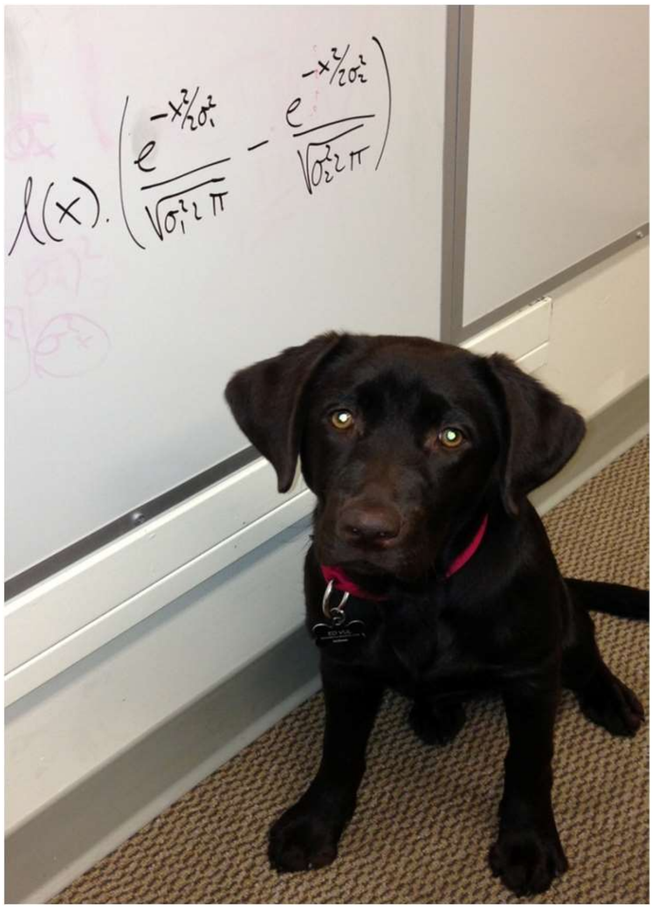
Learning to associate

CS786

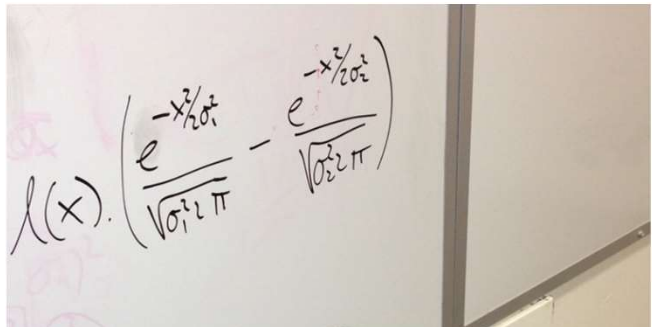
6th August 2024

What RW could explain



What it couldn't

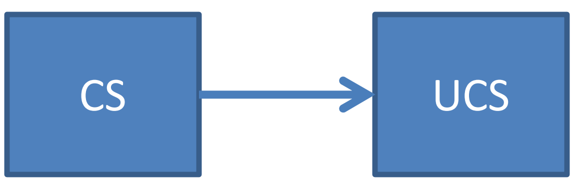
Pre-exposed



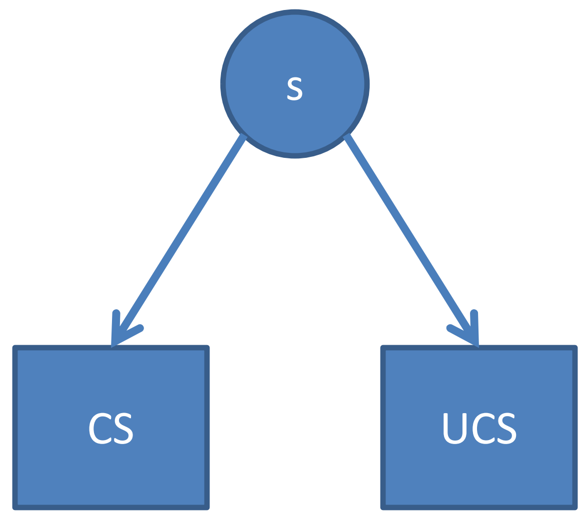
Latent inhibition

Latent cause modeling of conditioning

Rescorla Wagner model

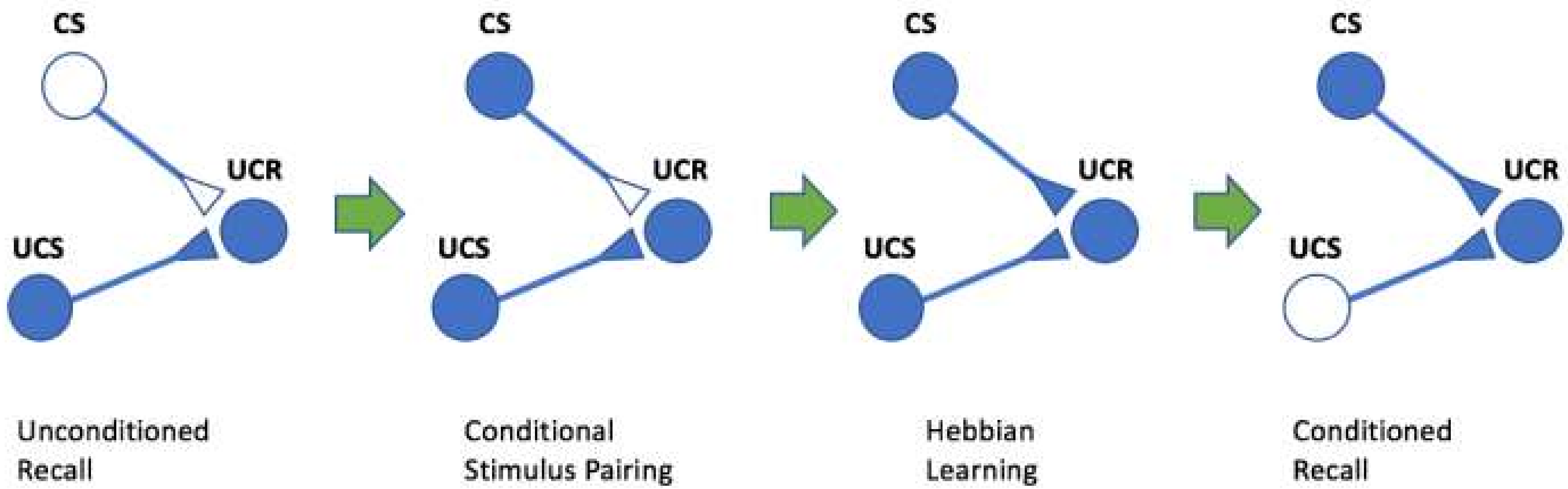


Latent cause model*



* See Courville, Daw & Touretzky (2005) for a formal description

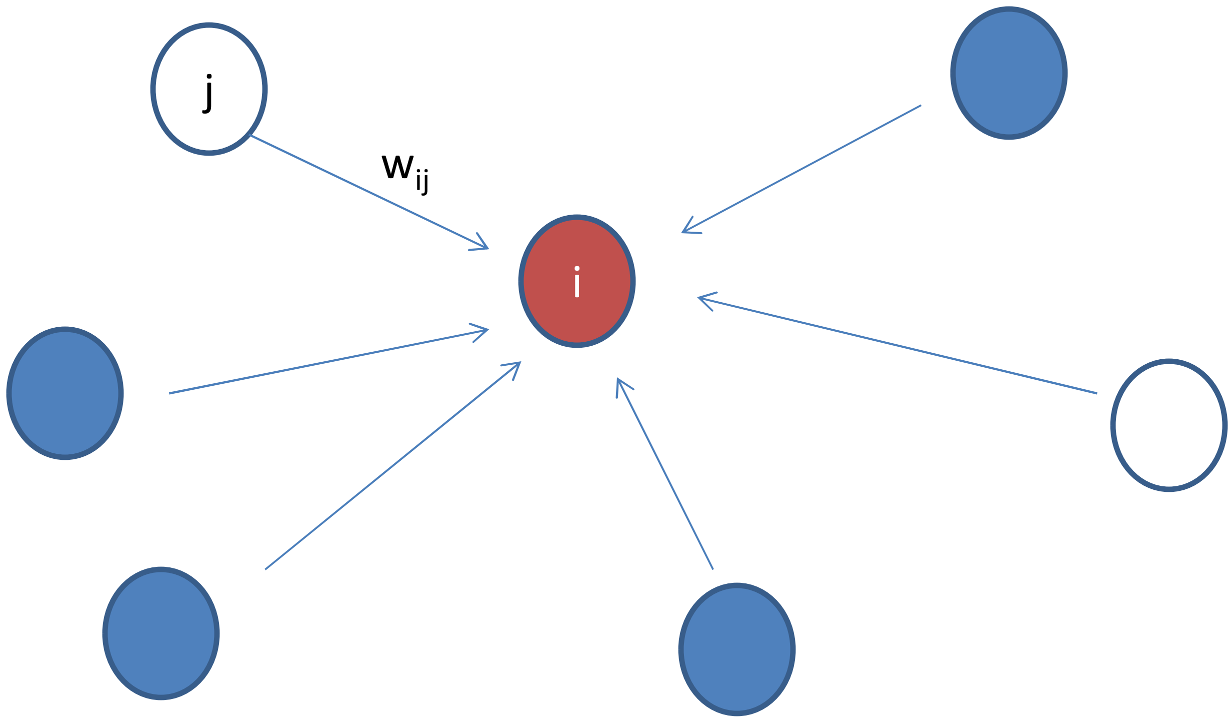
Explaining associativity



Hebbian learning

- If two information processing units are activated simultaneously, their activity will become correlated, such that activity in one will make activity in the other more likely
- We will see
  - How Hebbian learning works in artificial neurons
  - How Hebbian learning works in real neurons

Hebbian learning



$$\Delta w_{ij} = x_i x_j$$

Hebb’s rule in action

- Common variant

$$\Delta \mathbf{w}_t = \eta \mathbf{x}_t y$$

$$y = \sum_j w_{ij} x_j$$

- Problem
  – No way to weaken weights
  – Weights can climb up without bound
  – Solution: normalization?

Normalizing Hebb's rule

- Oja's rule can be derived as an approximate normalized version of Hebb's rule

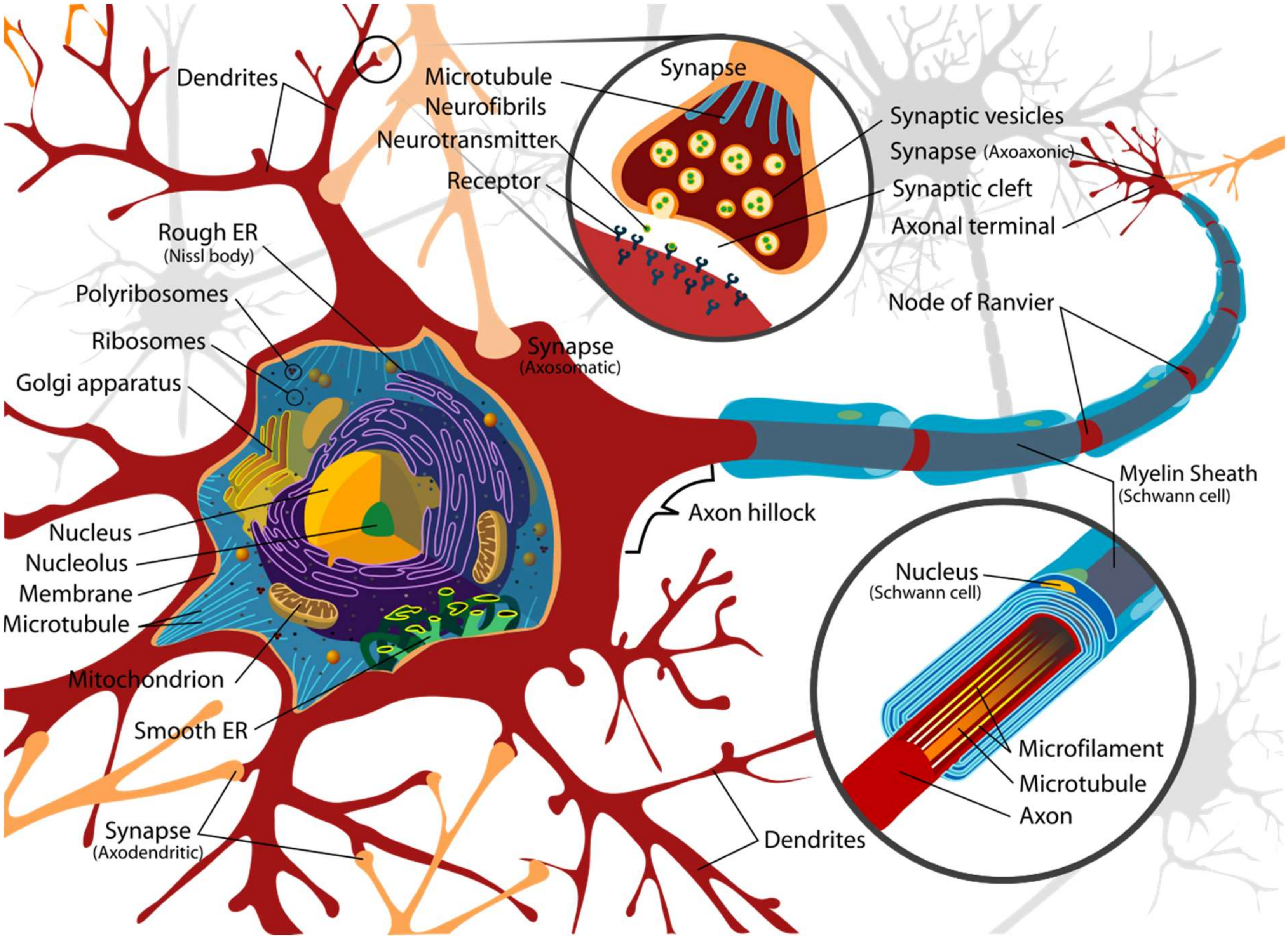
$$\Delta \mathbf{w}_n = \eta y_n (\mathbf{x_n} - y_n \mathbf{w}_n)$$

