Basic neurophysics

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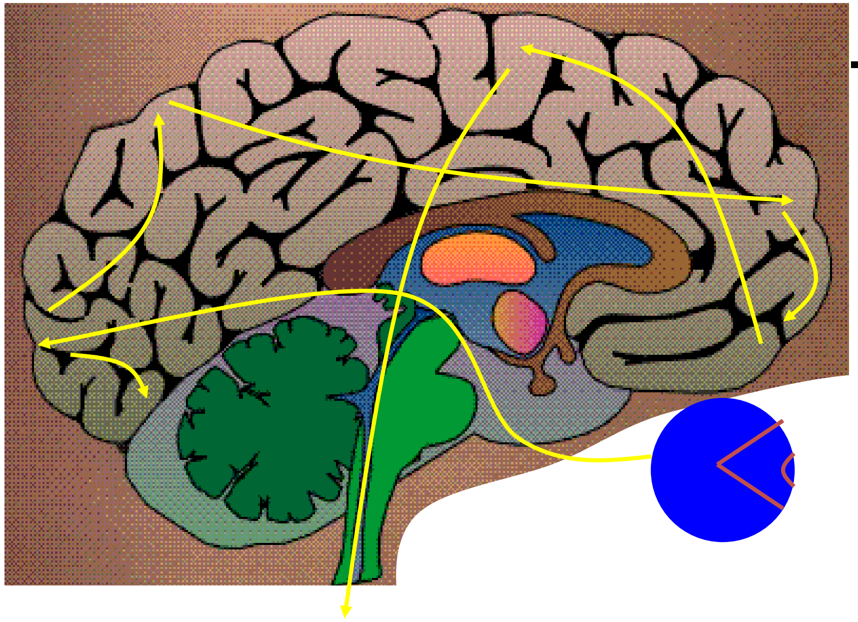
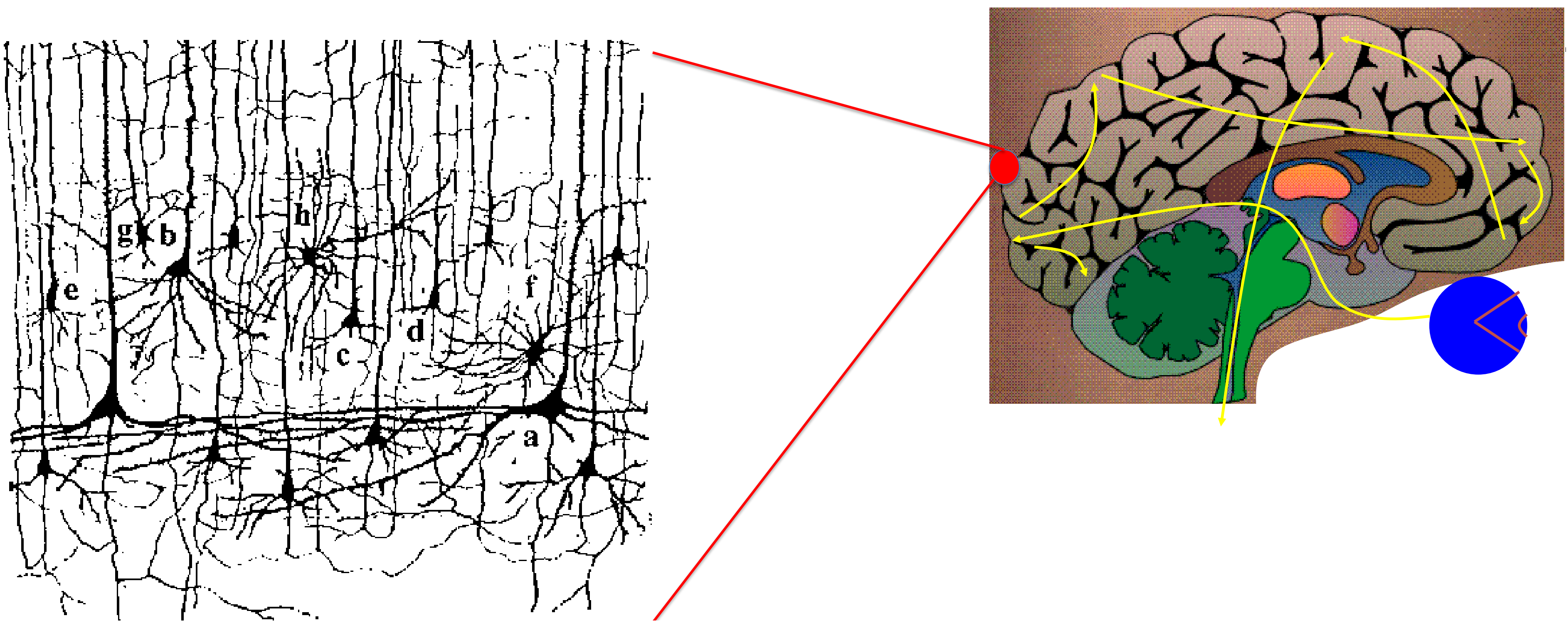
sources (except where cited otherwise)

- Peter Dayan and Larry F Abbot: *Theoretical Neuroscience*, MIT Press, Cambridge MA, 2001
  - sections 1.1, 1.2, 1.4, 2.3
- Wulfram Gerstner, Werner M. Kistler, Richard Naud and Liam Paninski: *Neuronal Dynamics: From single neurons to networks and models of cognition*. Cambridge University Press, 2014
  - section 2
  - http://neuronaldynamics.epfl.ch/index.html

