PSYCH 260

Cellular neuroscience II

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Measuring potentials in actual neurons (4:20)

Action Potentials from Squid feat. Alan Hodgkin

Announcements

- Exam 1 Thursday, 9/23
    - 40 questions
    - **No in-person/in-class meeting**
    - On Canvas, live at 3:05 PM; open until 10:00 PM

Today's Topics

- Electrical communication in neurons
- The action potential

How do neurons communicate

Types of neural electrical potentials

- Resting potential
- Action potential

Where does the resting potential come from?

- Ions (charged atoms)
- Ion channels
- Separation between charges
- A balance of forces

We are the champIONs, my friend

- Potassium, K^+
- Sodium, Na^+
- Chloride, Cl^-
- Organic anions, A^-

Party On

- Annie (A^-) was having a party.
  - Used to date Nate (Na^+), but now sees Karl (K^+)
- Hired bouncers called
  - “The Channels”
  - Let Karl and friends in or out, keep Nate out
- Annie’s friends (A^-) and Karl’s (K^+) mostly inside
- Nate and friends (Na^+) mostly outside
- Claudia (Cl^-) tagging along

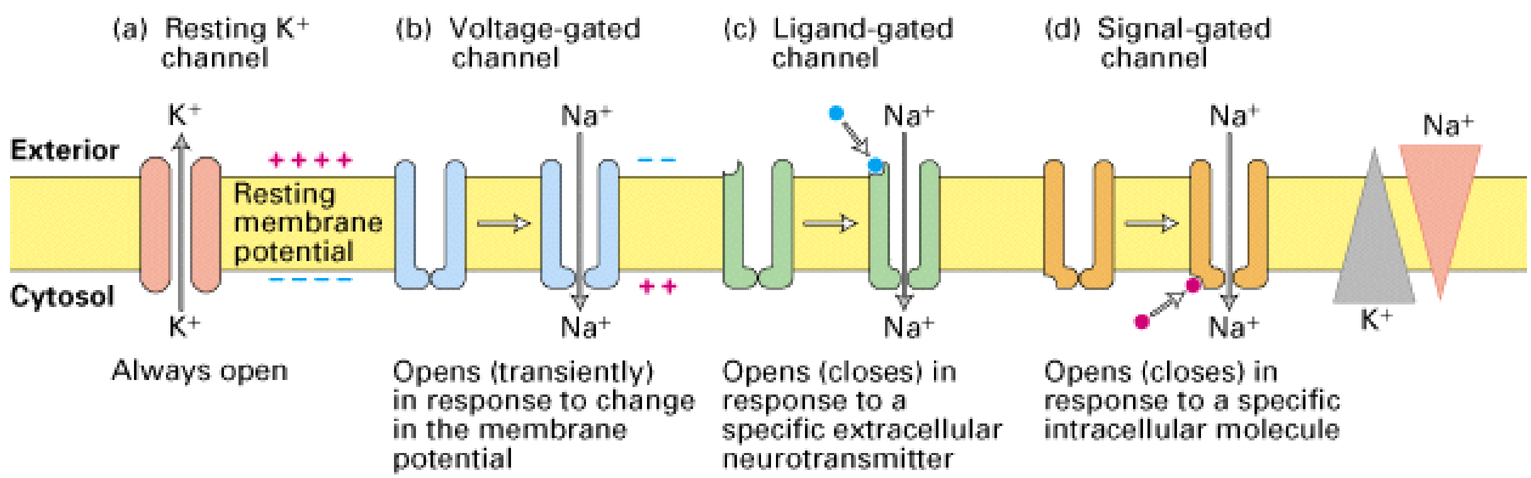
Resting potential arises from

- A balance of forces
  - *Force of diffusion*
  - *Electrostatic force*
- Forces cause ion flows across *membrane*
- Ion channels allow ion flow

Ion channels

- Openings in neural membrane
- Selective for specific ions
- Vary in permeability (how readily ions flow)
- Types
  - *Passive/leak (always open)*
  - *Voltage-gated*
  - *Ligand-gated (chemically-gated)*
  - *Transporters/pumps*