- Other formulations are also possible, e.g. BCM, generalized Hebb
- Hebbian learning partially explains how neurons can encode new information
  - And explains how this learning is fundamentally associative

What neurons do – the ML version

- A neuron collects signals from *dendrites*
- Sends out spikes of electrical activity through an *axon*, which splits into thousands of branches.
- At the end of each branch, a *synapse* converts activity into either exciting or inhibiting activity of a dendrite at another neuron
- Neuron *fires* when exciting activity surpasses inhibitory activity above some threshold Learning changes the strength of synapses

Real neurons

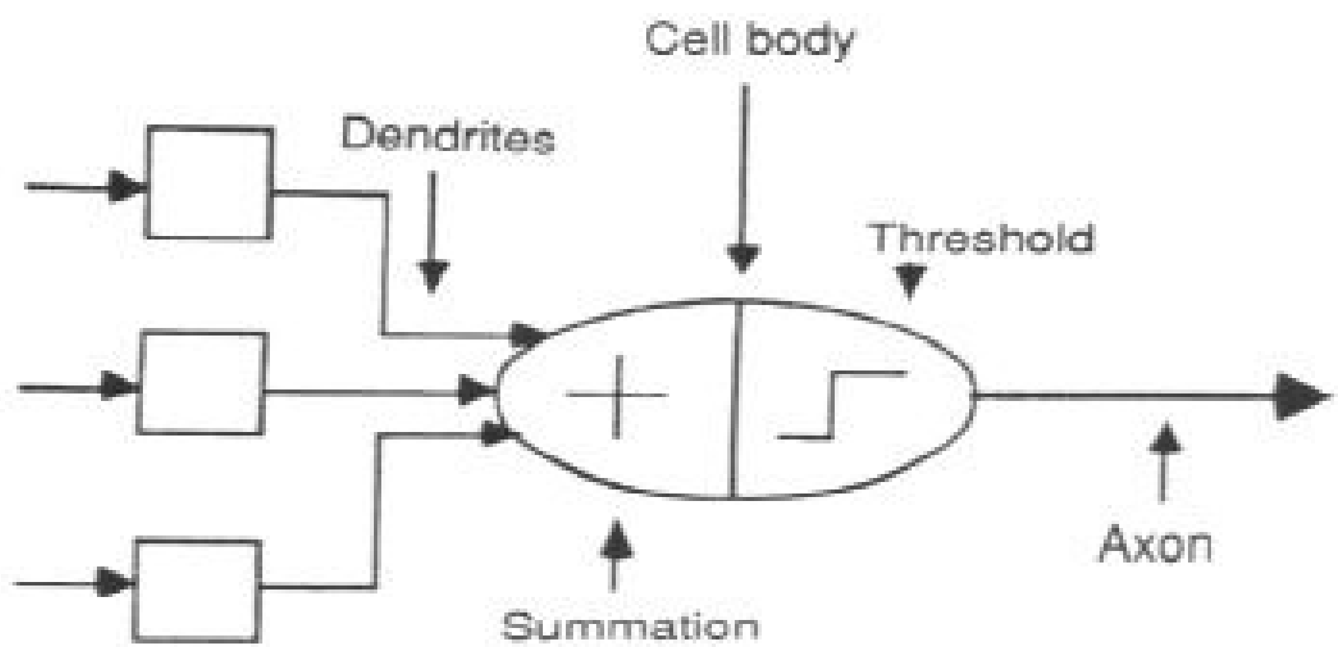


What neurons do – the ML version

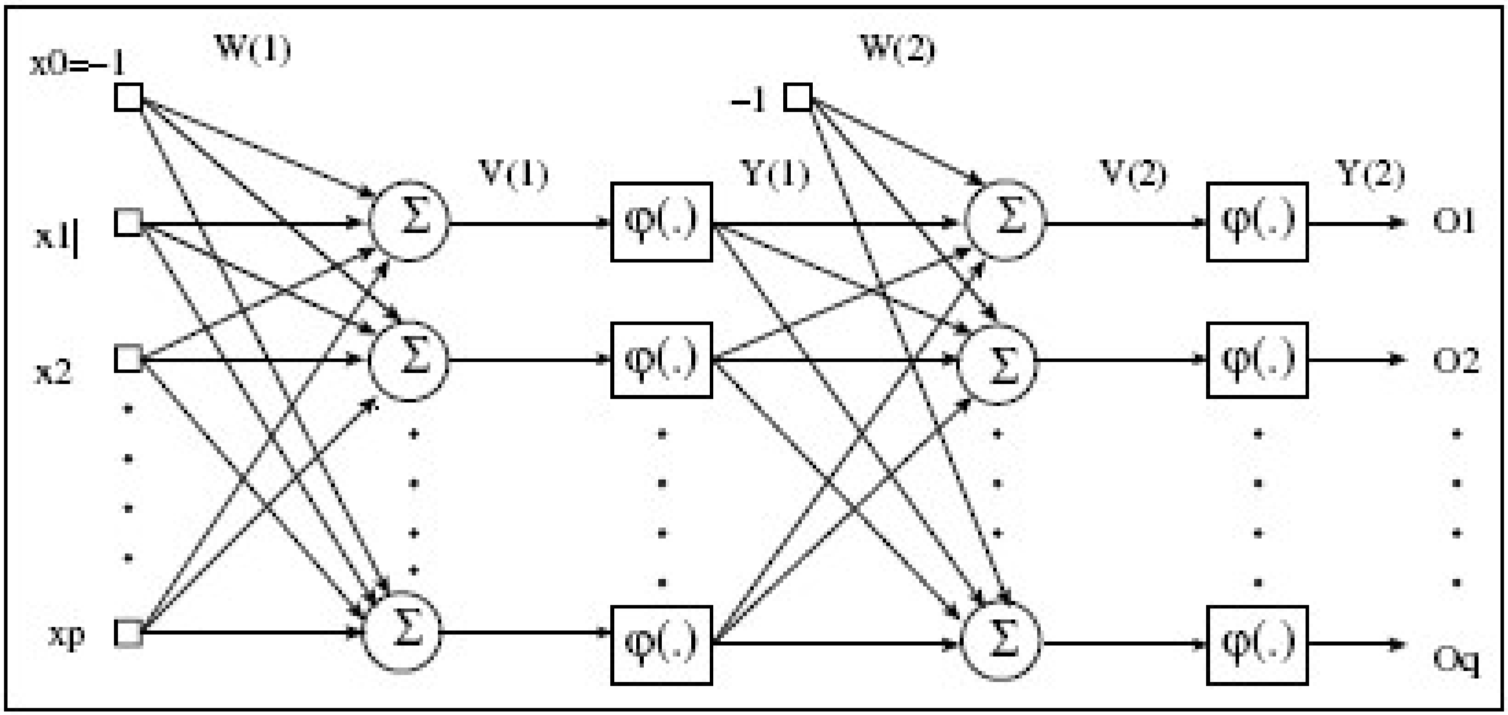
- A neuron collects signals from *dendrites* *(not quite)*
- Sends out spikes of electrical activity through an *axon*, which splits into thousands of branches.
- At the end of each branch, a *synapse* converts activity into either exciting or inhibiting activity of a dendrite at another neuron *(more complicated than this)*
- Neuron *fires* when exciting activity surpasses inhibitory activity above some threshold *(neurotransmitters govern the threshold and activity rate)*
- Learning changes the strength of synapses (*but what sort of learning?*)

Artificial neurons

- Logical abstraction of natural neurons to perform these functions



ANN Forward Propagation



ANN Forward Propagation

- Apply input vector **X** to layer of neurons.
- Calculate $$V_j(n) = \sum_{i=1}^{p} w_{ij} x_i + w_0$$
  - where x_i is the activation of previous layer neuron i
  - w_{ji} is the weight of going from node i to node j
  - p is the number of neurons in the previous layer
- Calculate output activation

