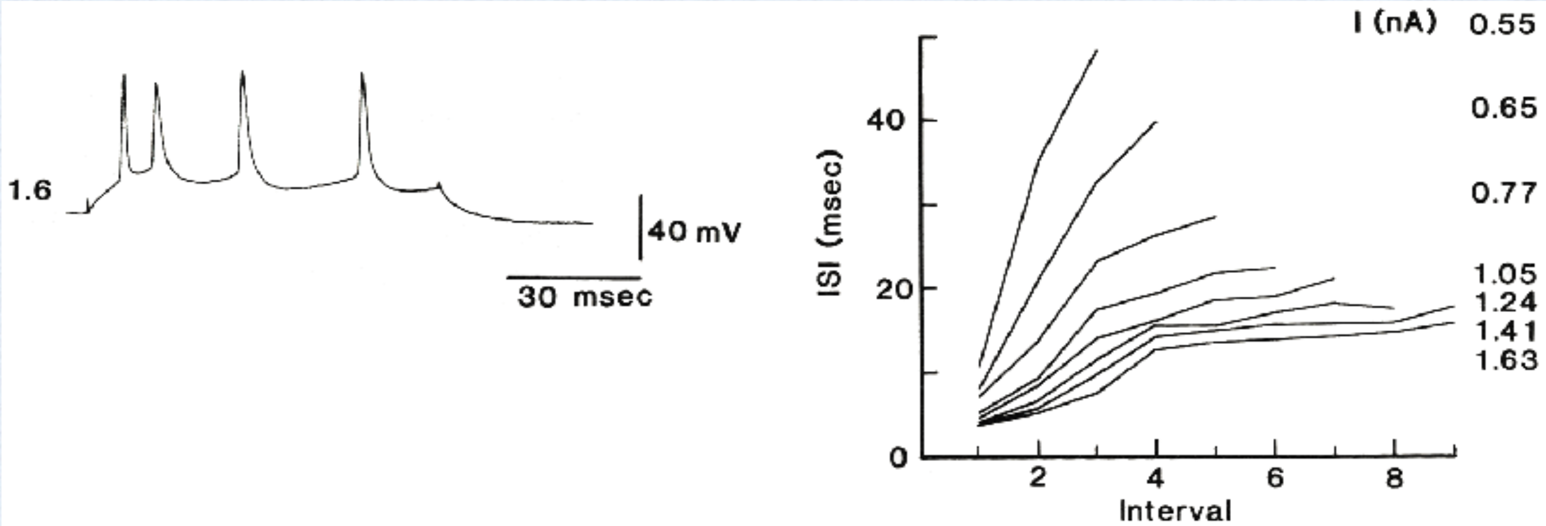
Complex Single Cell Models

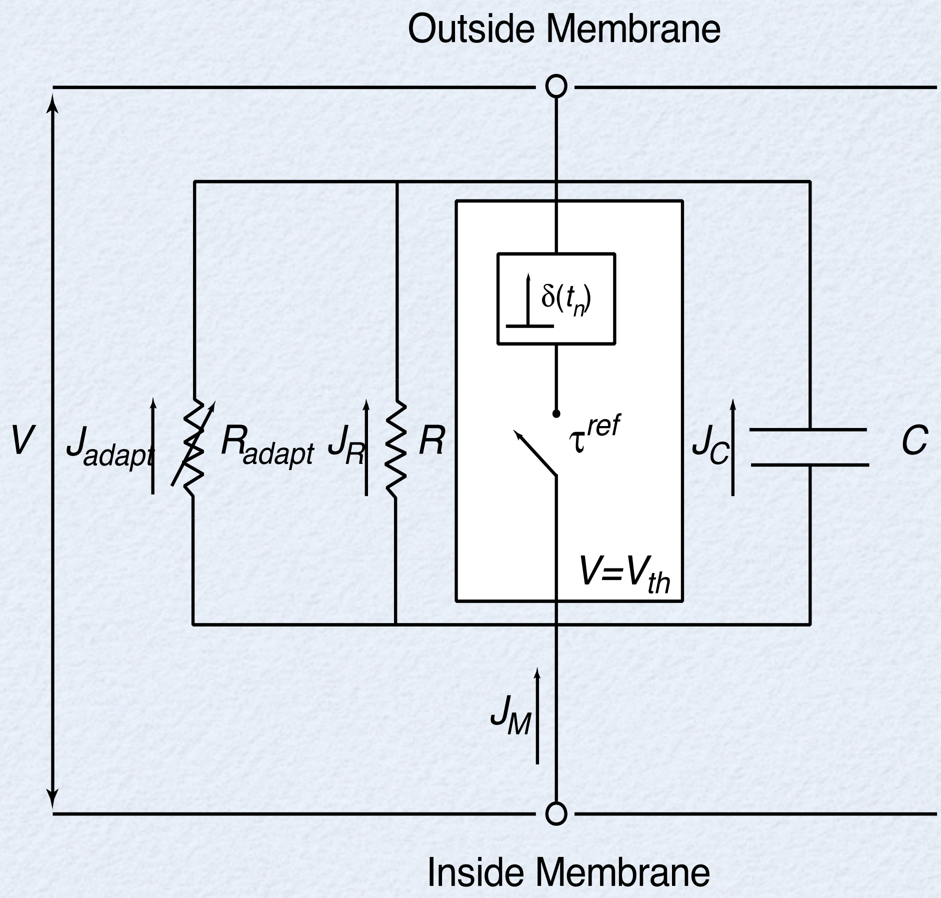
Adaptation

- ‘Regular spiking’ cells most common in cortex
- Adaptation occurs because of a slow hyperpolarizing K current in these cells



