M260/NS M206/EE M255
Neuroengineering

Basic neuroanatomy and neurophysiology for neural engineering students

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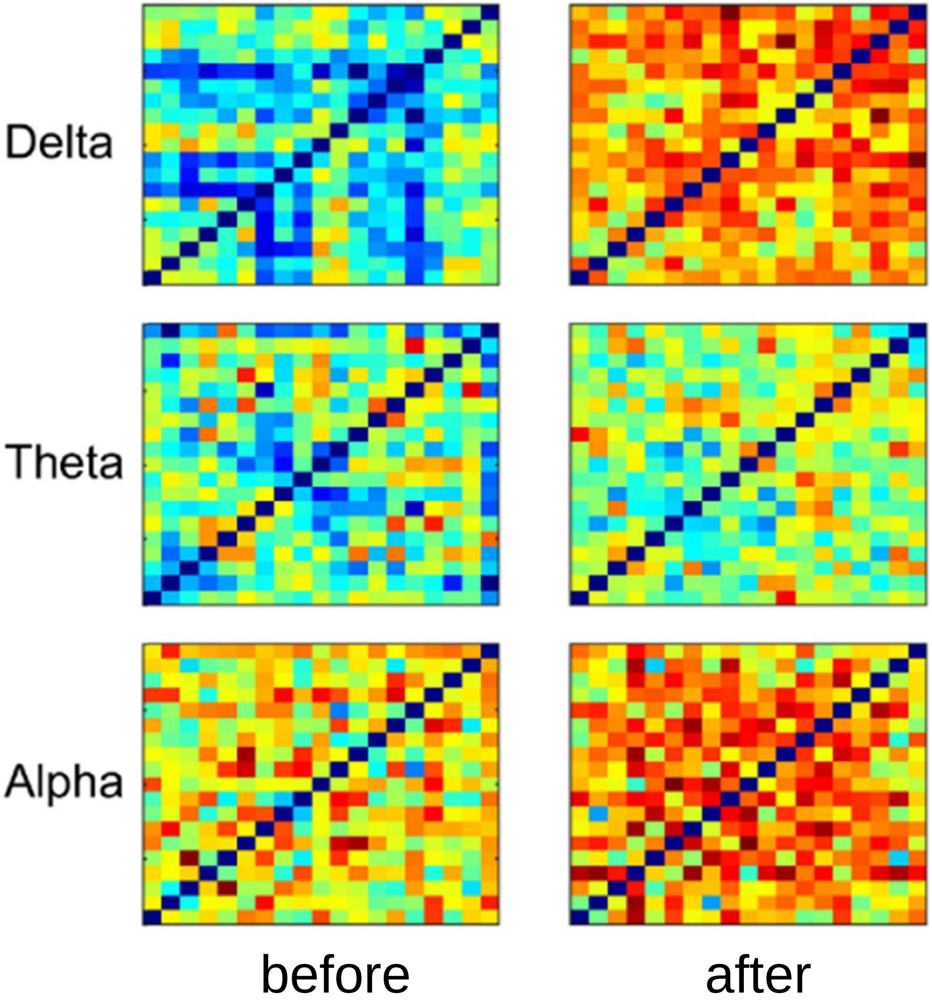
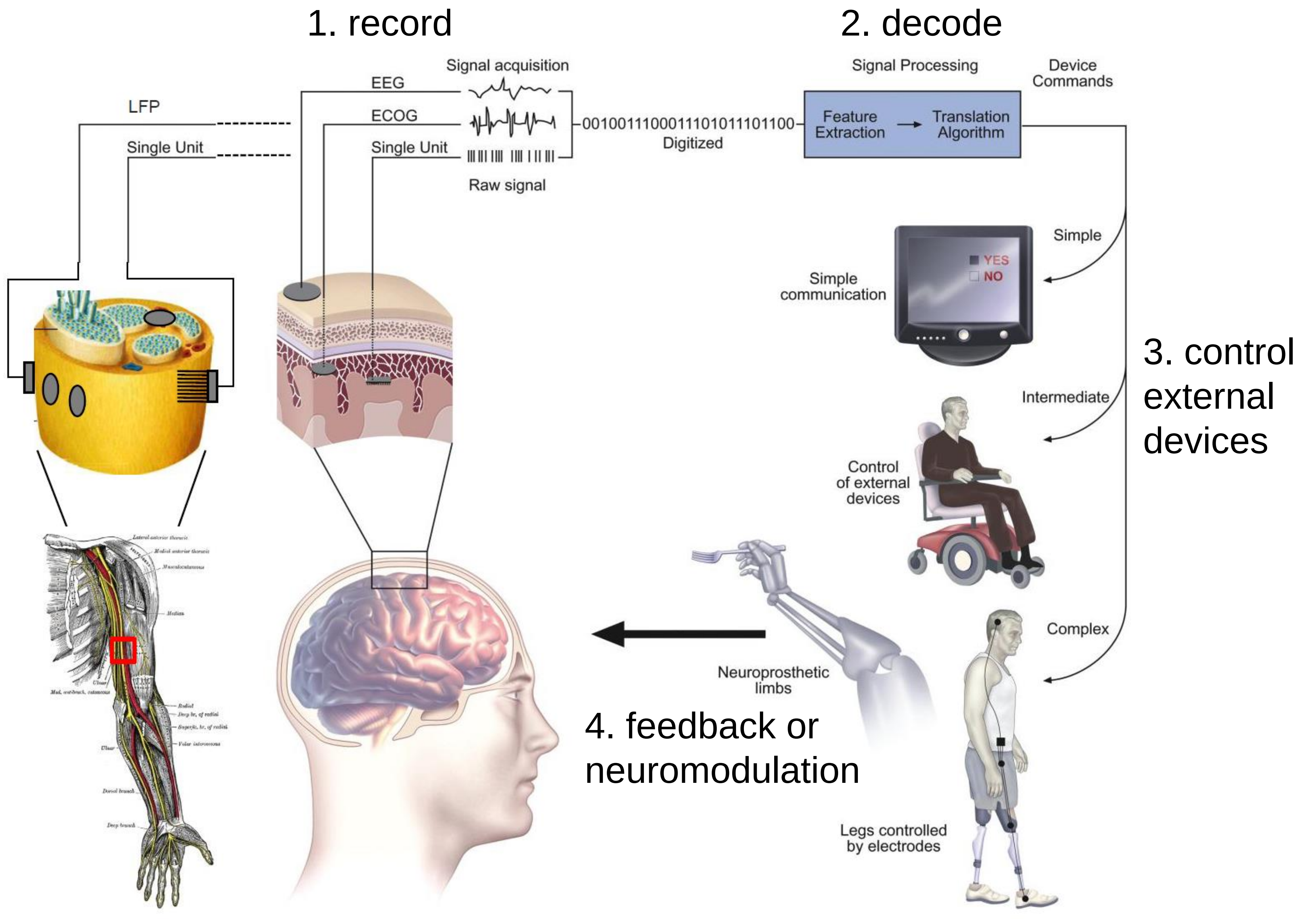
How can we use neural interfaces: future versus now

BCI: connect to computers and AI

neuromodulation: restore balance and entropy in the aging brain



Key components of a neural interface

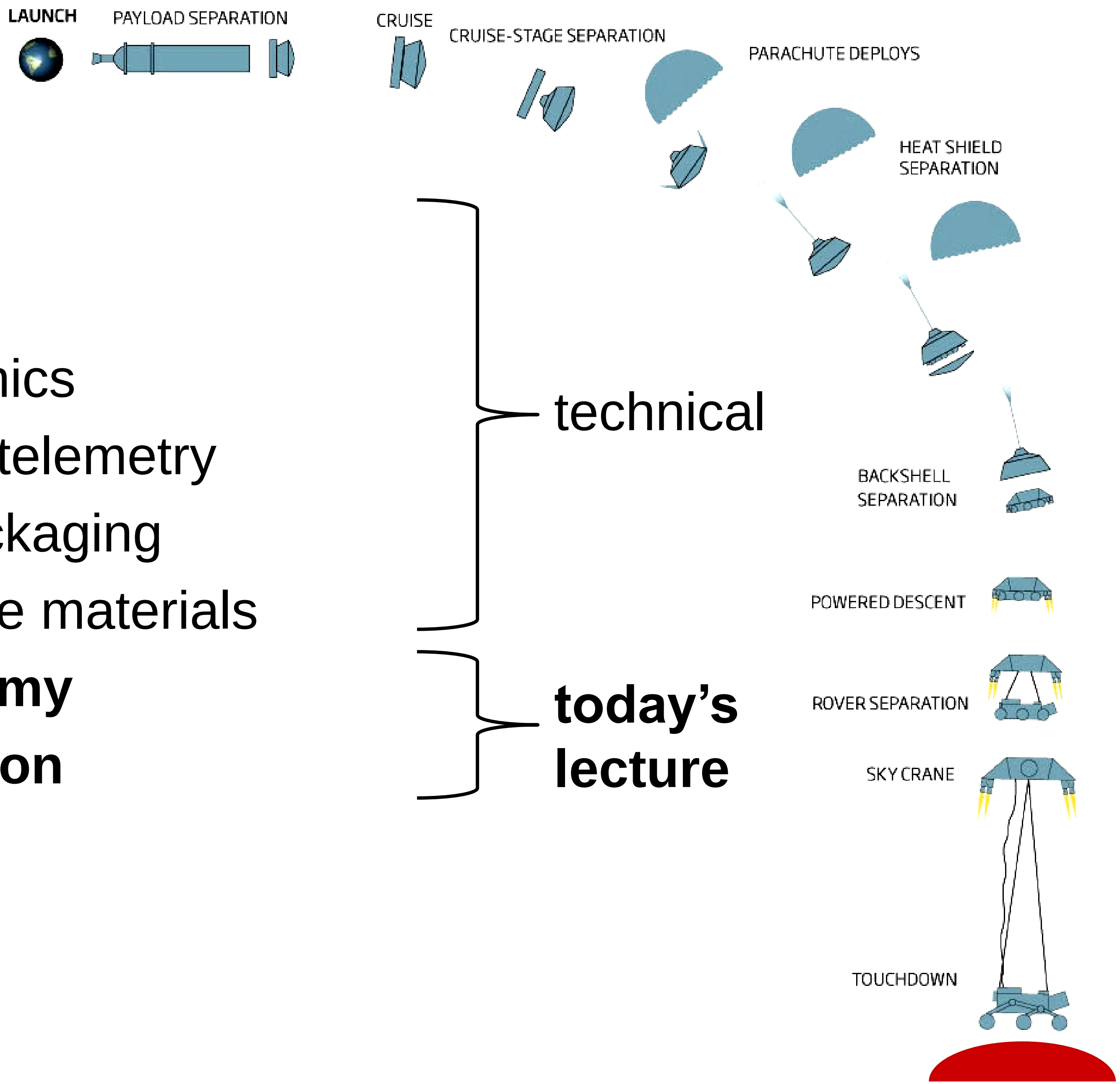


Challenges in the design of neural interfaces

- Electrodes
- Connectors
- Microelectronics
- Bidirectional telemetry
- Hermetic packaging
- Biocompatible materials
- **target anatomy**
- **target function**

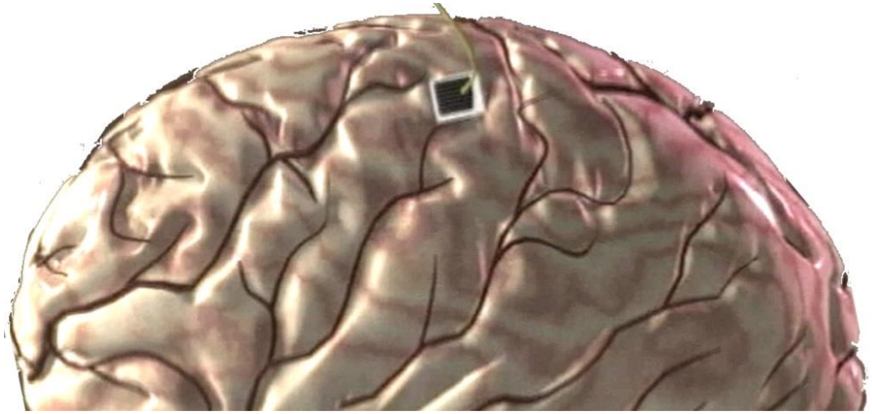
technical

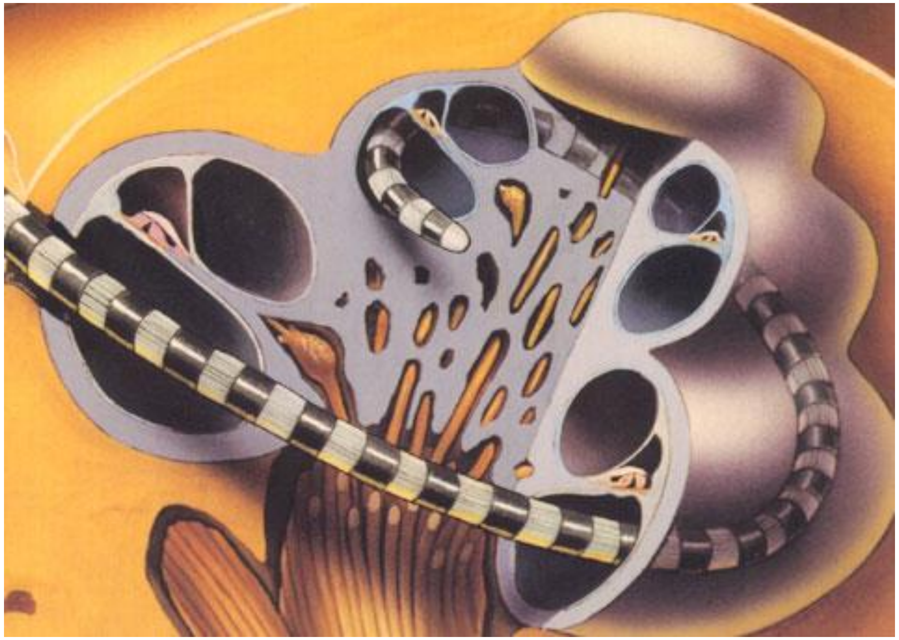
today's lecture

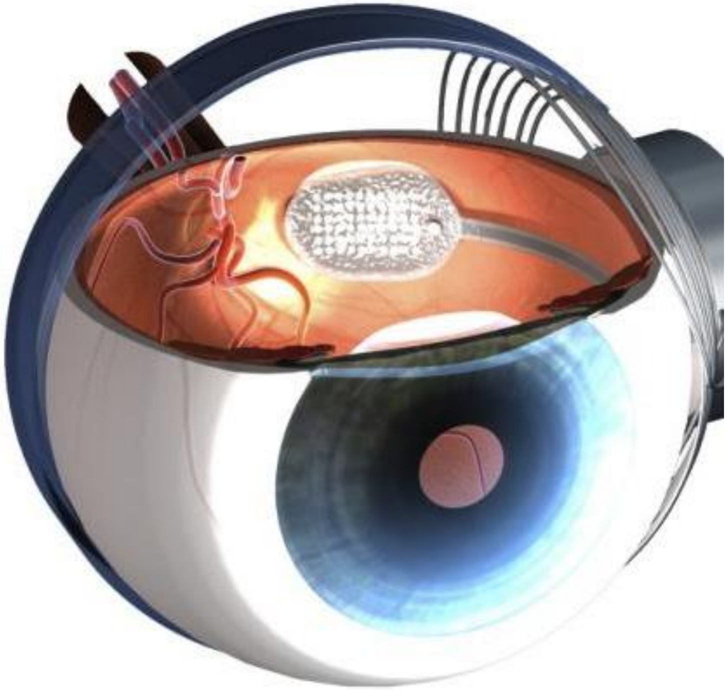


target anatomy drives the neural interface design

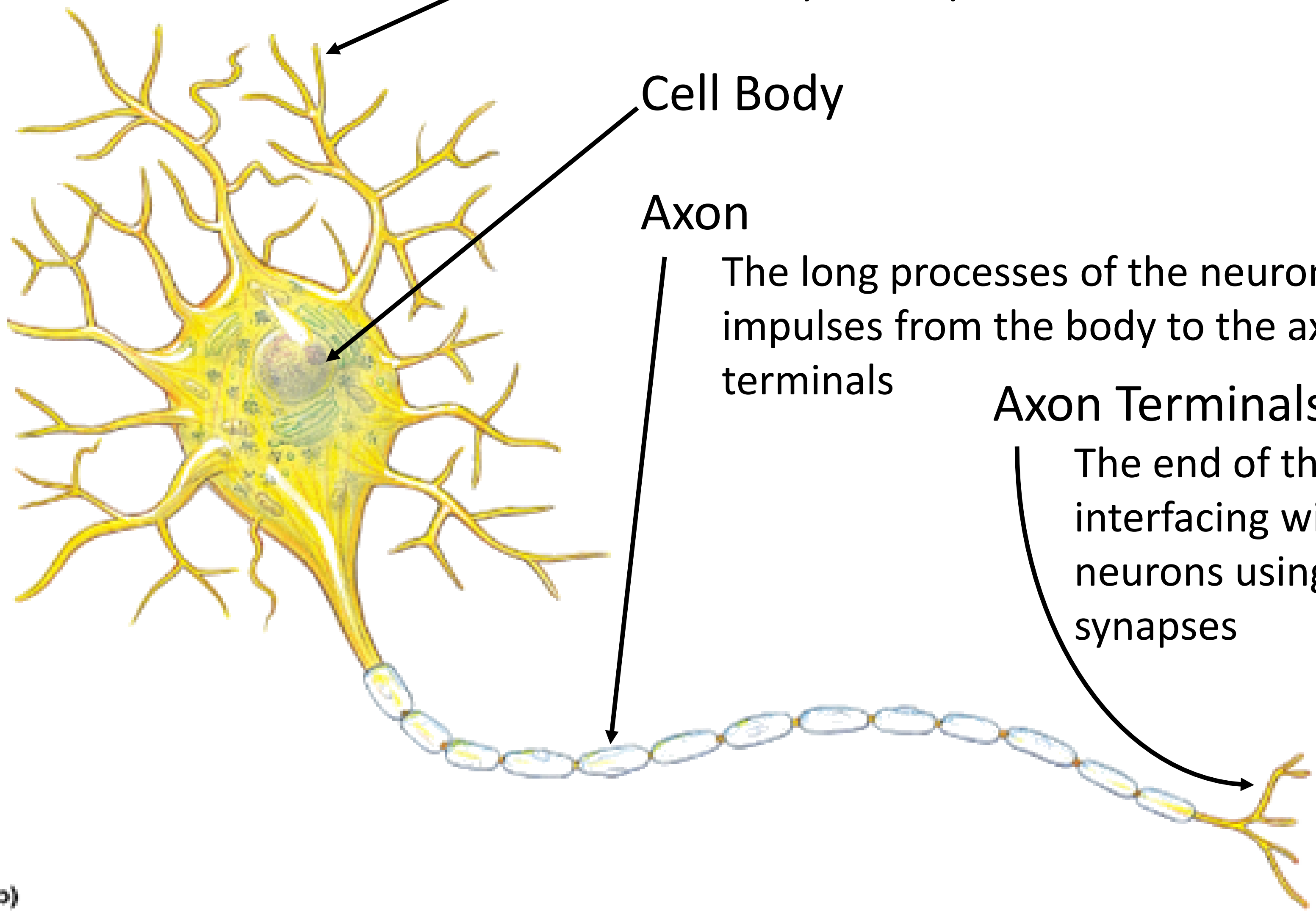
- one size/shape ***does not*** fit all targets
- ***recording*** versus ***stimulation***
- different requirements for the ***number of electrodes*** and ***data throughput***







