

A microscopic image of neurons, likely from a brain slice, showing various cell bodies and their processes. The image is overlaid with a cyan/blue color scheme. One neuron in the center-left has a red nucleus. Another neuron on the right is highlighted in a bright cyan/green. The background is dark blue.

AIL4230: Basics of Computational Neuroscience

Saurabh Gandhi

Fall 2024

Administratrivia

- Evaluation

- Major: 40% (~30% post-minor, 10% based on combining what you learnt throughout the course)
- Minor: 30%
- Assignments: 20% (hands on computational work, roughly 4 through the semester)
- Class participation: 10% (pop-up quizzes that will promote interactions in the class)

- Attendance

- Class participation will take care of attendance. No separate requirement.
- NOTE: Exams will be based on whatever is covered **in the class**. This may or may not include things covered in the prescribed textbooks / reference books. Therefore attend all classes and take proper notes.

- Contacting me

- No specific office hours, but can pre-arrange a time and meet
- Typically available immediately after the class (or before if pre-arranged)
- Do not email me as far as possible. Keep all communication on Google Classroom (this helps me keep all information in one place. Otherwise I may misplace something important you communicated)

Administratrivia 2

Textbooks:

1. [Gerstner, Wulfram, Werner M. Kistler, Richard Naud, and Liam Paninski. Neuronal dynamics: From single neurons to networks and models of cognition. Cambridge University Press, 2014](#)

Reference books:

1. Dayan, Peter, and Laurence F. Abbott. Theoretical neuroscience: computational and mathematical modeling of neural systems. MIT press, 2005
2. Izhikevich, Eugene M. Dynamical systems in neuroscience, MIT press, 2007

Online course material:

1. Introduction to Computational Neuroscience:
<https://nptel.ac.in/courses/102/106/102106023/>

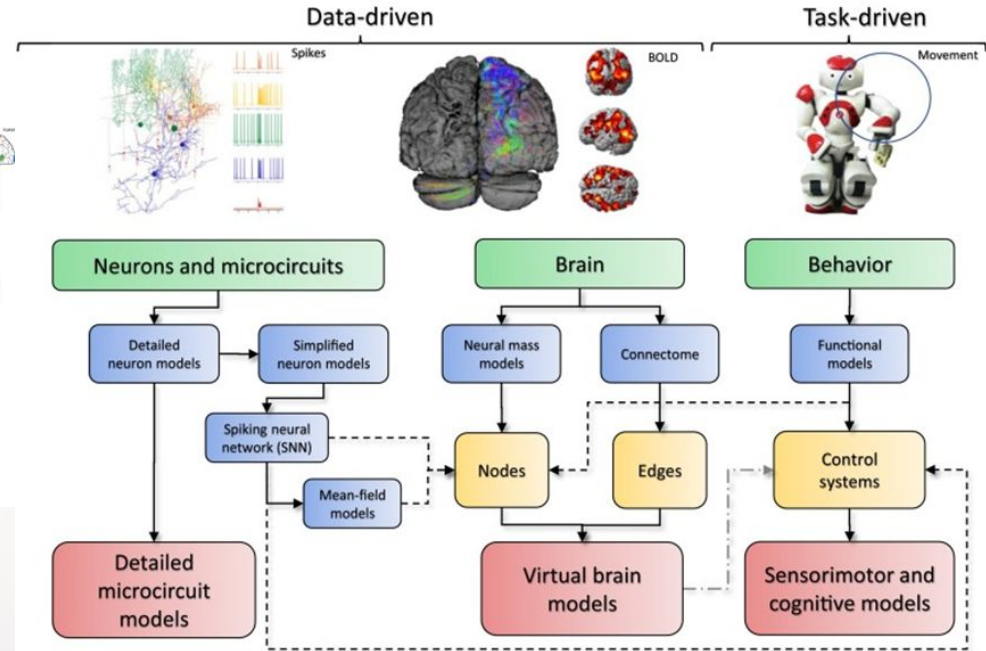
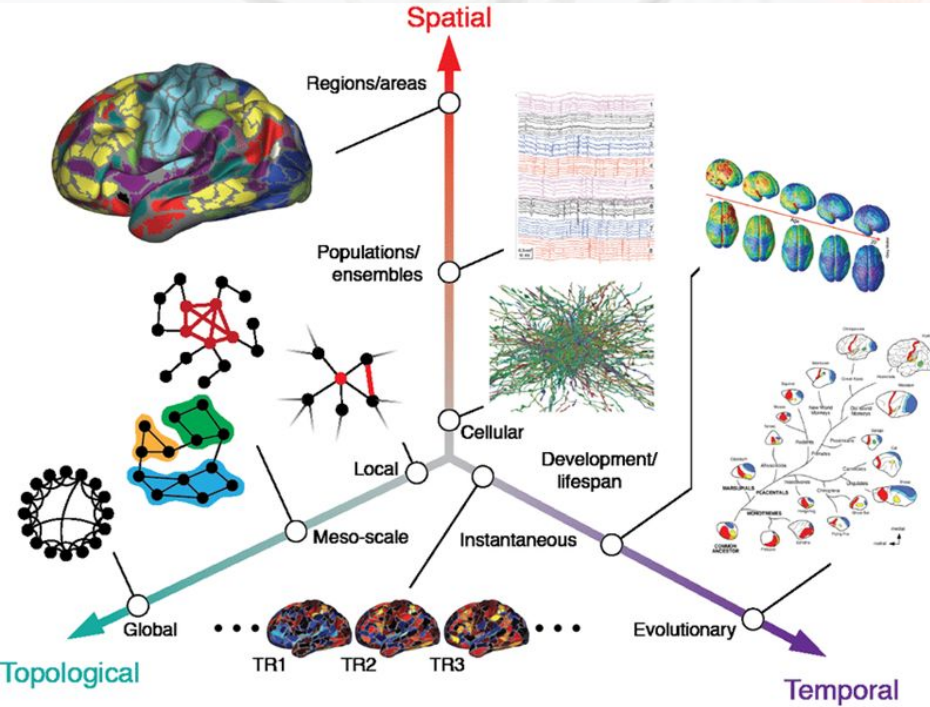
Backgrounds

- What are your interests (that are relevant to this course)?
- Why are you taking this course?
- Labels are no limitations!
- Physics → ecology and evolution of microorganisms → computational neuroscience → doing experiments on humans (sign up!)
- The brain is complex and needs a bit of everything to even begin understanding
- This course will surely push your boundaries: a pinch of biology, a big spoonful of physics, and models!

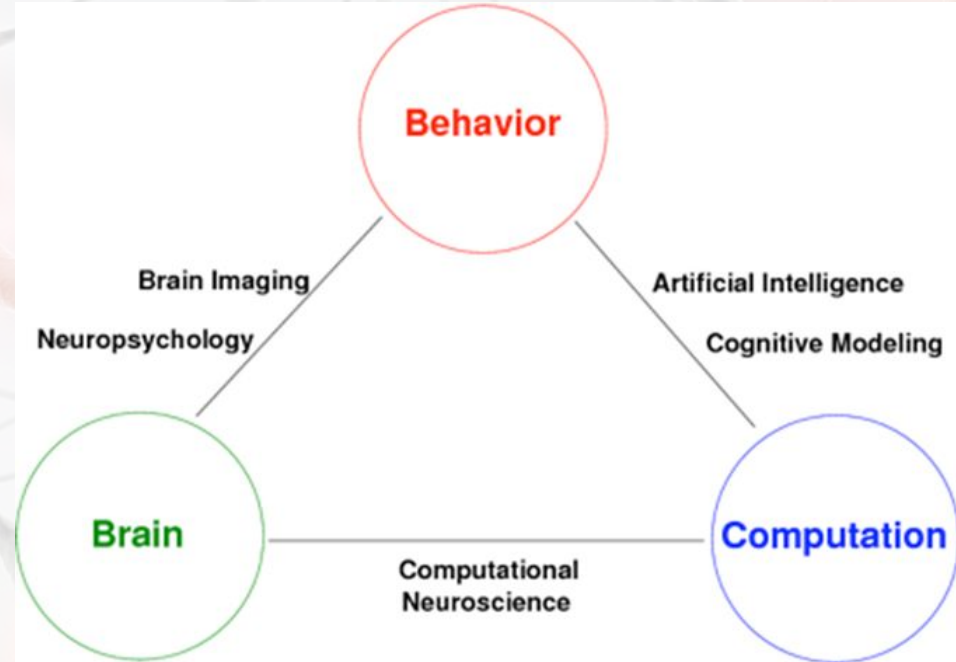
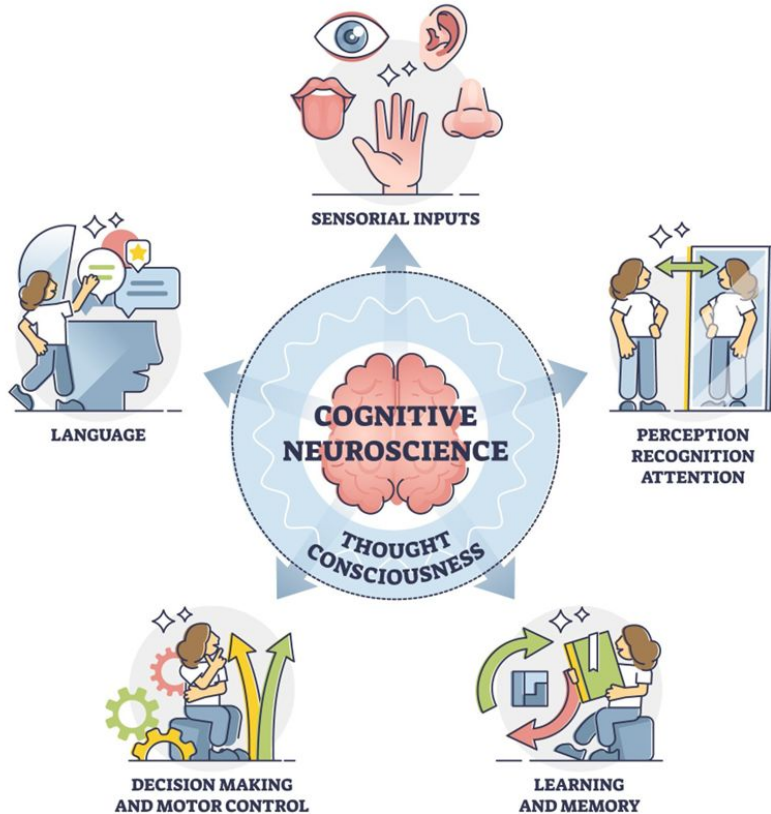
What this course is about

