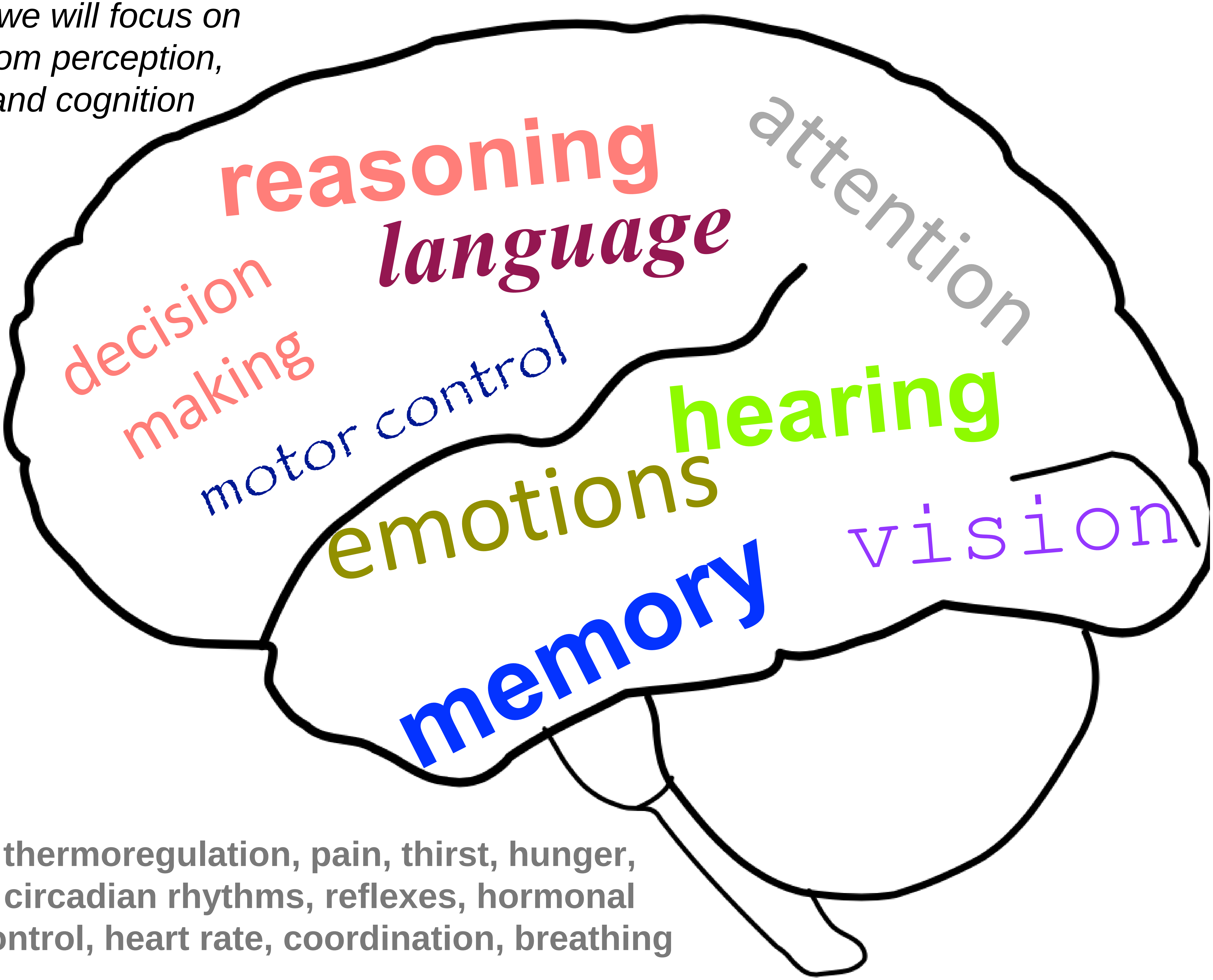
Divide and Conquer Strategy - The Brain has Parts



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, memory, and cognition



thermoregulation, pain, thirst, hunger, circadian rhythms, reflexes, hormonal control, heart rate, coordination, breathing

At What Physical Levels of Analysis to Model?

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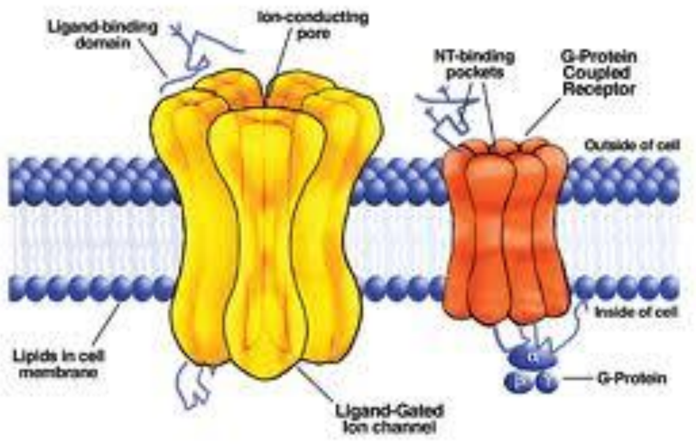
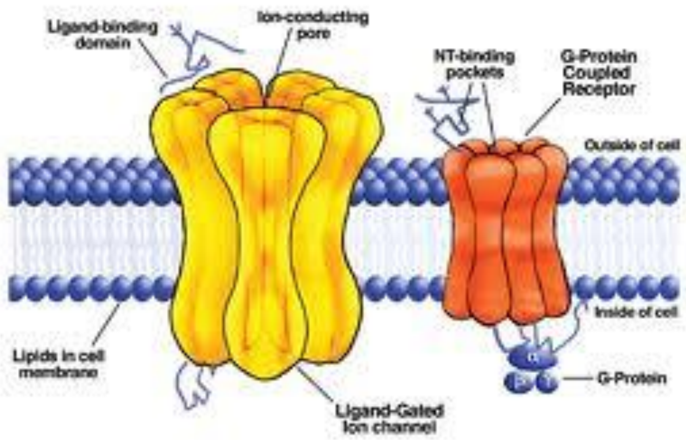
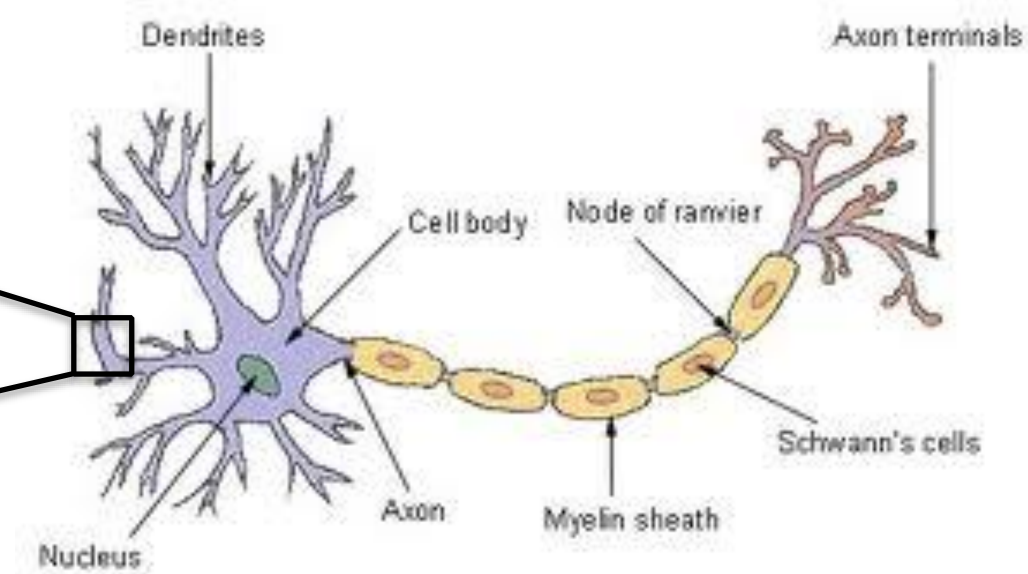


models of ion channels

At What Physical Levels of Analysis to Model?