Adapting LIF circuit

- A variable resistor, R_{adapt}, can account for this K



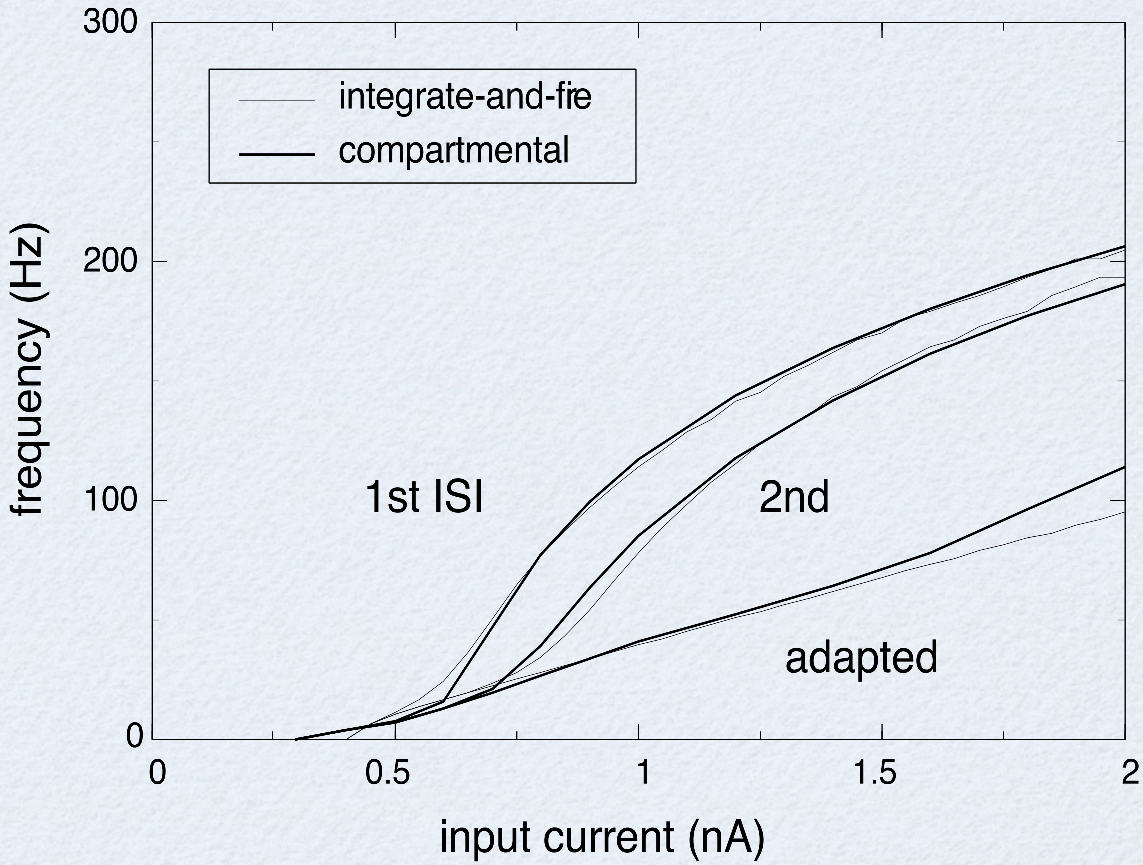
aLIF Behaviour

- Adapt channels stay closed until a spike, then they open (by decreasing R_{adapt}) essentially lowering the reset voltage, making it harder for the next spike to be fired.

- Between spikes, the channels start to close, raising R_{adapt} at a speed determined by τ_{adapt}.

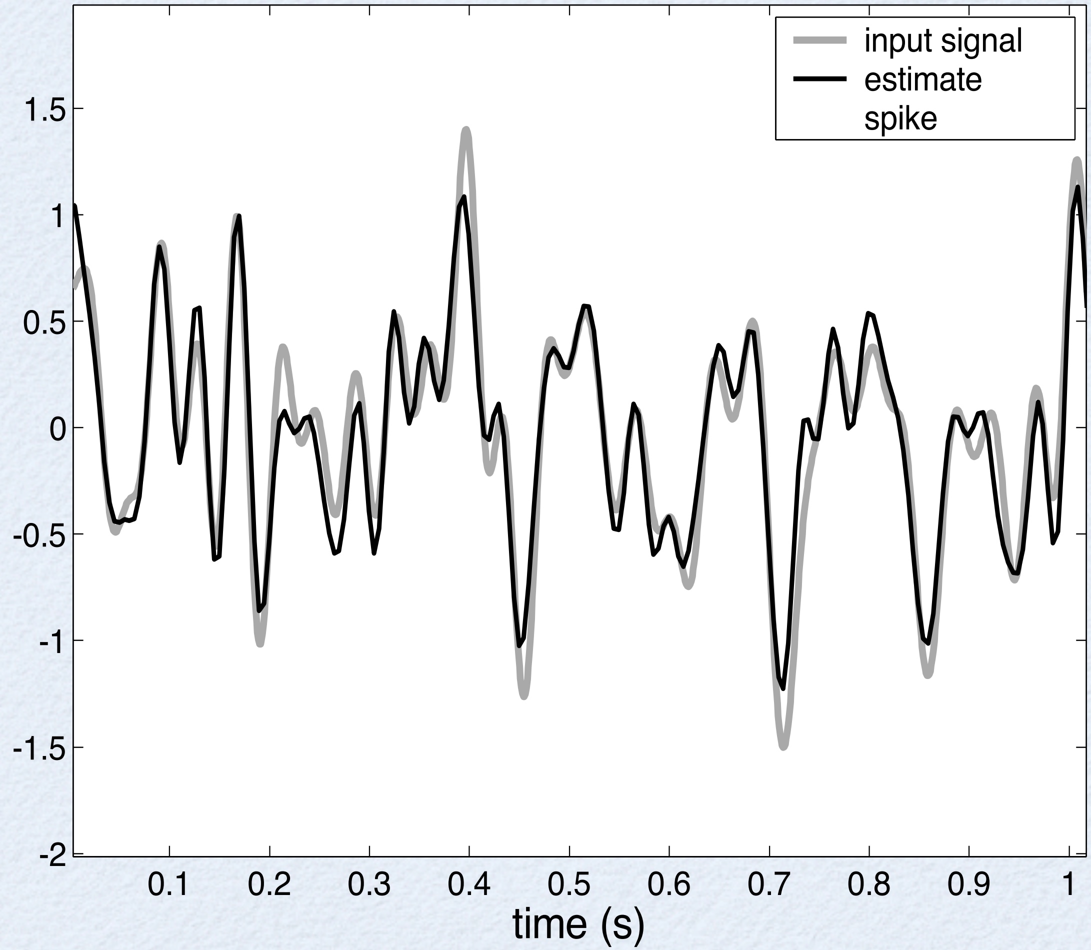
$$
\begin{aligned}
\frac{dV}{dt} &= -\frac{1}{\tau^{RC}}\left(V\left(1+\frac{R}{R_{adapt}}\right)-J_M R\right) \\
\frac{dR_{adapt}}{dt} &= \frac{R_{adapt}}{\tau_{adapt}}
\end{aligned}
$$