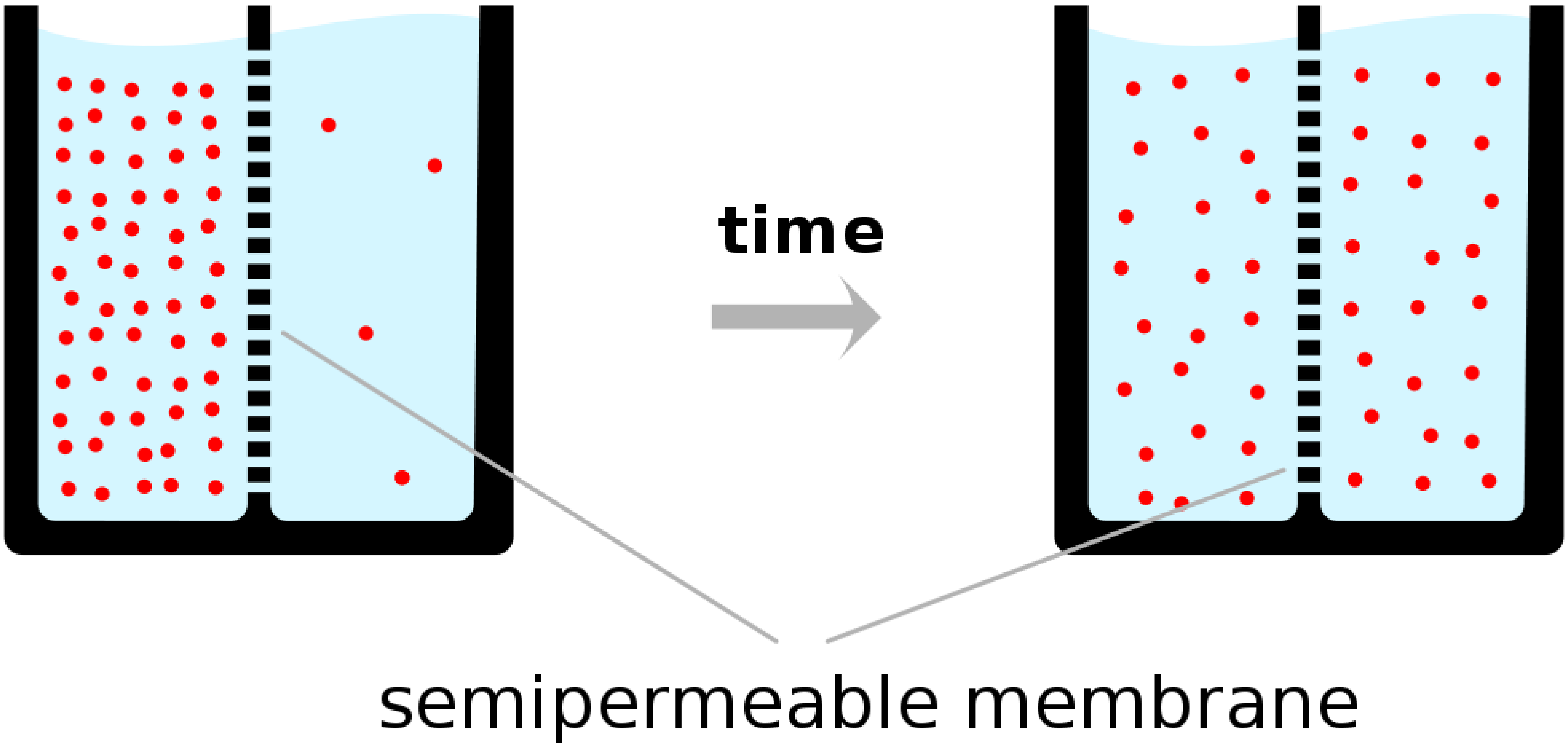
Ion channels



Neuron at rest permeable to K^+

- Passive K^+ channels open
- $[K^+]$ concentration inside >> outside
- K^+ flows out