models of ion channels

detailed models of a neuron

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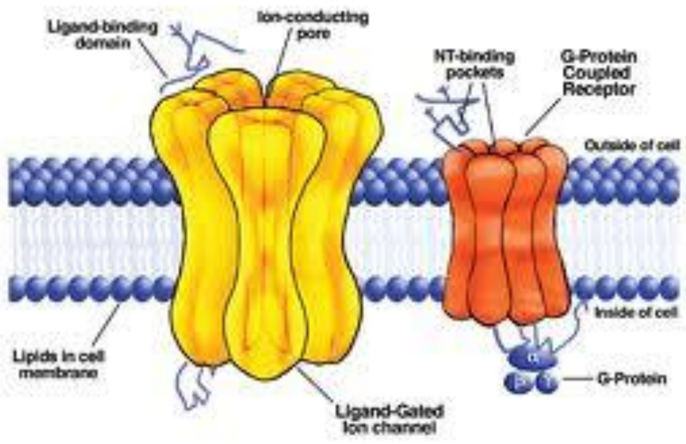

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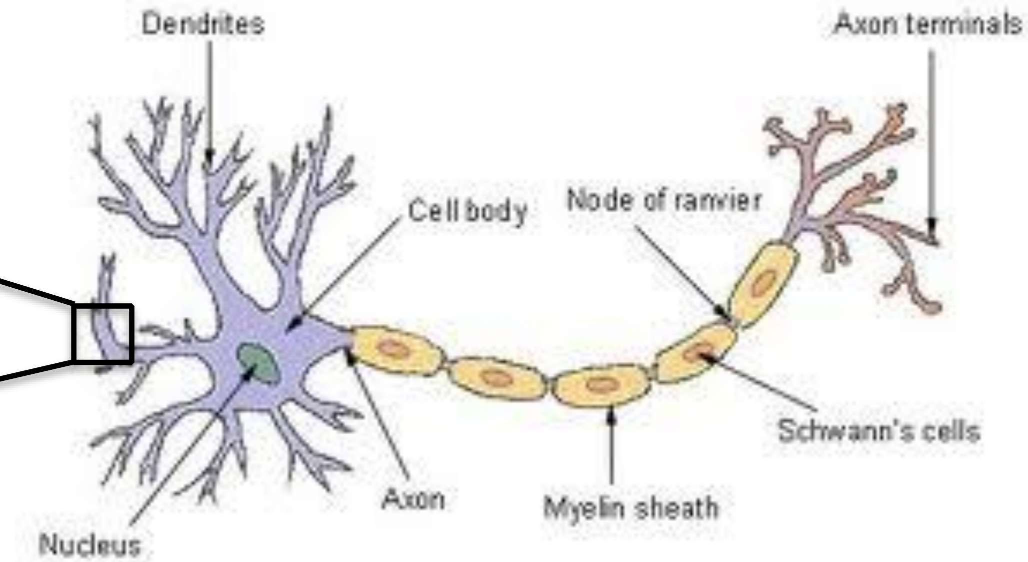
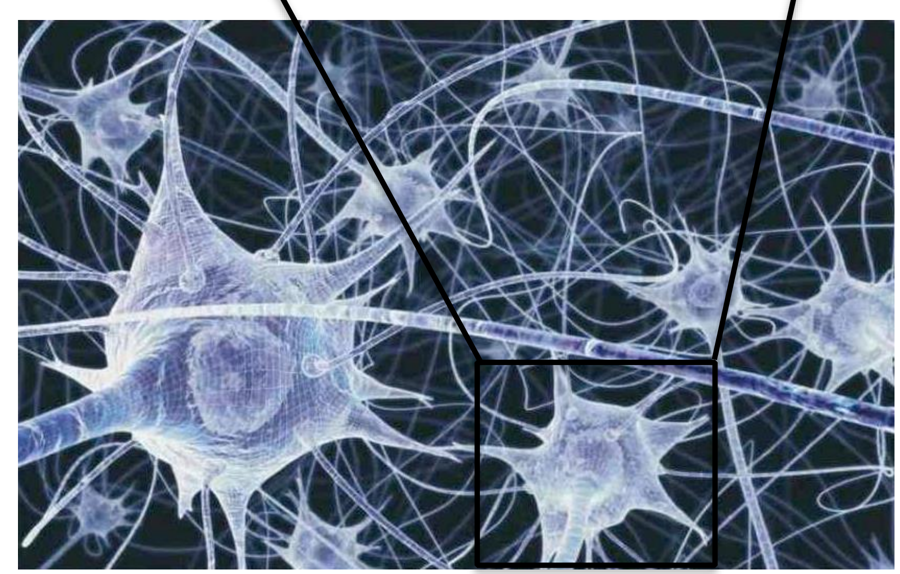


detailed models of a neuron



models of neural circuits

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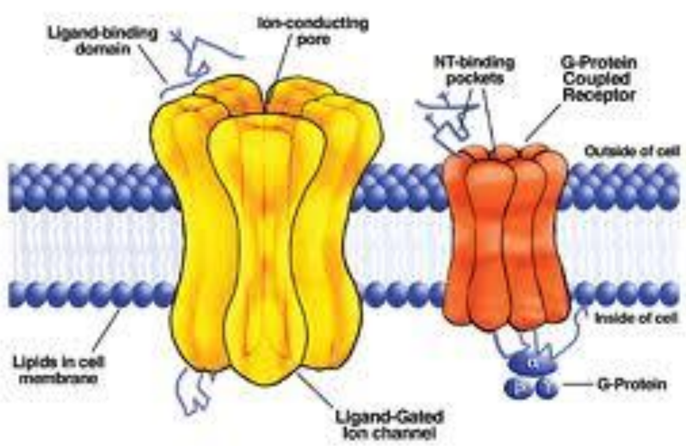
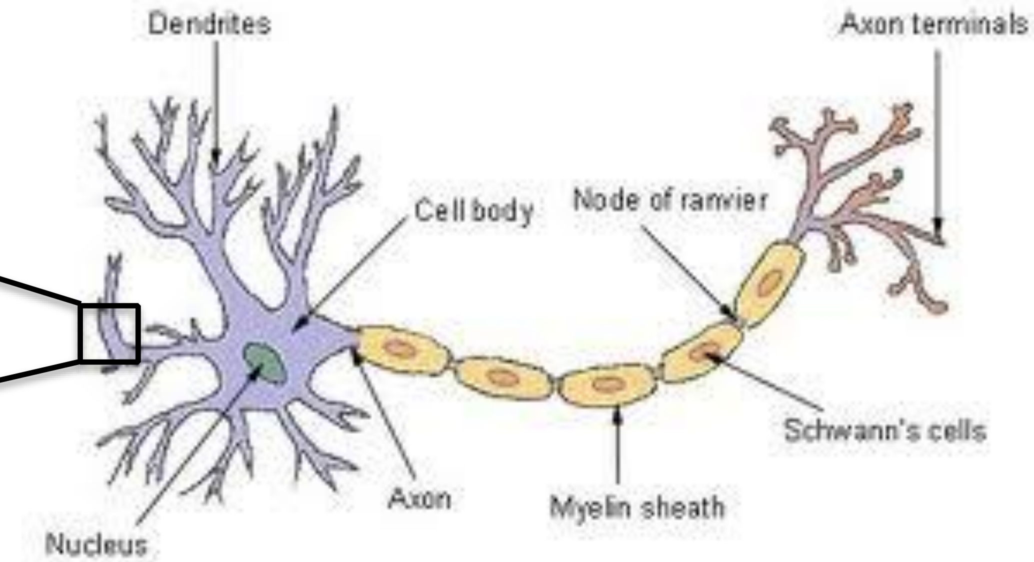


