COMPUTATIONAL NEUROSCIENCE

Research group at the University of Tartu

Introduction to Computational Neuroscience

Lecture 2: Structure and function of the NS

Lesson	Title
1	Introduction
2	Structure and Function of the NS
3	Windows to the Brain
4	Data analysis
5	Single neuron models
6	Network models
7	Artificial neural networks
8	Artificial intelligence
9	Learning and memory
10	Perception
11	Attention & decision making
12	Brain-Computer interface
13	Neuroscience and society
14	Future and outlook
15	Projects presentations
16	Projects presentations

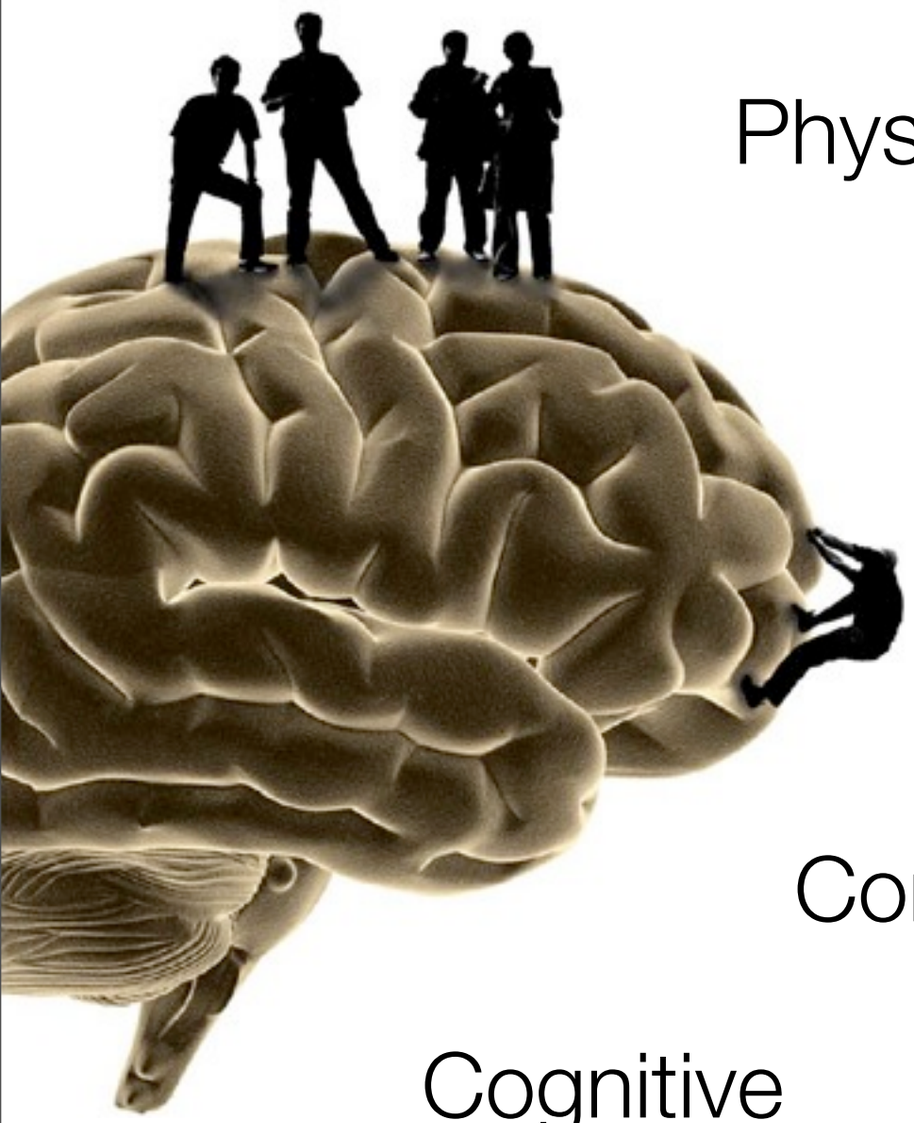
Basics

Analyses

Models

Cognitive

Applications



Physiology → Function

Anatomy → Structure

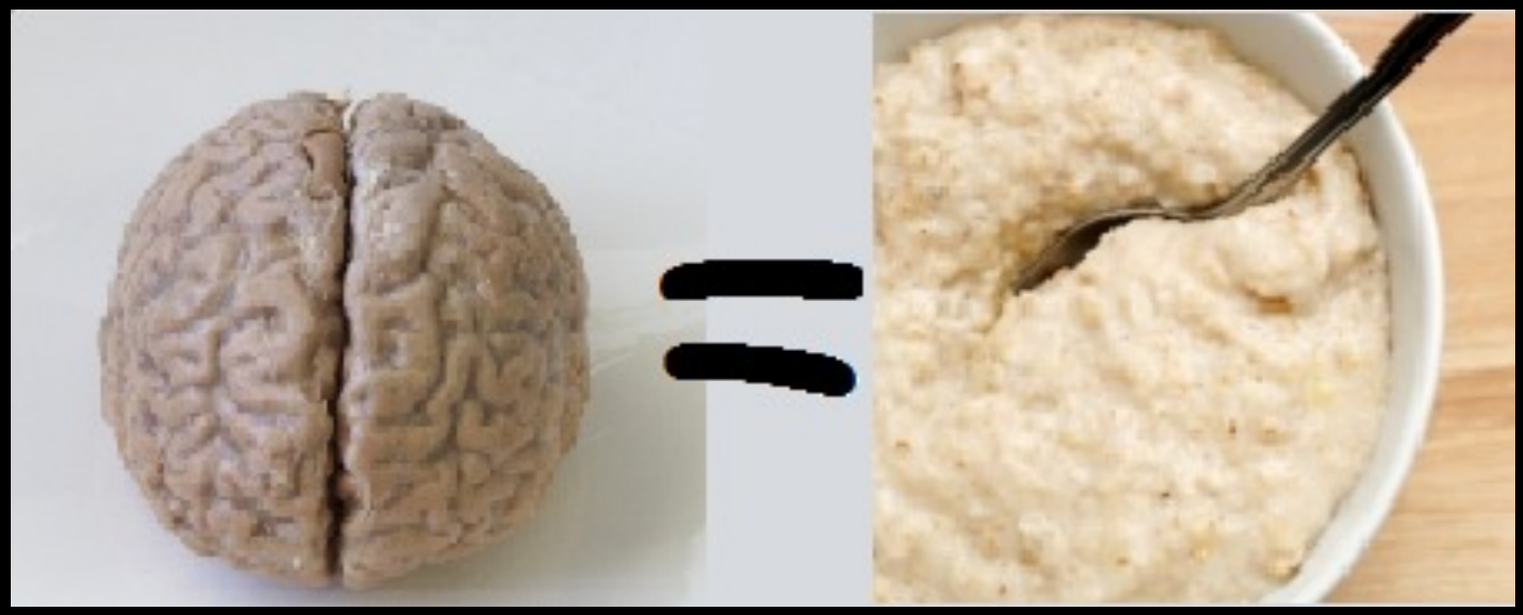
Clinical

Computational → Information processing

Cognitive

Behavioral

Cellular, Molecular, Developmental, Evolutionary,...



“One of the difficulties in understanding the brain is that it is like nothing so much as a lump of porridge”

R.L. Gregory

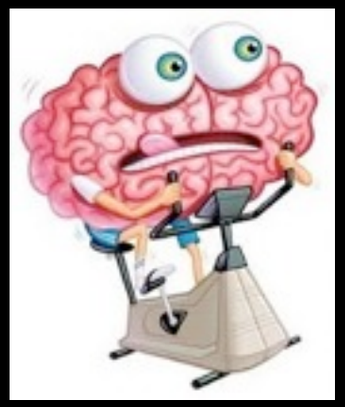
Eye and the Brain: the psychology of seeing,
New York, 1966, McGraw-Hill

“What I cannot create, I don’t understand”

R. Feynman

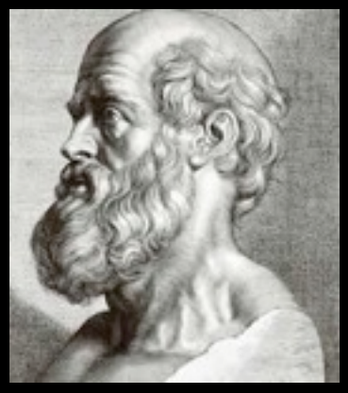
Where mental faculties sit?

vs.



Ancient Egypt

Aristotle



Hippocrates

Plato

Galen

What are the building blocks?

1906 Nobel Prize in Medicine or Physiology

Learning objectives

- Cell types (neurons and glial cells)
- Methods of communication (synapses)
- Organization of the NS (the basic plan)

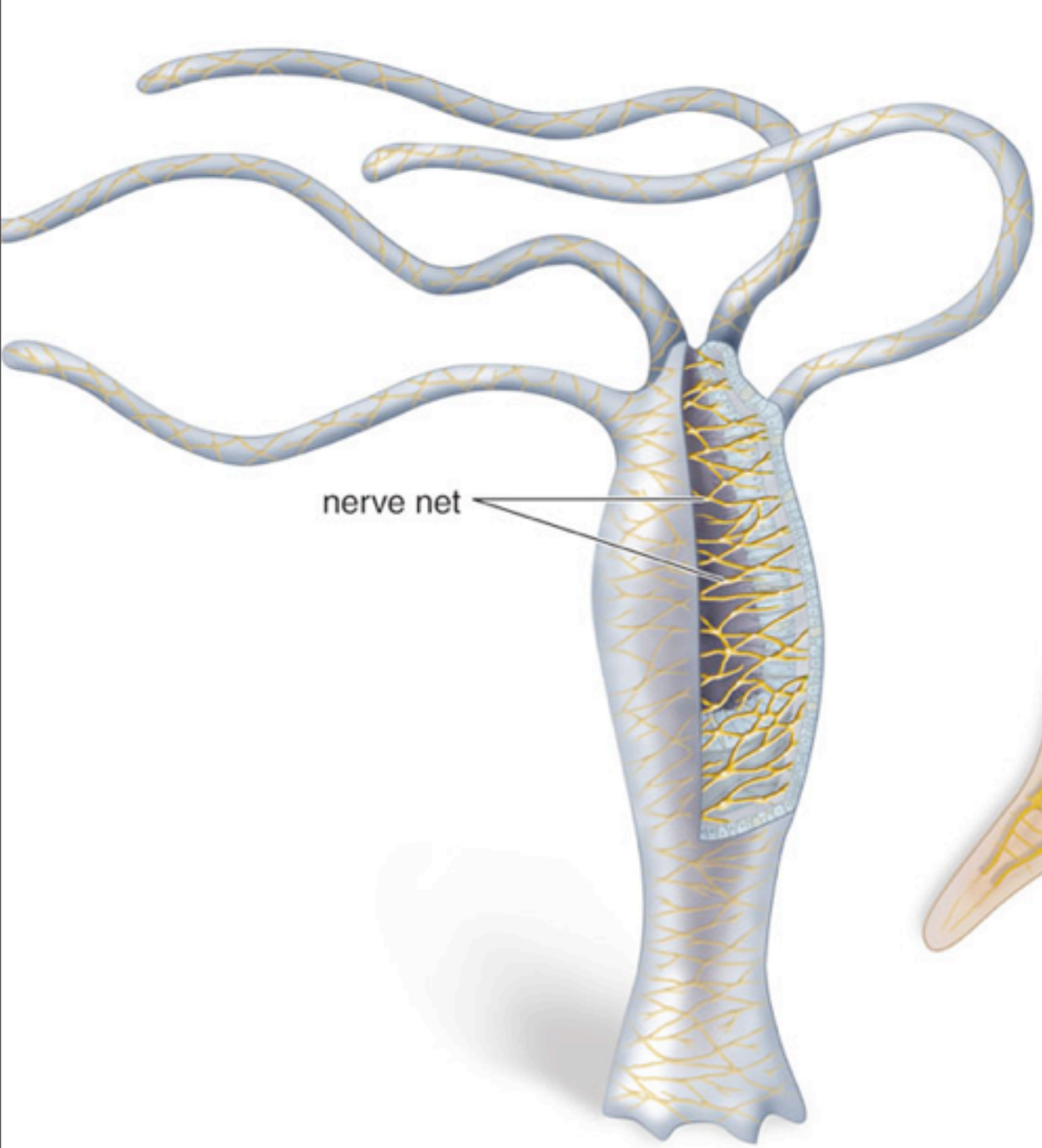
Introduction to the NS

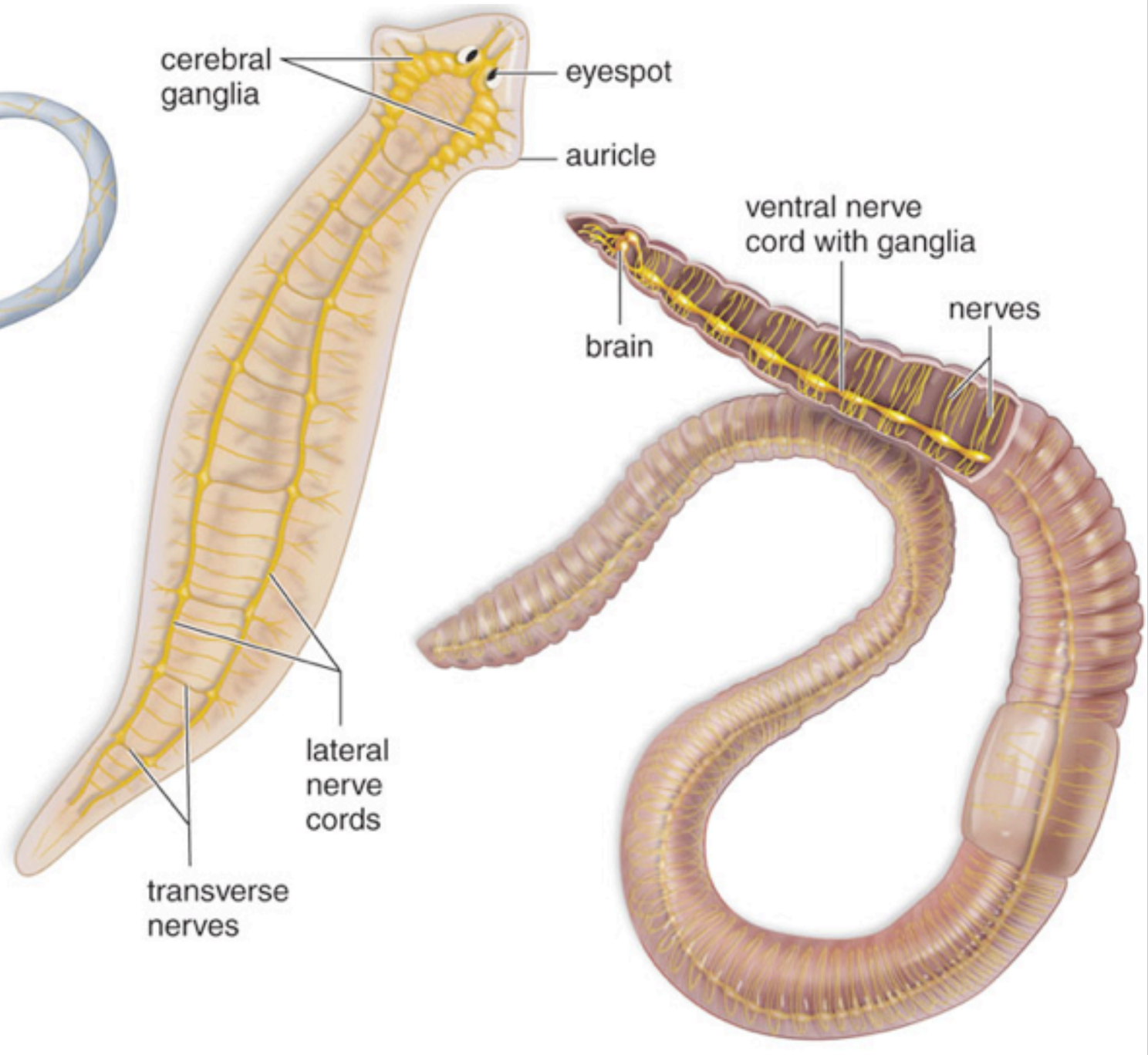
Gross anatomy of the CNS

Neuronal signaling

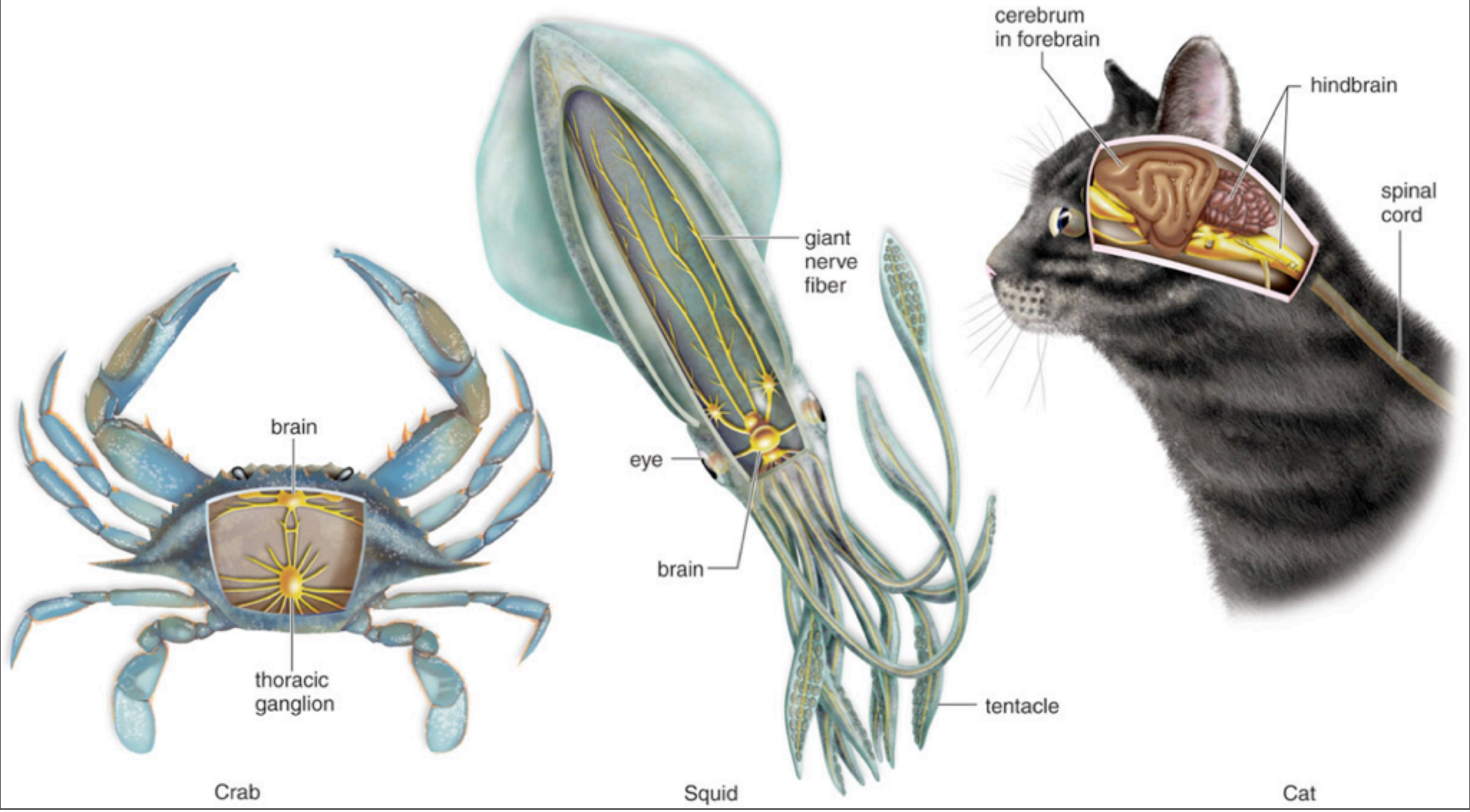
Most animals have a nervous system that allows responses to stimuli