- What do you think?
- What are the different contexts in which computational approaches might be necessary in neuroscience?
- **Building models of the brain** is just one application of computation
- Models
 - What is a model?
 - What is the purpose of building models?
 - What are the different types of models?

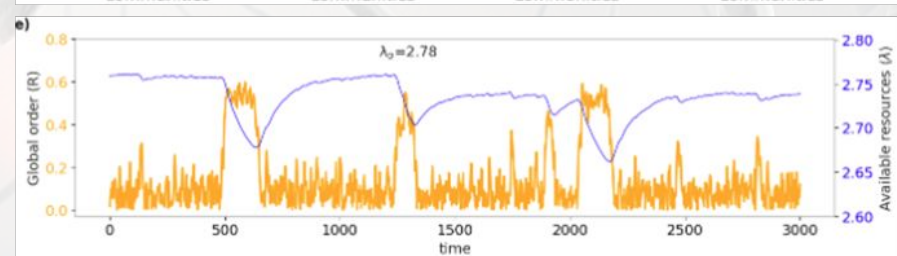
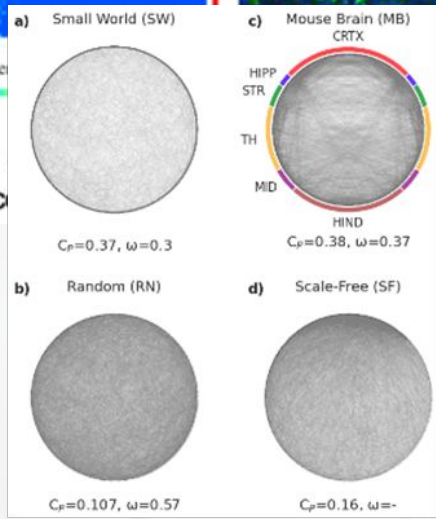
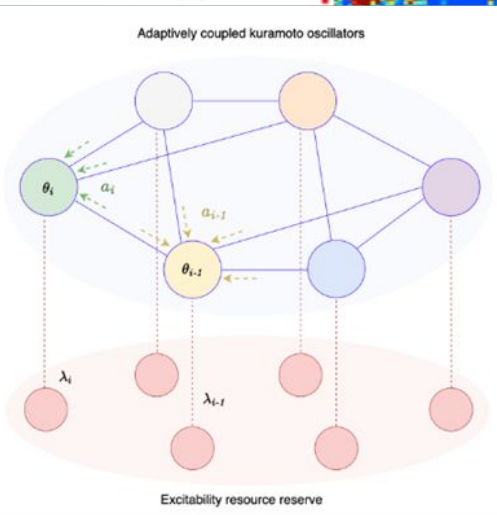
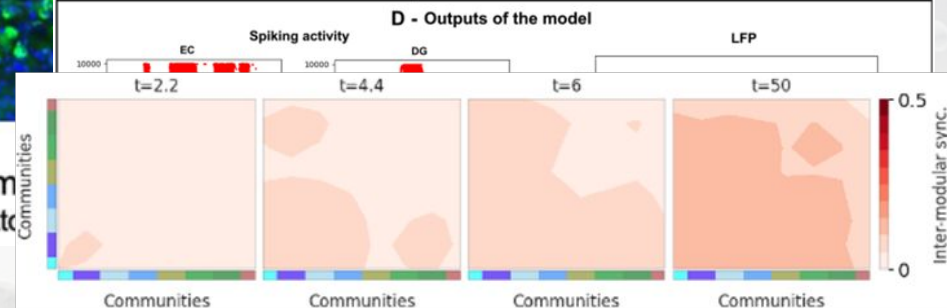
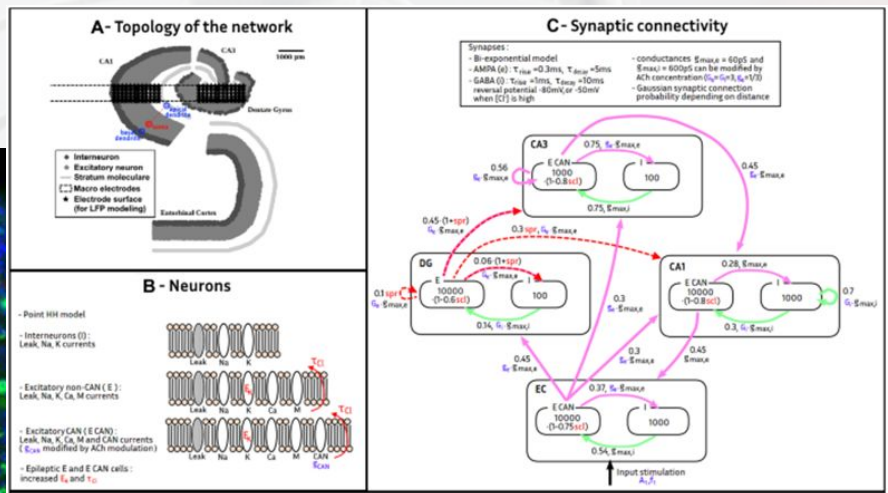
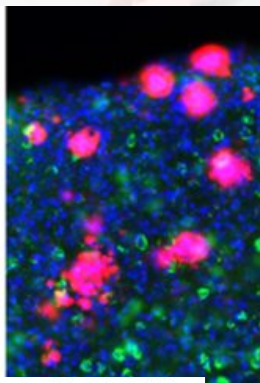
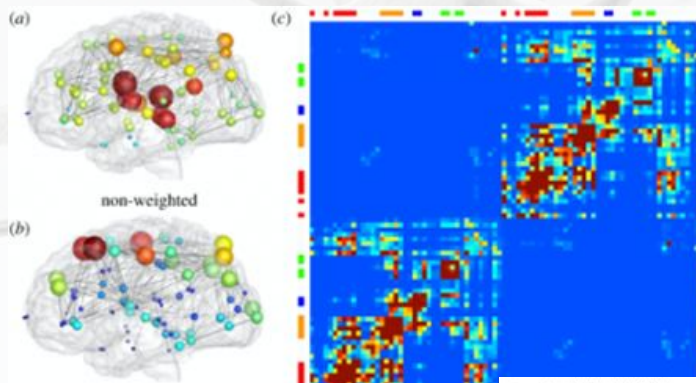
(Mechanistic) Understanding of the brain



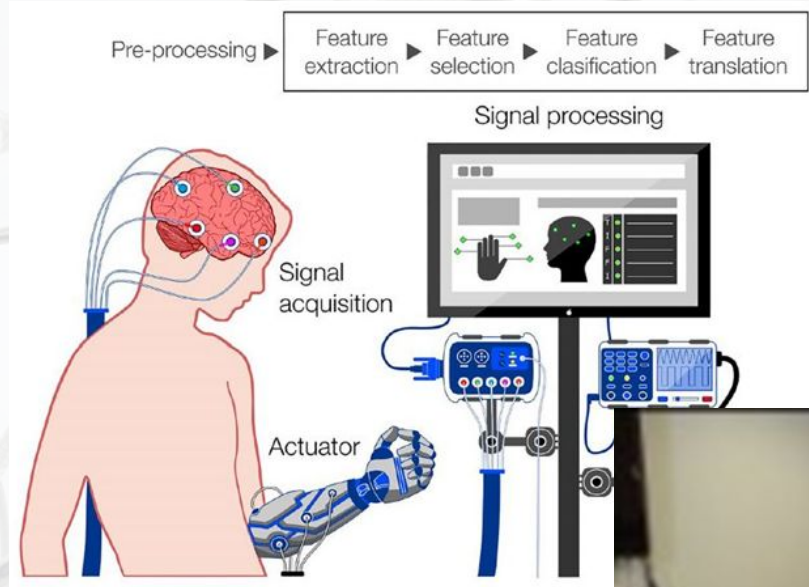
(Functional) Understanding of the brain: how do we?