the brain

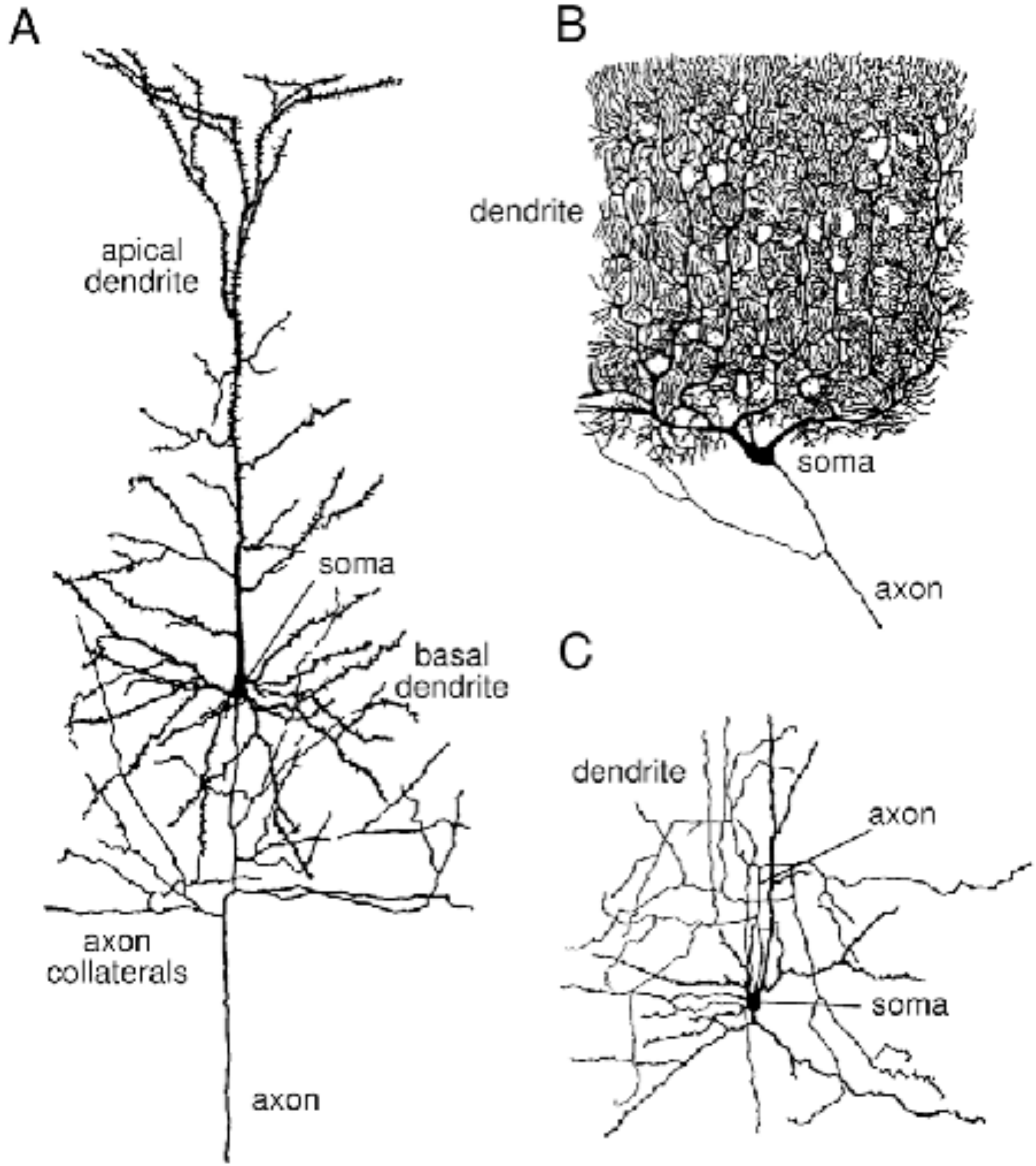


neurons



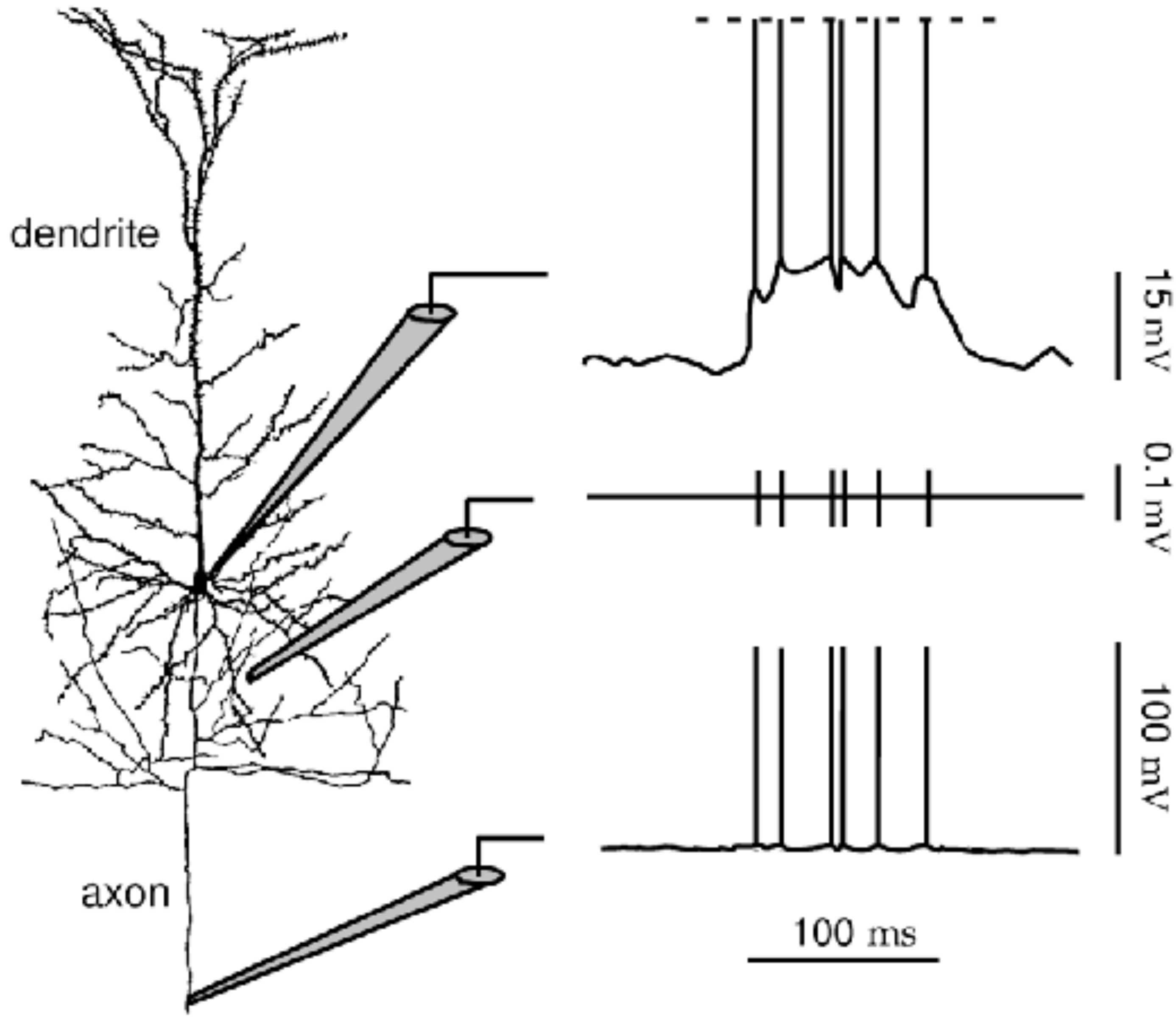
~10^11 with 10000 synapses each

neurons


A
apical dendrite
soma
basal dendrite
axon collaterals
axon
B
dendrite
soma
axon
C
dendrite
axon
soma

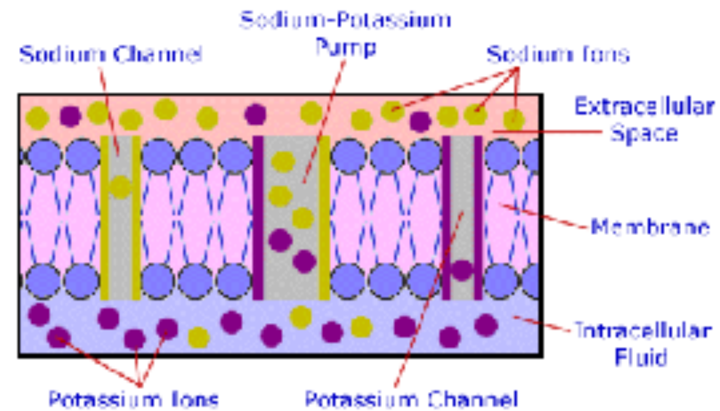
neurons as input-output units

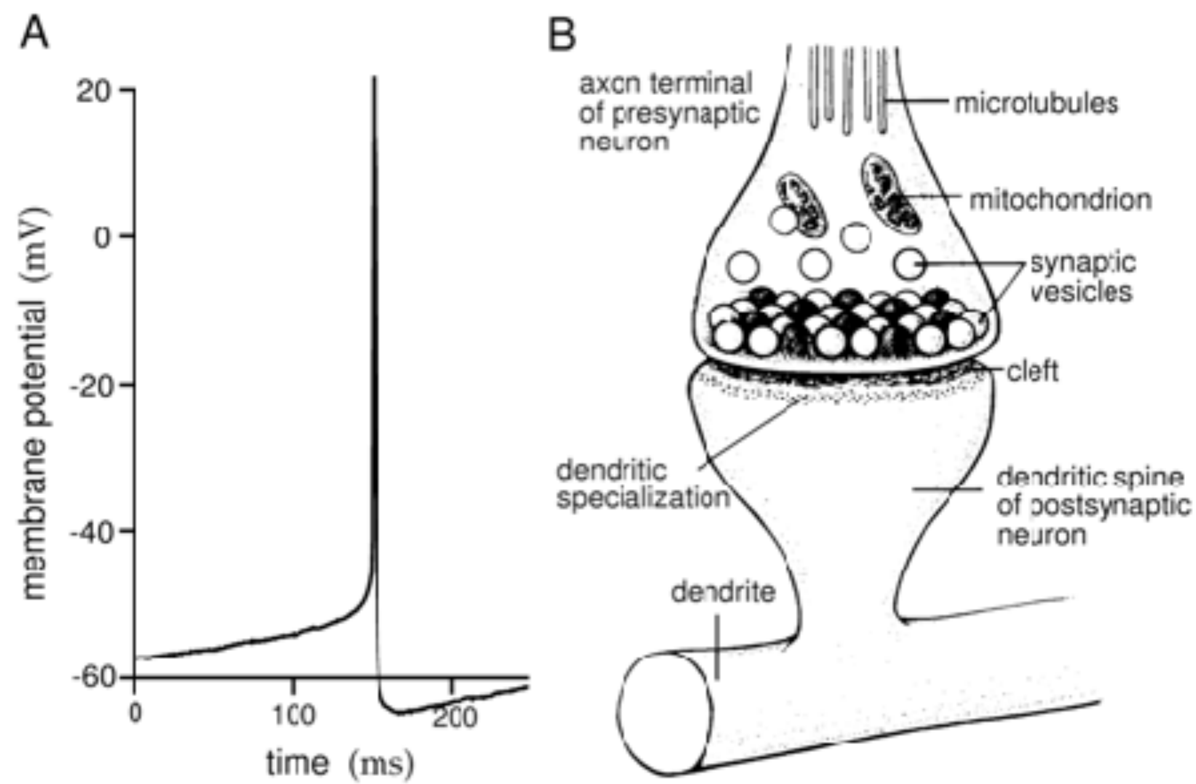
- inputs from dendrites
- spike formation at soma
- output at axon



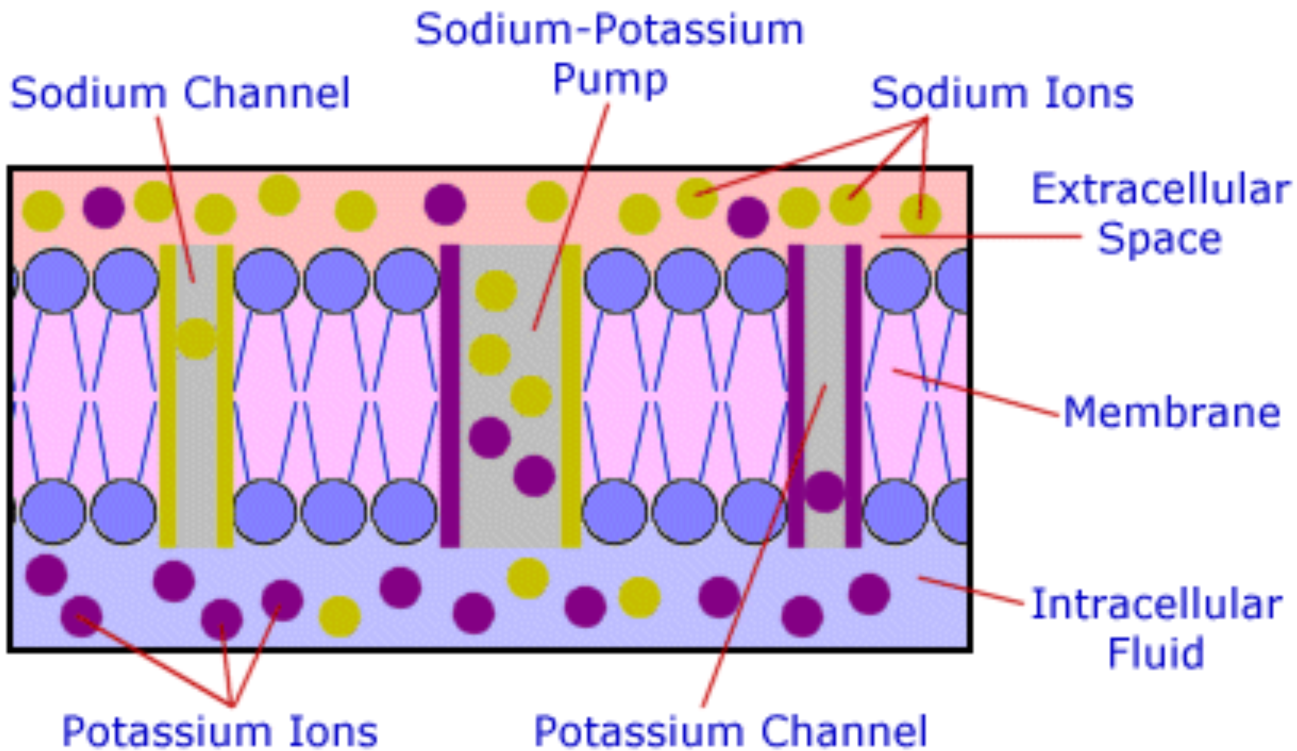
two functional components

- membranes: dendrites, soma, axons
- synapses





membrane



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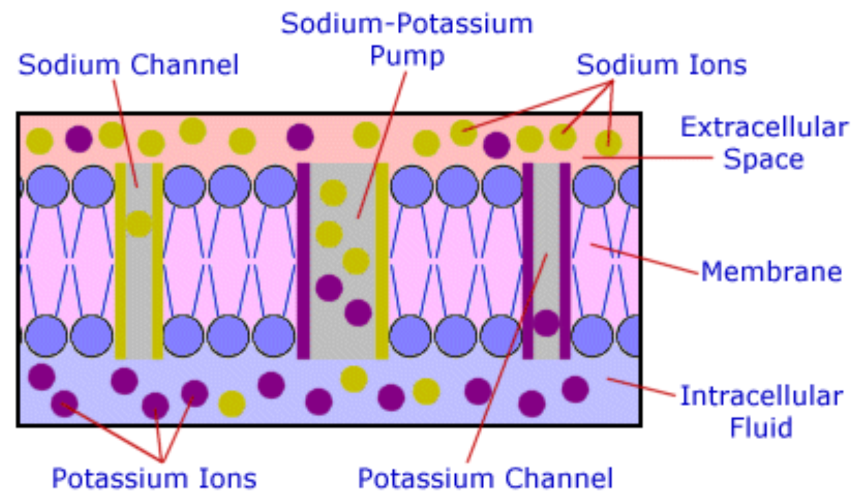
http://www.columbia.edu/cu/psychology/courses/1010/mangels/neuro/neurosignaling/neurosignaling.html]

membrane

- membrane=double lipid layer that is an electrical insulator
- neuron is electrically charged: more negative potential inside than outside cell
- based on ions K+, Na+, and Cl-