Neuron



(b)

Dendrites

Carry the impulses toward the cell body

Cell Body

Axon

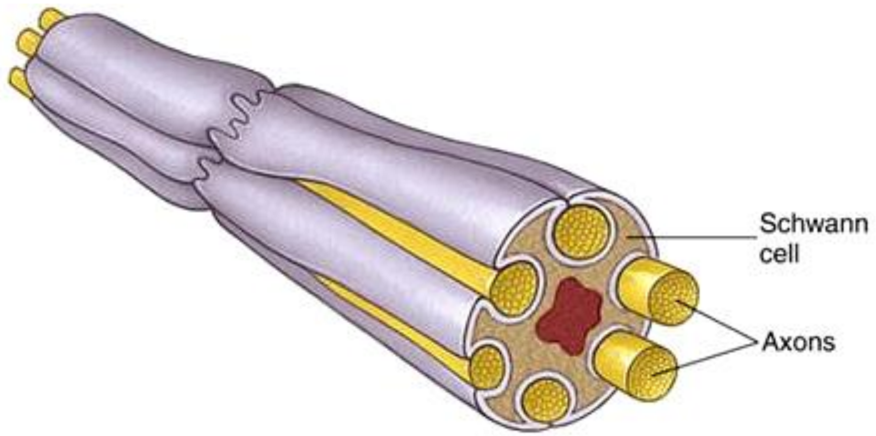
The long processes of the neuron that carry impulses from the body to the axon terminals

Axon Terminals

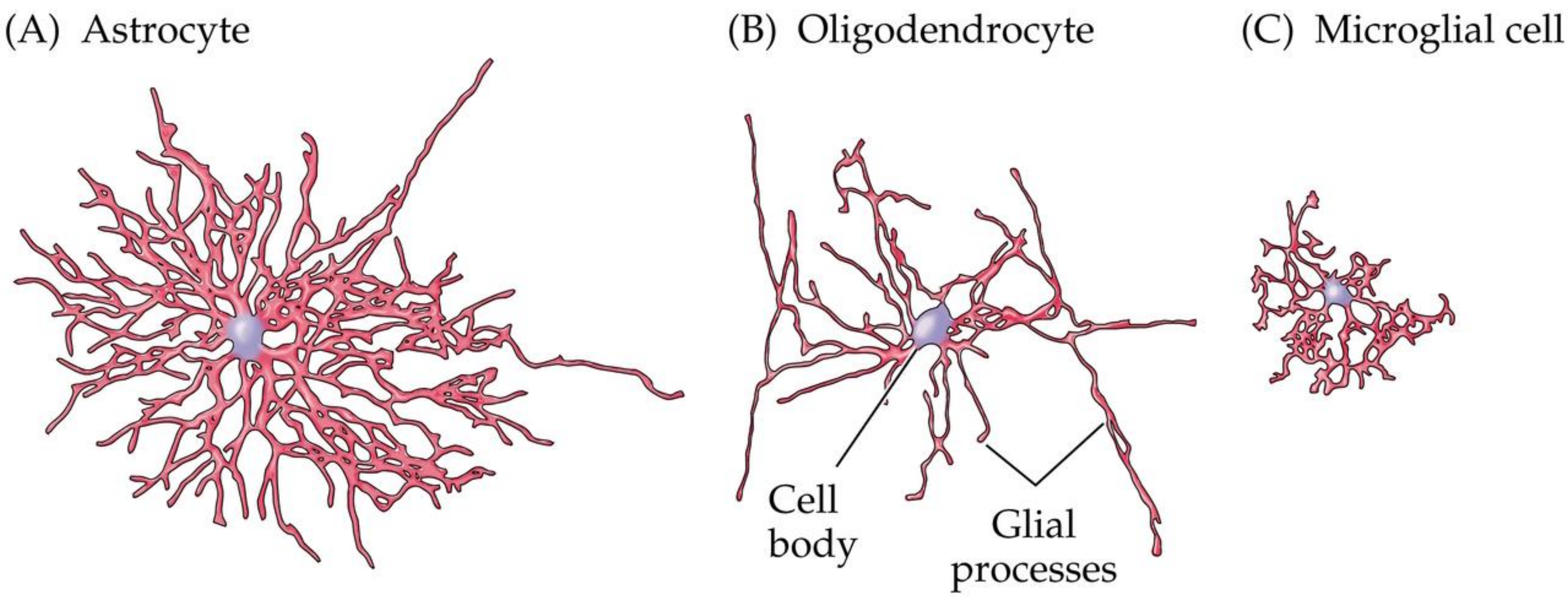
The end of the neuron, interfacing with other neurons using the synapses

Glia

inside nerves: Schwann cells



inside brain:



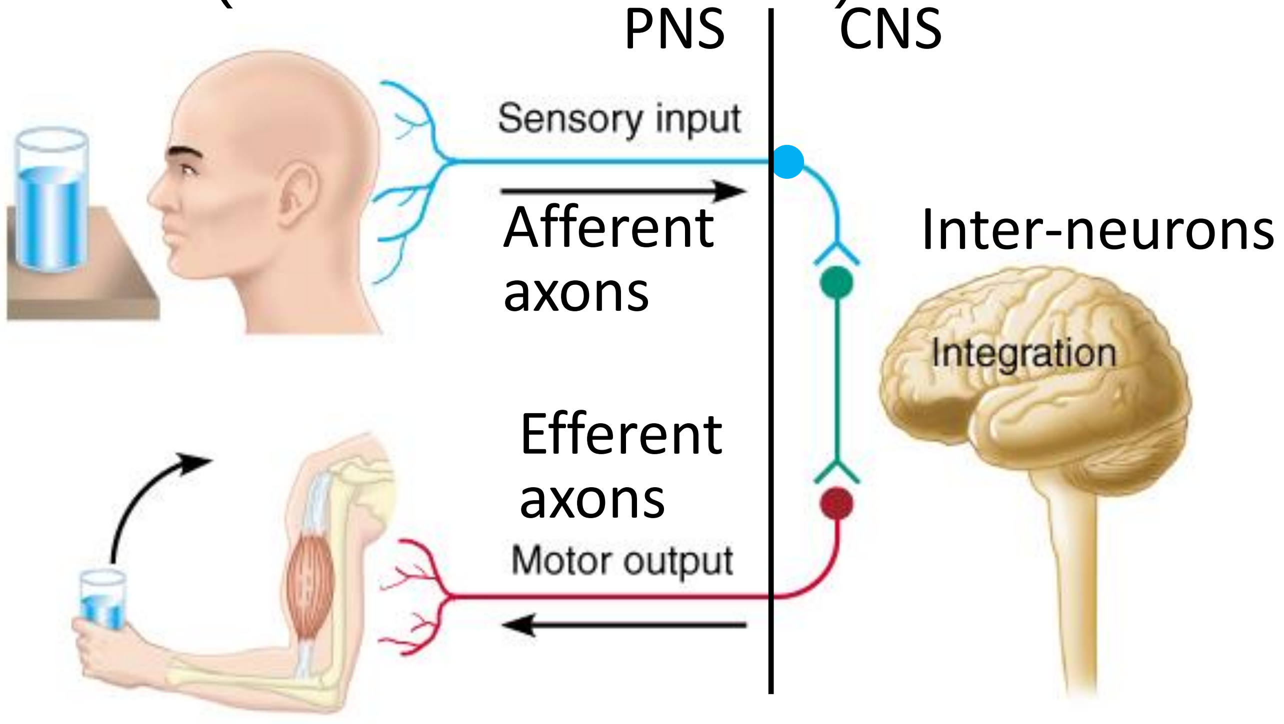
Nervous system subdivision

Central Nervous System (CNS)

- Brain (cortex, brainstem, cerebellum)
- Spinal cord

Peripheral Nervous System (PNS)

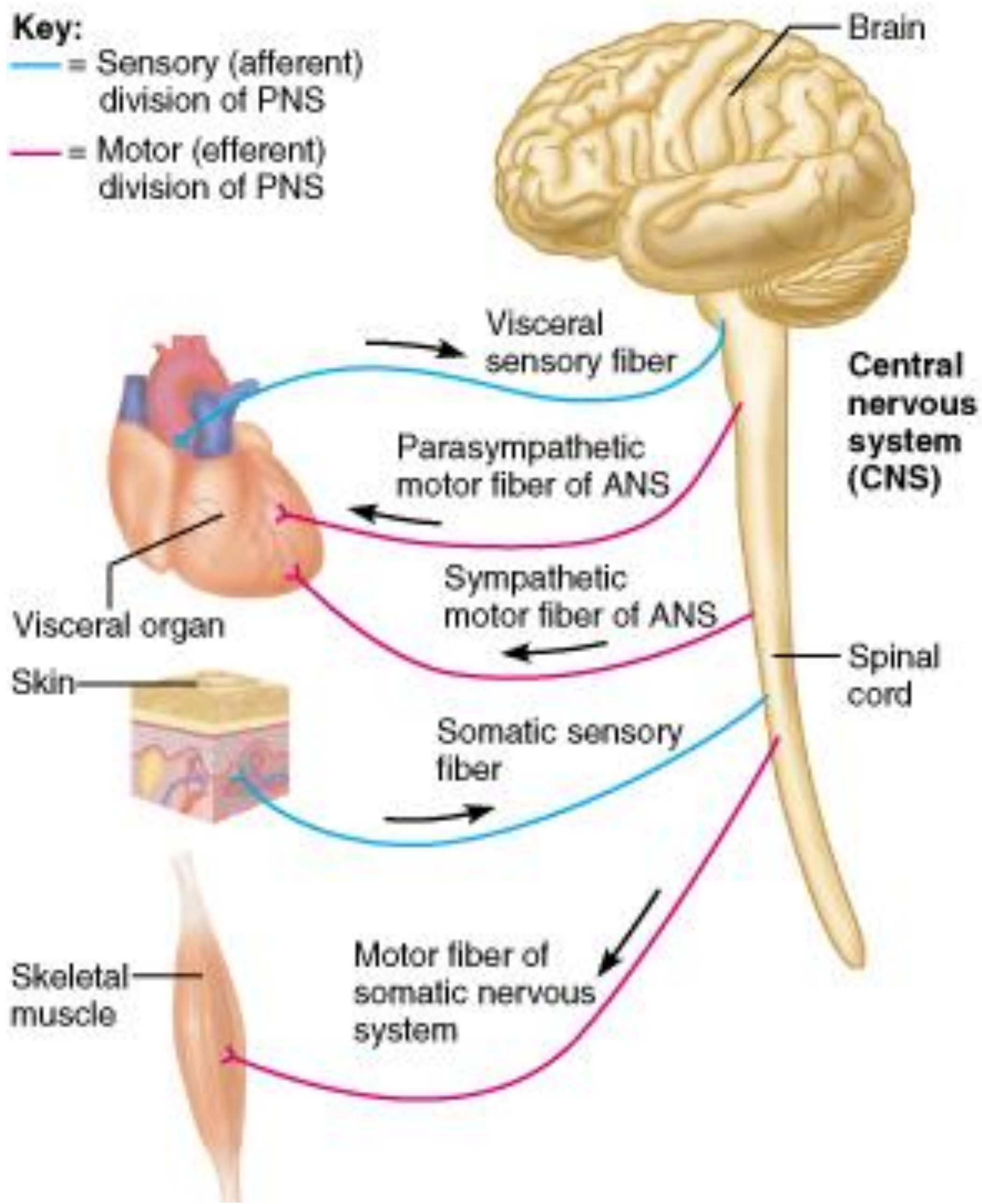
- Afferent (sensory) axonal fibers
- Efferent (motor and autonomic) axonal fibers