Understanding diseases



New ways to interact with the world: BCIs

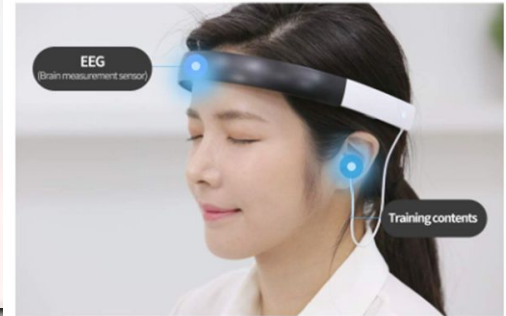


Optimised brain condition

Measure and analyze your brain condition!

Brain measurement with OMNIFIT Brain

OMNIFIT Brain can detect and analyze the electrical flow in front of the frontal lobe through a two-channel EEG sensor for real-time verification.




Real-time brain measurement


Analysis/Guide


Concentration / Stress ↑ ↓

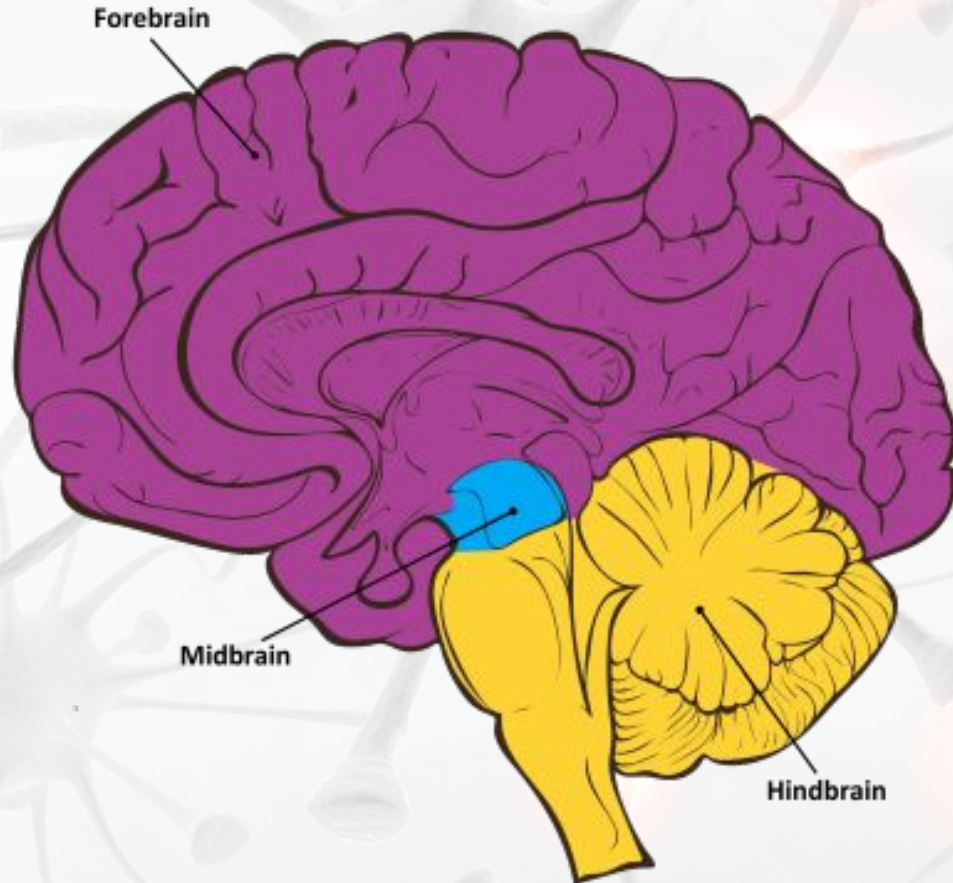


A primer on the brain

https://mpfi.org/wp-content/uploads/2019/04/Brain_Facts_BookHighRes1.pdf

<https://www.ninds.nih.gov/health-information/public-education/brain-basics/>

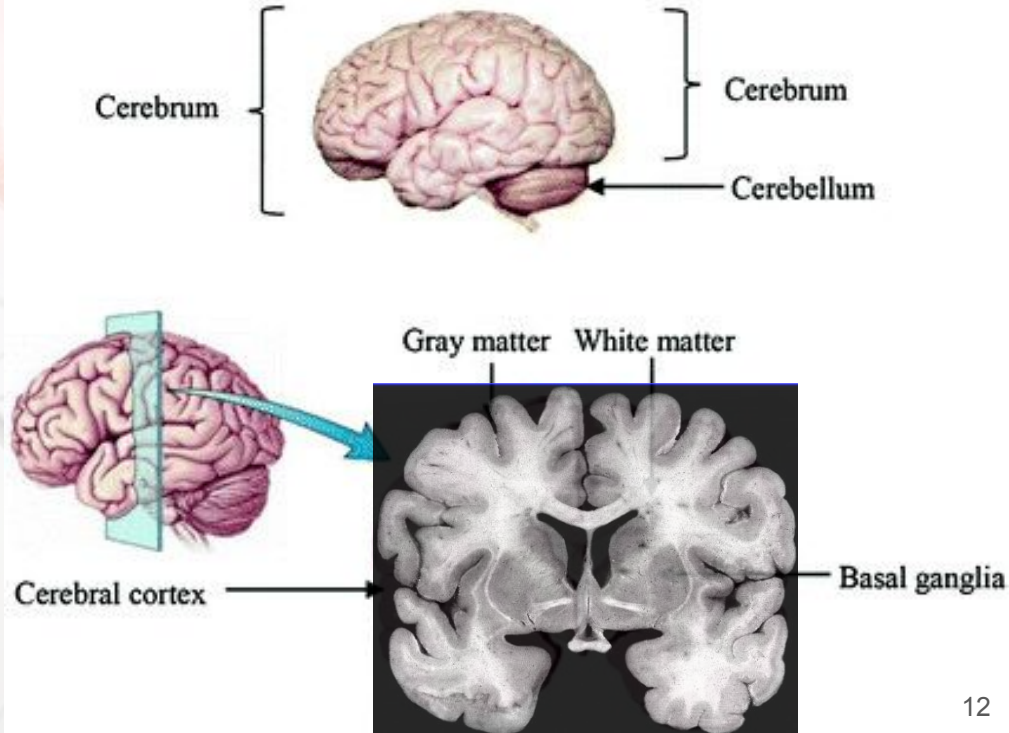
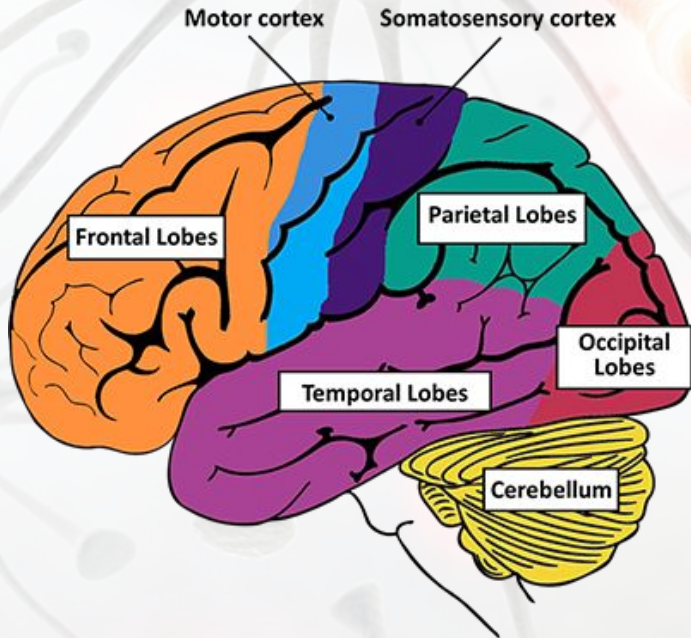
The human brain - basic anatomy