$$Y_j(n) = \frac{1}{1 + \exp(-V_j(n))}$$

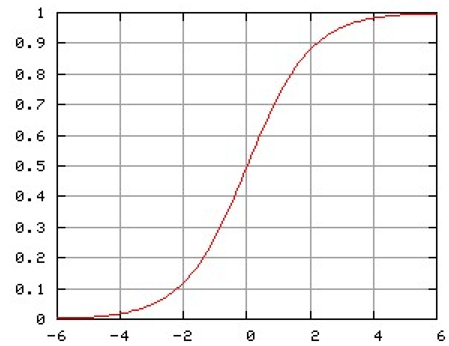
Possible firing rules

- Firing Rules: Sigmoid functions:
  - Hyperbolic tangent function

$$\varphi(v) = \tanh(v/2) = \frac{1-\exp(-v)}{1+\exp(-v)}$$

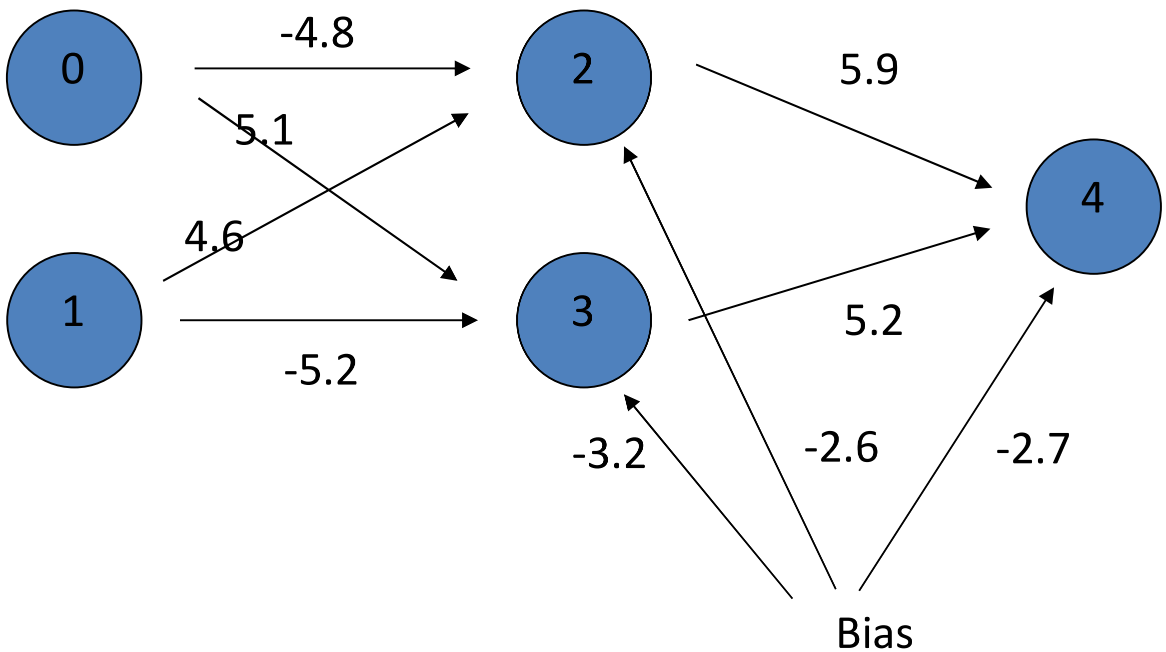
  - Logistic activation function

$$\varphi(v) = \frac{1}{1+\exp(-v)}$$



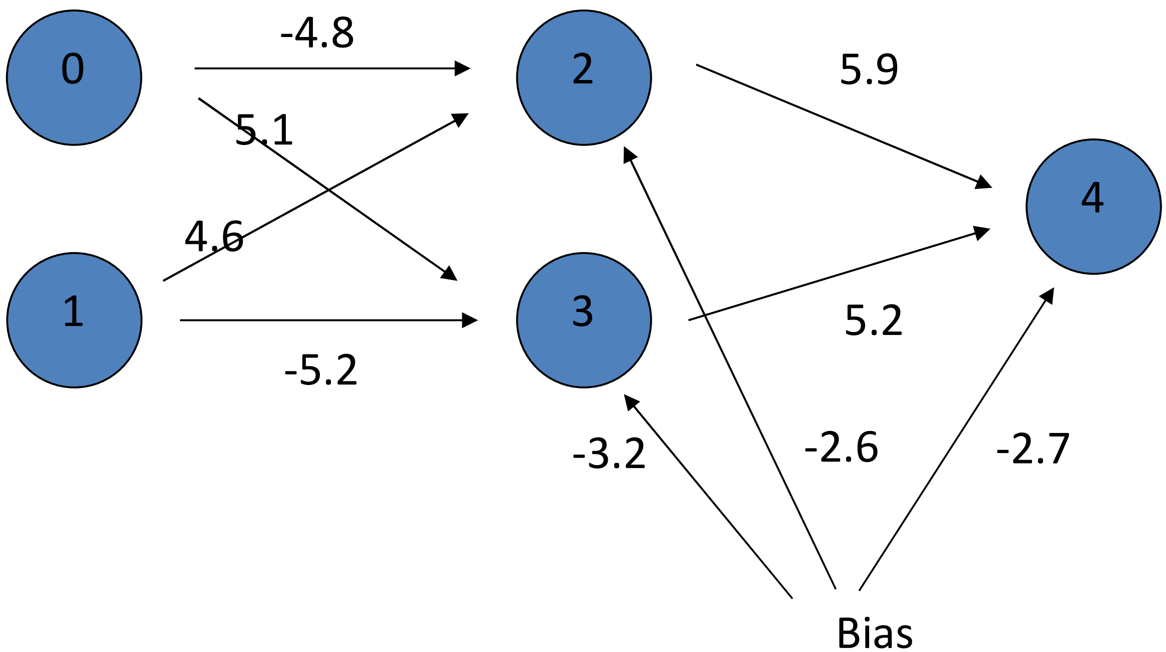
ANN Forward Propagation

- Example: Three layer network
  - Calculates xor of inputs



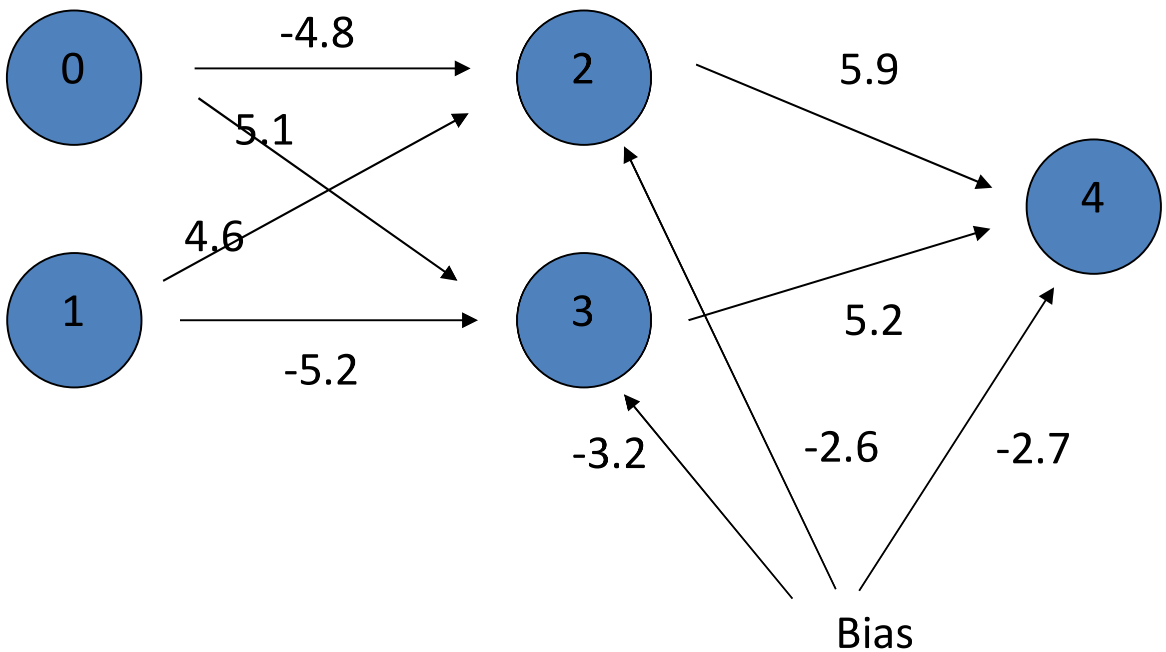
ANN Forward Propagation

- Input (0,0)



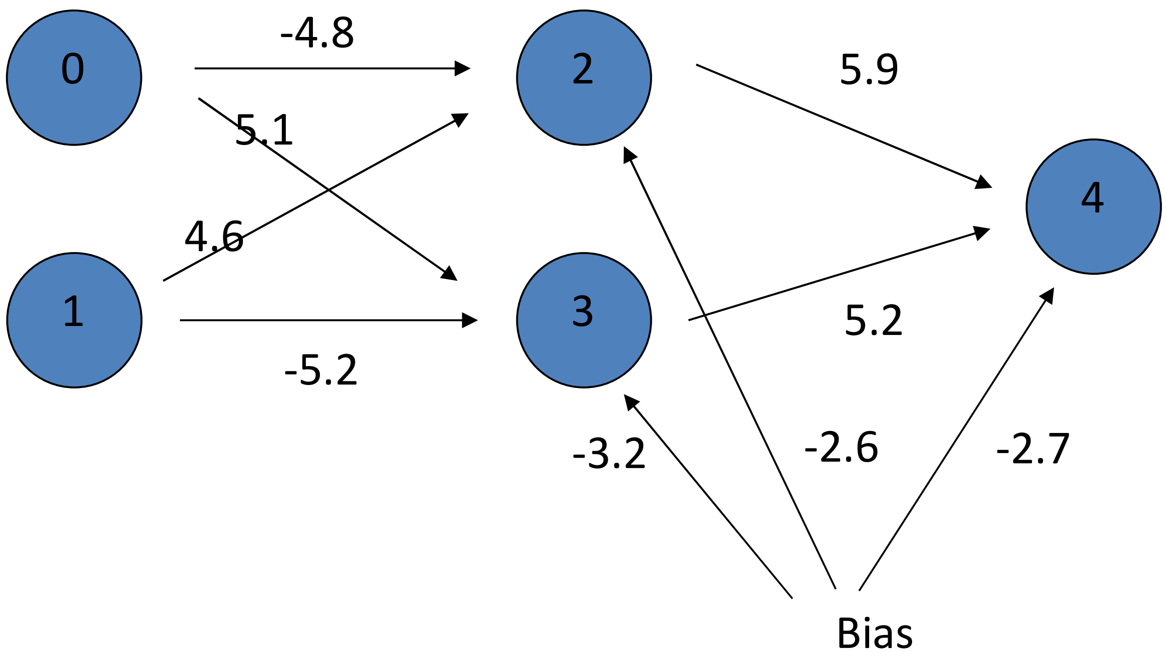
ANN Forward Propagation

- Input (0,0)
  - Node 2 activation is $\varphi(-4.8 \cdot 0+4.6 \cdot 0 - 2.6)=$ 0.0691



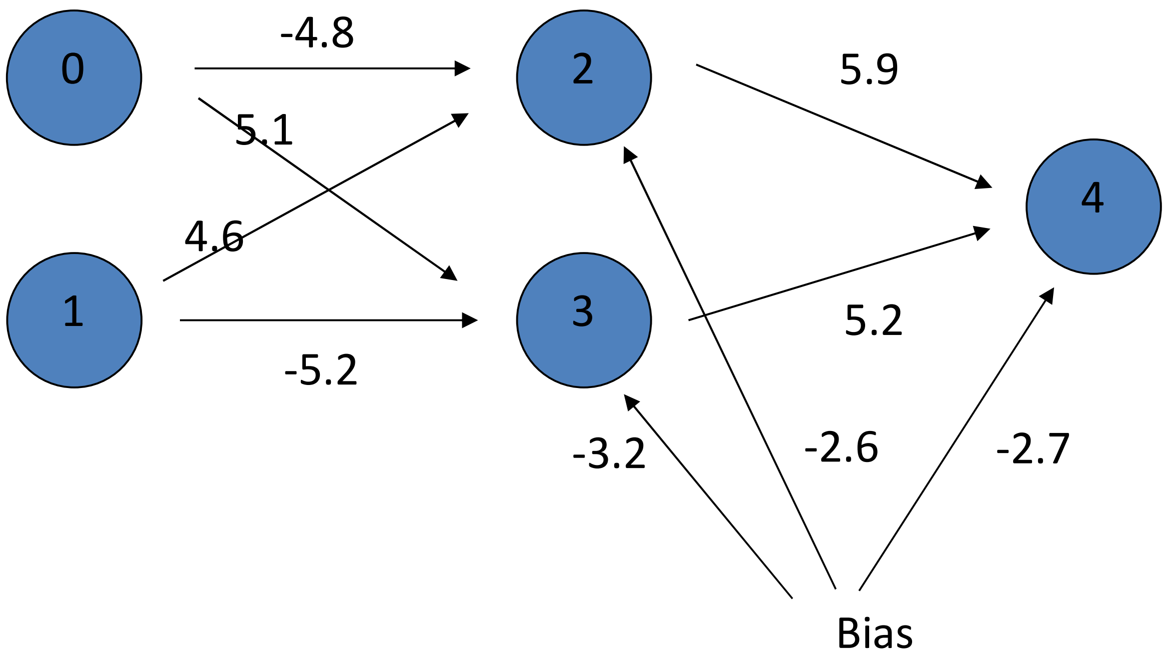
ANN Forward Propagation

- Input (0,0)
  - Node 3 activation is $\varphi(5.1 \cdot 0 - 5.2 \cdot 0 - 3.2) = 0.0392$



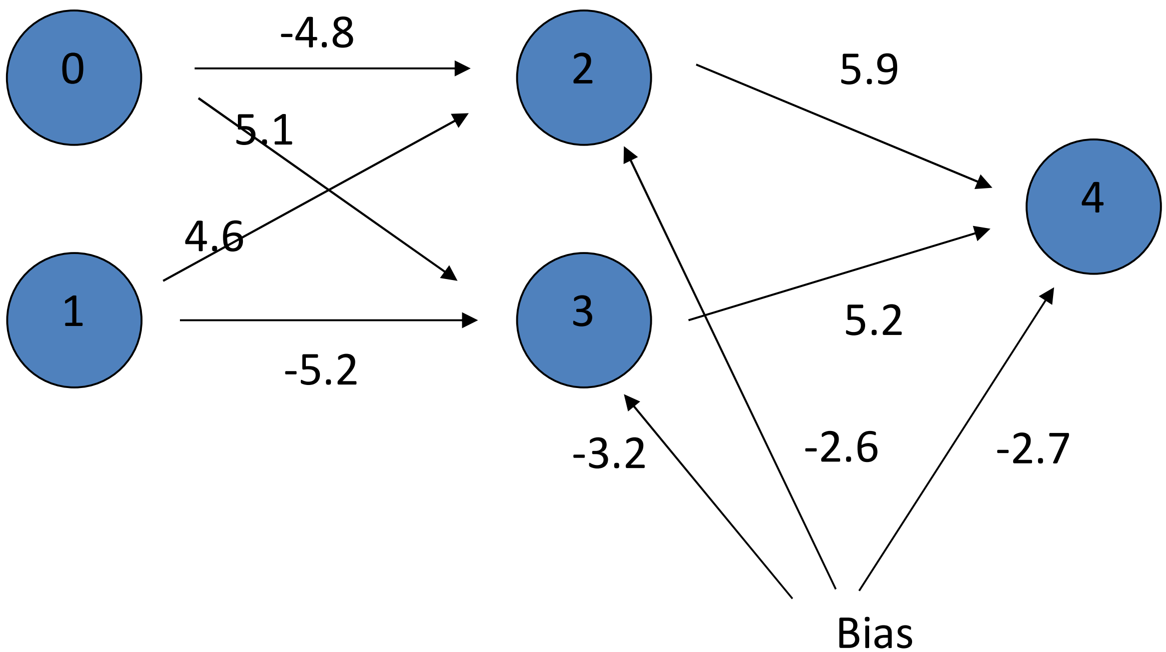
ANN Forward Propagation

- Input (0,0)
  - Node 4 activation is $\varphi(5.9 \cdot 0.069 + 5.2 \cdot 0.04 - 2.7) = 0.110227$