- Comparison of aLIF response function to a complex conductance model

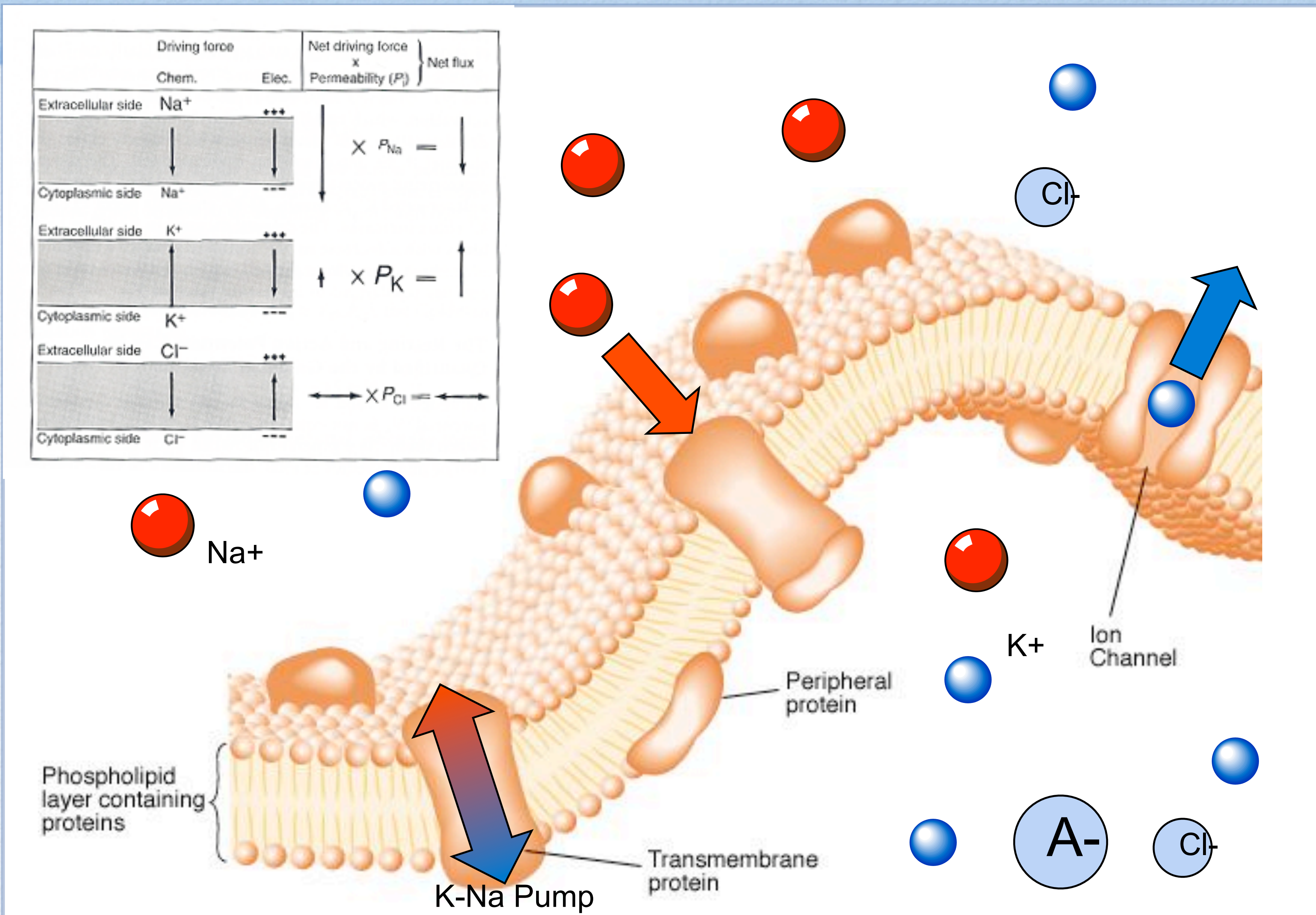


aLIF decoding

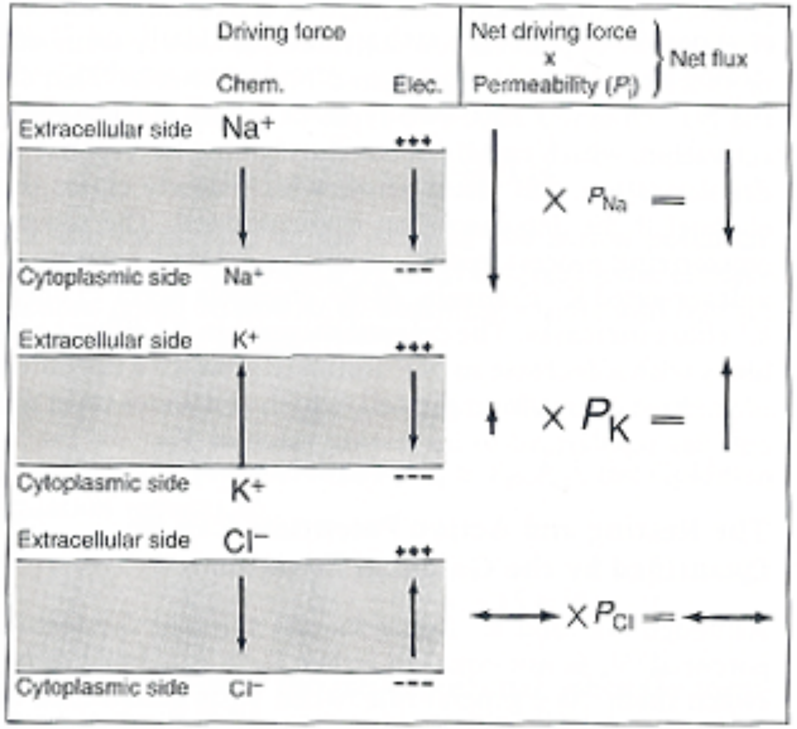
- aLIF (as we will see) is more efficient