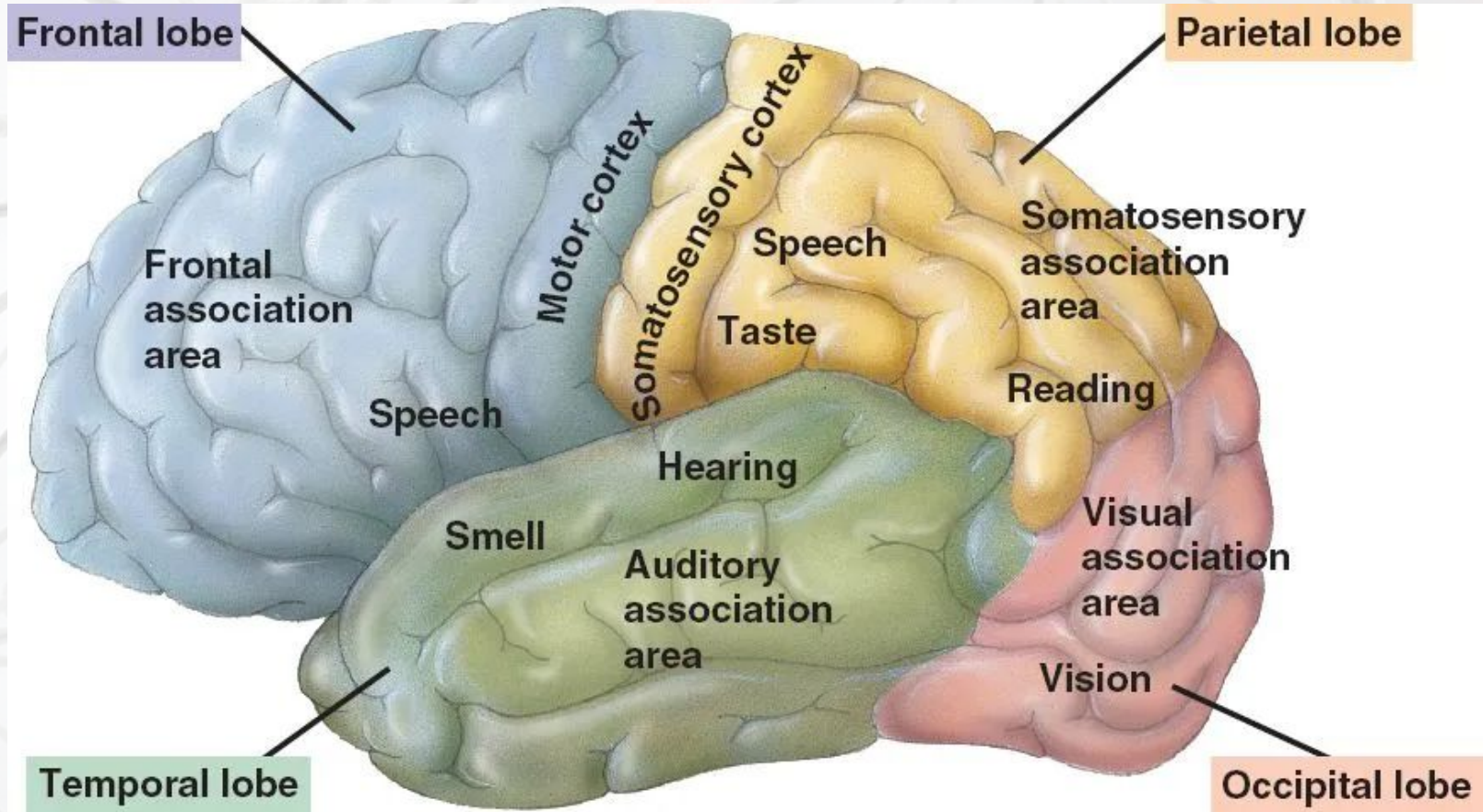
- The **hindbrain** controls the body's vital functions such as respiration and heart rate.
- The **cerebellum** coordinates movement and is involved in learned movements.
- The **midbrain** controls reflex actions, eye movements and other voluntary movements.
- The **forebrain** is the largest and most highly developed part of the human brain

The human brain - basic anatomy

- **Gray matter:** Where thinking happens!
- **White matter:** Communication between thinking centers
- **Cerebral cortex | neocortex | cortex:** Most developed and 'thinking' part
- **Subcortical:** Memory, emotion etc.



Different parts of the cortex for different functions

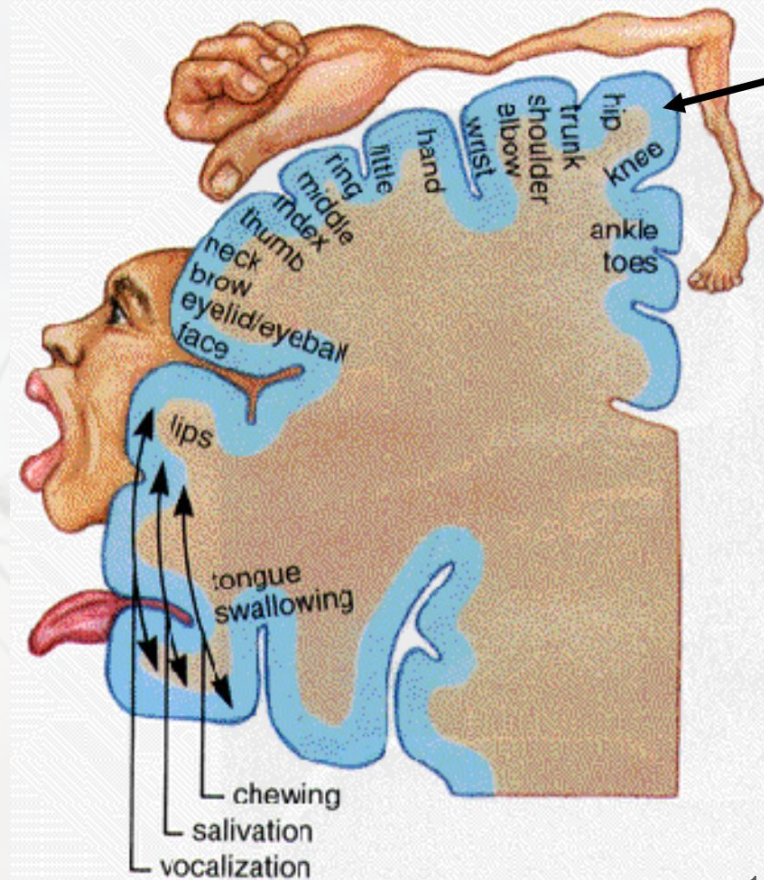


Homunculus: the little person inside your brain



"Whoa! That was a good one! Try it, Hobbs—just poke his brain right where my finger is."

Copyright: Gary Larson

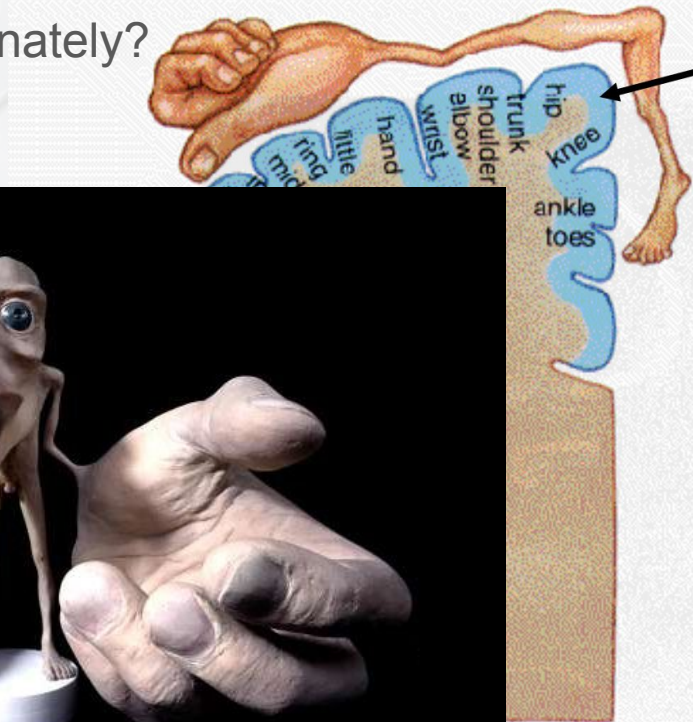


Homunculus: the little person inside your brain

Different brain regions represent different parts of the body for movement or sensation

Why are the different body parts shown so disproportionately?

Which one is motor and which is sensory? Why?



Different parts of cortex for different functions

Phineas Gage: Phineas Gage was a railroad worker in the 19th century living in Cavendish, Vermont. One of his jobs was to set off explosive charges in large rock in order to break them into smaller pieces. On one of these instances, the detonation occurred prior to his expectations, resulting in a 42 inch long, 1.2 inch wide, metal rod to be blown right up through his skull and out the top. The rod entered his skull below his left cheek bone and exited after passing through the anterior frontal lobe of his brain.



Frontal

Different parts of cortex for different functions

Remarkably, Gage never lost consciousness, or quickly regained it (there is still some debate), suffered little to no pain, and was awake and alert when he reached a doctor approximately 45 minutes later. He had a normal pulse and normal vision, and following a short period of rest, returned to work several days later. However, he was not unaffected by this accident.