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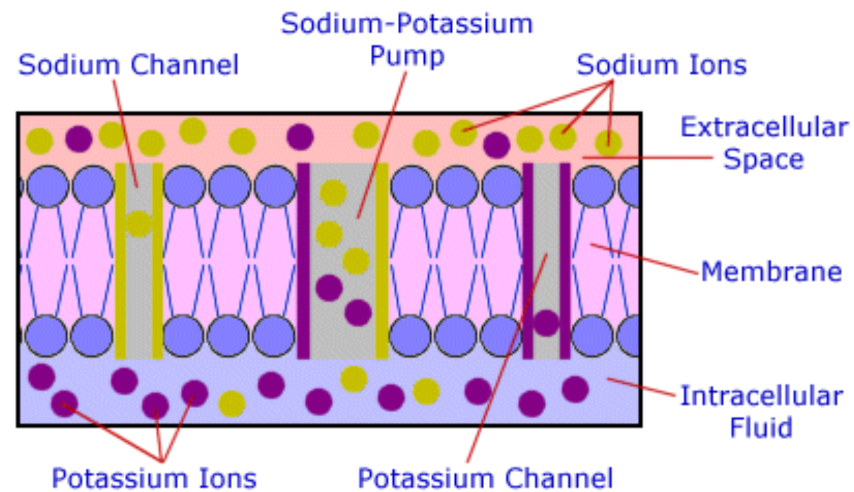
membrane

- higher concentration of K+ inside cell
- lower concentration of Na+ inside cell
- membrane less permeable to Na+ than to K+
  - => Na+ gradient is steeper than the K+ gradient
  - => more positive outside cell
  - => negative potential



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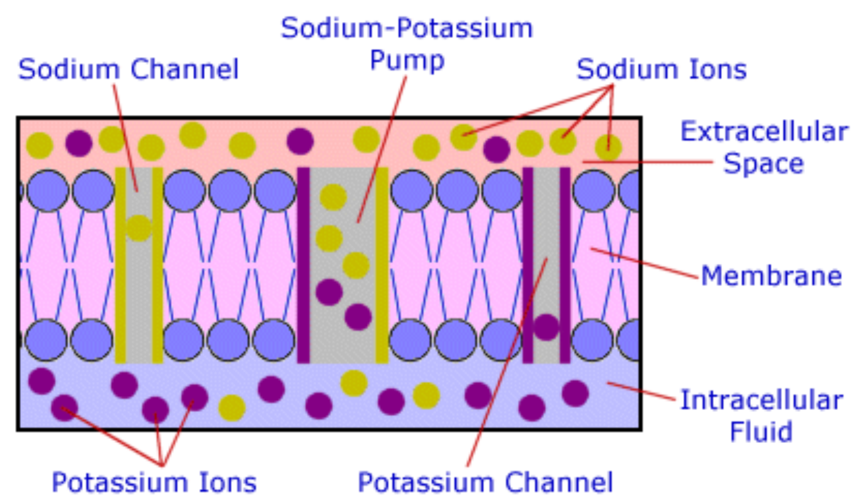
membrane

- gradient comes from ion pumps: protein channels in membrane that transport Na+ out of cell, K+ into cell, establishing gradient
- this is where energy is consumed (a lot): ATP used to pump ions



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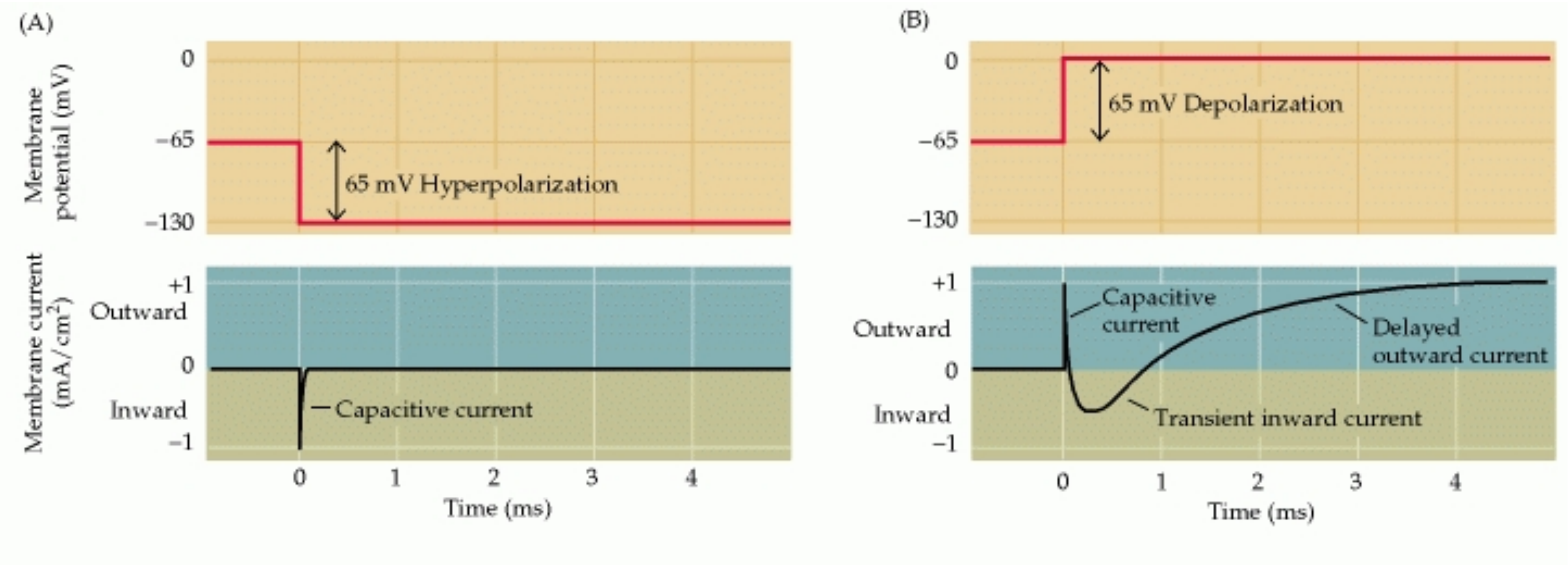
membrane

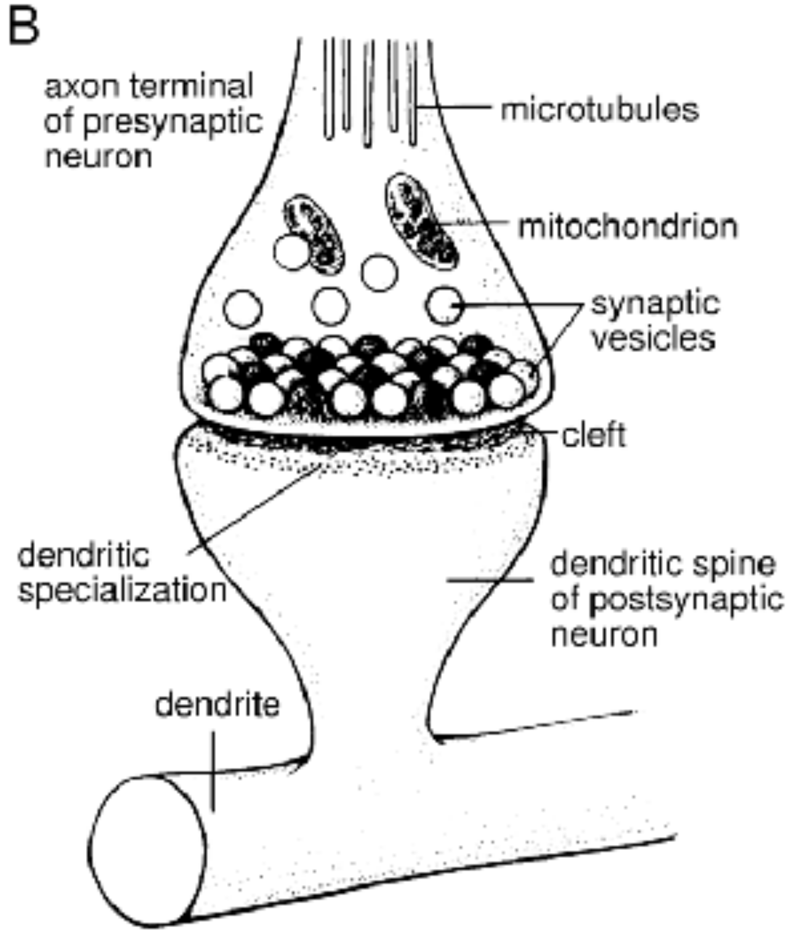
- giant squid axon… used to establish basic biophysics of membrane dynamics
- voltage-clamp



[Source: Neuroscience. 2nd edition.
Purves D, Augustine GJ, Fitzpatrick D, et al., editors.
Sunderland (MA): Sinauer Associates; 2001.]