Evolution of the NS

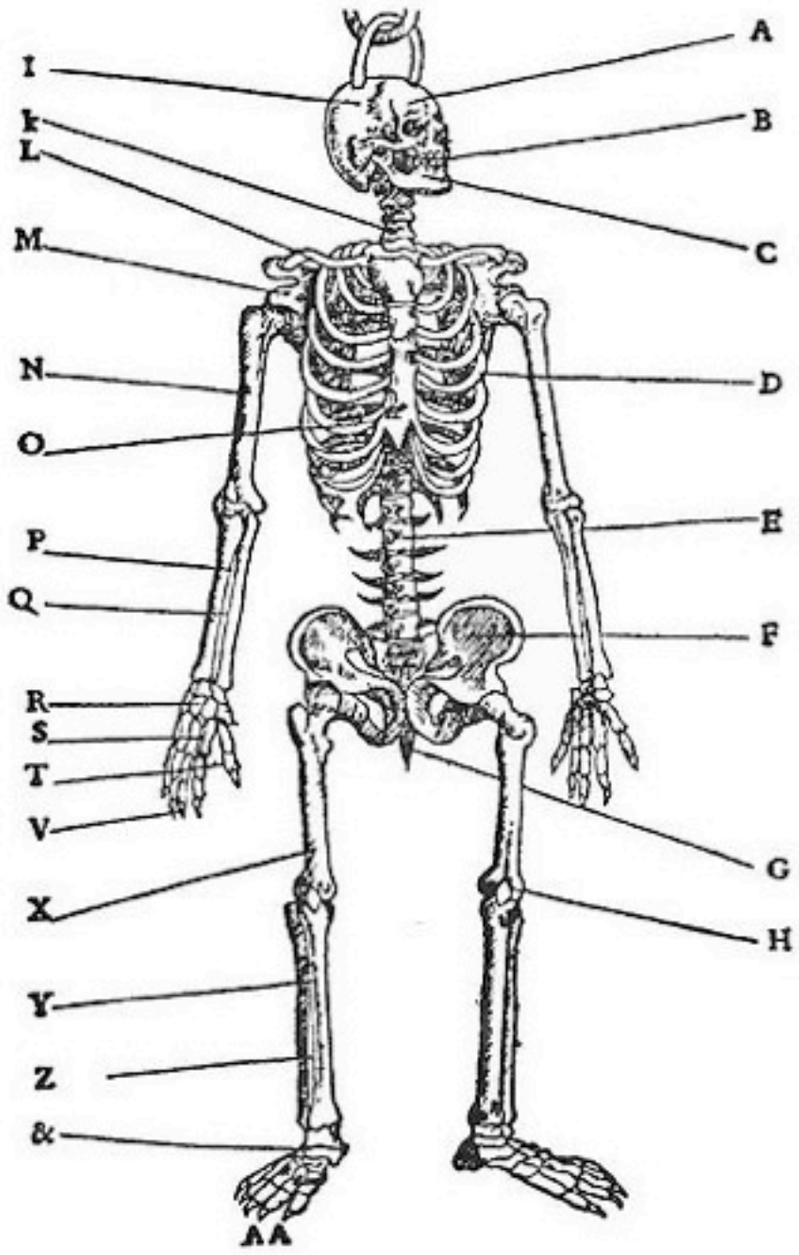




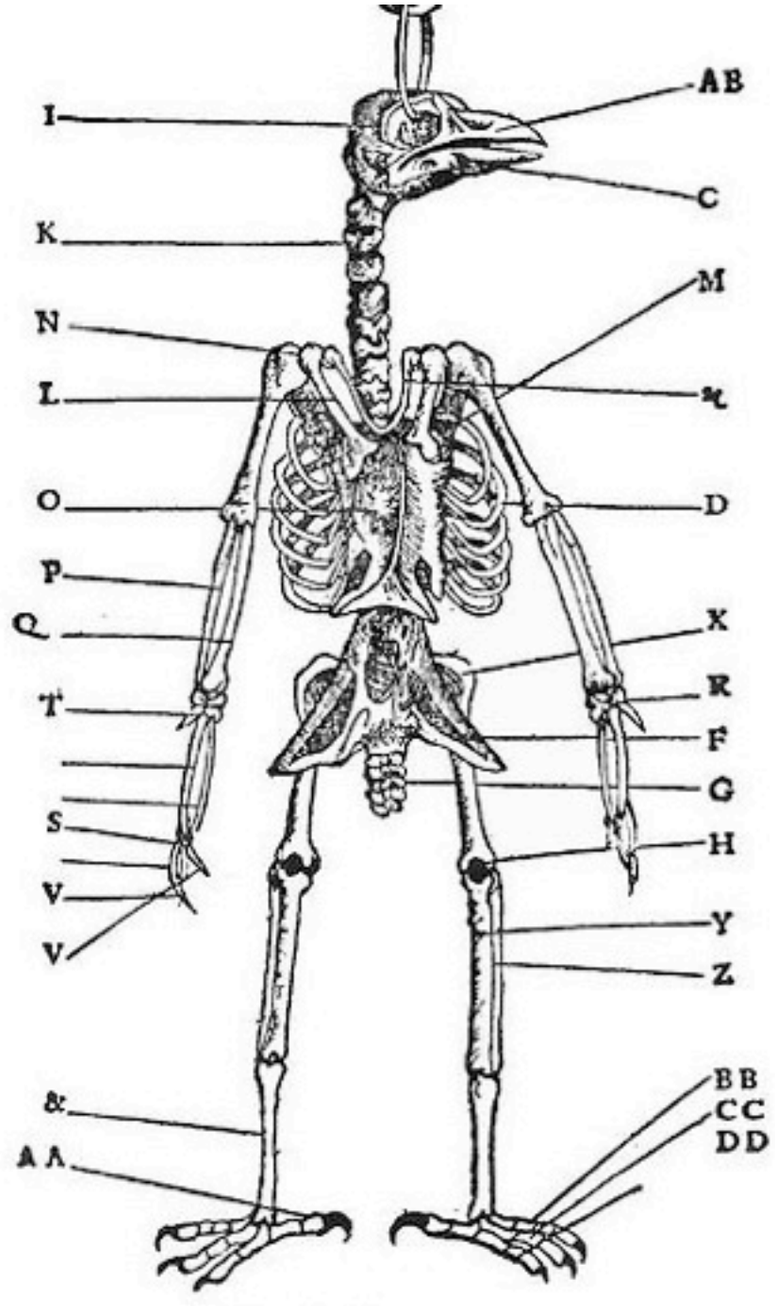
Evolution of the NS



Evolution of the NS



HUMAN SKELETON.



BIRD'S SKELETON.

From Belon's *Book of Birds*, 1555.

Division of the vertebrate NS

The nervous system has central and peripheral parts:

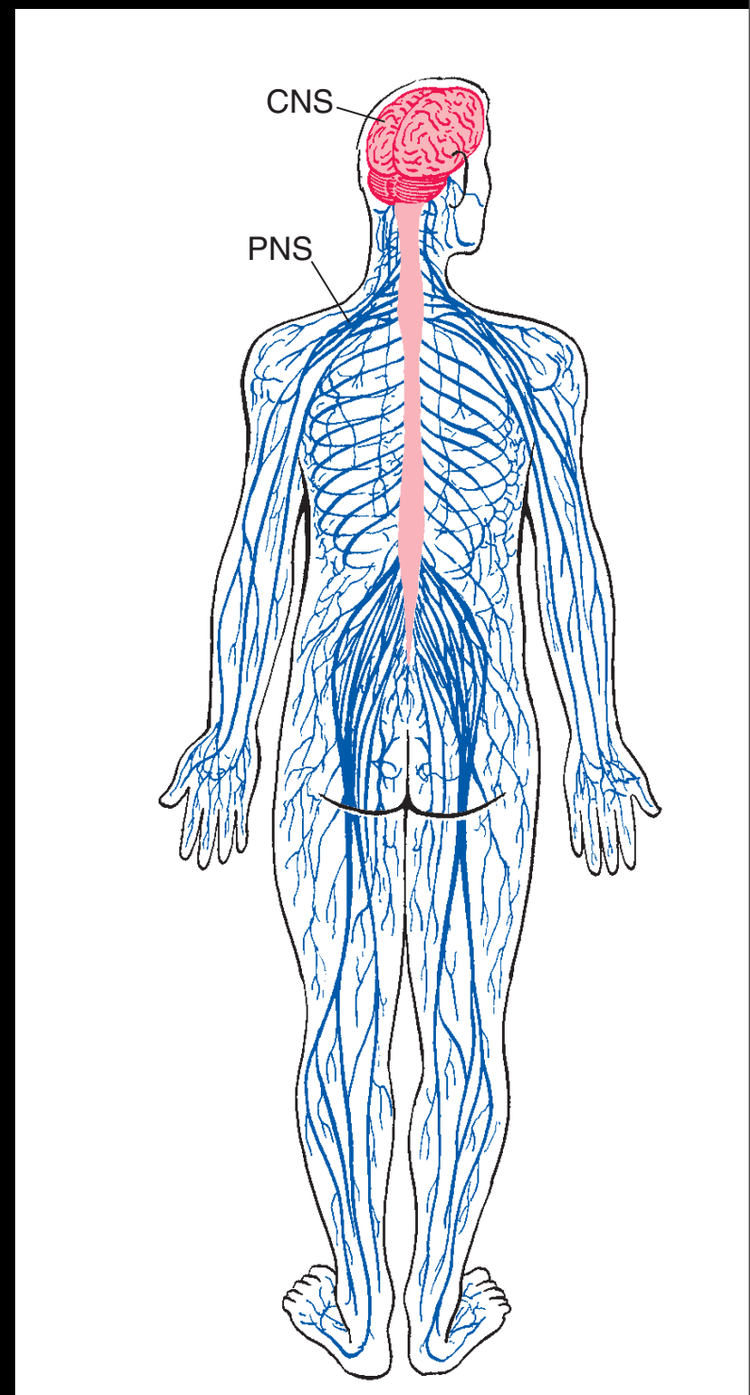
Central Nervous System (CNS)

* Brain
* Spinal cord

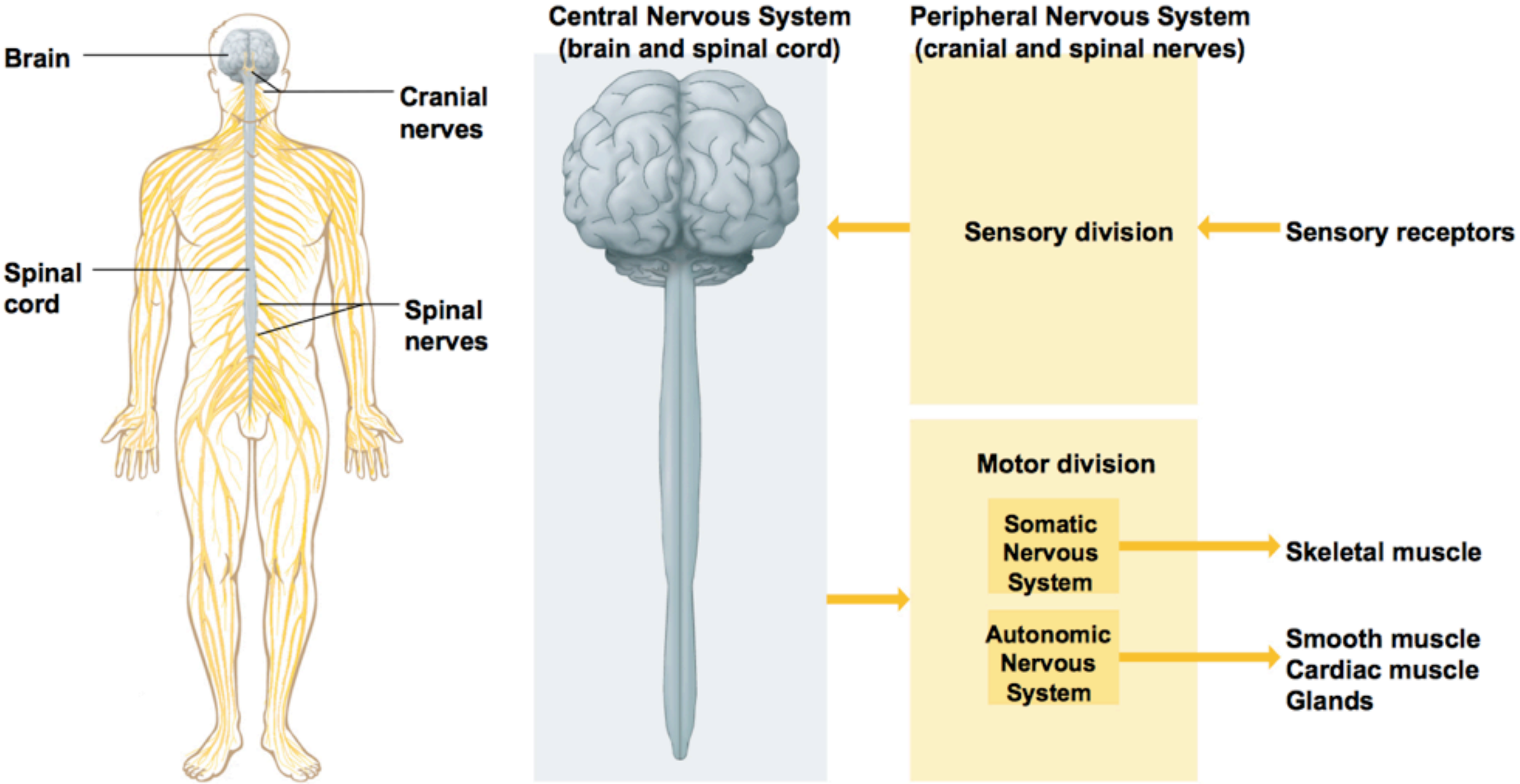
Peripheral Nervous System (PNS)

Nerves outside the brain and spinal cord

* Cranial nerves
* Spinal nerves



Division of the vertebrate NS



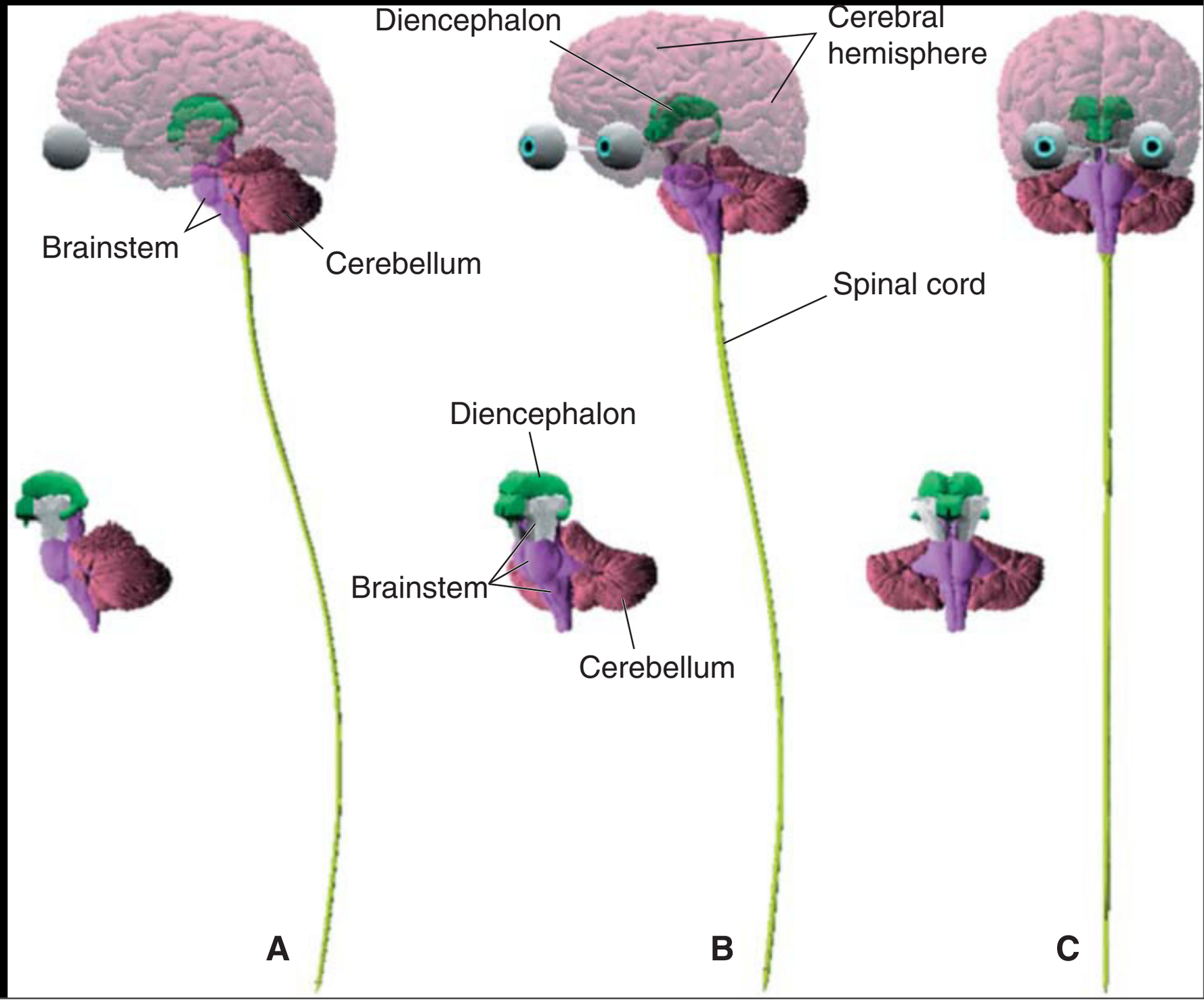
Division of the CNS

The brain itself has multiple subdivisions:

Cerebrum

Cerebellum

Brain stem



Division of the PNS

Sensory division

Picks up sensory information and delivers it to the CNS

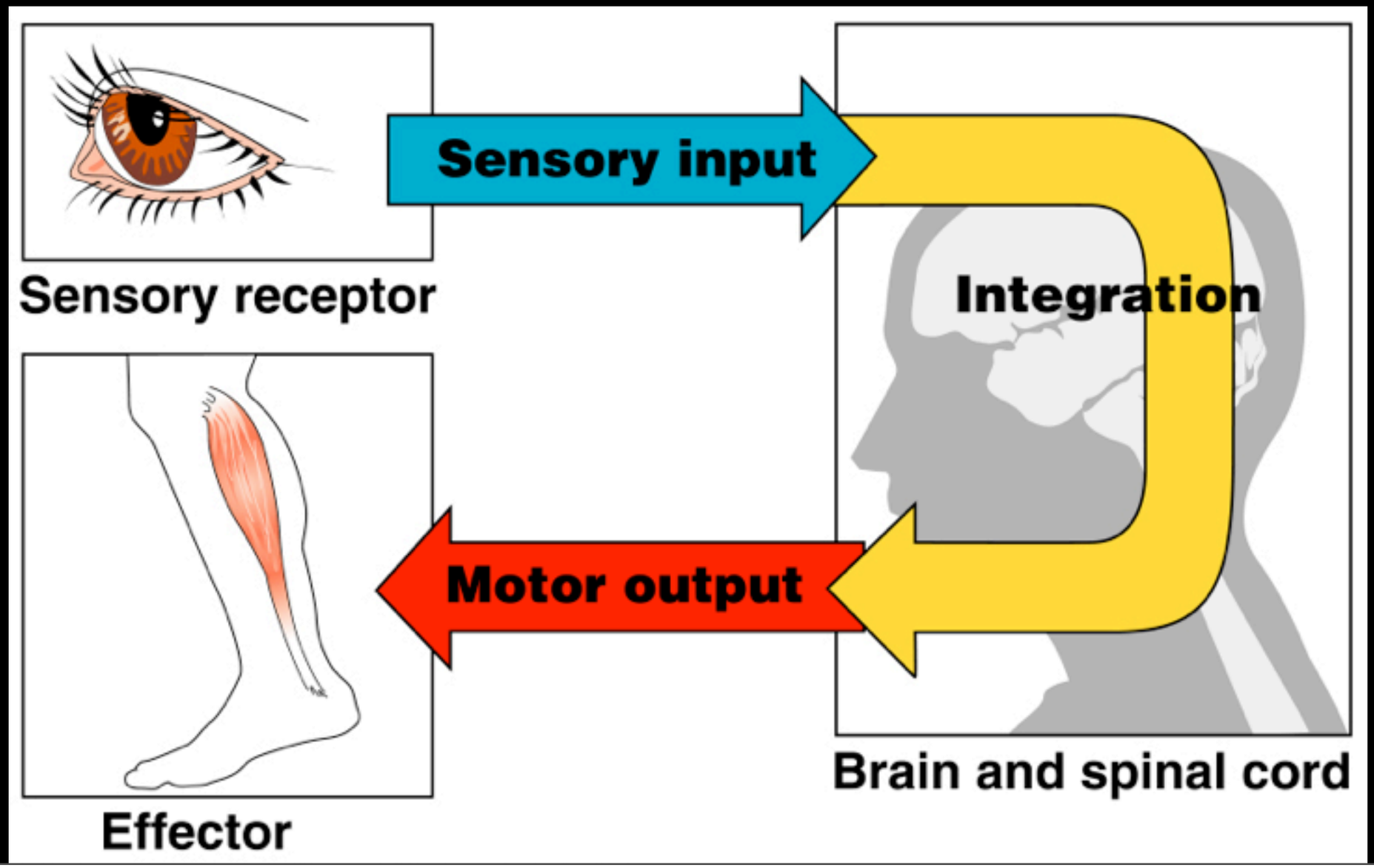
Motor division

Carries information to muscles and glands

* Divisions of the Motor division
    * Somatic carries information to skeletal muscle
    * Autonomous carries information to smooth muscle, cardiac muscle, and glands

Function of the NS

CNS and PNS must work in harmony to carry 3 main functions



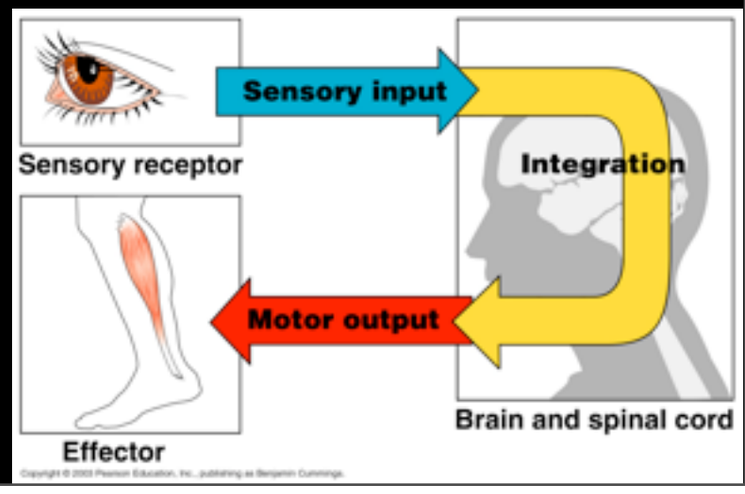
Function of the NS

CNS and PNS must work in harmony to carry
3 main functions

1 Receive sensory input

Monitor changes occurring inside and outside the body (changes = stimuli)

* Sensory receptors gather information
* Information is carried to the CNS



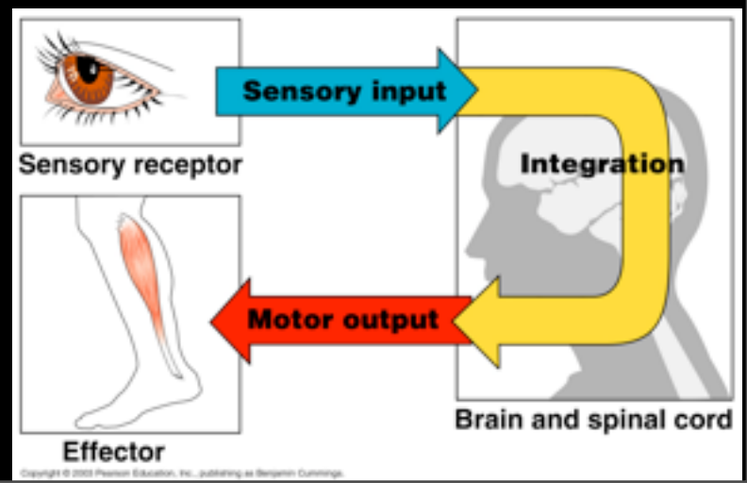
Function of the NS

CNS and PNS must work in harmony to carry
3 main functions

2 Perform integration

To process and interpret sensory input and decide if action is needed

Sensory information is used to create
* Sensations
* Memory
* Thoughts
* Decisions



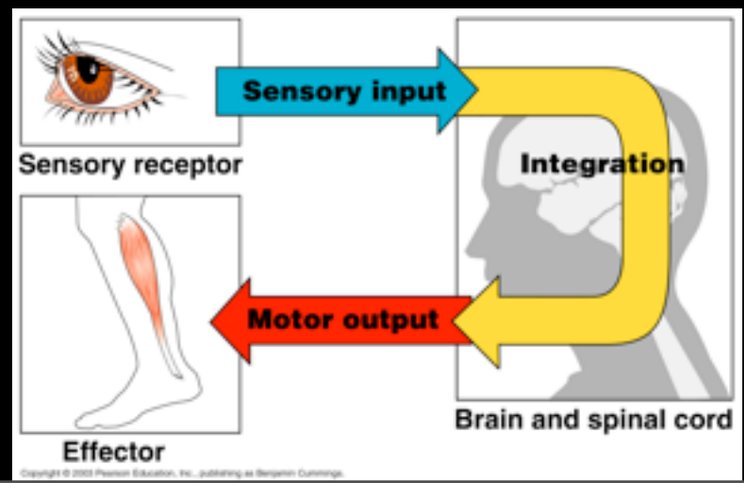
Function of the NS

CNS and PNS must work in harmony to carry
3 main functions

3 Generate motor output

A response to integrated stimuli is given

* Decisions are acted upon
* Impulses are carried to effectors (muscles or glands)

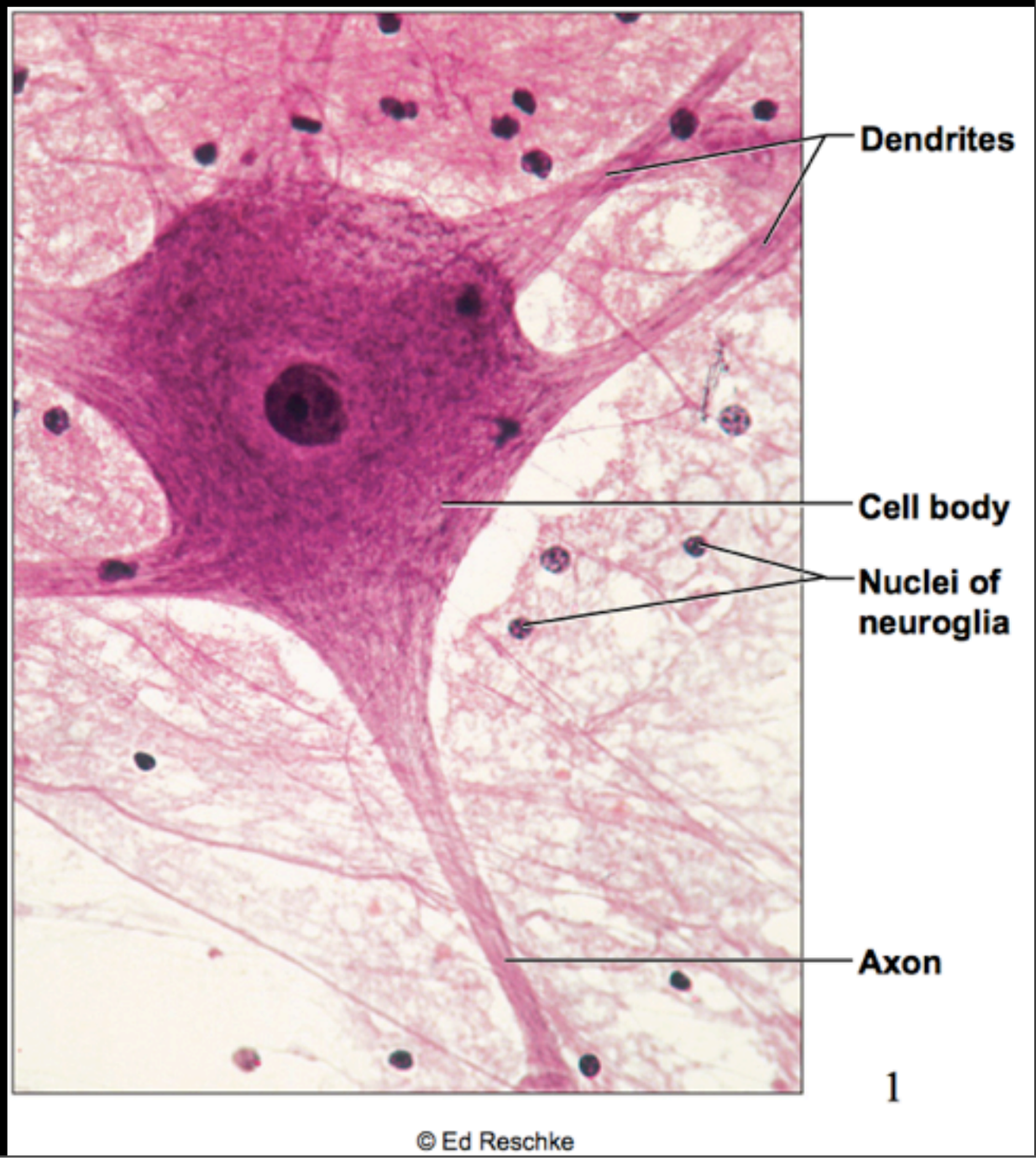


Cellular elements

2 cell categories in the nervous system:

Neurons (information processing, signaling elements, 100 billion)

Glial cells (supporting roles, 10 x neurons)



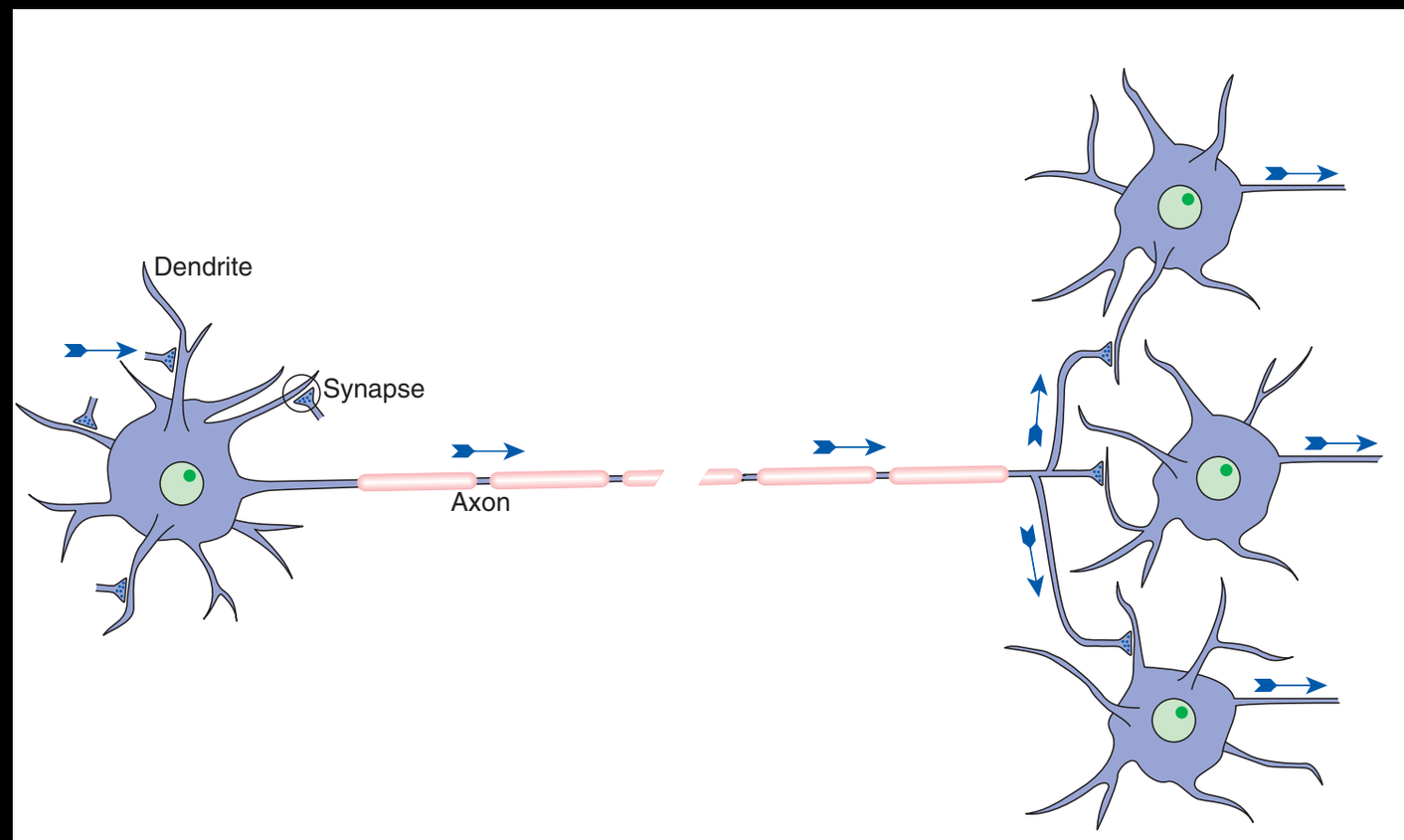
Neurons: compartments

Neurons have specialized zones for collecting, integrating, conducting, and transmitting information.