models of ion channels



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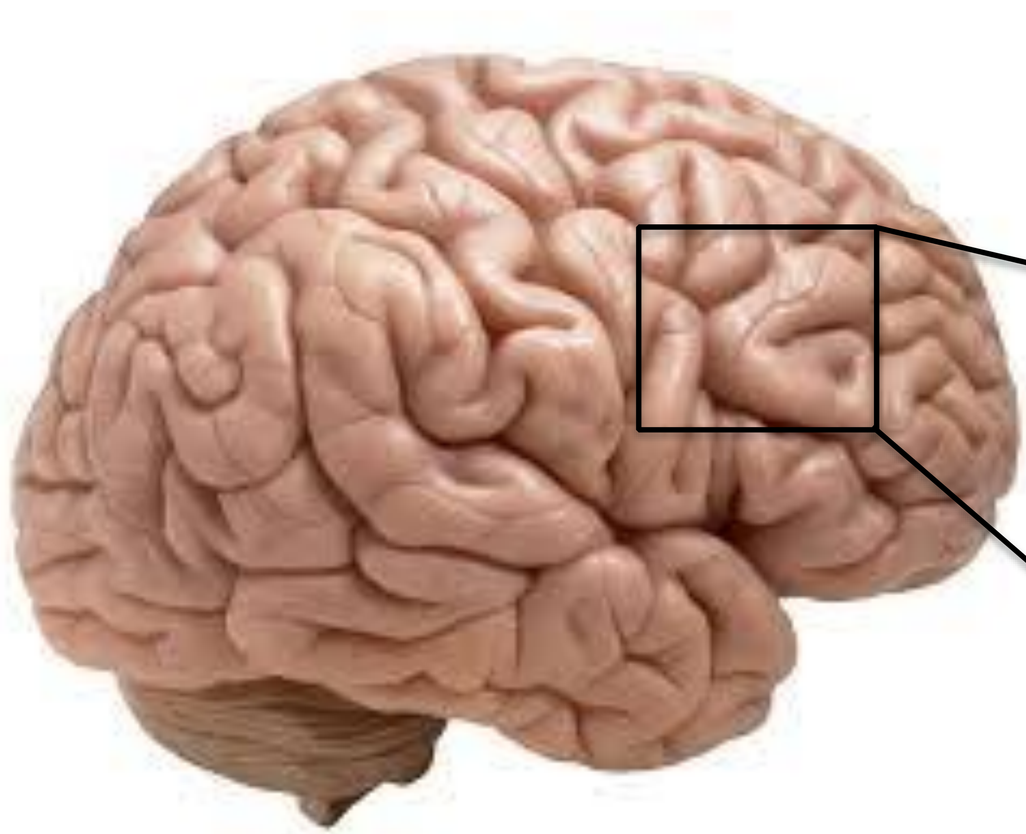
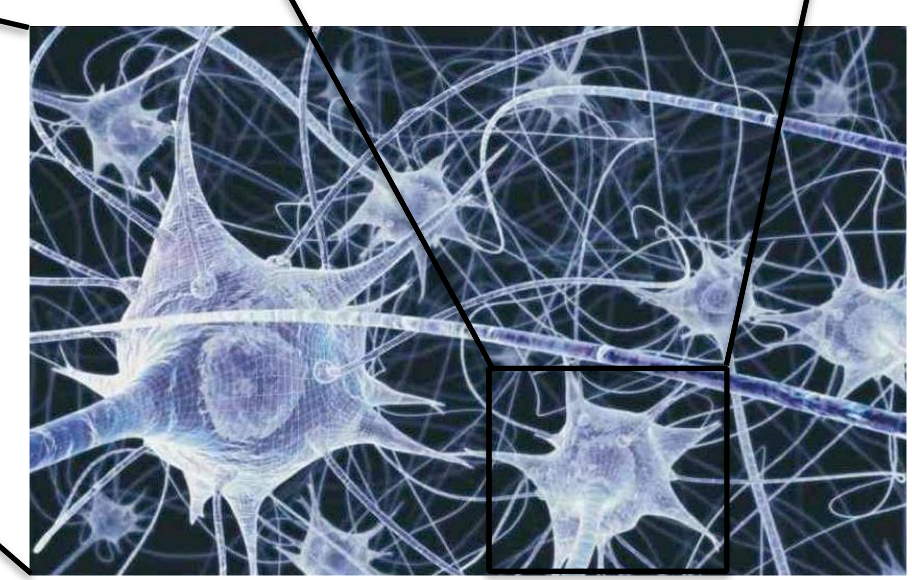