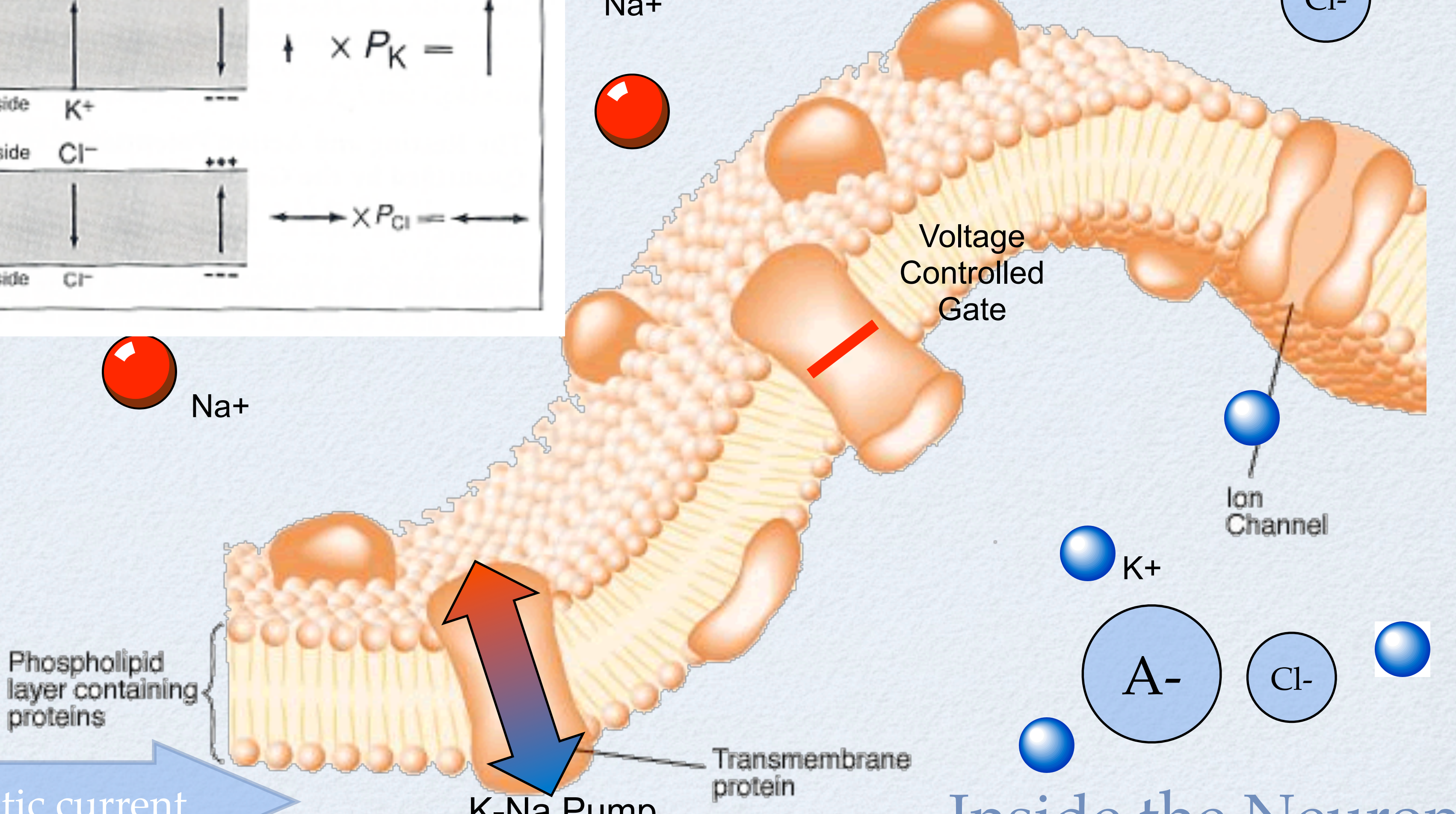
Ion flow: rest



Net Force at Rest

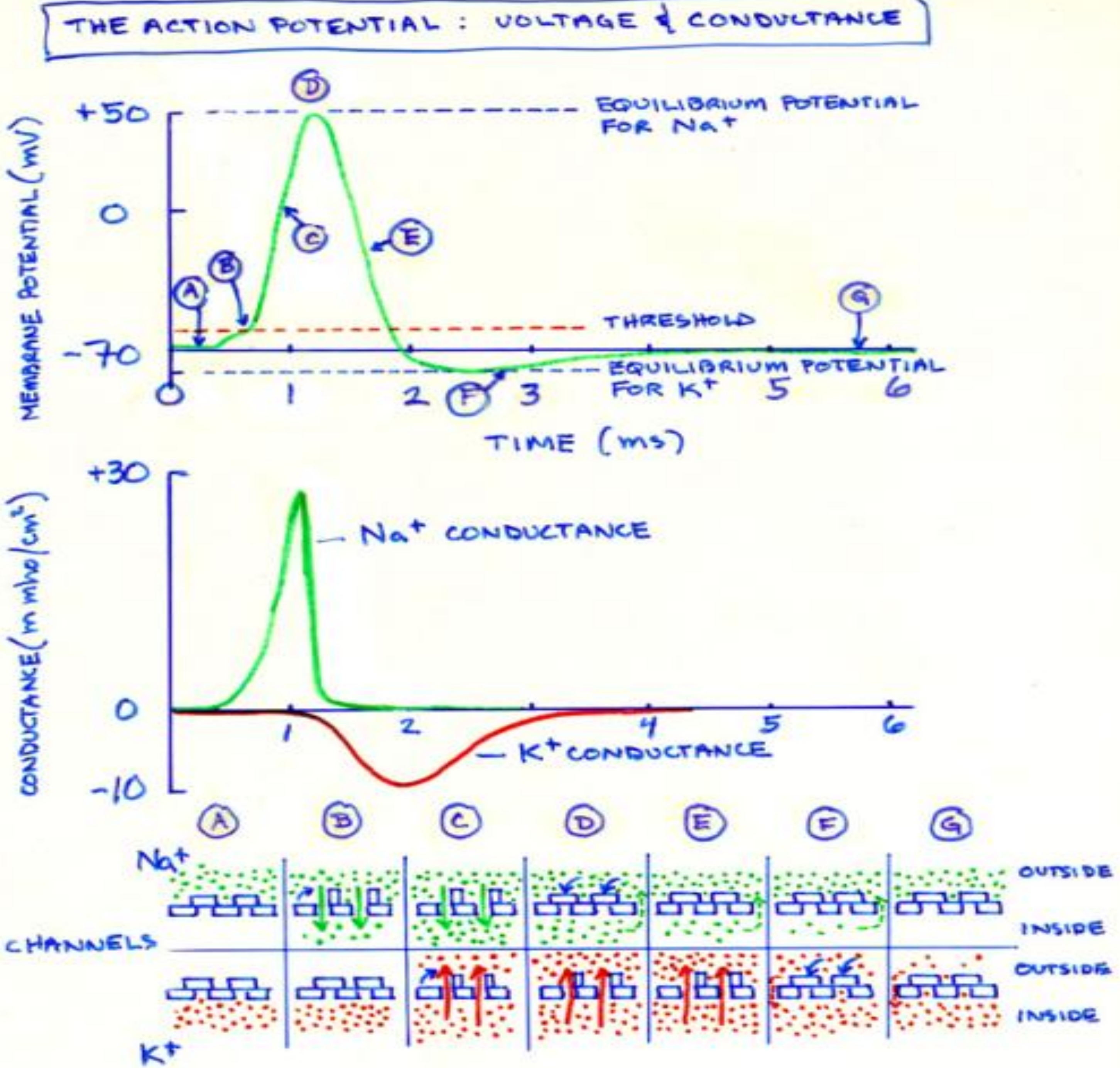


Outside the Neuron



Dendritic current

Inside the Neuron



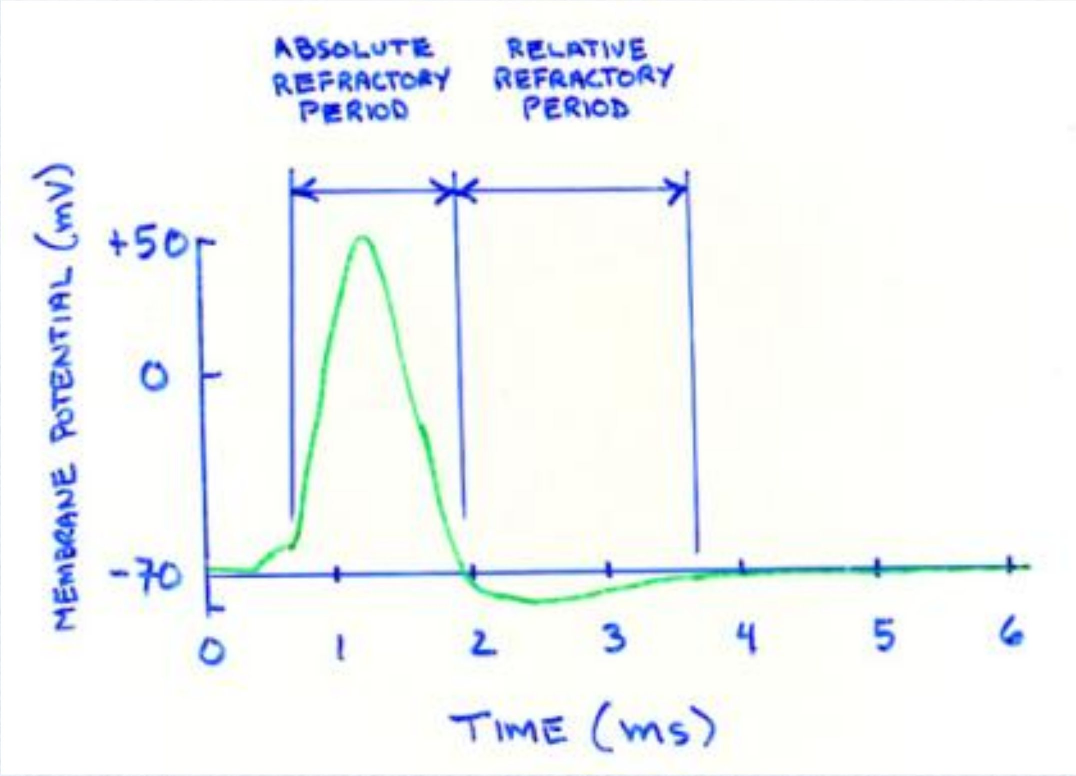
B: Na open
C: K open
D: Na close
E: Na pump
F: K close
G: Pumps

