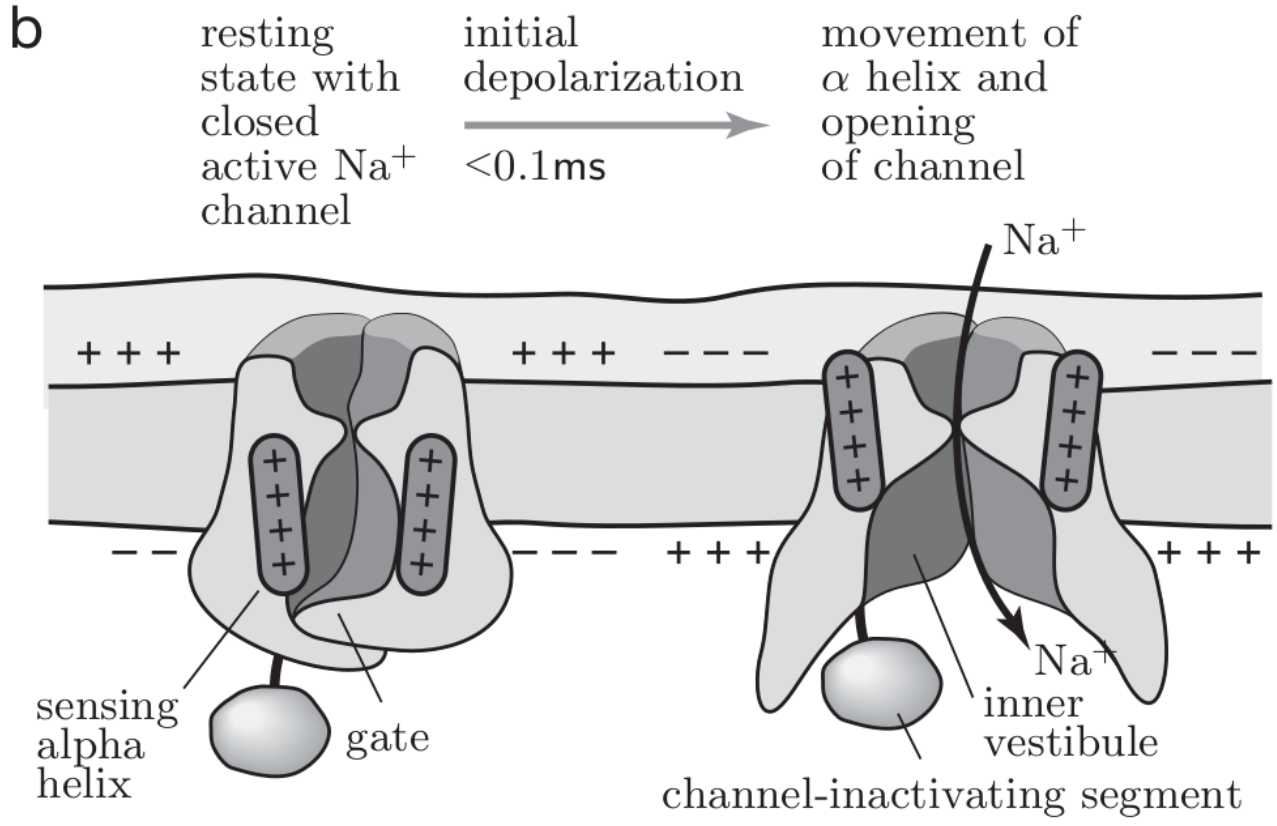
Voltage-gated Na^+ channel



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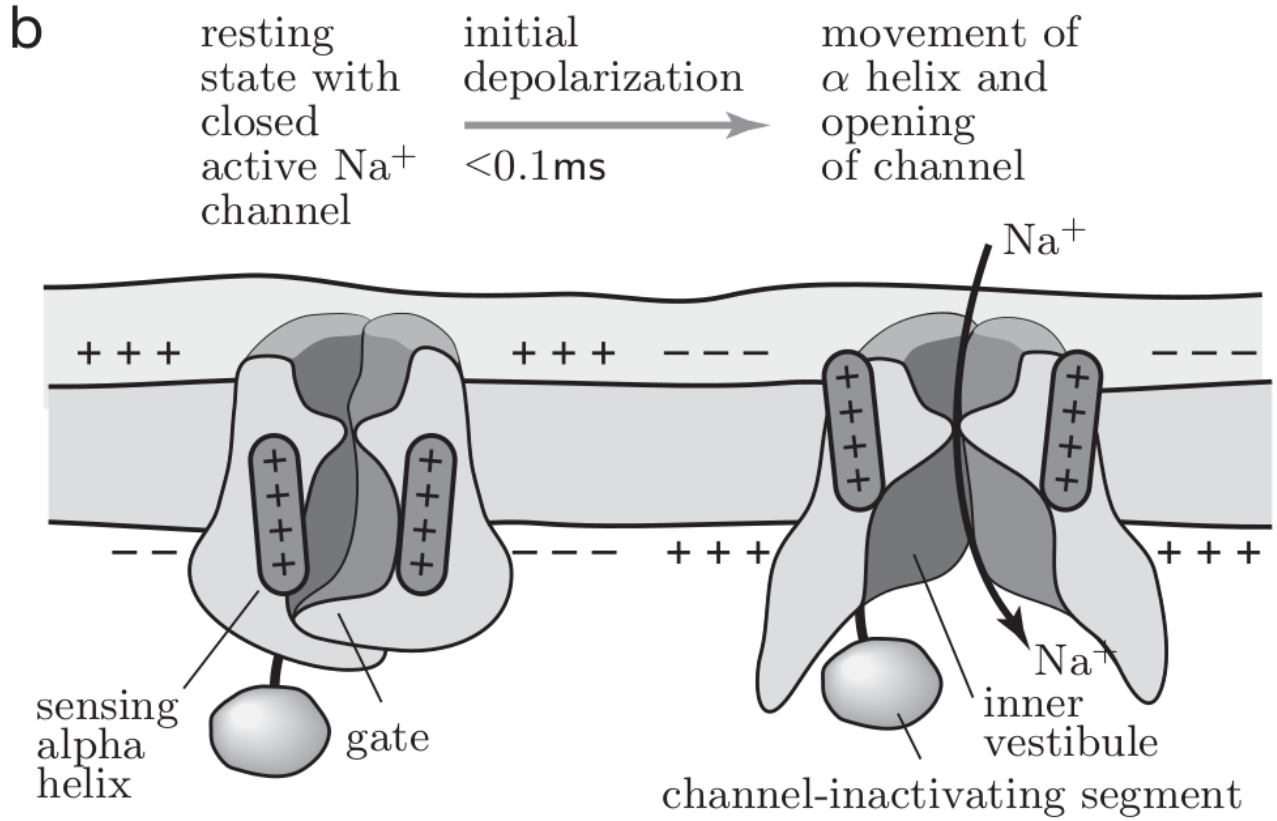