Force of diffusion

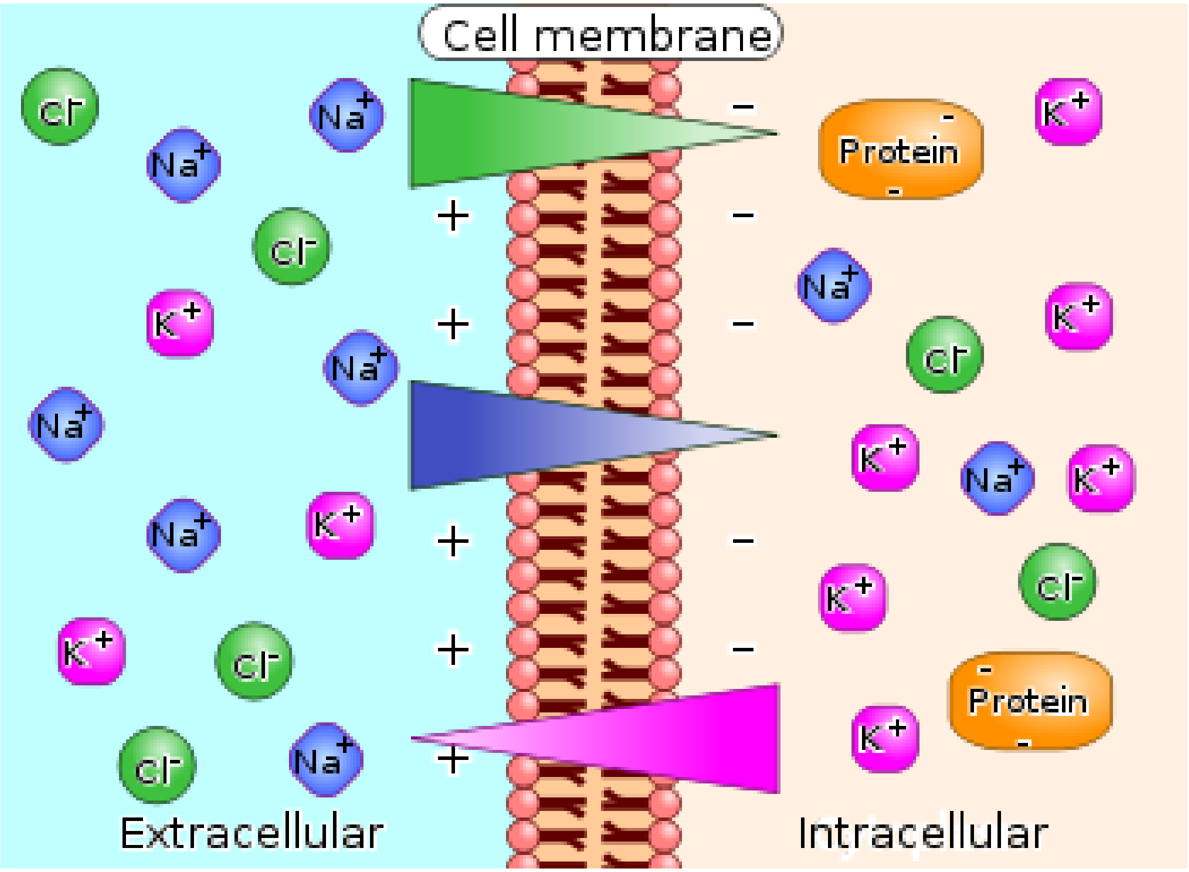


Force of diffusion

Neuron at rest permeable to K^+

- Organic anions (A^-) to large to move outside of cell
- A^- and K^+ largely in balance == no net internal charge
- K^+ outflow creates *charge separation*: K^+ <-> A^-
- Charge separation creates a voltage
- Outside +/inside -
- Voltage build-up stops outflow of K^+

The resting potential



Balance of forces in the neuron at rest

- **Force of diffusion**
    - K^+ moves from high concentration (inside) to low (outside)