K-Na pump

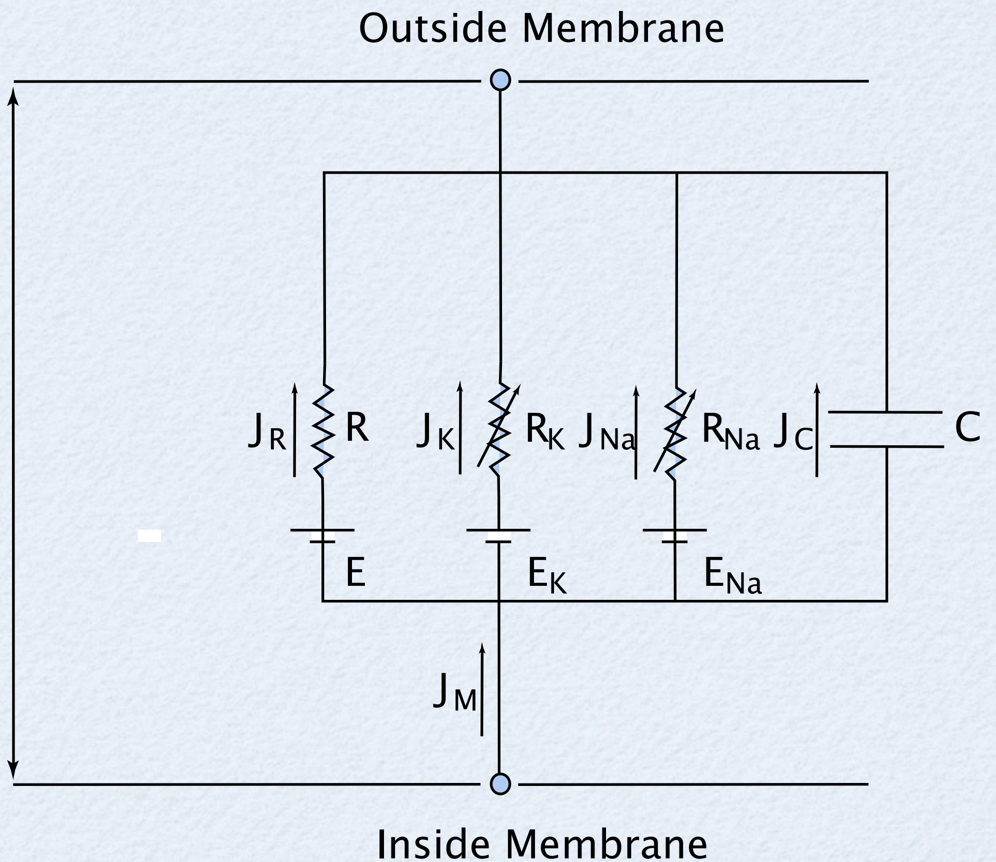
http://tx.technion.ac.il/~yarmola/bioPhys/Nerve%20impulse%20propagation.htm

- Absolute: Na channels are open or recovering. No second spike

- Relative: K channels are open memberane is hyperpolarized (-80mV), so hard to generate 2nd spike (usually from -70mV)



Hodgkin-Huxley circuit



Class II circuit

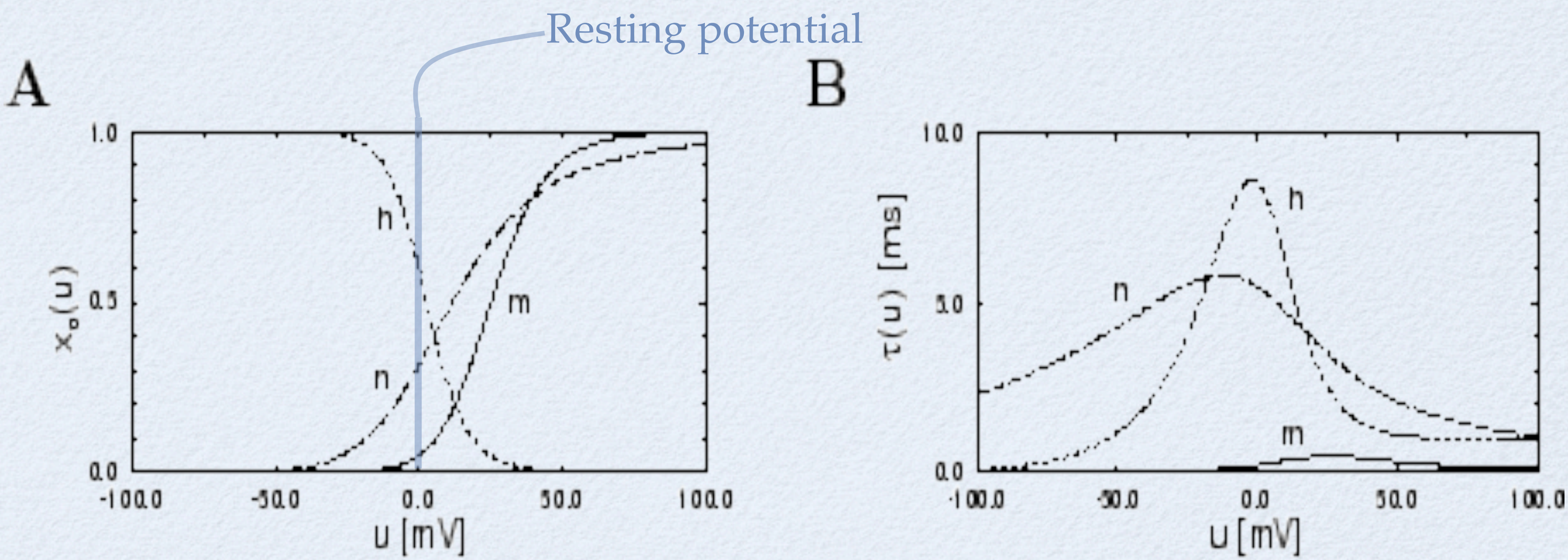
Hodgkin-Huxley equations

- 4D nonlinear differential equation

$$
\begin{aligned}
C\frac{dV}{dt} &= -g_{Na}m^3h(V-E_{Na}) - g_K n^4(V-E_K) - g(V-E) + J_M \\
\frac{dm}{dt} &= \frac{1}{\tau_m(V)}(-m + M(V)) \\
\frac{dh}{dt} &= \frac{1}{\tau_h(V)}(-h + H(V)) \\
\frac{dn}{dt} &= \frac{1}{\tau_n(V)}(-n + N(V)).
\end{aligned}
$$