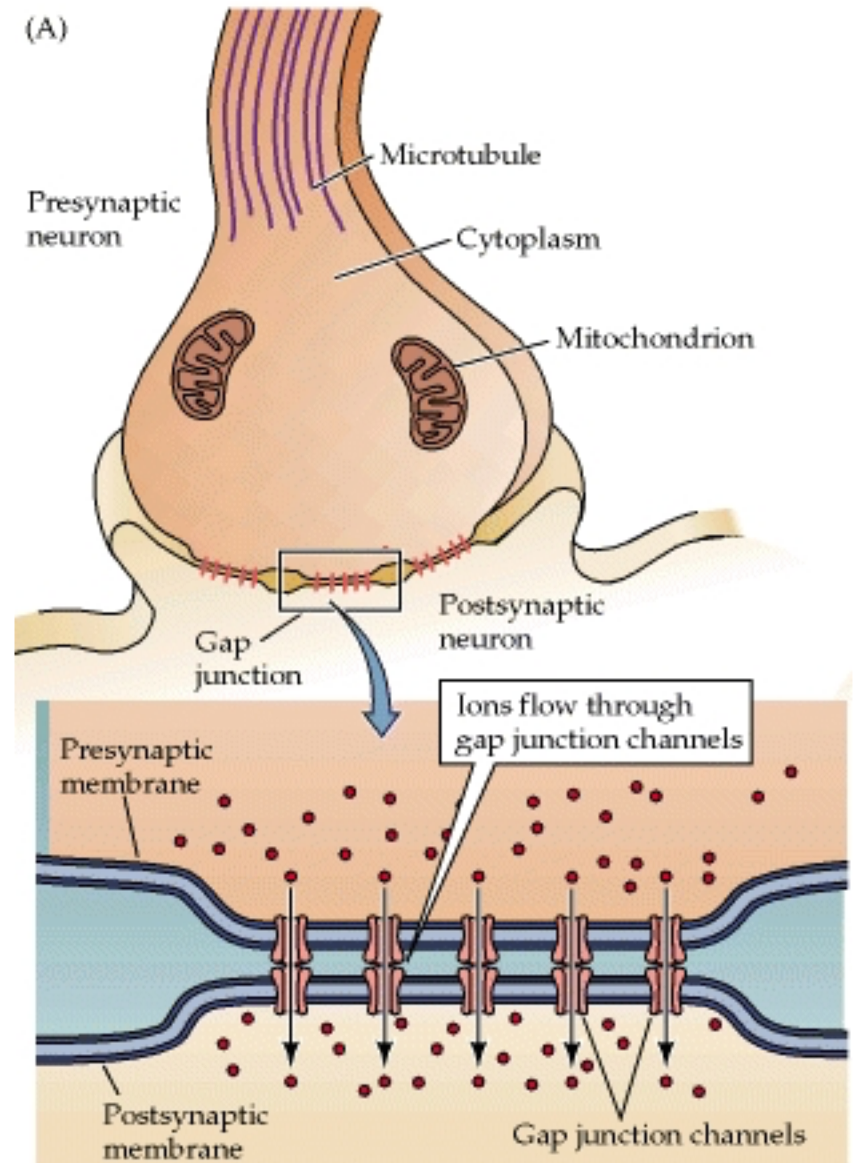
synapses

- at a synapse, the membranes of two neurons comes very close
- => this is where transmission across neurons takes place



two types of synapses

- electrical: currents across the membrane directly from one cell to another through "gap junctions"
  - very fast, but not flexible.
  - exists in the peripheral nervous system… but not very common
- chemical: the common one
- that is much more flexible…



[Source: Neuroscience. 2nd edition.
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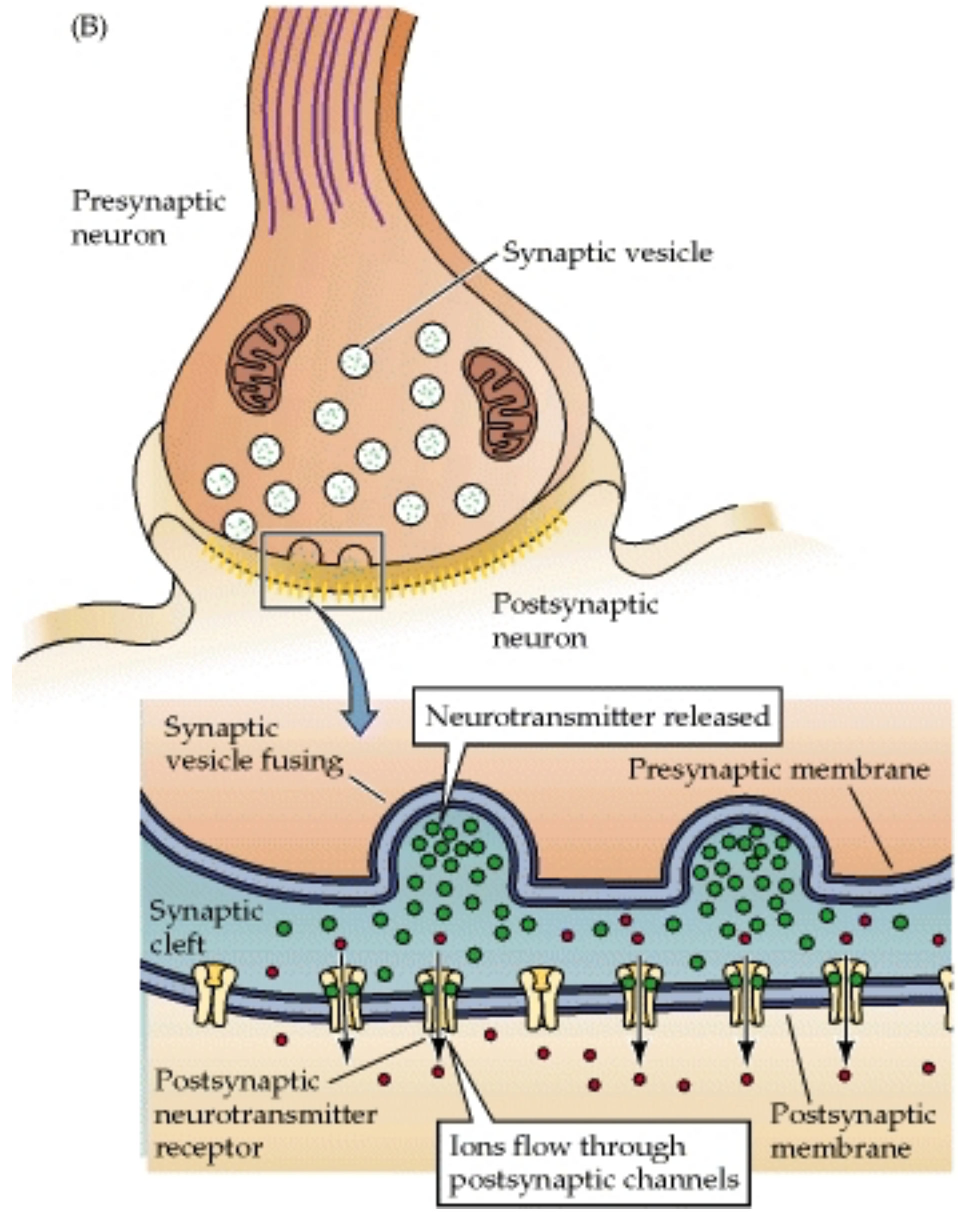
two types of synapses

- chemical: the more common one
  - pre-synaptic cell releases neurotransmitter in response to an action potential that arrives through the axon
  - post-synaptic potential induced by action of neurostransmitters on receptors



[Source: Neuroscience. 2nd edition.
Purves D, Augustine GJ, Fitzpatrick D, et al., editors.
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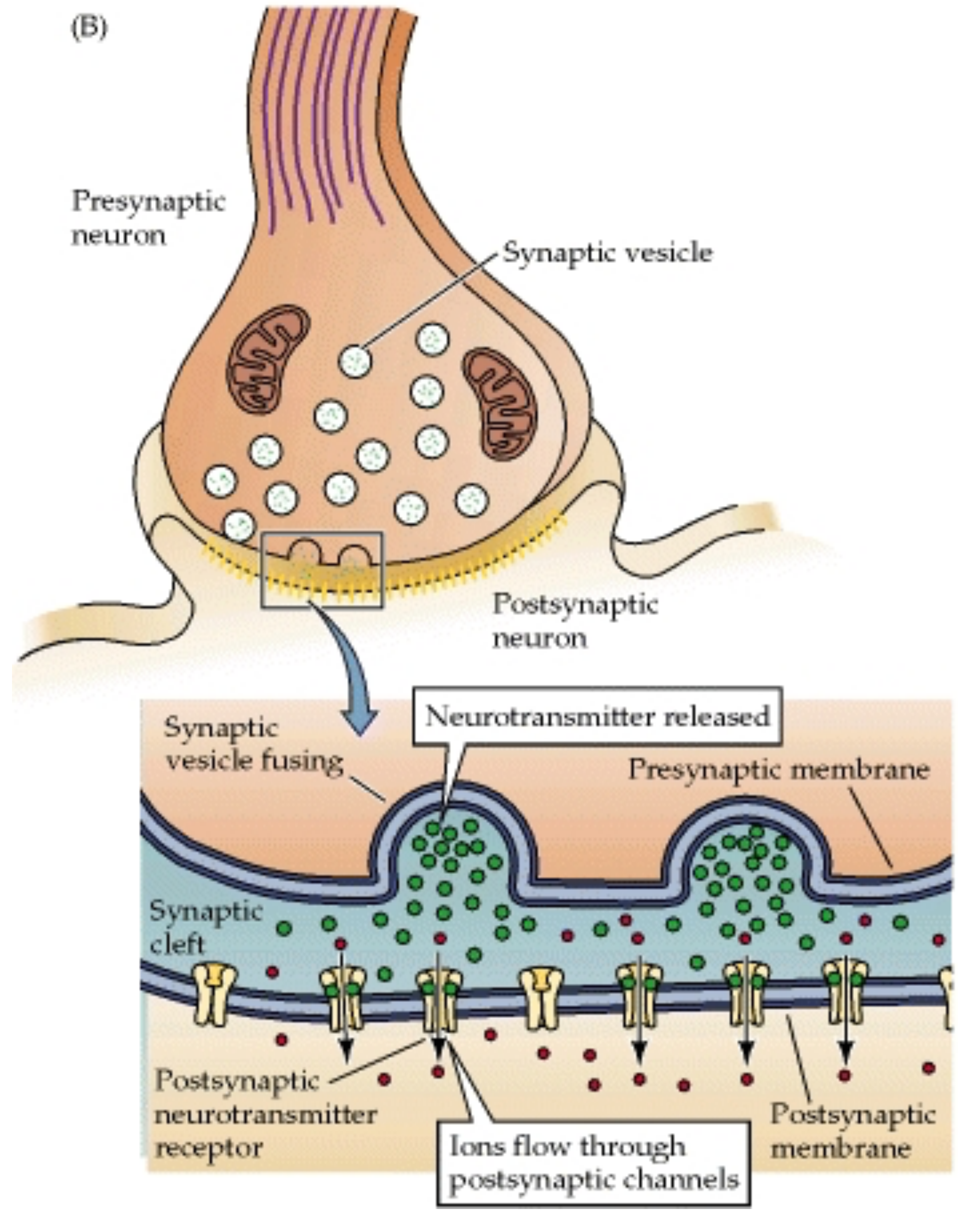
two types of synapses

- chemical synapse
  - slower transmission… 1 to 2 ms
  - but more flexible: tuned by changes in receptors