Simple thermodynamic model: state 1 = **closed**, state 2 = **open**

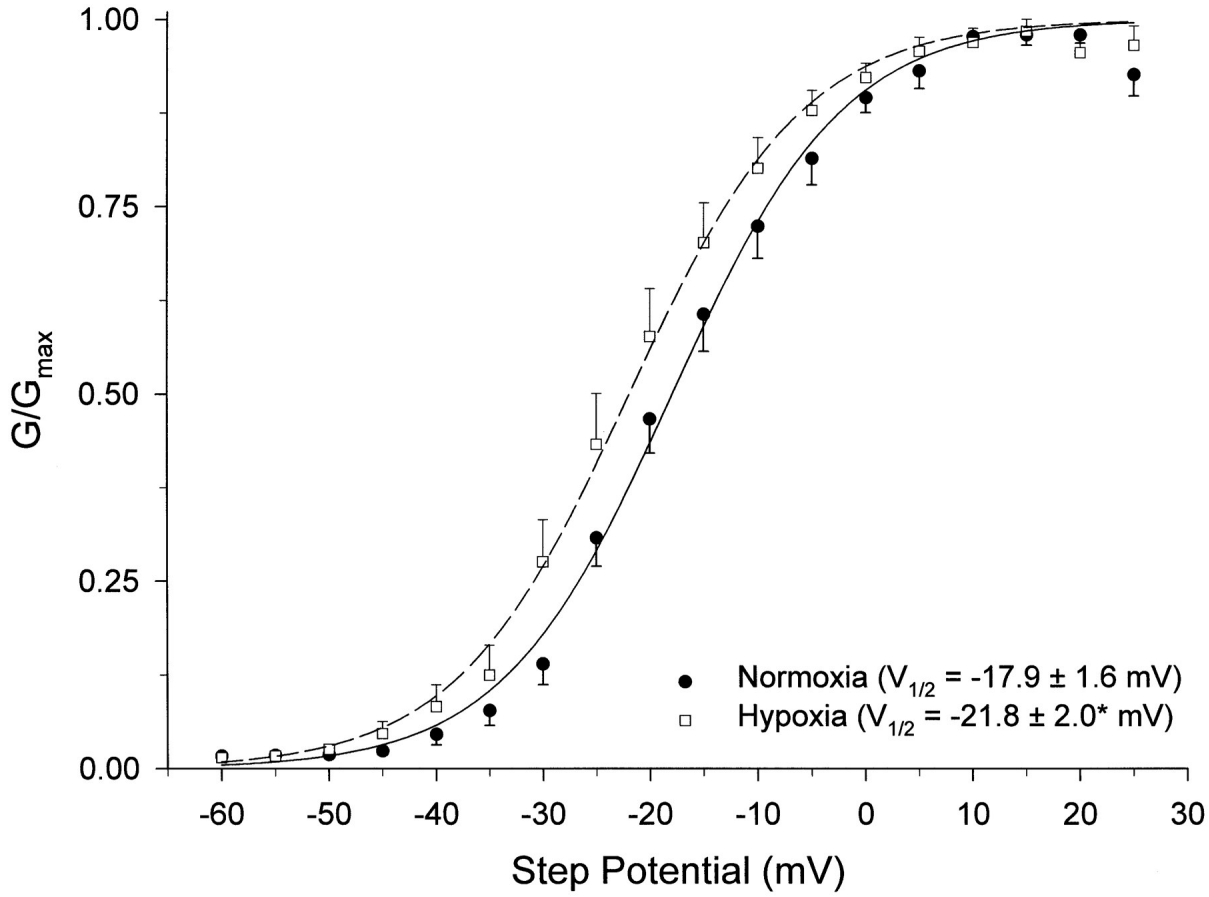
$$\frac{k_{21}}{k_{12}} = e^{-\beta(G_2 - G_1 - Q\ell V/d)}$$

where Q is the "gating charge", ℓ is the distance it moves, and V/d is the electric field ($d = 4$ nm is membrane thickness).