HH parameter dynamics

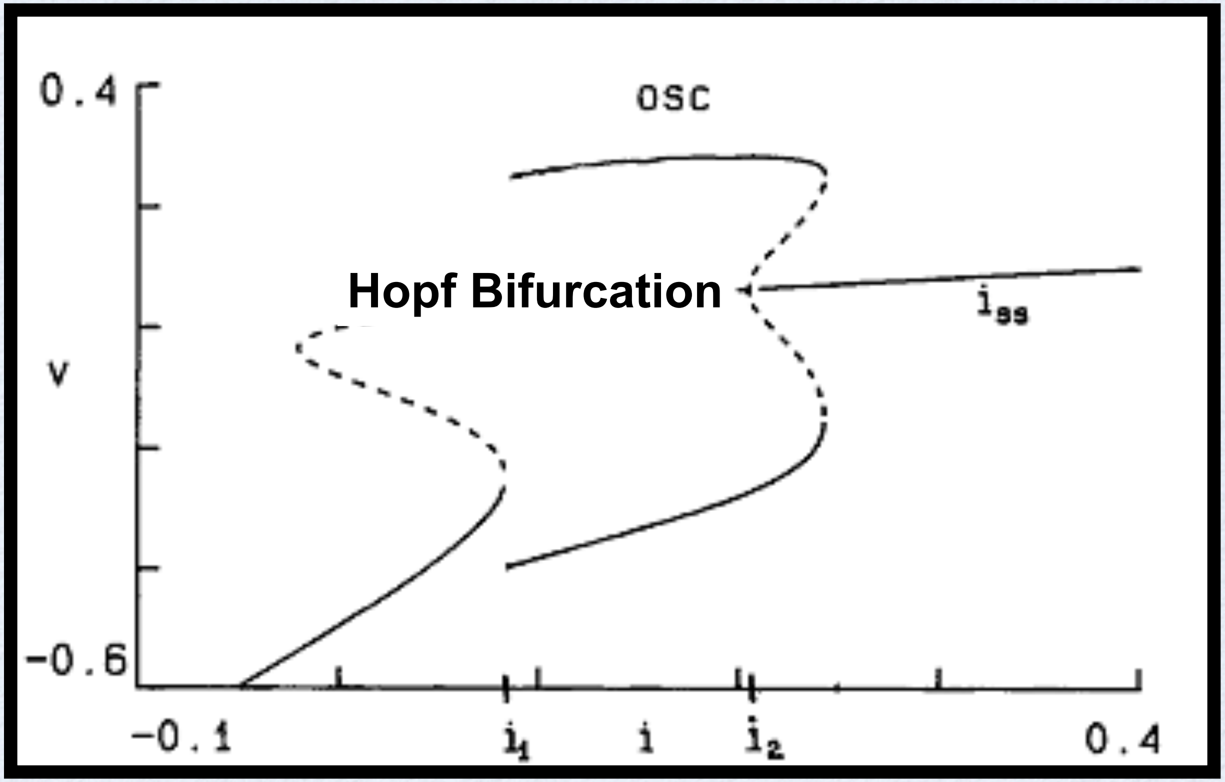
- *m*, *n* activation; *h*, inactiviation params
- all approach some asymptote (e.g., *N*(*V*)) with a time constant (e.g., τ_n).



Asymptotic V value (x%)