Balance of forces in the neuron at rest

- **Electrostatic force**
  - Voltage build-up stops K^+ outflow
  - Specific voltage called *equilibrium potential* for K^++
  - K^+ positive, so equilibrium potential negative (w/ respect to outside)
  - Equilibrium potential close to neuron resting potential

Equilibrium potential and Nernst equation

$$V_{\mathrm{K}} = \frac{RT}{(+1)F} \ln \frac{[\mathrm{K}^+]_o}{[\mathrm{K}^+]_i}$$

Equilibrium potentials calculated under typical conditions

Ion	[inside]	[outside]	Voltage
K^+	~150 mM	~4 mM	~ -90 mV
Na^+	~10 mM	~140 mM	~ +55-60 mV
Cl^-	~10 mM	~110 mM	- 65-80 mV

$$V_K = \frac{RT}{(+1)F} \ln \frac{[K^+]_o}{[K^+]_i}$$

Resting potential ≠ K^+ equilibrium potential

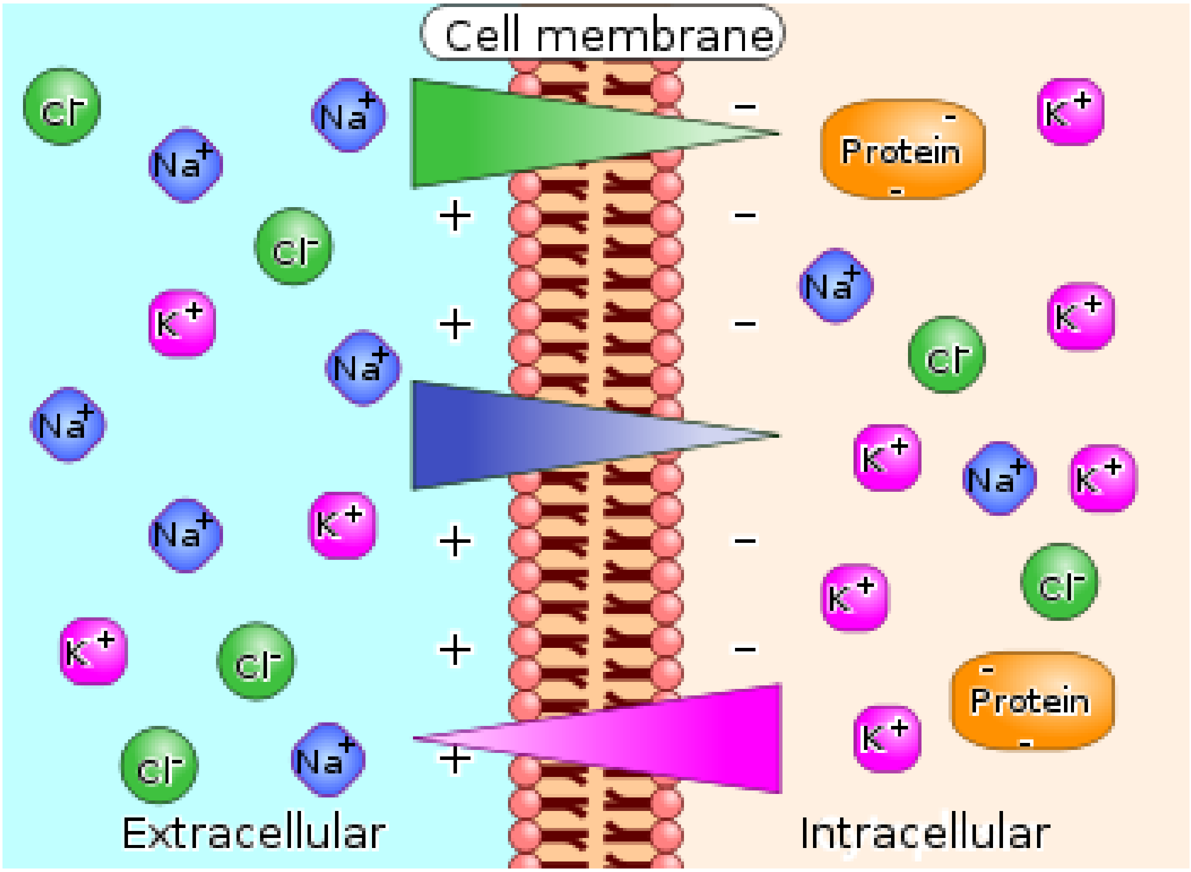
- Resting potential not just due to K^+
- Other ions flow
- Resting potential == net effects of all ion flows across membrane