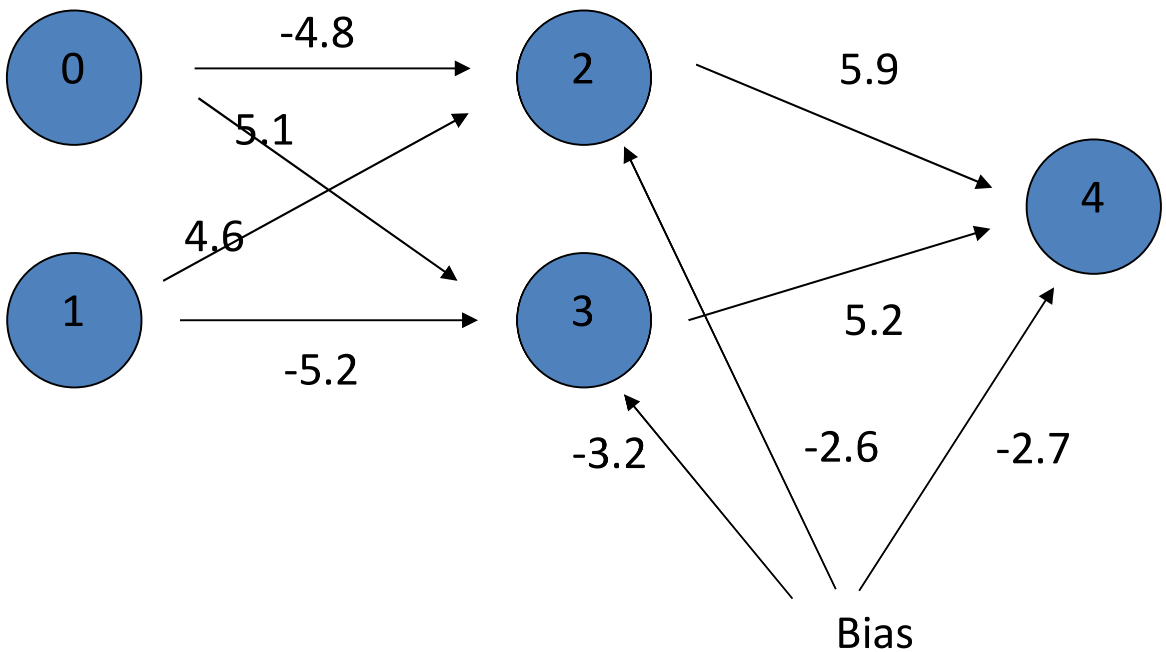
ANN Forward Propagation

- Input (0,1)
  - Node 2 activation is $\varphi(4.6 - 2.6) = 0.153269$



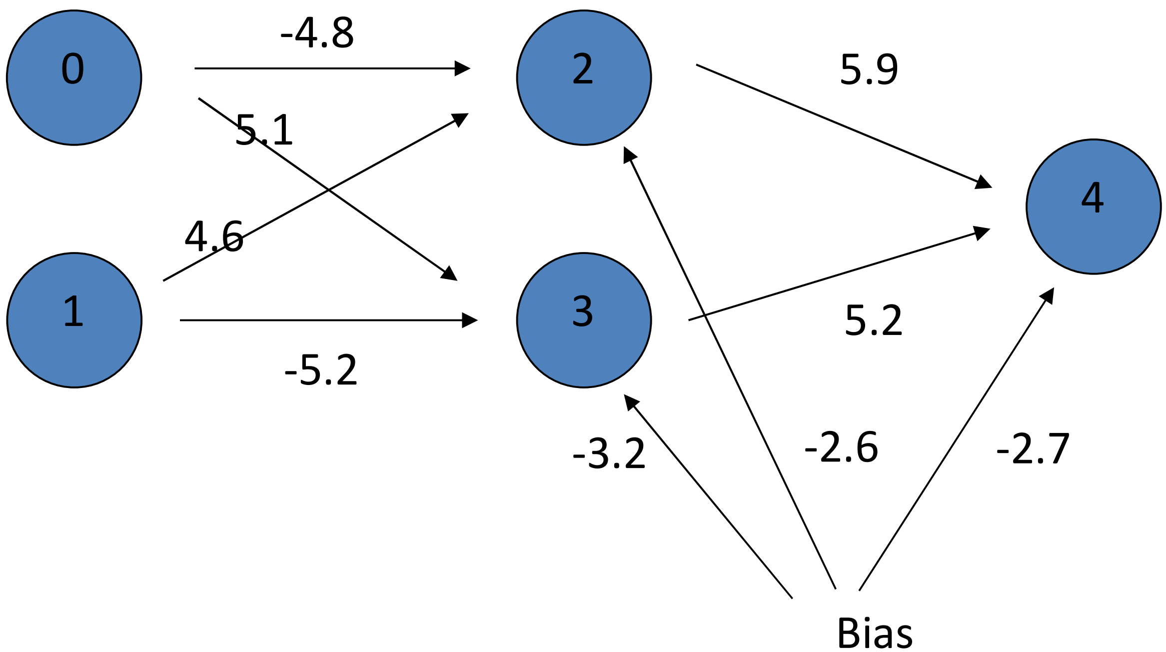
ANN Forward Propagation

- Input (0,1)
  - Node 3 activation is $\varphi(-5.2 -3.2)=$ 0.000224817



ANN Forward Propagation

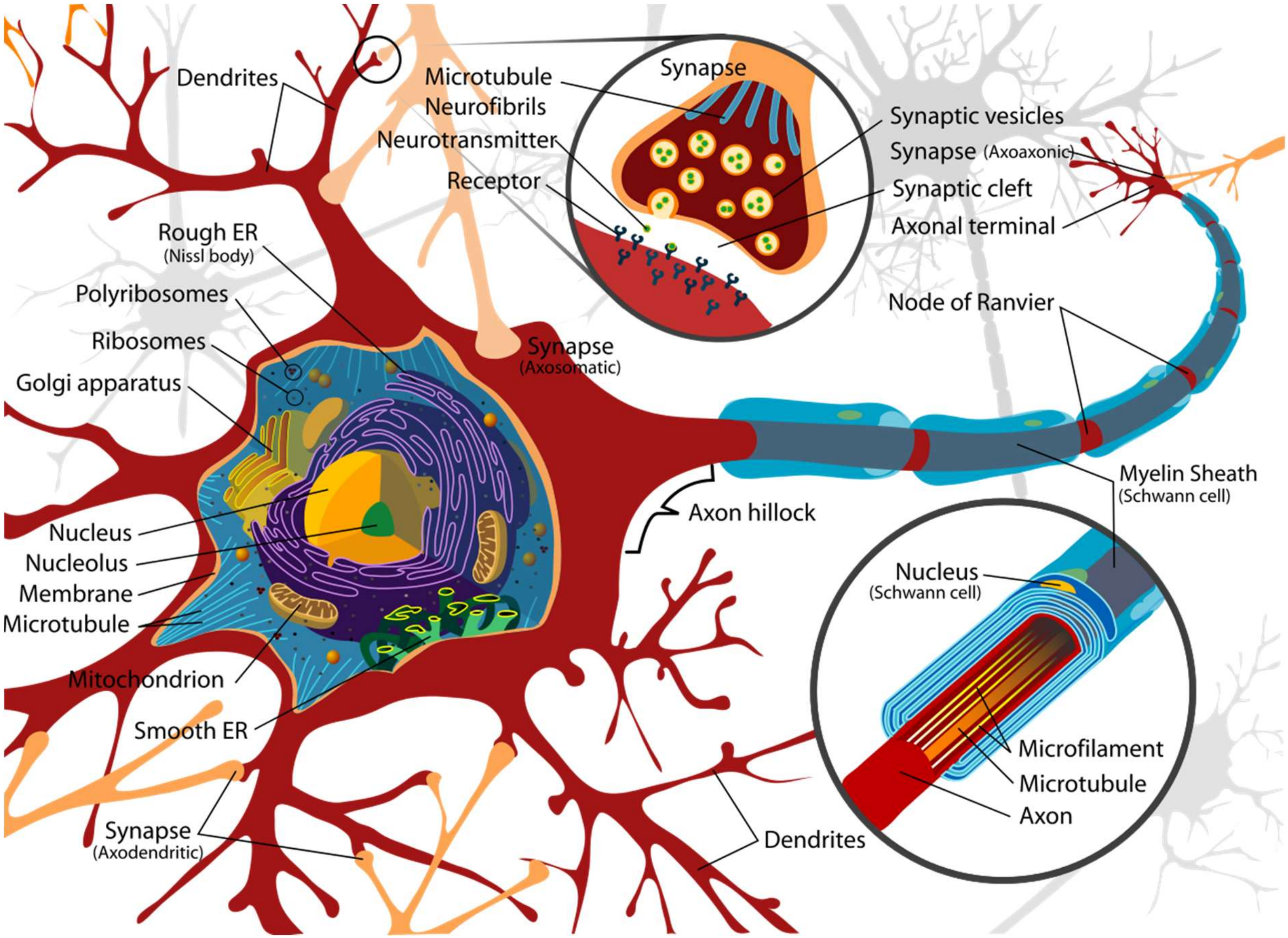
- Input (0,1)
  - Node 4 activation is $\varphi(5.9 \cdot 0.153269 + 5.2 \cdot 0.000224817 - 2.7) = 0.923992$

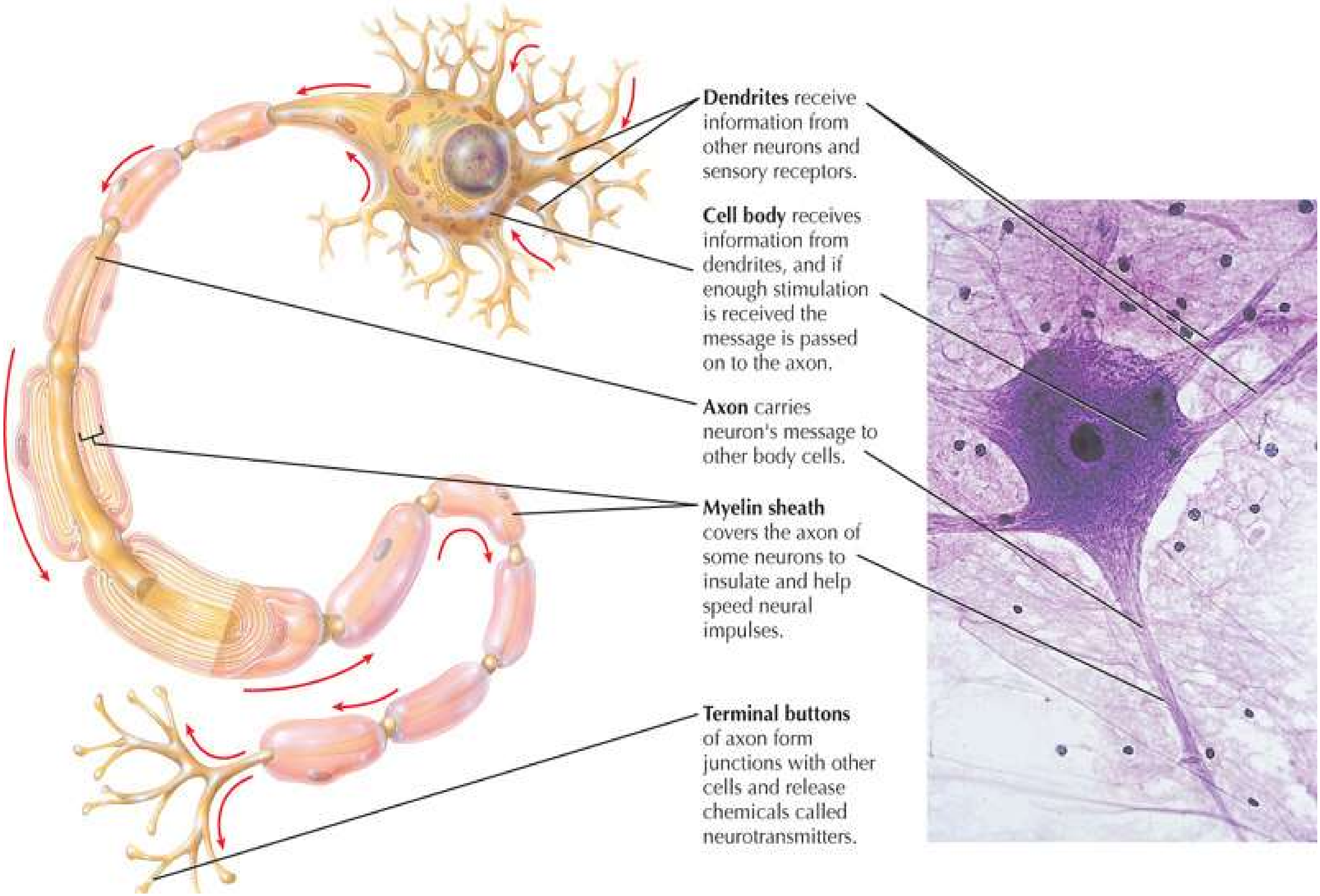


ANN Forward Propagation

- Network can learn a non-linearly separated set of outputs.
- Need to map output (real value) into binary values.

