Movement control: Motor cortex and Basal ganglia

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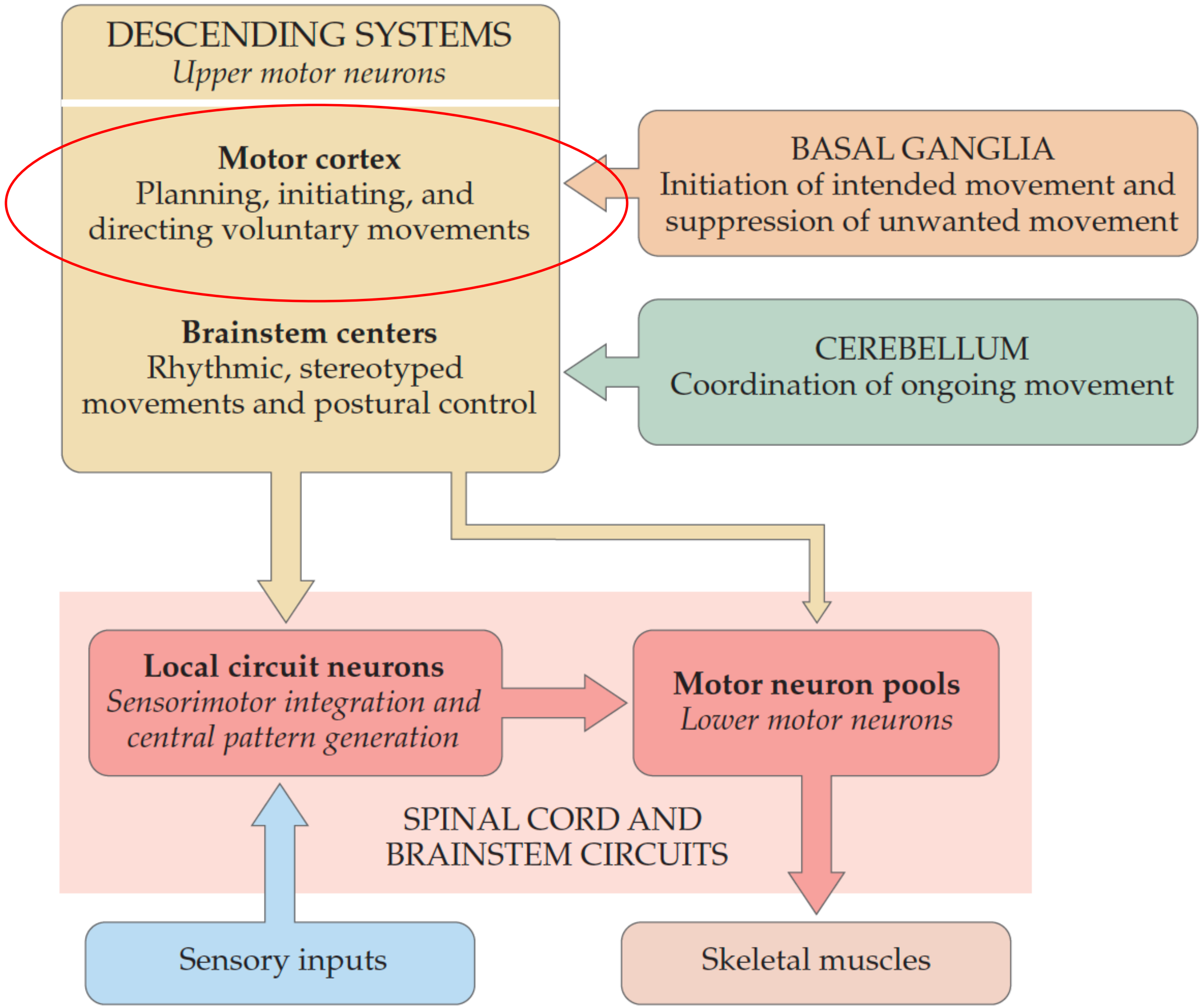
https://stan.md/3DHkir3

Mackenzie Mathis

Reading – **Purves** Chapter 17 pp. 381 - 397; Chapter 18 pp. 407 - 417

BIO-311

The neural control of movement

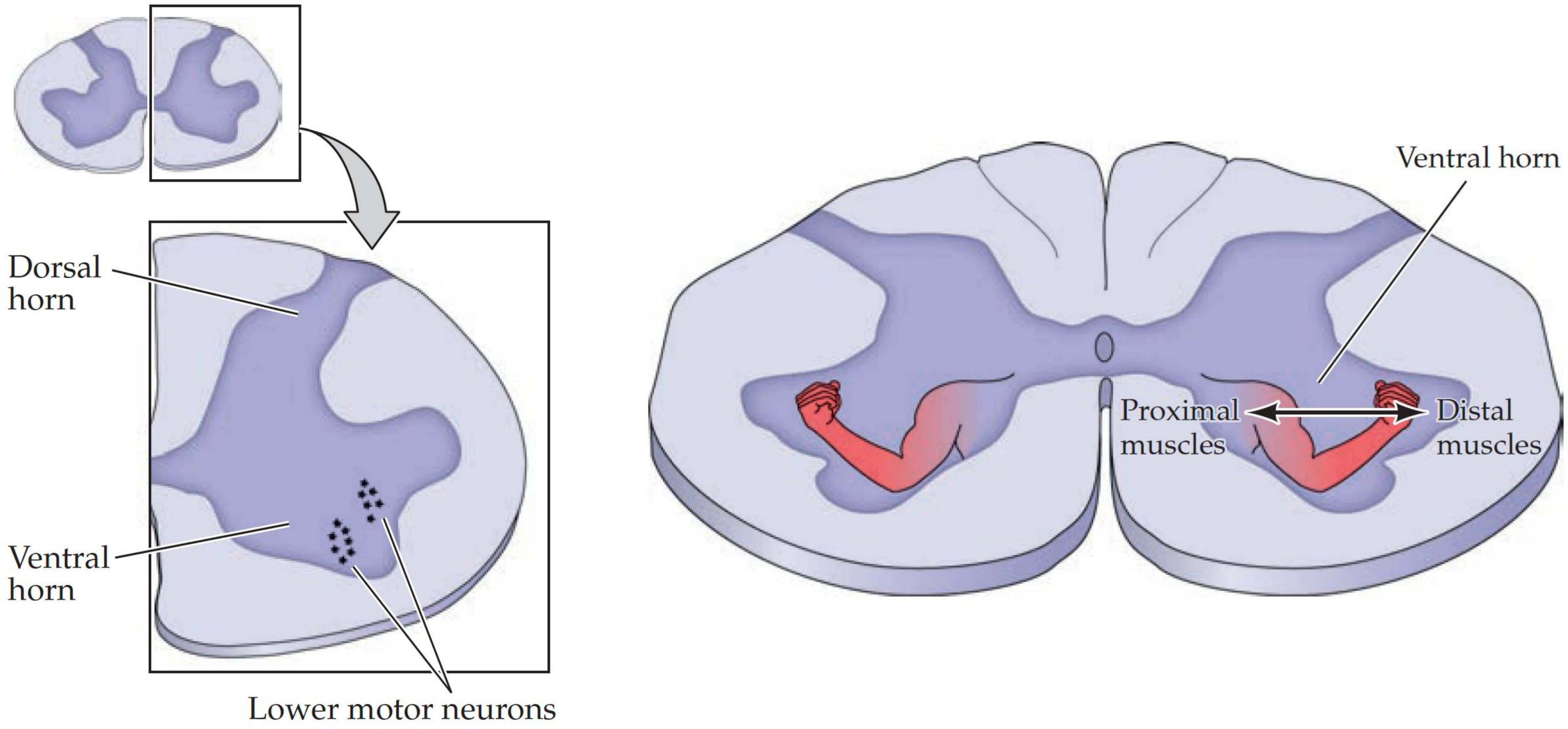


Purves, Figure 16.1

Four systems make essential and distinct contributions to motor control:

- The **spinal cord** (and brainstem circuits)
- The **cerebellum**
- *Descending control centers in the cerebral cortex and brainstem*
- *The basal ganglia*

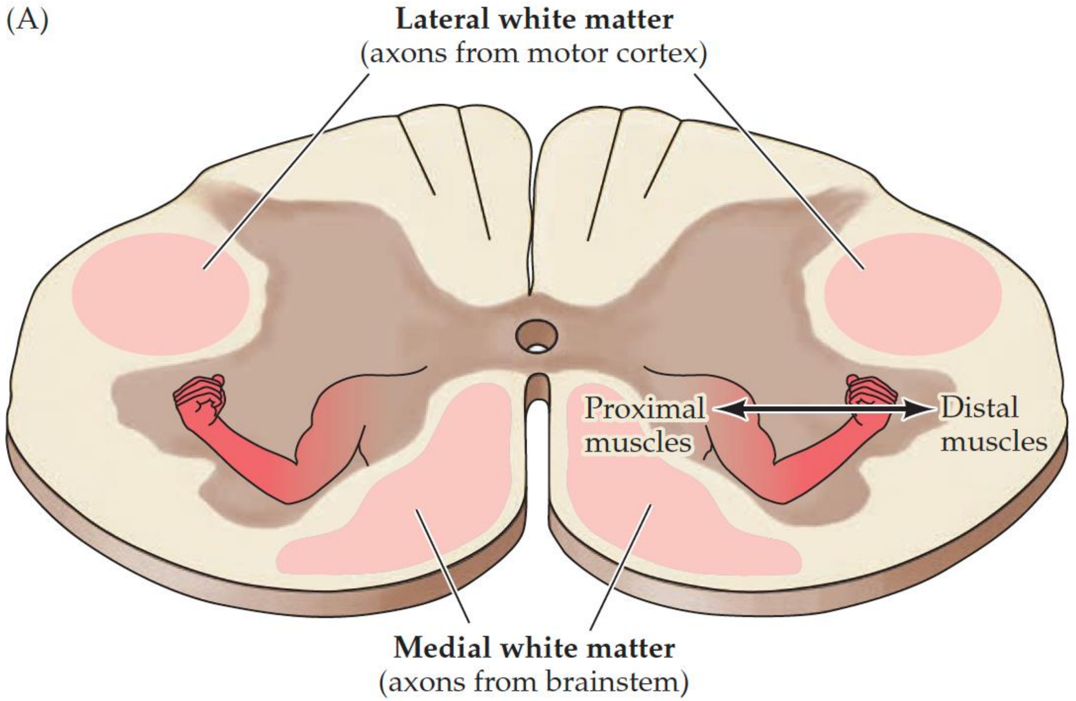
Reminder: spinal cord neuroanatomy basics



Lower motor neurons **send their axons out of the brainstem and spinal cord to innervate the skeletal muscles** of the head and body, respectively

Purves, Figure 16.2

Spinal motor neurons are targeted by two major descending projections

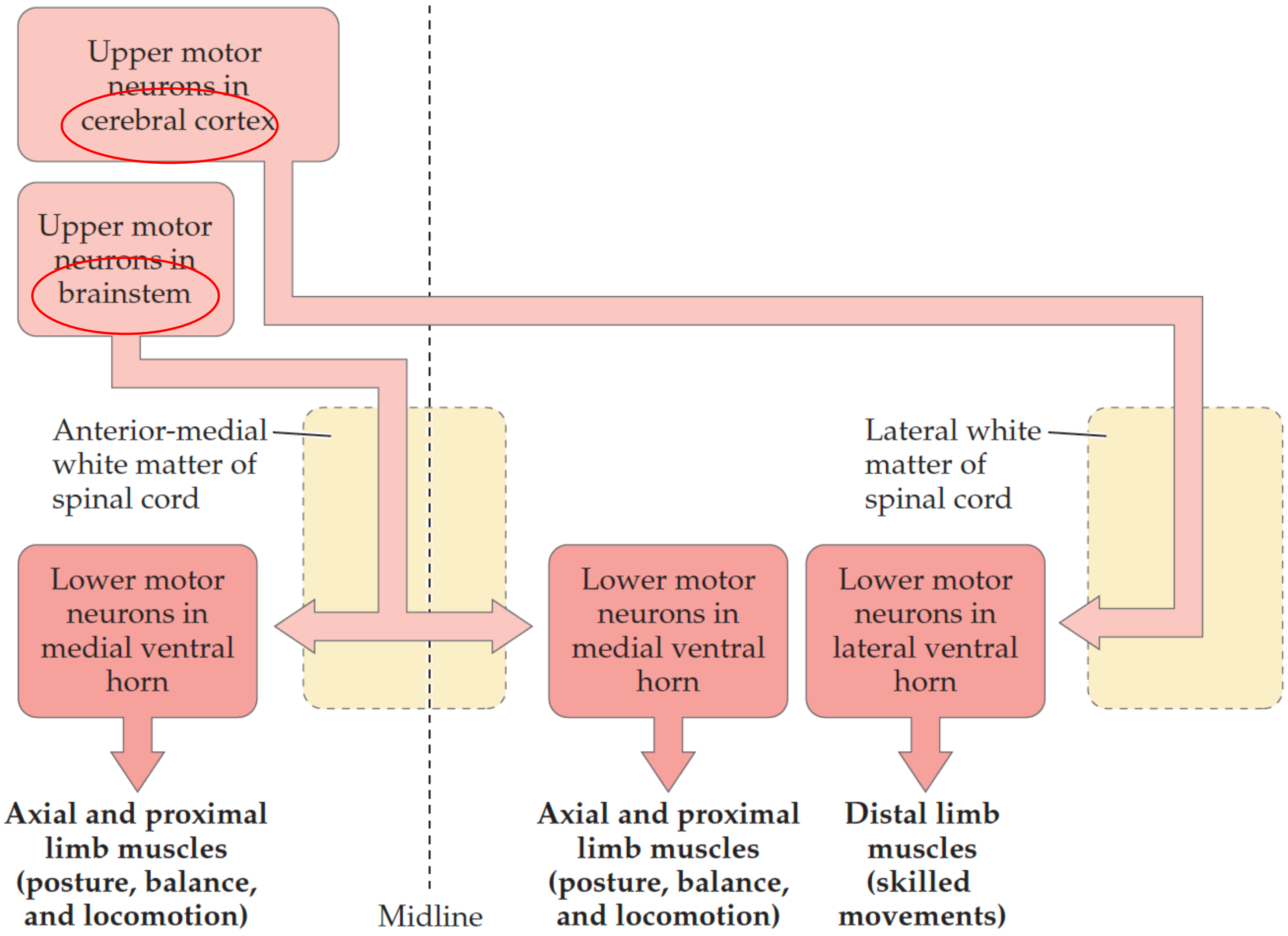


(1) The **lateral** motor system (corticospinal tract) contacts motor neurons that innervate muscles of the extremities (hand/arms, foot/legs, involved in reaching, fine manipulations, walking)