Peripheral Nervous System (PNS) subdivision

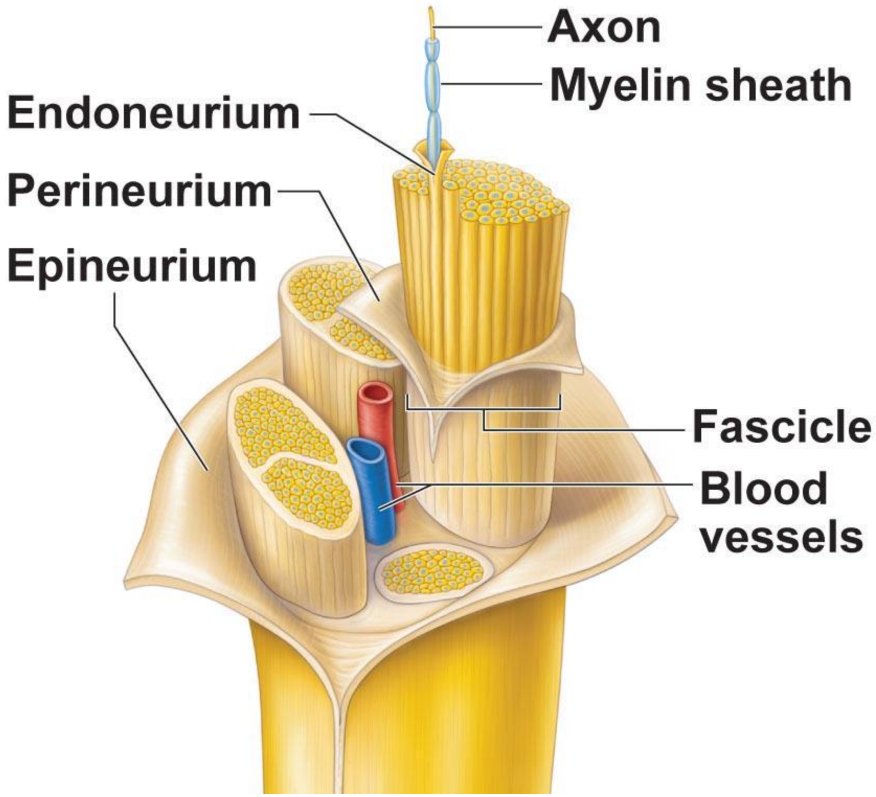
autonomic

somatic

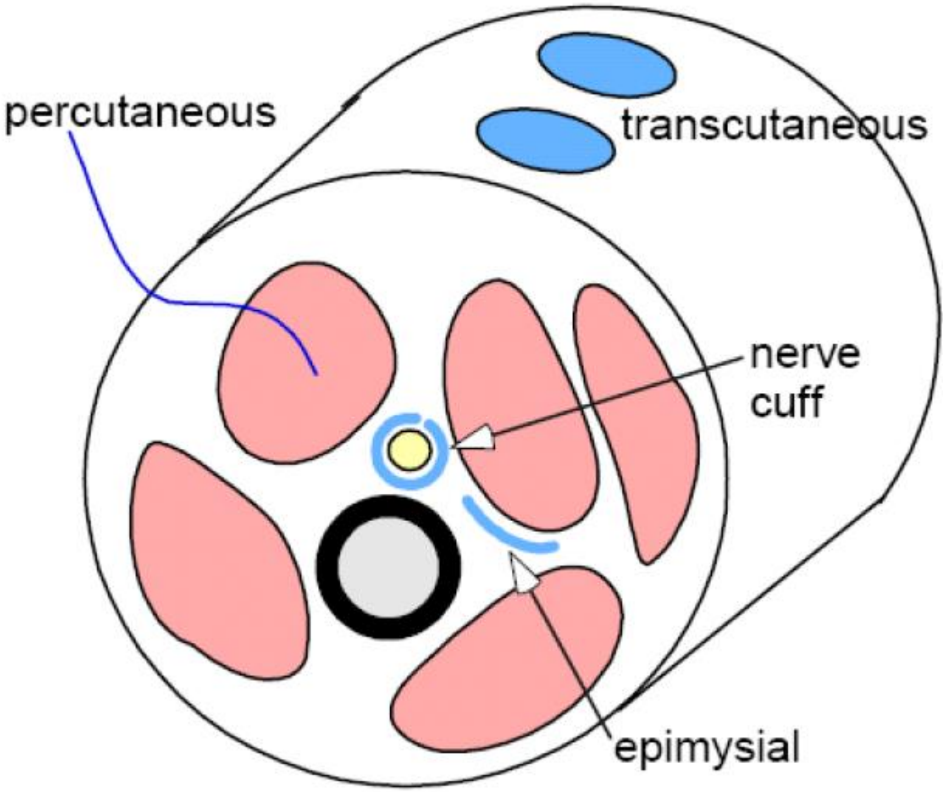


PNS: Nerve structure and nerve interfaces

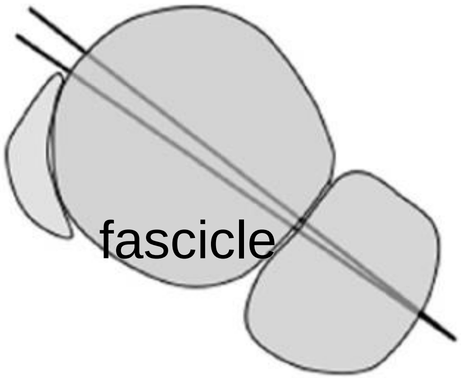
Multi-fascicular nerve

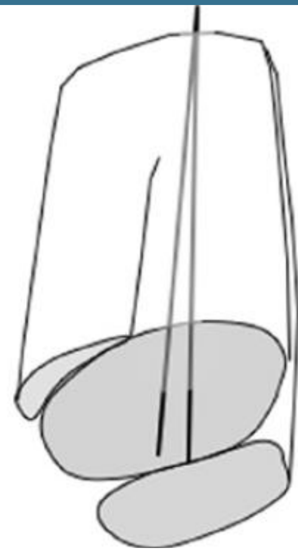


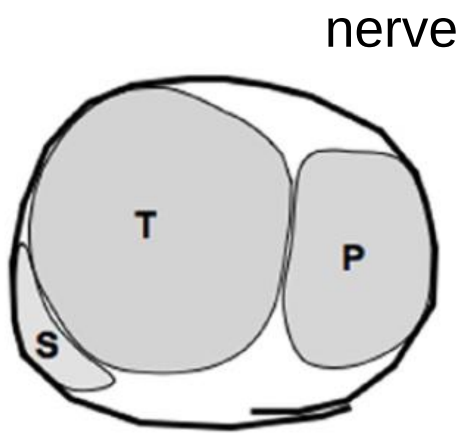
Nerve interfaces in the arm



Comparison of key nerve interfaces



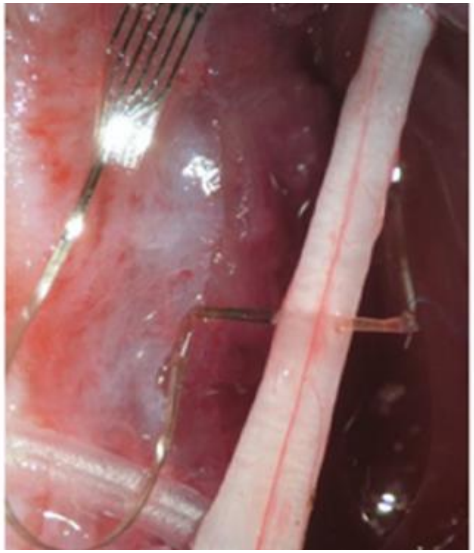


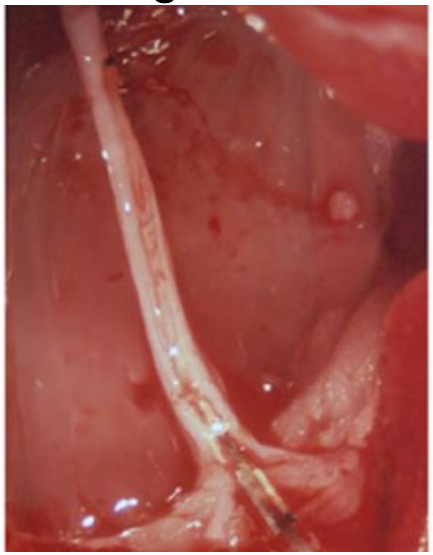


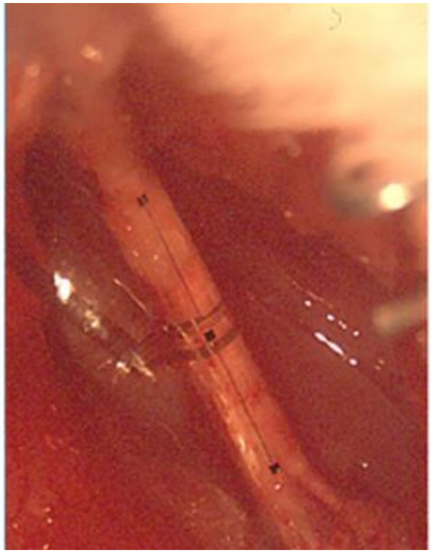
transverse

longitudinal

cuff







access to multiple fascicles

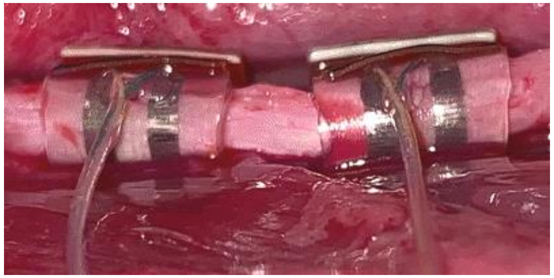
low stimulation voltage

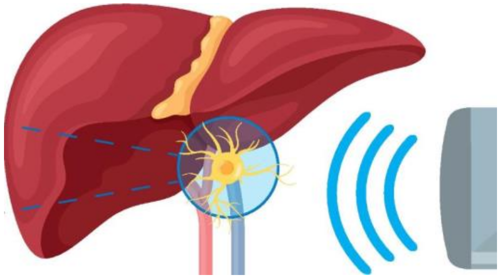
minimal nerve trauma

Key components of the nerve interface

Front-end:

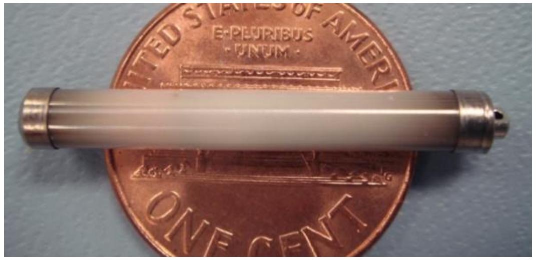
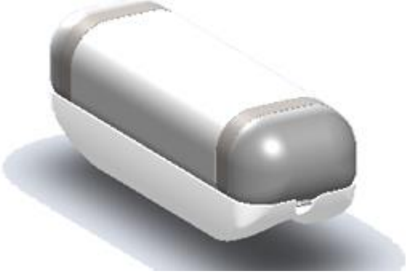
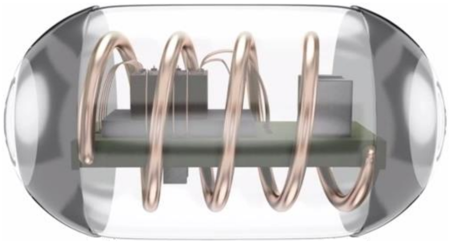
- electrical/optical/ultrasound electrodes for nerve recording/stim
- coatings to reduce impedance



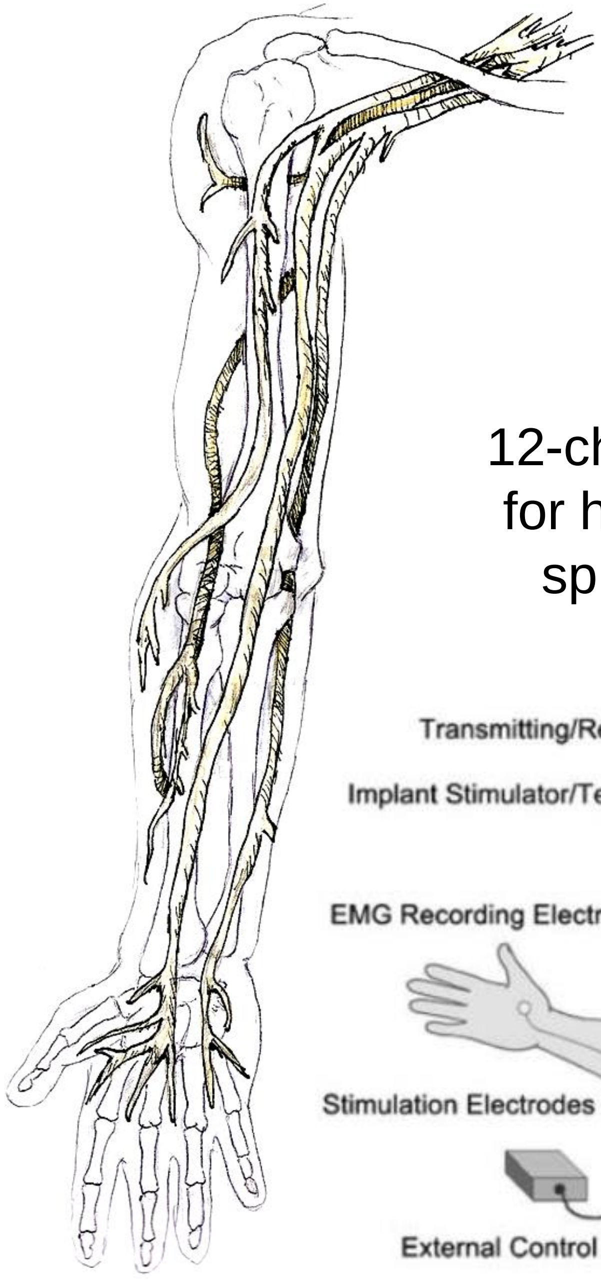


Back-end:

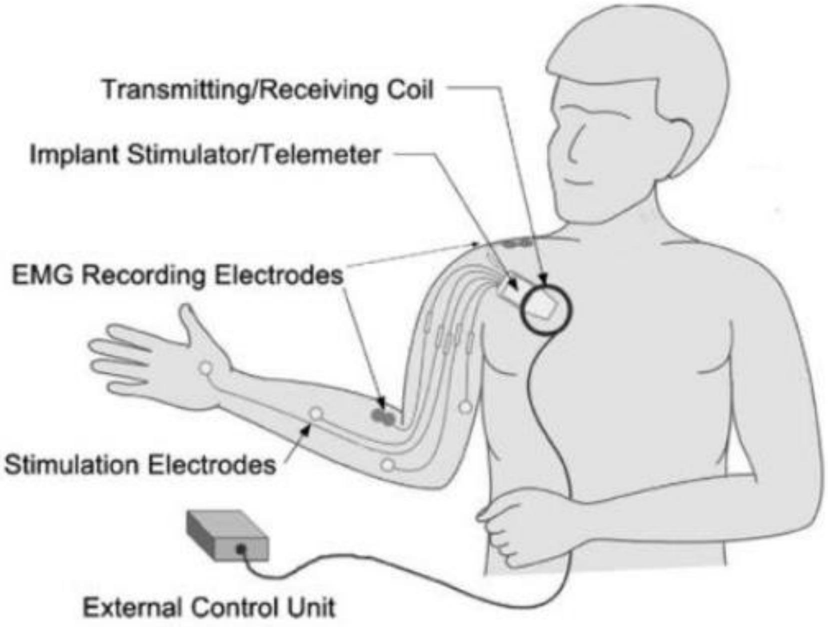
- Data and power telemetry
- Low-noise (<1 µV), low-power amplifiers
- Signal processing and artifact suppression
- Miniature hermetic packaging

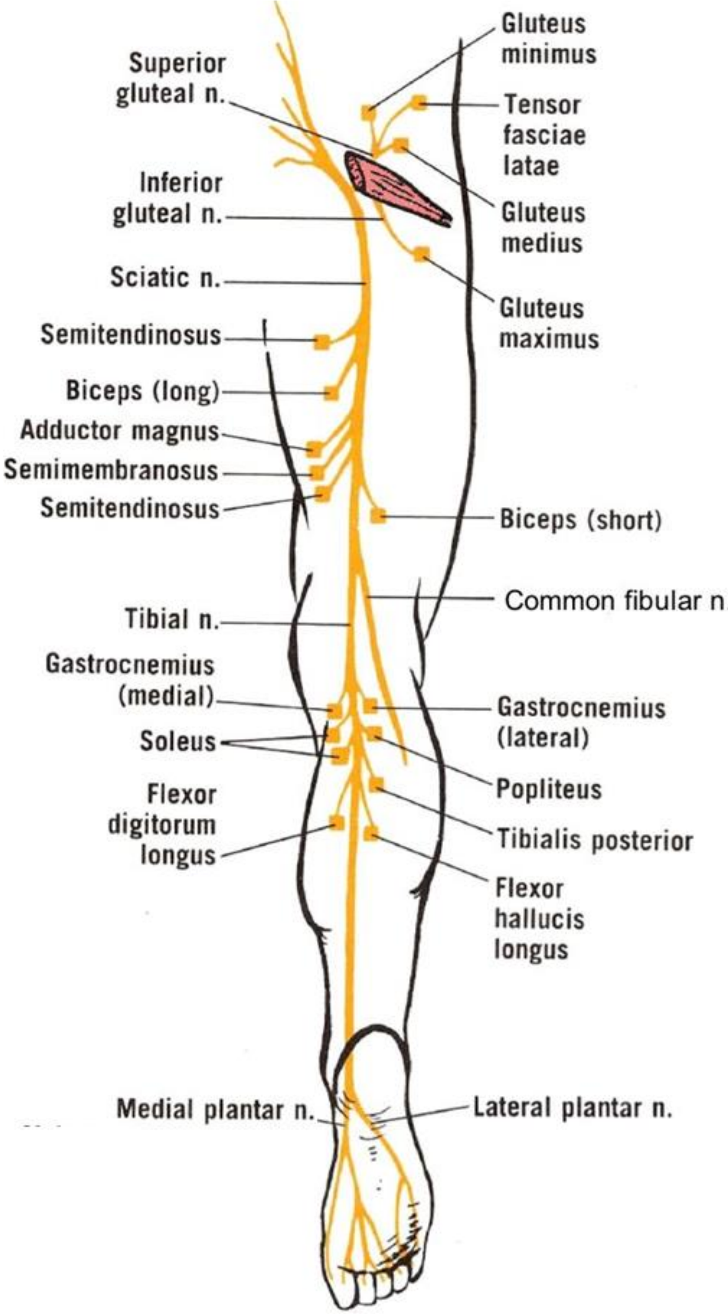




Clinical applications of somatic nerve interfaces

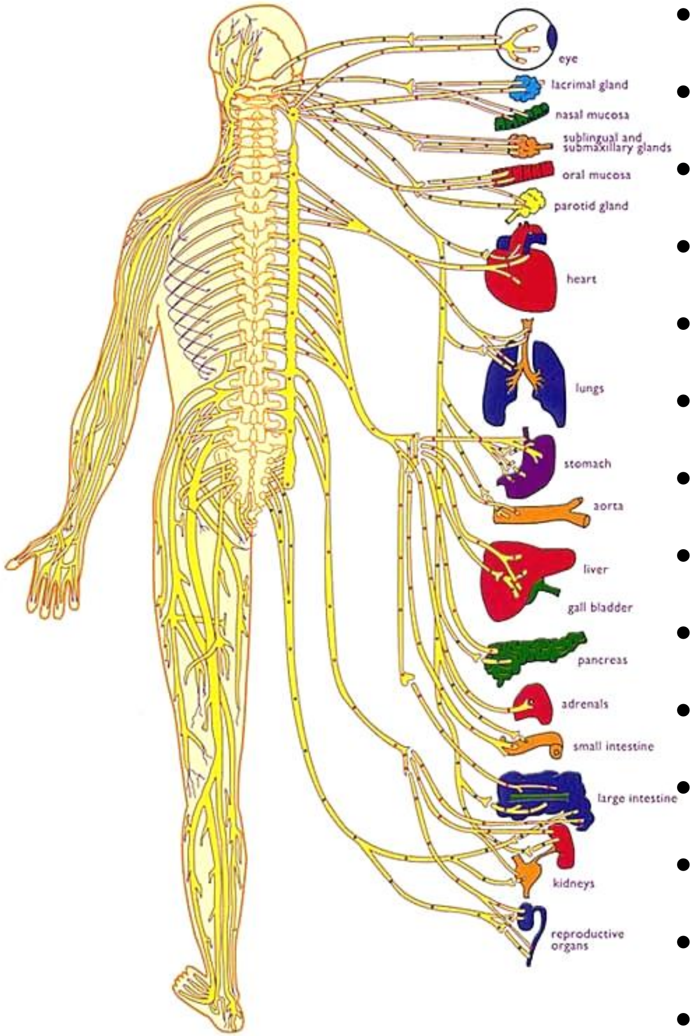


12-channel stimulator for hand paralysis in spinal cord injury





Future clinical applications of autonomic nerves



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- tongue: obstructive sleep apnea
- carotid sinus in the neck: type 2 diabetes
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- heart: heart failure, arrhythmia
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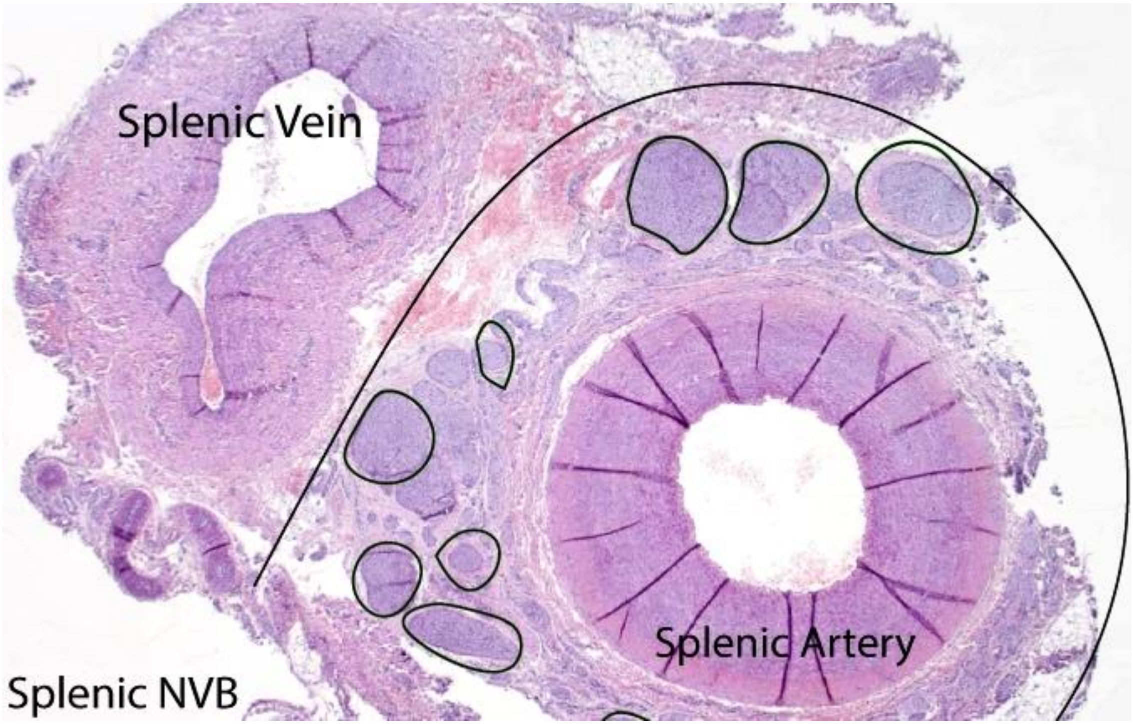
- spleen: rheumatoid arthritis, lupus
- adrenal gland: psychosis, asthma, hypertension
- kidney: chronic kidney disease, central sleep apnea
- bladder: incontinence
- ovary: polycystic ovarian syndrome

by 2033, expected to treat 2 billion patients, 25% of people

Challenges in developing autonomic nerve interfaces

Surgical challenges:

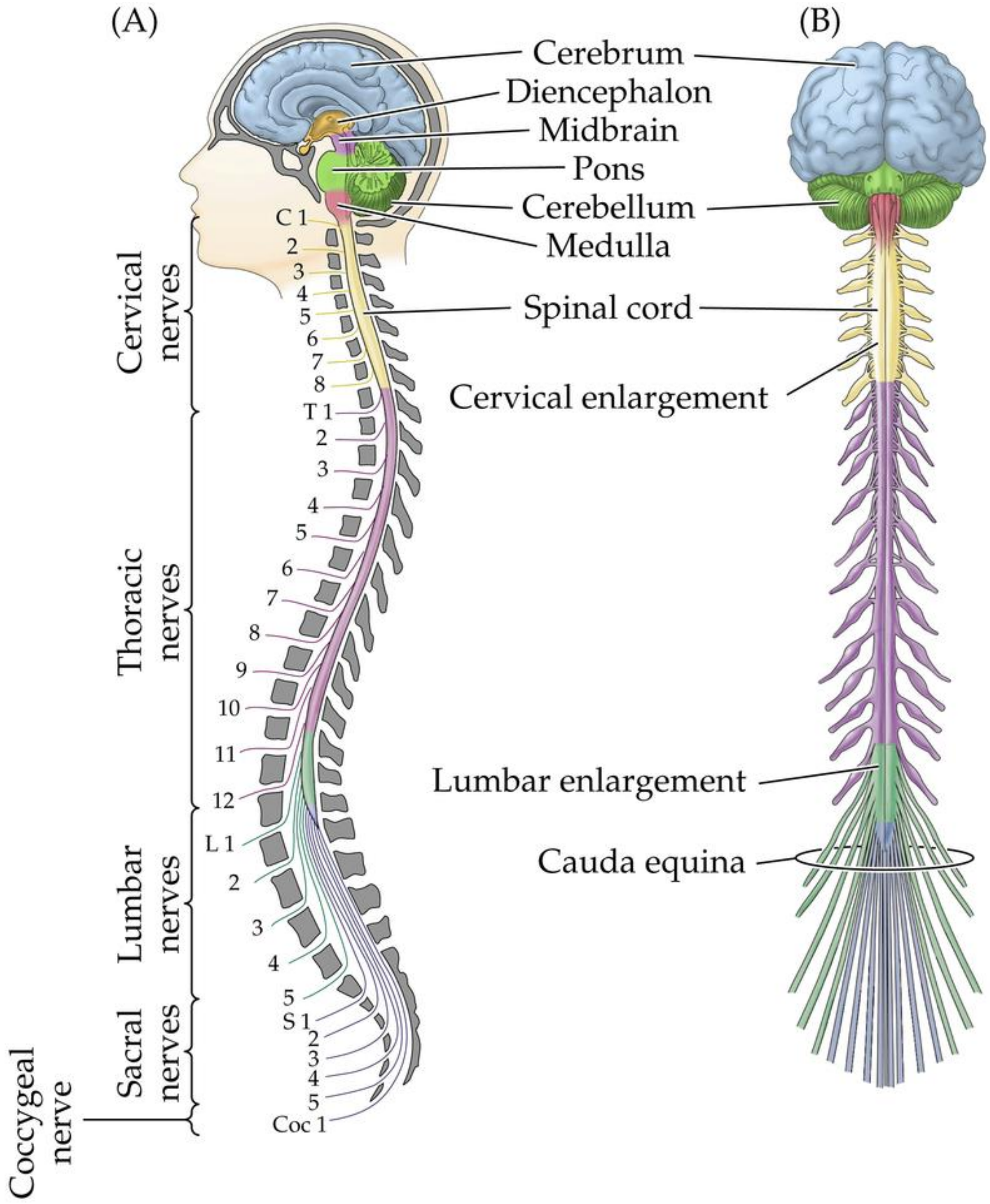
- small transparent nerves are difficult to visualize
- nerves are buried inside vessel walls, ligaments, or adipose tissue



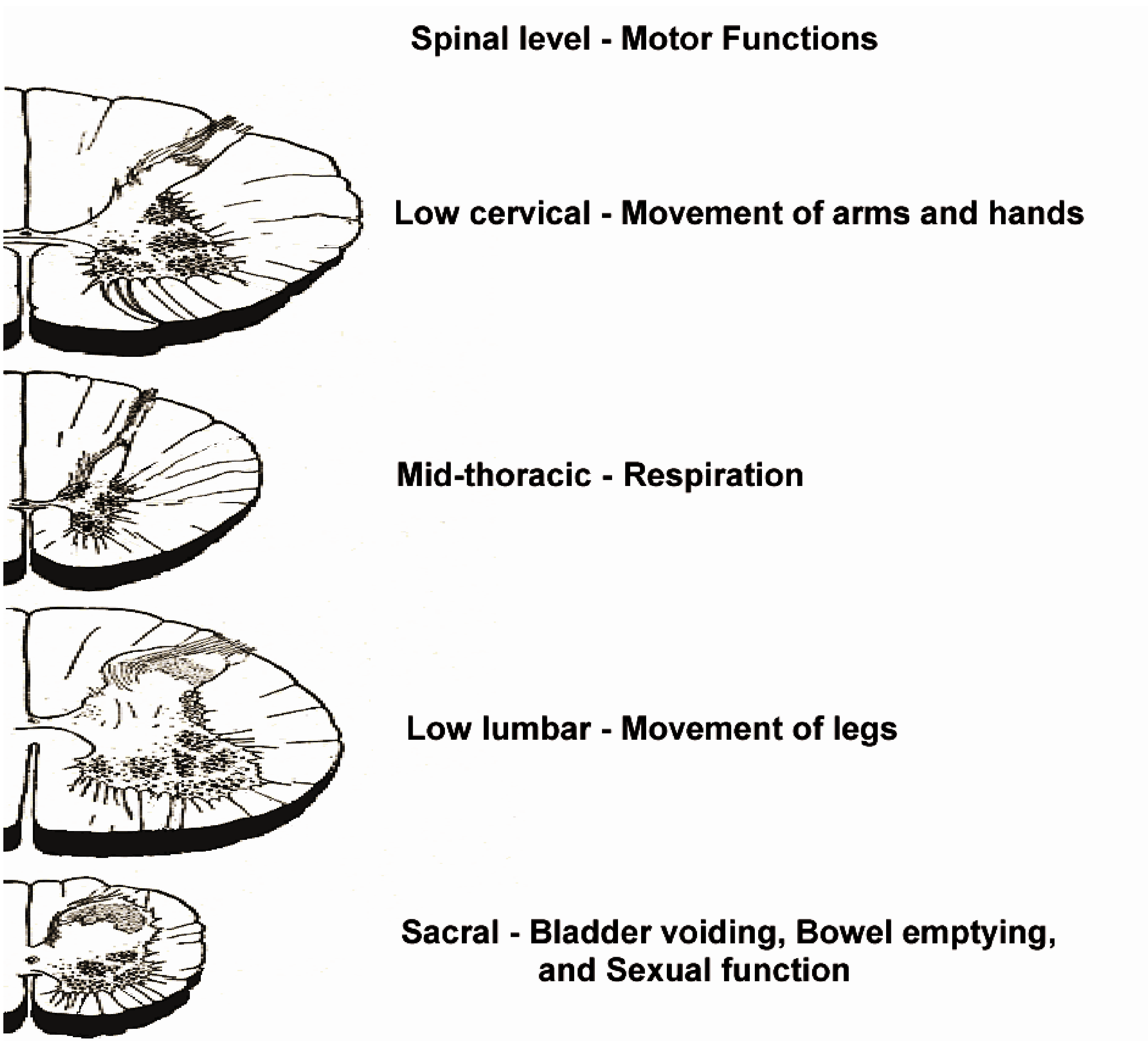
Technical challenges:

- nerve cuff requires soft materials to avoid compression
- difficult to stimulate, as majority of axons are unmyelinated
- Difficult to record, as nerve is surrounded by electrically-noisy organs, e.g. heart, lungs, intestines, and bladder

CNS subdivision



Spinal segments have different functions

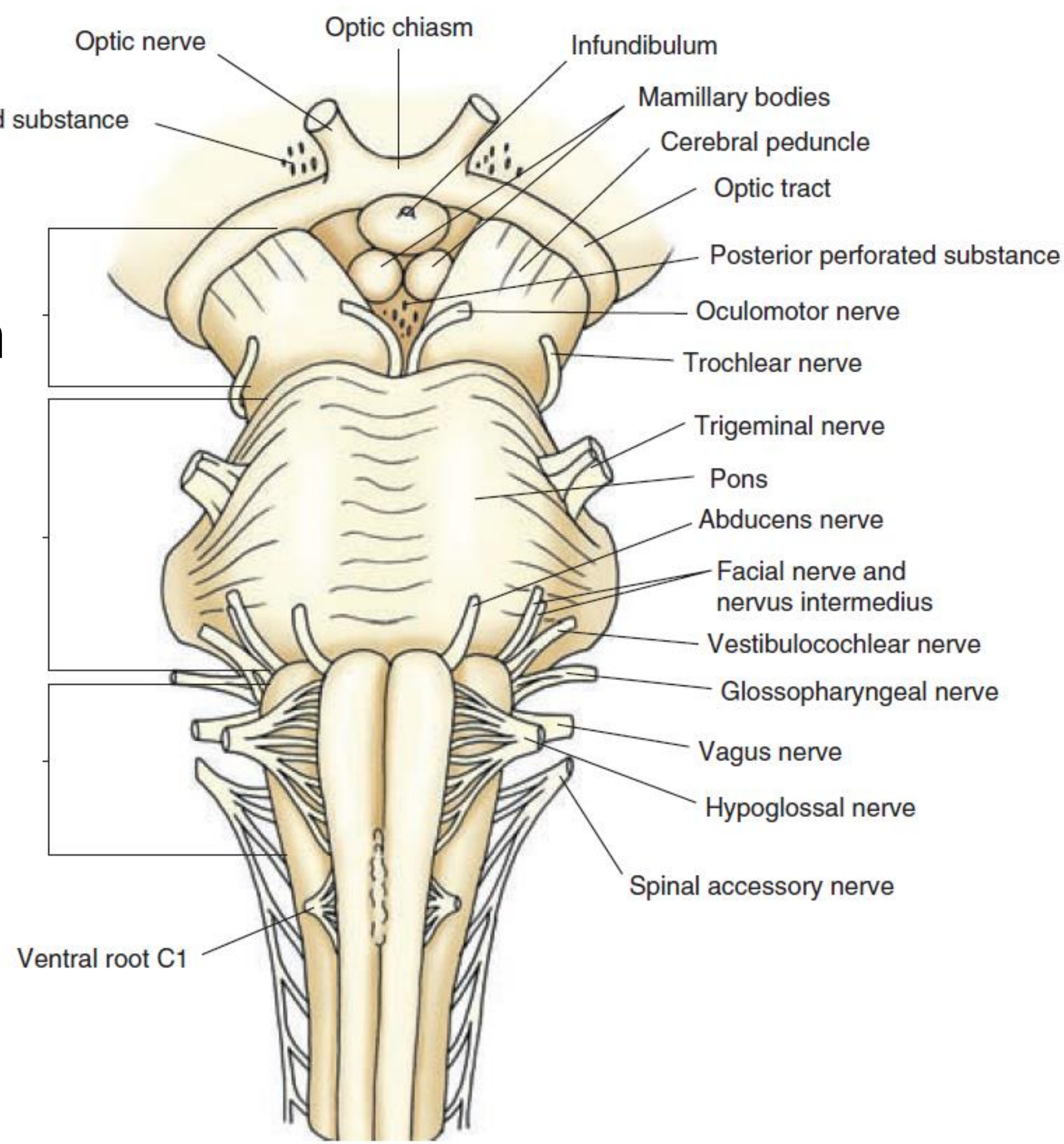


Brainstem has many functions

Brainstem has:

- 3 major parts — midbrain, pons, medulla

- 12 cranial nerves with sensory, motor, and autonomic functions



Cranial nerves and nuclei: anatomy

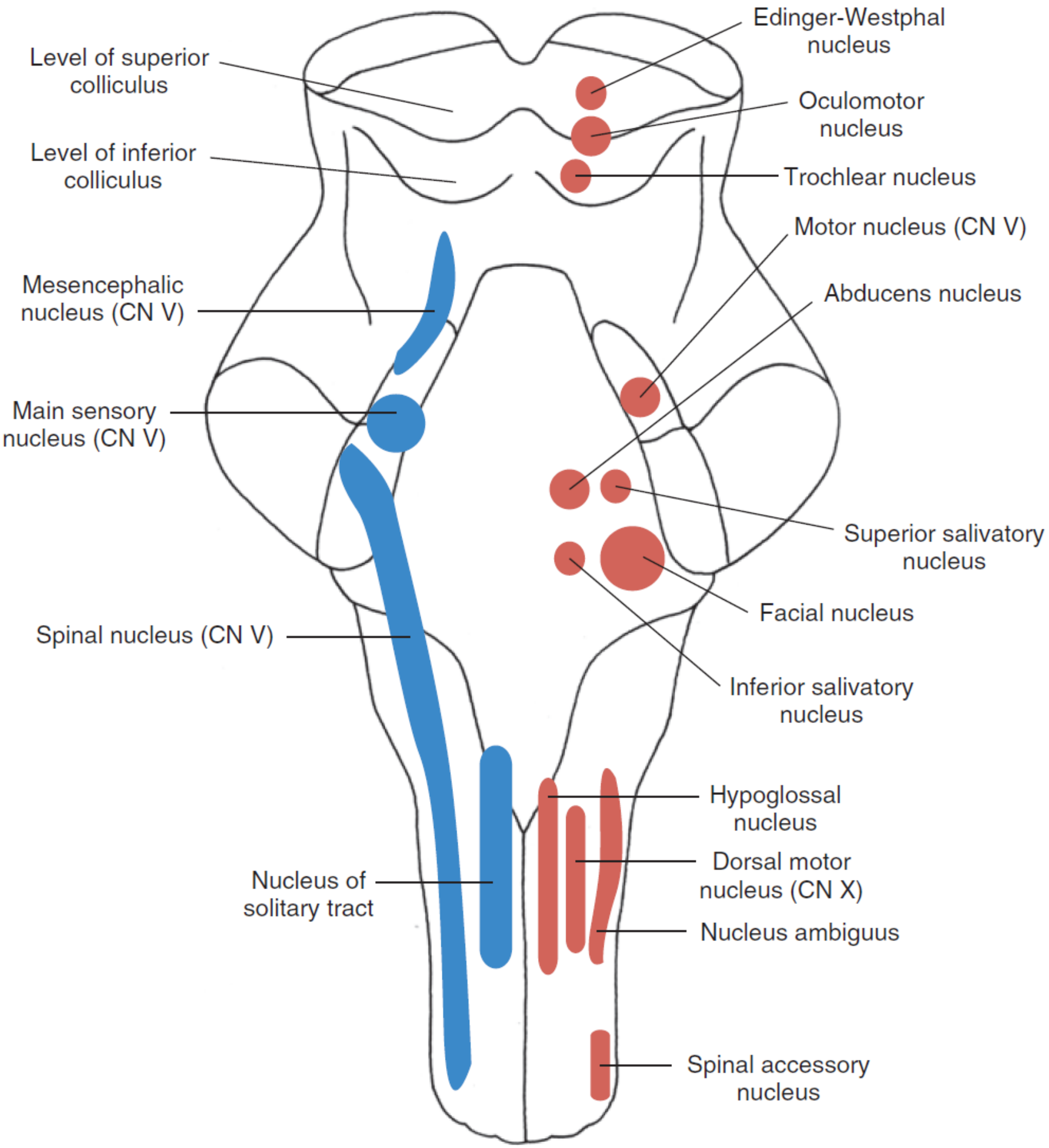
Sensory only:
olfactory (I), optic (II)

Mixed (motor/autonomic):
oculomotor (III)