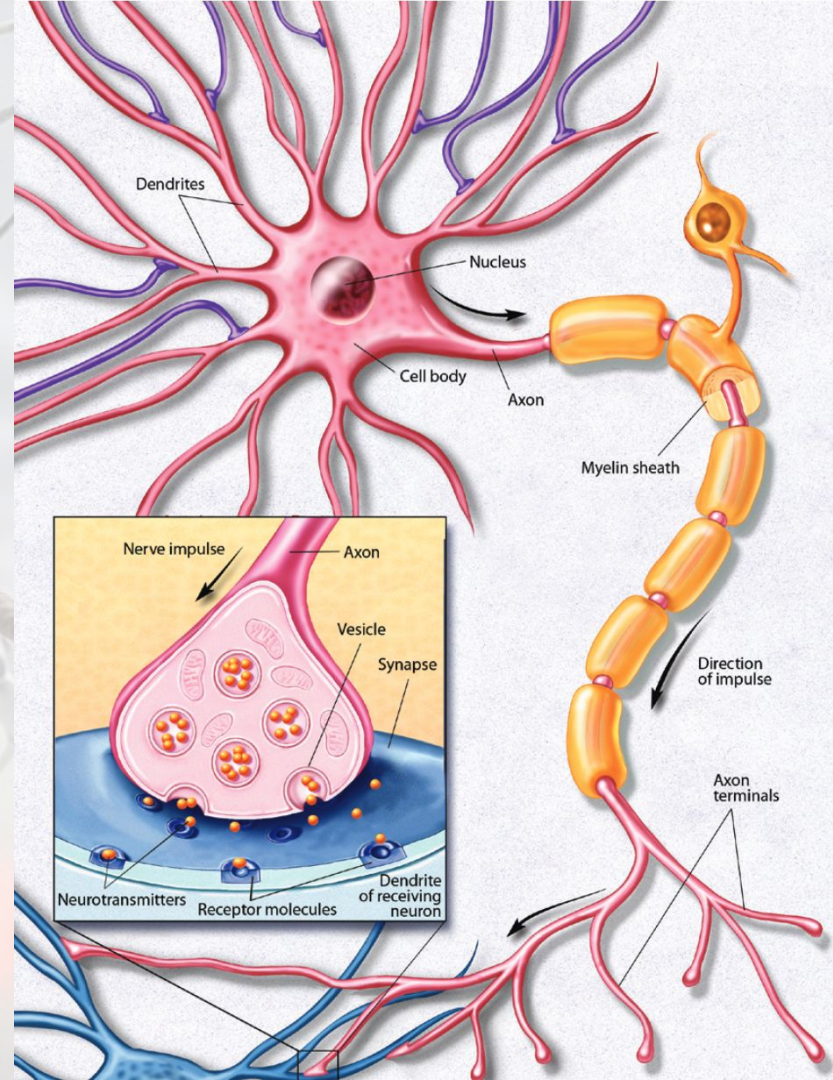


A: Gage's personality, reasoning, and capacity to understand and follow social norms had been diminished or destroyed. He illustrated little to no interest in hobbies or other involvements that at one time he cared for greatly. 'After the accident, Gage became a nasty, vulgar, irresponsible vagrant. His former employer, who regarded him as "the most efficient and capable foreman in their employ previous to his injury," refused to rehire him because he was so different.'

Photo by Dr. Anthony A. Walsh

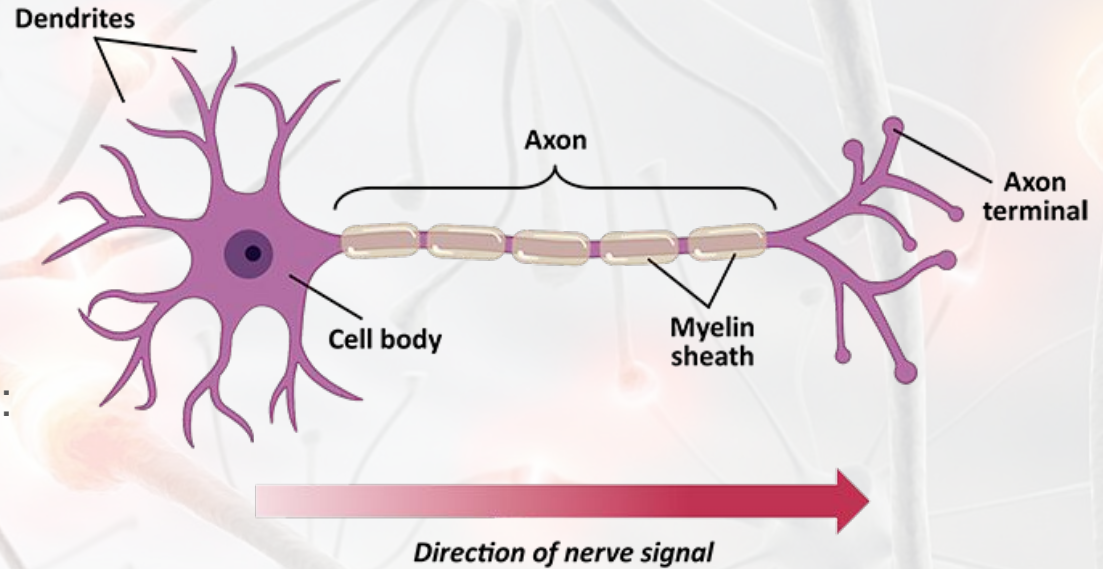
<http://www.sruweb.com/~walsh/gage5.jpg>

How does the brain work?



Neurons

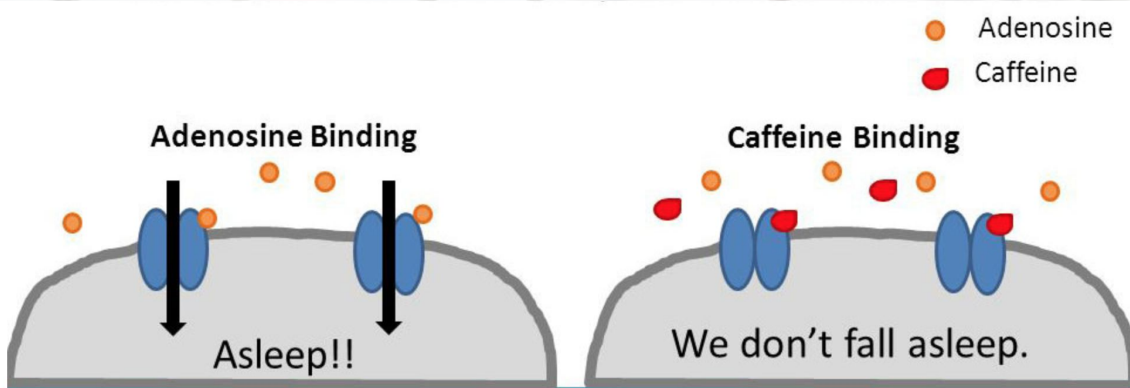
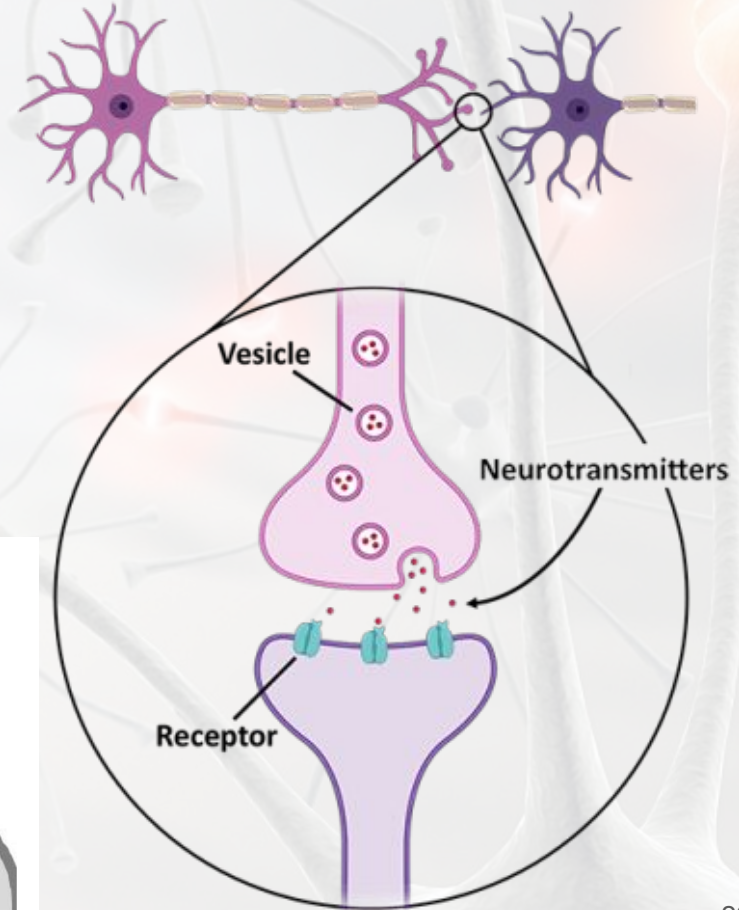
- The primary functional unit in the brain is a cell called the **neuron**
- Neurons consist of three parts: the **cell body**, **dendrites**, and the **axon**