(2) The **medial** motor system (via brainstem) supply proximal muscles in the **trunk** (involved in postural control, balance)

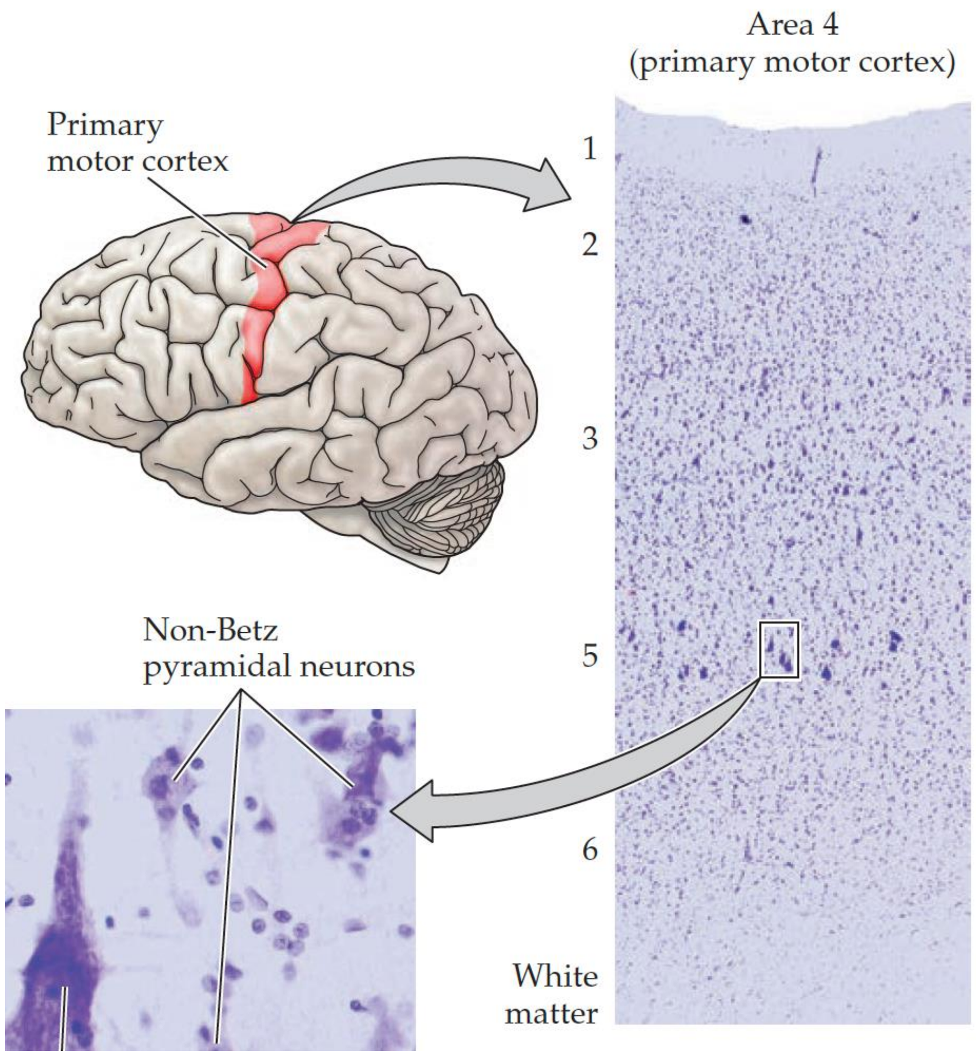
Purves, Figure 17.1

Spinal motor neurons are targeted by two major descending projections



Purves, Figure 17.1

Primary motor cortex (M1) has massive output neurons in Layer 5 (L5)

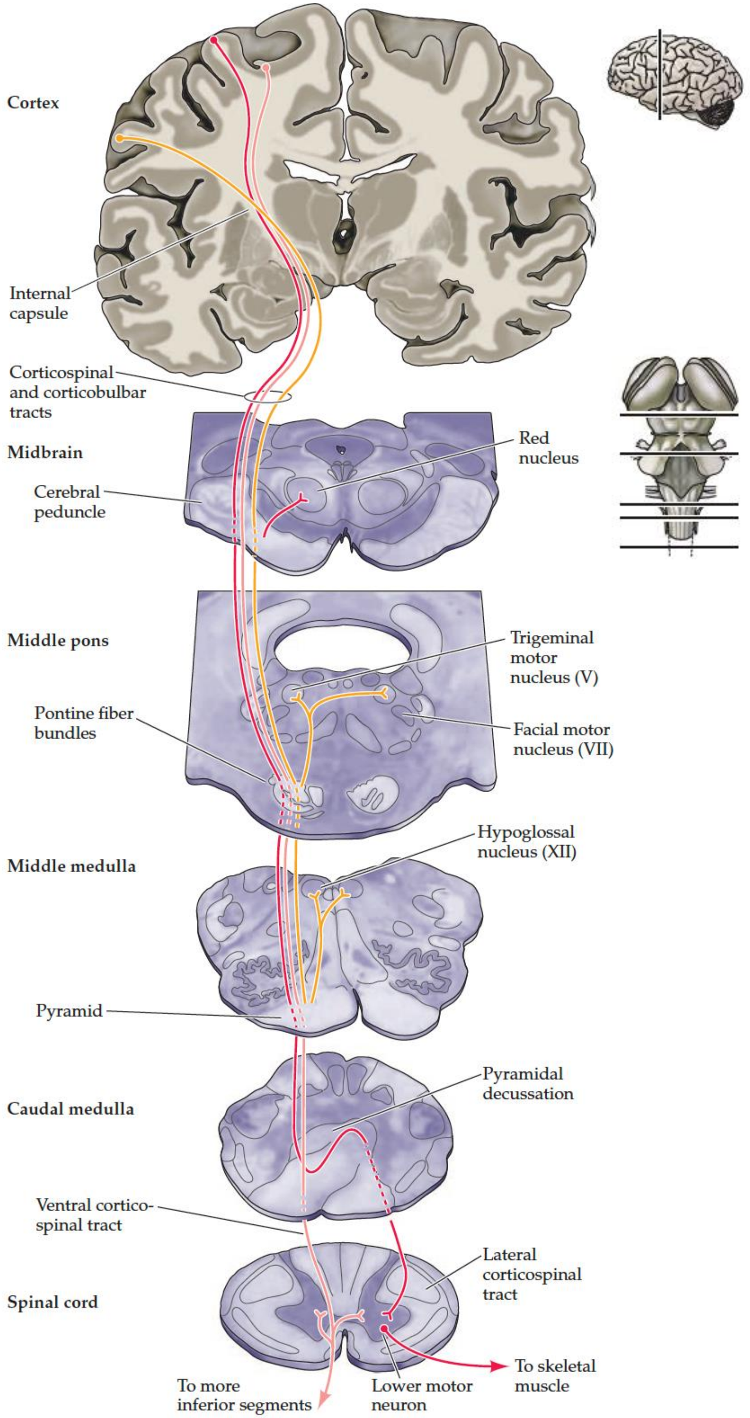


Primary Motor cortex (M1) is characterized by:

- Large layer 5 with **large neurons**
- L5 neurons are long-range output neurons in the **corticospinal tract**!
- Lower threshold for electrical stimulation to elicit movements

Purves, Figure 17.3

The corticospinal tract



The corticospinal tract (red):

- Distinct from ”corticobulbar” tract (gold) that descends to the brainstem (”bulbar”).
- Axons cross-over to other body side at "pyramidal decussation"
- Some axons directly contact *motor* neurons in the ventral horn to control distal extremities
- Most contact local circuits

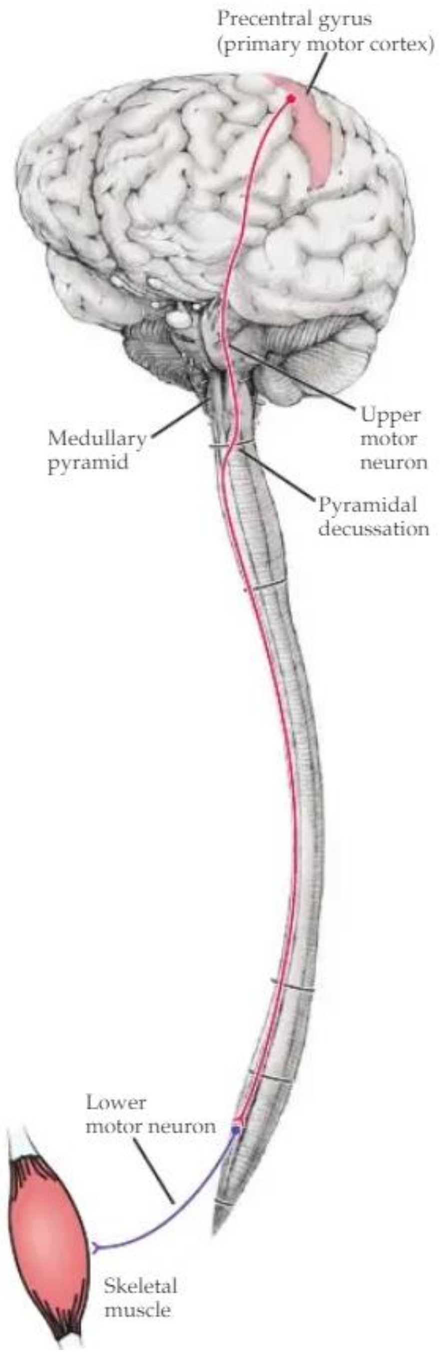
Purves, Figure 17.4

The corticospinal tract

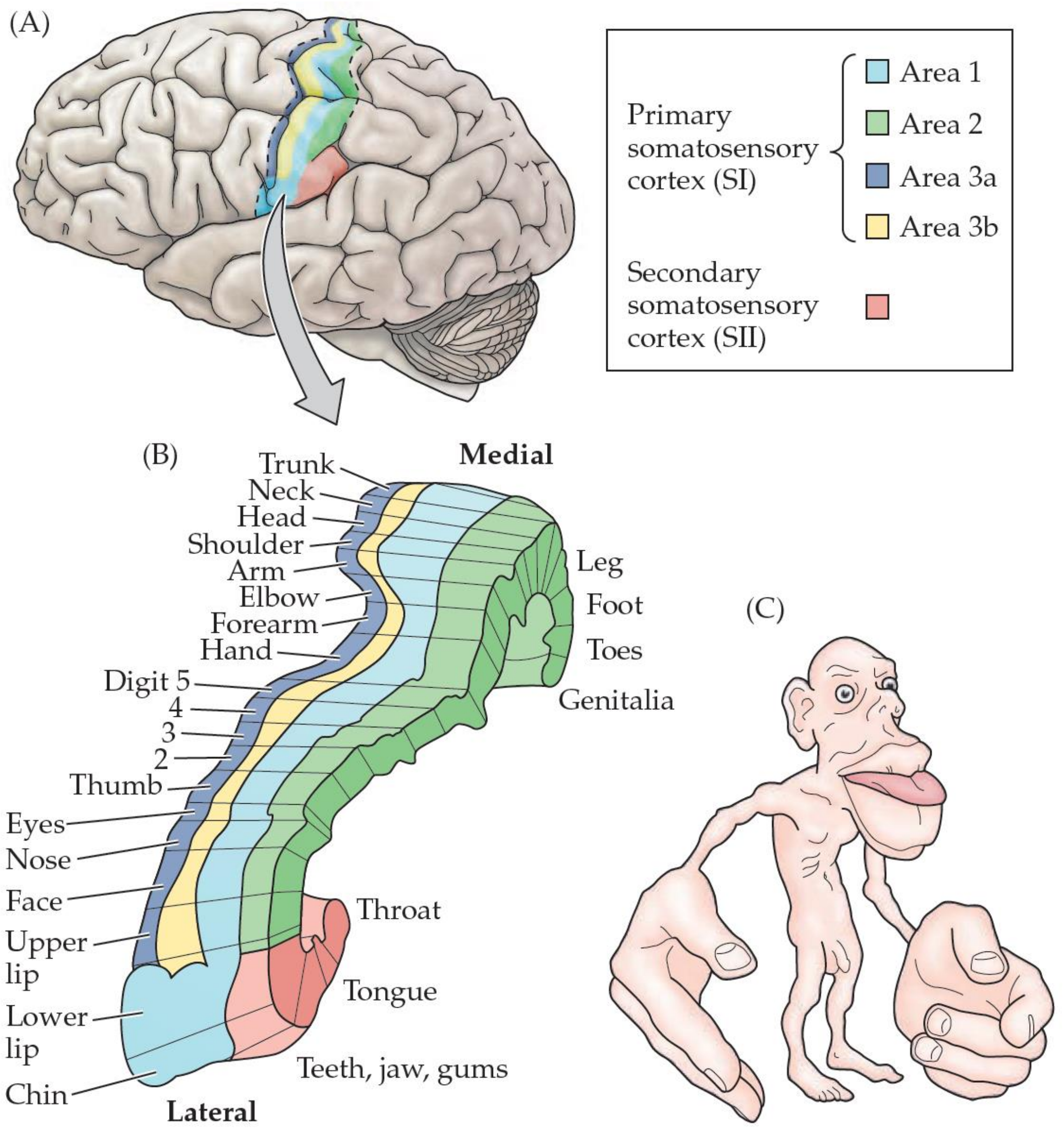
The corticospinal tract:

• L5 neurons in M1 project to motor neurons in the spinal cord (axon **length** ~ 0.8 m!)