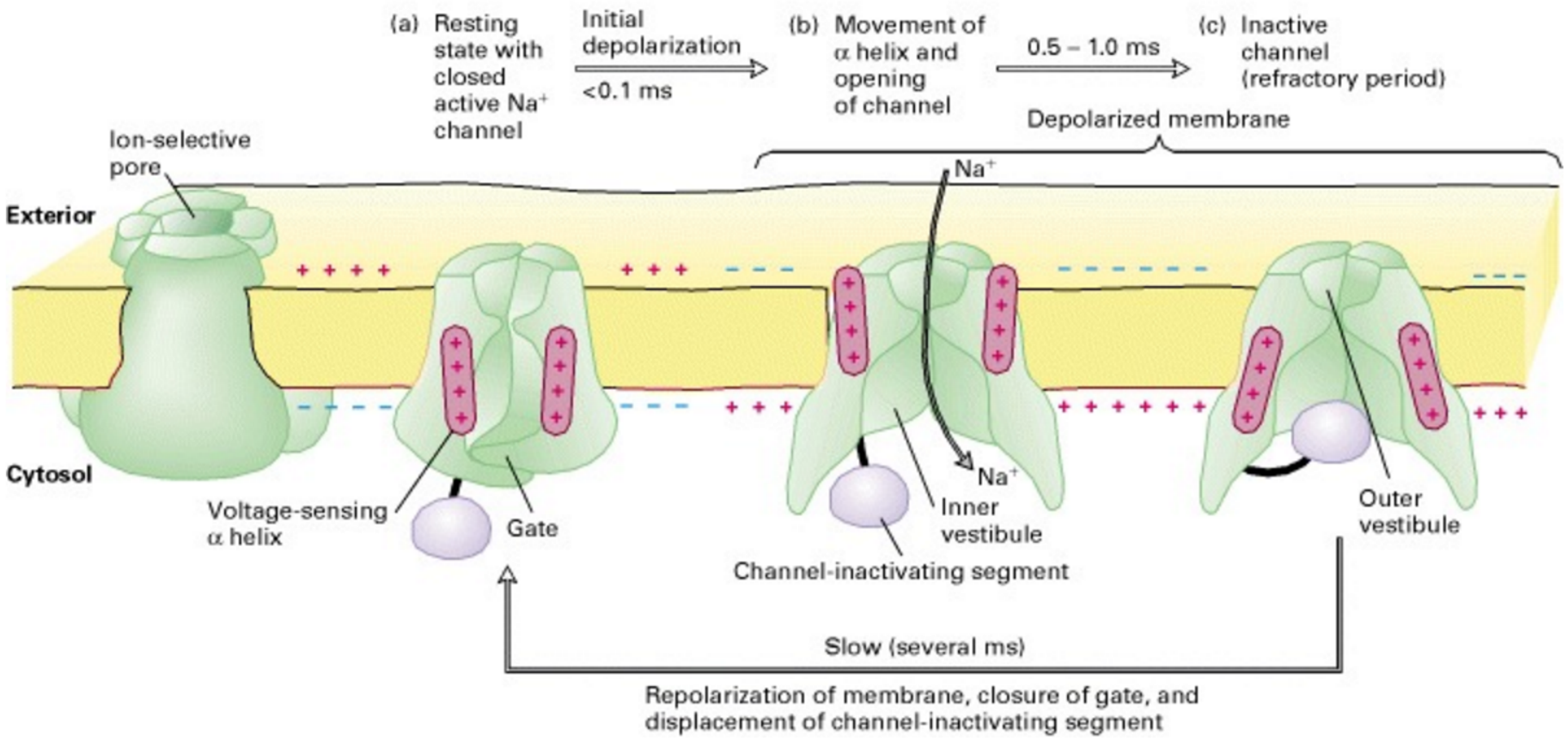
Voltage-gated Na^+ channel

Probability for channel to be open in stationary state at given V:

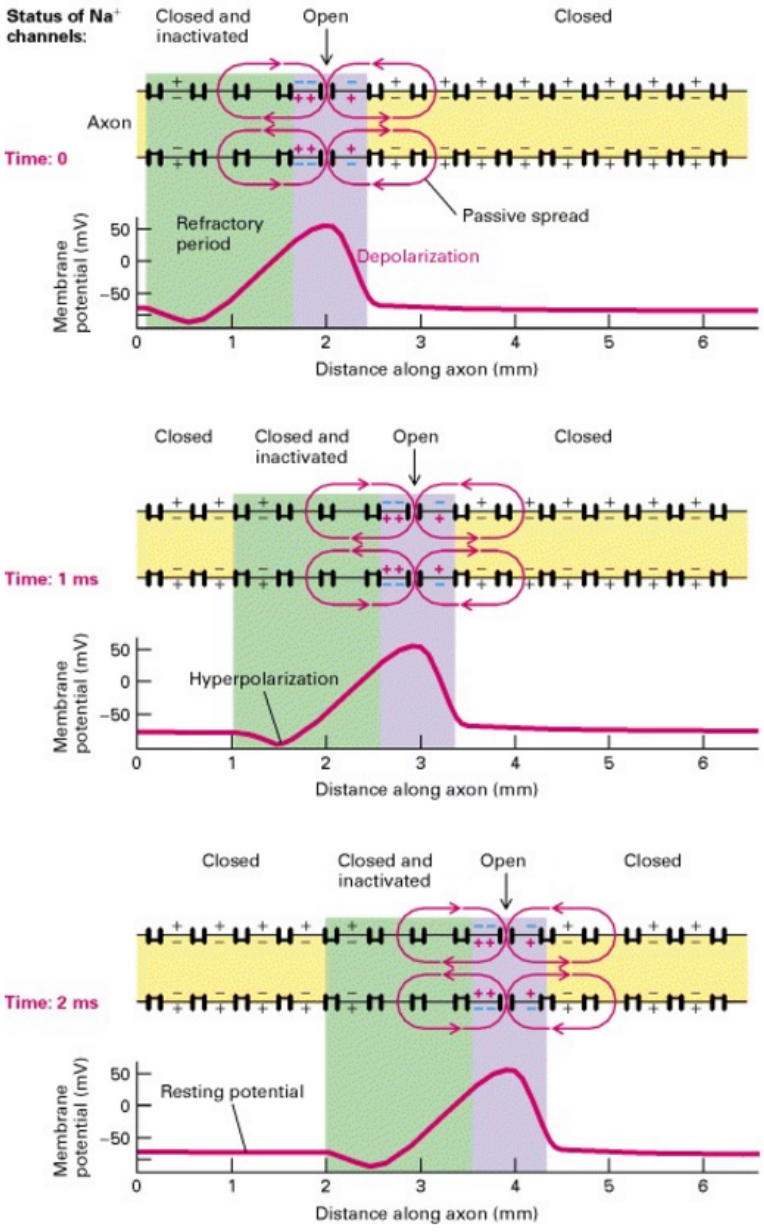
$$p_{Na}(V) = p_2^s = \frac{k_{21}}{k_{21} + k_{12}} = \frac{1}{1 + e^{\beta(G_2 - G_1 - Q\ell V/d)}}$$



Channel inactivation



Action potential



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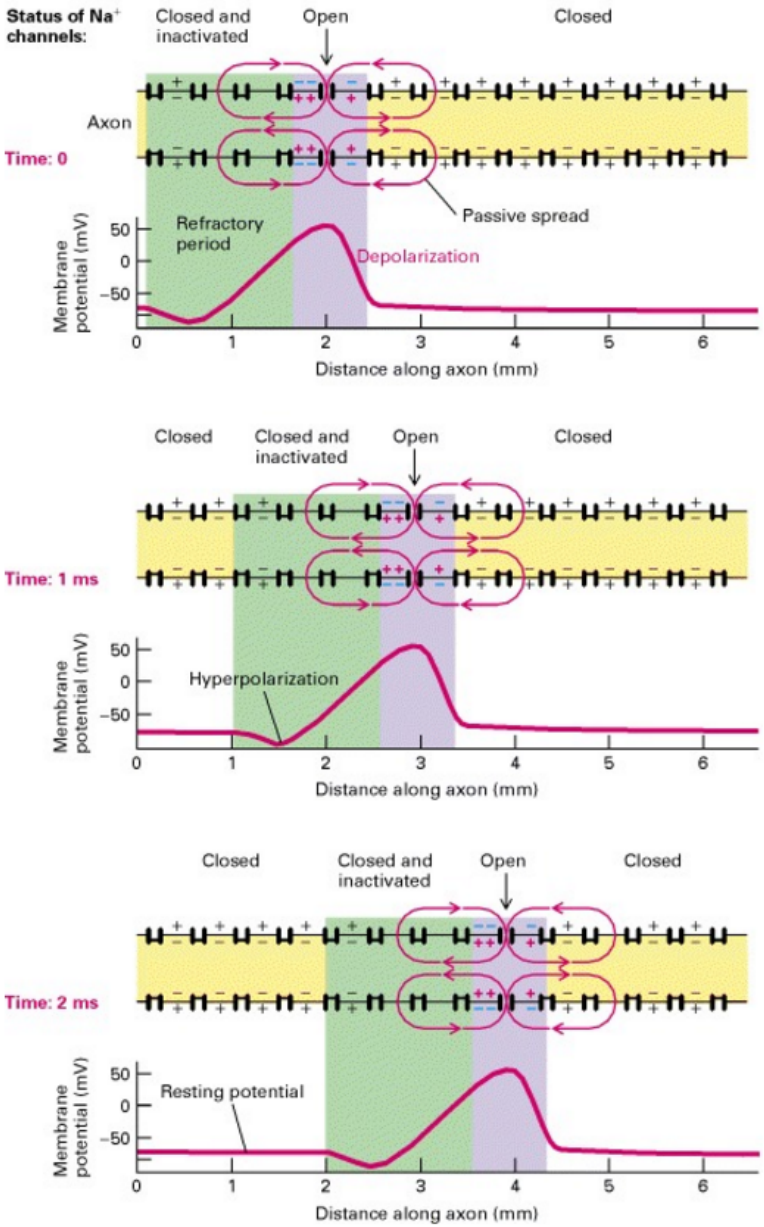


velocity:

$$s \propto \frac{\lambda}{\tau} = \frac{1}{C_s}\sqrt{\frac{\rho\kappa g_{\text{tot}}}{2}}$$