models of brain circuits



models of neural circuits

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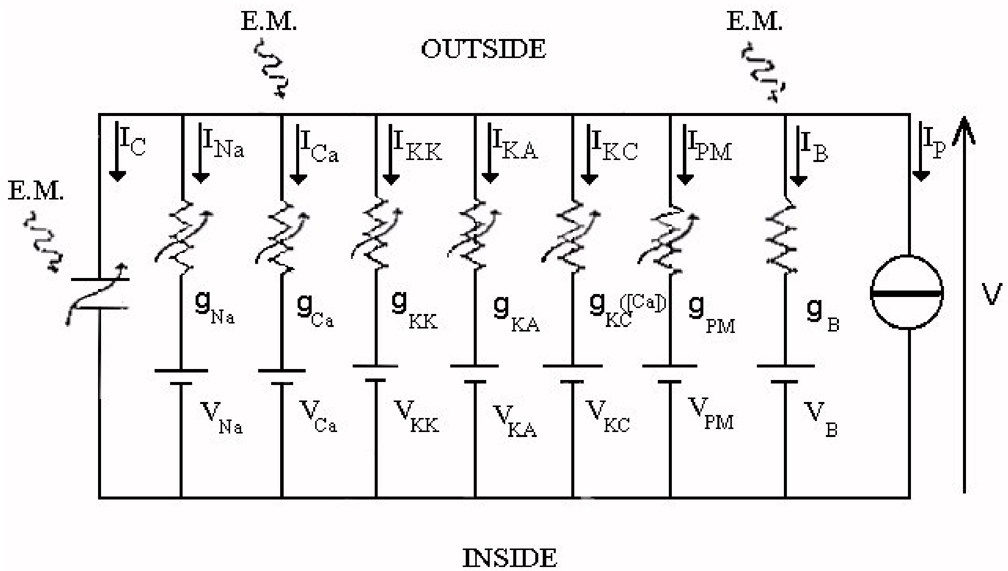
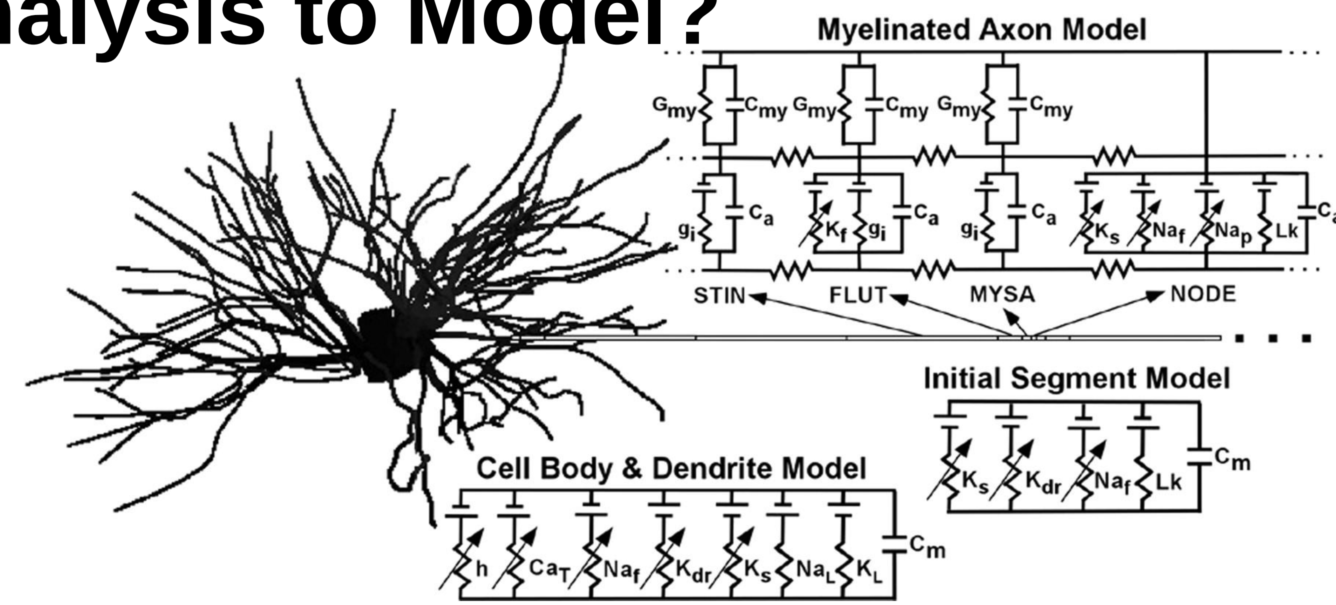
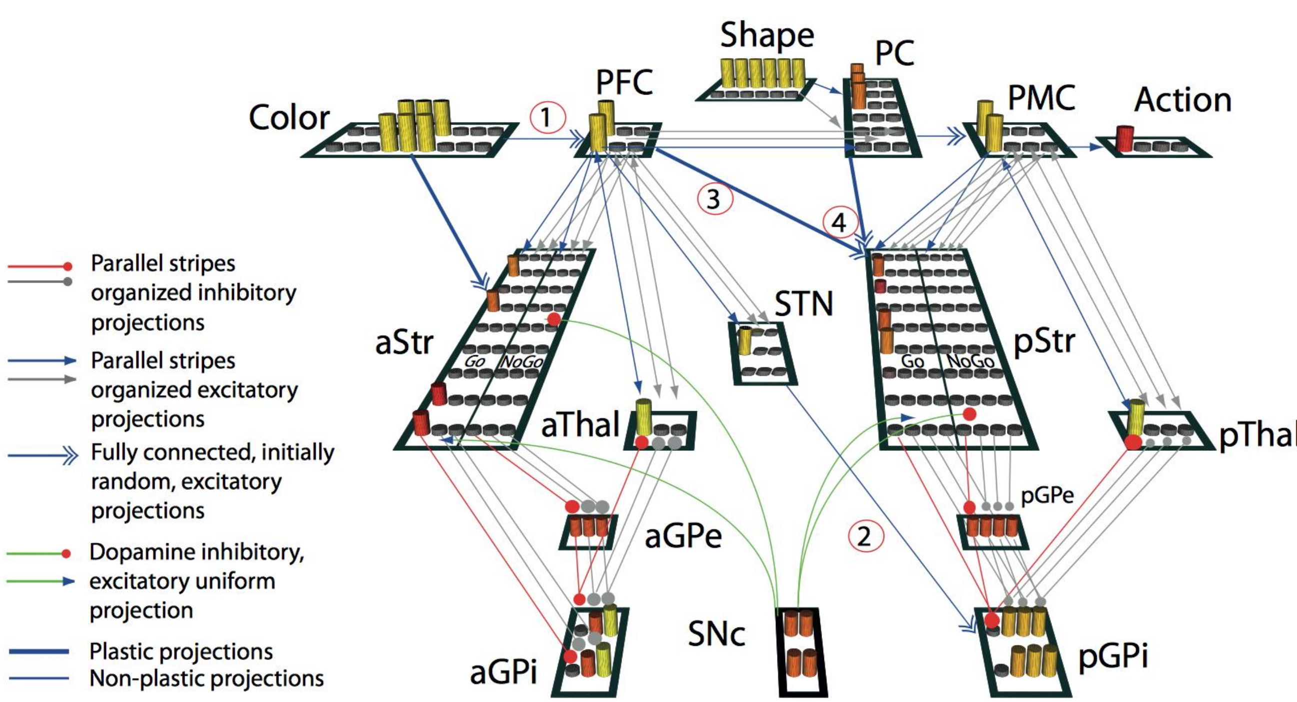