• These are called "**upper motor neurons**”

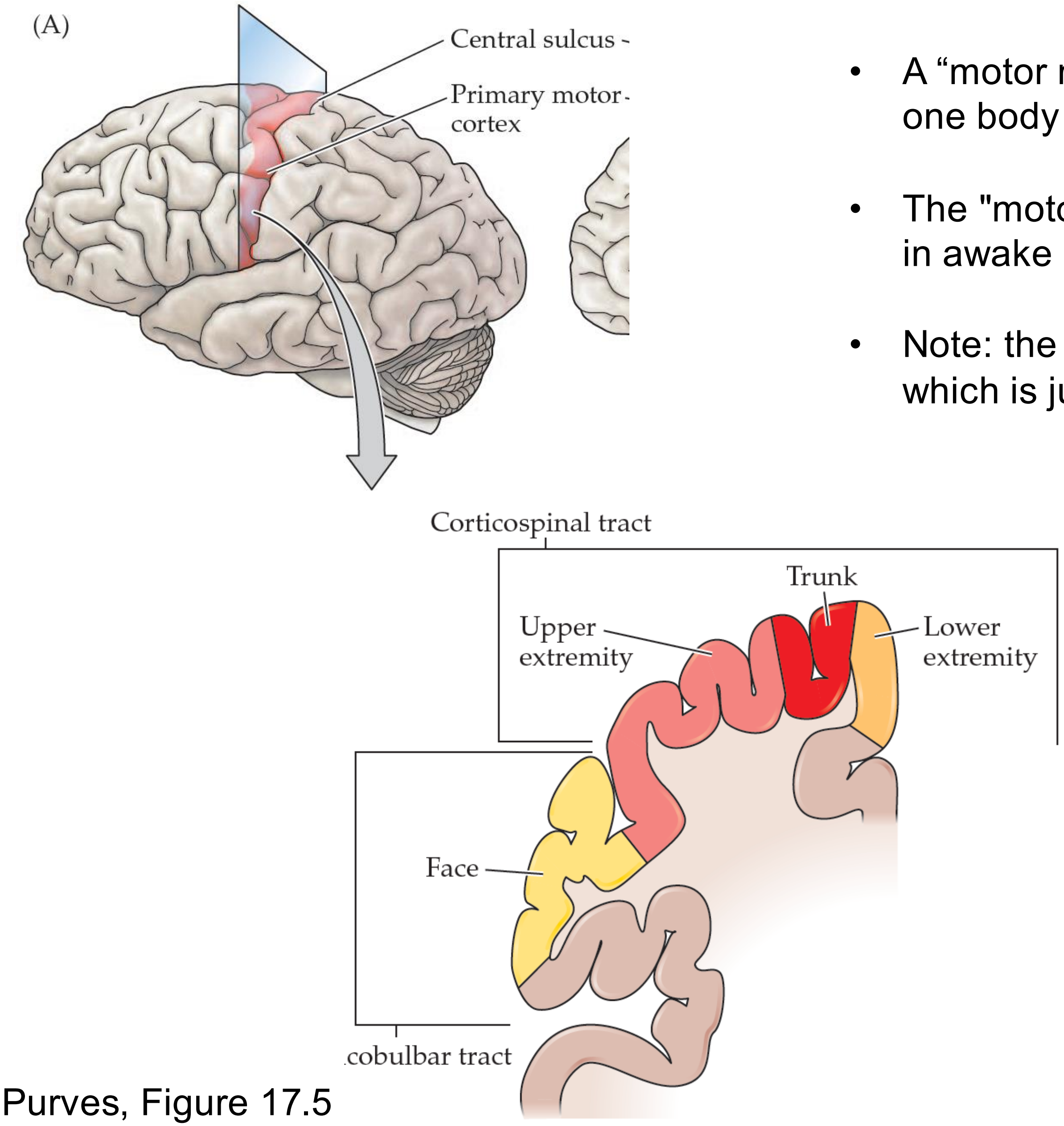


Reminder: Precise somatotopy of primary somatosensory cortex



Purves, Figure 9.11

Motor maps in motor cortex are coarser

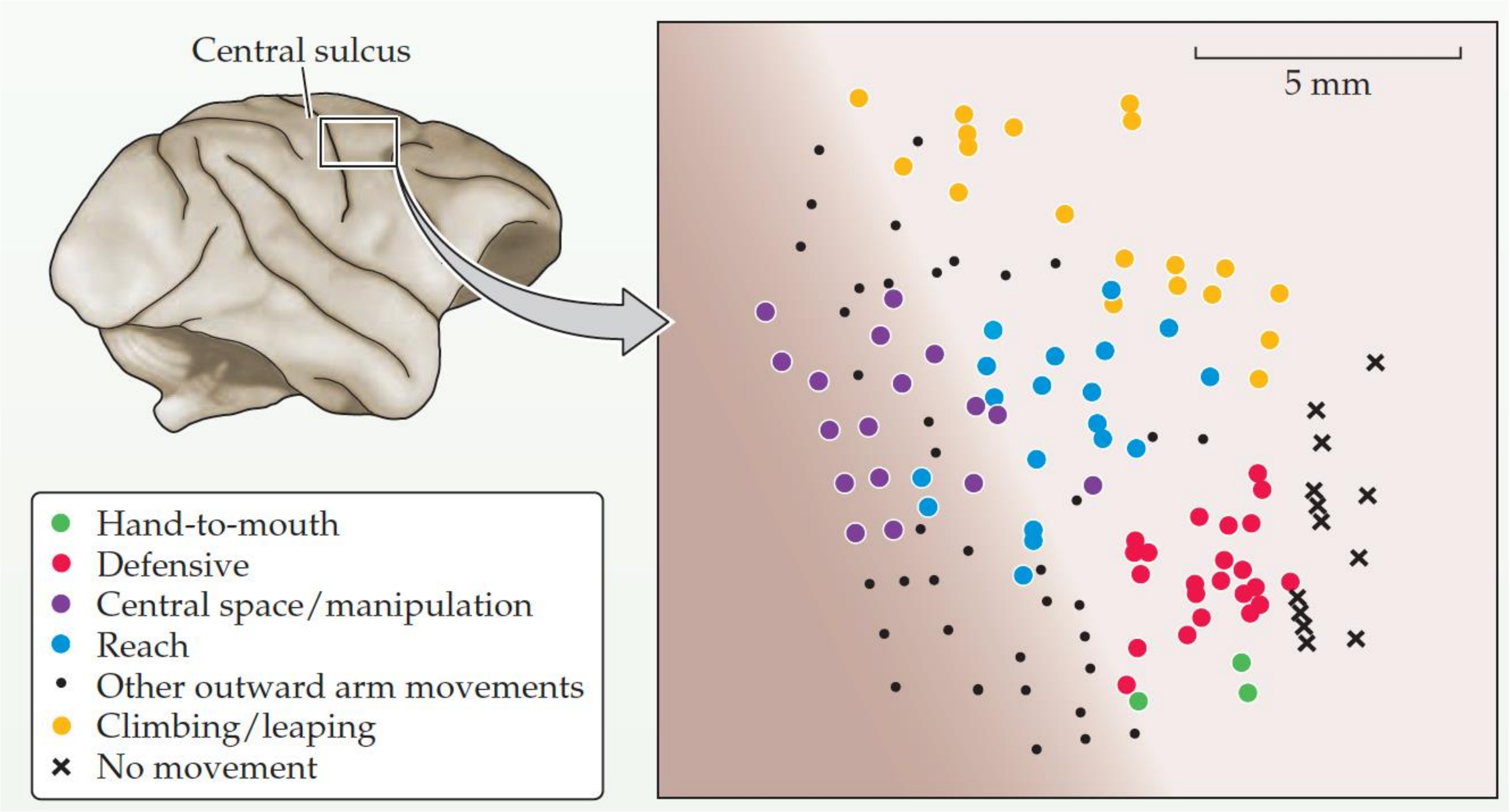


Purves, Figure 17.5

- A “motor map“ was suggested by the systematic “march“ of **seizures** from one body part to another
- The "motor map" was confirmed from **microstimulation** of motor cortex in awake patients (Wilder Penfield ~1950)
- Note: the "motor map" is **congruent with** the map of primary sensory cortex, which is just posterior to M1, posterior to central sulcus

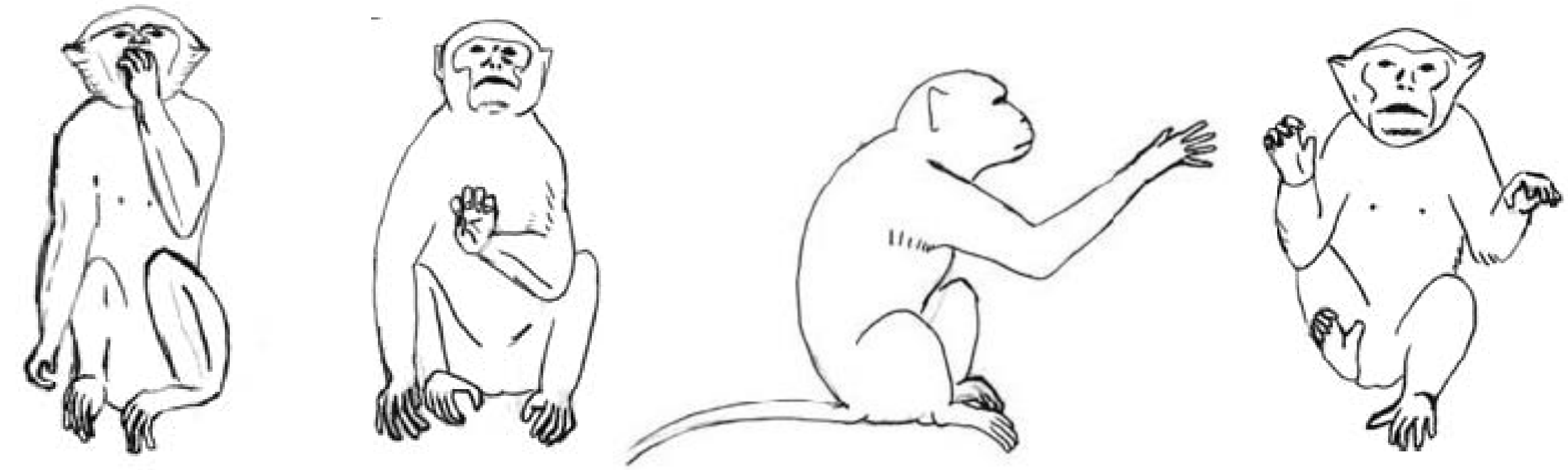
But the "motor map" is **not** the full story!

Electrical *microstimulation* of specific sites in M1 drive “movement primitives"

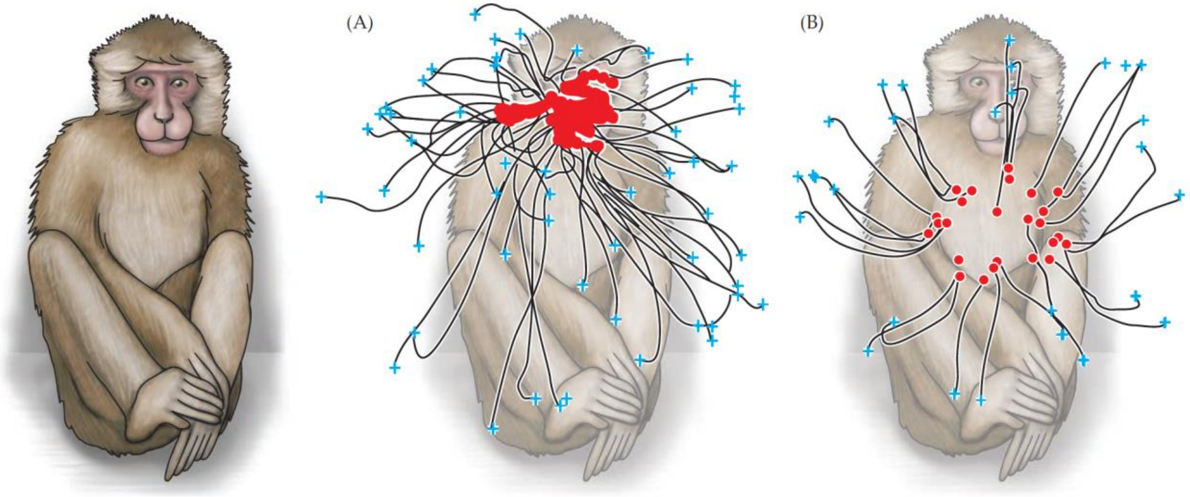


Purves, Box 17A

Electrical *microstimulation* of specific sites in M1 drive “movement primitives"



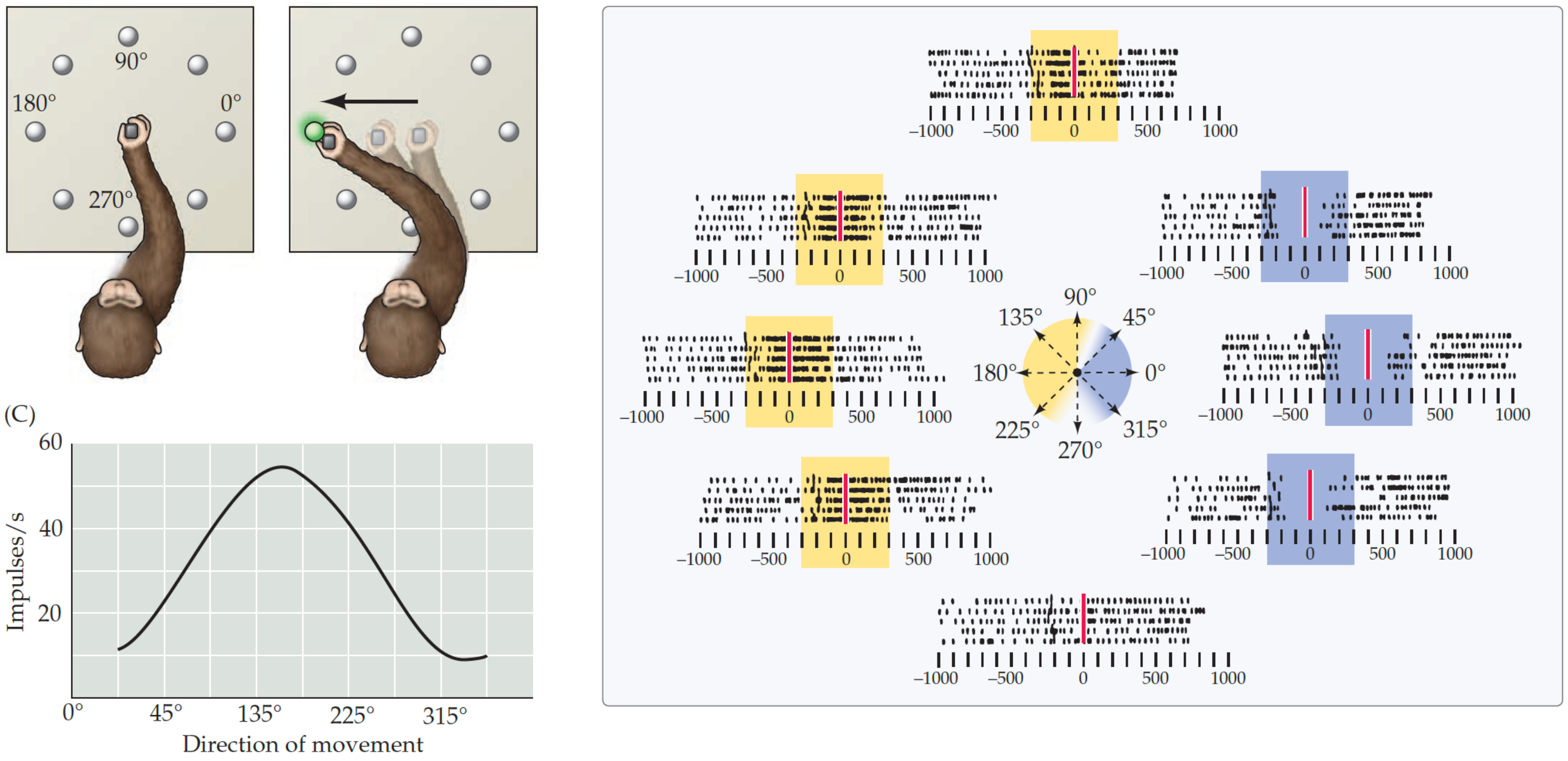
Hand-to-Mouth Defensive gesture Reaching Climbing