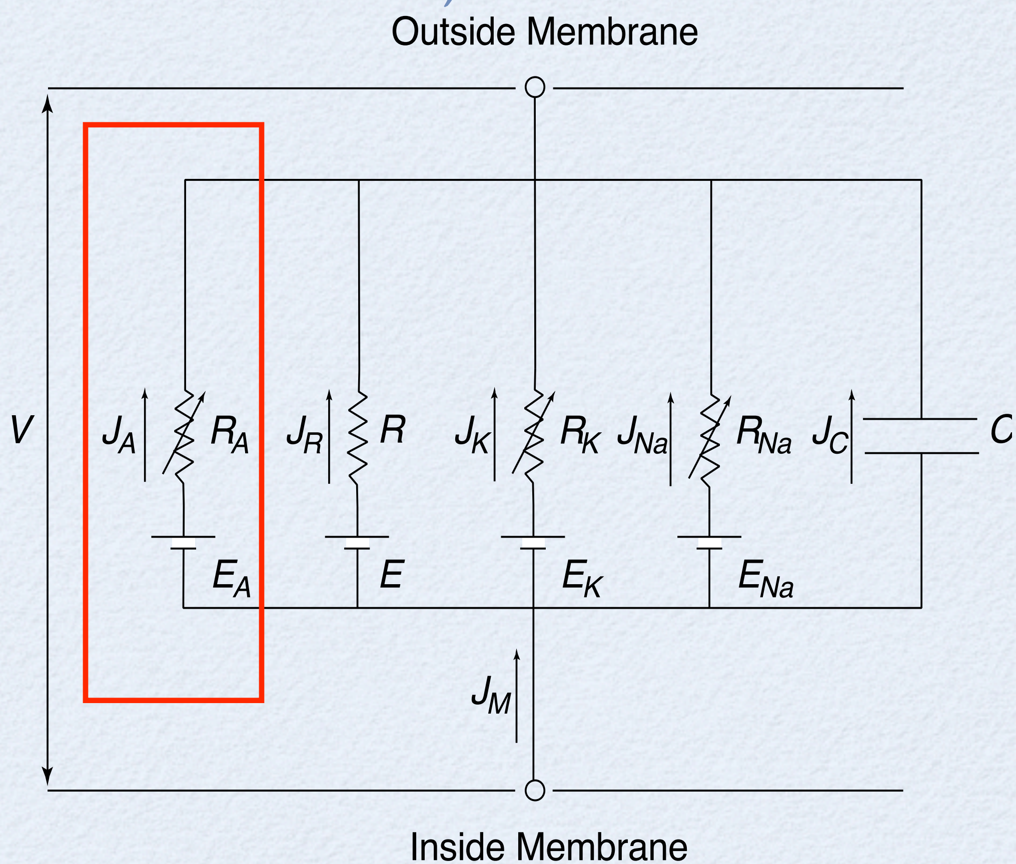
Time constant to x

HH Dynamics: Hopf



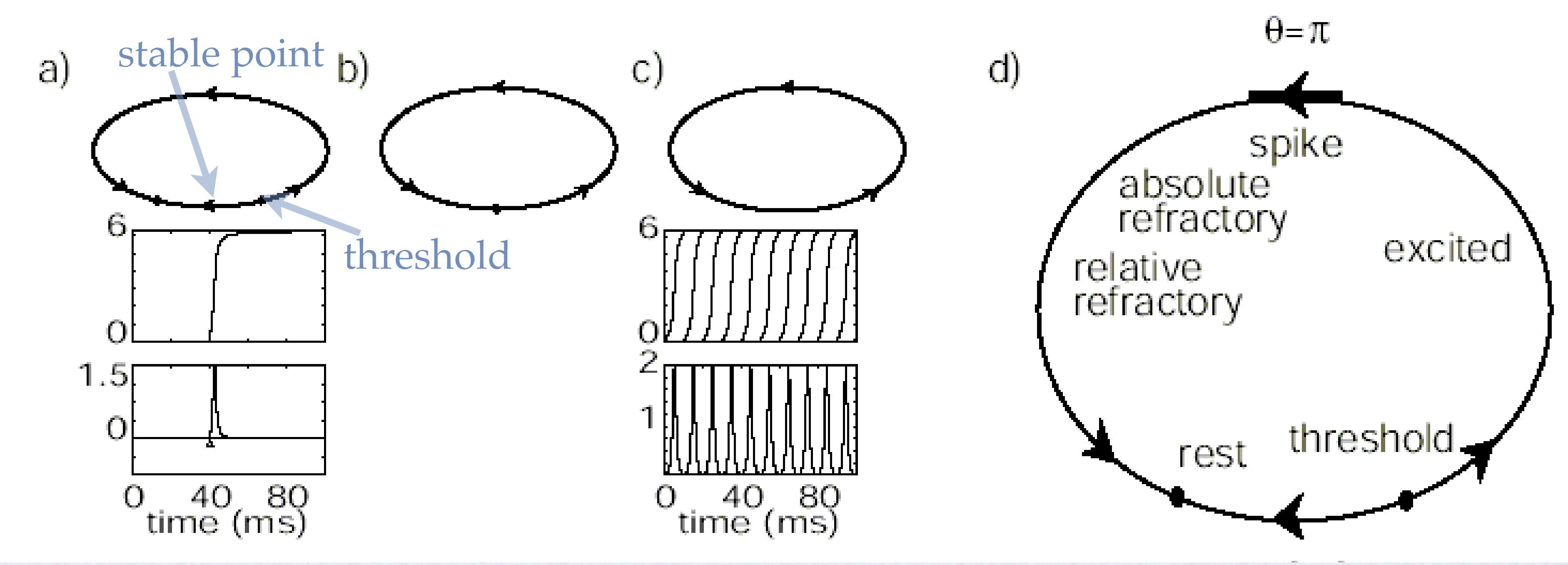
Class I circuit

- zero minimum spiking hz and grow monotonically
- need to add A-current, another fast K current



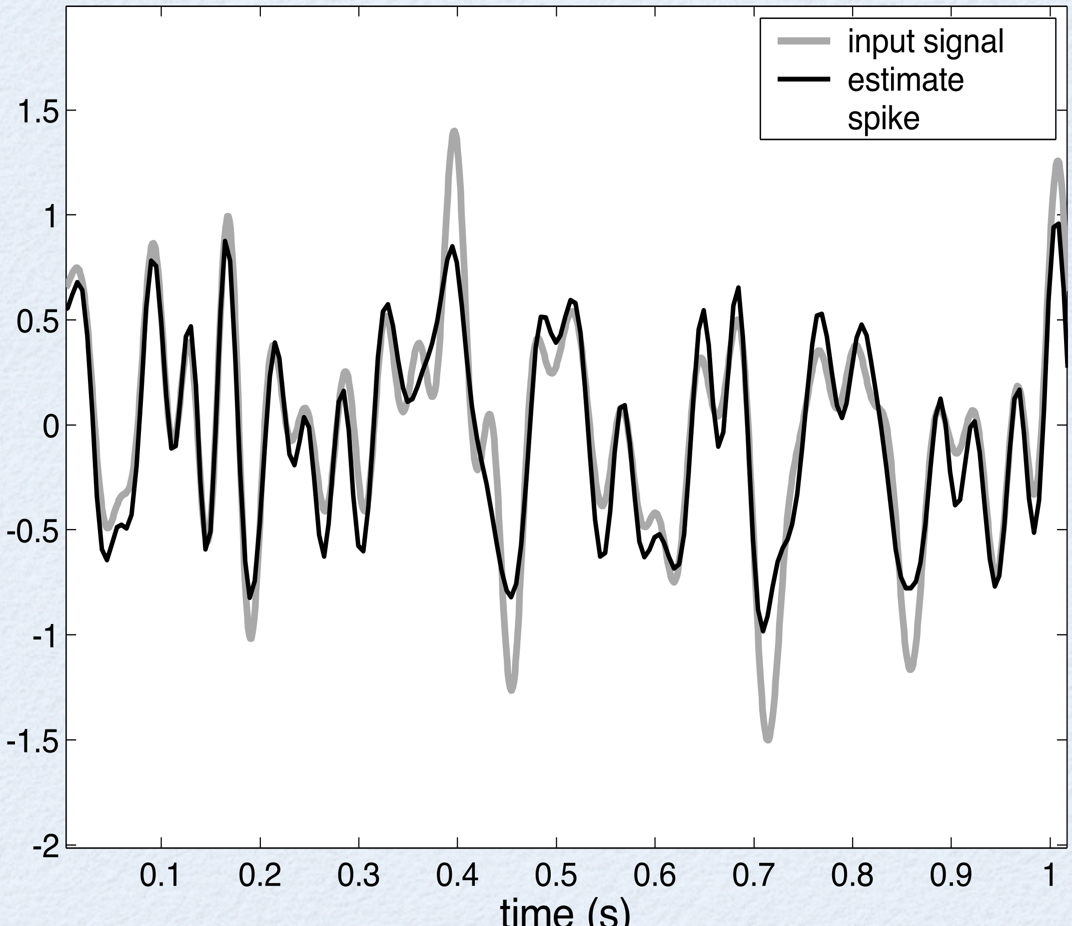
Theta neuron behaviour

- Canonical model of saddle-node bifurcation
- Phase variable maps to neural states