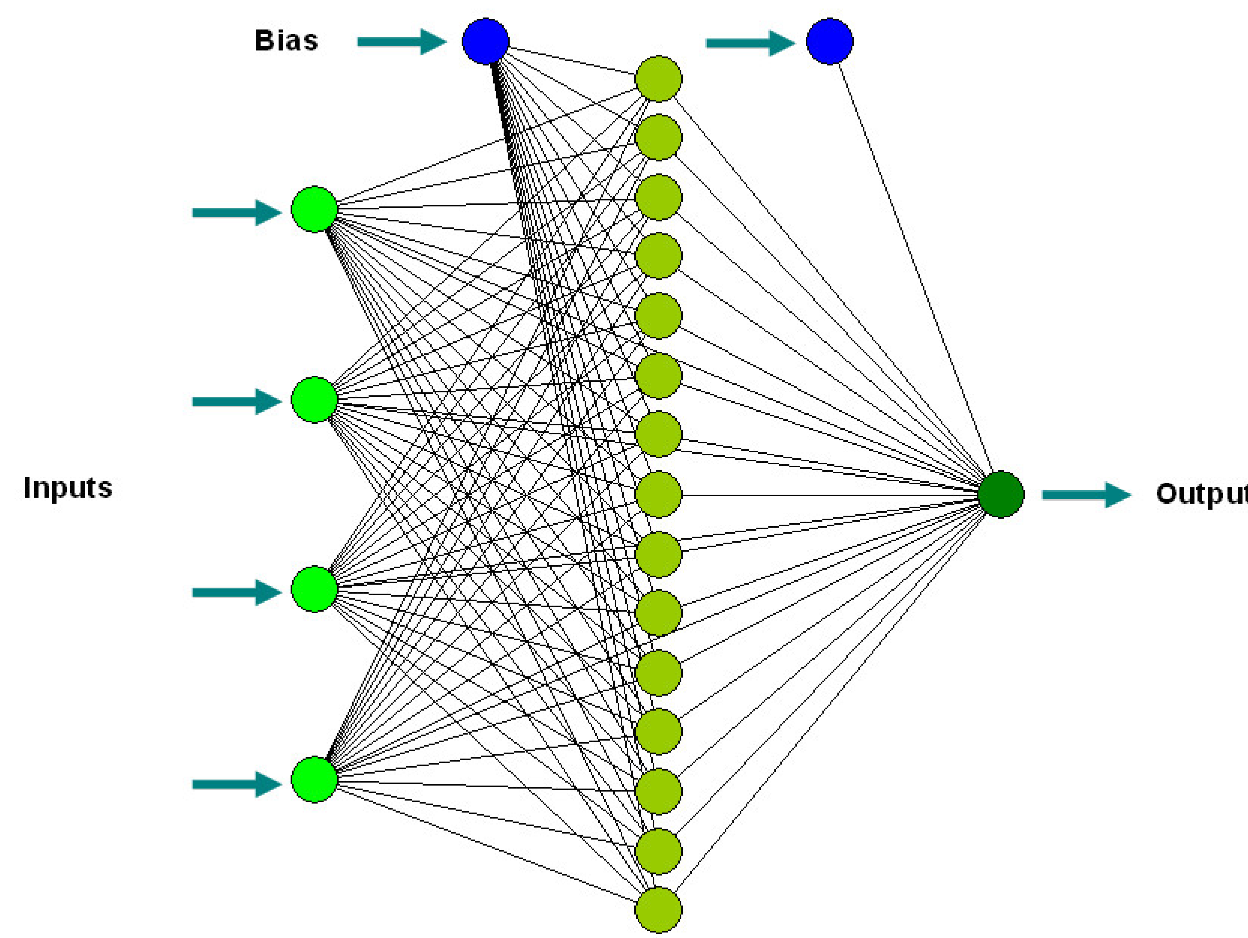
models of ion channels



detailed models of a neuron



models of brain circuits



models of neural circuits

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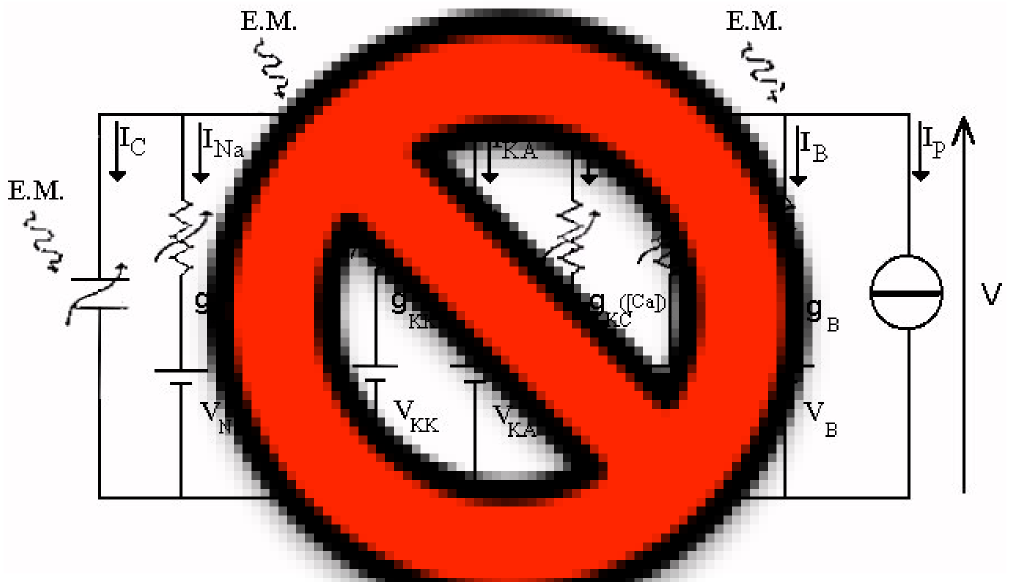
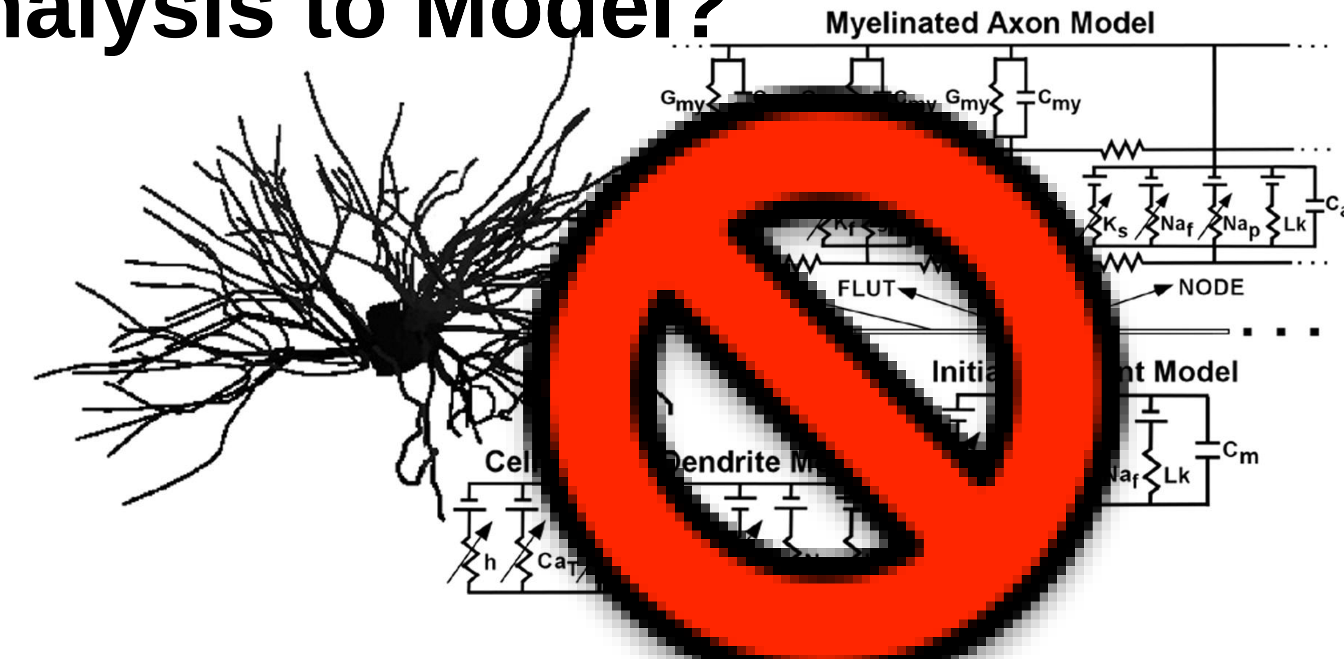
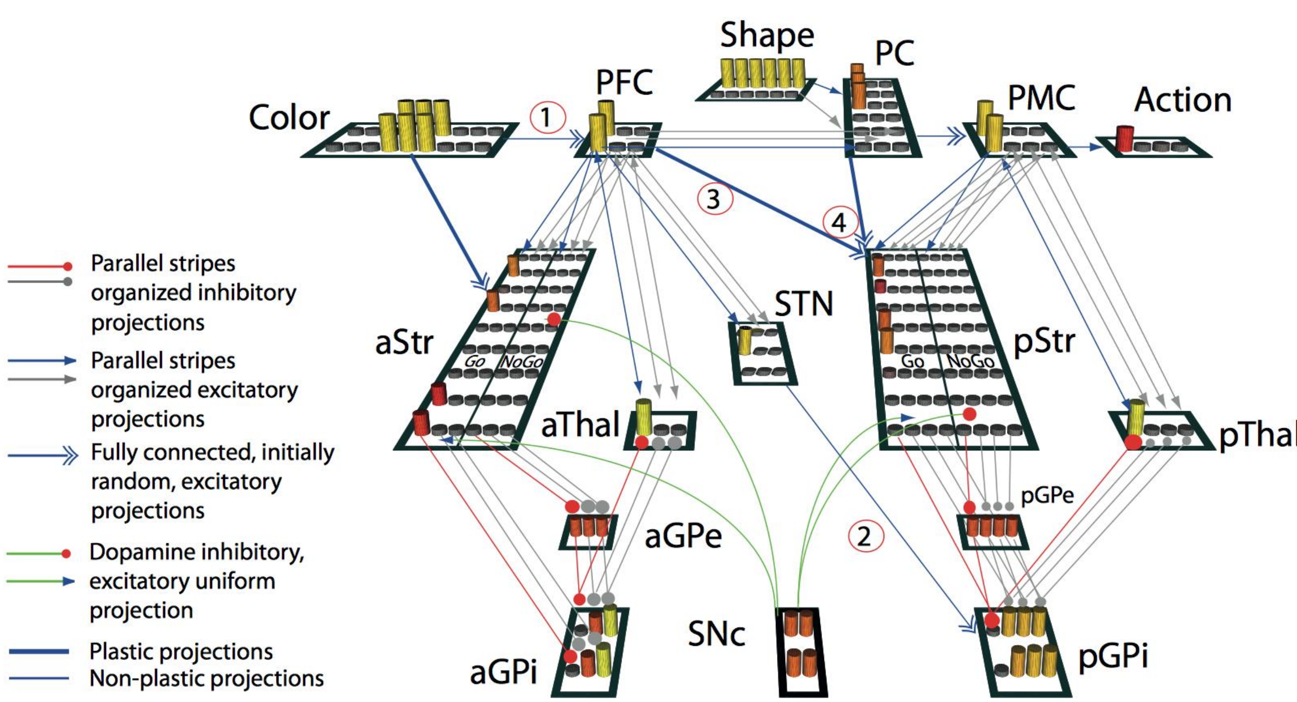