[Source: Neuroscience. 2nd edition.
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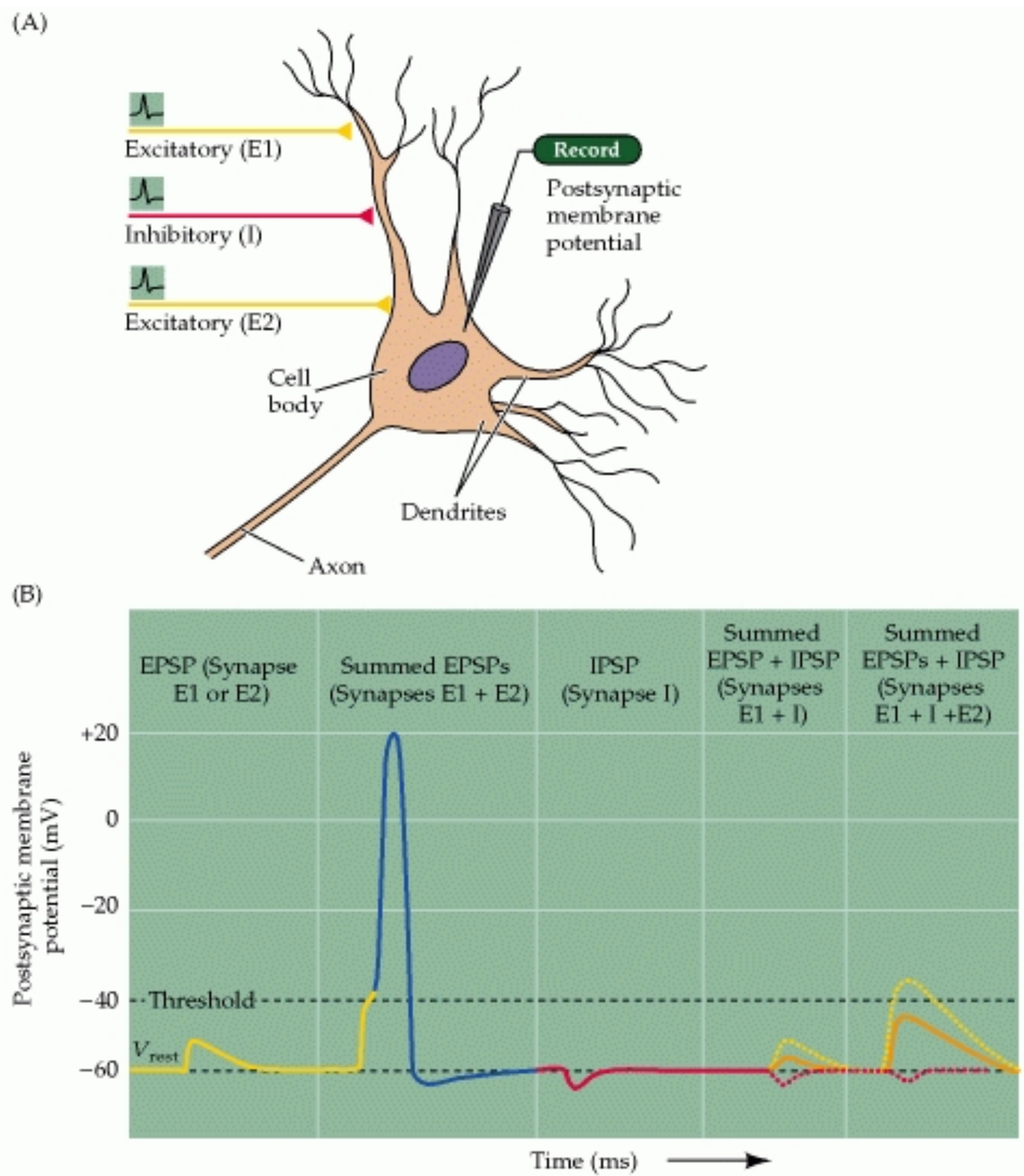
Sunderland (MA): Sinauer Associates; 2001.]

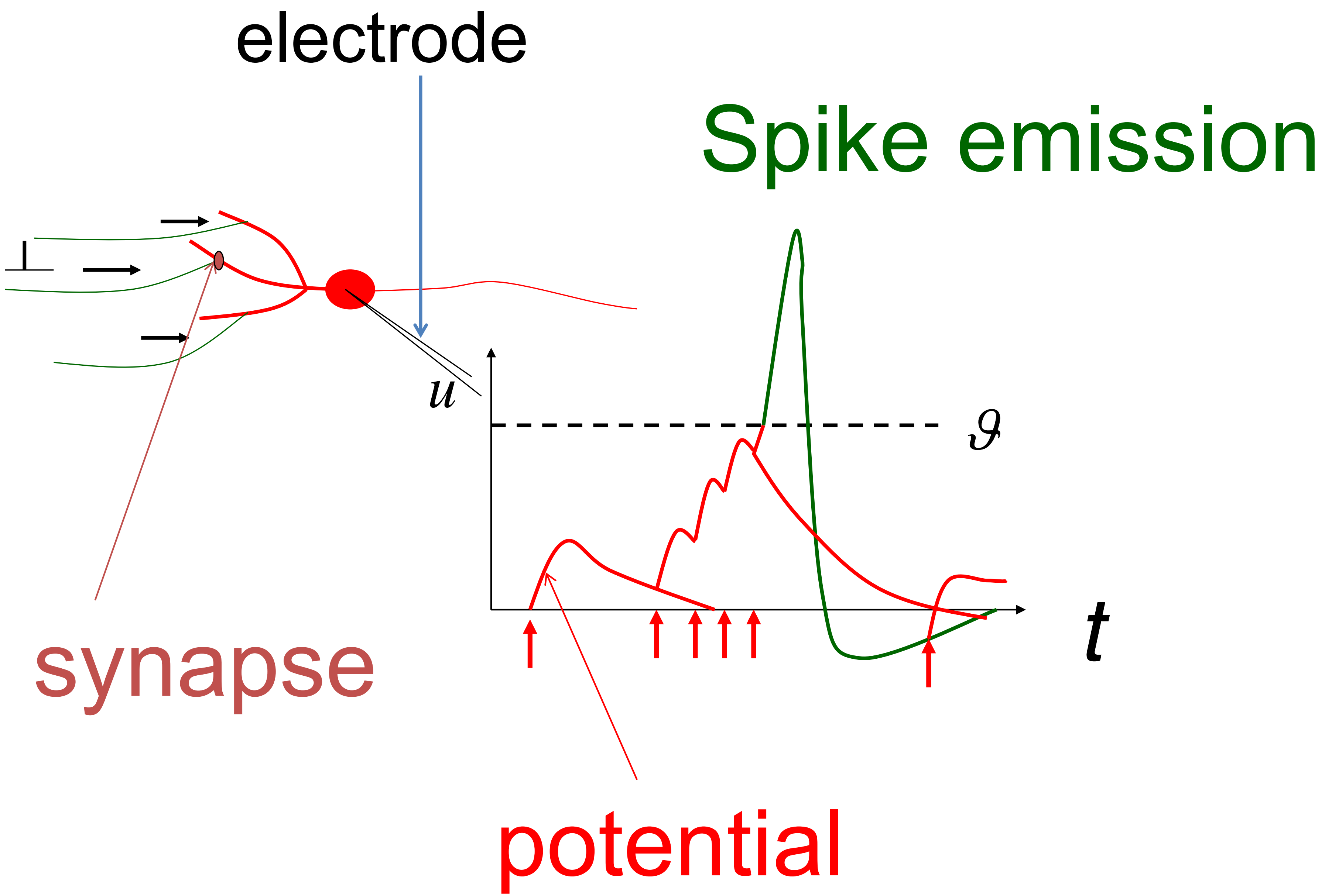
post-synaptic potentials

- depending on the receptor type, synaptic transmission induces post-synaptic potentials of different forms and sign
- that travel to the soma, where a spiking decision is made



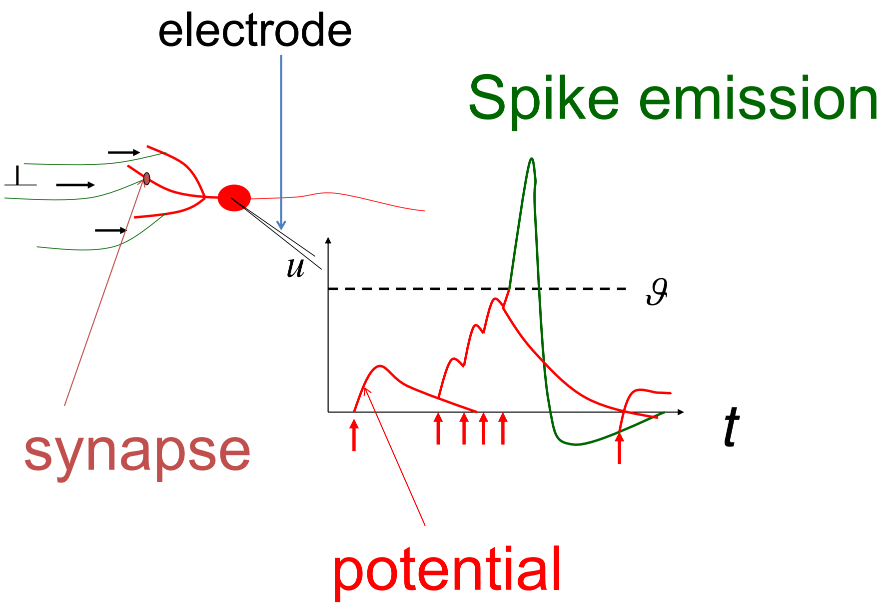
[Source: Neuroscience. 2nd edition.