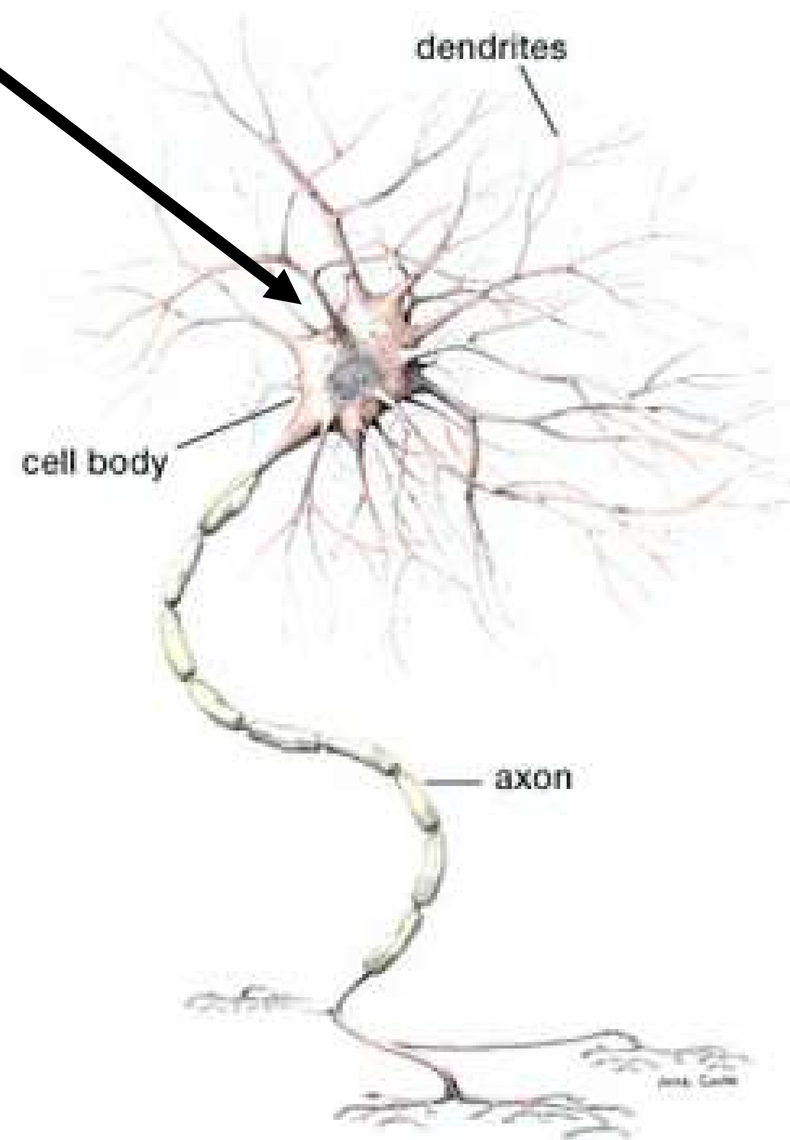
Real neurons




Dendrites receive information from other neurons and sensory receptors.
Cell body receives information from dendrites, and if enough stimulation is received the message is passed on to the axon.
Axon carries neuron's message to other body cells.
Myelin sheath covers the axon of some neurons to insulate and help speed neural impulses.
Terminal buttons of axon form junctions with other cells and release chemicals called neurotransmitters.

The Neuron

2. *<u>The Cell body</u>* contains the ce nucleus



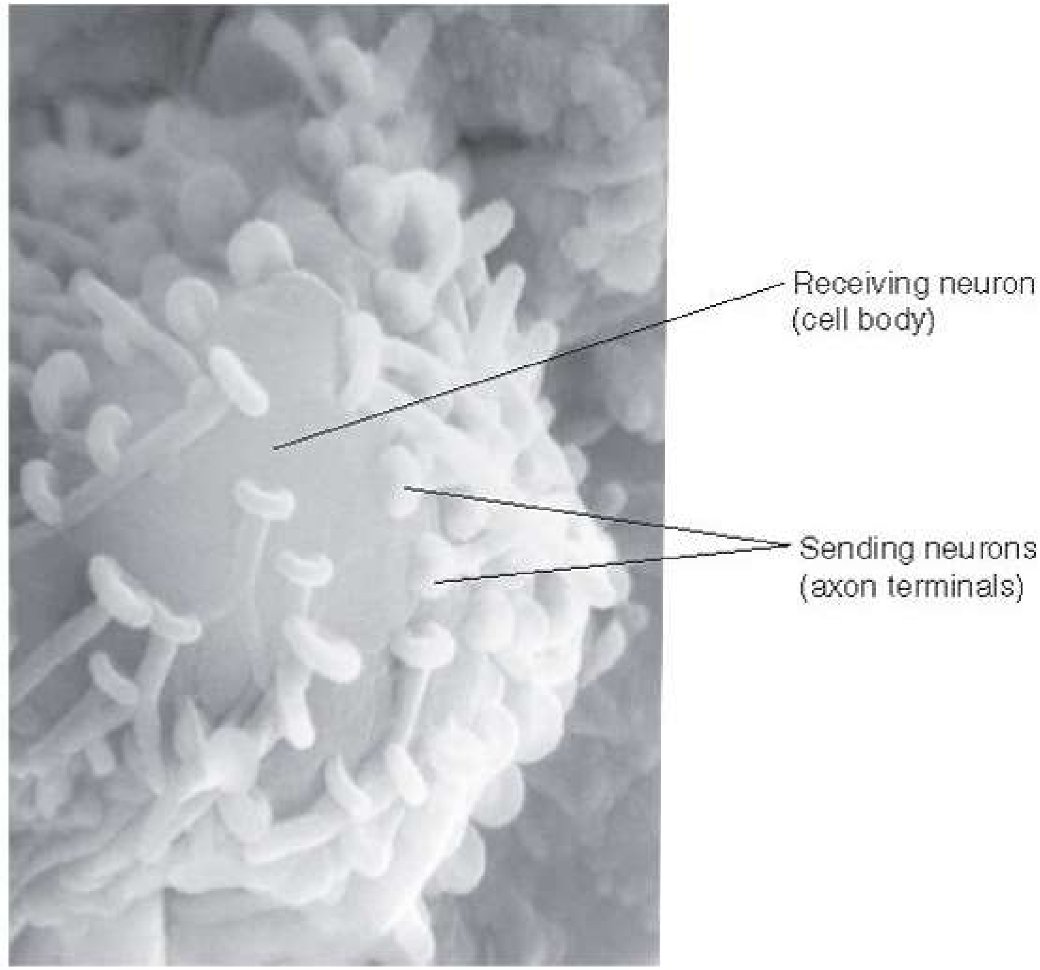
- The cell body relays the information down to the axon

Figure 2.17

A Cell Body Virtually Covered With Axon Terminals.

Source: © Science VU/Lewis-Everhart-Zeevi / Visuals Unlimited

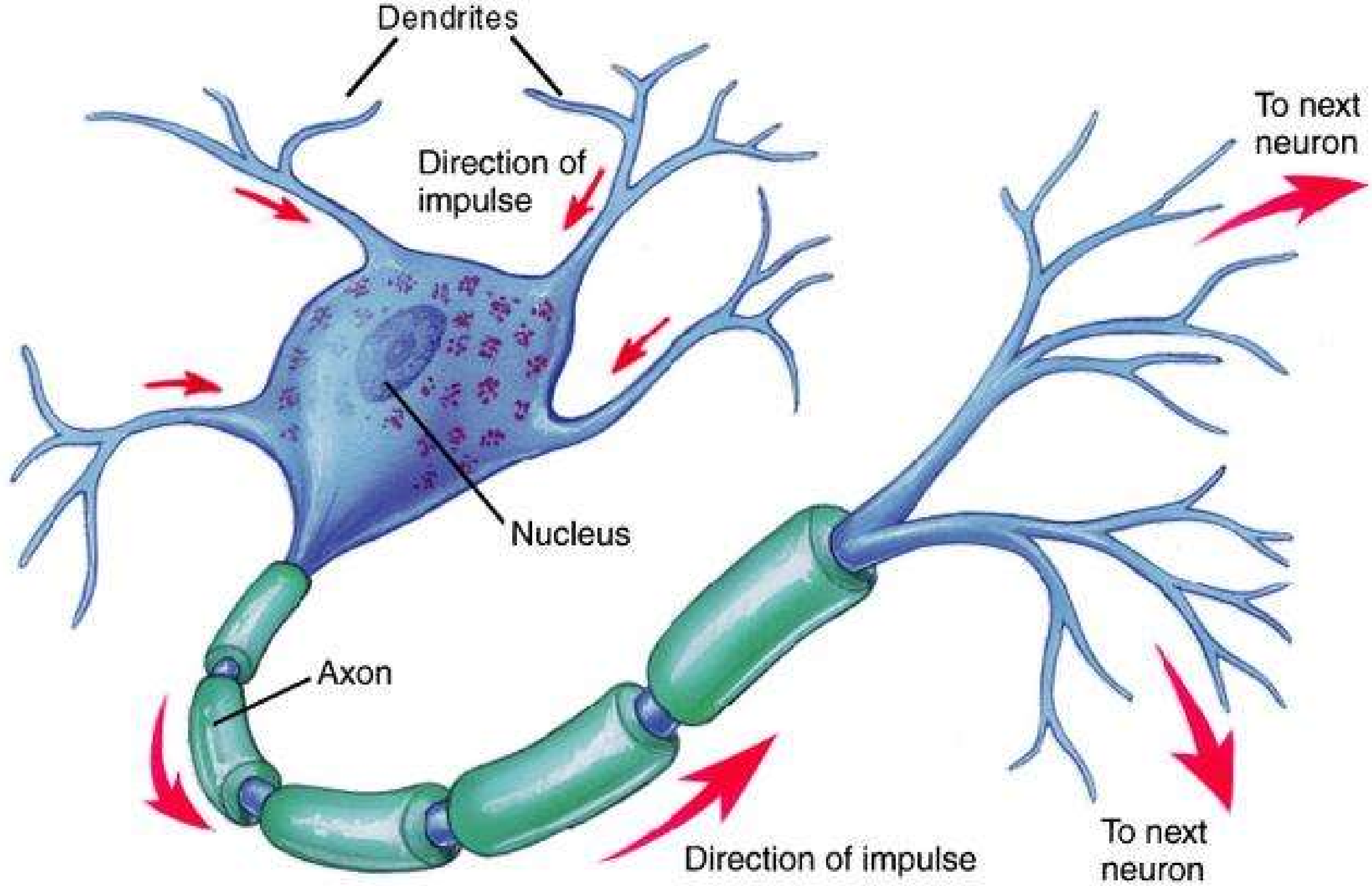
The cell body is covered with Axon Terminals



How do Neurons Communicate?