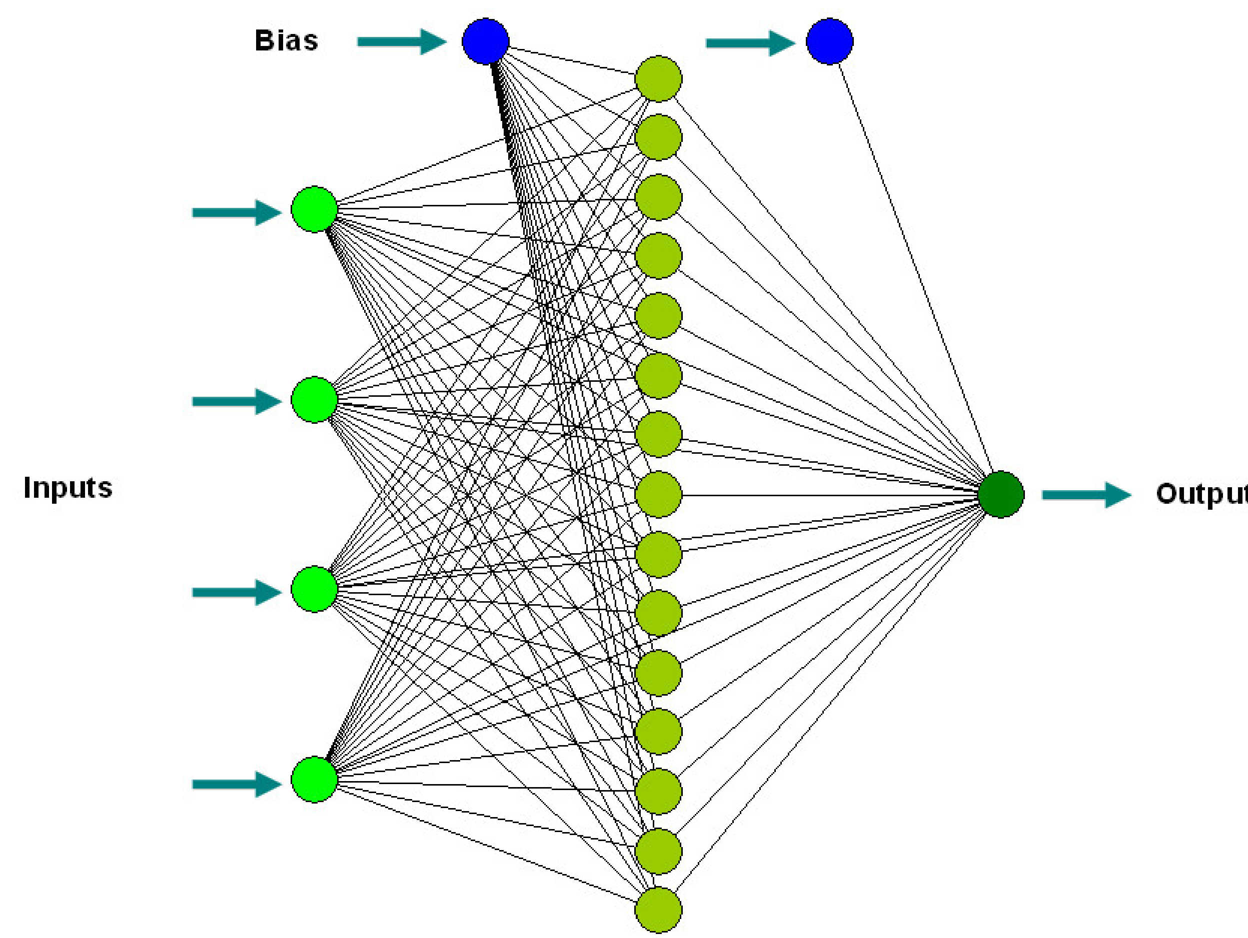
models of ion channels



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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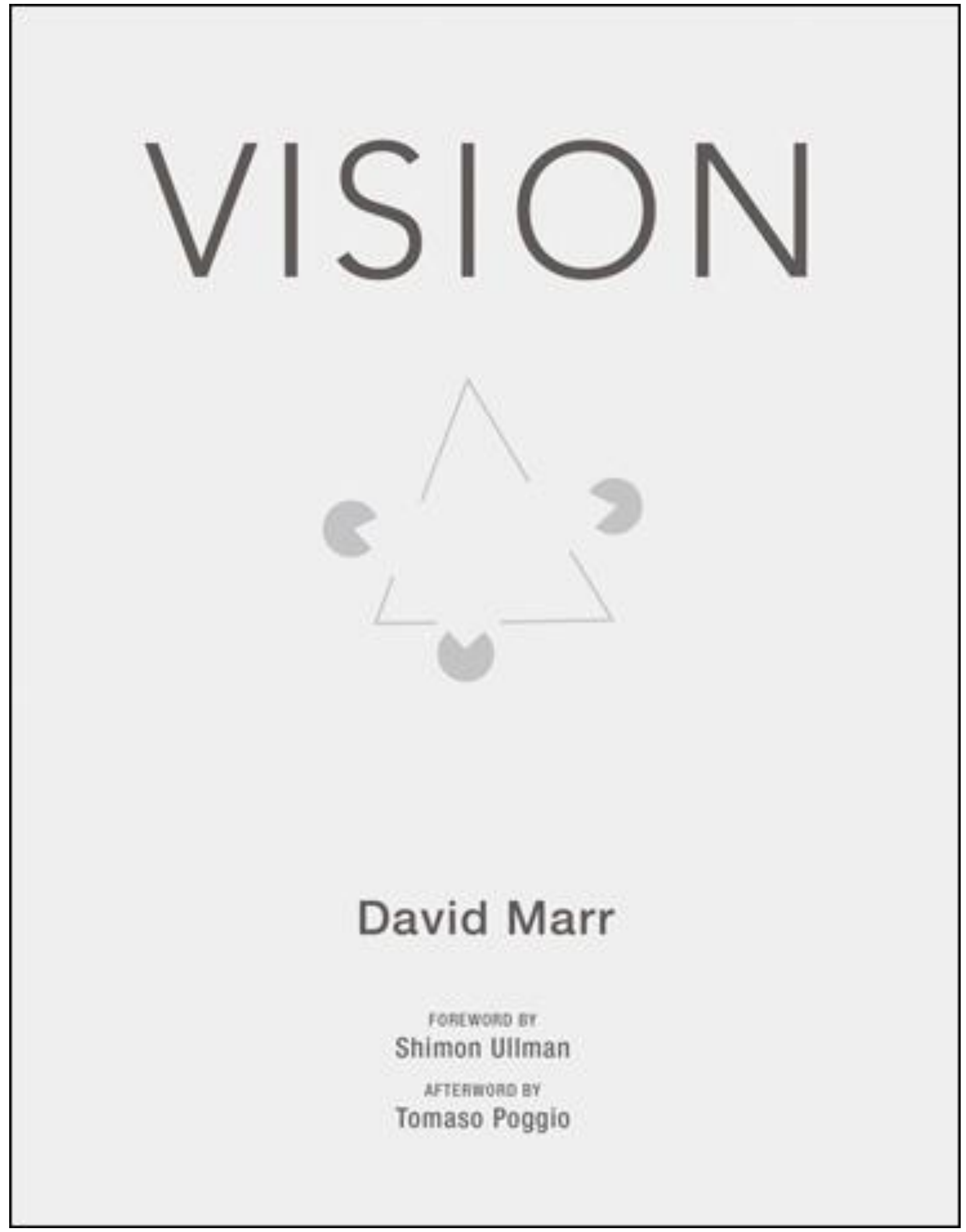