C_s: membrane capacitance / area
$\sim 1\ \mu\text{F/cm}^2$

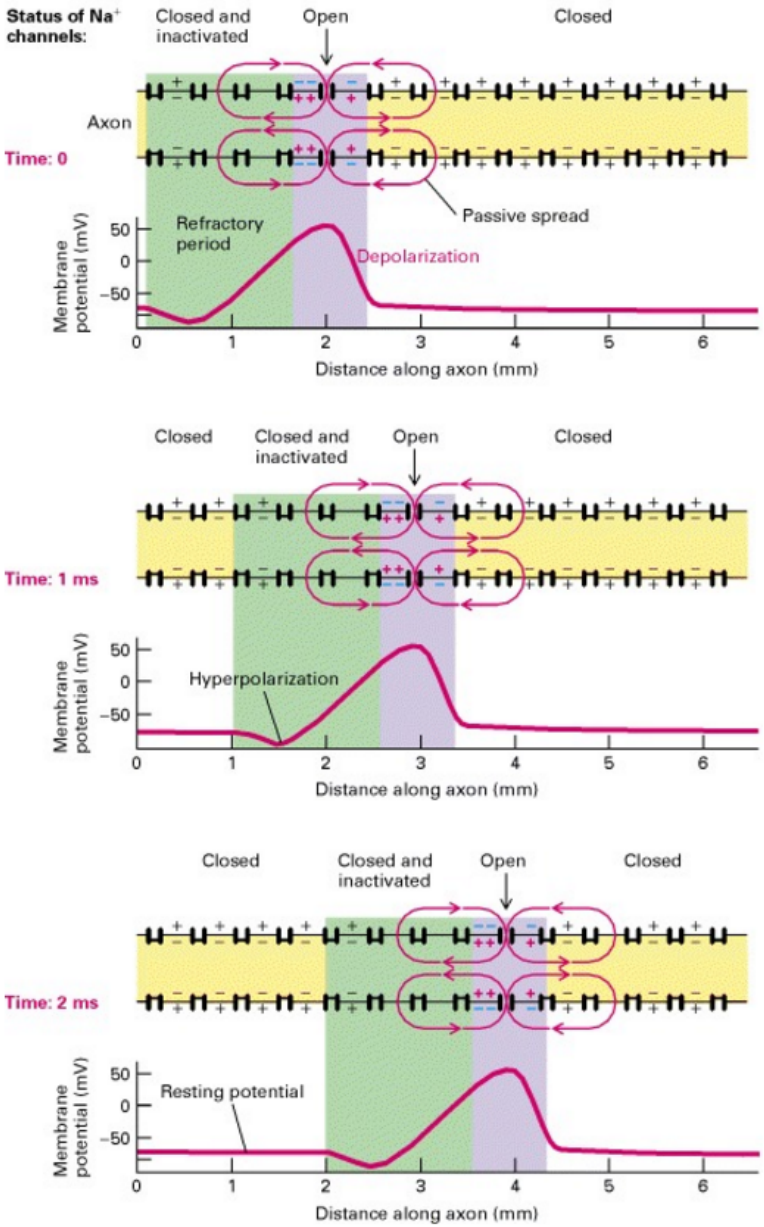
ρ: axon radius
~ 0.5 mm (squid)

κ: $\beta D c_{\text{tot}} e^2 \propto$ axial conductance
$\sim 3\ \Omega^{-1}\text{m}^{-1}$

g_{tot}: membrane conductance / area
$\sim 10\ \Omega^{-1}\text{m}^{-2}$

$\Rightarrow s \sim 9$ m/s (fast!)

Action potential



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But...

$\rho \sim 0.5\ \mu$m in giraffes

$\Rightarrow s \sim 0.3$ m/s (less fast!)

17 seconds from head to toe??