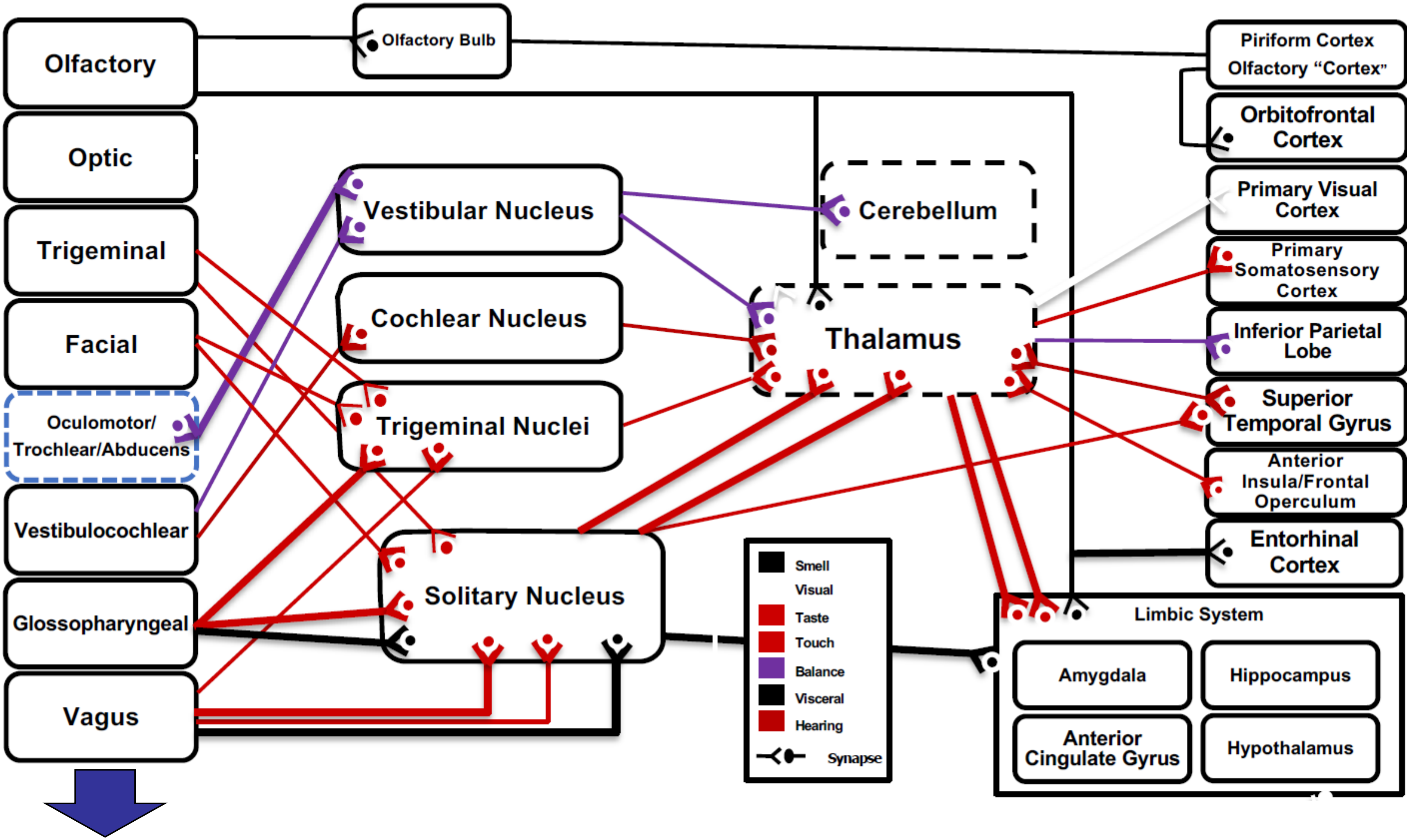
Mixed (sensory/motor):
trigeminal (V)

Mixed (sensory/motor/autonomic):
glossopharyngeal (IX)

Motor only:
hypoglossal (XII)

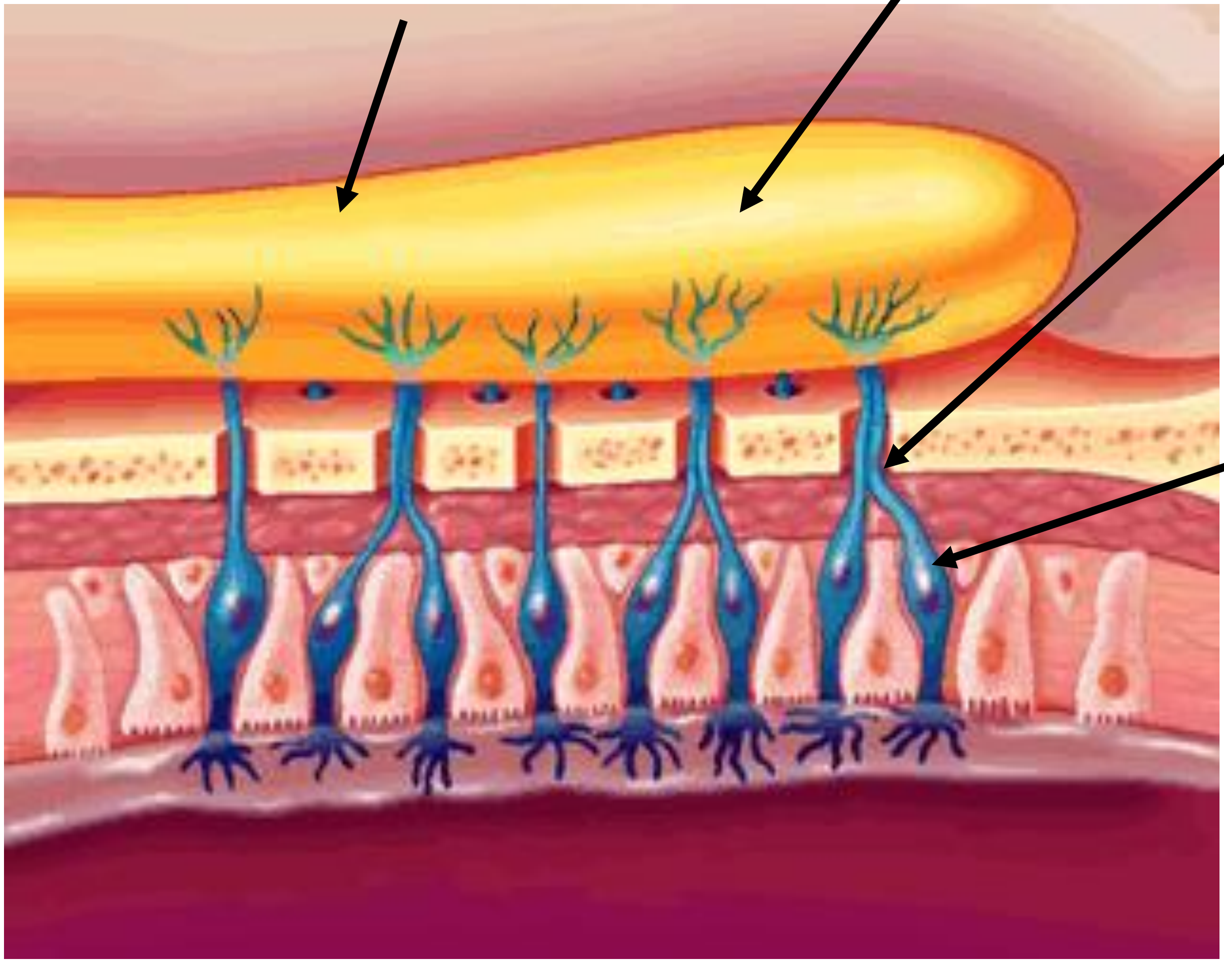


Cranial nerves and nuclei function as a gateway to the brain

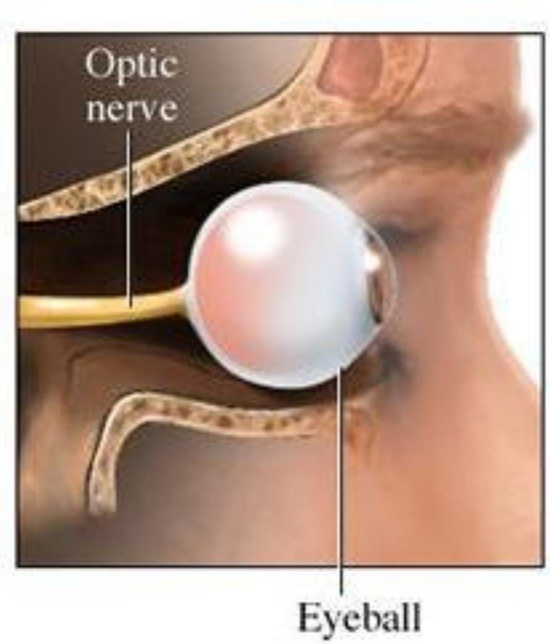


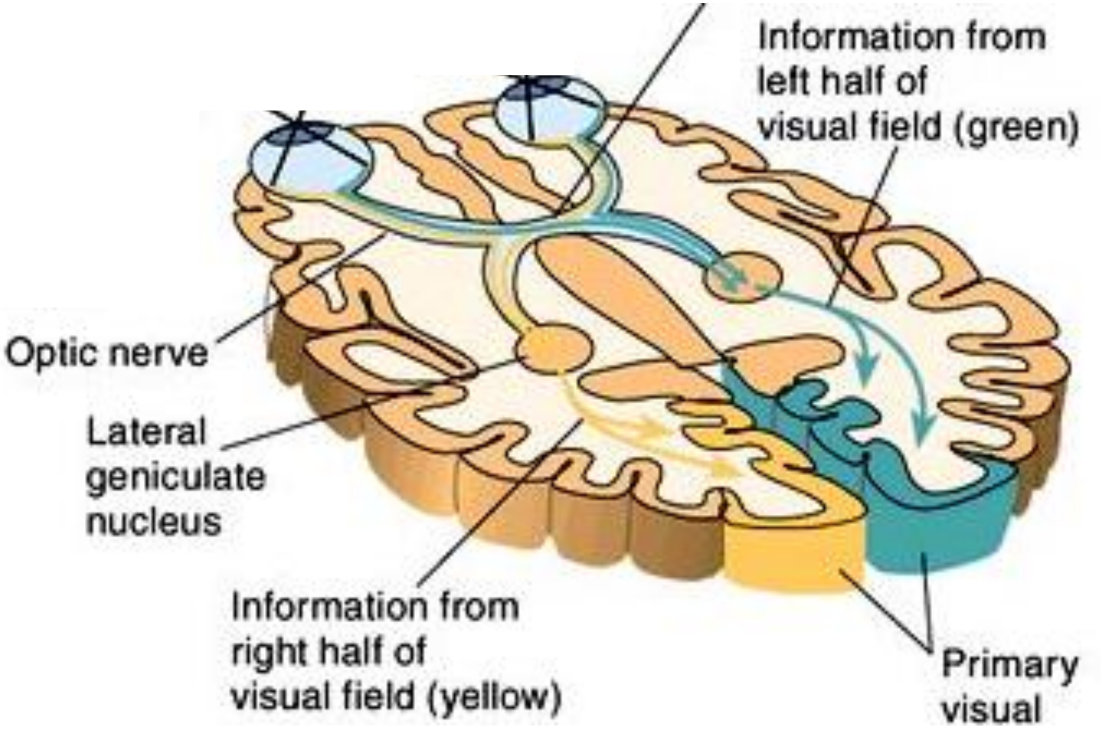
sensory organs, muscles, internal organs