-Electrical Communication

-Chemical Communication

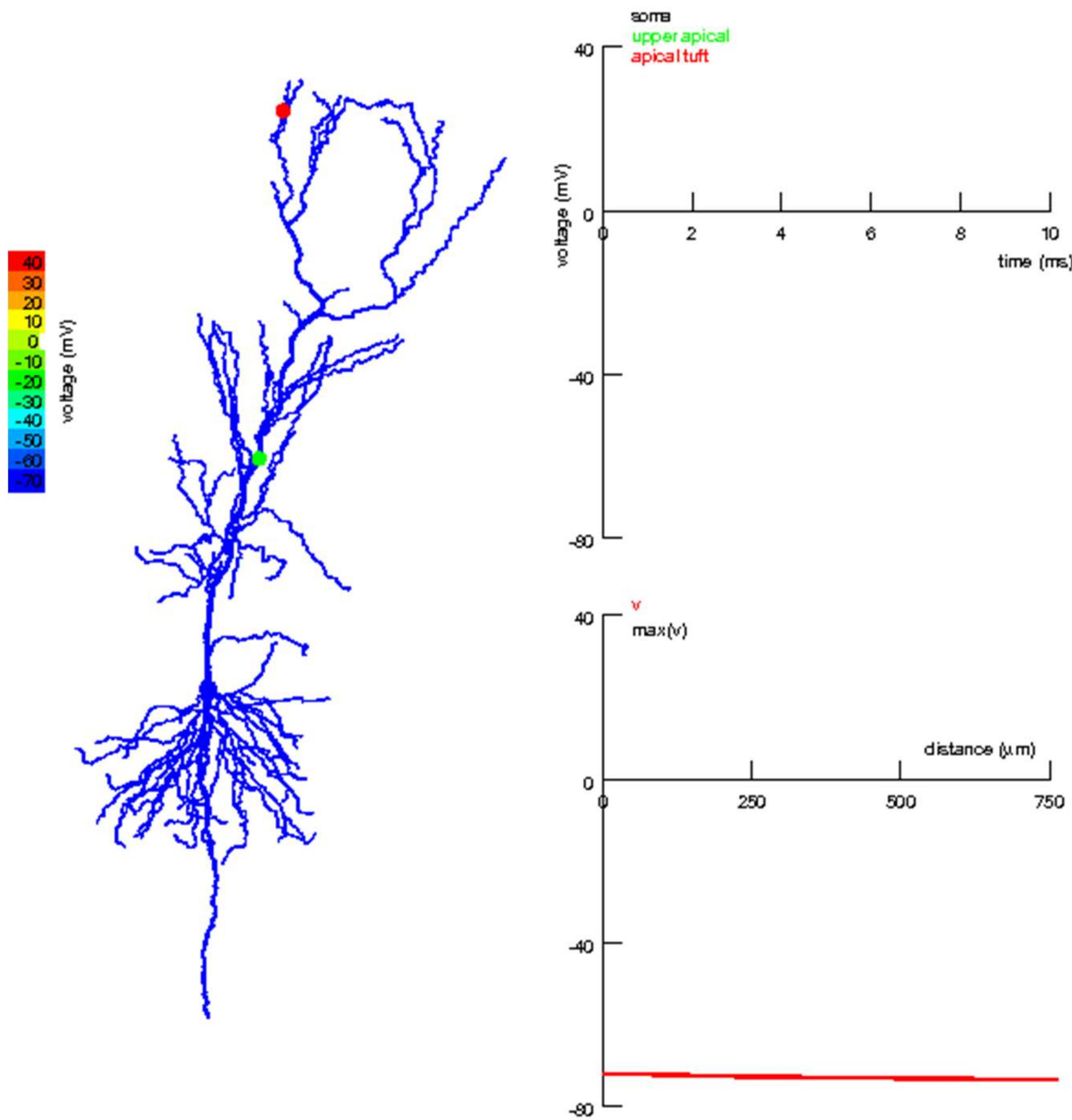

Dendrites
Direction of impulse
To next neuron
Nucleus
Axon
Direction of impulse
To next neuron

The Electrical Part

- **Action potential** is an electrical current sent down the axon.

- The activity **within** the neurons is electrical. This current causes the neuron to "fire"

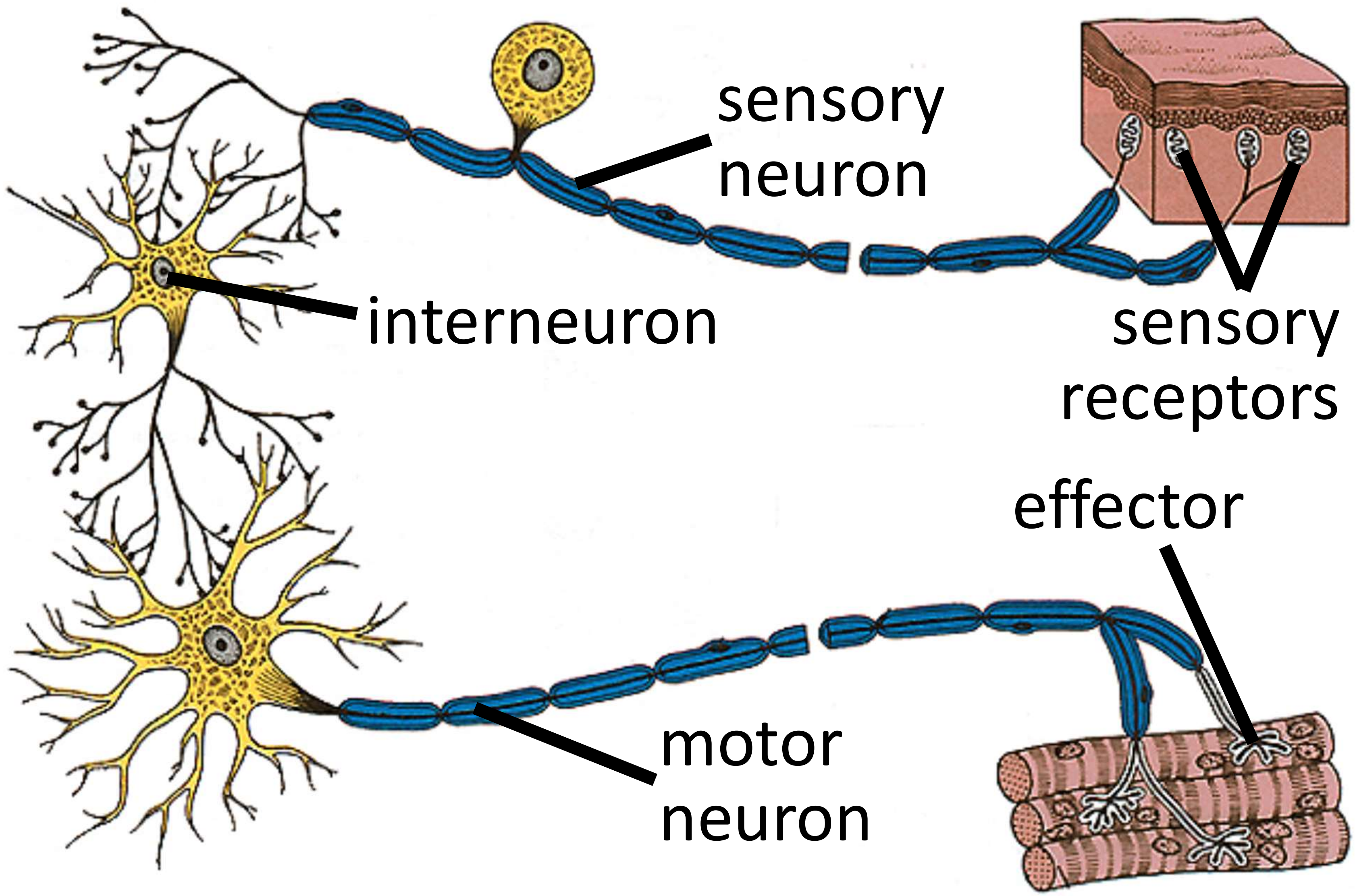
  – This is an "all-or-none" process


40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
voltage (mV)
soma
upper apical
apical tuft
40
0
-40
-80
voltage (mV)
0
2
4
6
8
10
time (ms)
v
max(v)
40
0
-40
-80
distance (μm)
0
250
500
750

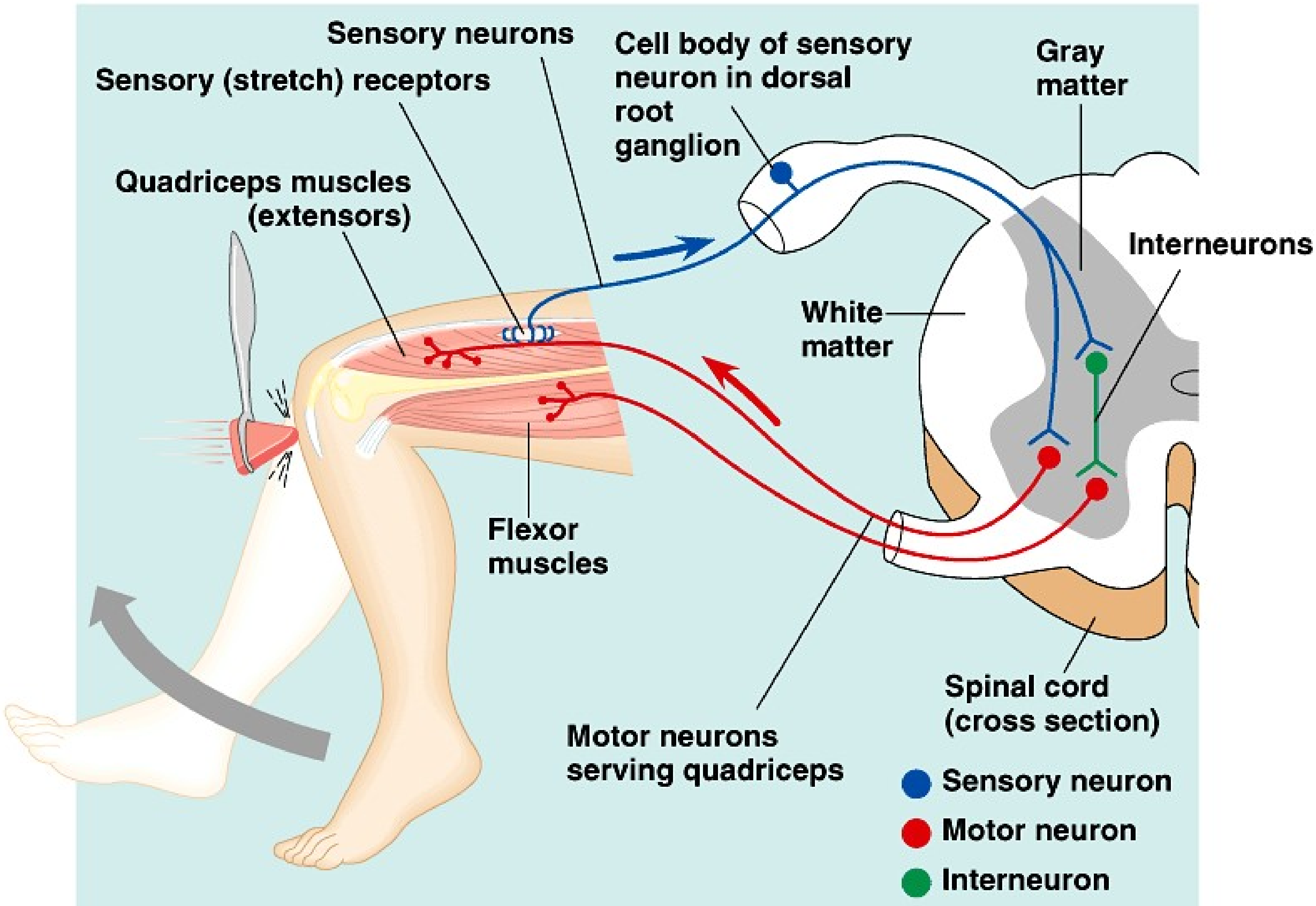
Synaptic transmission

- The *Synapse* is the space between neurons
  - The synaptic gap or cleft
- Information must be transmitted across the synapse to other neurons via the *neurotransmitters*.
- This is an *electrochemical process*