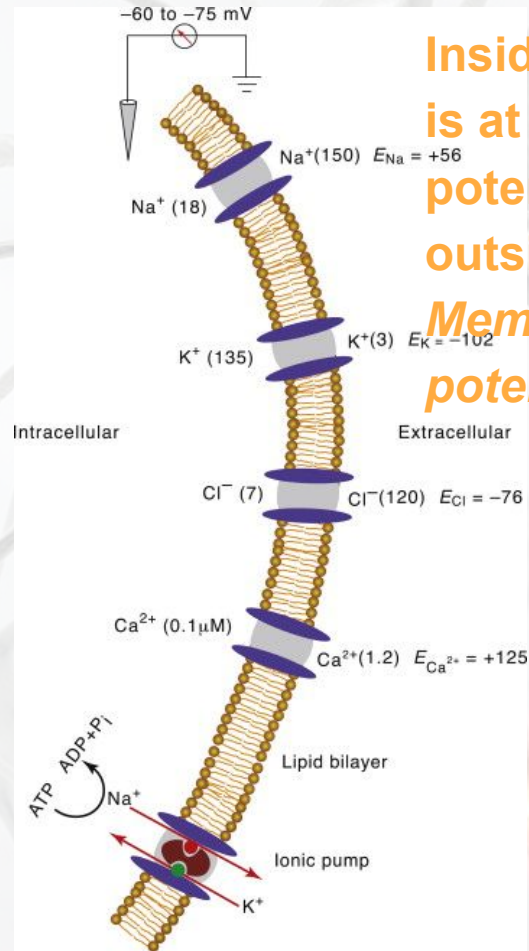
- **Dendrites** – Collect electrical signals from upstream neurons
- **Cell body** – Integrates incoming signals and generates the output
- **Axon** – Passes the generated output signal to the downstream neuron

Synapses – connections between neurons

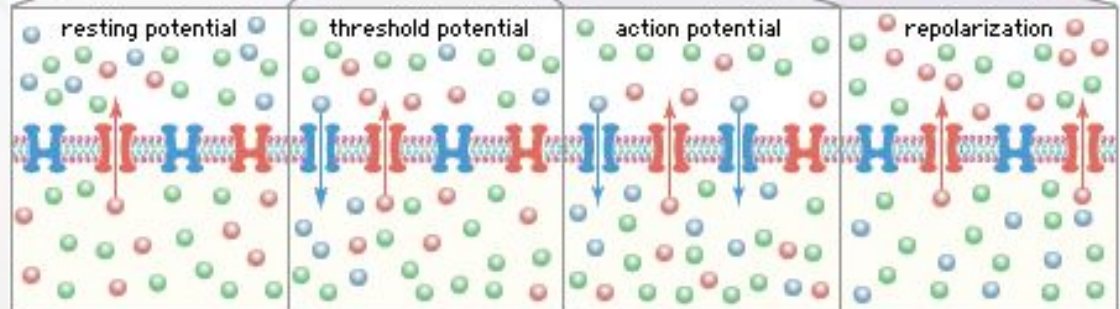
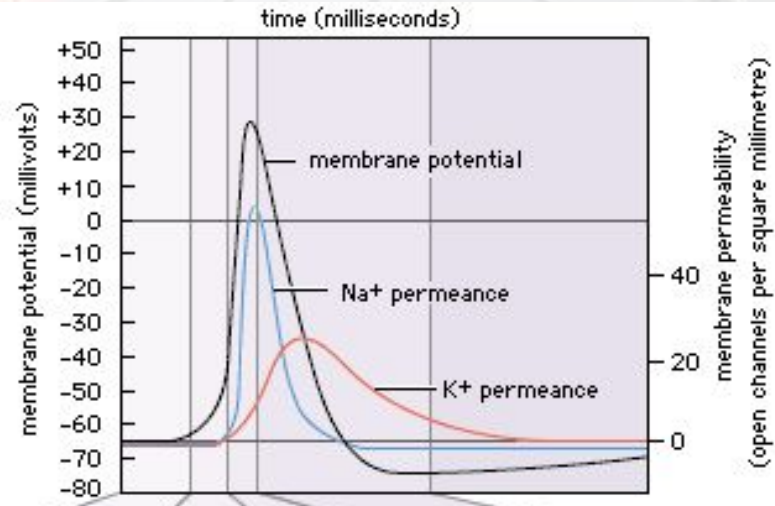
- When the signal from cell body reaches the end of the axon it stimulates the release of tiny sacs called **vesicles**
- These vesicles release chemicals known as **neurotransmitters** into the **synaptic cleft**
- The neurotransmitters cross the synapse and attach to **receptors** on the neighboring cell



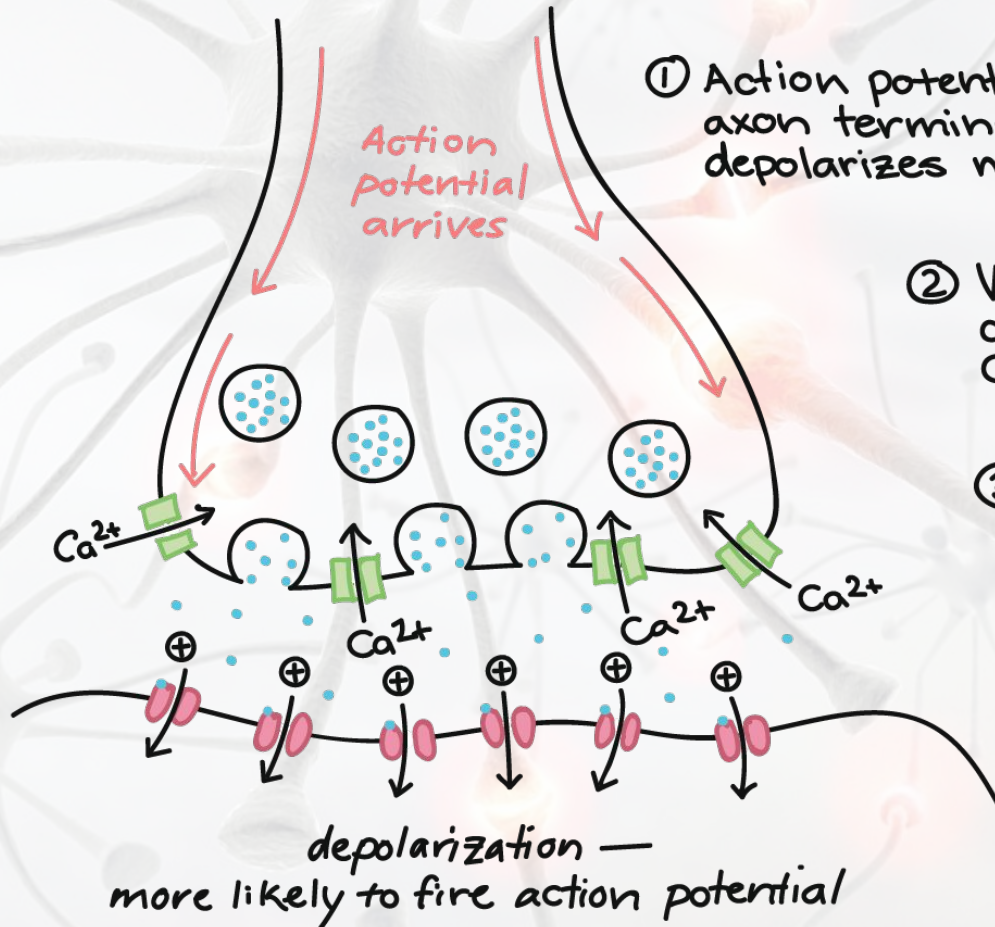
Action potentials – the signals inside neurons