Olfactory nerve: sense of smell

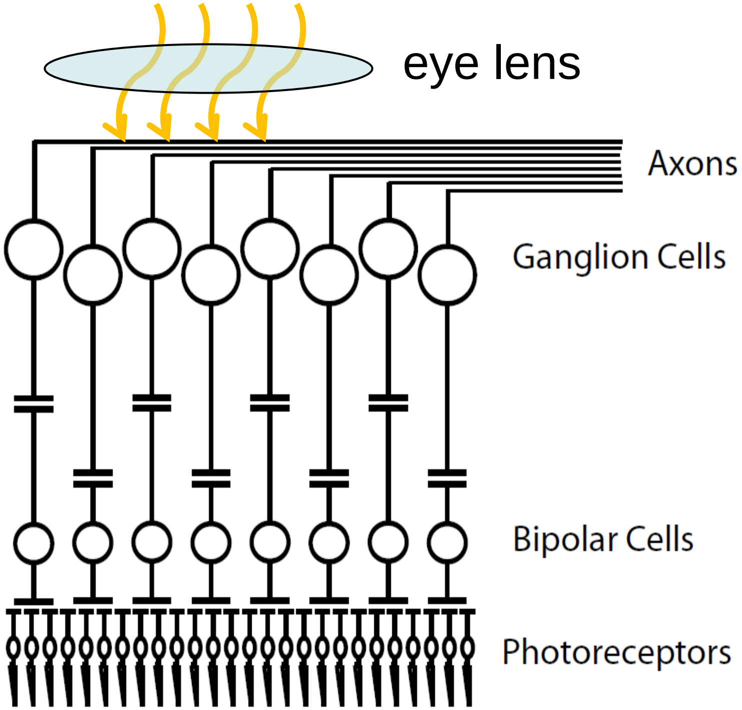


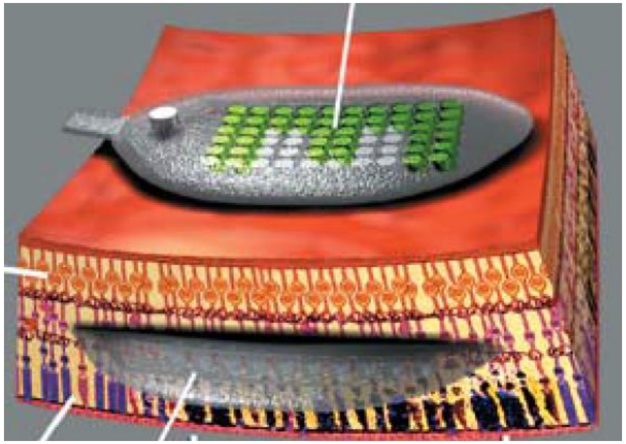
Optic nerve: vision





Retinal implants

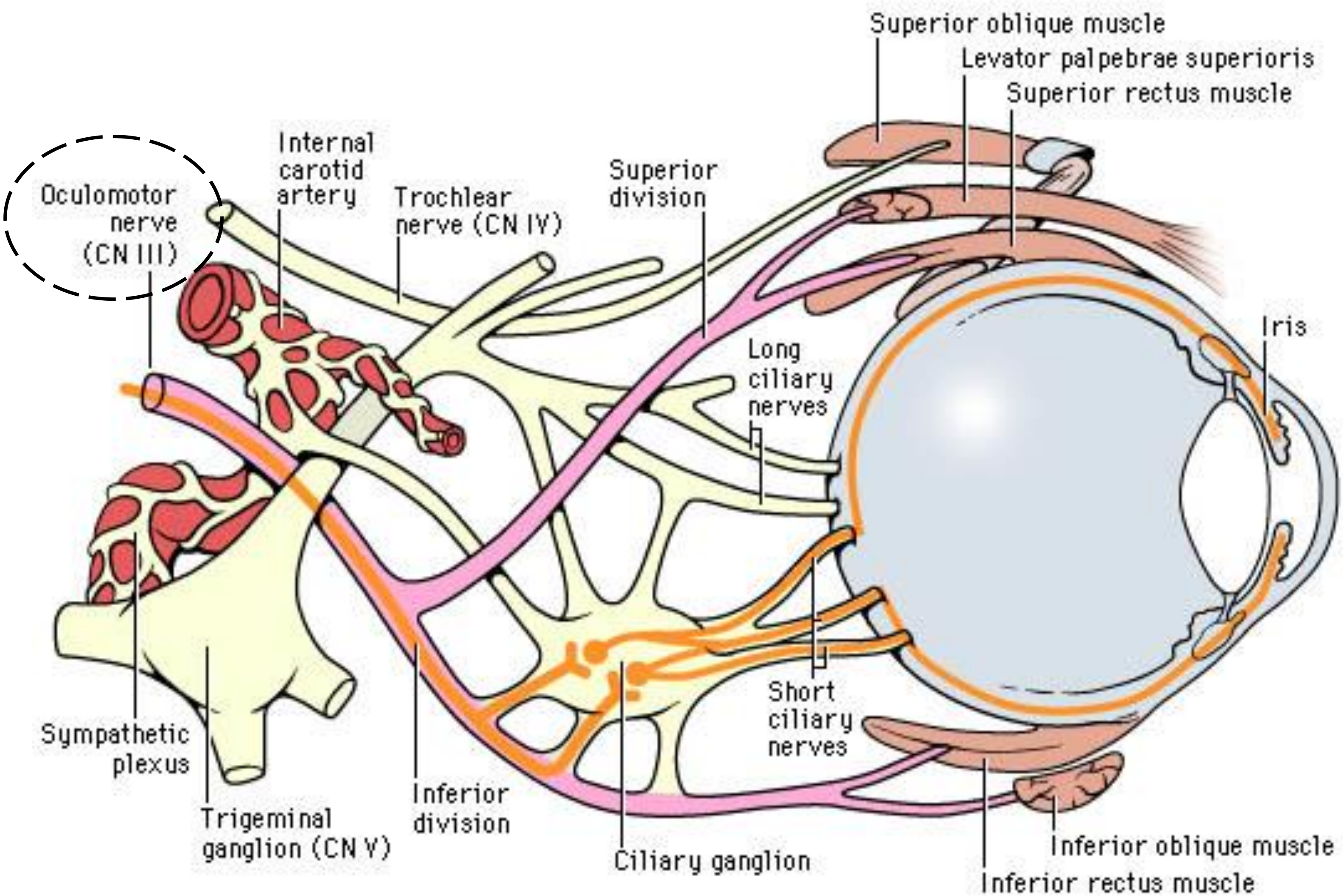




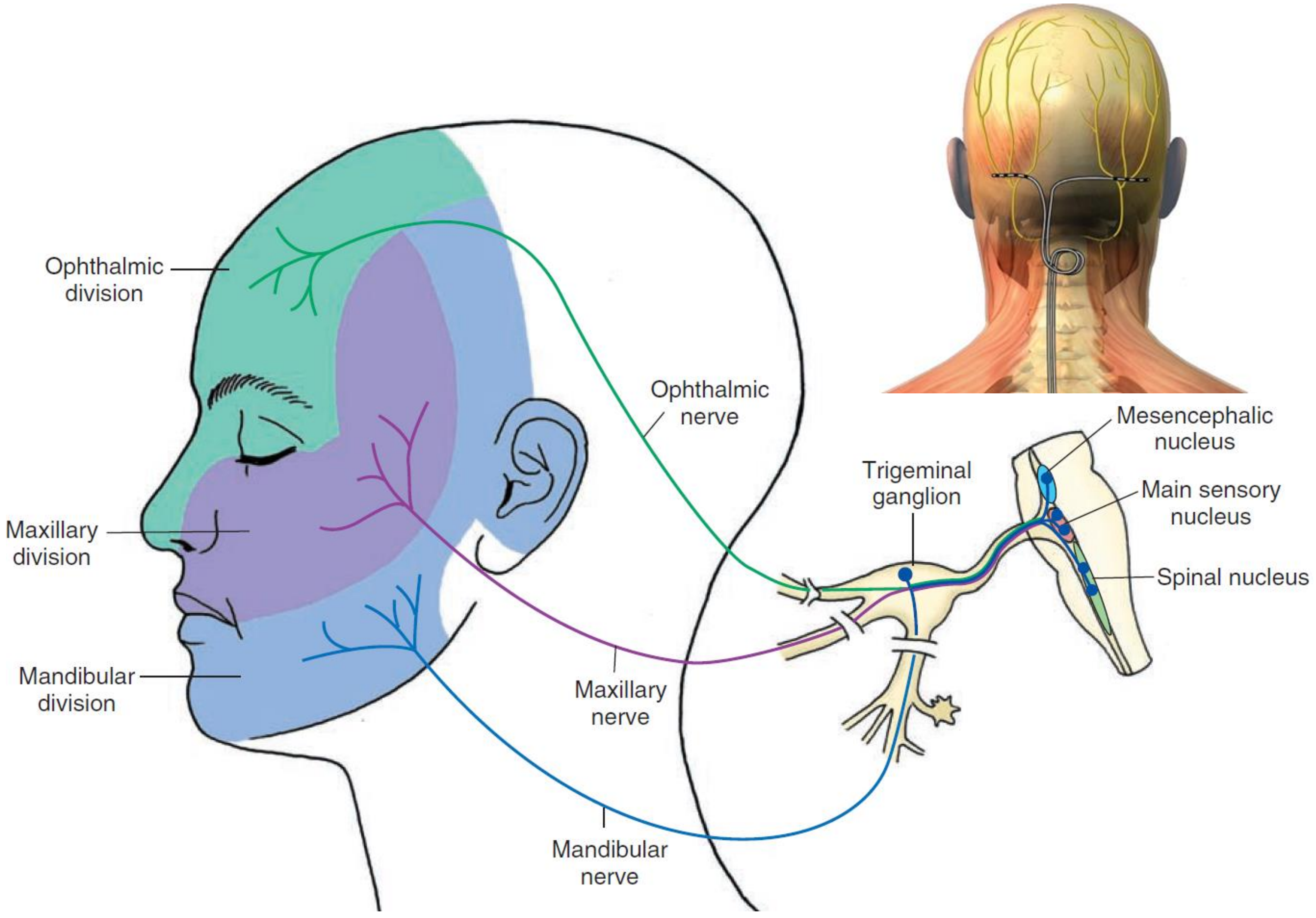
Surgical placement in the eye:

- epiretinal (attached with tacks)
- subretinal

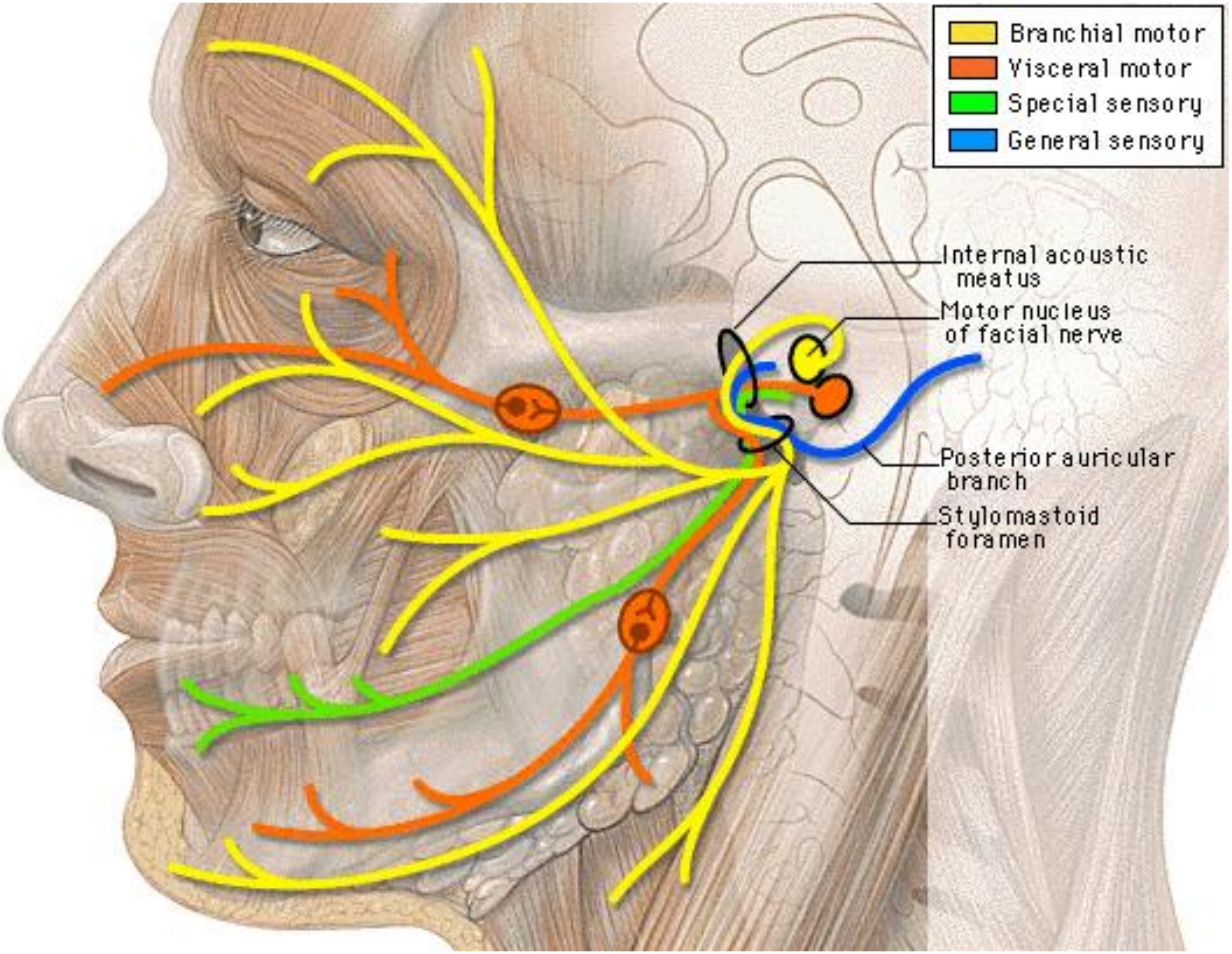
Oculomotor nerve: movement of eye muscles



Trigeminal and occipital nerves: sensory input from the head

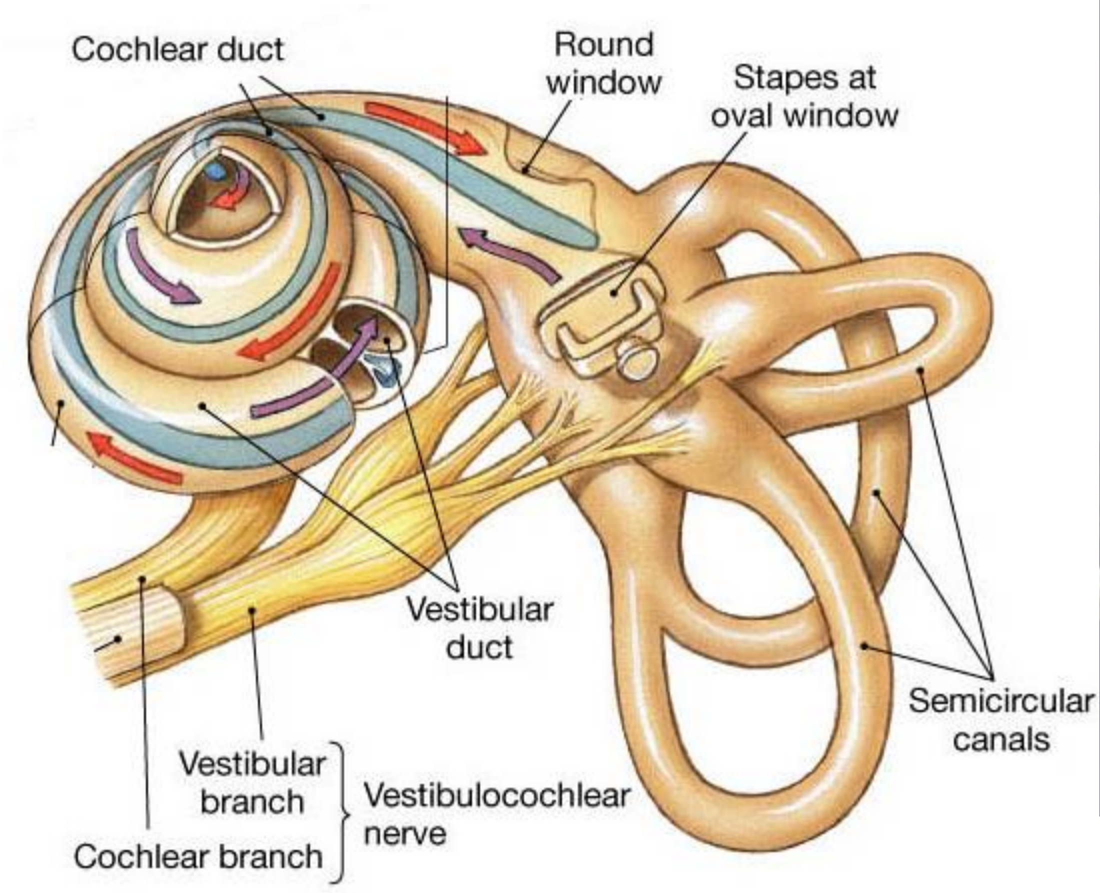


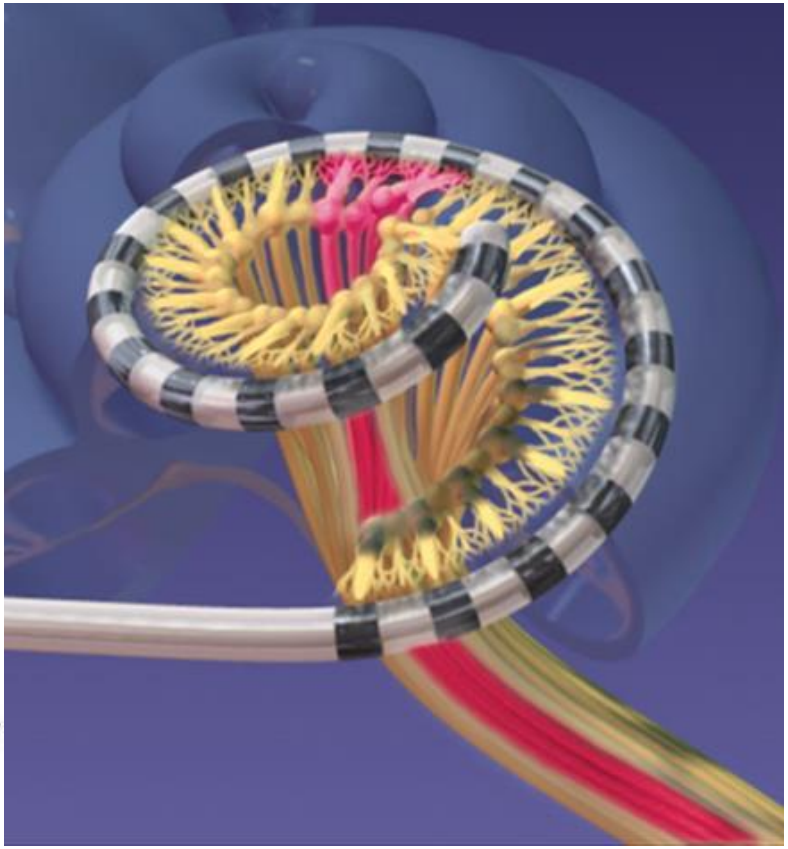
Facial nerve: control of facial expressions



Vestibulocochlear nerve: hearing and balance

- Speech perception can be restored with 10-20 electrodes stimulating 30,000 axons in the cochlear nerve (no need for selective stimulation of every axon)
- Better hearing restoration soon after hearing loss





Vagus nerve: parasympathetic control of nearly all internal organs

- eye: dry eye, macular degeneration, glaucoma
- tongue: obstructive sleep apnea
- carotid sinus in the neck: type 2 diabetes
- thyroid gland: hypothyroid syndrome, osteoporosis
- lungs: asthma, COPD, long COVID
- GI tract: IBD, IBS, gastroparesis, fecal incontinence
- pancreas: type 1 diabetes
- heart: heart failure, arrhythmia
- blood vessels: hypertension
- spleen: rheumatoid arthritis, lupus
- adrenal gland: psychosis, asthma, hypertension
- kidney: chronic kidney disease, central sleep apnea
- bladder: incontinence
- ovary: polycystic ovarian syndrome

by 2033, expected to treat 2 billion patients, 25% of people

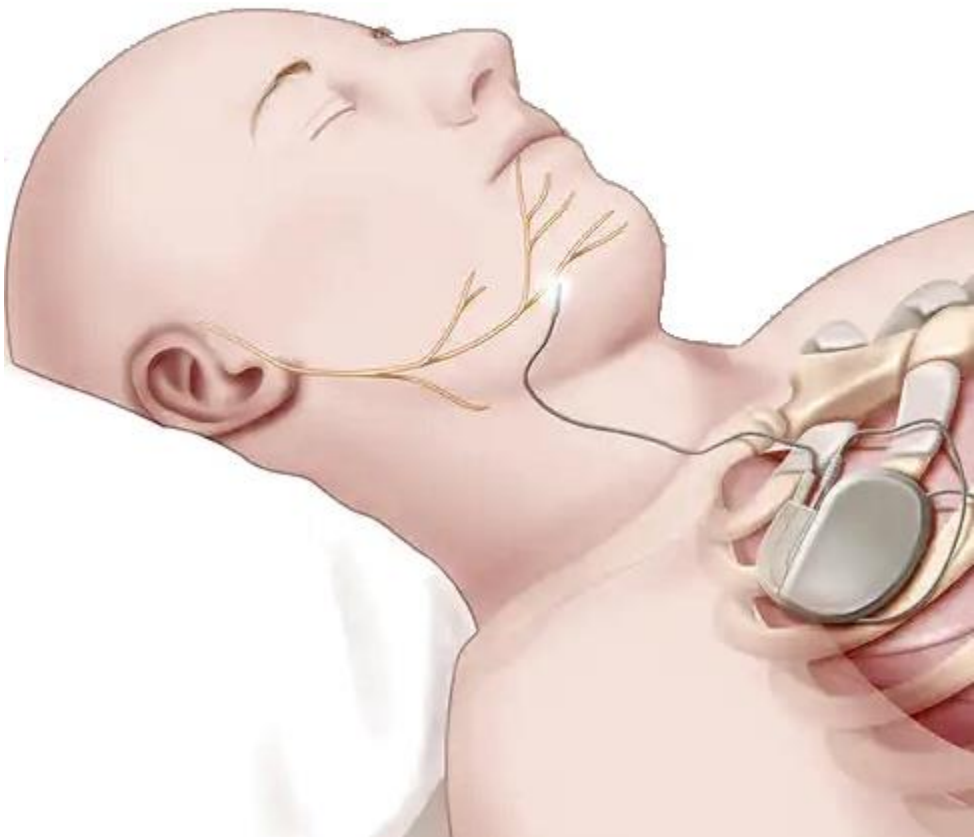
Hypoglossal nerve: tongue contraction for obstructive sleep apnea