Goldman-Hodgkin-Katz equation

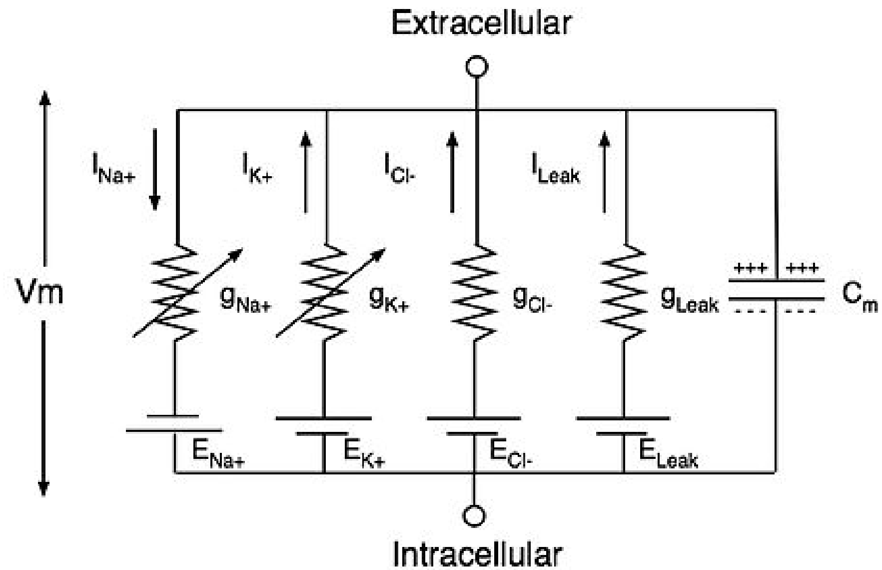
$$V_{\mathrm{m}} = \frac{RT}{F} \ln\left(\frac{p_{\mathrm{K}}[\mathrm{K}^+]_{\mathrm{o}} + p_{\mathrm{Na}}[\mathrm{Na}^+]_{\mathrm{o}} + p_{\mathrm{Cl}}[\mathrm{Cl}^-]_{\mathrm{i}}}{p_{\mathrm{K}}[\mathrm{K}^+]_{\mathrm{i}} + p_{\mathrm{Na}}[\mathrm{Na}^+]_{\mathrm{i}} + p_{\mathrm{Cl}}[\mathrm{Cl}^-]_{\mathrm{o}}} \right)$$

Na^+ role

- Na^+ concentrated **outside** neuron
- Membrane at rest not very permeable to Na^+
- Some, but not much Na^+ flows *in*
- Na^+ has equilibrium potential ~ + 60 mV
- Equilibrium potential is positive (with respect to outside)
- Would need positive interior to keep Na^+ from flowing in