Inside of neuron
is at a negative
potential wrt
outside!
Membrane potential



Action potential – generation



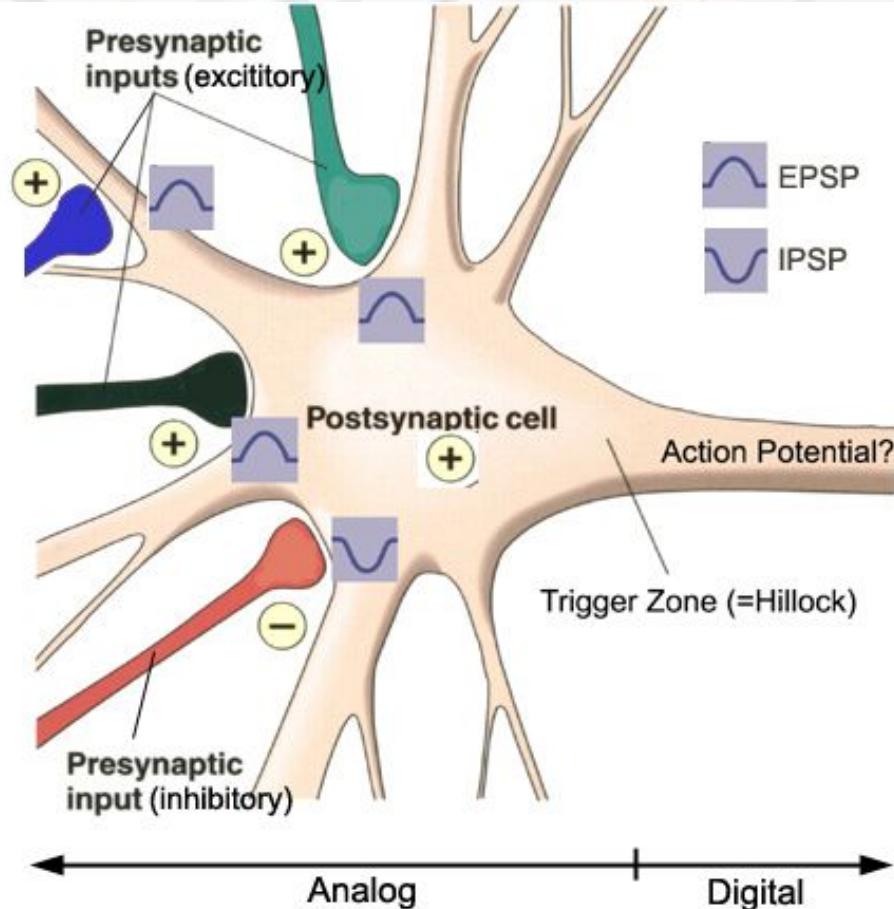
① Action potential reaches axon terminal and depolarizes membrane.

② Voltage-gated Ca^{2+} channels open and Ca^{2+} flows in.

③ Ca^{2+} influx triggers synaptic vesicles to release neurotransmitter.

④ Neurotransmitter binds to receptors on target cell (in this case, causing positive ions to flow in).

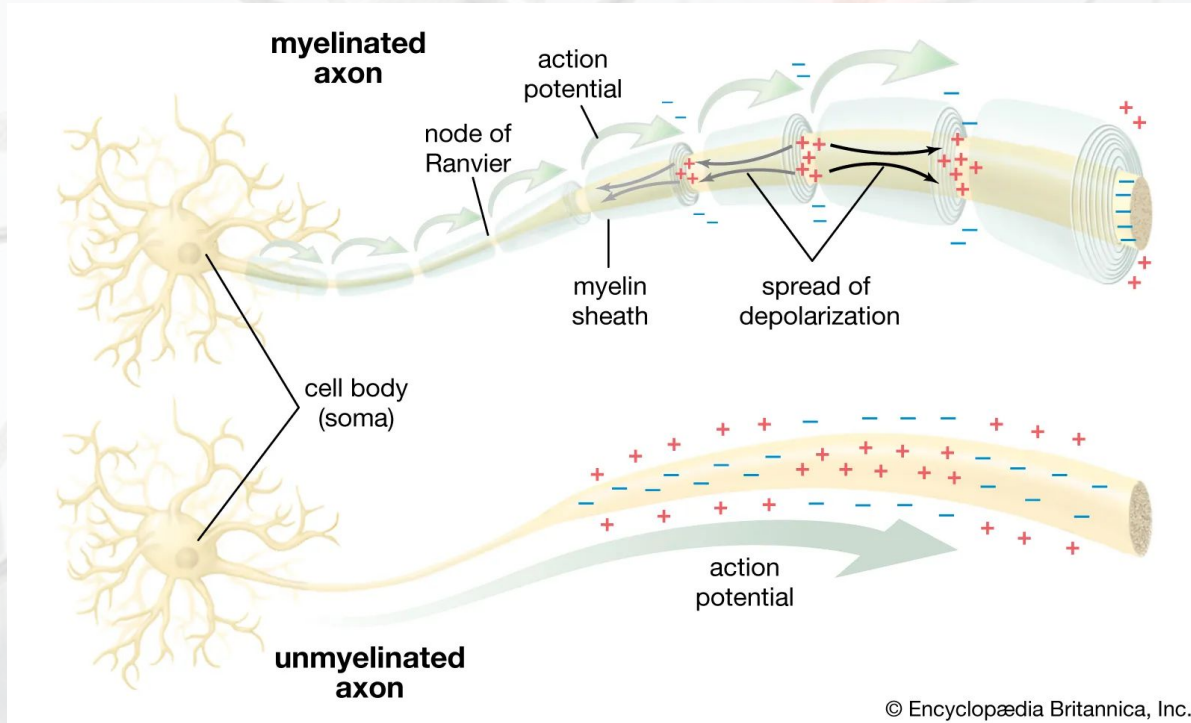
Action potential – integration



Different types of neurons
(and neurotransmitters):

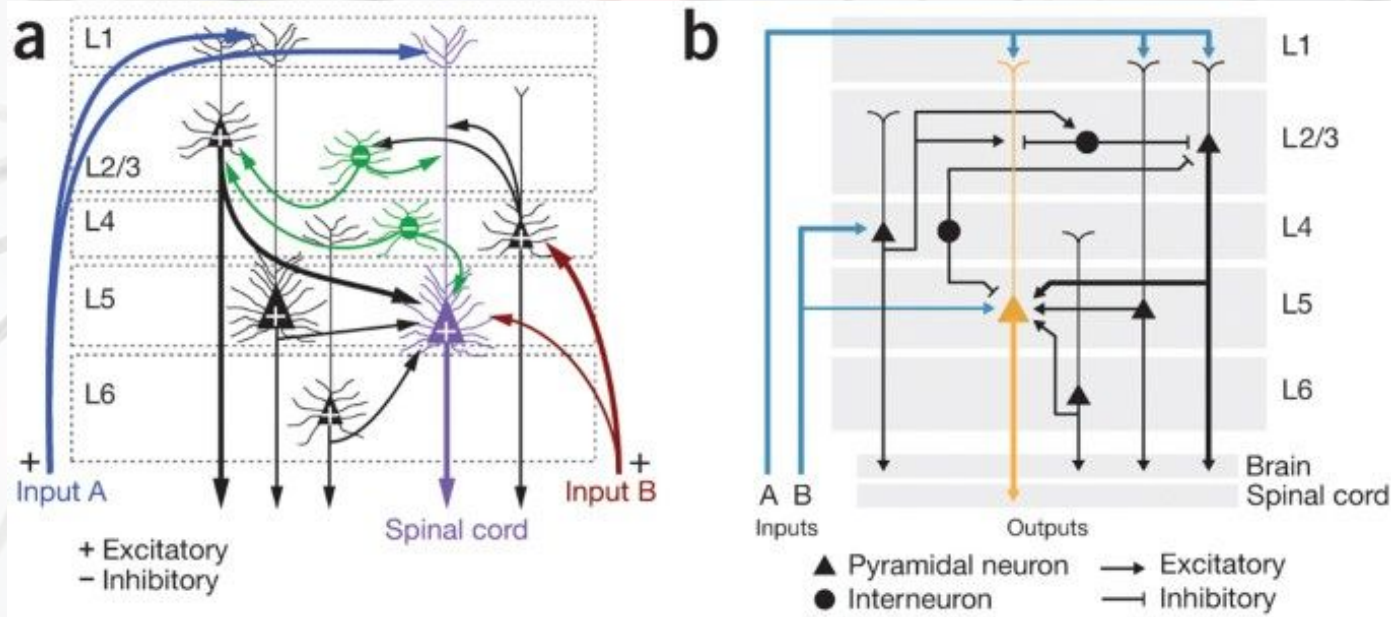
- **Inhibitory**: suppress the probability of firing of postsynaptic neuron (**hyperpolarization**)
- **Excitatory**: enhance the probability of firing of postsynaptic neuron (**depolarization**)
- *Excitatory (/Inhibitory)
Post Synaptic Potential