“Apnea” = "without breath“

Tongue muscle relaxes during sleep and falls back, obstructing the airway

During each episode of hypoxia (lack of oxygen) neurons in the brain die

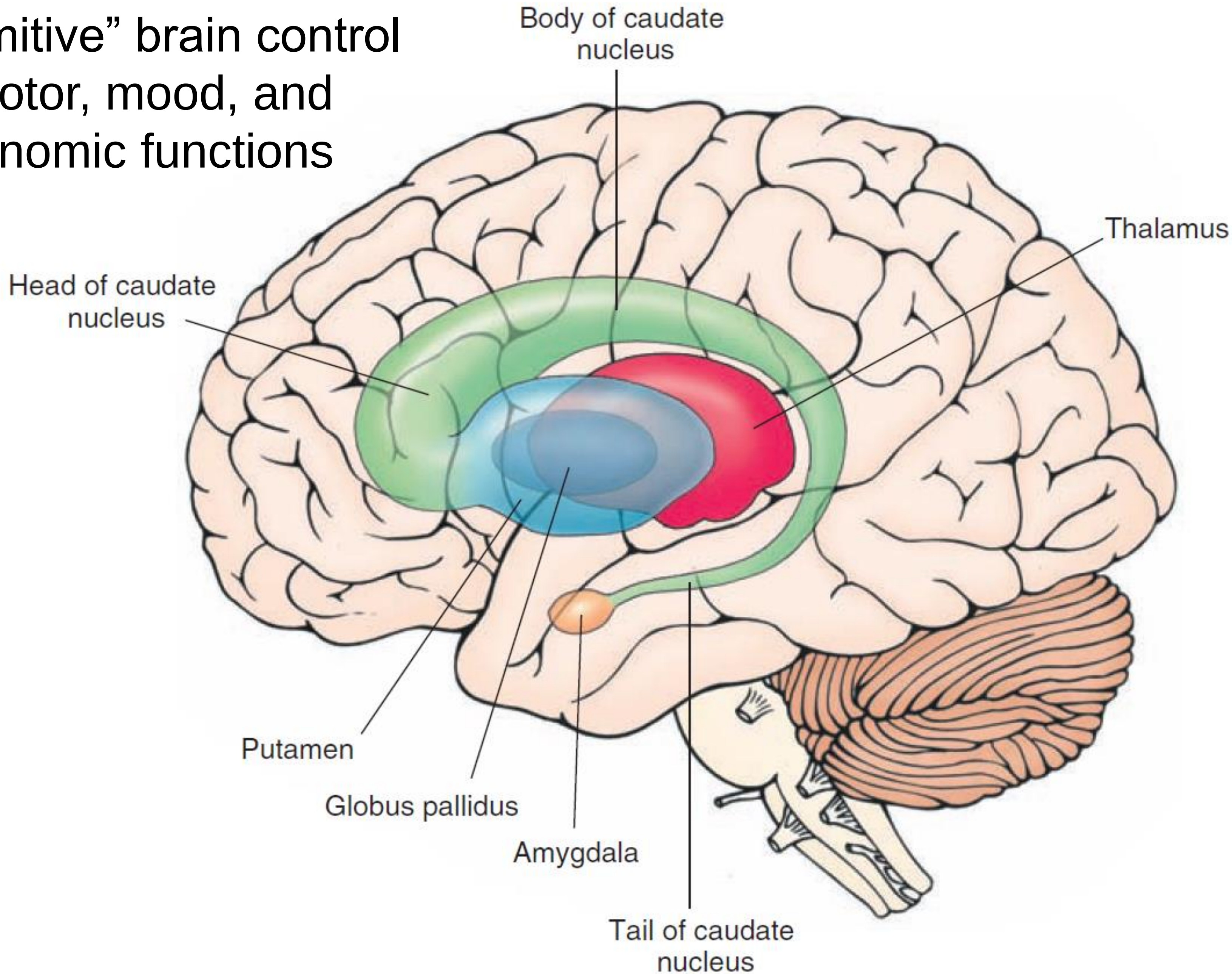
Over time, this can lead to dementia and Alzheimer's disease



In the US, 5% have diagnosed OSA, 30% – undiagnosed

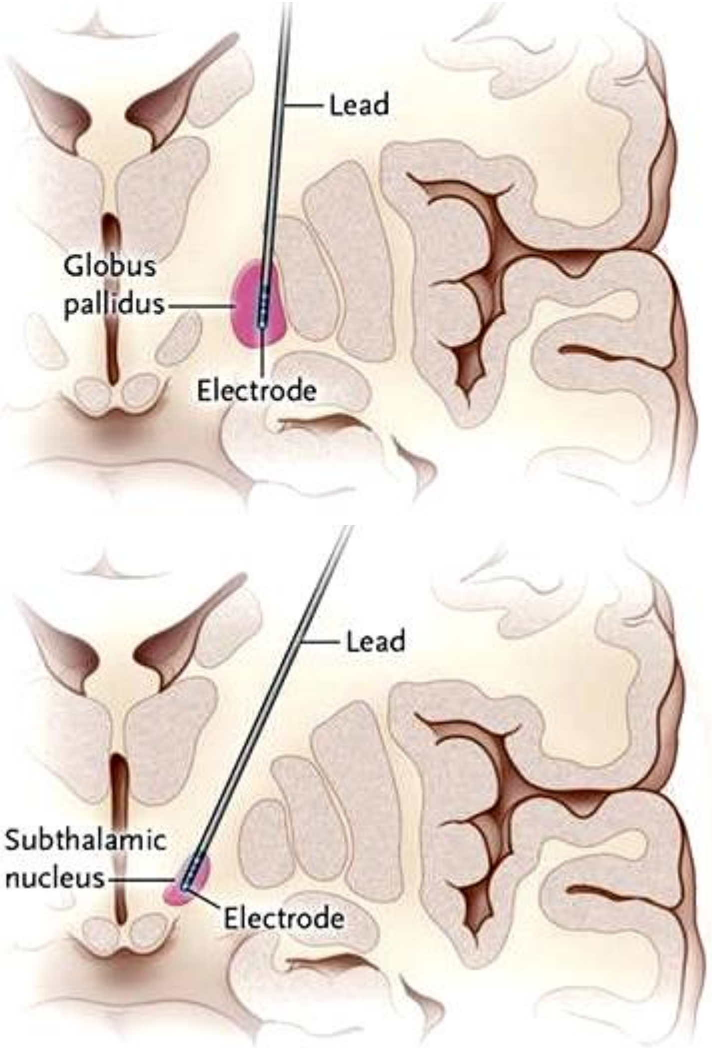
Thalamus + basal ganglia (caudate nucleus, putamen, globus pallidus)

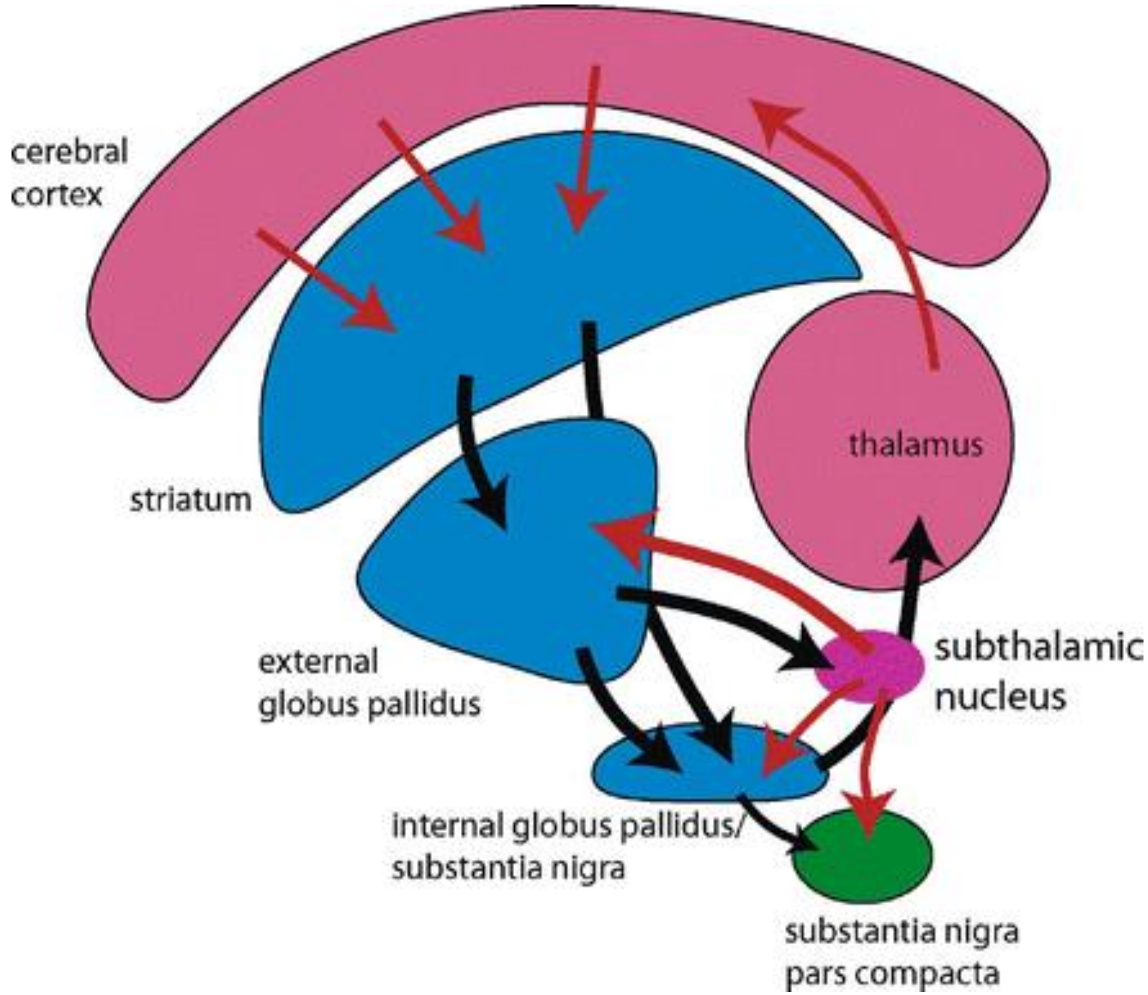
"Primitive" brain control of motor, mood, and autonomic functions



Restoring motor and mood control with deep bran stimulation

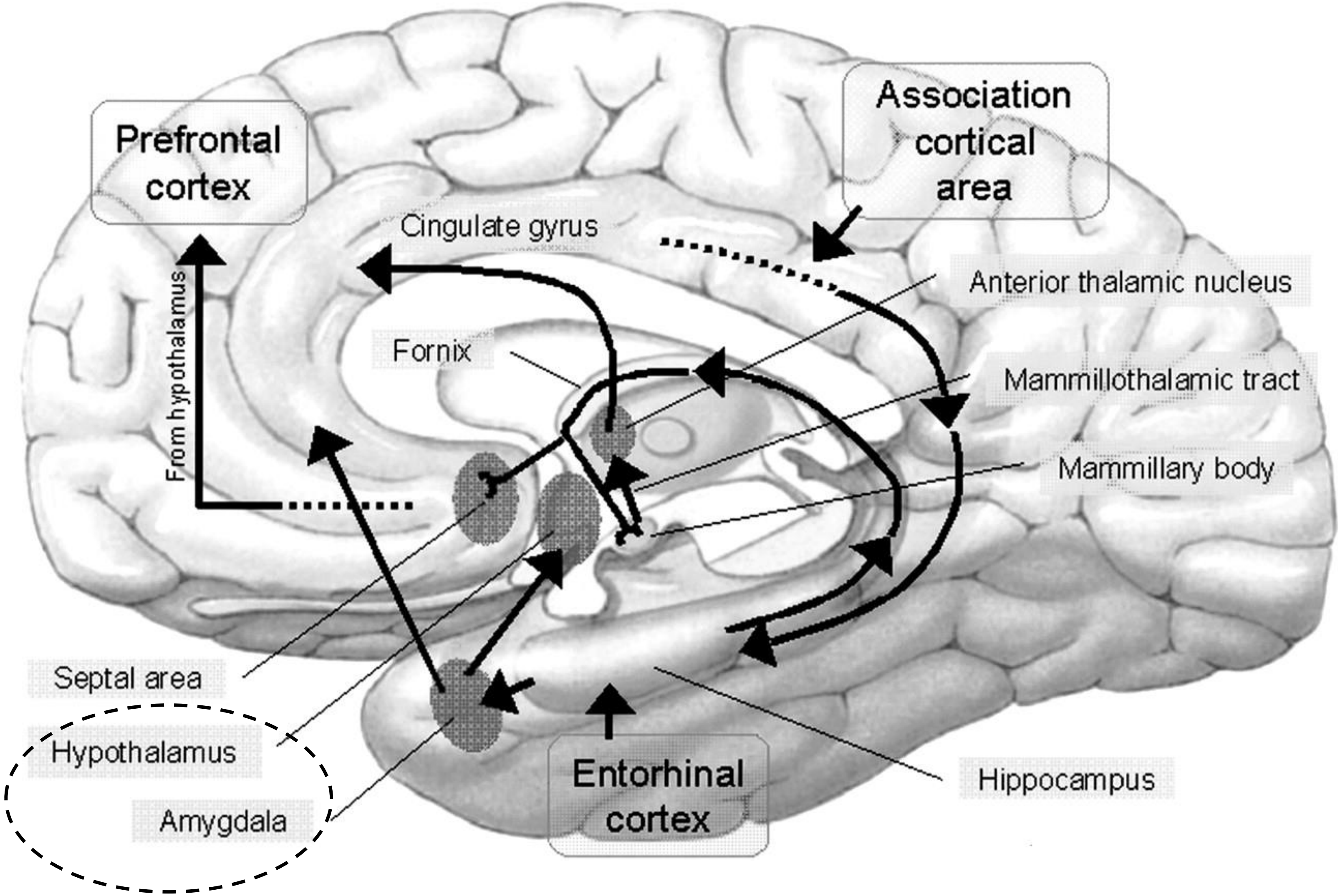
High-frequency stimulation (150 Hz) of globus pallidus or subthalamic nucleus can reducing tremor in Parkinson's disease and essential tremor patients (7 million in the US)





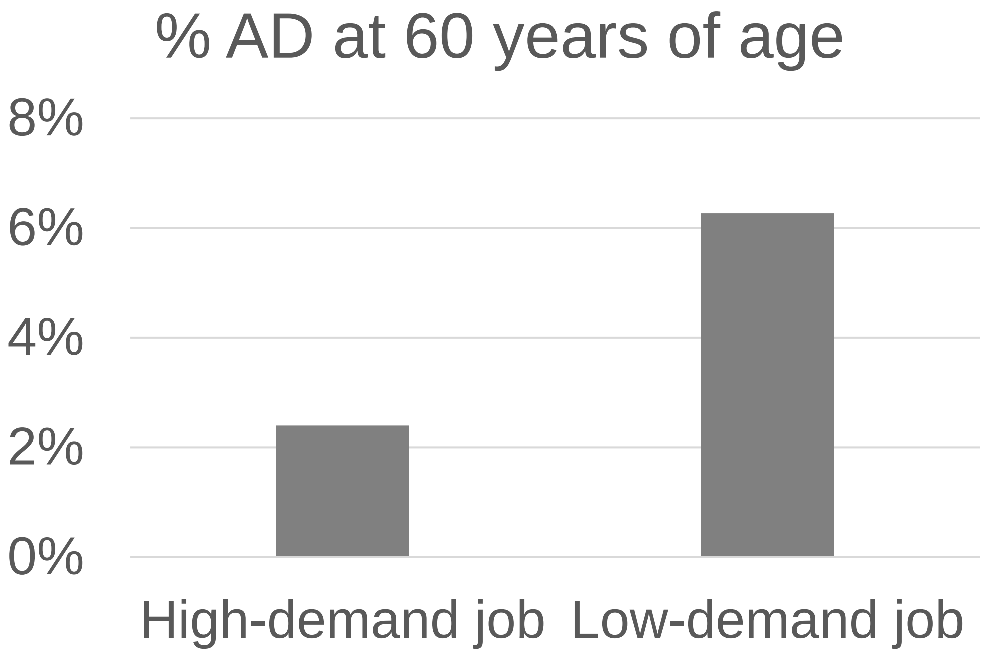
Limbic system: “primitive” brain control of emotions and learning

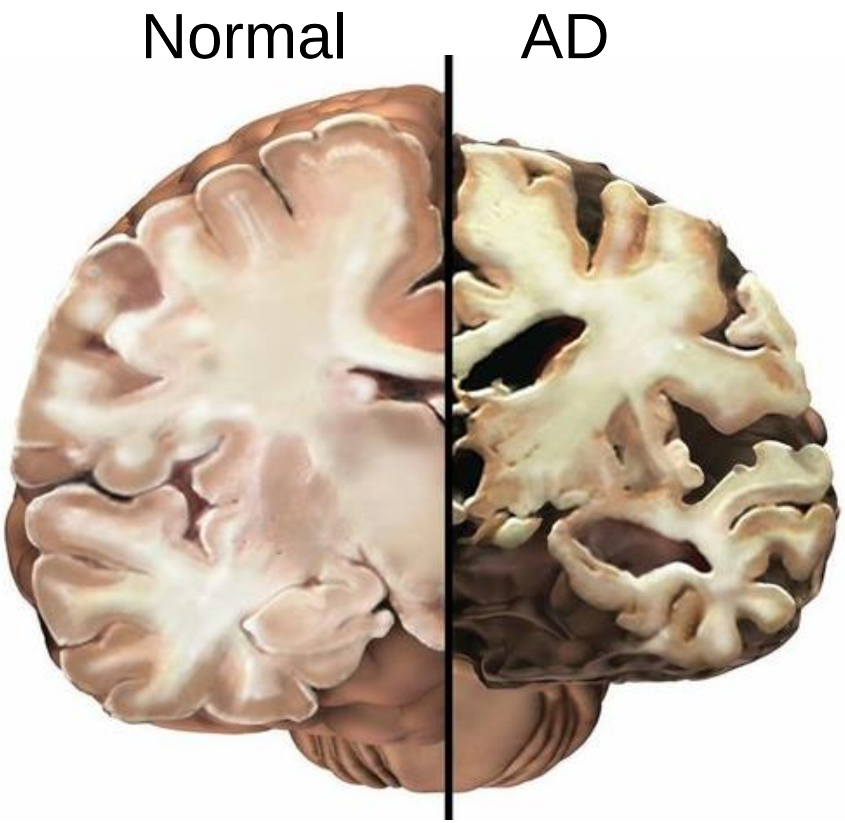
Limbic system: hippocampus, septal area, amygdala, n. accumbens and adjoining regions of cortex