spiking mechanism



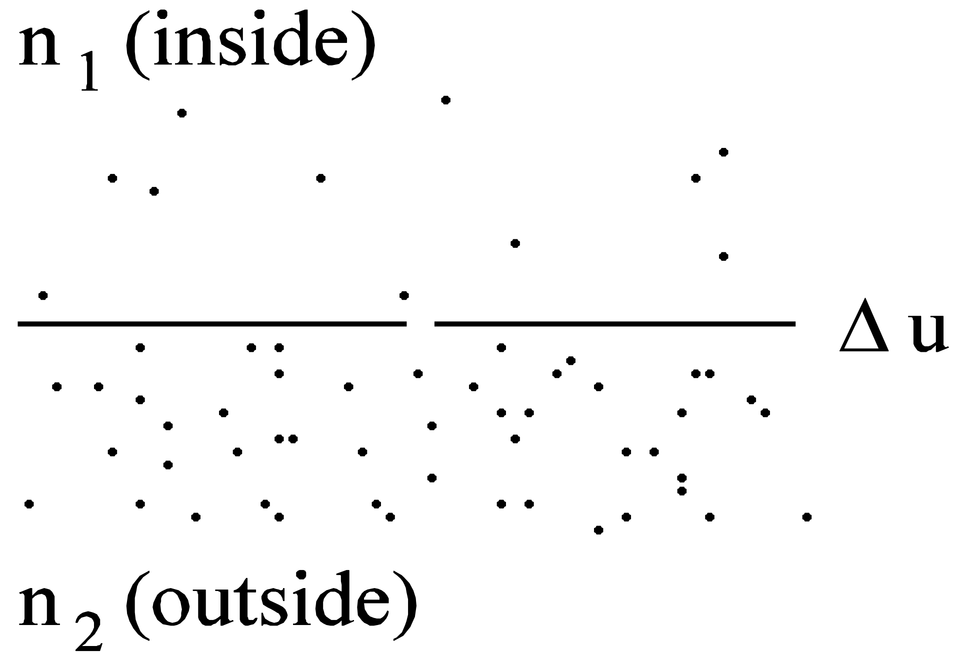
spiking mechanism

- all or none nature of spikes
- spike generation is coincidence detection
  - overlap of incoming post-synaptic potentials that have propagated to soma within about 10 ms required to sum…
  - typical in cortex: 10 inputs needed, 10000 potential inputs…
- neuron as a “switch”



Hodgkin-Huxley

- relationship potential-ionic concentration



$$\Delta u = u_1 - u_2 = \frac{-kT}{q} \ln \frac{n(u_1)}{n(u_2)}$$

Hodgkin-Huxley

- dynamic model of potential change and three ion currents
- which come from three ion channels
- phenomenological dynamics of the ion ion channels

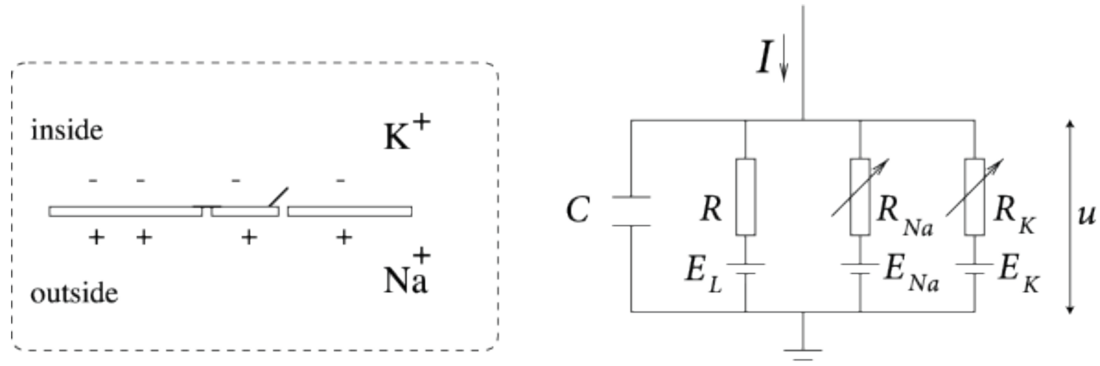


Fig. 2.2: Schematic diagram for the Hodgkin-Huxley model.

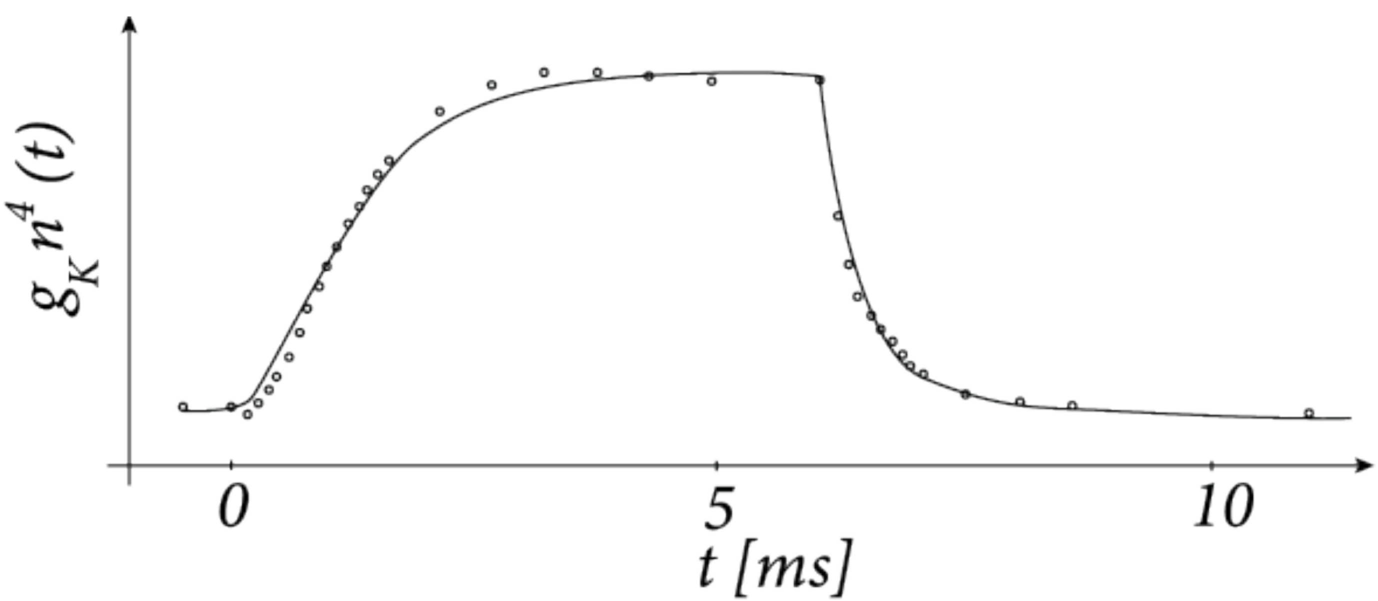
$$C\frac{\mathrm{d}u}{\mathrm{d}t} = -\sum_k I_k(t) + I(t) \ .$$

$$\sum_k I_k = g_{\mathrm{Na}}\, m^3 h\ (u - E_{\mathrm{Na}}) + g_{\mathrm{K}}\, n^4\ (u - E_{\mathrm{K}}) + g_L\ (u - E_L) \, .$$

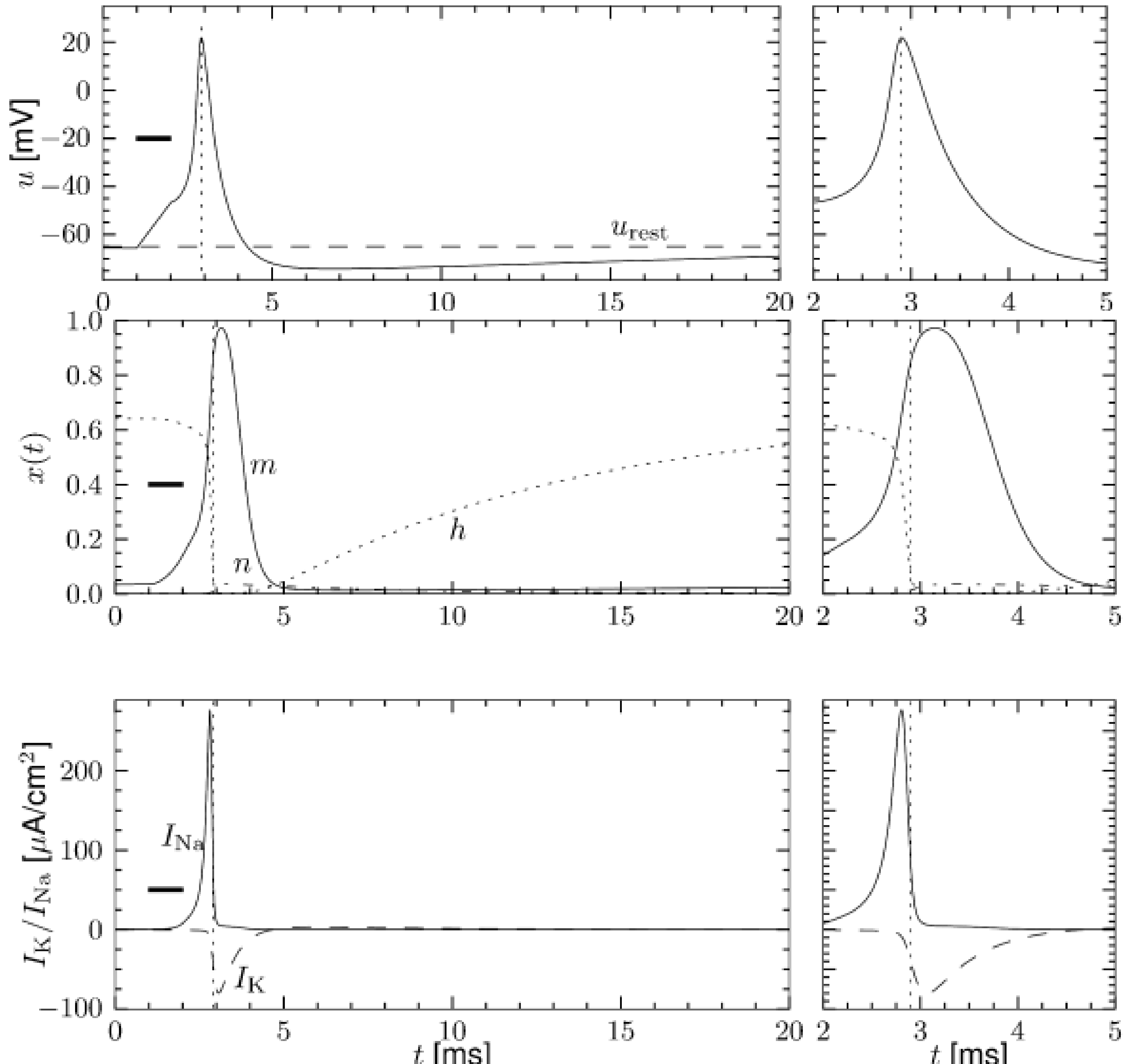
$$\begin{aligned}
\dot{m} &= \alpha_m(u)\ (1-m) - \beta_m(u)\ m \\
\dot{n} &= \alpha_n(u)\ (1-n) - \beta_n(u)\ n \\
\dot{h} &= \alpha_h(u)\ (1-h) - \beta_h(u)\ h.
\end{aligned}$$