Action potential – transport



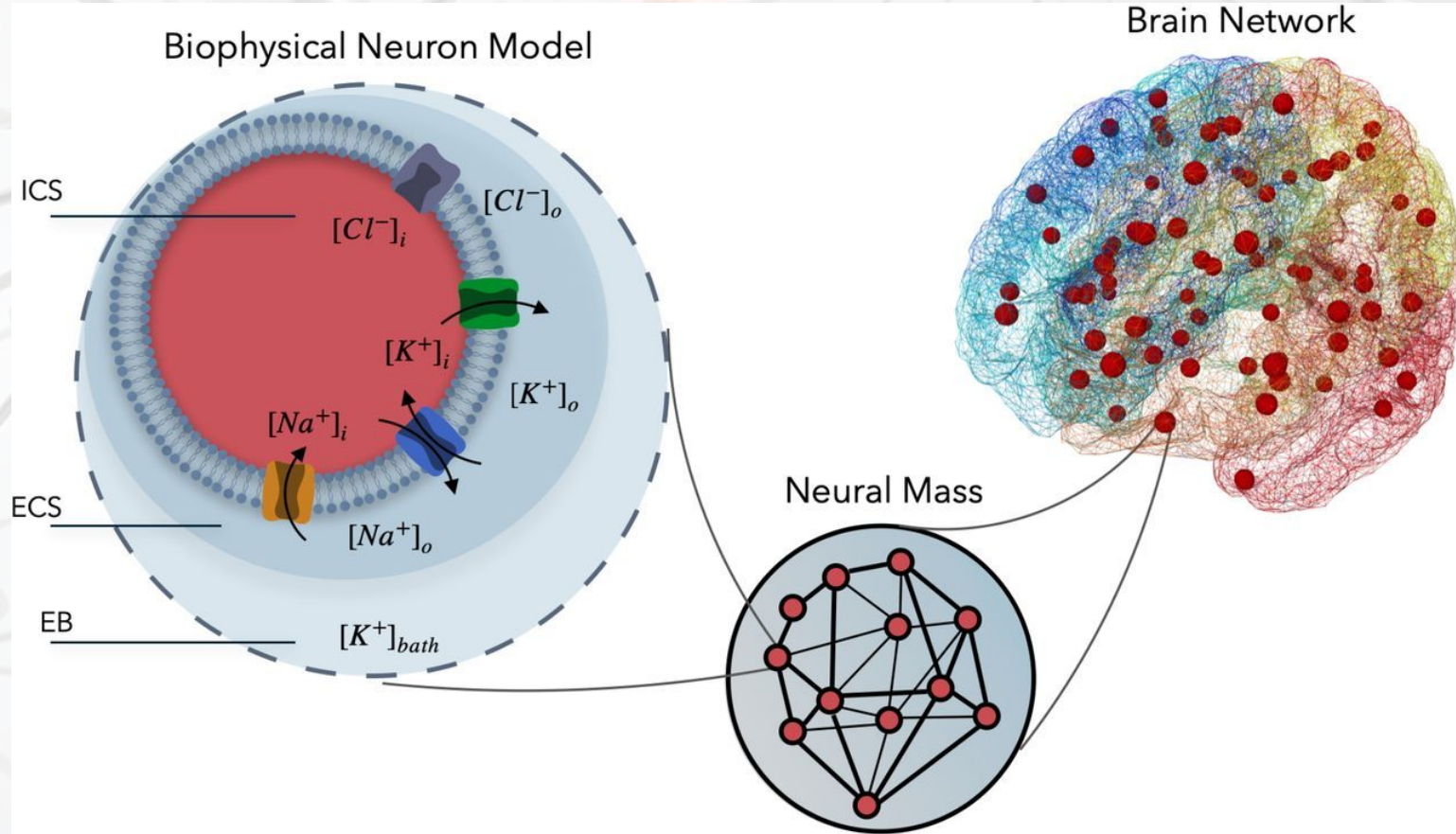
- **Unmyelinated axon:** AP flows along the axon as neighboring ion channels open and close
- **Myelinated axon:** AP jumps from one node to the next; much faster, and lower energy loss

From neurons to circuits



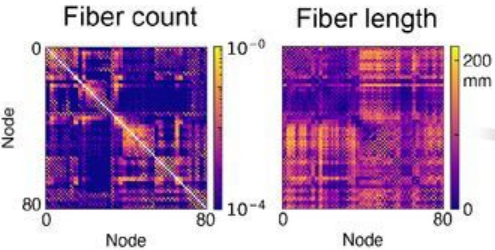
- How are specific micro-computations implemented? For example:
- How do sensory and motor systems form a feedback loop for guiding movement?
- How do neurons compute error between predicted and actual sensory inputs?

From circuits to neural masses

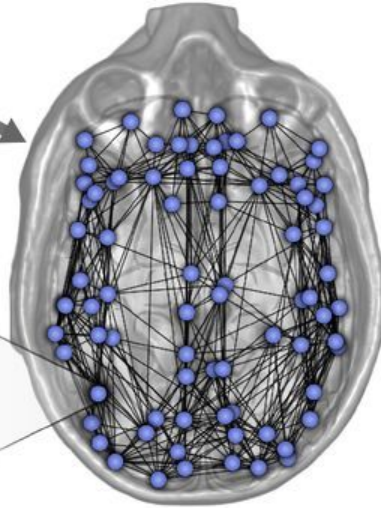


Whole-brain models

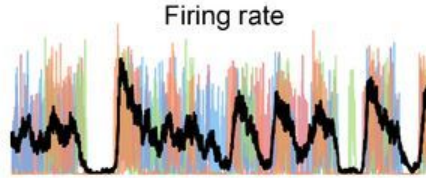
Structural connectivity



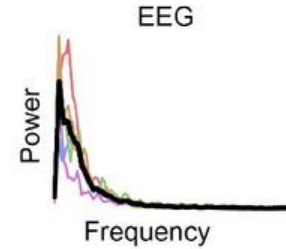
Whole-brain model



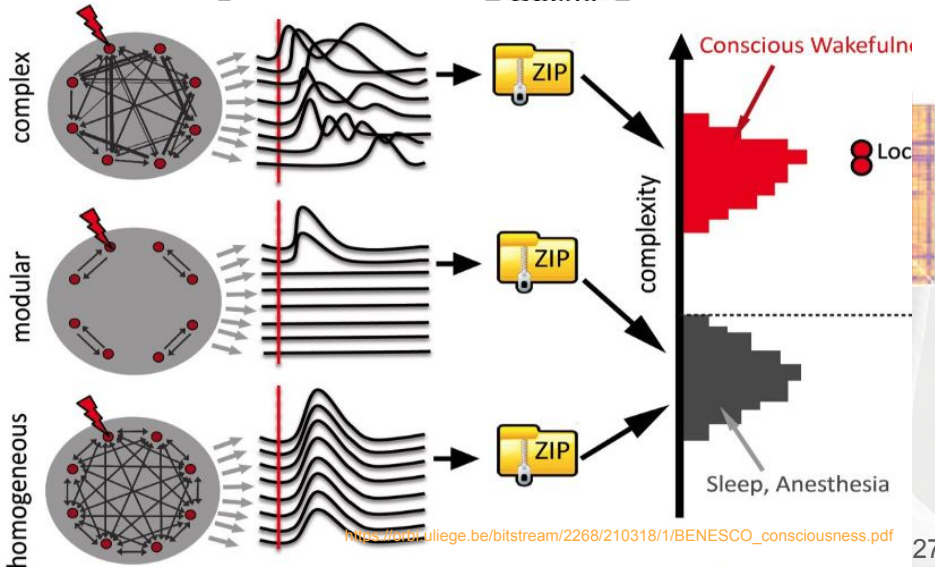
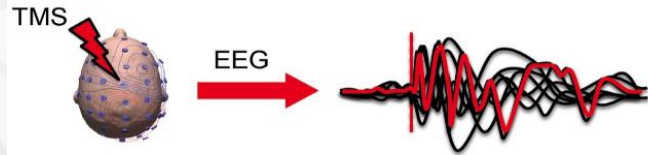
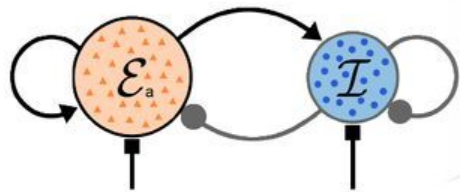
Simulated output



Empirical recordings



Neural mass model



Overview of topics

I Foundations of Neuronal Dynamics

1 Introduction

2 The Hodgkin-Huxley Model

3 Dendrites and Synapses

4 Dimensionality Reduction and Phase Plane Analysis

II Generalized Integrate-and-Fire Neurons

5 Nonlinear Integrate-and-Fire Models

6 Adaptation and Firing Patterns

7 Variability of Spike Trains and Neural Codes

8 Noisy Input Models: Barrage of Spike Arrivals

9 Noisy Output: Escape Rate and Soft Threshold

10 Estimating Models

11 Encoding and Decoding with Stochastic Neuron models

III Networks of Neurons and Population Activity

12 Neuronal Populations

13 Continuity Equation and the Fokker-Planck Approach

14 The Integral-equation Approach

15 Fast Transients and Rate Models

IV Dynamics of Cognition

16 Competing Populations and Decision Making

17 Memory and Attractor Dynamics

18 Cortical Field Models for Perception

19 Synaptic Plasticity and Learning

20 Outlook: Dynamics in Plastic Networks