Soma supports metabolic and synthetic needs

Dendrites receive information from other neurons via synapses

Axon conducts information away from cell body



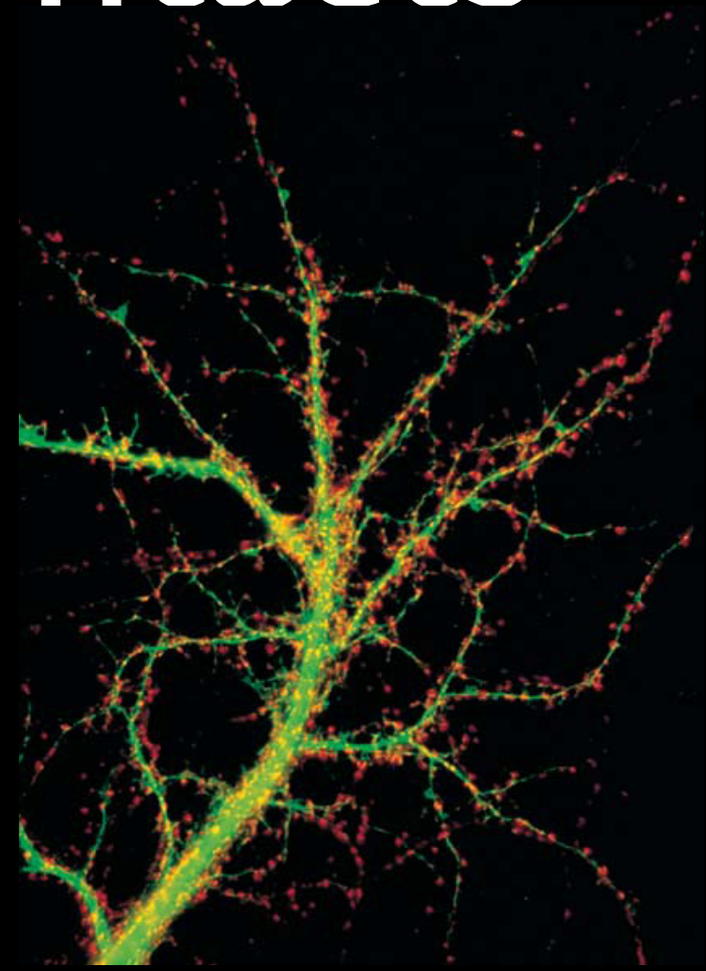
Neurons: synaptic contacts

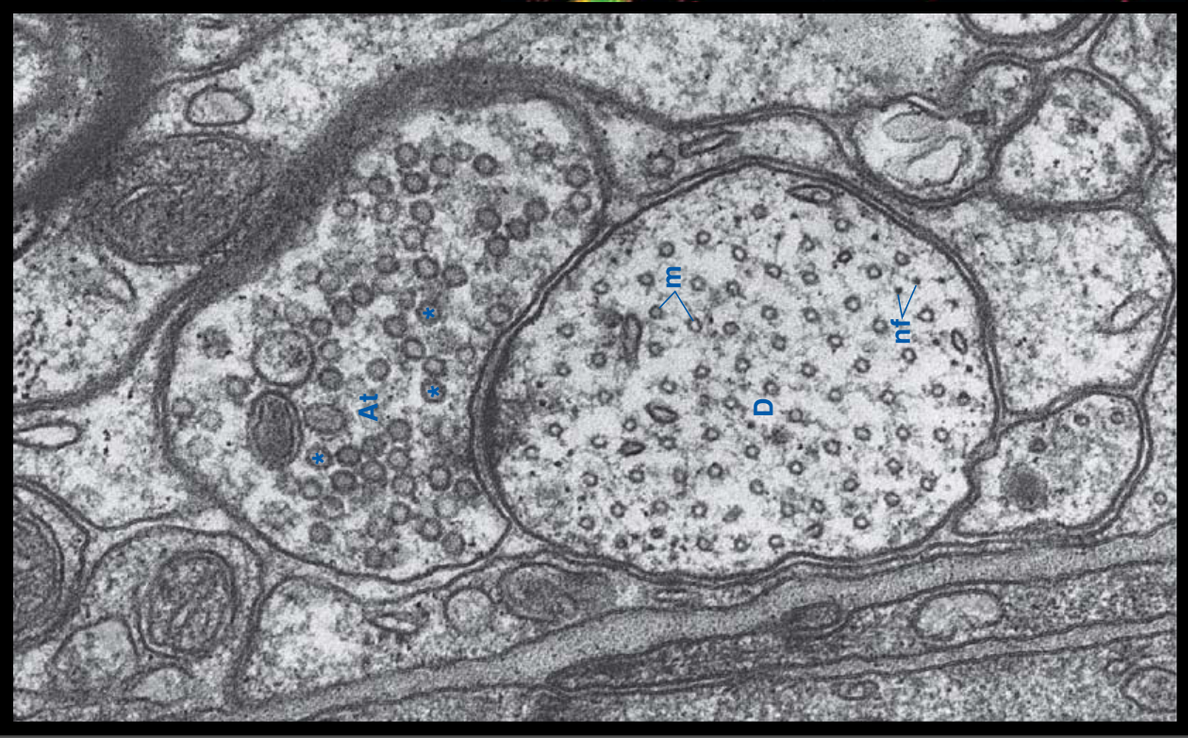
Synapse: axonal end abupts on other neuron (dendrites). A few thousand per cell

2 to 20 nm space (Cajal vs Golgi)

Electrical ⟶ Chemical ⟶ Electrical
(neurotransmitters)

Computational advantages



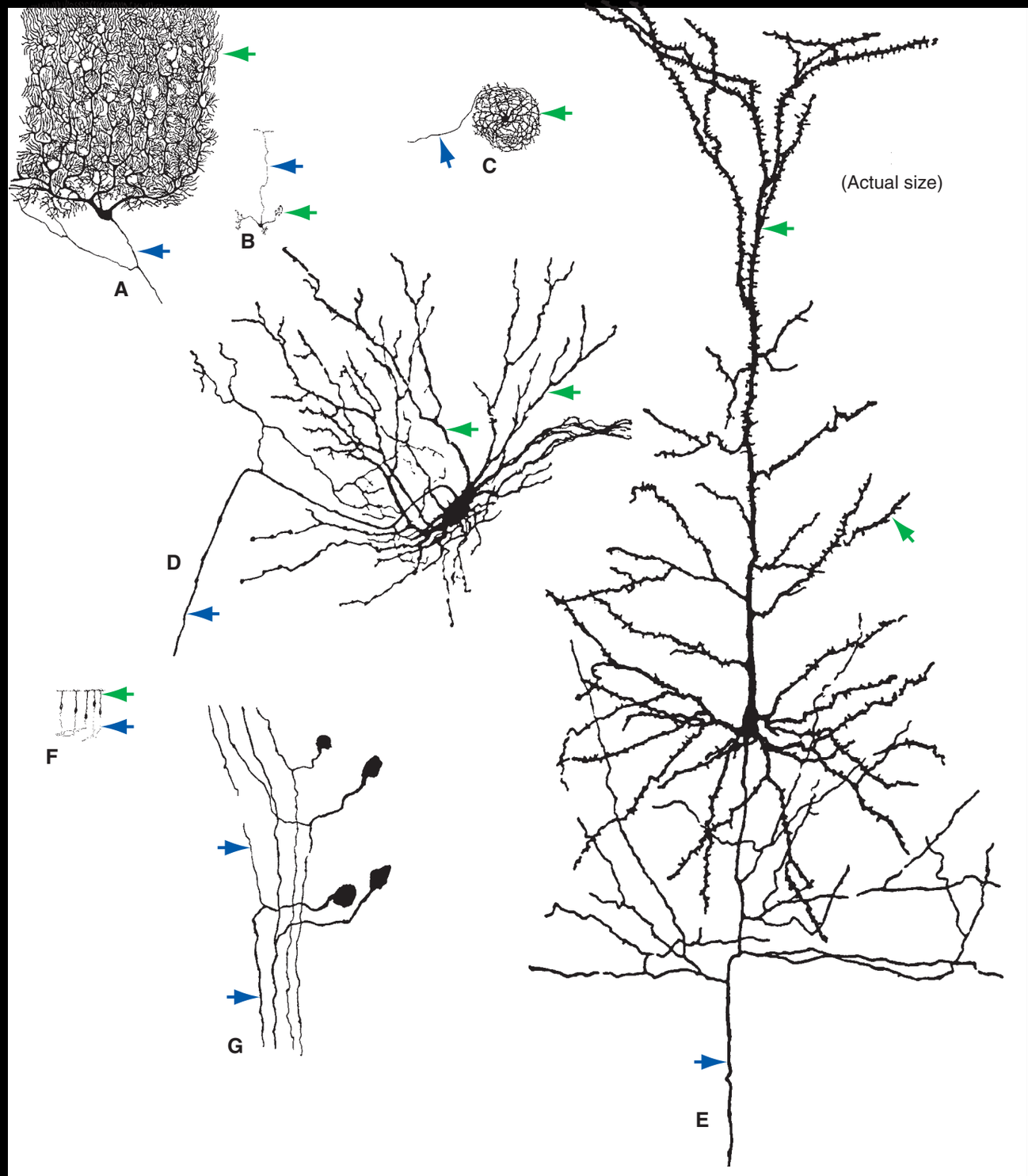


Neurons: diversity

Neurons come in a variety of sizes and shapes, but all are variations of the same theme

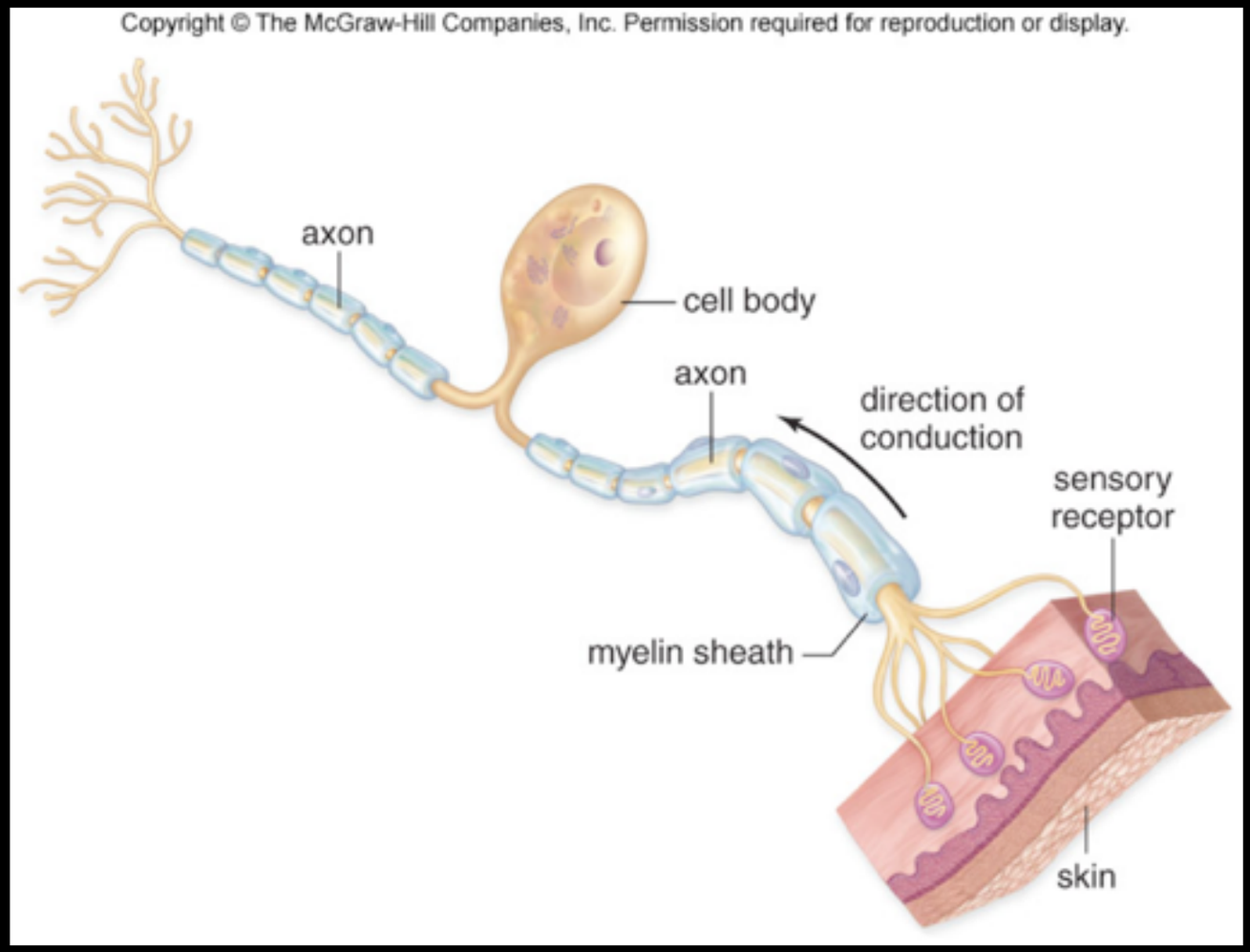
Cell bodies range from 5 to 100 micras in diameter

Most axons around 1 mm but some 1 m



Neurons: functional types

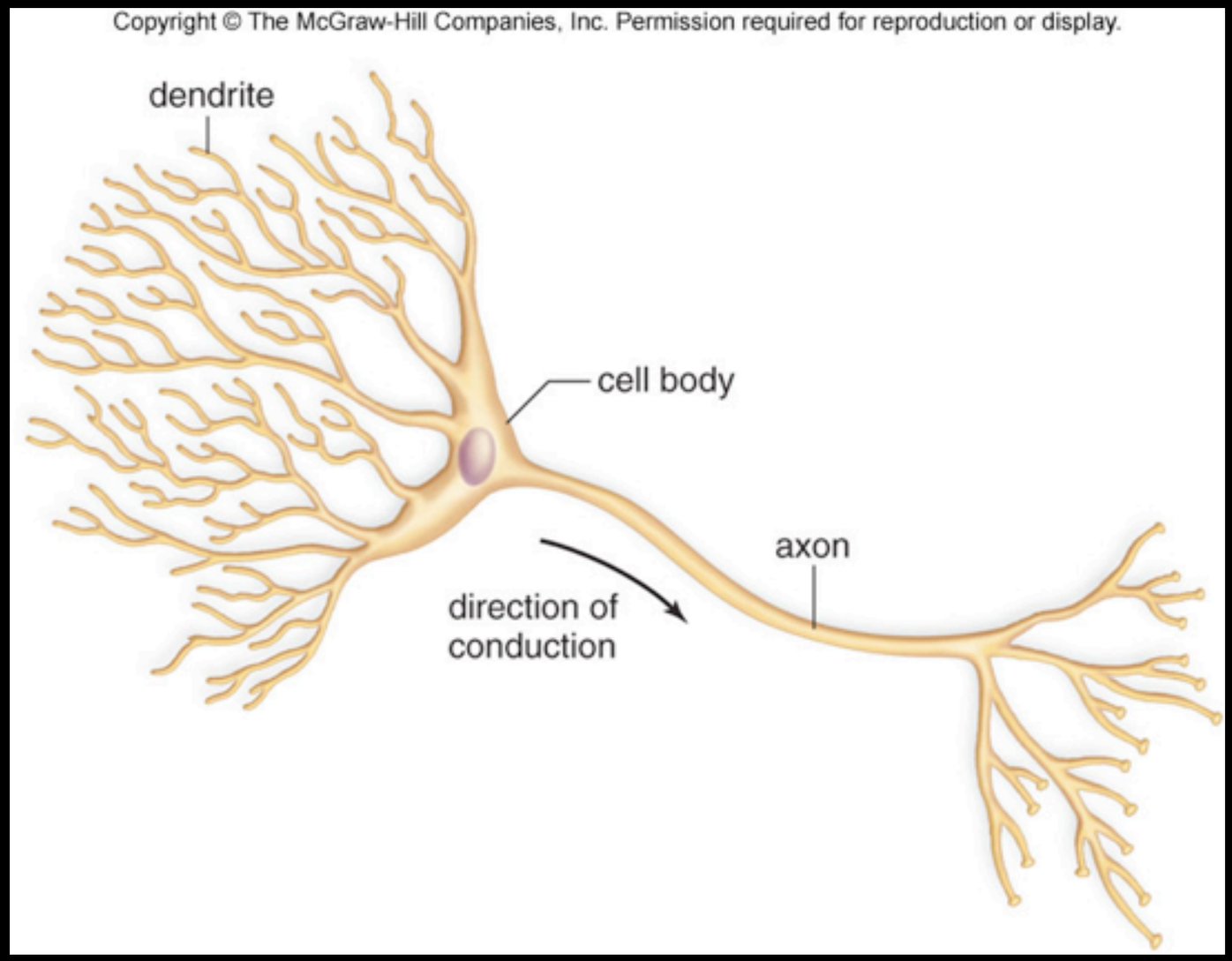
Sensory neurons take nerve impulses from sensory receptors to CNS



Sensory receptors may be the end of a sensory neuron itself (a pain or touch receptor), or may be a specialized cell that forms a synapse with a sensory neuron