Purves, Figure 17.7

Hand-to-Mouth Arm to visually inspect

Recorded responses of a single M1 neuron during arm movements in many different directions



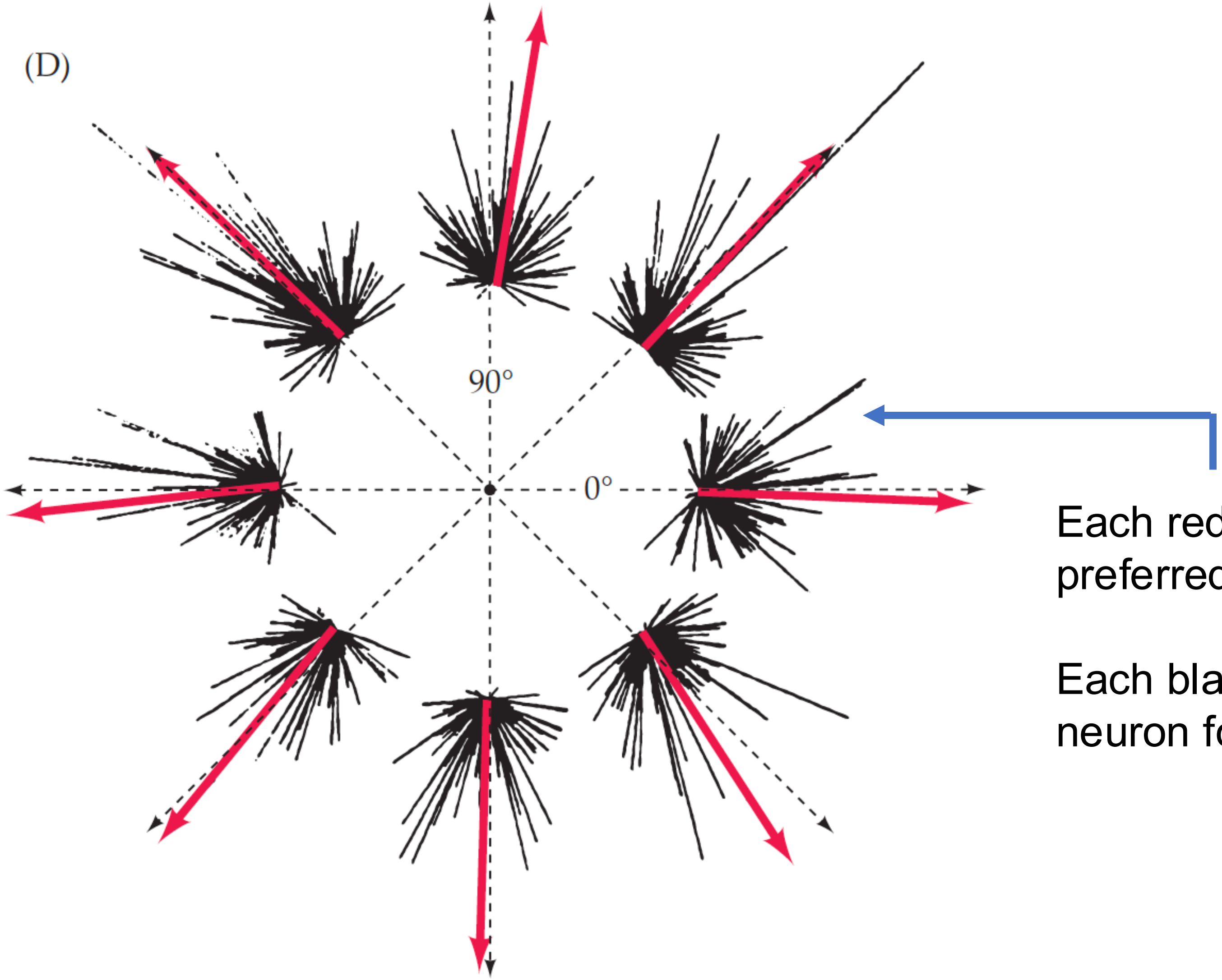
A monkey was trained to move its arm toward a green light:

- A single neuron in M1 was recorded
- Time 0 indicates movement onset

  Note: the neuron starts firing *before* movement onset!
- There is a “preferred movement direction" for this neuron (as in vision), and reduced firing in the opposite movement direction

Purves, Figure 17.8

The activity of *many* M1 neurons gives a "population vector" that defines the observed movement direction

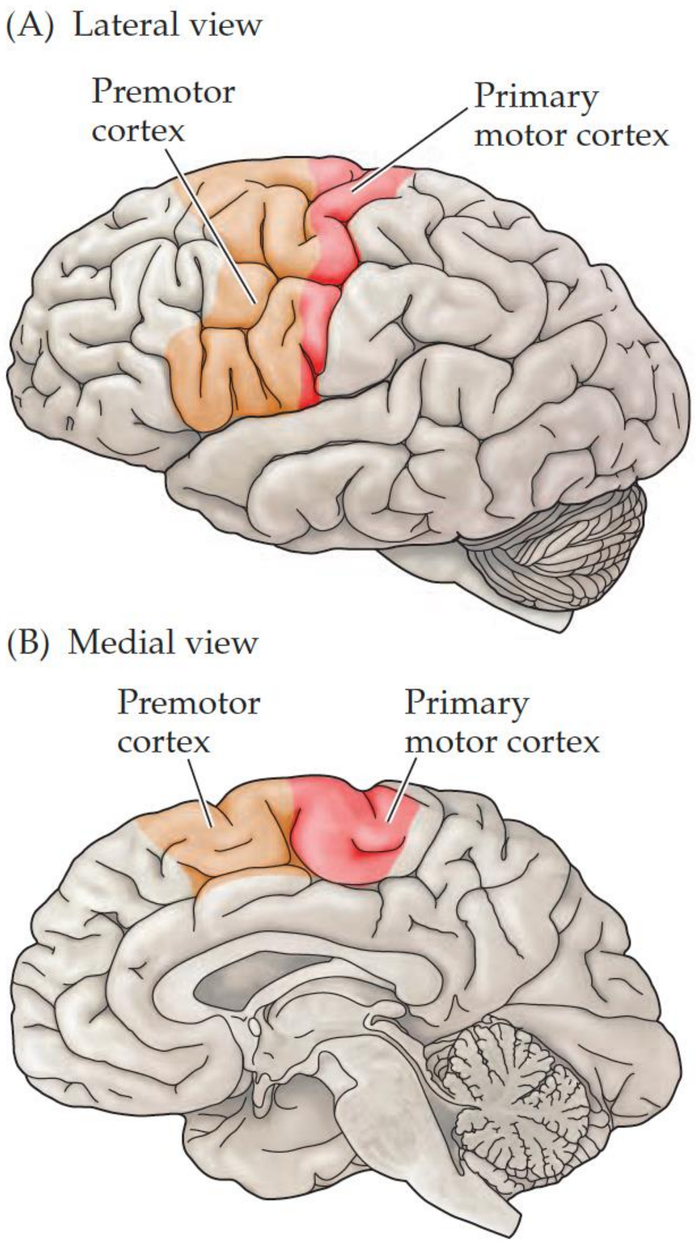


Each red arrow is one motor cortex neuron‘s preferred arm movement vector.

Each black line is the firing rate for that motor neuron for each direction of arm movement

Purves, Figure 17.8

Premotor cortex is another movement-related area

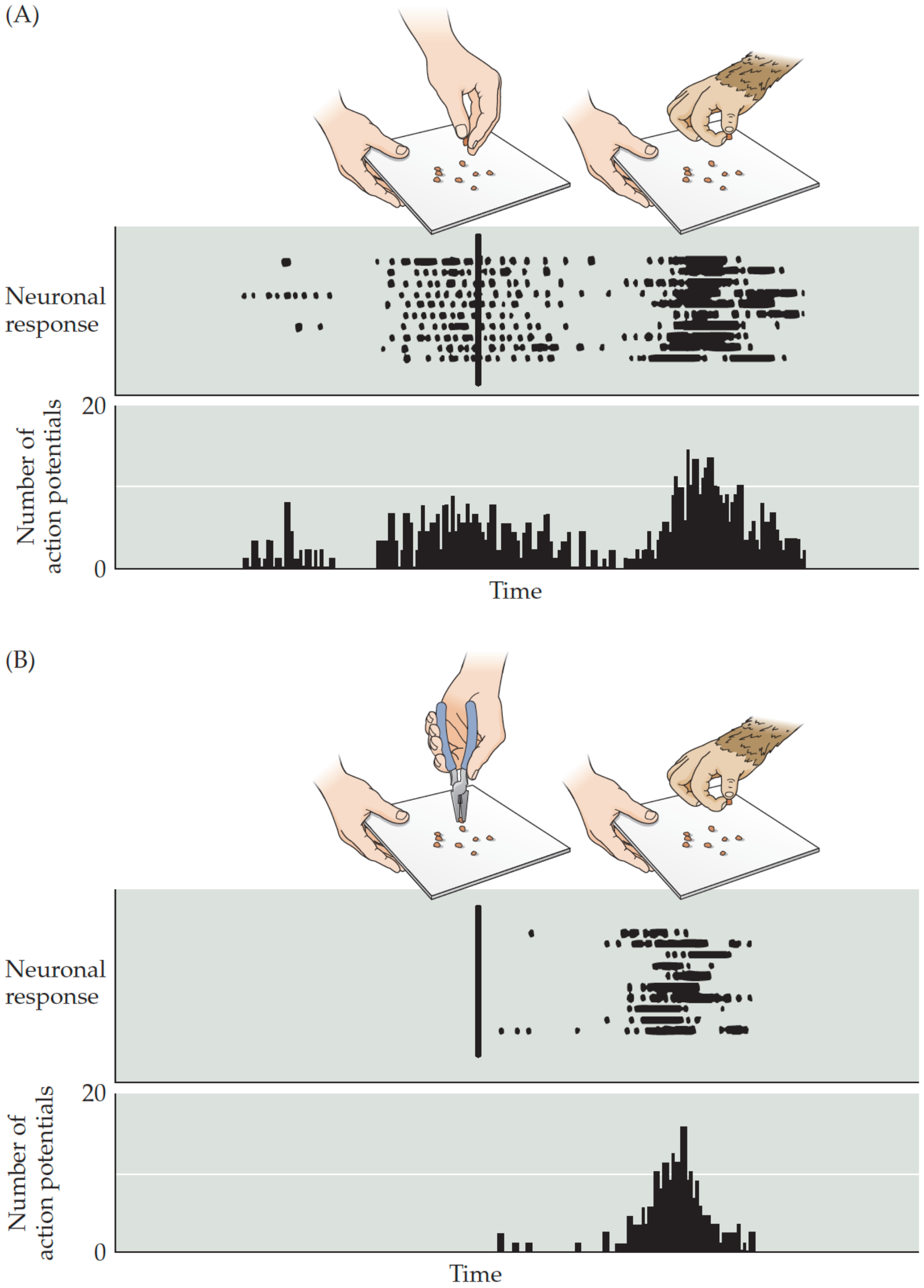


Premotor cortex neurons:

- Represent 30% of corticospinal tract neurons
- Encode the ***intention*** to perform a movement
- Some also respond when an action is ***observed***!

Purves, Figure 17.2

‘Mirror’ neurons in premotor cortex respond to observed movements

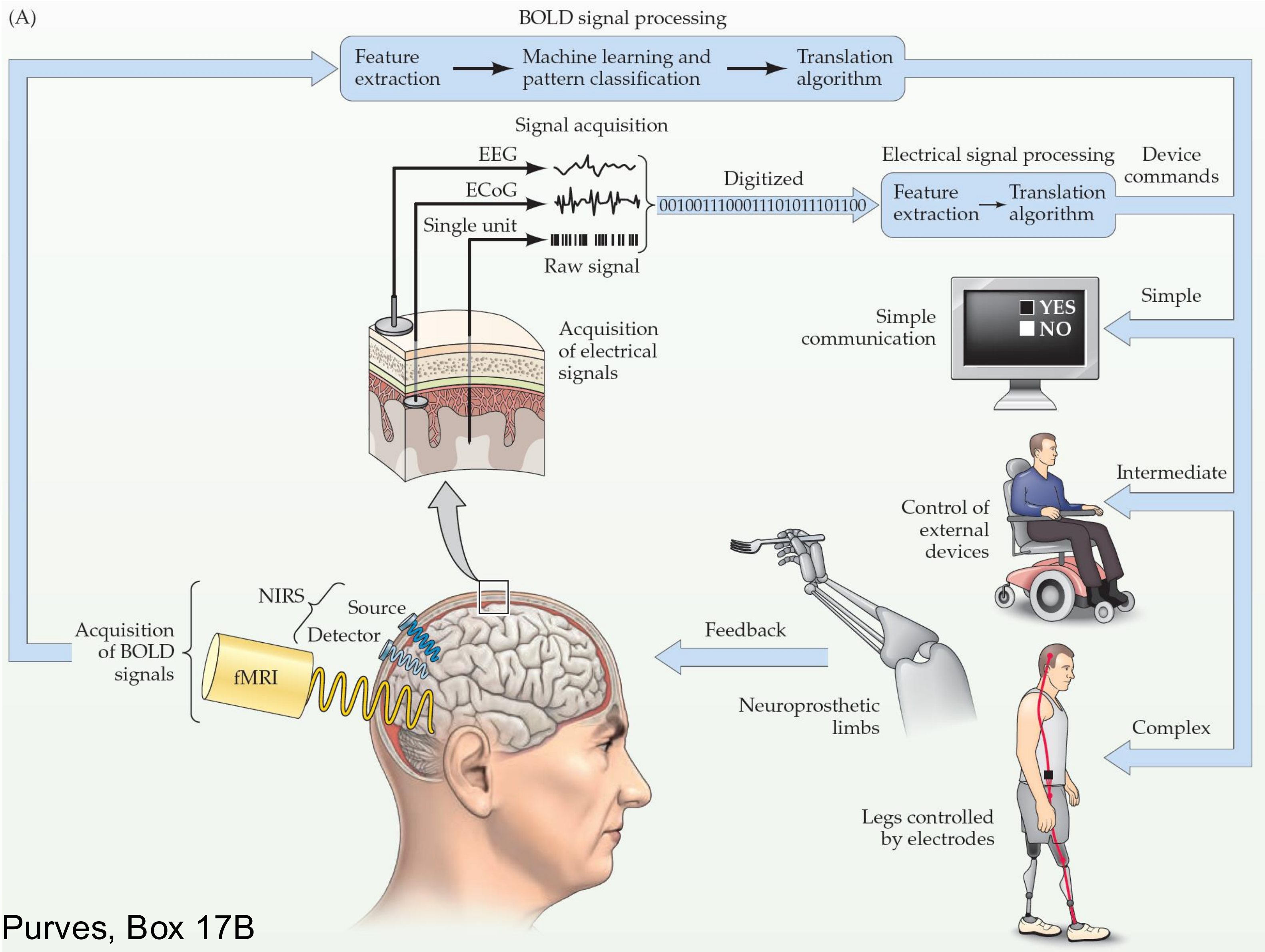


Purves, Figure 17.10

Mirror neurons:

- **Respond** when **observing** a behavior (picking food morsels)
- Do **not** respond when observing a **different** but related behavior (e.g., using pliers to pick up the food morsels)

Application: Brain-Machine Interfaces (BMIs) use brain signals (here from motor cortex) to control external devices



Purves, Box 17B

Brain-machine interfaces:

- Thought-controlled operation of virtual or real actuators
- Involve:
  (i) **acquisition** of brain signals,
  (ii) **decoding** using ANNs,
  (iii) implementation as **control signals**,
  (iv) and generation of sensory **feedback** to adapt
- Can be invasive (AP recordings) or non-invasive (e.g., EEG, fMRI)

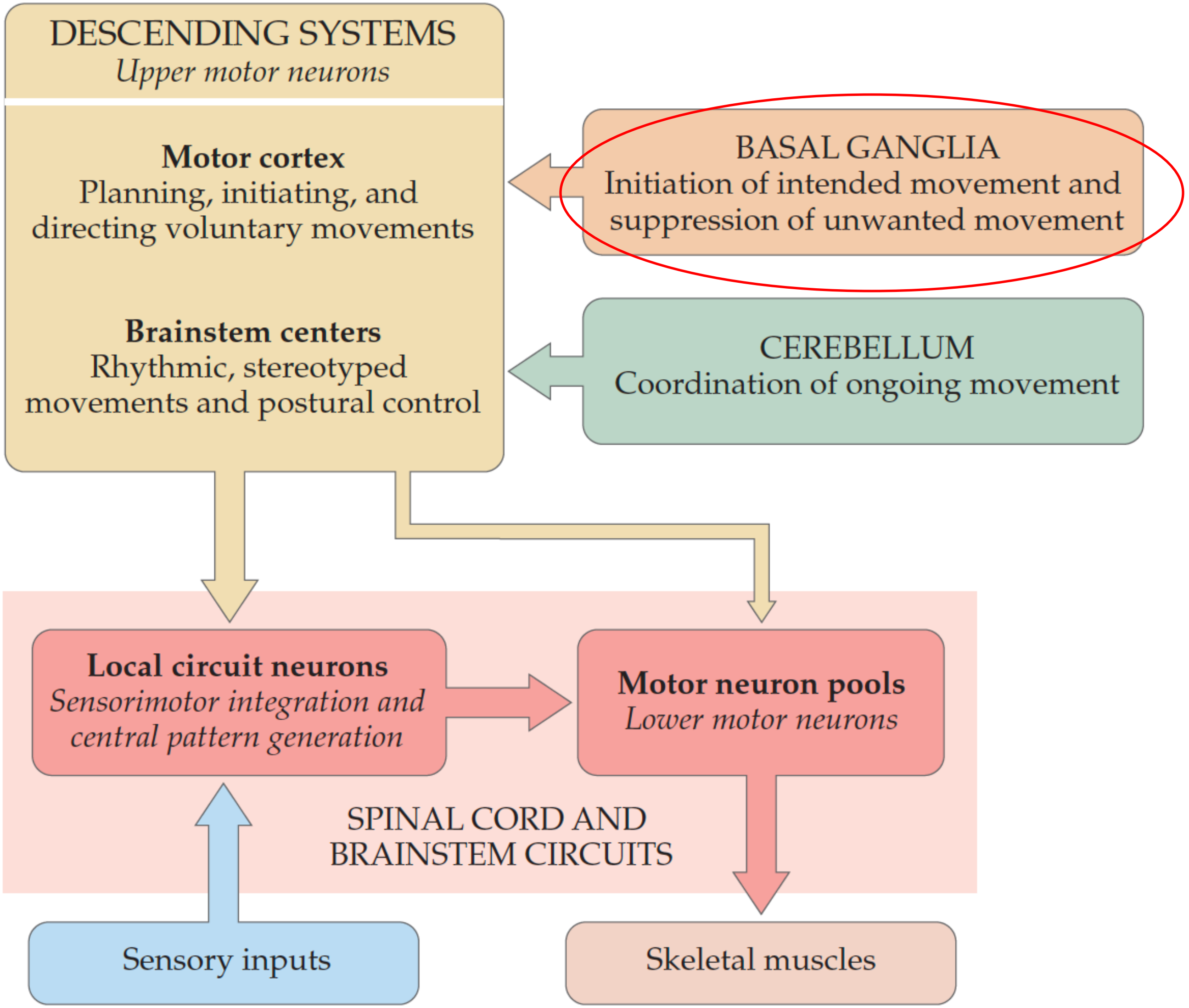
Motor cortex BMI. - Neuralink

https://www.youtube.com/watch?v=rsCul1sp4hQ

Explanation

Basal ganglia:
Action selection and initiation

The neural control of movement



Four systems make essential and distinct contributions to motor control:

- The **spinal cord** (and brainstem circuits)
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Purves, Figure 16.1

Basal ganglia: Major anatomical structures

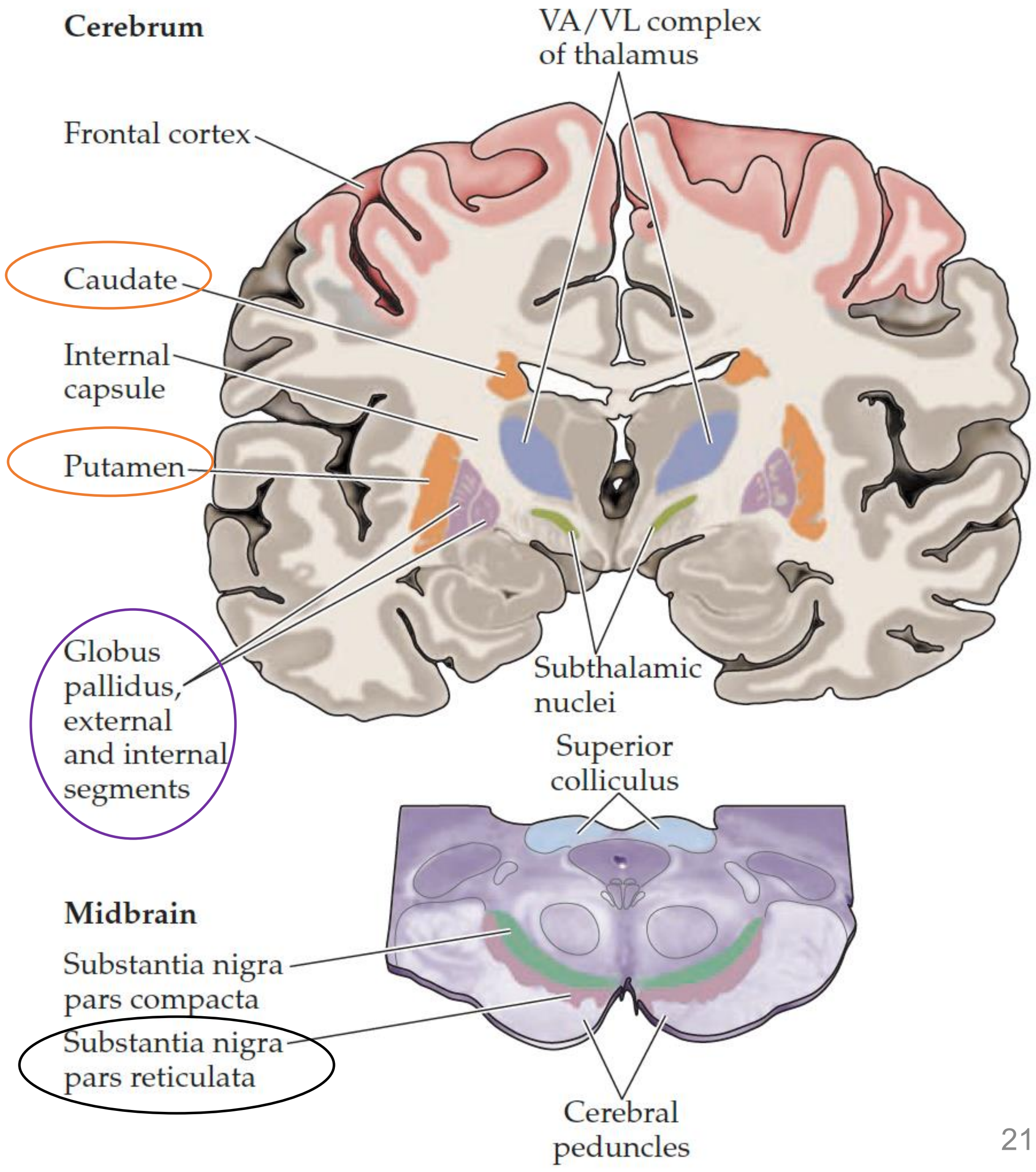
Caudate
Putamen } "Striatum" — Input of BG

Globus Pallidus,
external segment (GPe)

Globus Pallidus,
internal segment (GPi)

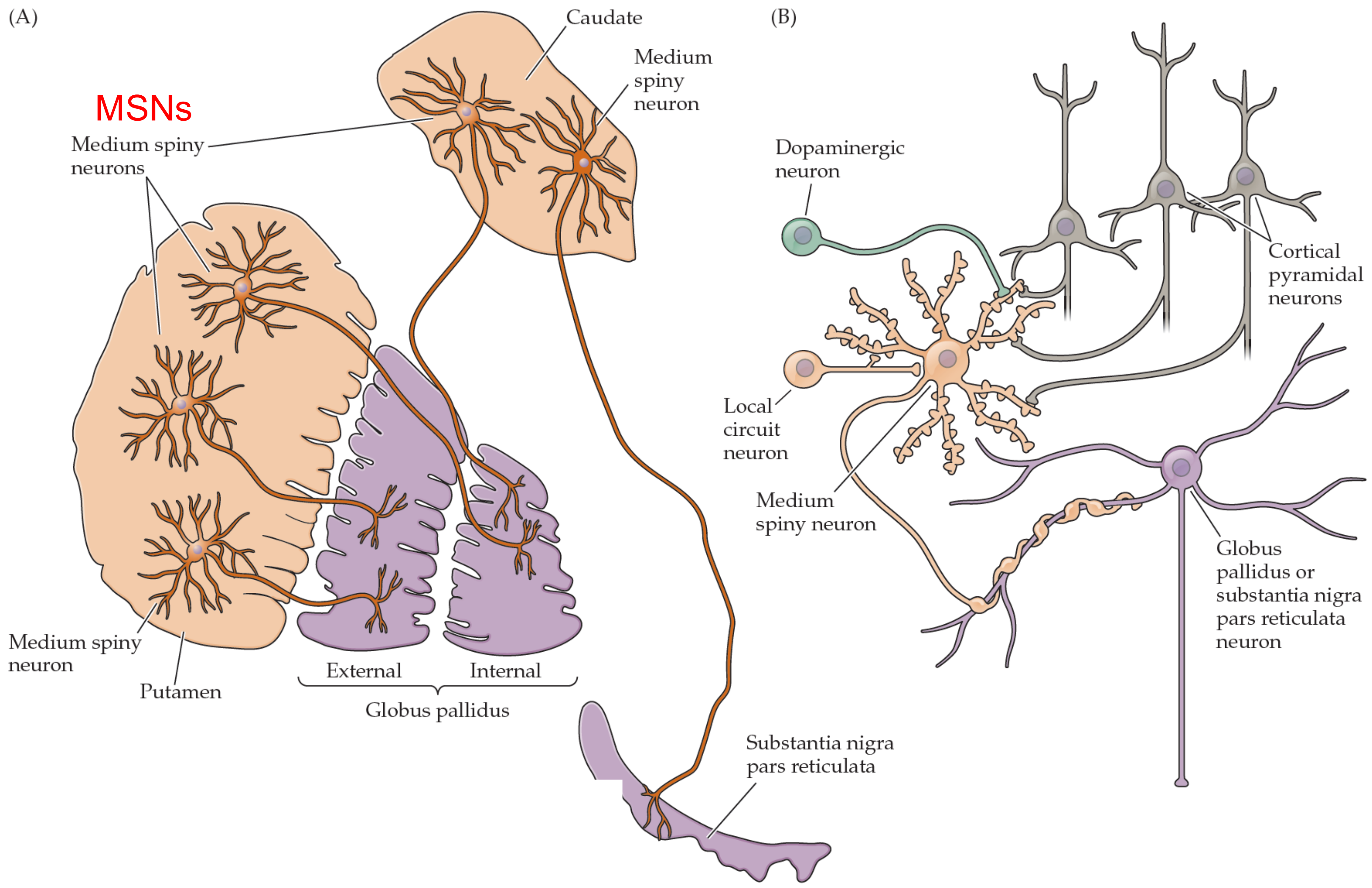
AND/OR
Substantia nigra pars reticulata
(SNpr)

} Output from the BG



Purves, Figure 18.1

Medium spiny neurons receive many inputs from cortex and dopamine



MSNs receive:

- **Many** cortical inputs (glutamate, excitatory)
- **Dopamine** inputs (SNpc, modulatory)
- **Local** modulatory inputs at cell body

MSNs output to the Pallidum (GP and SNpr)

Activity may encode **decision to move** to a goal (compare with M1 which encodes direction & amplitude)

Purves, Figure 18.3

Basal ganglia: Fundamental scheme

Caudate
Putamen } "Striatum" Input of BG

Globus Pallidus,
external segment (GPe)

Globus Pallidus,
internal segment (GPi)