Giraffes really do have slow reflexes... but not *that* slow

INSIDE JEB

TREADING CAREFULLY: SLOW SENSING AND RESPONDING IN GIRAFFES

Nicola Stead

Journal of Experimental Biology 2013 216: iii doi: 10.1242/jeb.085415

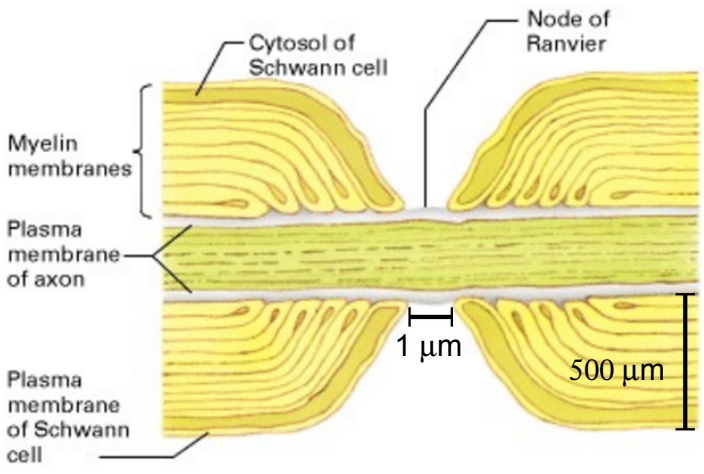
Article | Info & metrics | PDF

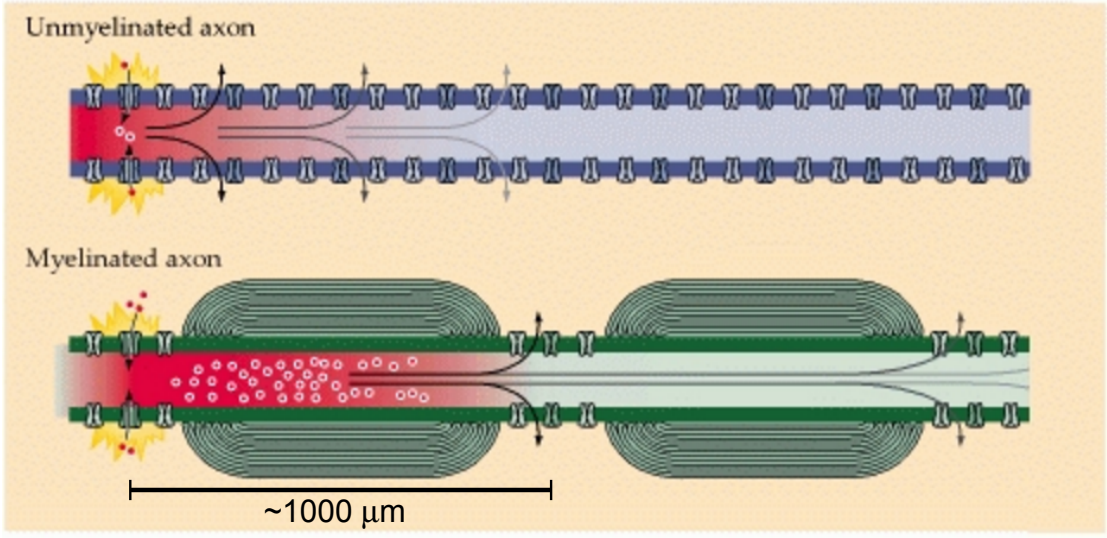


When you're stretching for something that is just out of reach do you ever envy the world's tallest land mammal – the giraffe? Although its size might seem like the perfect solution for reaching the highest leaves, being tall does have drawbacks. As animals grow bigger, electric impulses have to travel farther along nerve fibres to deliver their commands. This could have important consequences for how quickly – and appropriately – these towering animals sense and respond to the world around them. Heather More, Shawn O'Connor (both from Simon Fraser University, Canada) and their colleagues travelled to South Africa to investigate just how much of a sensing and responding delay the giraffes' colossal dimensions caused (p. 1003).

Myelin to the rescue

Vertebrate axons have a myelin sheath, interrupted at nodes of Ranvier:





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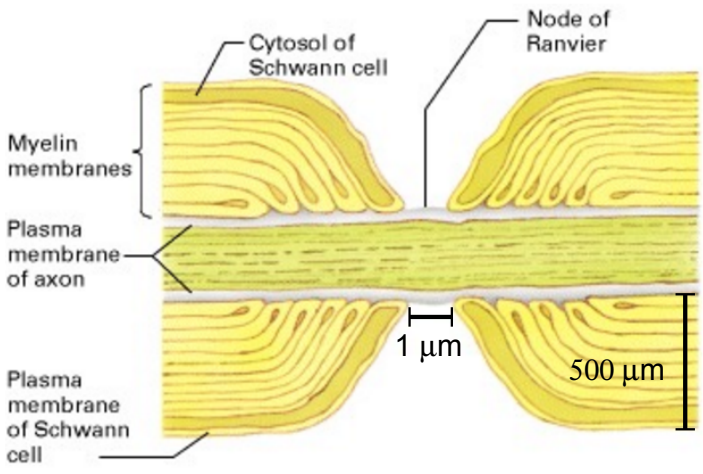
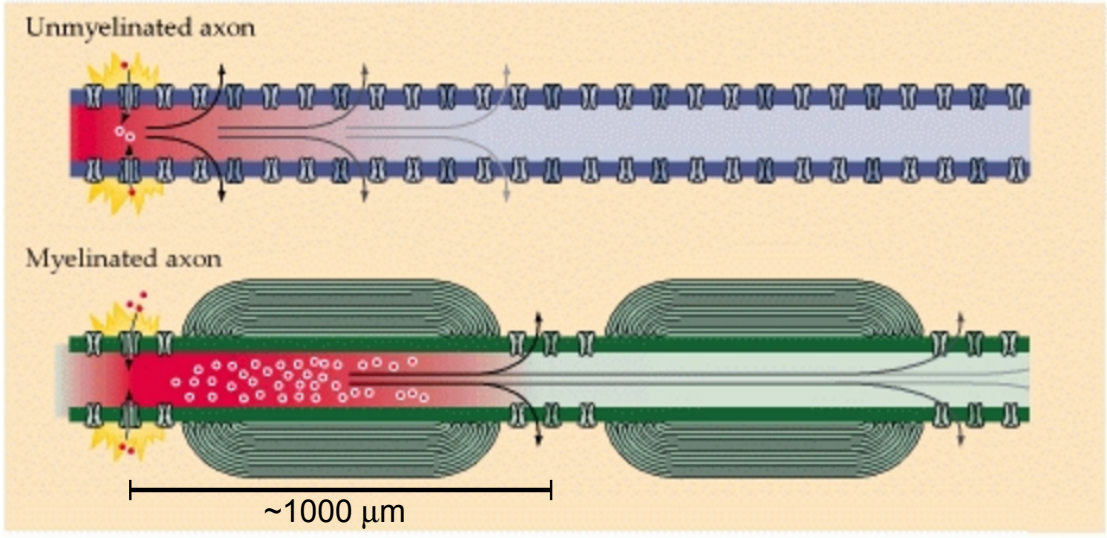