Theta neuron decoding

- Takes 100x longer than LIF to run



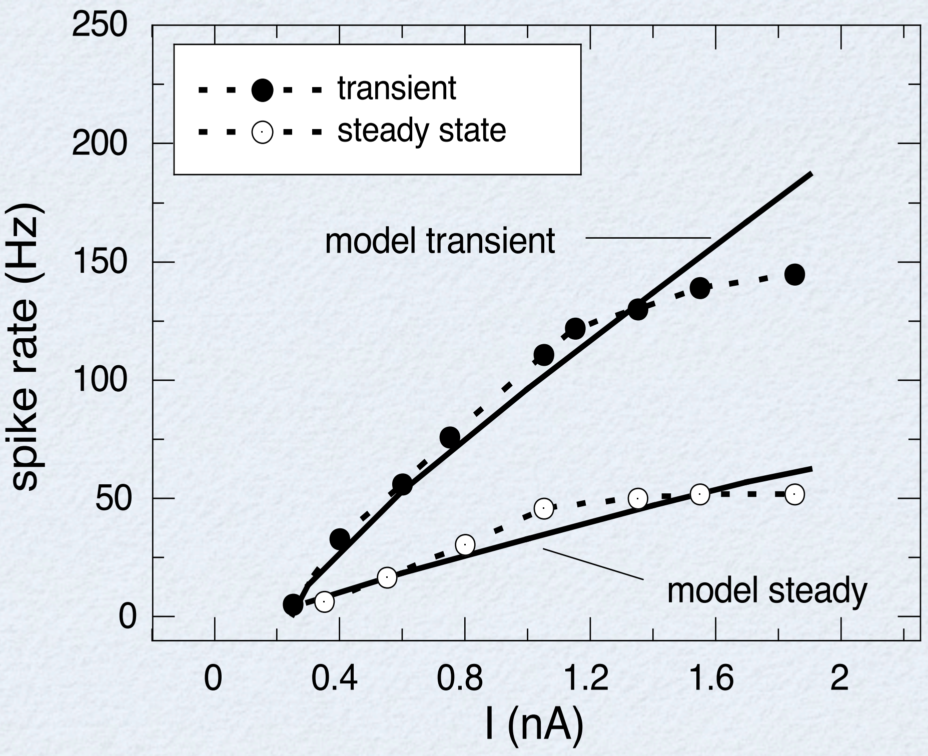
Wilson Neuron (reduced)

- Start with a HH neuron model. Rinzel simps:
  - Na activation is very fast (\tau(V)) is really small), so allow m=M(V) (no dynamics)
  - Na inactivation is equal and opposite to K activation, so let h=1-n (combine h & n -> R)
- We need the A-current. Rose & Hindmarsh simp:
  - Make the dynamics for R quadratic.
- Include adaptation variable with slow dynamics
- Have 3D class I model!

Wilson neuron equations

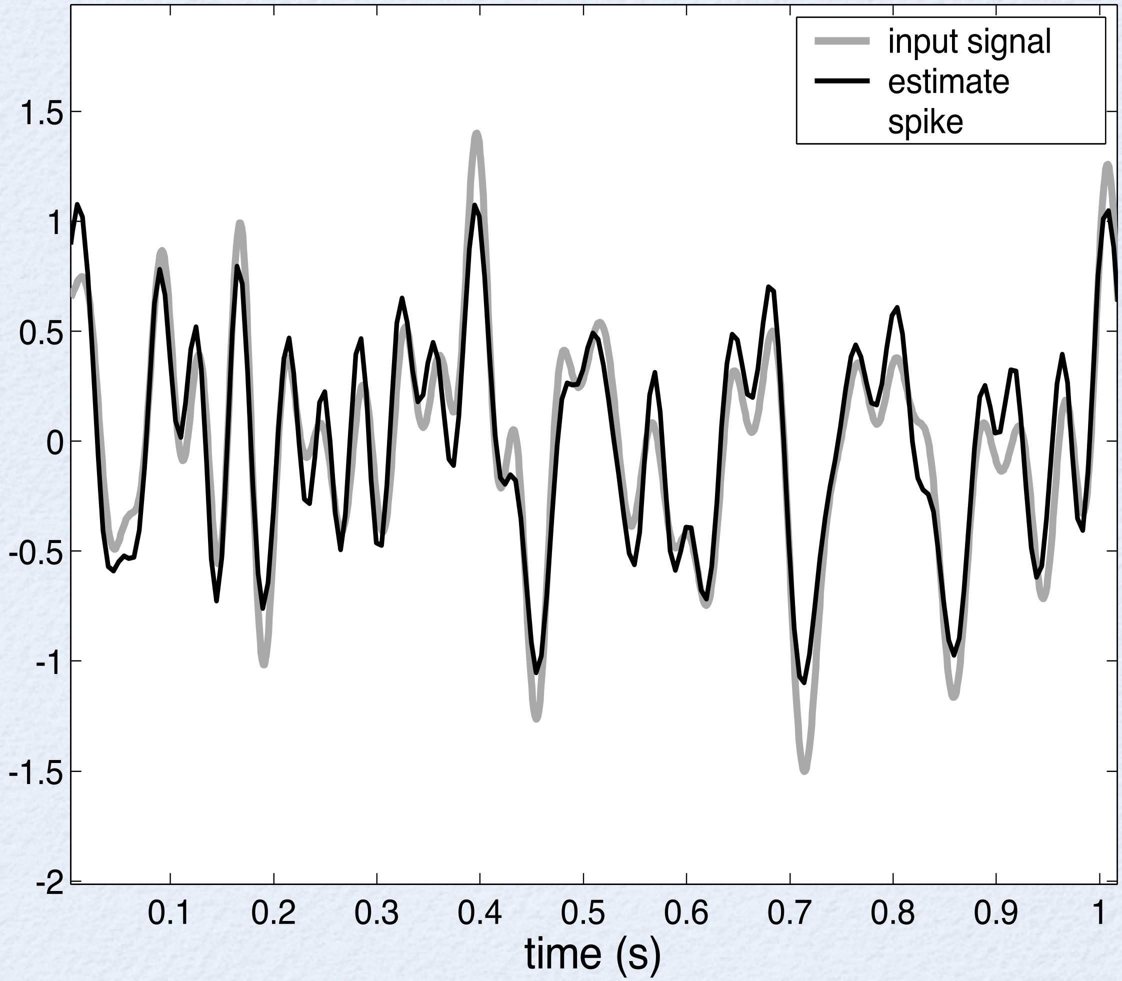
$$
\begin{aligned}
C\frac{dV}{dt} &= -\left(1781 + 4758V + 3380V^2\right)(V - 48) \\
&\quad -26R(V + 95) - 13H(V + 95) + J_M \\
\frac{dR}{dt} &= \frac{1}{5.6}\left(-R + 129V + 79 + 330(V + 38)^2\right) \\
\frac{dH}{dt} &= \frac{1}{99.0}(-H + 11(V + 75.4)(V + 69)).
\end{aligned}
$$

- Comparison of Wilson neuron and real data



- Pros: it's a class I, adapting neuron with spike dynamics; captures spike height changes, spike shape, and after-hyperpolarizations (overshoot of the resting value after a spike)
- Cons: 600x slower than LIF

Wilson neuron decoding



Comparison of neurons

Neuron	Rate	Bits/spike	RMSE	Run time (s)
LIF	114	1.24	0.153	0.18
Adapting LIF	114	2.23	0.153	0.24
θ-Neuron	109	0.96	0.160	20.1
Wilson Model	91	2.00	0.186	125.2

Summary

- variety: `phenomenological' models through to more complete models that include adaptation, spike dynamics, and ion channel dynamics.
- We haven't discussed are compartmental models. (http://diwww.epfl.ch/~gerstner/SPNM/node17.html).
- All of the models have info rates between 1-3 b/s
- Adaptation seems to help improve efficiency (using Gaussian white noise here)
- LIF are very computationally efficient and have reasonable info trans efficiency.