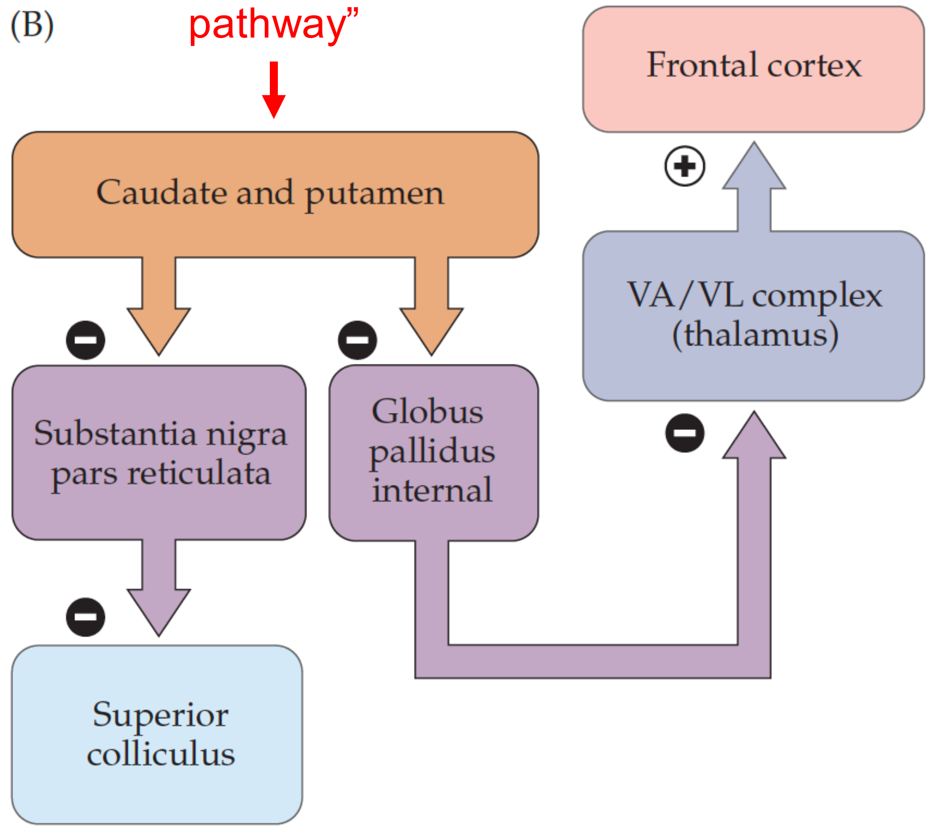
AND/OR
Substantia nigra pars reticulata
(SNpc)

} Output

} Principal neurons are ***inhibitory* (-)** (GABAergic)

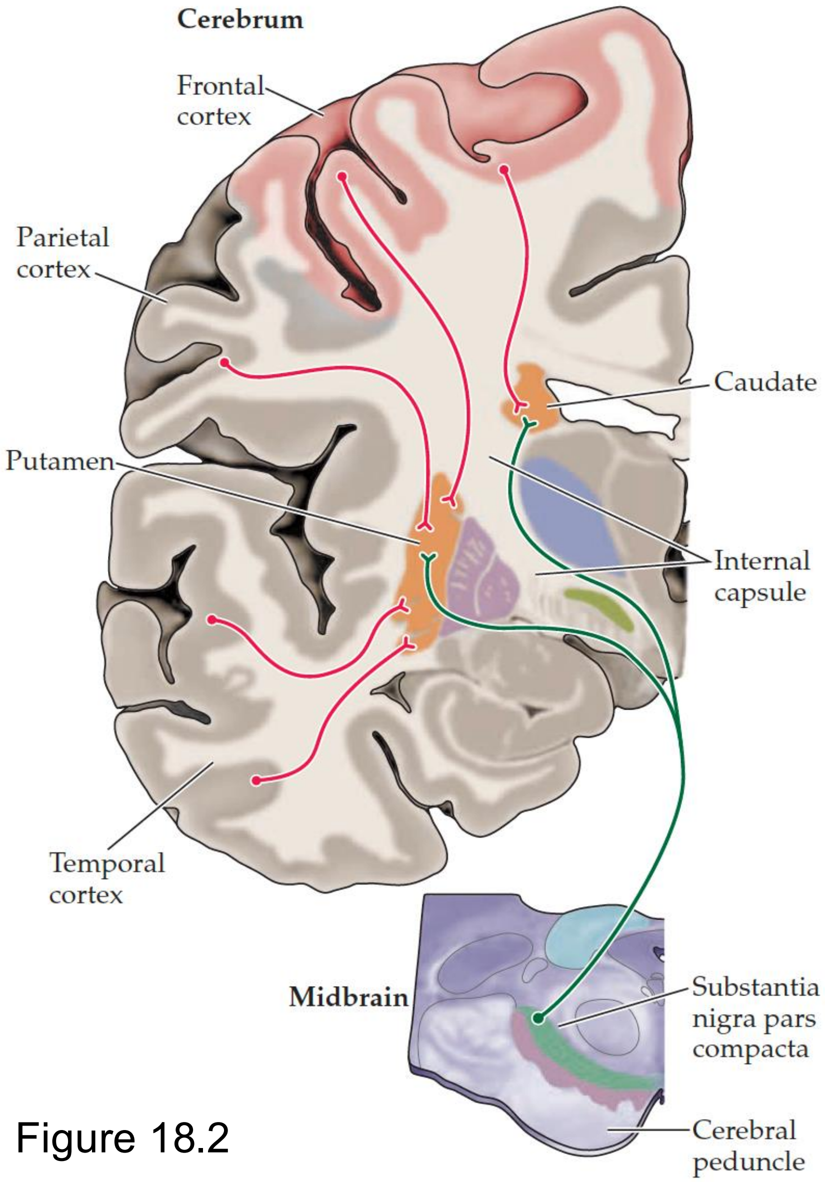
Nearly all regions of cerebral cortex "corticostriatal pathway"

A loop!

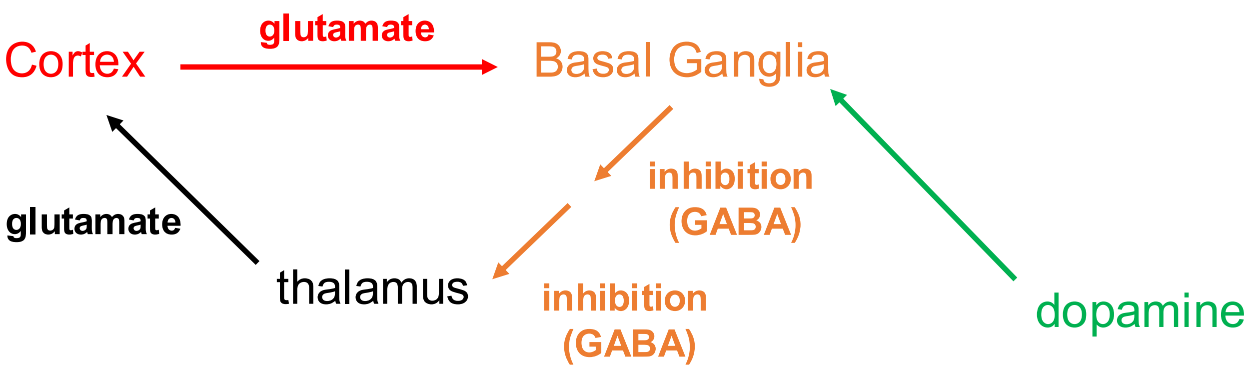


Purves, Figure 18.4

Anatomical organization of inputs to the basal ganglia

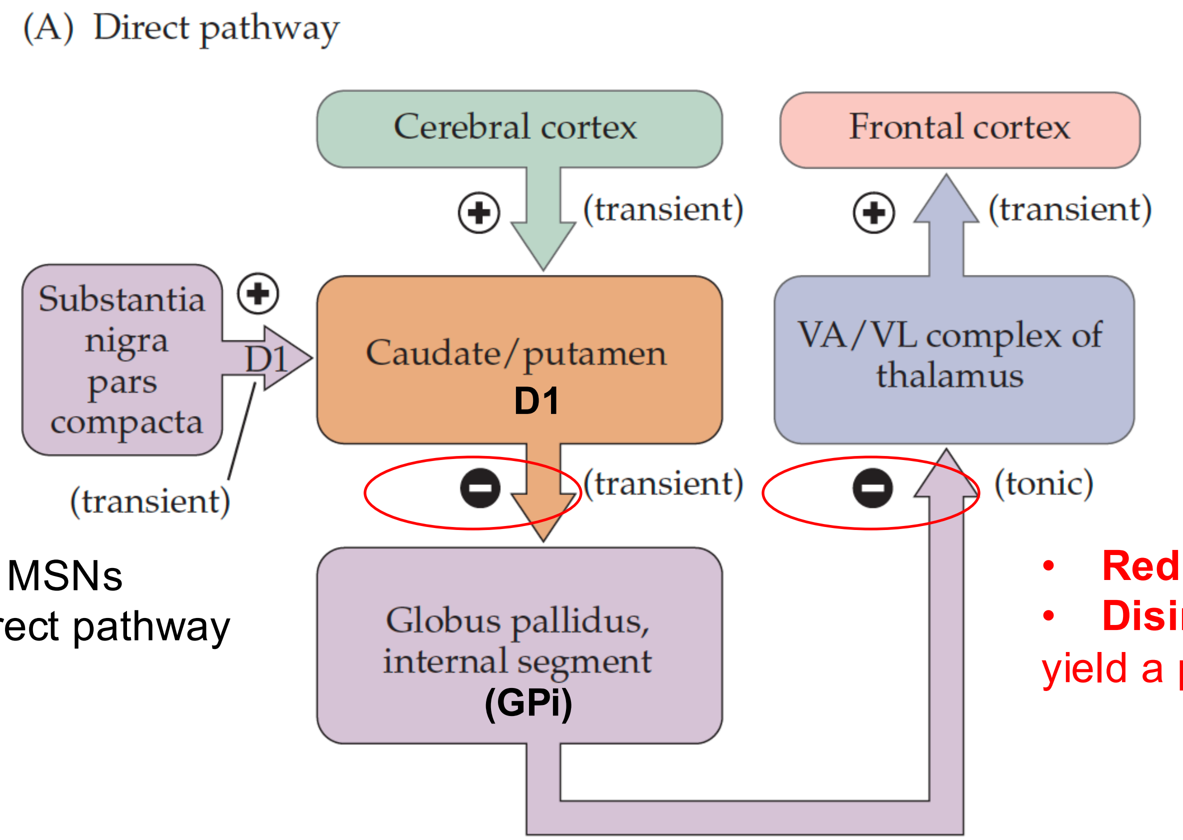


Purves, Figure 18.2



the essential Basal ganglia loop

Major pathway 1: disinhibition in the **direct** pathway **activates** cortex



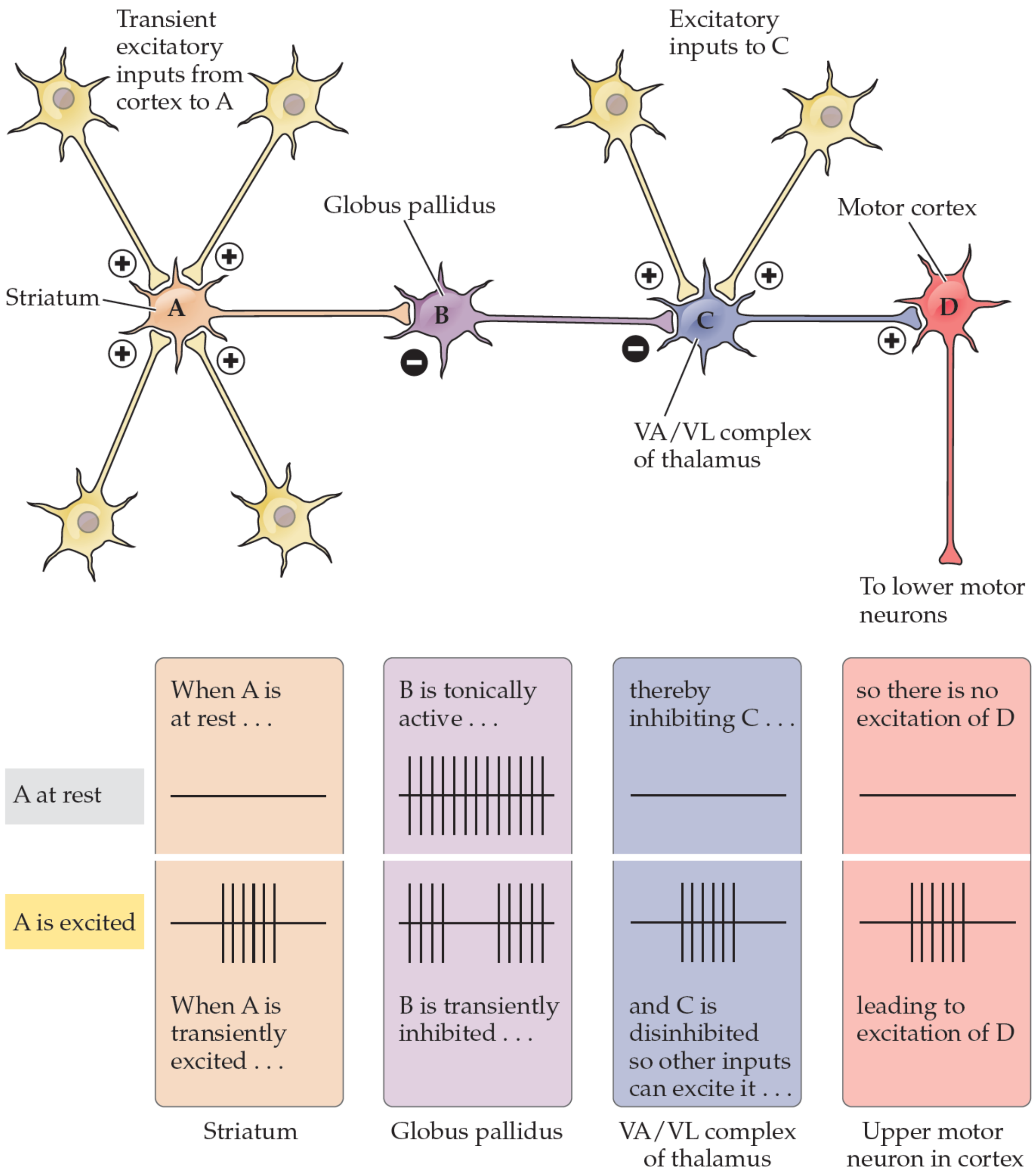
Note:
⊕ : excitation
⊖ : inhibition

Dopamine increases activity of D1 MSNs in striatum & facilitates output of direct pathway