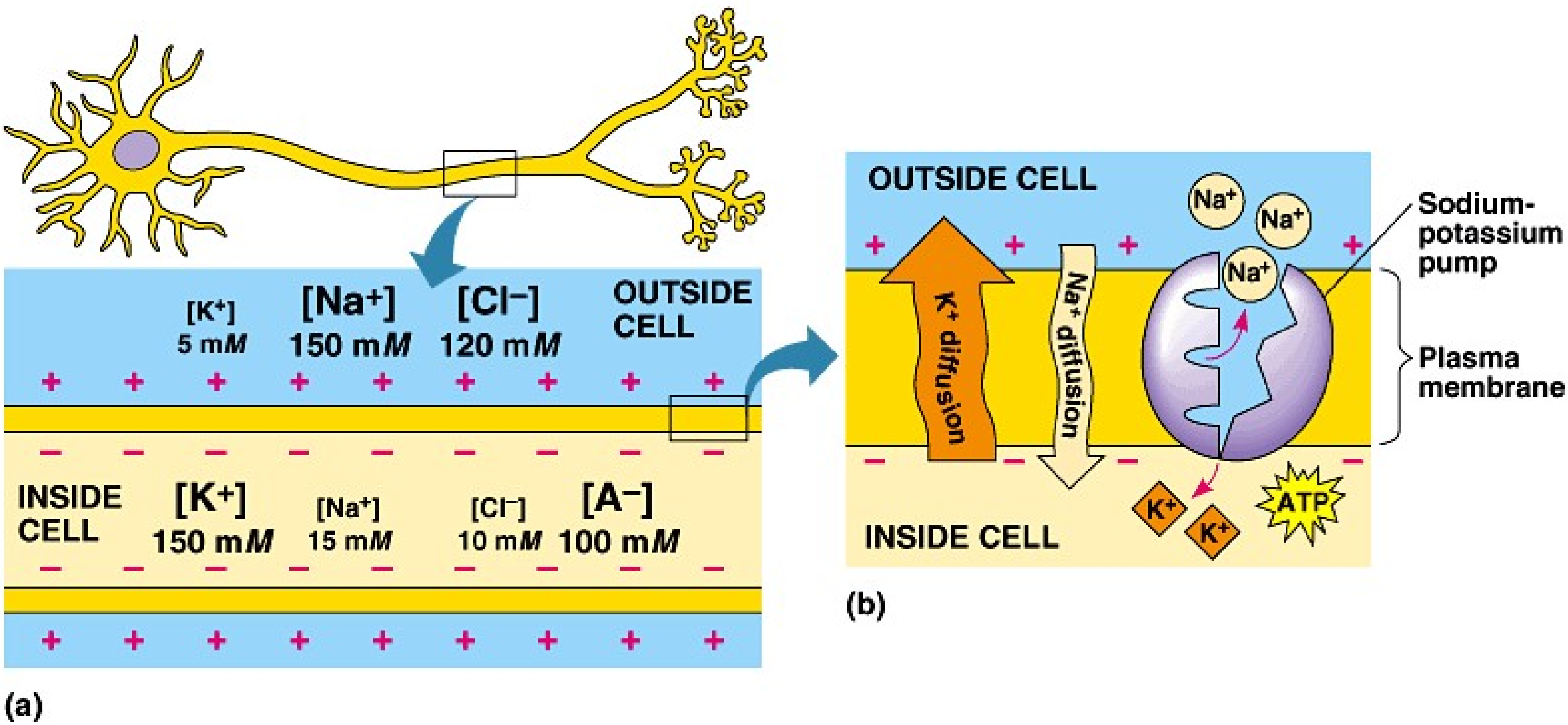
The perception-action circuit



- A Simple Nerve Circuit – the Reflex Arc.
  - A **reflex** is an autonomic response.

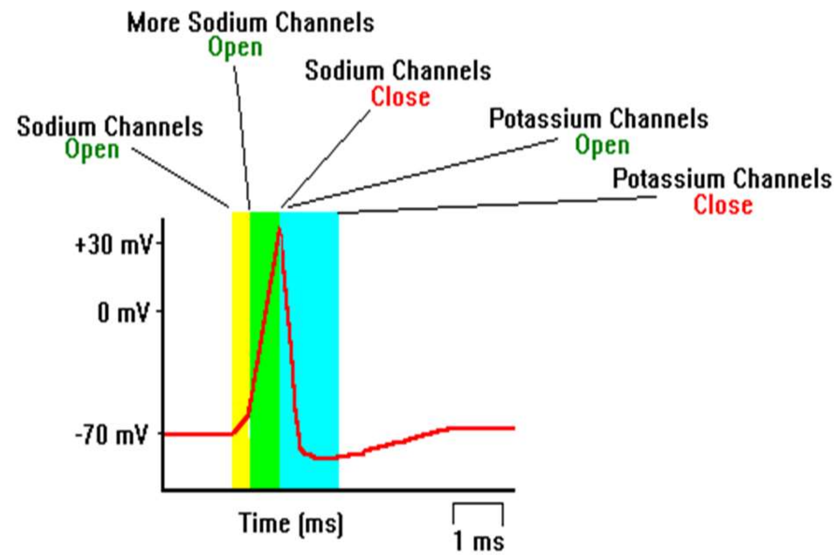


Neuron electrochemistry

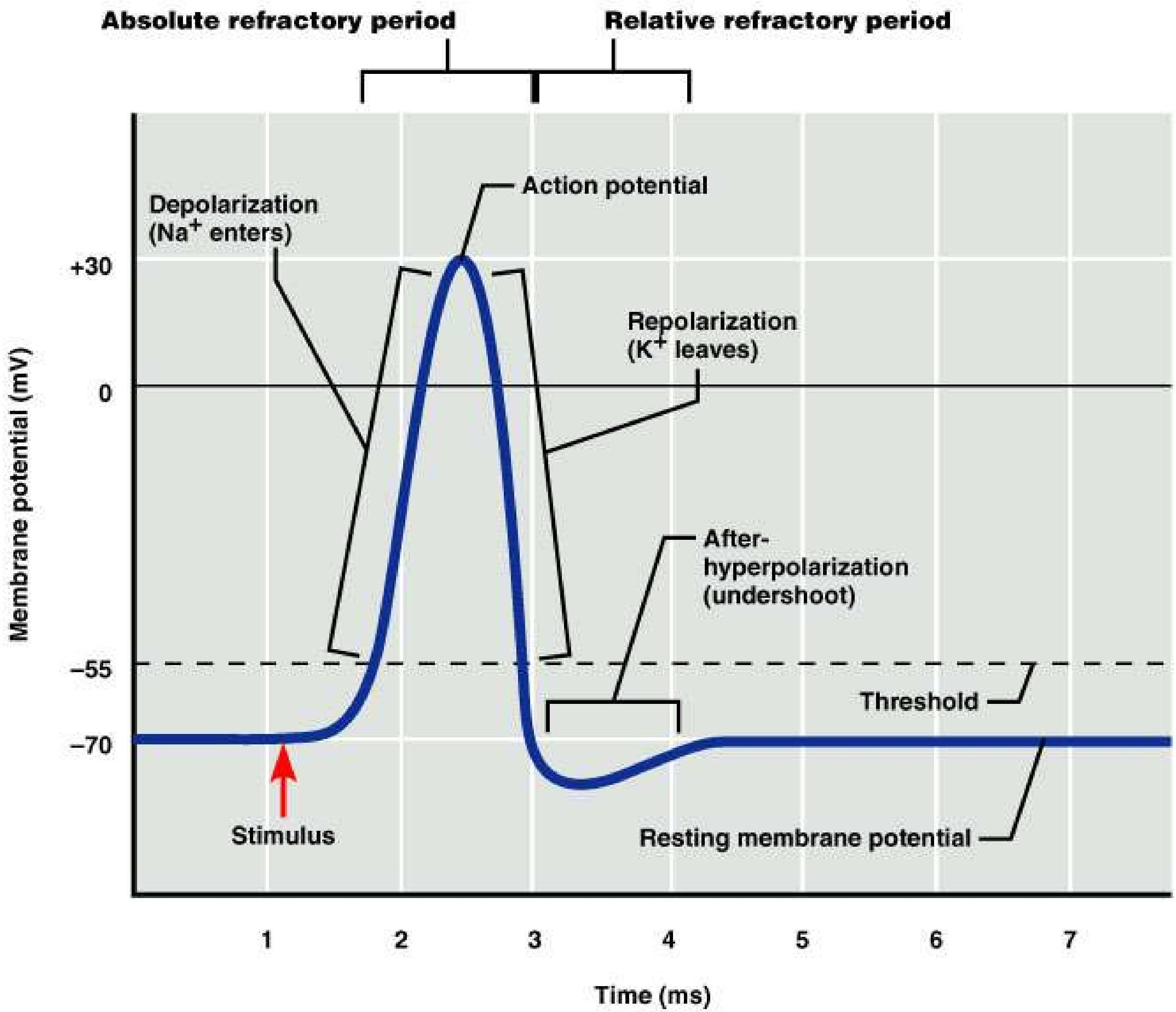


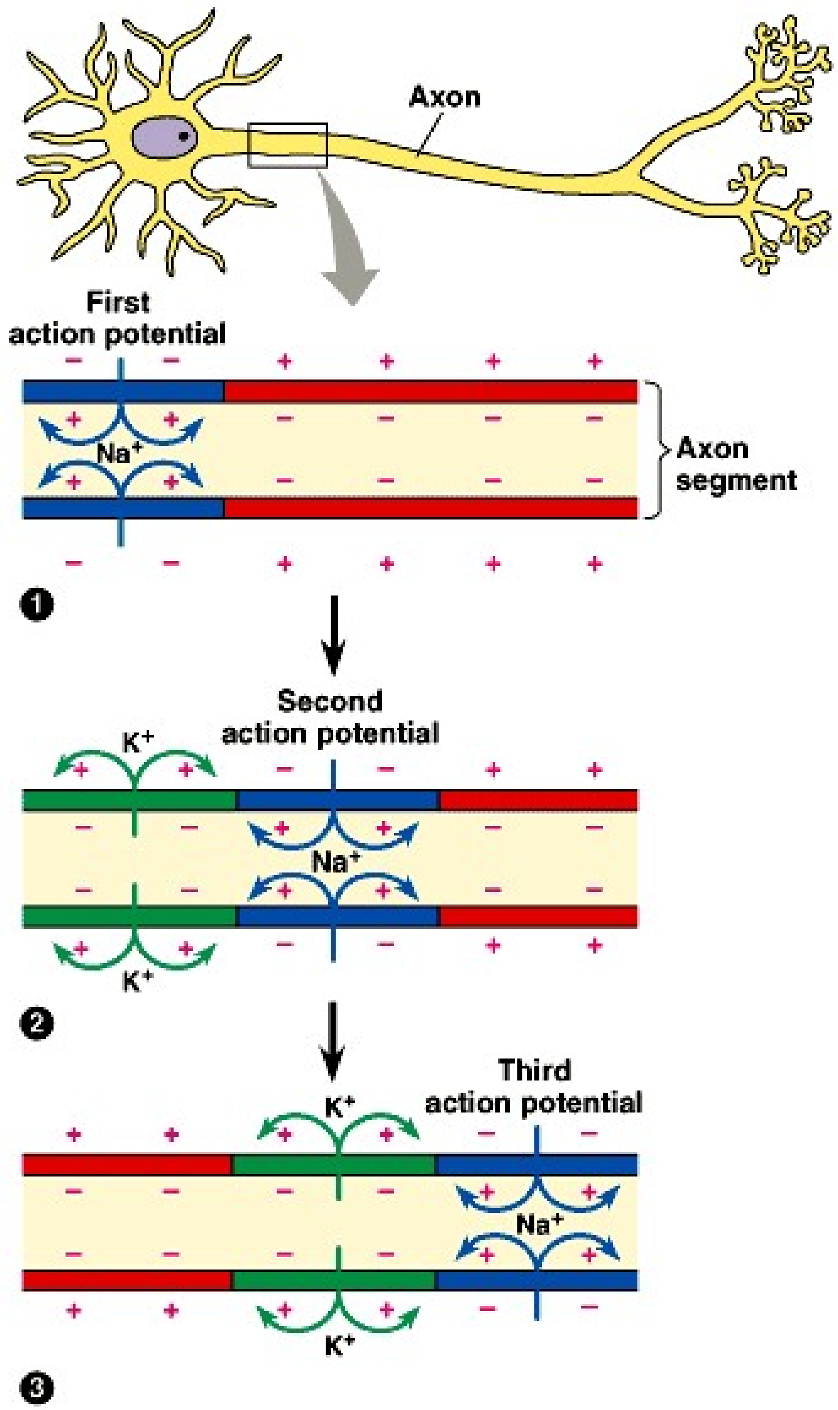
Neuron electrochemistry

- At rest, the neuron has a higher concentration of K than Na
- Channels
  - Na channels are quick-responding
  - K channels are slow-responding
- Impulse from neurotransmitters opens ion channels locally in neuron
- Na rushes into neuron cell body quickly
- K takes time, because channels are slower



Action potential




Axon
First action potential
Na+
Axon segment
1
K+
Second action potential
Na+
K+
2
Third action potential
K+
Na+
K+
3

Three Steps for firing

- Resting potential: voltage is about -70mV
  - Dendrites receive incoming signals
  - If sufficient, cell goes into firing mode
- Action potential
  - Voltage changes from -70mV to +40mV
  - Ions exchange places
  - Repeats itself rapidly down axon
  - Only in places where myelin sheath doesn’t cover: Nodes of Ranvier
- Refractory Period:
  - below resting or lower than -70mV
  - Cell recovers from firing
  - Absolute refractor period: Brief time period when cannot fire again
  - Relative refractory period: Brief time period when difficult for it to fire again.