Neurons: functional

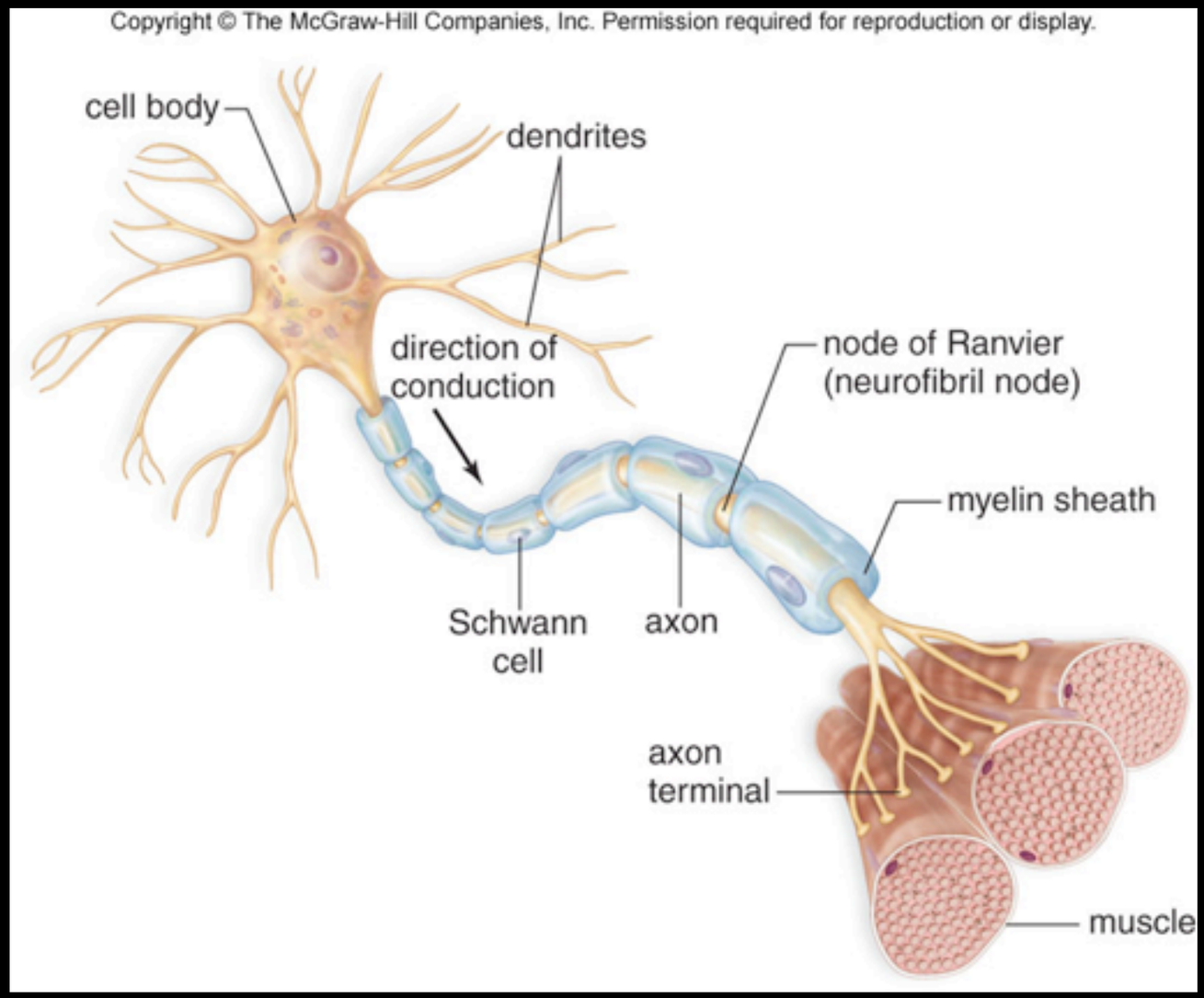
Interneurons occur entirely within the CNS



Convey nerve impulses between various parts of the CNS

Neurons: functional

Motor neurons carry nerve impulses from CNS to muscles or glands



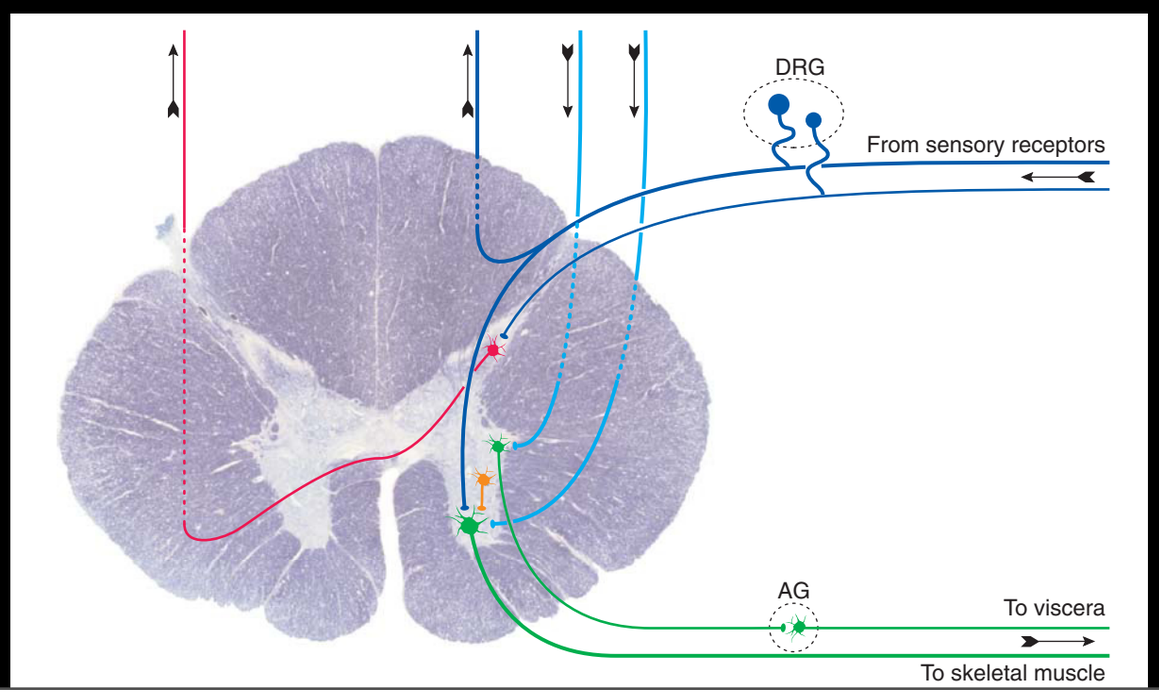
Have many dendrites and a single axon
Cause muscle to contract or glands to secrete

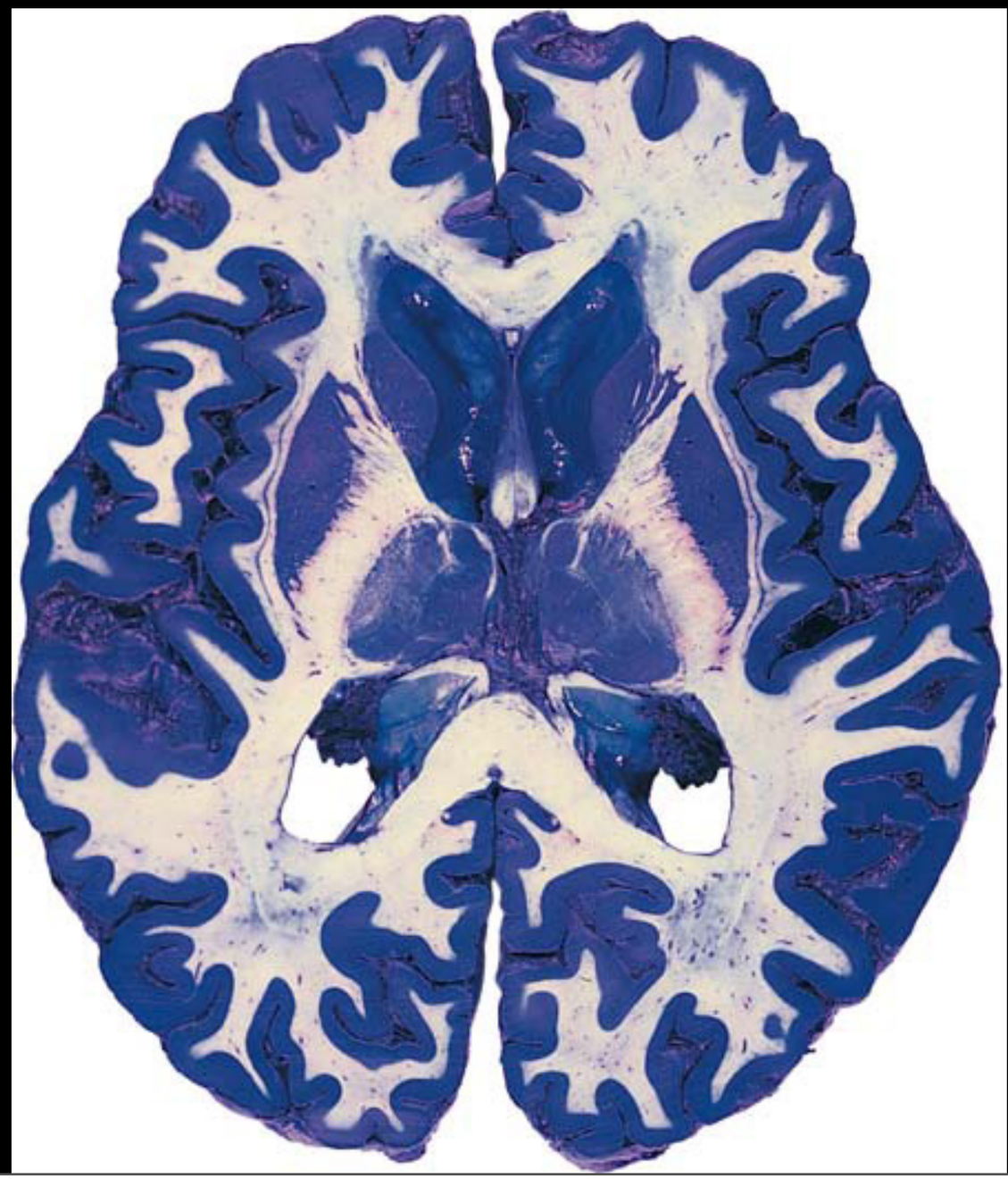
Neurons: segregation

Neuronal cell bodies and axons are largely segregated within the CNS

Grey matter: cell bodies and dendrites (pinkish due to blood supply)

White matter: axons (myelin)





Glial cells (PNS)

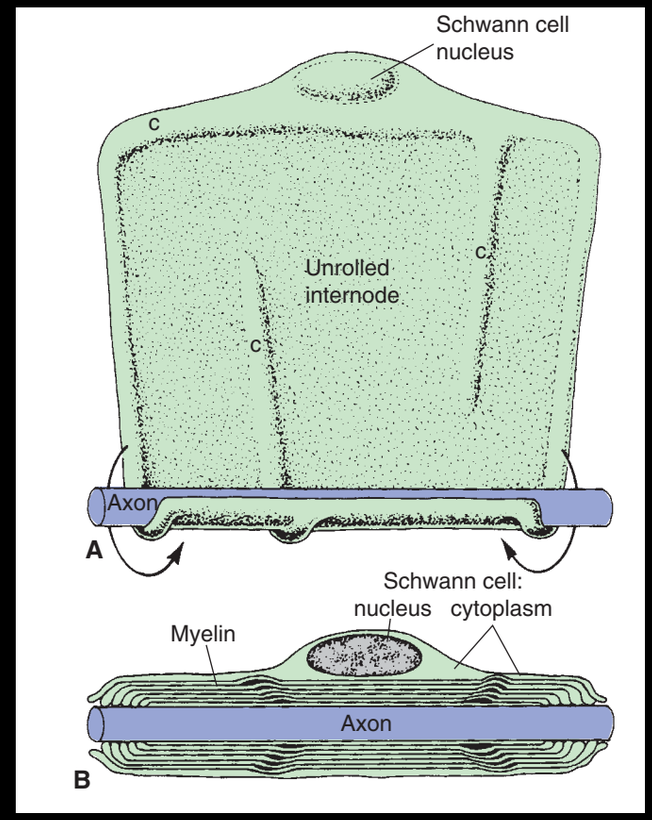
Glia = glue in Greek

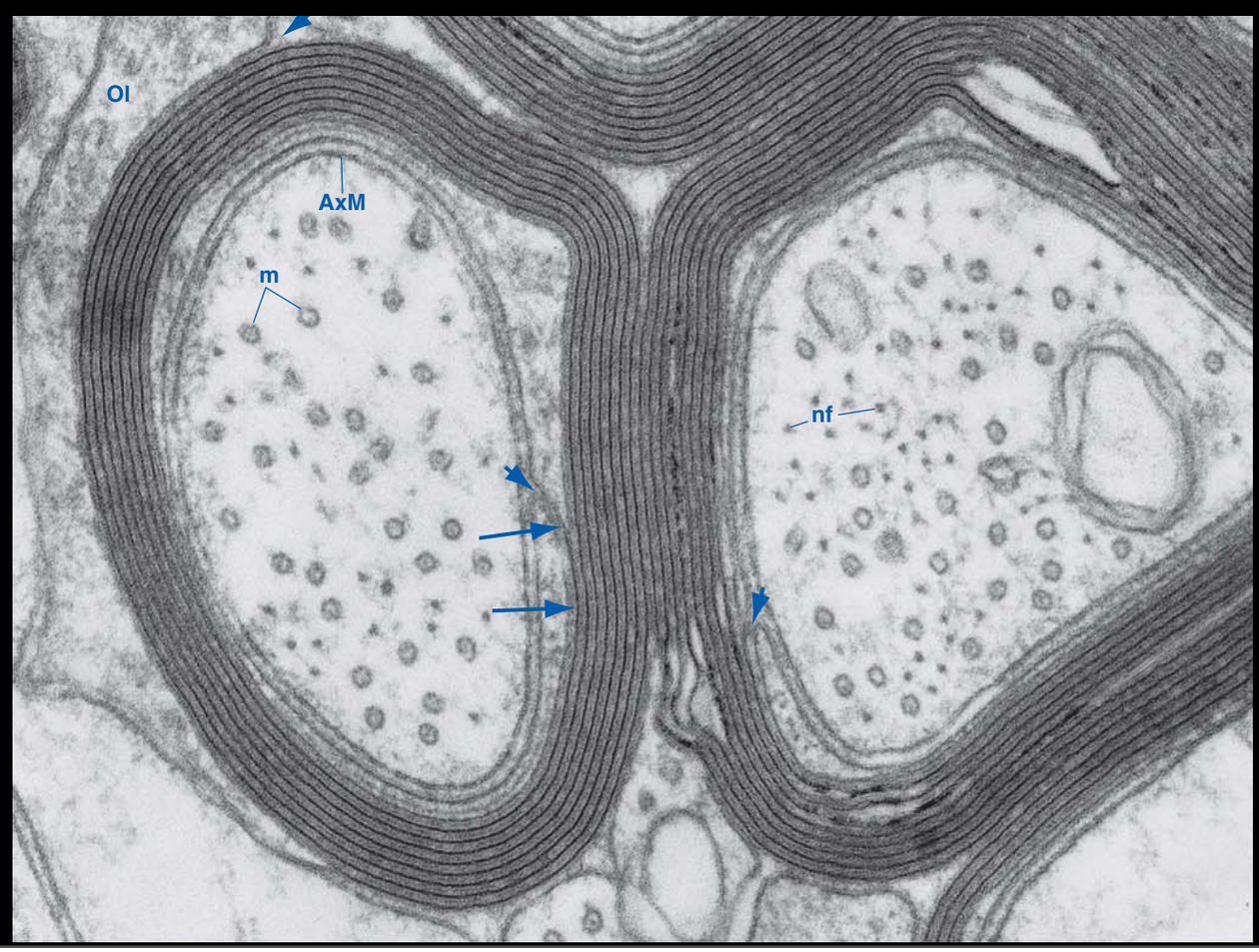
Schwann cells:

* Form myelin sheath in the PNS
* Speed up axonal transmission

Satellite cells:

* Support clusters of neuron bodies (ganglia)





Glial cells (CNS)

Microglia

* Dispose of debris
* Respond to injury

Oligodendrocytes

* Form myelin sheaths

Astrocytes

* Mop up excess ions
* Connect neurons to blood vessels (Blood-brain barrier)
* Scar tissue

Ependymal

* Line ventricles
* Secrete CSF

Neurons vs. Glial cells

Glial cells (astrocytes) could be involved in processing

The vast majority of neurons do not divide. Why?

Glial cells divide

Most brain tumors are gliomas

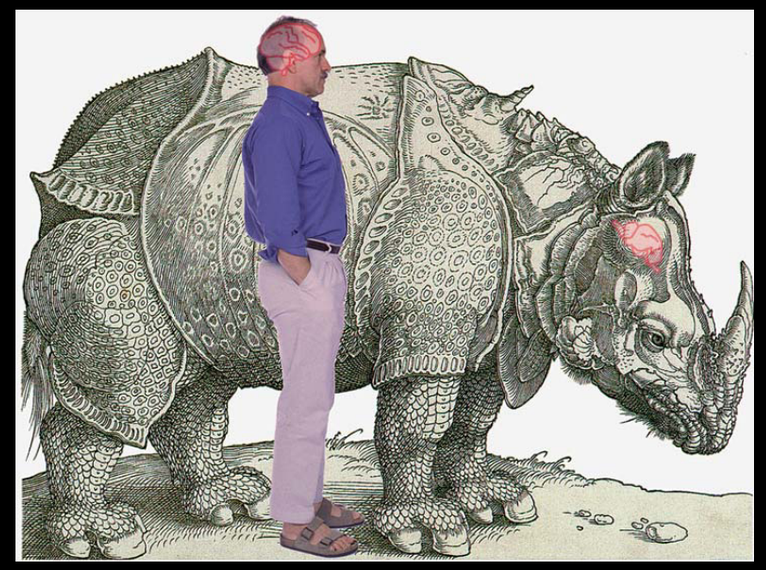
Introduction to the Nervous System

Gross anatomy of the CNS

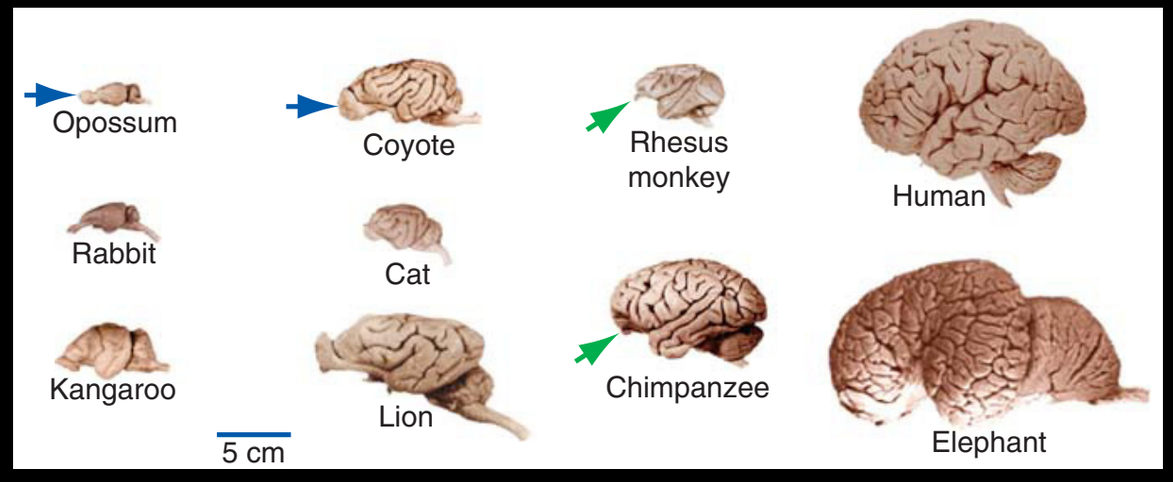
Neuronal signaling

Gross anatomy

Humans have large brains
relative to other animals (1.1 to 1.7 kg)