Hodgkin-Huxley

- based on data from squid-axon…

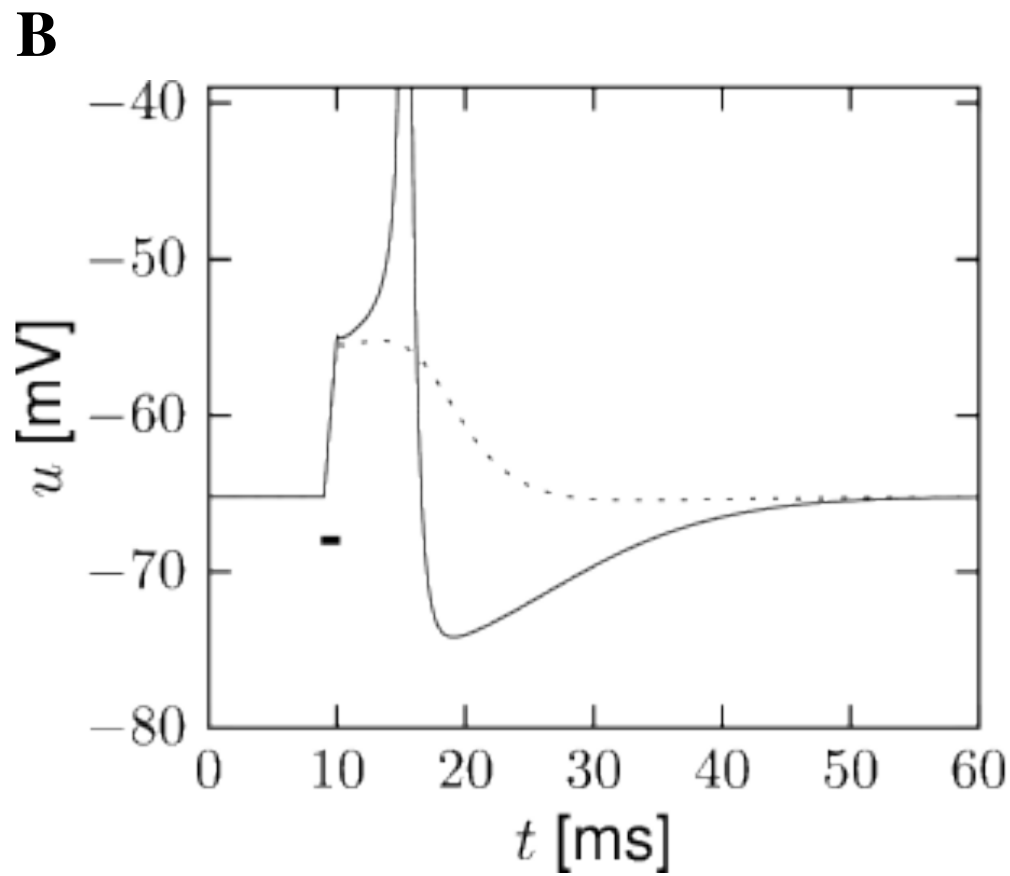


spikes



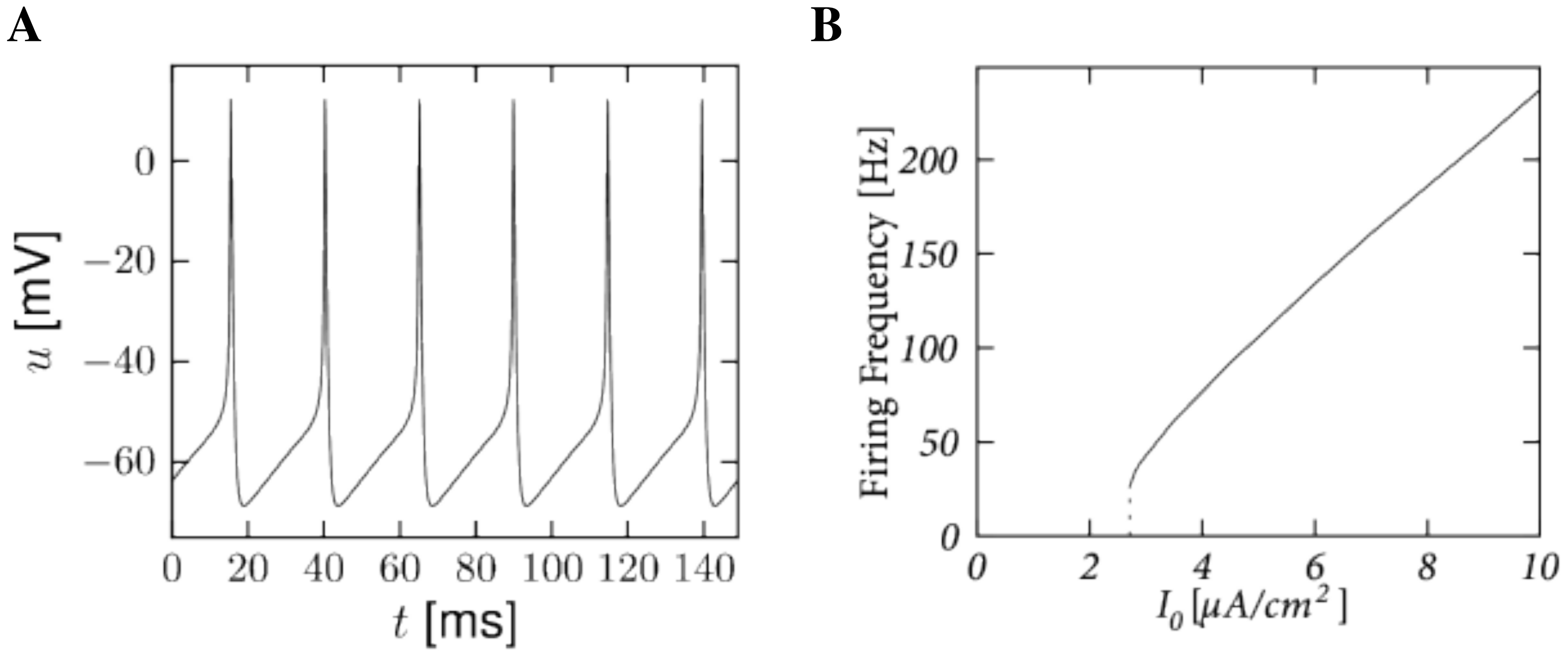
Hodgkin Huxley

- the spiking mechanism is an instability => threshold effect



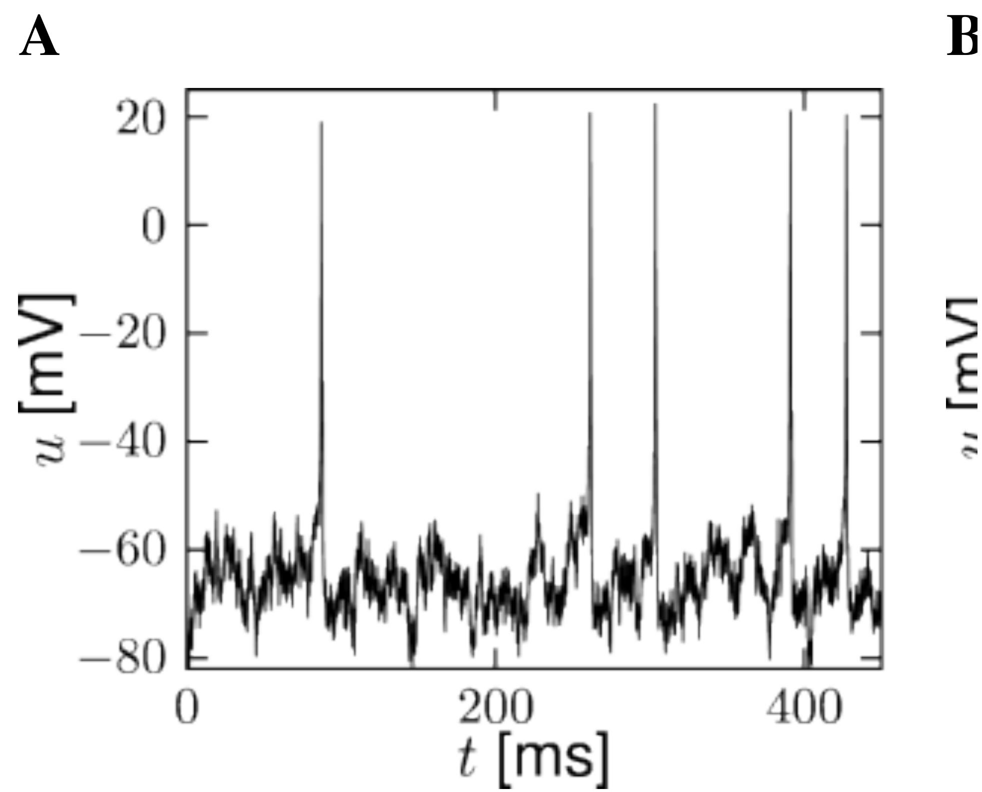
Hodgkin Huxley

- spike rate reflects input current



Hodgkin Huxley

- time varying inputs make time varying rate

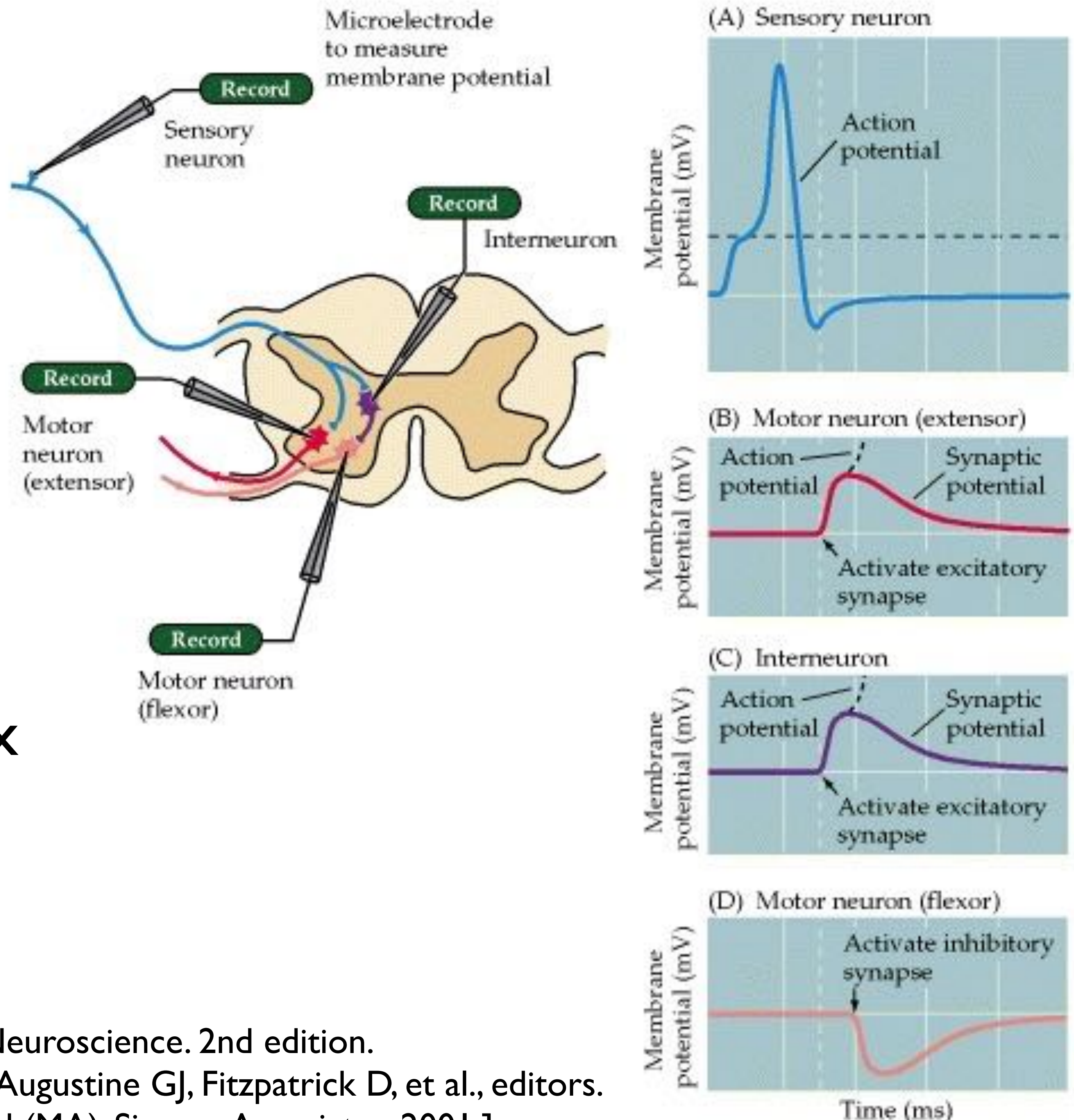


Synaptic dynamics

- represent the current induced by a presynaptic spike as a time dependent conductivity of the dendritic membrane, $g_{syn}(t)$ and induces a current $I_{syn}=g_{syn}(t)\,(u - E_{syn})$
- $g_{syn}(t)$=exponential time course with time scale in ms range

Example: neural circuit