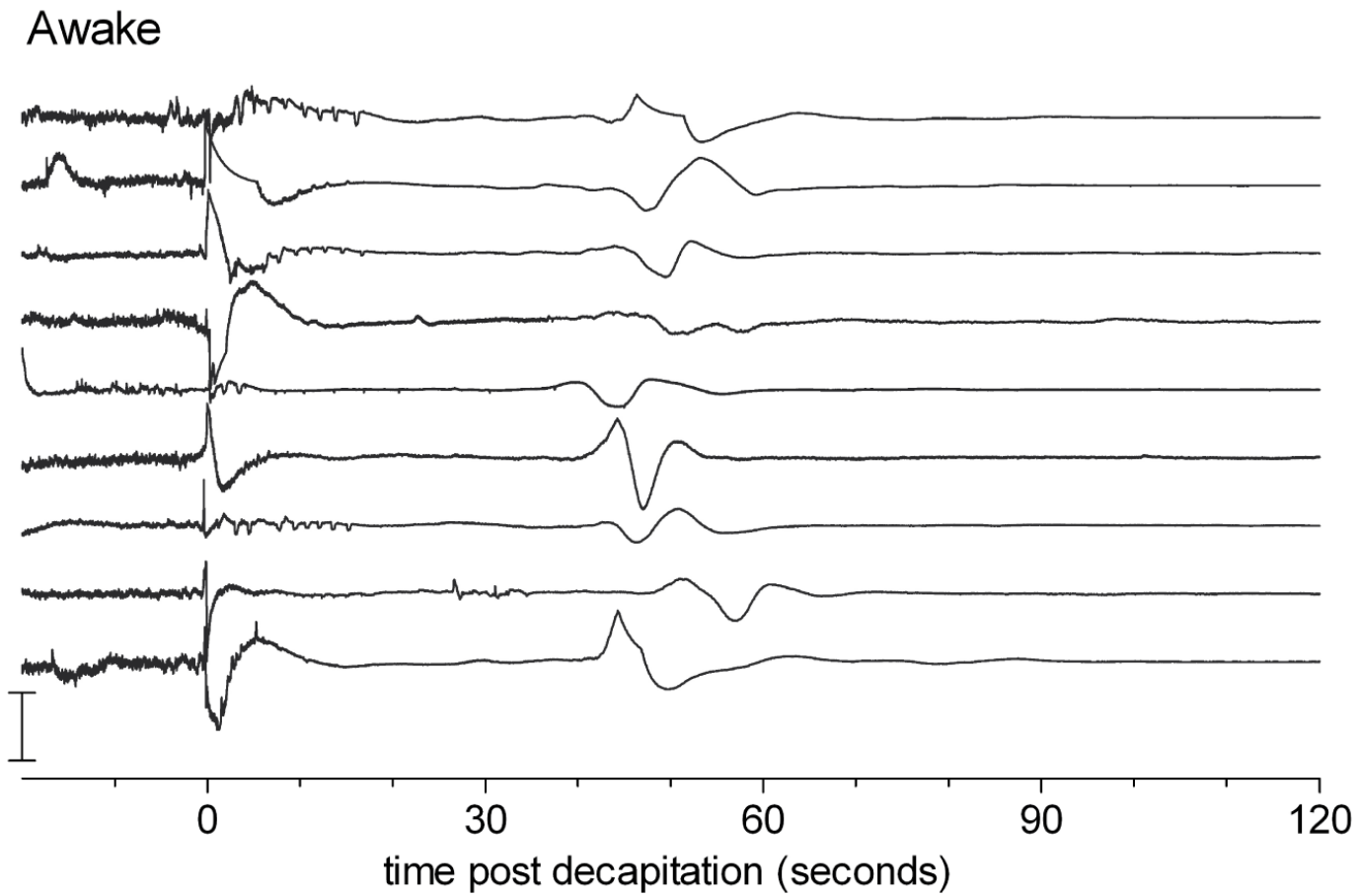
Squid vs. giraffe: $\rho_{\text{squid}} = 10^3 \rho_{\text{gir}}$, $C_s^{\text{squid}} = 10^3 C_s^{\text{gir}}$, $g_{\text{tot}}^{\text{squid}} = 10^3 g_{\text{tot}}^{\text{gir}}$