Cell membrane
Cl⁻
Na⁺
K⁺
Protein
Extracellular
Intracellular

Electrical circuit model



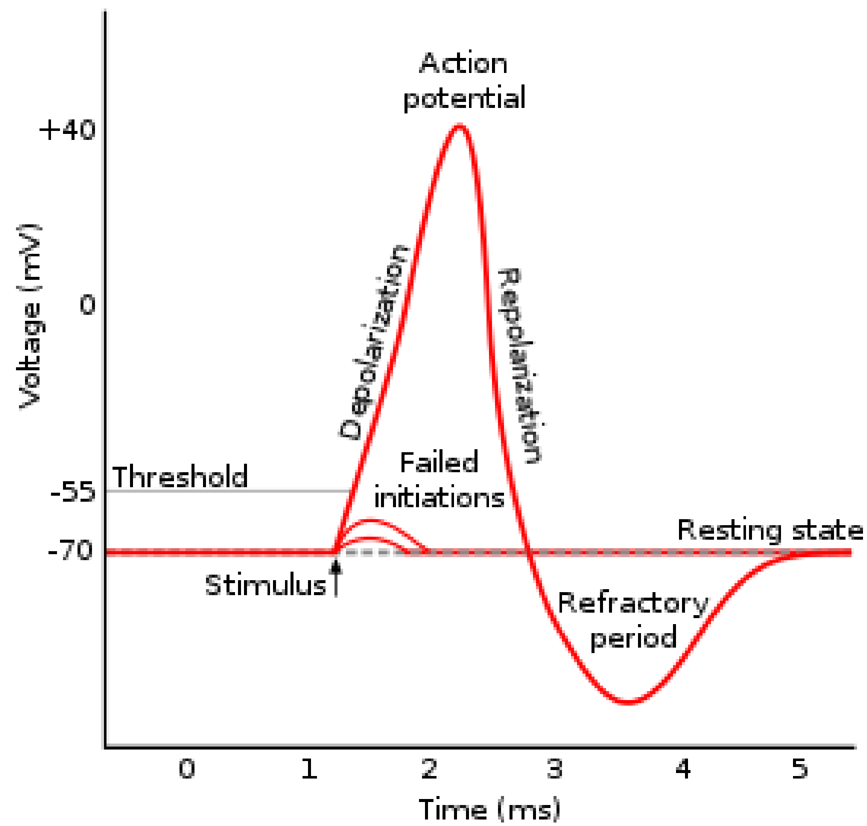
Summary of forces in neuron at rest

Ion	Concentration gradient	Electrostatic force	Permeability
K^+	Inside >> Outside	- (pulls K^+ in)	Higher
Na^+	Outside >> Inside	- (pulls Na^+ in)	Lower

What happens if something changes?

- Easier for Karl [K^+] to exit?
- Easier for Nate [Na^+] to enter?
- Some action!

Action potential



Action potential

- Threshold of excitation
- Increase (rising phase/depolarization)
- Peak
  - at positive voltage
- Decline (falling phase/repolarization)
- Return to resting potential (refractory period)