Vision: A Computational Investigation into the Human Representation and Processing of Visual Information

By David Marr, 1980, MIT Press

(Chapter 1 on Brightspace)

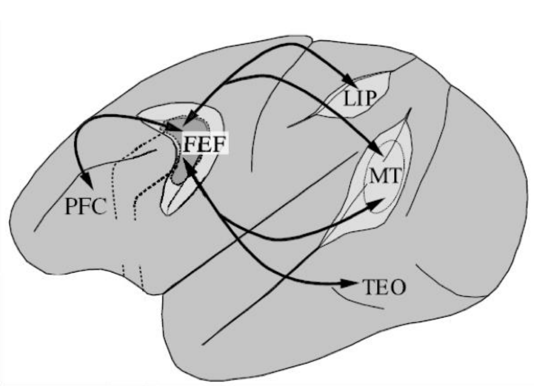
At What Conceptual Levels of Analysis to Model?

(yet another sense of "computational")

Computational Level

(a.k.a. "rational")

Algorithmic/ Representational Level



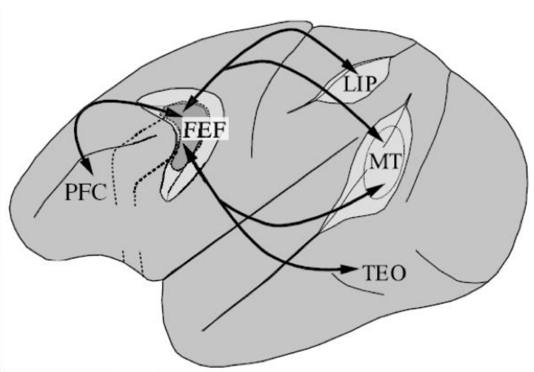
Implementation/ Biophysical Level

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level

Implementation/ Biophysical Level

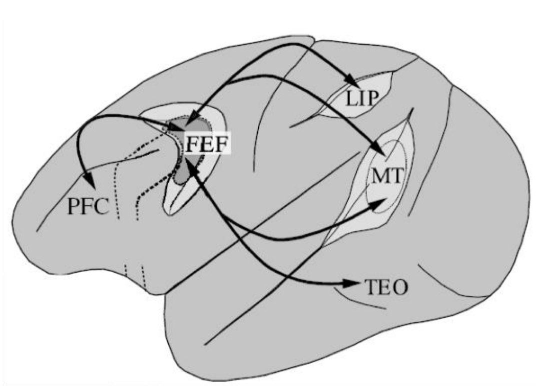


Marr's Three Levels of Analysis

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level



Implementation/ Biophysical Level

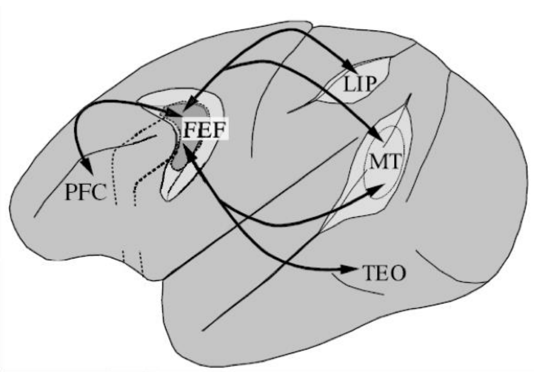
how mechanisms are physically realized within a biological substrate (neurons and their connections)

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)

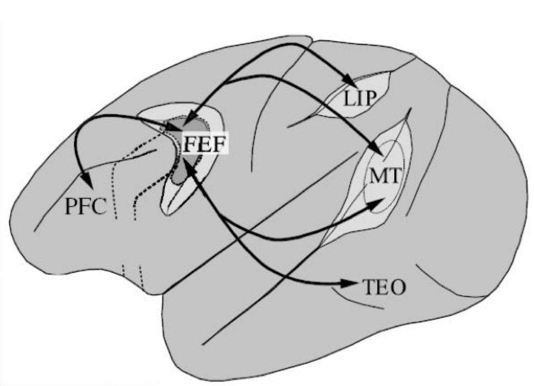
At What Conceptual Levels of Analysis to Model?

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

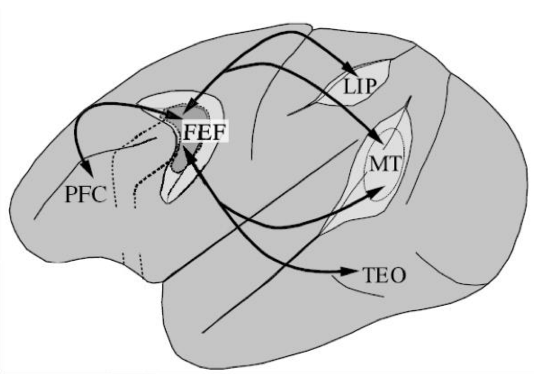
NORMATIVE

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

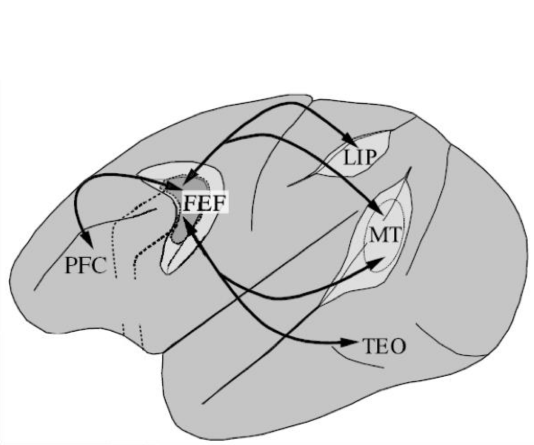
HARDWARE

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

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level



Implementation/ Biophysical Level

BOTTOM UP APPROACH

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

At What Conceptual Levels of Analysis to Model?