Brain tissue degeneration: Alzheimer's disease

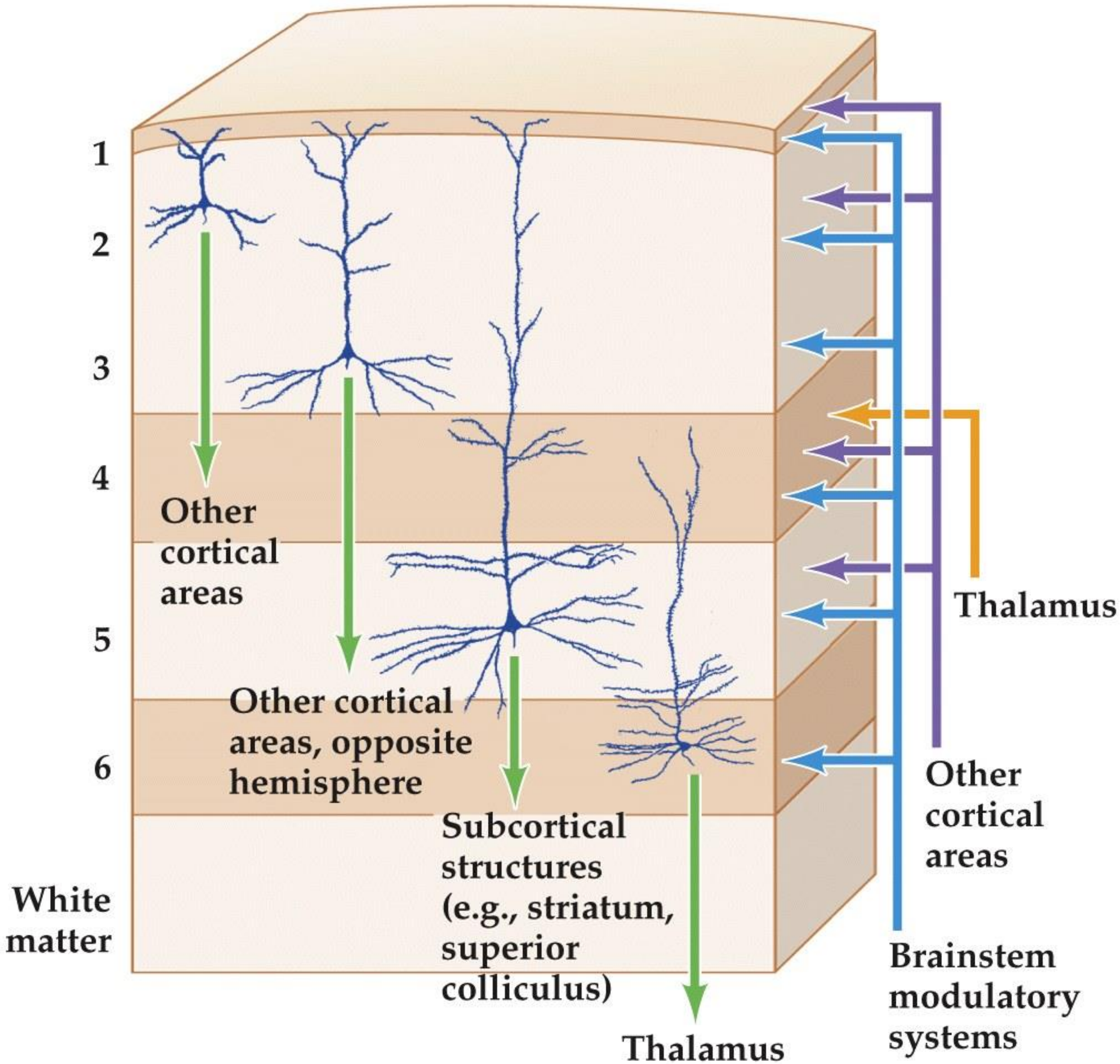
- 8% of the US healthcare budget
- 6 million people in the US





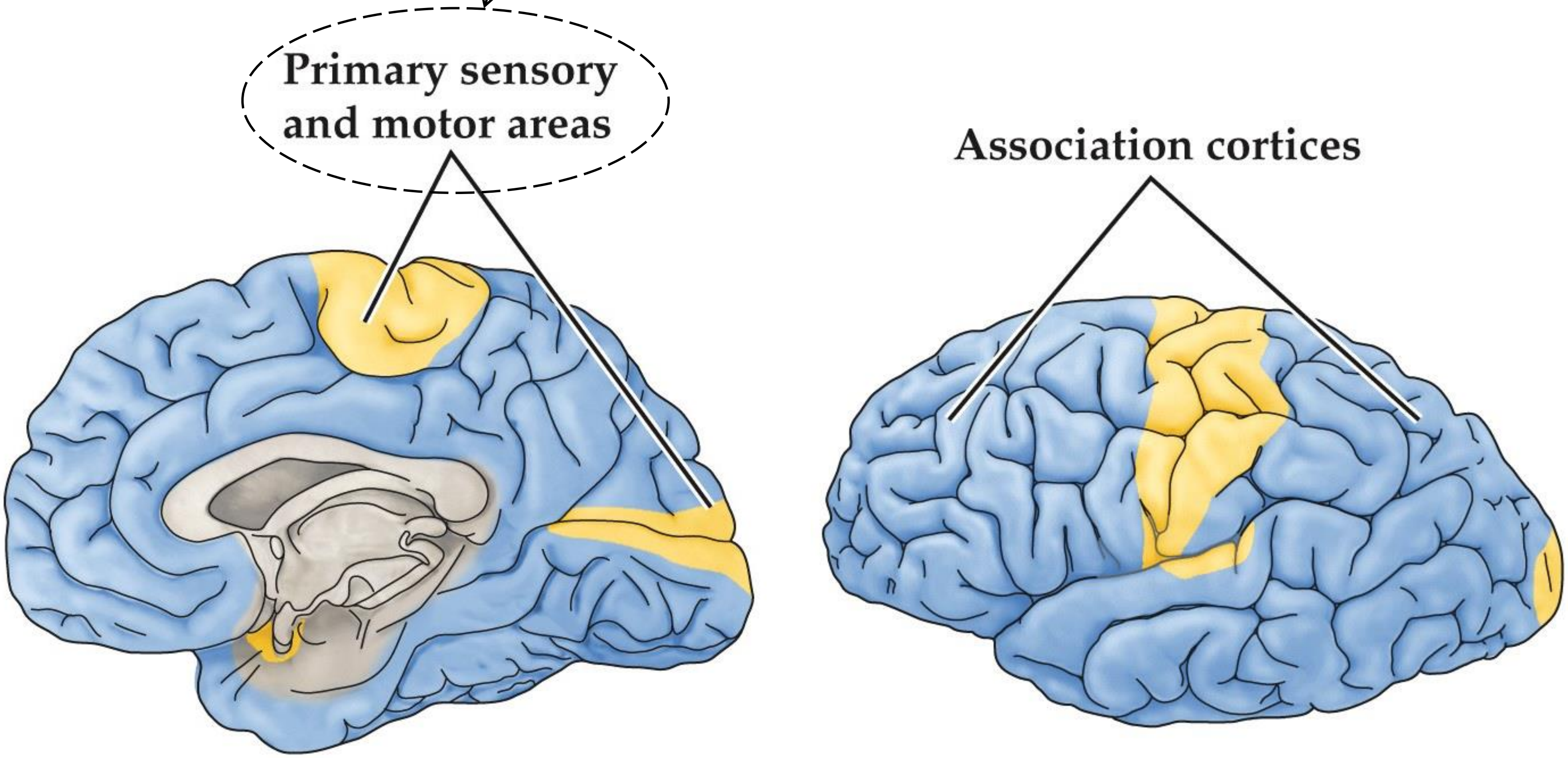
Electrical stimulation of limbic networks controlling emotions and learning may soon be approved (study to finish in 2024)

Cortex: layered structure and key connections

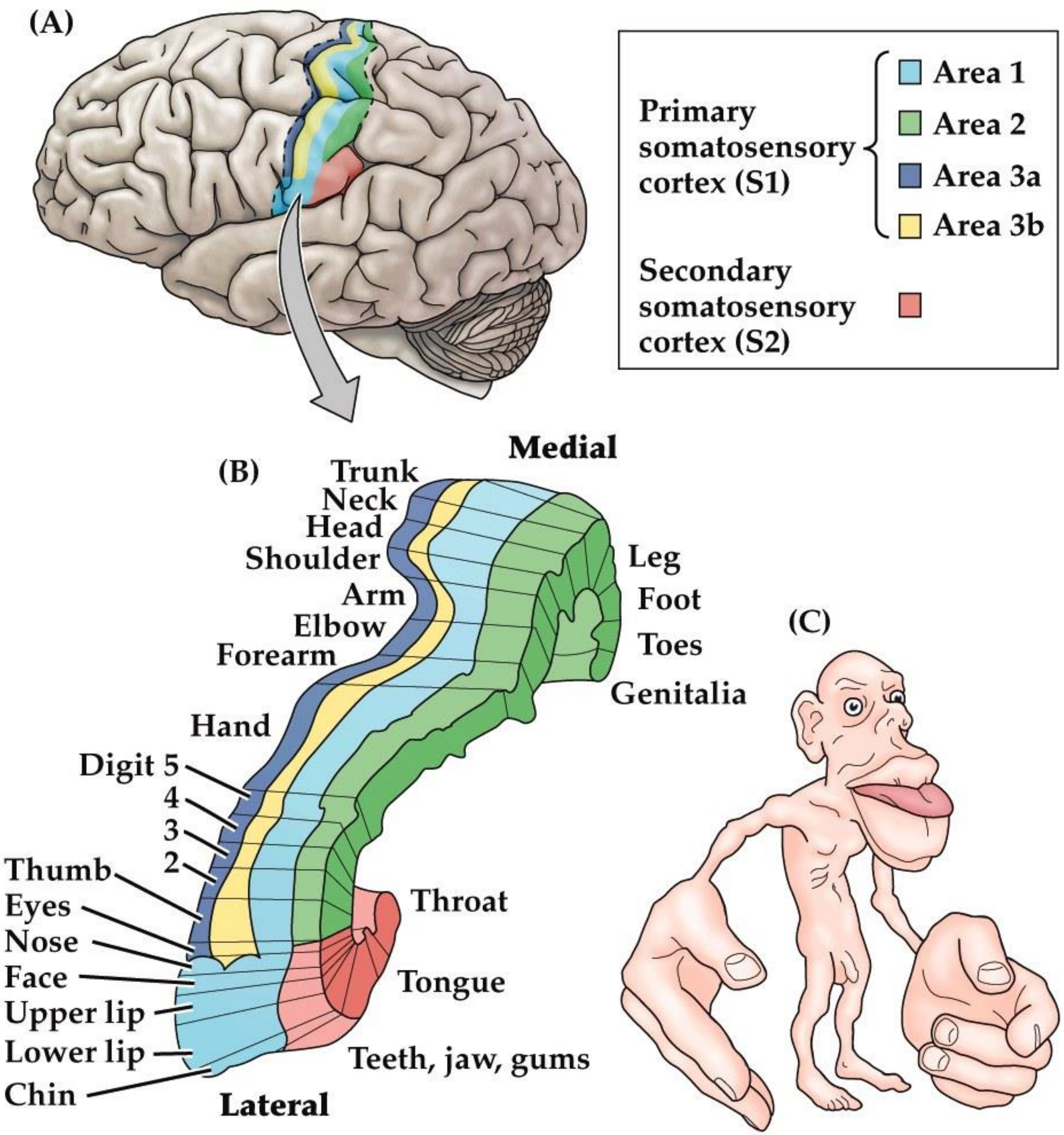


Sensory, motor, and association cortices

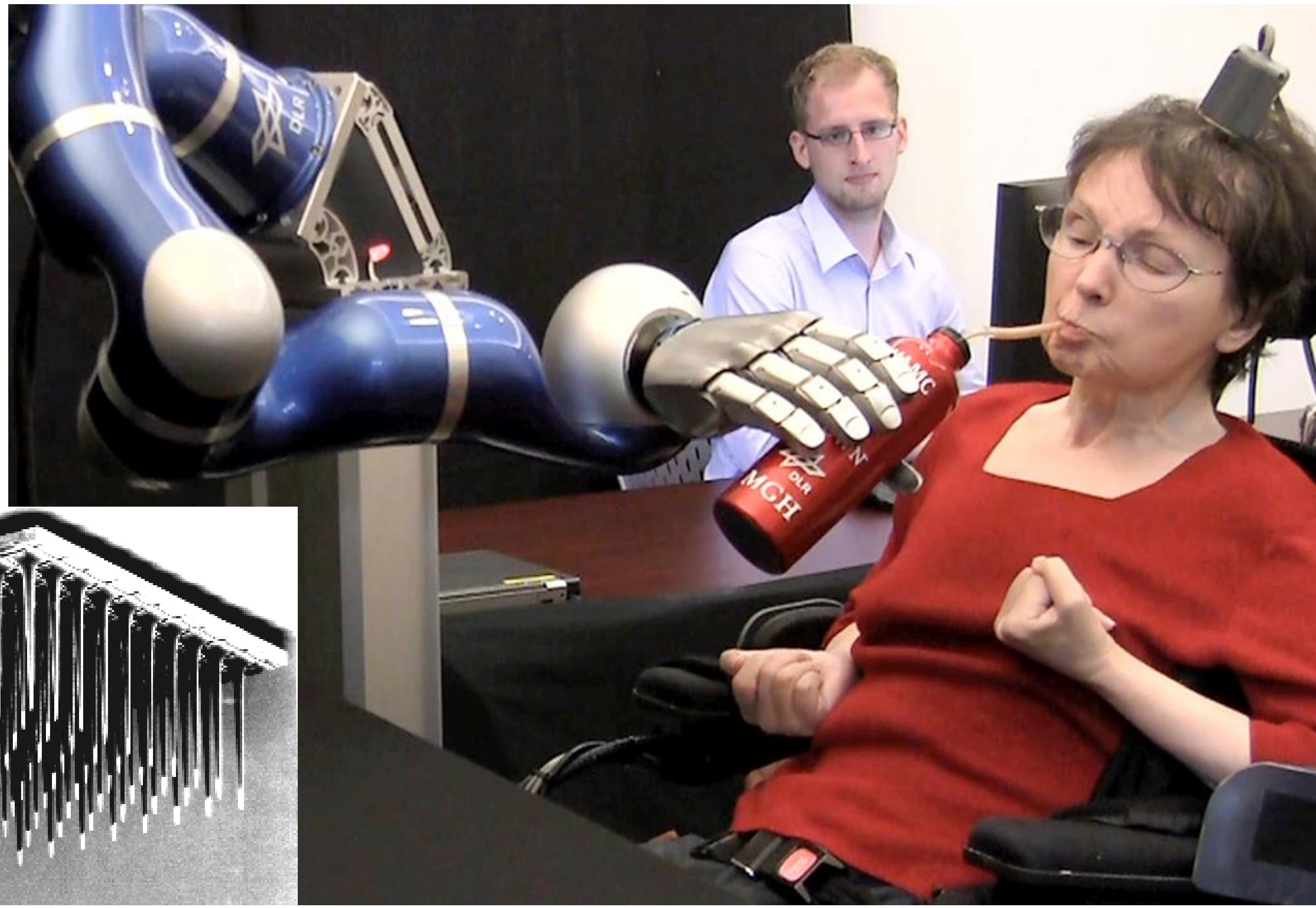
Targets of existing neuroprosthetic devices

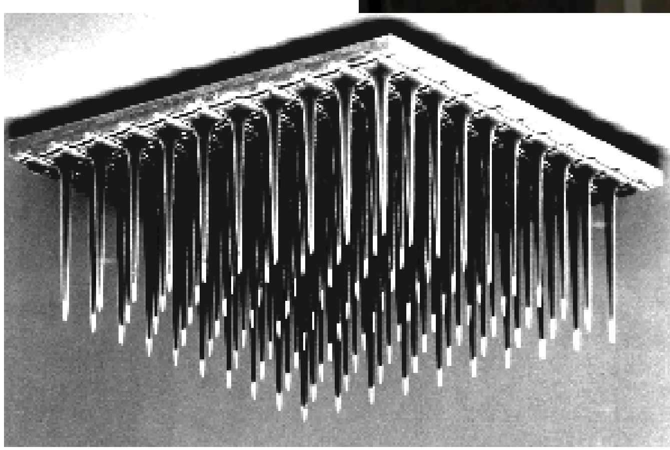


Body maps in the somatosensory and motor cortex



Recording movement intent with one 100-electrode array in paralyzed patients



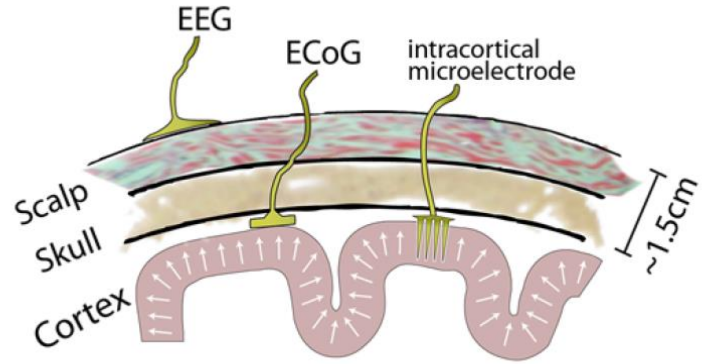


Motor cortex interface

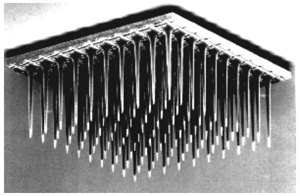
Recording face and tongue movement with two 100-electrode arrays in paralyzed patients at 62 words per minute!

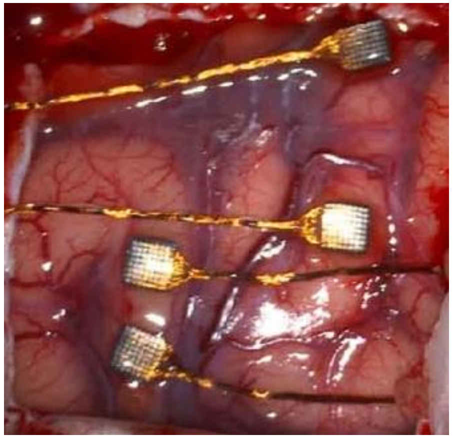
https://www.nature.com/articles/s41586-023-06377-x

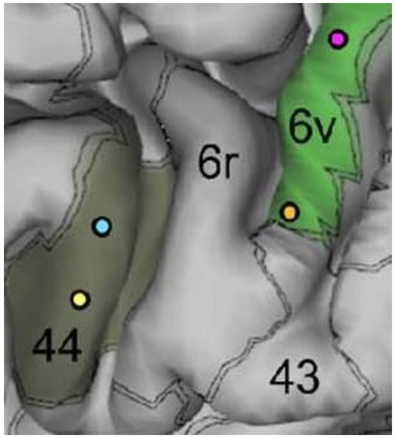
BCI interfaces: getting close to cortical neurons



2x100 intracortical electrodes:
62 words per minute







2x64 subdural electrodes:
2 words per minute