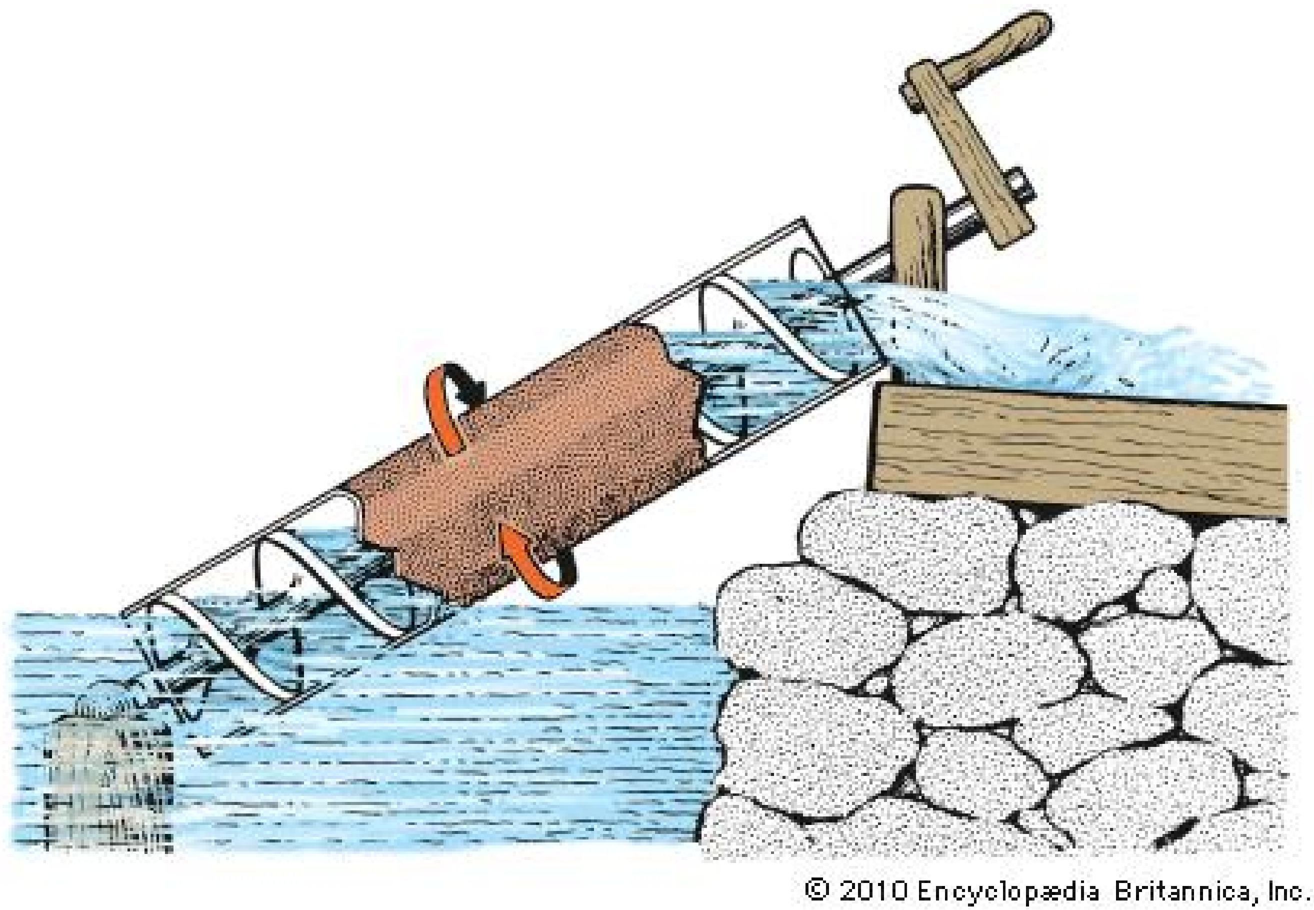
Action potential break-down

Phase	Neuron State
Rise to threshold	+ input makes membrane potential more +
Rising phase	Voltage-gated Na^+ channels open, Na^+ flows in
Peak	Voltage-gated Na^+ channels close and deactivate; voltage-gated K^+ channels open
Falling phase	K^+ flows out
Refractory period	Na^+/K^+ pump restores [Na^+], [K^+]; voltage-gated K^+ channels close

What's a Na^+/K^+ pump?

- Enzyme (Na^+/K^+ *ATP-ase*) embedded in neuron membrane
- Pumps Na^+ and K^+ *against* concentration gradients
- Na^+ out; K^+ in
- Uses ATP or chemical energy

Example in another domain



Refractory periods

- *Absolute*
  - Cannot generate action potential (AP) no matter the size of the stimulus
  - Voltage-gated Na^+ channels inactivated, reactivate in time.