- **Reduces** inhibition of thalamus:
- **Disinhibition** is when two negatives (-) yield a positive (+)

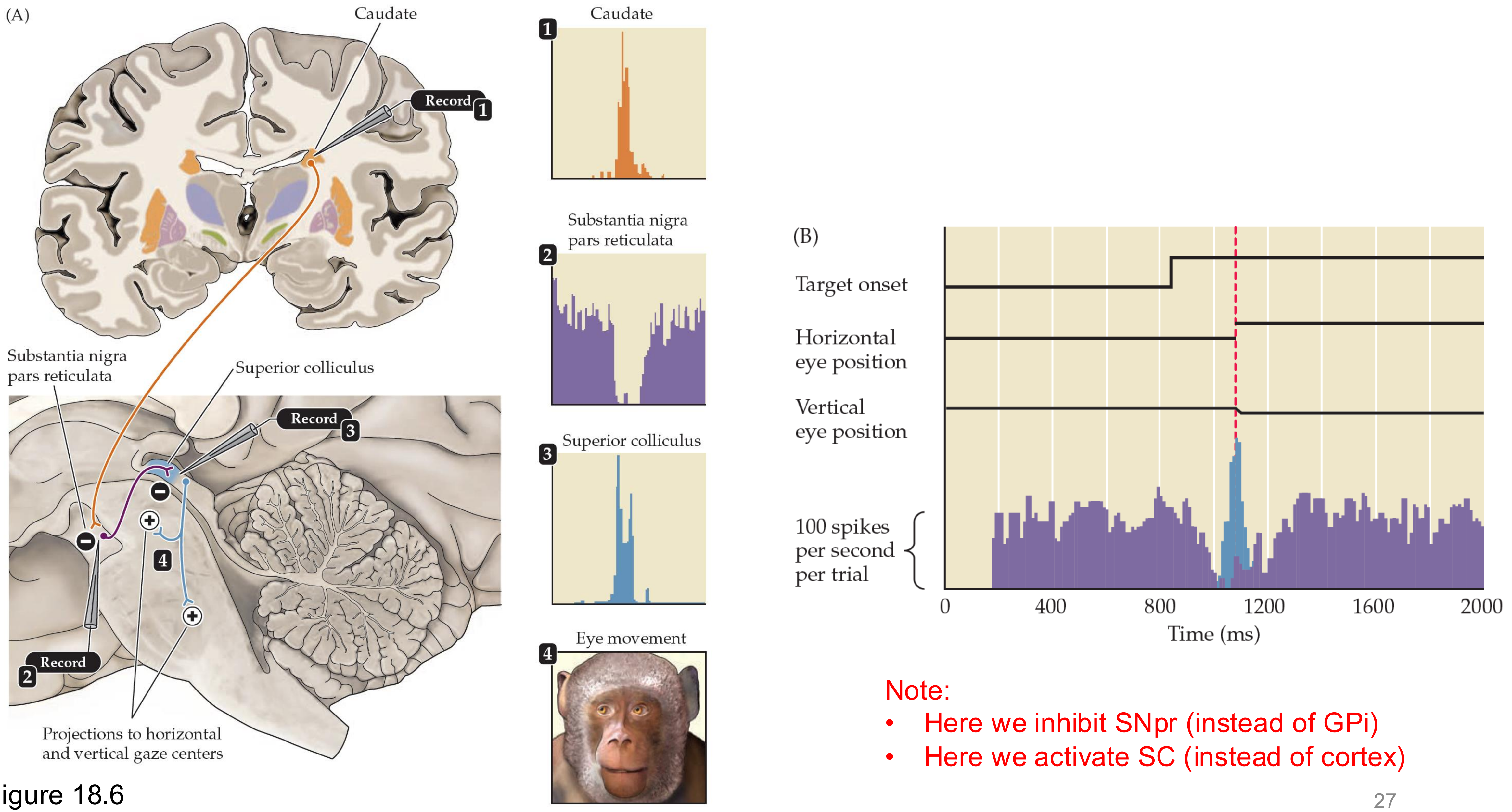
Purves, Figure 18.7

Major pathway 1 *example 1*: the direct pathway **activates** motor cortex



Purves, Figure 18.5

Major pathway 1 *example* 2: the direct pathway **drives** eye movements

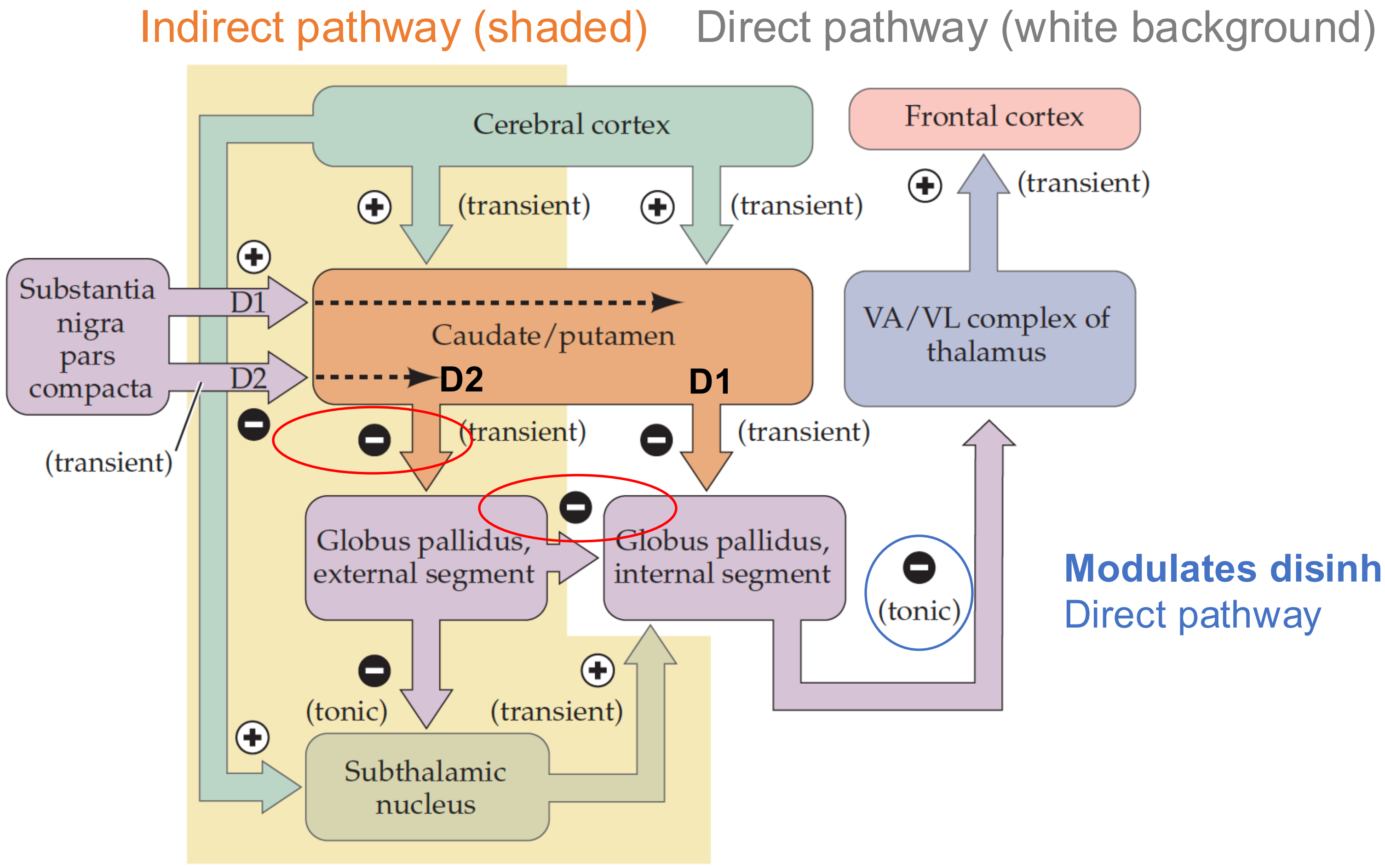


Note:

- Here we inhibit SNpr (instead of GPi)
- Here we activate SC (instead of cortex)

Purves, Figure 18.6

Major pathway 2: the **Indirect** pathway **suppresses** cortex



Modulates disinhibition of the Direct pathway

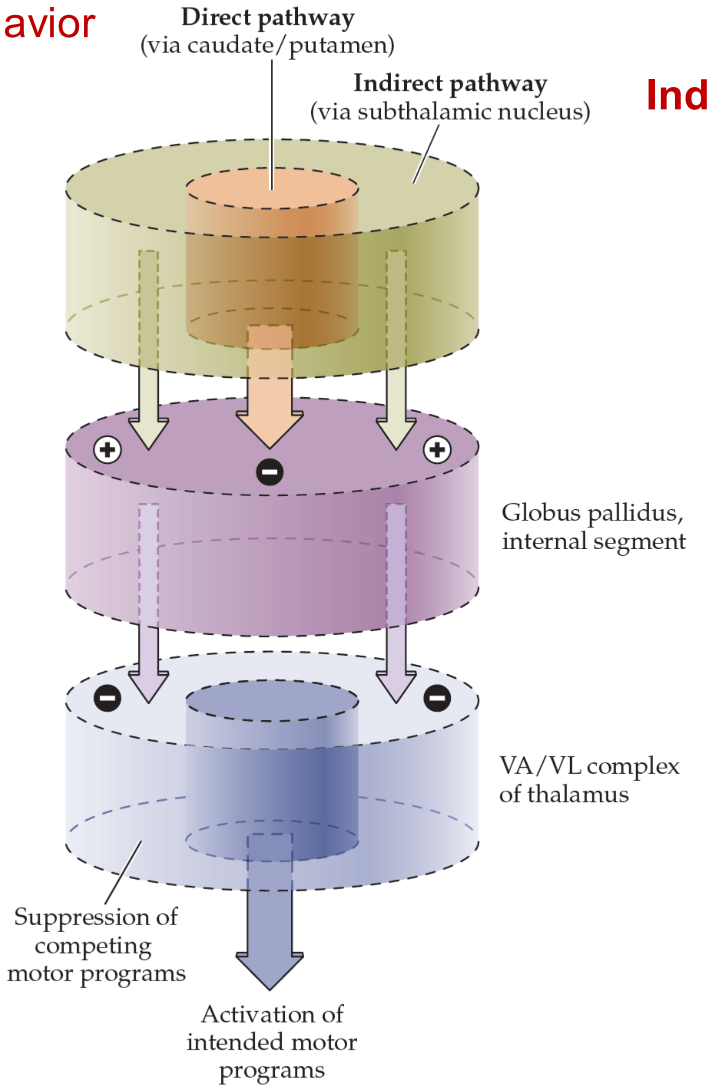
Also:
Disinhibition of subthalamic nuc.
Activates Gpi, **increases inhibition** of thalamus and cortex

Purves, Figure 18.7

The direct and indirect pathways suggest a ‘center-surround’ activation-suppression model for action selection

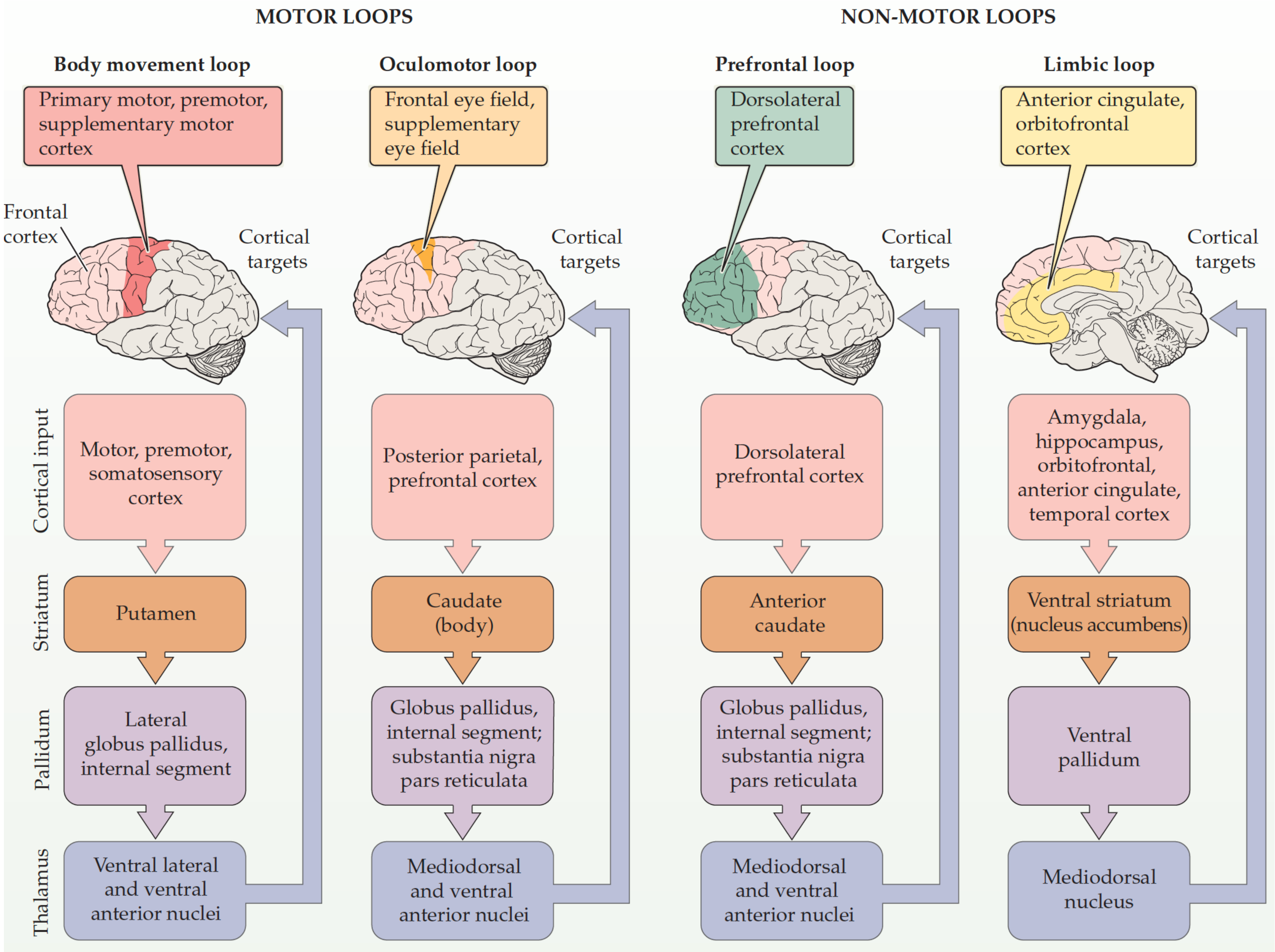
Direct pathway activates/selects one behavior