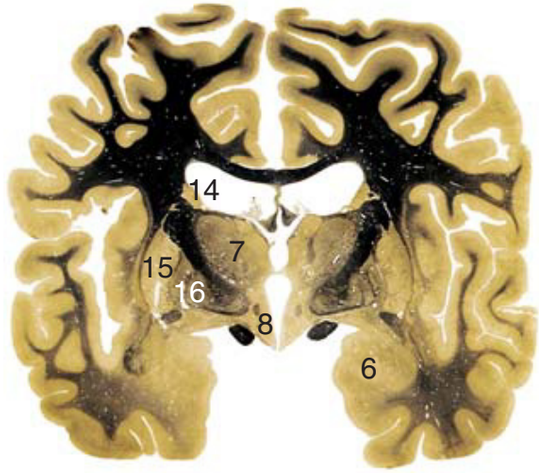
More complex interconnections and
selective expansions of cerebral cortex
involved in higher functions



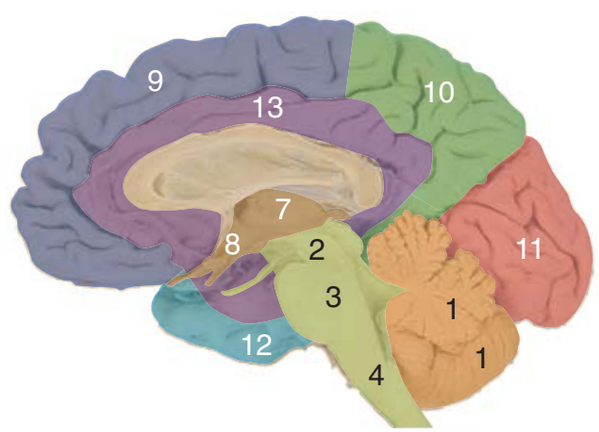
400 gr at birth
1400 gr adult (due to increase in
myelin and new connections)
50-80k neurons die every day

Gross anatomy

Overview of the subdivisions of the CNS



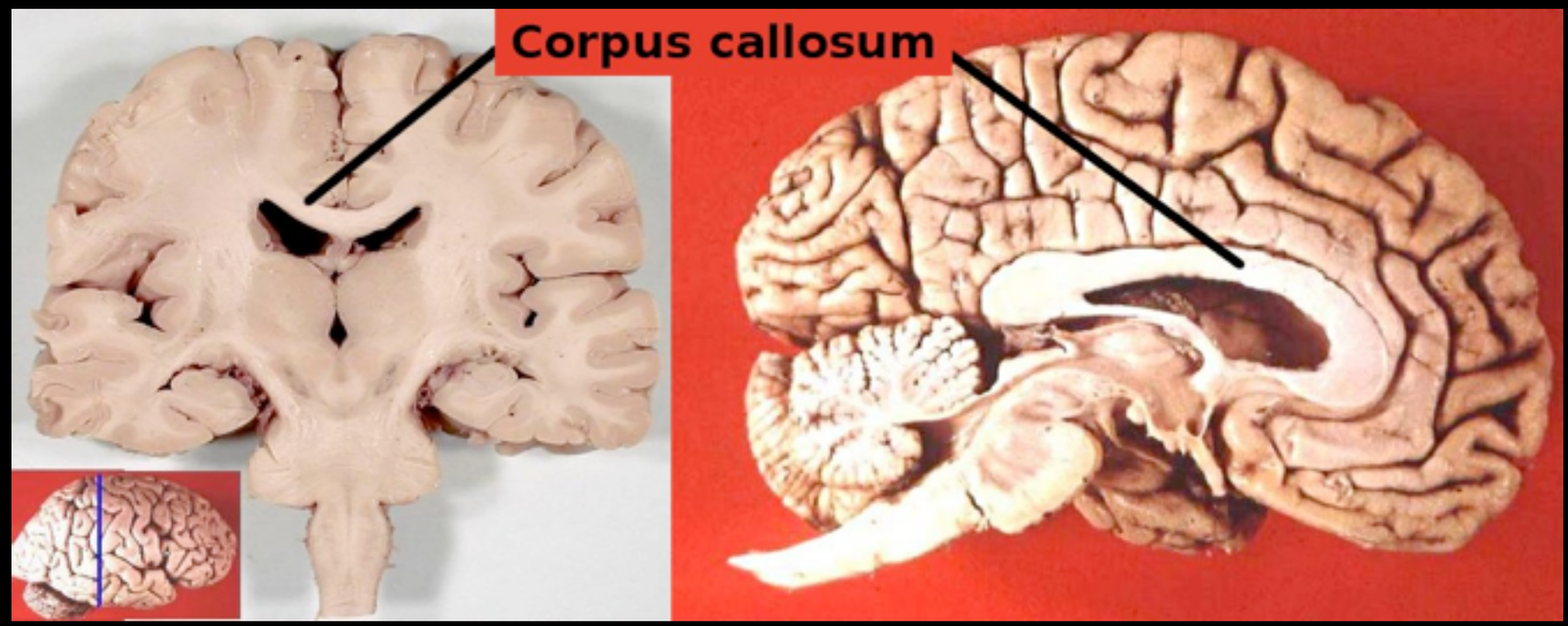
- Central nervous system
  - Brain
    - Cerebrum
      - Cerebral hemisphere
        - Cerebral cortex
          - Frontal lobe (9) (motor cortex)
          - Parietal lobe (10) (somatosensory cortex)
          - Occipital lobe (11) (visual cortex)
          - Temporal lobe (12) (auditory cortex)
          - Limbic lobe (13) (drives, emotions, memory)
        - Basal ganglia (movement control; related structures in brainstem)
          - Caudate nucleus (14)
          - Lenticular nucleus (putamen [15] and globus pallidus [16])
        - Hippocampus (5), amygdala (6) (limbic structures; drives, emotions, memory)
      - Diencephalon
        - Thalamus (7) (relay to cortex)
        - Hypothalamus (8) (control of autonomics)
    - Cerebellum (1) (coordination)
    - Brainstem
      - Midbrain (2)
      - Pons (3)
      - Medulla (4)
  - Spinal cord



Gross anatomy

Cerebral hemispheres are folded and convoluted

* Gyri: bumps
* Sulci: grooves

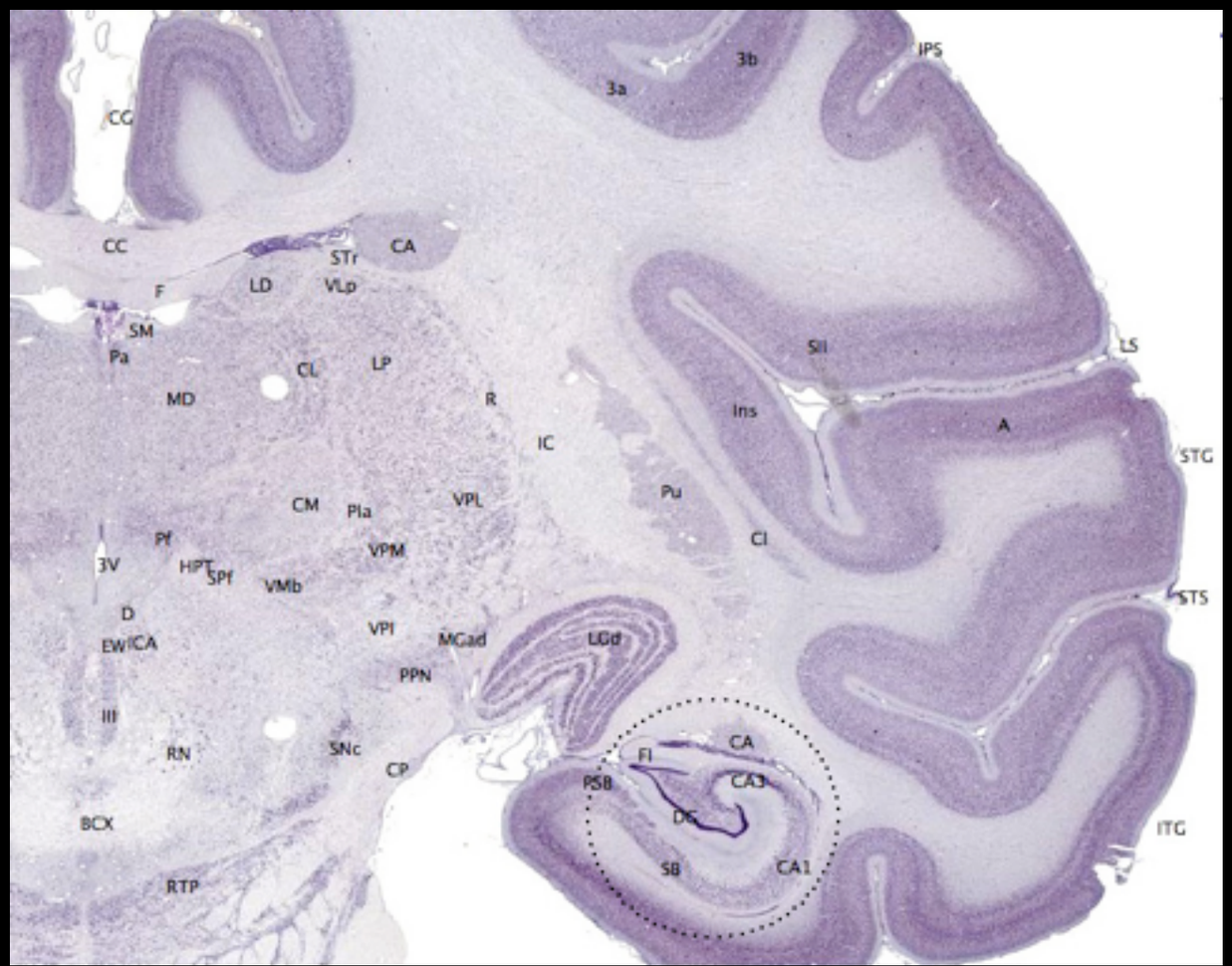


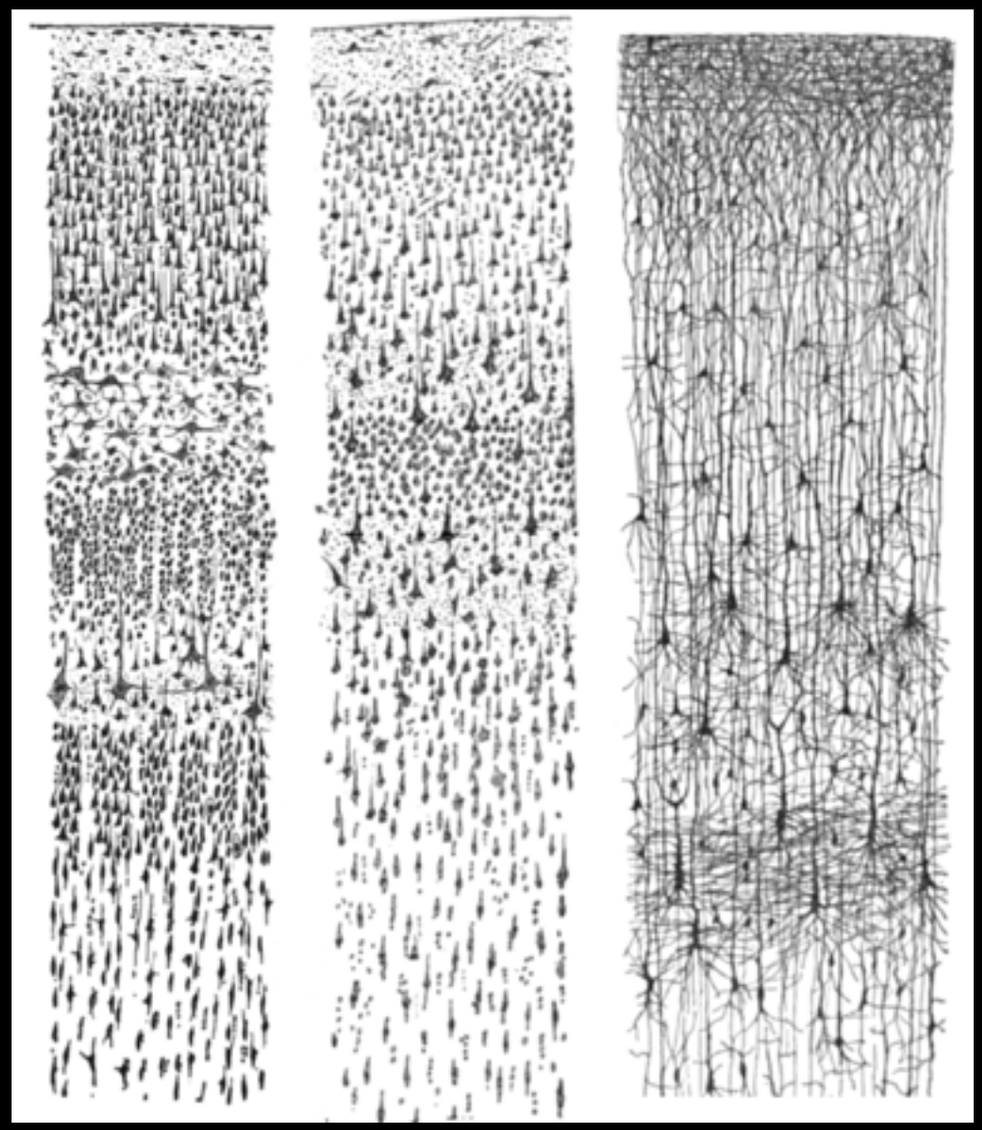
Corpus callosum is a huge bundle of axons connecting the two hemispheres (severed in split-brain patients)

Ventricles filled with cerebro-spinal fluid that bath the brain and provide protection and chemical environment of neurons

Gross anatomy

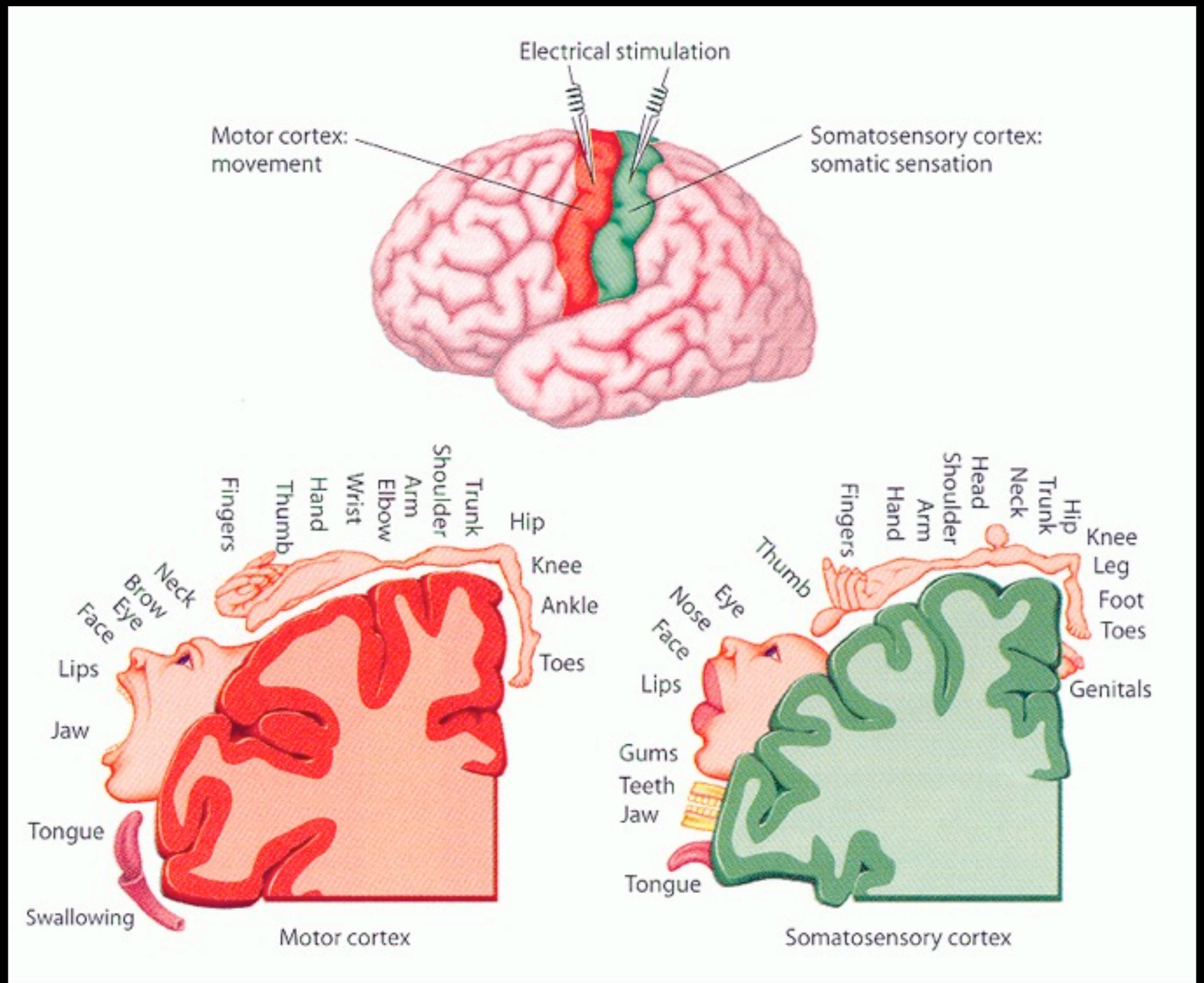
Cerebral cortex: outermost 6 layered structure of the neural tissue of human and other mammals (2-4 mm). Key role in high cognitive functions (memory, attention, language, ...)