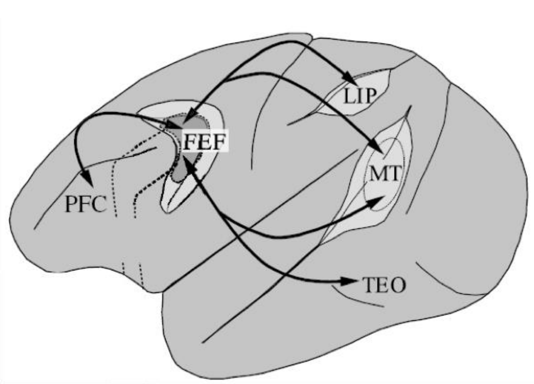
Computational Level

TOP DOWN APPROACH

what are the goals of the organism

what is optimal for survival

Algorithmic/ Representational Level



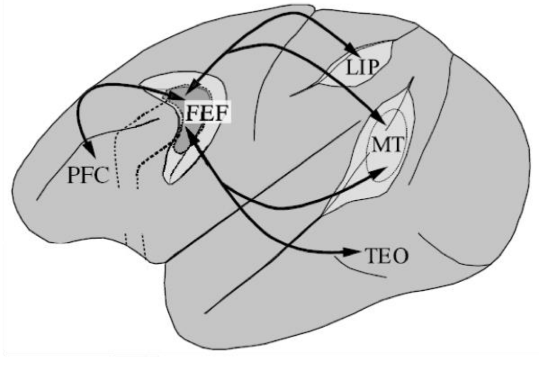
Implementation/ Biophysical Level

At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level

INSIDE OUT APPROACH
what kinds of representations and computations are performed

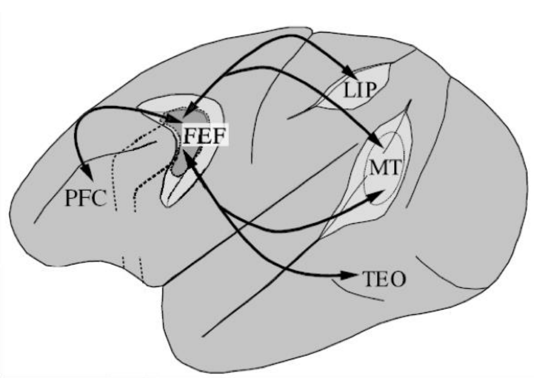


Implementation/ Biophysical Level

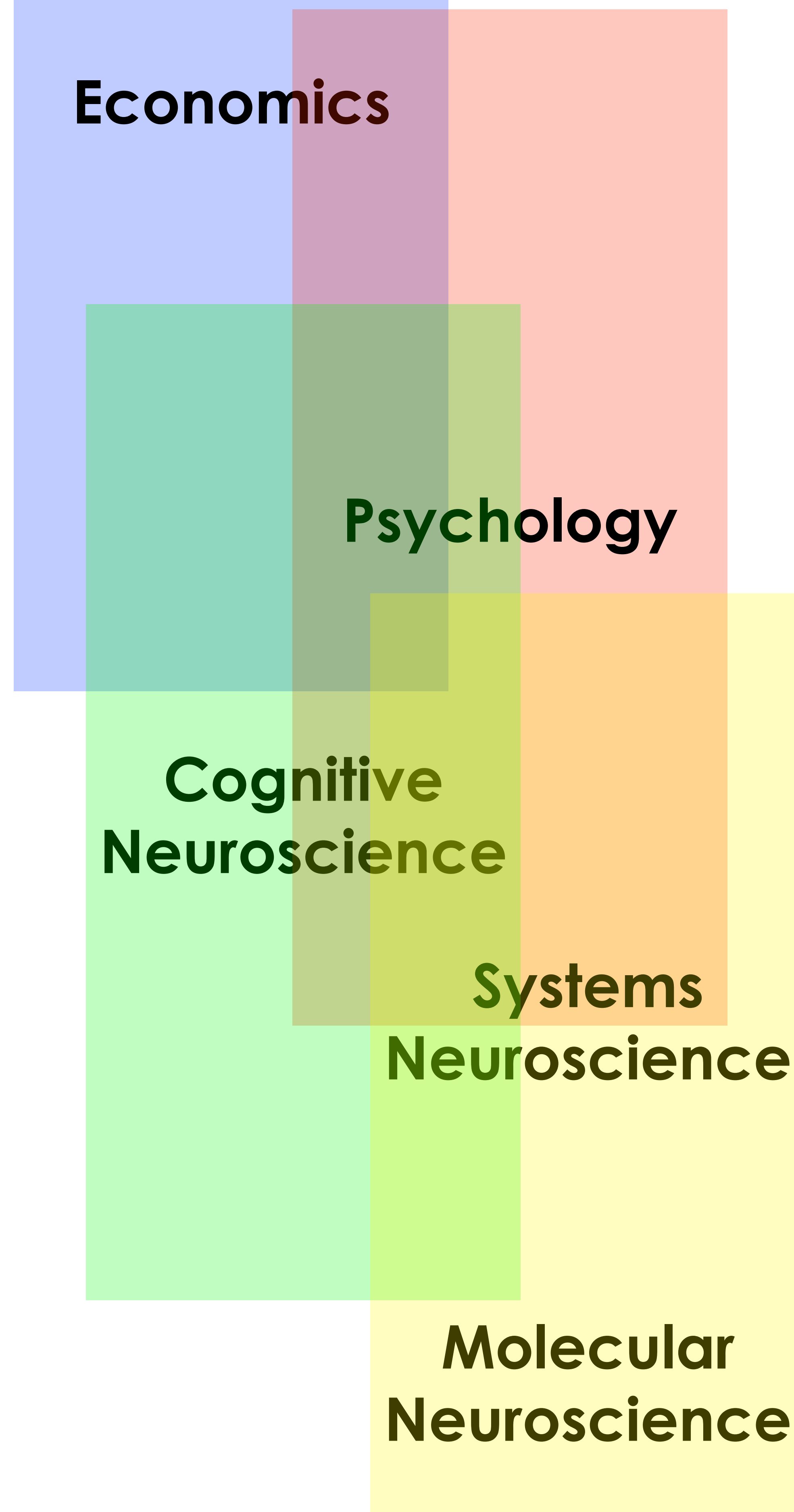
At What Conceptual Levels of Analysis to Model?

Computational Level

Algorithmic/ Representational Level



Implementation/ Biophysical Level



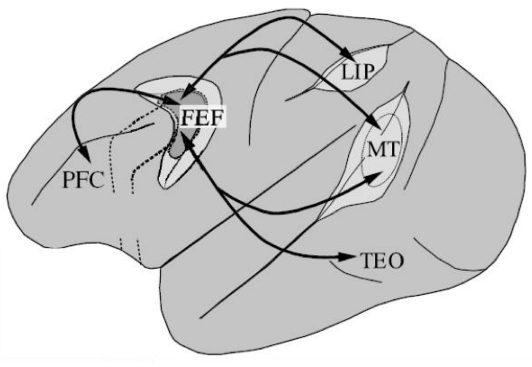
At What Conceptual Levels of Analysis to Model?

Computational Level

what features are statistically most informative in a large collection of images?
image statistics, information theory

Algorithmic/ Representational Level

2nd derivative of a Gaussian smoothed image highlights changes in the image
image and signal processing



Implementation/ Biophysical Level

how do certain neurons in primary visual cortex (area V1) operate
spiking neural network models

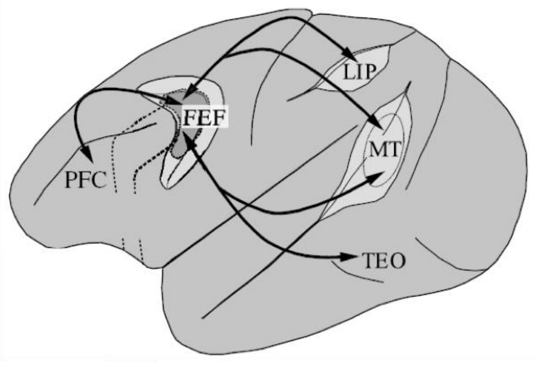
At What Conceptual Levels of Analysis to Model?

Computational Level

what is the most optimal way to make decisions and make choices?
economic theory, Bayesian statistics

Algorithmic/ Representational Level

decisions are made by accumulating noisy evidence over time to threshhold
cognitive modeling



Implementation/ Biophysical Level

how do large ensembles of spiking neurons integrate excitatory and inhibitory inputs
spiking neural network models