Indirect pathway suppresses all other behaviors



Purves, Figure 18.8

Basal ganglia loops for motor, prefrontal, and limbic control

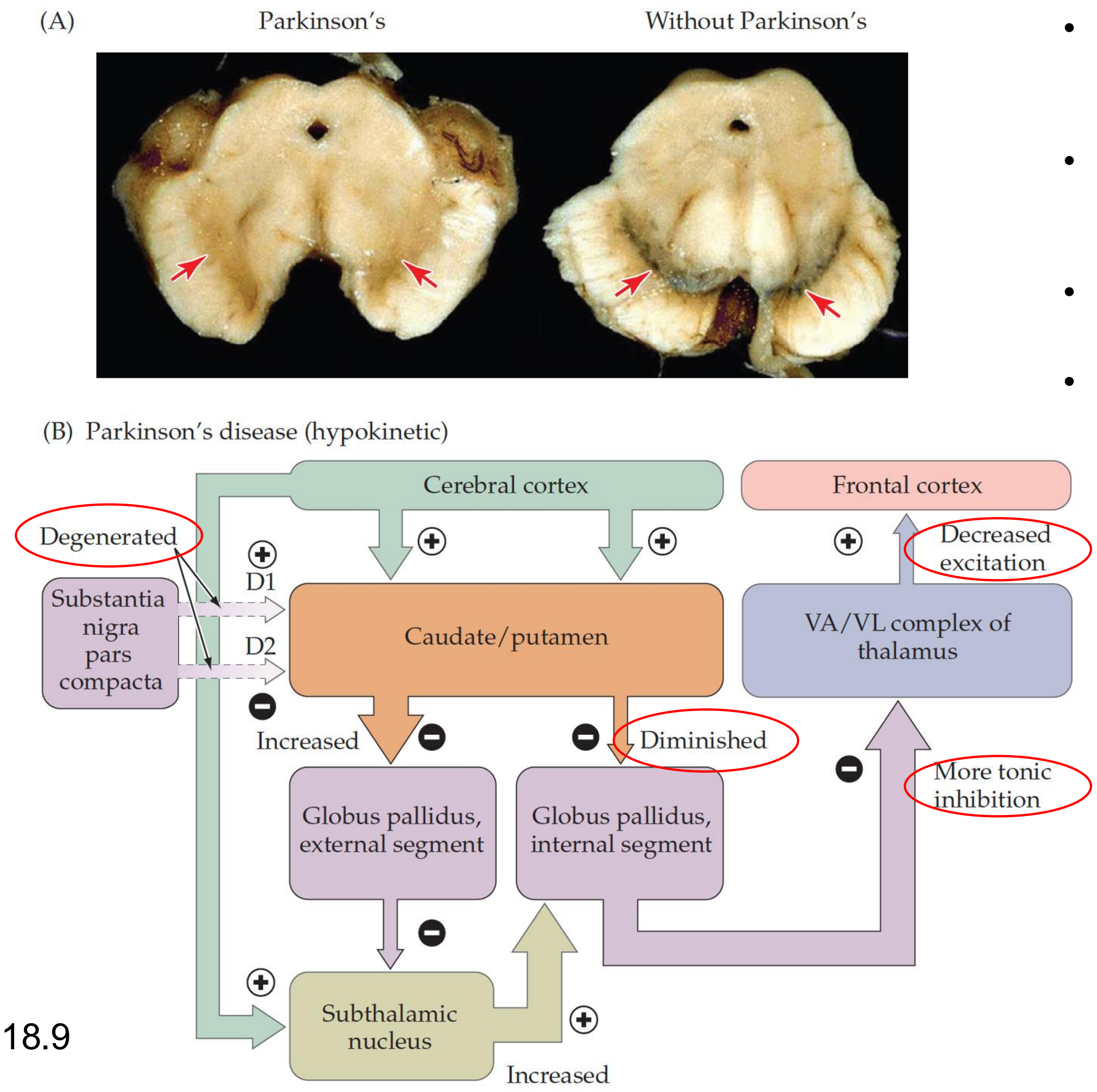


Limbic loop
Anomalies lead to:
OCD, depression, anxiety?

Prefrontal loop:
Start and stop planning, short-term memory, and attention; schizophrenia?

Purves, Box 18B

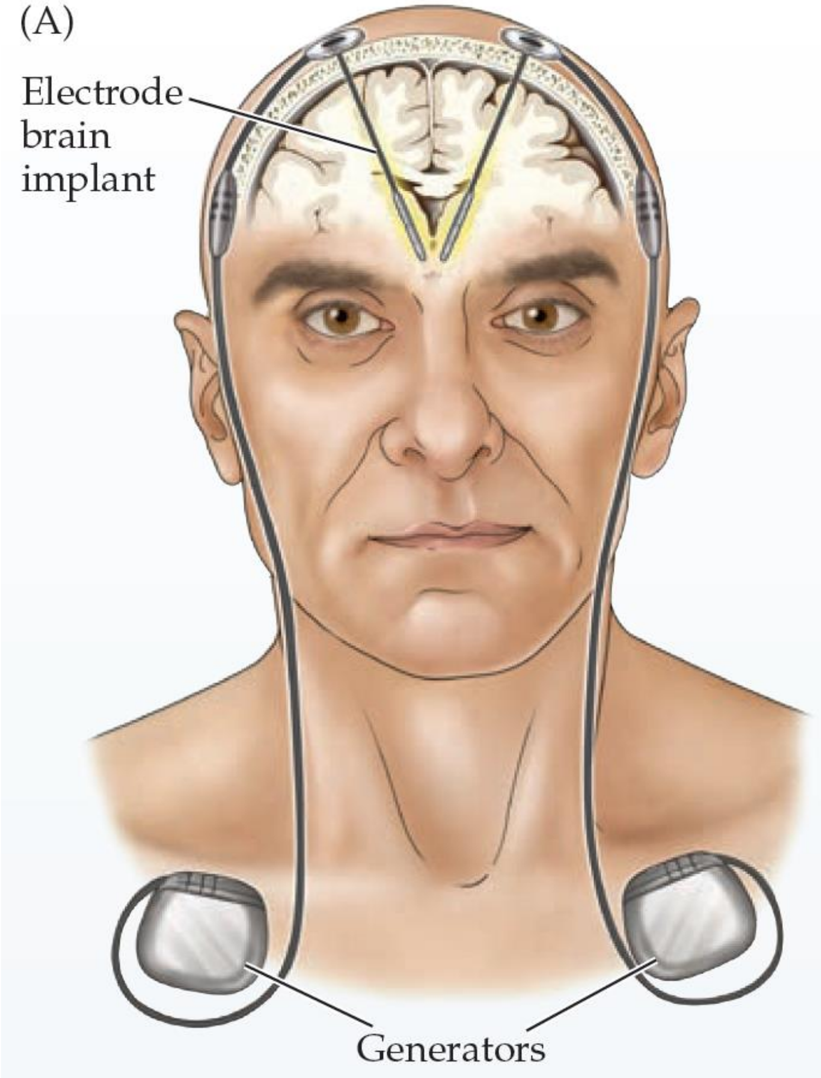
Clinical relevance of basal ganglia 1: Parkinson's disease



- Characterized by slow movements and difficulty initiating movements (e.g., get out of bed)
- Observe **degeneration** of SNpc dopaminergic neurons
- This leads to **decreased** activation of cortex
- **Inhibits movement initiation**

Purves, Figure 18.9

Deep brain stimulation to regulate dopamine release in PD

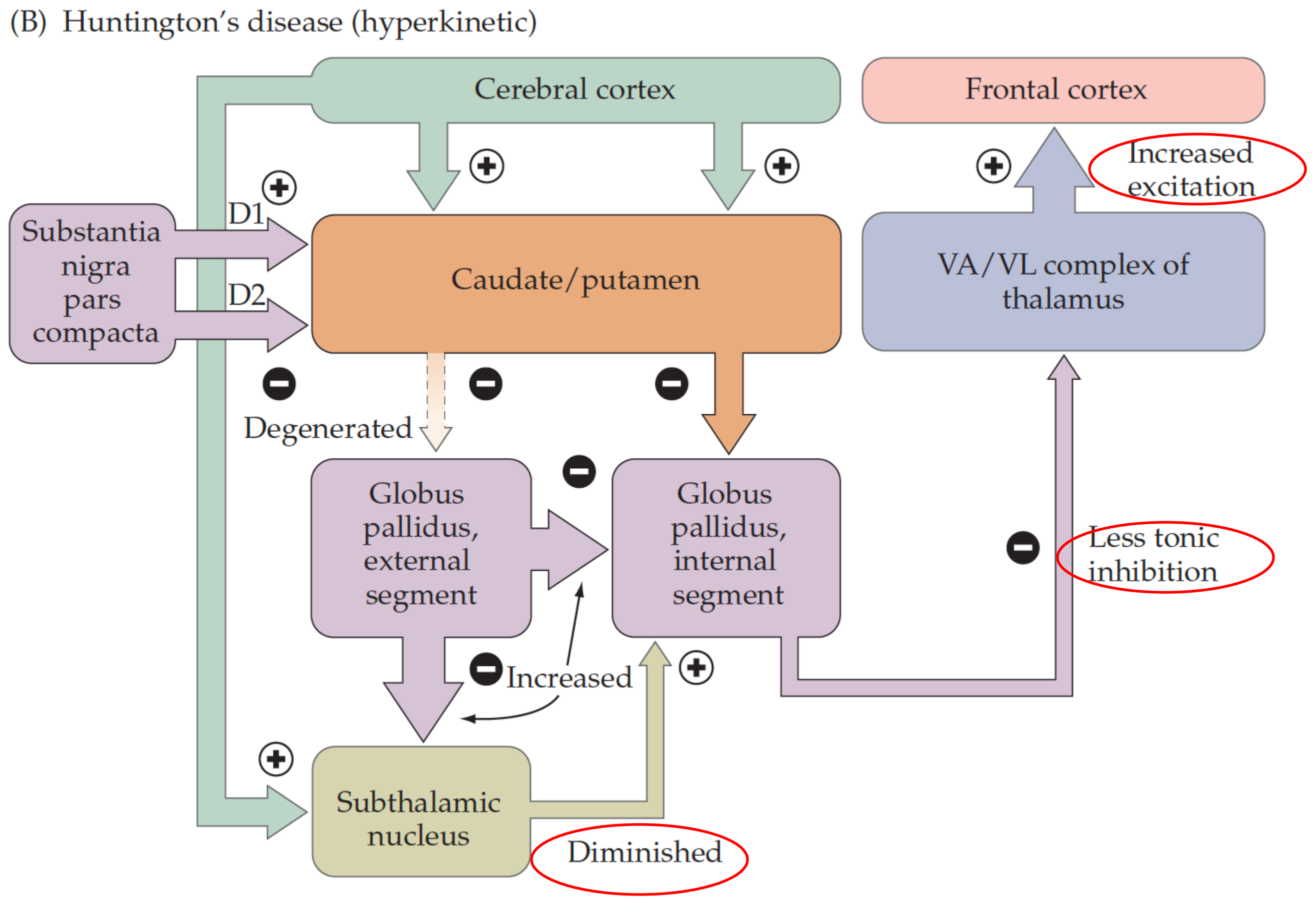


(A) Illustration of a patient following implantation of a device for deep brain stimulation.

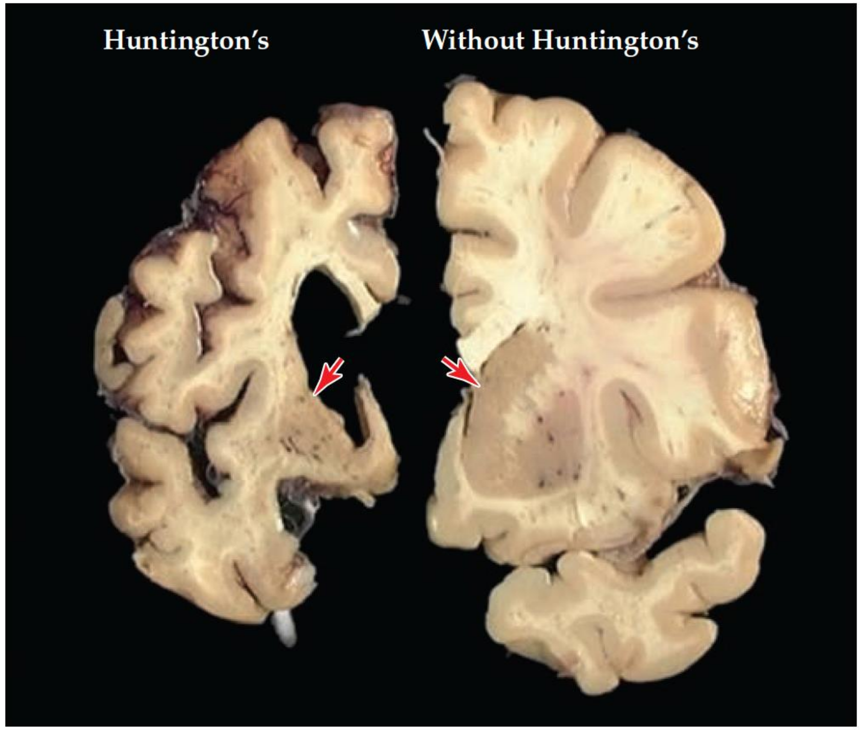
- Strategy: block indirect pathway’s movement suppression
- Deep brain stimulation can silence Subthalamic nucleus.
- Mechanisms not entirely clear.

Purves, Figure 18.Clinical Applications

Clinical relevance of basal ganglia 2: Huntington's disease



- **Unwanted** movements (e.g., tics)
- Observe **degeneration** of **indirect** pathway neurons
- This leads to **increased** activation of thalamus/cortex
- Activates **unwanted movements**



Purves, Figure 18.10

Summary: Movement control by Motor Cortex and Basal Ganglia
Important concepts and keywords

- Principle scheme of brain areas involved in motor control
- Primary motor cortex (M1), output layer (L5), lateral corticospinal tract
- ”Coding" of movement primitives in M1
- Principles and applications of a Brain-Machine Interface

Basal ganglia:

- Principal nuclei and their connectivity
- Medium spiny neurons (MSNs) in the Striatum
- Input and output structures (brain nuclei) of basal ganglia
- Direct and indirect pathways: modulation and roles in action selection and movement
- Explanations for Parkinson’s and Hungtington’s disease symptoms based on knowledge of basal ganglia organization and function