Myelin's low capacitance and conductivity compensates for thinner axon:

speed $s = \frac{1}{C_s}\sqrt{\frac{\rho\kappa g_{\text{tot}}}{2}} \sim 9$ m/s **roughly the same!**

Wave of death

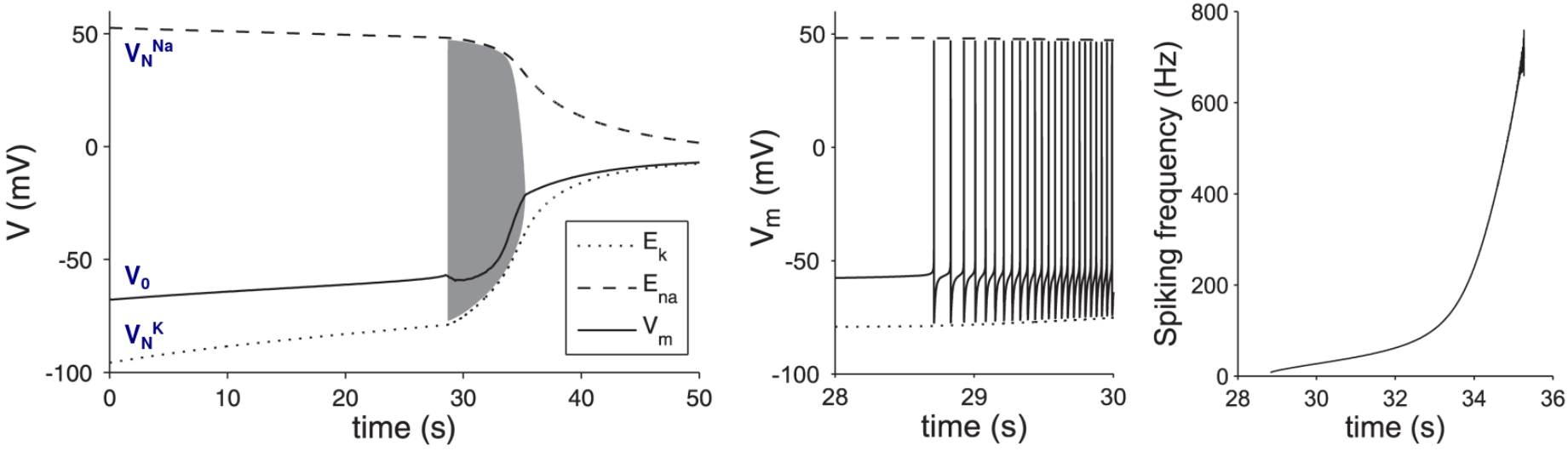
Slow depolarization in the absence of ATP driving the membrane pumps eventually triggers opening of Na^+ channels:



B. Zandt *et al.*, PLoS ONE 6, e22127 (2011)

Wave of death

Simulation:



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Wave of death

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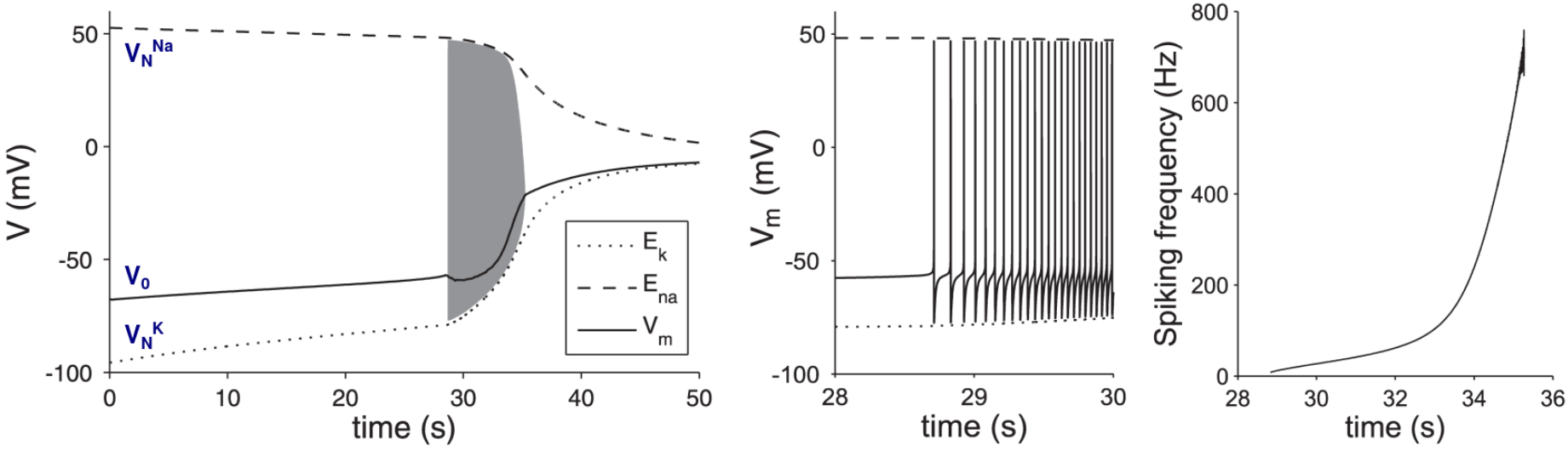

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Warning: the next slide contains graphic imagery of a dead squid

Triggering squid action potentials with soy sauce