Gross anatomy

CNS contains systematic distorted maps



Introduction to the Nervous System

Gross anatomy of the CNS

Neuronal signaling

Neuronal signaling

Within the neuron (conduction)

To achieve long distance (several cm), rapid communication (150 m/s), neurons have evolved special abilities for sending electrical signals (Action potentials)

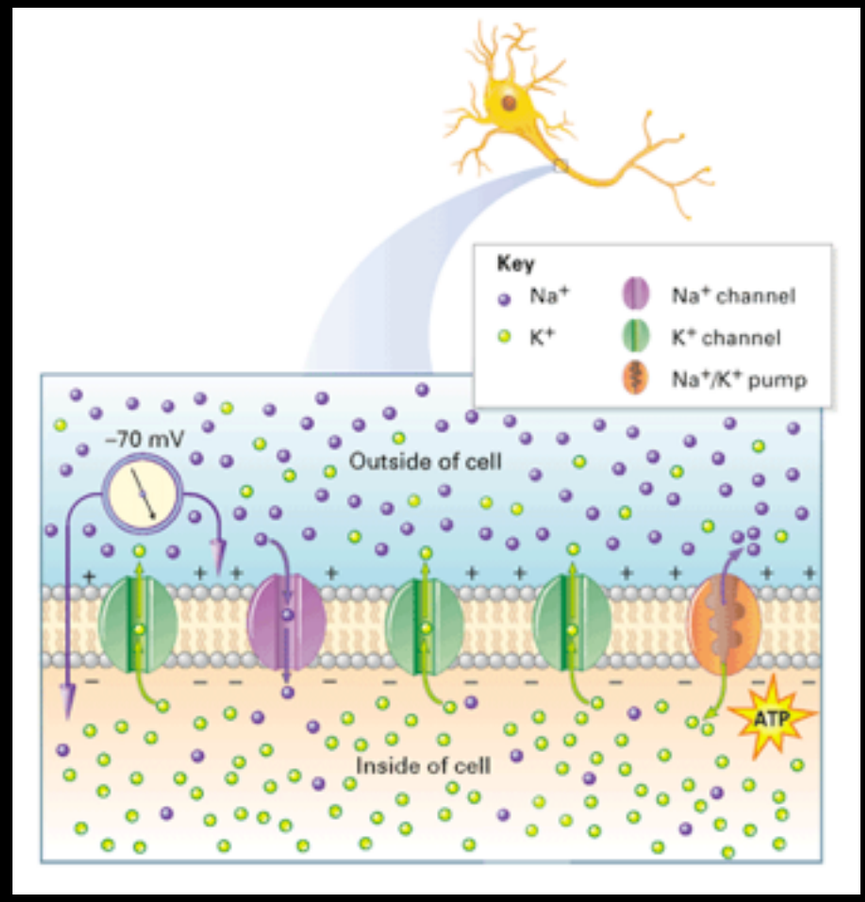
Between neurons (transmission)

Communication between neurons is achieved at synapses by the process of neurotransmission

Electrical properties

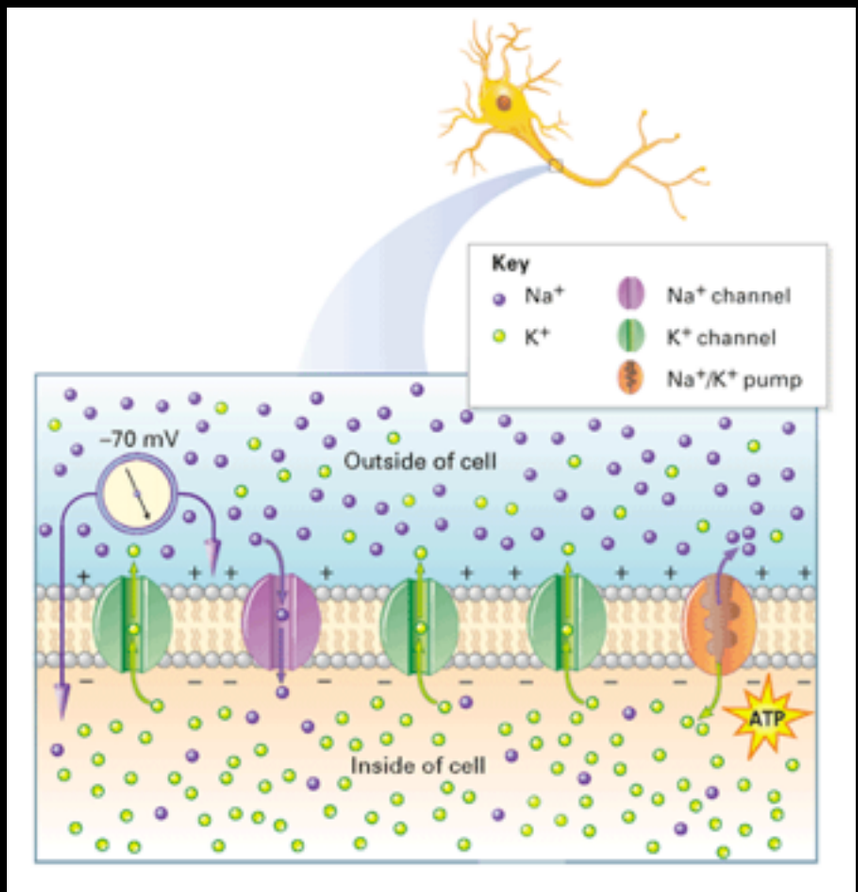
Lipid bilayer at the cell surface acts as a capacitor (able to store charges)

Neurons spend a lot of energy to keep different concentration of ions inside and outside (resting membrane potential -70 mV)



Electrical properties

Neuron membranes are filled with pores that enable the selective pass of ions (ion channels)



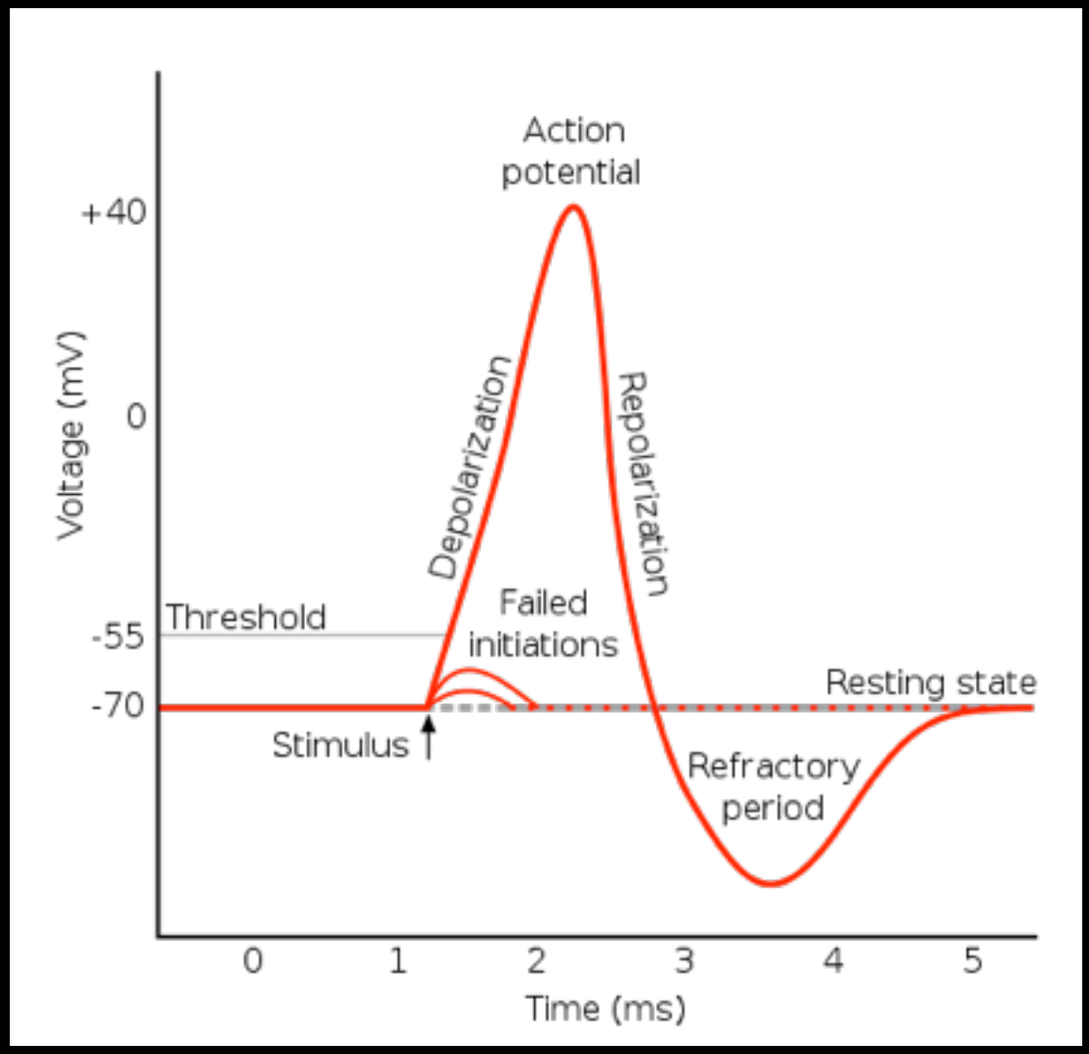
Ion channels open and close as a function of the membrane potential (voltage-gated channels)

Diffusion: when channels open ions tend to move to less crowded places

Conduction: Action

http://www.youtube.com/watch?v=7EyhsOewnH4

Conduction: Action potential

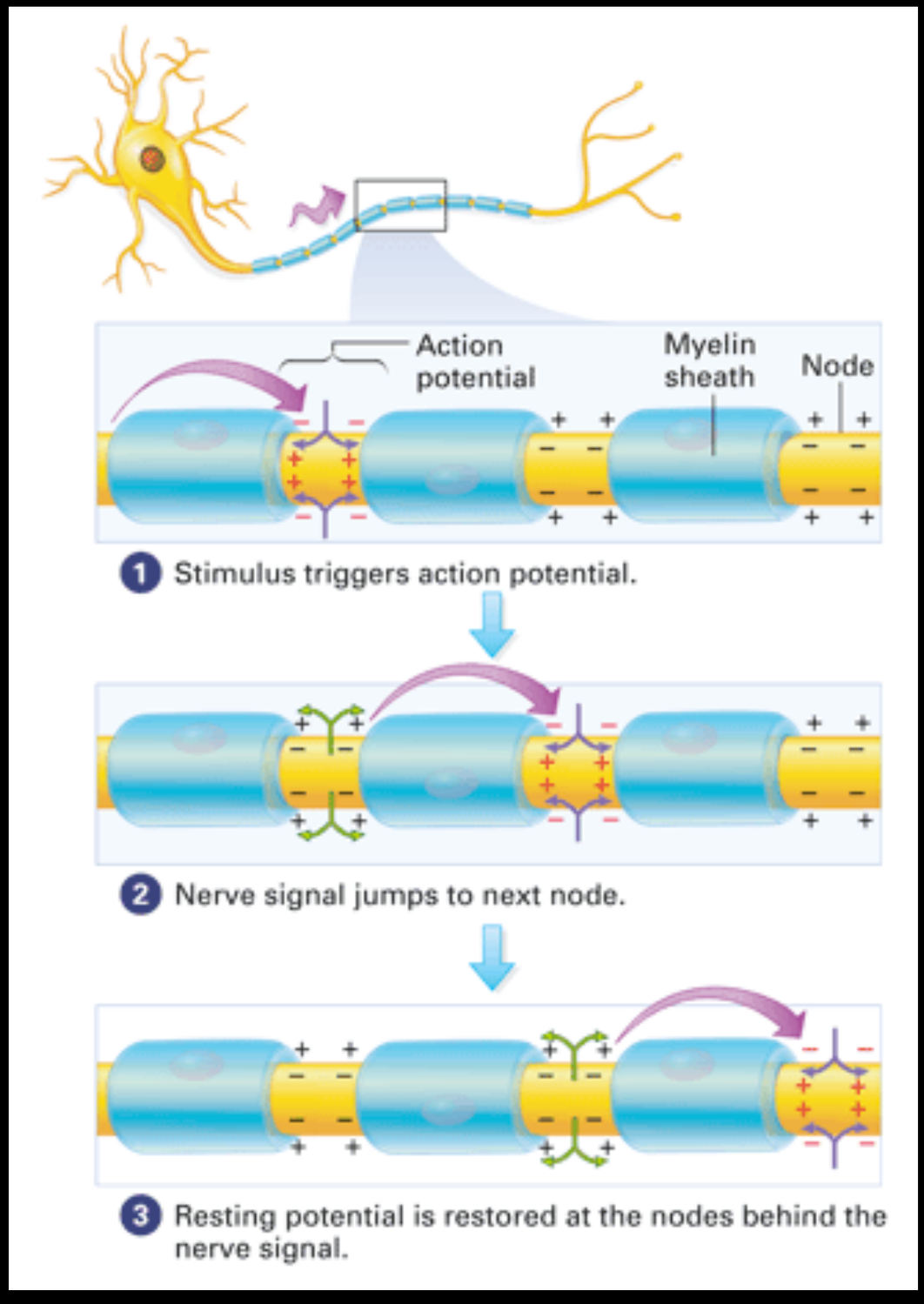


An action potential is conducted whenever an input of threshold intensity or above is applied to the initial part of an axon (each action potential has the same strength)

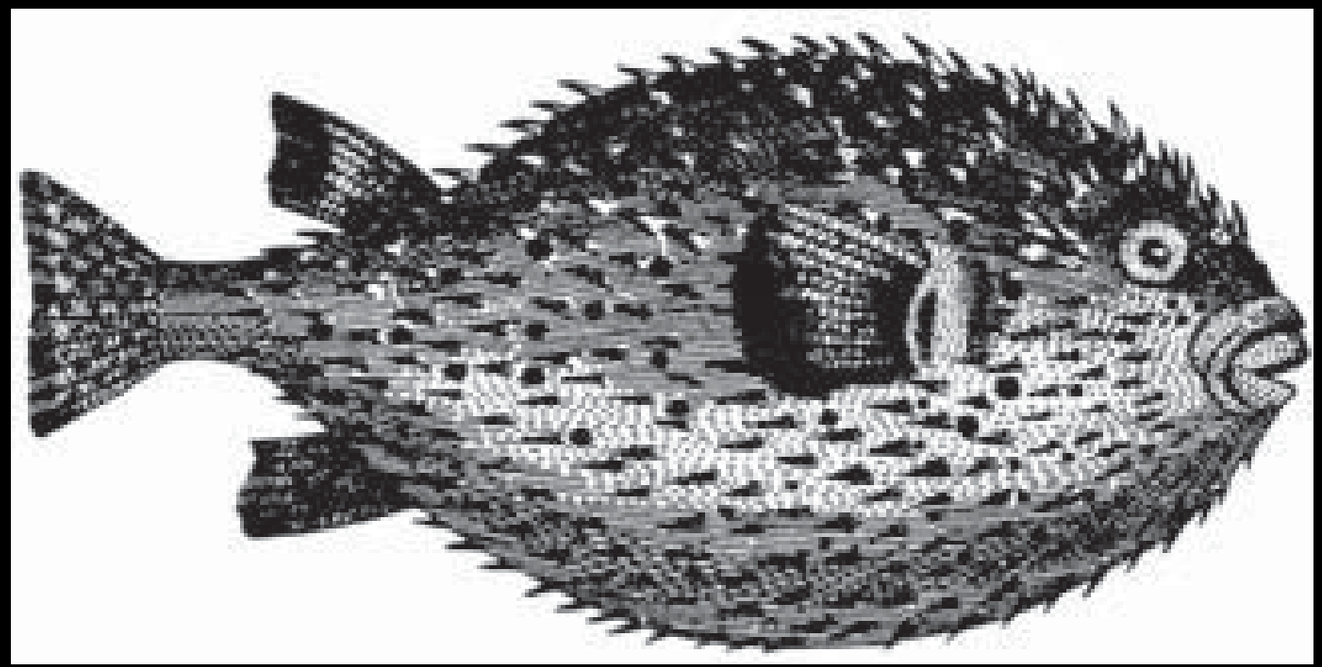
Conduction: Action potential

Saltatory conduction: action potential jumps between nodes but needs to be regenerated

Speed up of transmission
* unmyelinated 5 m/s
* myelinated 150 m/s
  (toe - spine in < 7 ms)



Conduction: Action potential



Puffer fish (fugu) contains a potent poison that blocks Na^+ channels resulting in failure to generate action potentials

Neuronal signaling

Within the neuron (conduction)

To achieve long distance (several cm), rapid communication (150 m/s), neurons have evolved special abilities for sending electrical signals (Action potentials)

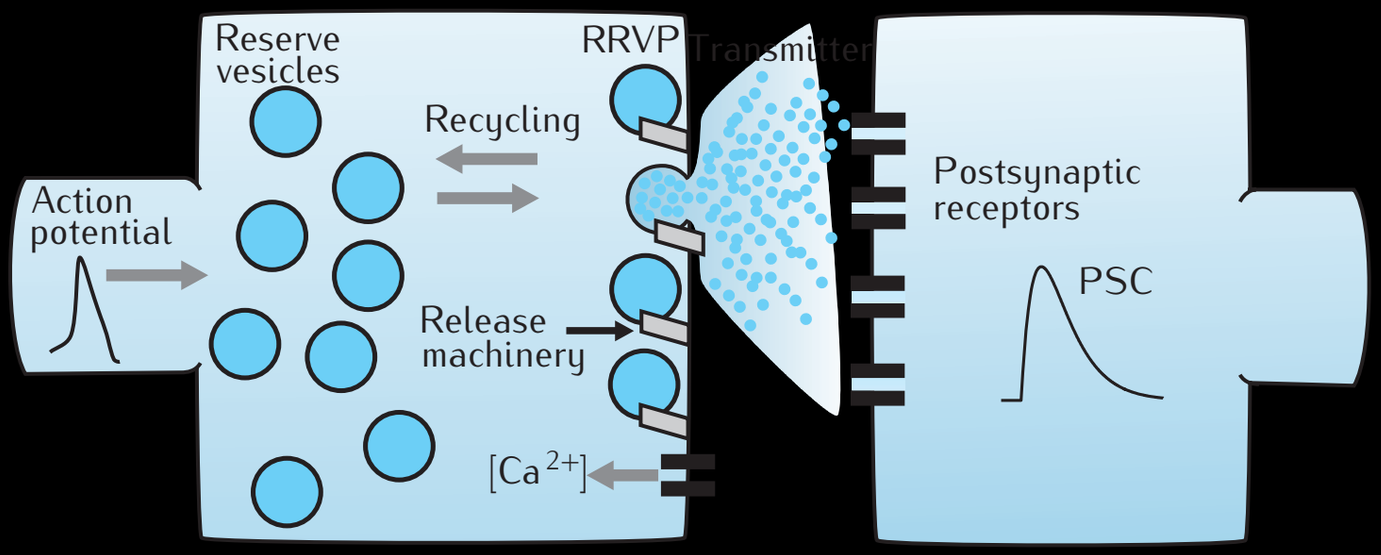
Between neurons (transmission)