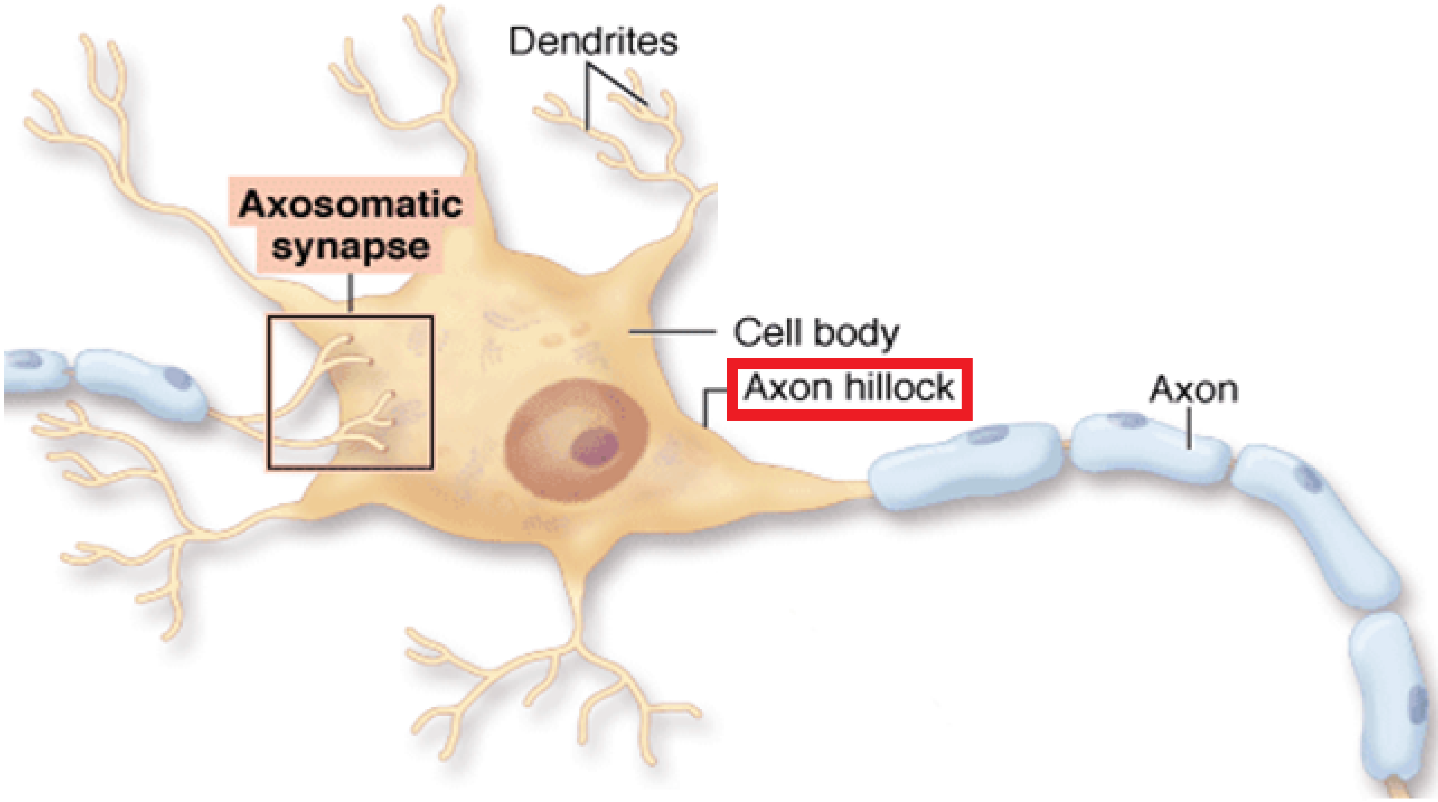
Refractory periods

- *Relative*
  - Can generate AP with larg(er) stimulus
  - Some voltage-gated K^+ channels still open
- Refractory periods put ‘spaces’ between APs

Generating APs

- *Axon hillock*
  - Portion of soma adjacent to axon
  - Integrates/sums input to soma
- *Axon initial segment*
  - Umyelinated portion of axon adjacent to soma
  - Voltage-gated Na^+ and K^+ channels exposed
  - If sum of input to soma > threshold, voltage-gated Na^+ channels open

Axon hillock, axon initial segment



Axon Hillock" by M.aljar3i - Own work. Licensed under CC BY-SA 3.0 via Commons

Nodes of Ranvier

- *Regenerate* action potential
- Na^+ and K^+ channels exposed to extracellular environment
- Between Nodes of Ranvier, ions can't move out, so move along
- Nodes of Ranvier -> Action potentials faster & reliable for a given diameter

Main points

- Resting potential maintained by balance of forces (diffusion, electrostatic)
- Action potential generated when balance is altered
  - $[Na^+]$ in: rising phase to + peak
  - $[K^+]$ out: falling phase

Next time

- Exam 1

References