- stretch reflex



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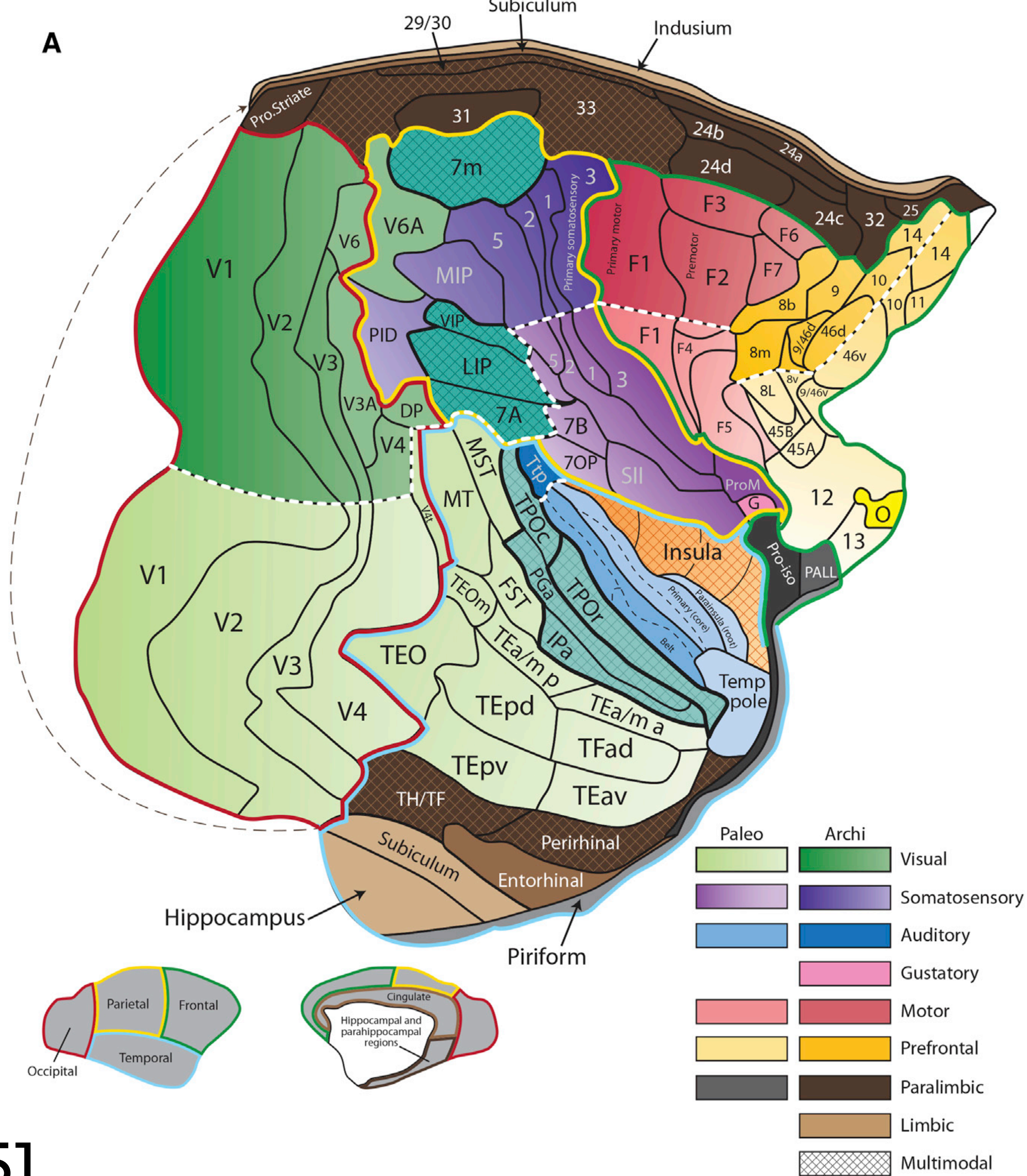
Purves D, Augustine GJ, Fitzpatrick D, et al., editors.
Sunderland (MA): Sinauer Associates; 2001.]

Learning

- mathematical models of how synaptic strengths evolve as a function of pre/post synaptic state…
- spike-time dependent plasticity
  - strengthening of synapses in which pre-synaptic spike precedes post-synaptic spike
  - weakening synapses when the temporal order is the reverse…

....back to the brain

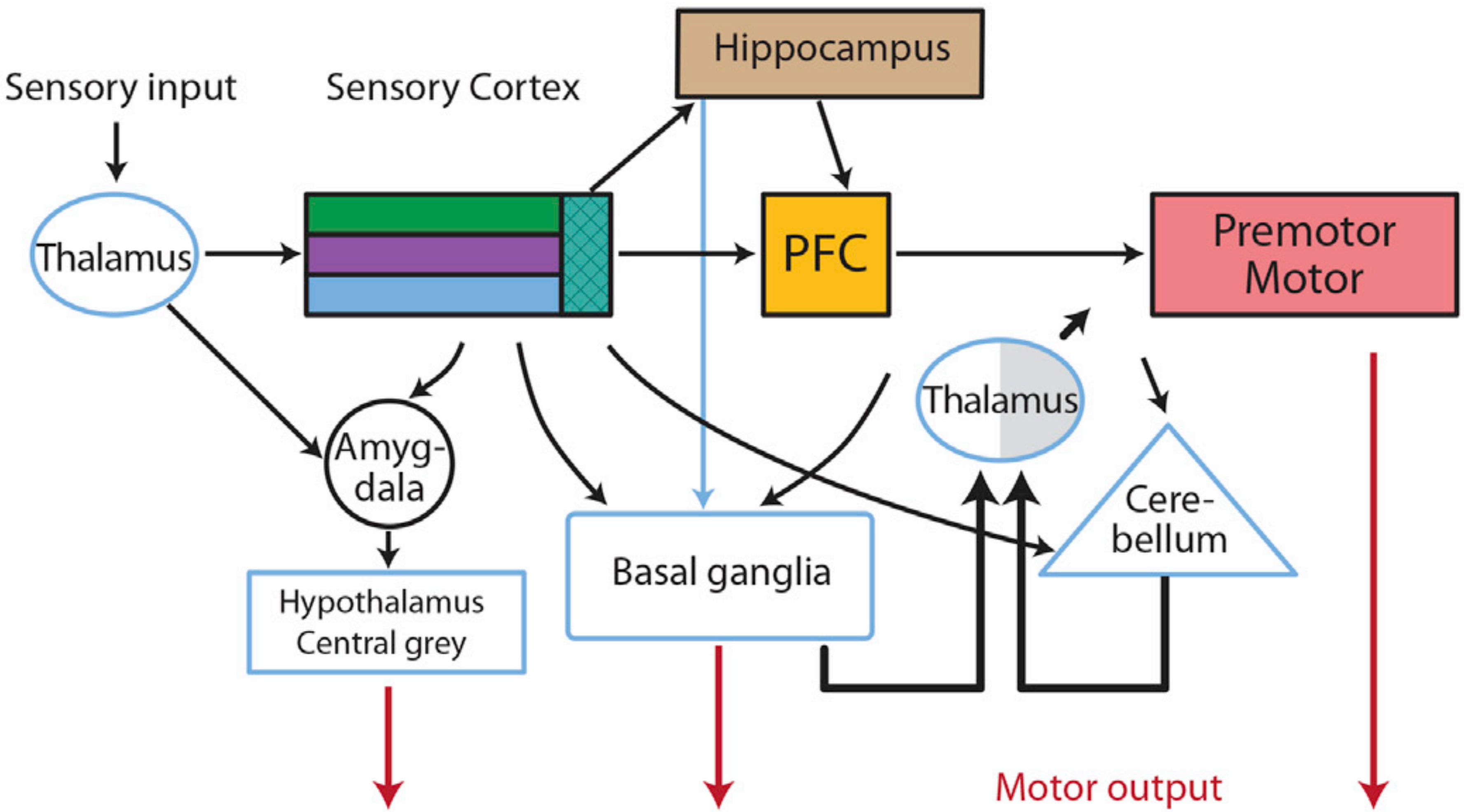


- organization of the brain in terms of cytoarchitectonics

[Lisman, *Neuron* 2015]

….back to the brain

- functional organization of the brain



[Lisman, *Neuron* 2015]