Communication between neurons is achieved at synapses by the process of neurotransmission

Synaptic transmission

Electrical synapses: gap junctions between cells that allow ions to flow from one neuron to another (also in cardiac cells)

Chemical synapses: most neurons communicate by means of neurotransmitters at chemical synapses. The receiving neuron responds with a graded potential that may or may not initiate an action potential



Synaptic transmission

1 Action potential arrives to the axon terminal (pre-synaptic neuron) stimulates the release of packets of neurotransmitters into the synaptic cleft

2 Neurotransmitters diffuse across the synaptic cleft

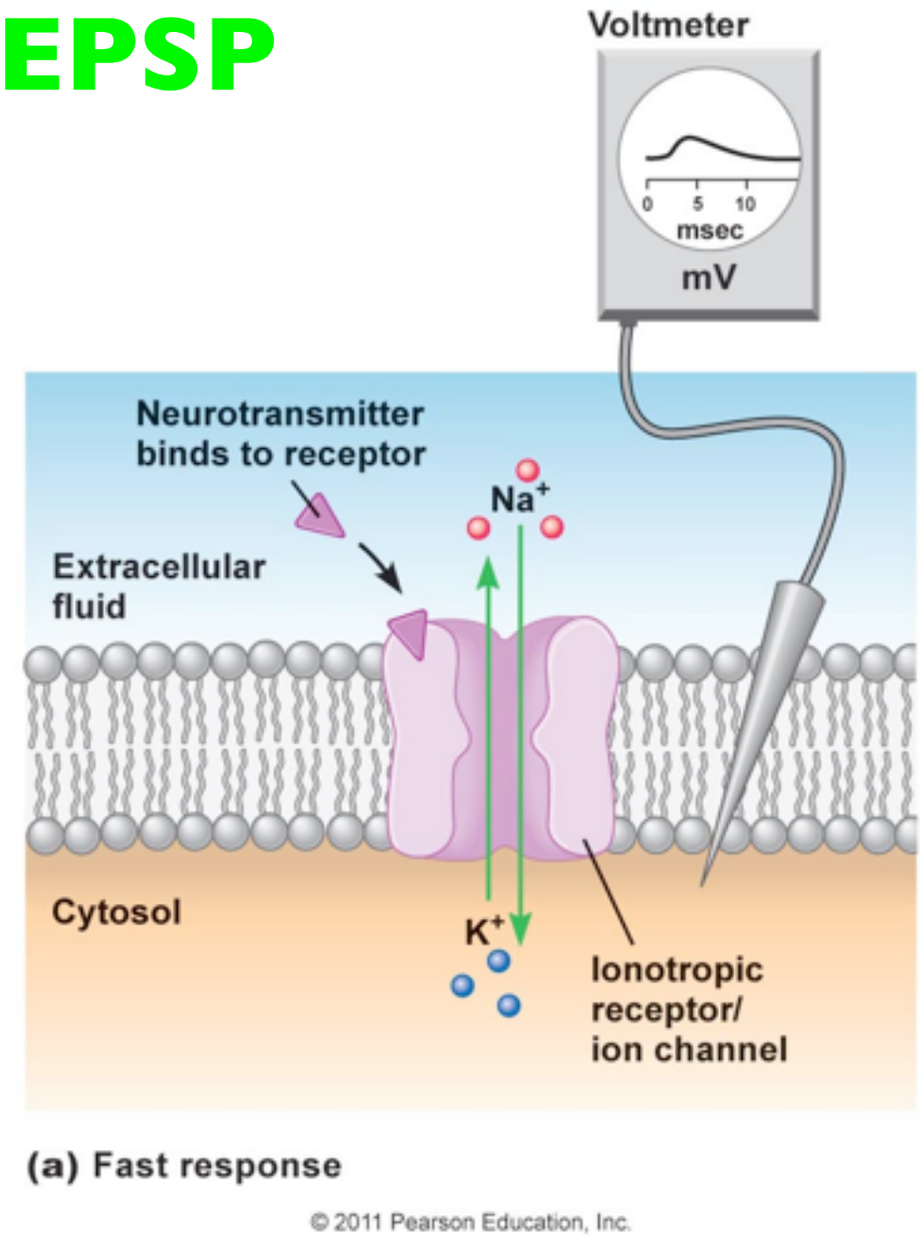
3 Neurotransmitters bind to receptors at the post-synaptic neuron causing ion channels to open

Synaptic transmission

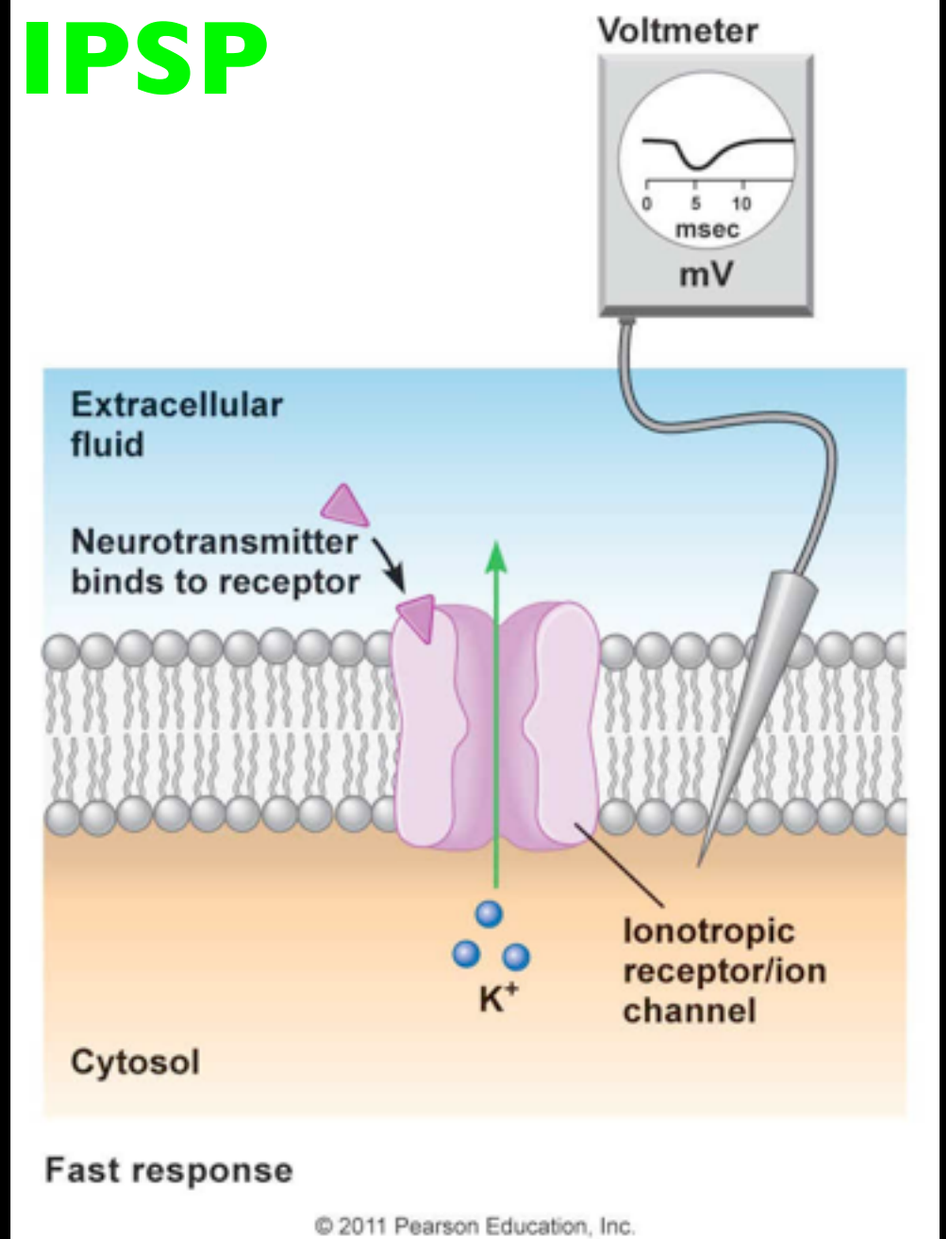
http://highered.mcgraw-hill.com/olcweb/cgi/pluginpop.cgi?it=swf::535::535::/sites/dl/free/0072437316/120107/anim0015.swf::Chemical%20Synapse

Synaptic transmission

EPSP



IPSP

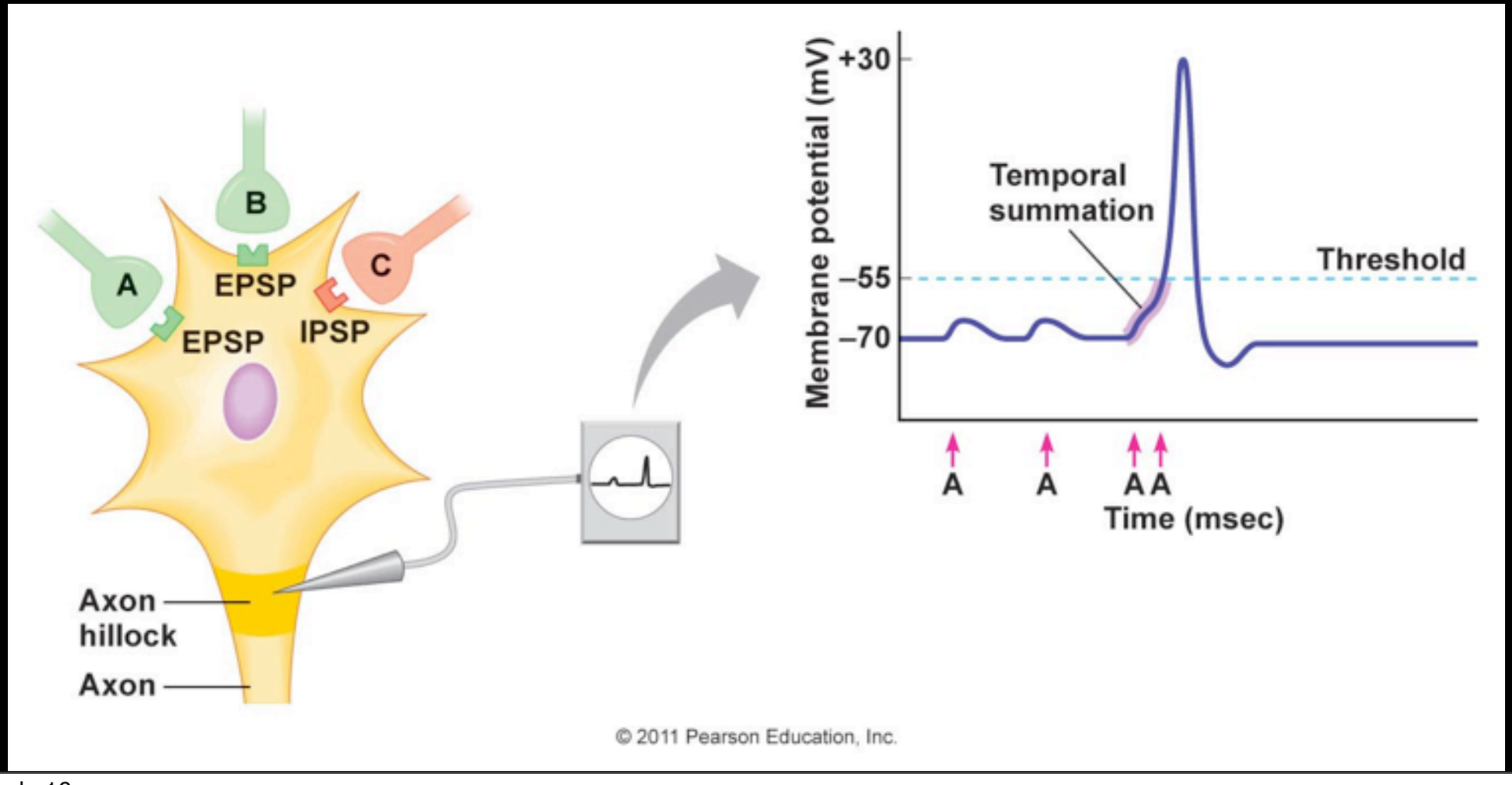


Depending on which receptor is activated at the post-synaptic neuron the electrical response can be excitatory or inhibitory

Synaptic transmission

Neural integration refers to the conduction and addition of all PSP produced by various excitatory and inhibitory synapses. It determines if an action potential is generated. Two types:

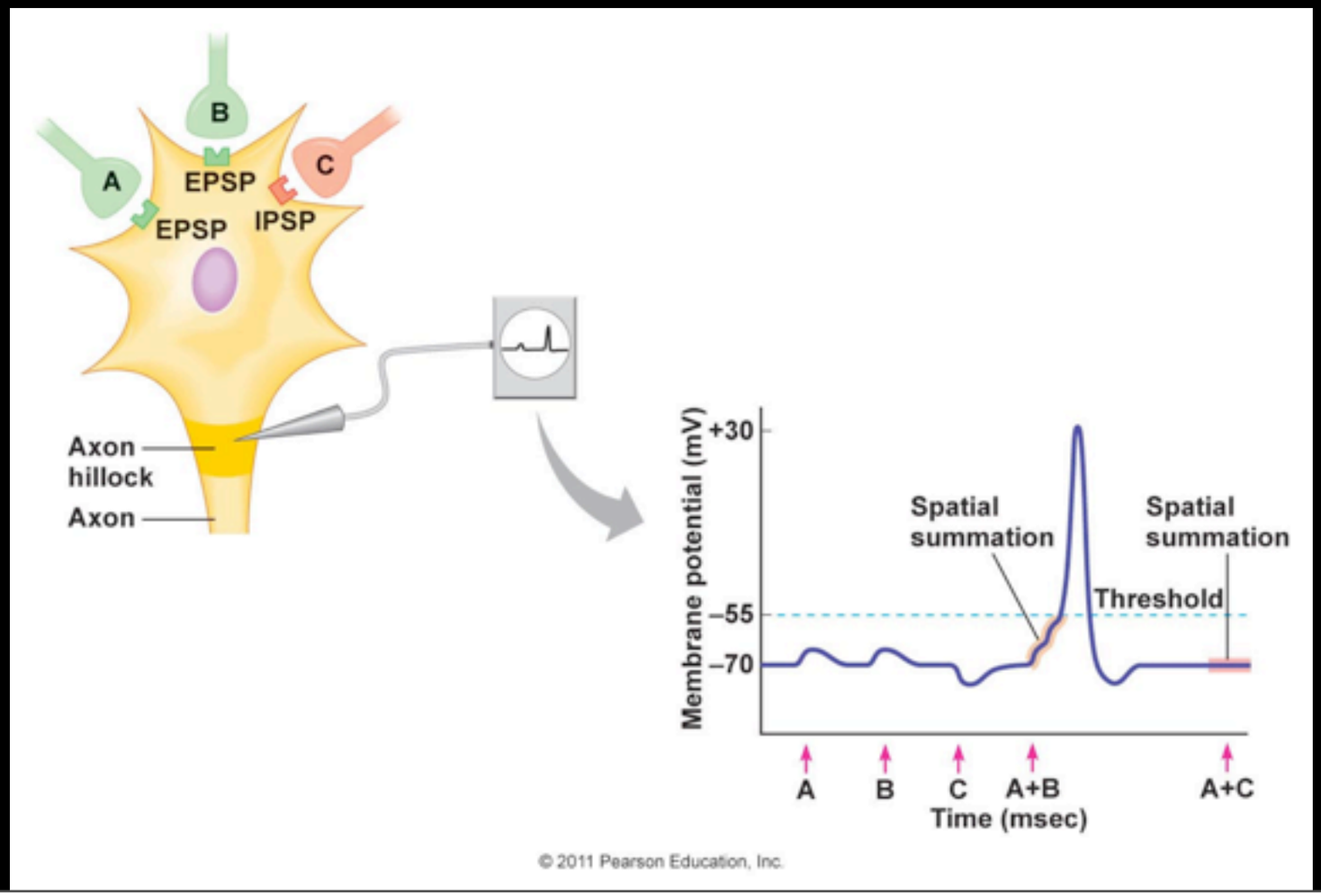
I Temporal summation



Synaptic transmission

Neural integration refers to the conduction and addition of all PSP produced by various excitatory and inhibitory synapses. It determines if an action potential is generated. Two types:

2 Spatial summation



Synaptic transmission

Synaptic strength can be enhanced or depressed by changing neurotransmitter release or the density of receptors (synaptic plasticity)

Drugs, diseases, and toxins interfere with synaptic neurotransmission (alcohol, nicotine, marihuana, antidepressants, botox,...)

too much botox...

Summary

- NS evolved to provide a fast and coordinated response to stimuli.
- 2 types of cells: neurons (information processing) and glial cells (supporting role).
- Neurons have specialized compartments to receive (dendrites), integrate (soma), conduct (axon), and transmit (synapses) impulses.
- NS is divided in CNS (brain and spinal cord) and PSN (cranial and spinal nerves), with further subdivisions involved in specialized processing.

To know more

http://cnx.org/content/m47519/latest/?collection=col11569/latest

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Chapters 1 and 3

The human brain: an introduction of its functional anatomy, John Nolte,

Mosby, 2002

Lesson	Title
1	Introduction
2	Structure and Function of the NS
3	Windows to the Brain
4	Data analysis
5	Single neuron models
6	Network models
7	Artificial neural networks
8	Artificial intelligence
9	Learning and memory
10	Perception
11	Attention & decision making
12	Brain-Computer interface
13	Neuroscience and society
14	Future and outlook
15	Projects presentations
16	Projects presentations

Basics

Analyses

Models

Cognitive

Applications