The Neuron Fires

- Action potential causes nearby Na+ channels to open, so another action potential is triggered right next to first one, and this continues all the way down the axon
  - Chain reaction
  - Like a bunch of dominoes

- Action potential ≠ local potential in several important ways:
  - Local potential = graded potential- it varies in magnitude depending on strength of stimulus that produced it; action potential is ungraded

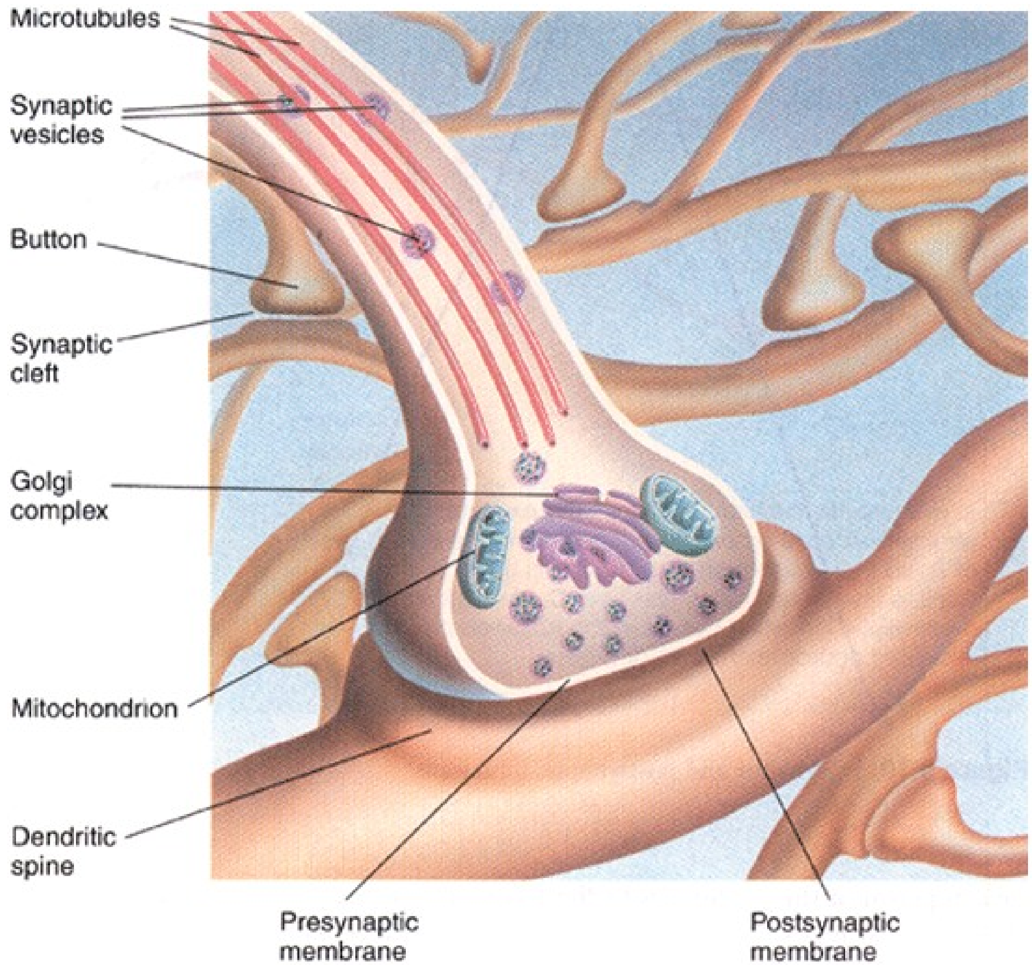
  - Action potential obeys all or none law: occurs at full strength or not at all

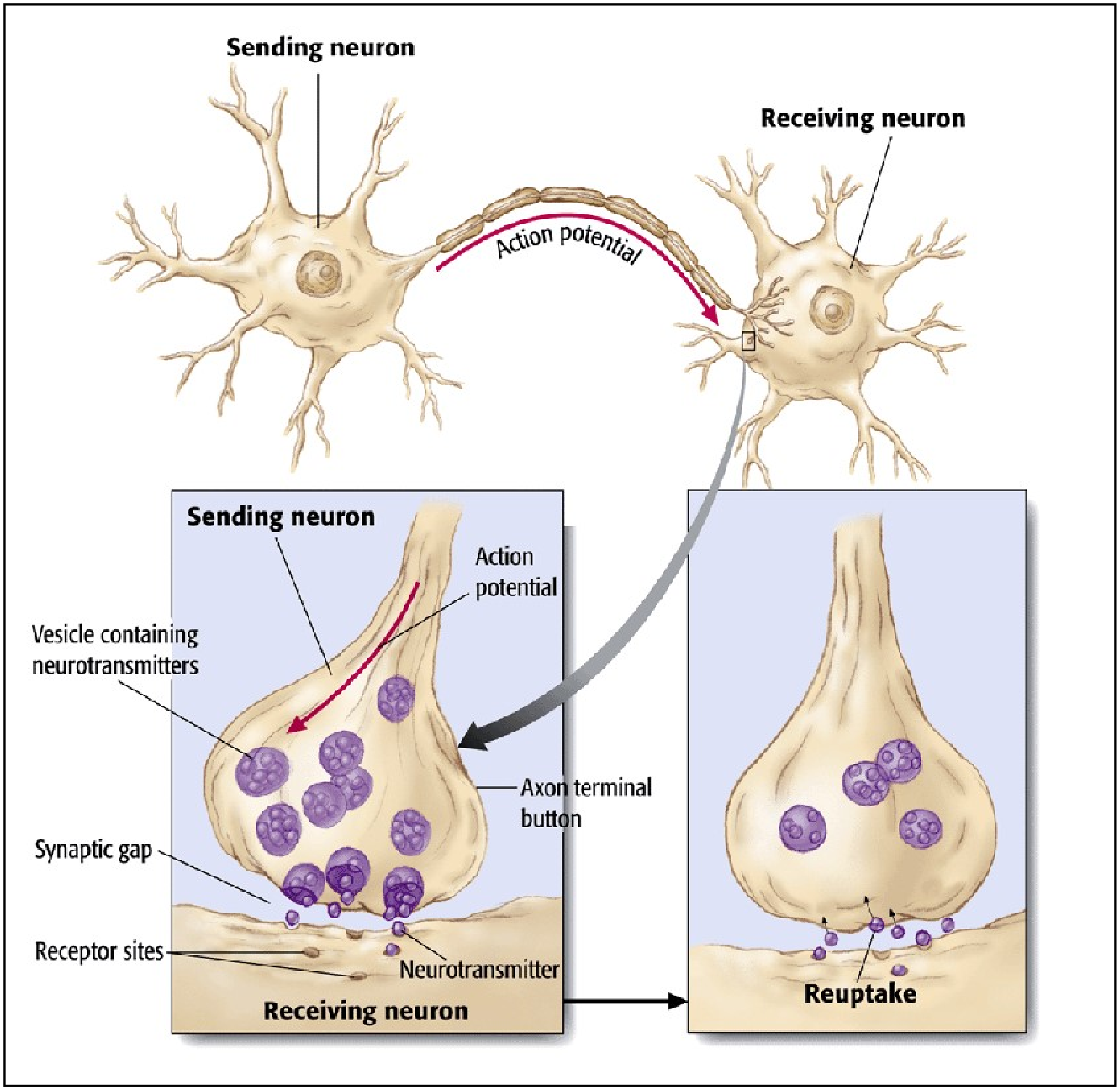
  - Action potential is nondecremental: does NOT lose strength at each successive point (local potentials do degrade)

The Neurotransmitter

- Neurotransmitter is chemical
  - Several specific kinds- each act on certain neurons
  - Most neurons respond to and release one kind of neurotransmitter
- **Neurotransmitter stored in synaptic vesicles**
- **The synaptic vesicles move to and fuse to end of membrane**
  - Action potential opens channels that allow Ca+ ions to enter terminals from extracellular fluid
  - Ca+ ions cause vesicles nearest the membrane to fuse with membrane
  - Membrane then opens and transmitter is dumped into synapse
  - Diffuses across synapse to postsynaptic neuron and attaches to chemical receptor

► Anatomy of a Typical Synapse




Sending neuron
Receiving neuron
Action potential
Sending neuron
Action potential
Vesicle containing neurotransmitters
Axon terminal button
Synaptic gap
Receptor sites
Neurotransmitter
Receiving neuron
Reuptake

Action in the Synapse

- **Neurotransmitter is released into the synapse**
  - diffuses across synapse to next neuron's dendrite
  - This "next dendrite" is post-synaptic

- **Neurotransmitter is attracted to the POST-synaptic side:**
  - receptor sites on the next neurons dendrites
  - neurotransmitter must match molecular shape of receptor site
  - Activation of receptor causes ion channels in membrane to open

Two kinds of Receptor Action

- **Ionotropic receptors** open channels directly to produce immediate reactions required for motor and sensory processing

- **Metabotropic receptors** open channels indirectly
  - slower: but produce longer-lasting effects
  - Sets off graded potentials for next action potential

- Movement across the synapse is relatively slow: several milliseconds

Excitation and Inhibition

- The NT opens ion channels on dendrites and soma
- Two effects on **local membrane** potential:
  - shifts in positive direction (towards 0), partially depolarizing
  - Shifts in negative direction (away from 0): hyperpolarization
- Thus two effects:
  - **Excitatory**: depolarization (moves toward and past 0)
  - **Inhibitory**: hyperpolarization (moves away from 0)

Two kinds of postsynaptic potentials:

- **EPSPs: excitatory postsynaptic potentials**
  - Excitatory effect: increases likelihood of action potential
  - Opens Na+ channels
- **IPSPs: inhibitory postsynaptic potentials**
  - Inhibitory effect: decreases likelihood of action potential
  - Opens K+ channels
- Thus: bidirectional effects
  - Summative effects
  - Overall change must be sufficient to produce action potential

Postsynaptic integration

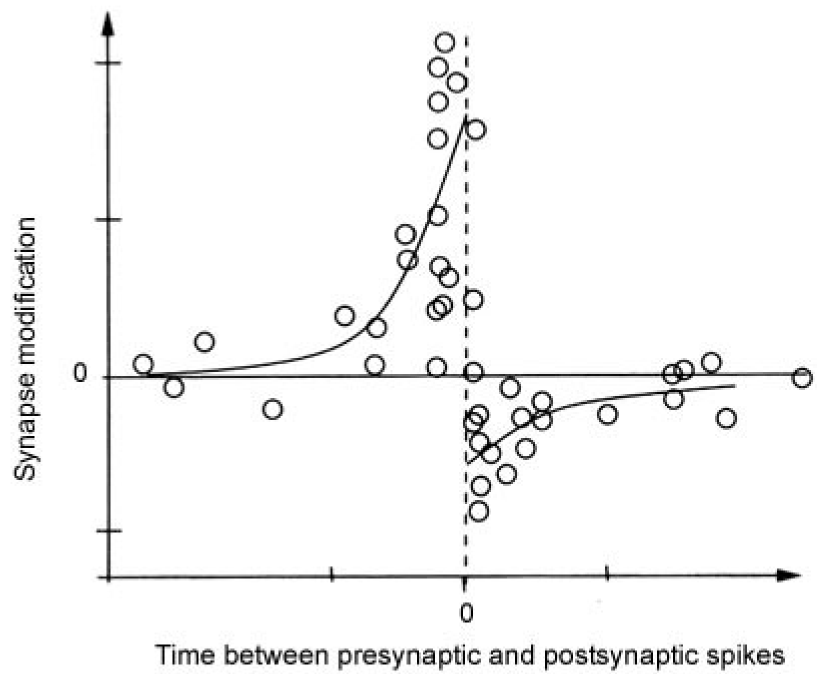
- Summation across all the IPSPs and EPSPs
  - Summates algebraically
  - Adds both positive and negatives together

- Two kinds:
  - **Spatial summation:**
    - Sum of all IPSPs and EPSPs occurring simultaneously at different locations along dendrites and cell body
    - Must be sufficient number of "hits"
  - **Temporal summation**
    - Sum of all IPSPs and EPSPs occurring within a short time
    - Must occur within a few milliseconds
    - Must get sufficient number of "hits" within certain time

- Neuron is an information integrator!
  - A decision maker
  - Small microprocessor

Temporal dynamics of synaptic response

- Spike-timing dependent plasticity has been experimentally documented



Neurotransmitters