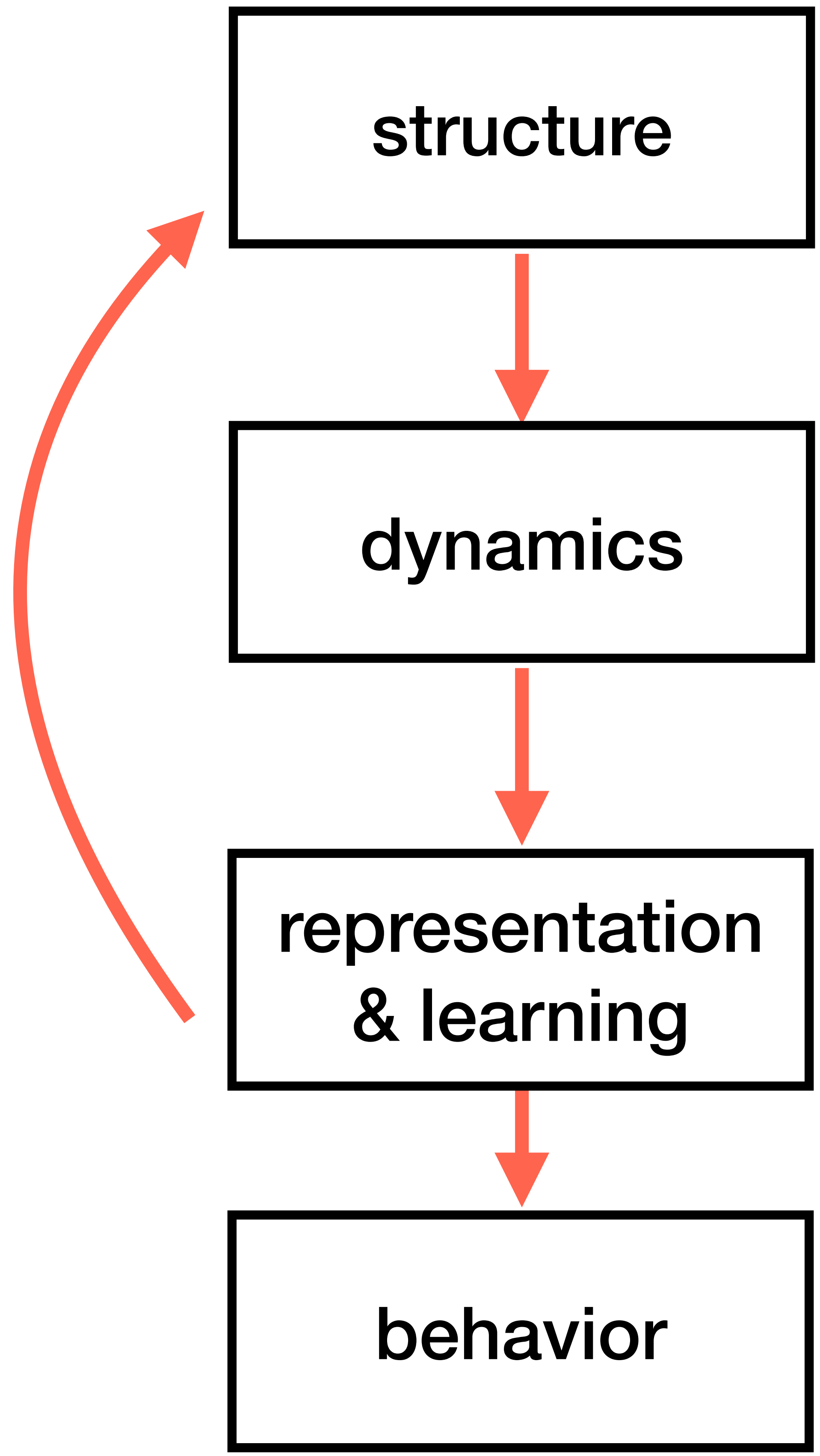
Single Neuron Computation


structure
dynamics
representation & learning
behavior

Course Curriculum

- **Introduction to Computational Neuroscience**
- **Single Neuron Computation**
- **Connect Neurons to Perform Computation**
- **Recurrent network and Attractor Dynamics**
- **E/I balance and Chaotic Dynamics**
- **Efficient coding principle**
- **Stimulus discrimination, Fisher information and Information-limited correlation**
- **Normative approach to neural computation and the emergence of sensory representation**
- **Dimensionality reduction and motor representation**
- **How does an animal move, an integrated approach, and insights from *C. elegans***
- **Reward and Reinforcement Learning**

https://github.com/Wenlab/Computation-Neuro-Course/tree/Fall2024

README MIT license

Computational-Neuroscience-Course

This repository serves as an ongoing effort to create a systems and computational neuroscience course. I hope to develop a two-semester course for USTC biophysics students. The first semester will cover some basic materials, and the second semester will introduce more advanced topics for undergraduate and graduate students.

When: Thursday 9:45 am - 11:20 am, Fall 2024
Where: 东区第二教学楼2403
Teacher: 温泉 qwen@ustc.edu.cn
Teaching Fellow: 冼奇琪 xianqiqi@mail.ustc.edu.cn 李懿轩 hyperdunk2019@mail.ustc.edu.cn

Recommended Textbooks:

- Theoretical Neuroscience: Computational and Mathematical Modeling the Neural System
- Principles of Neural Design

For a general reader:

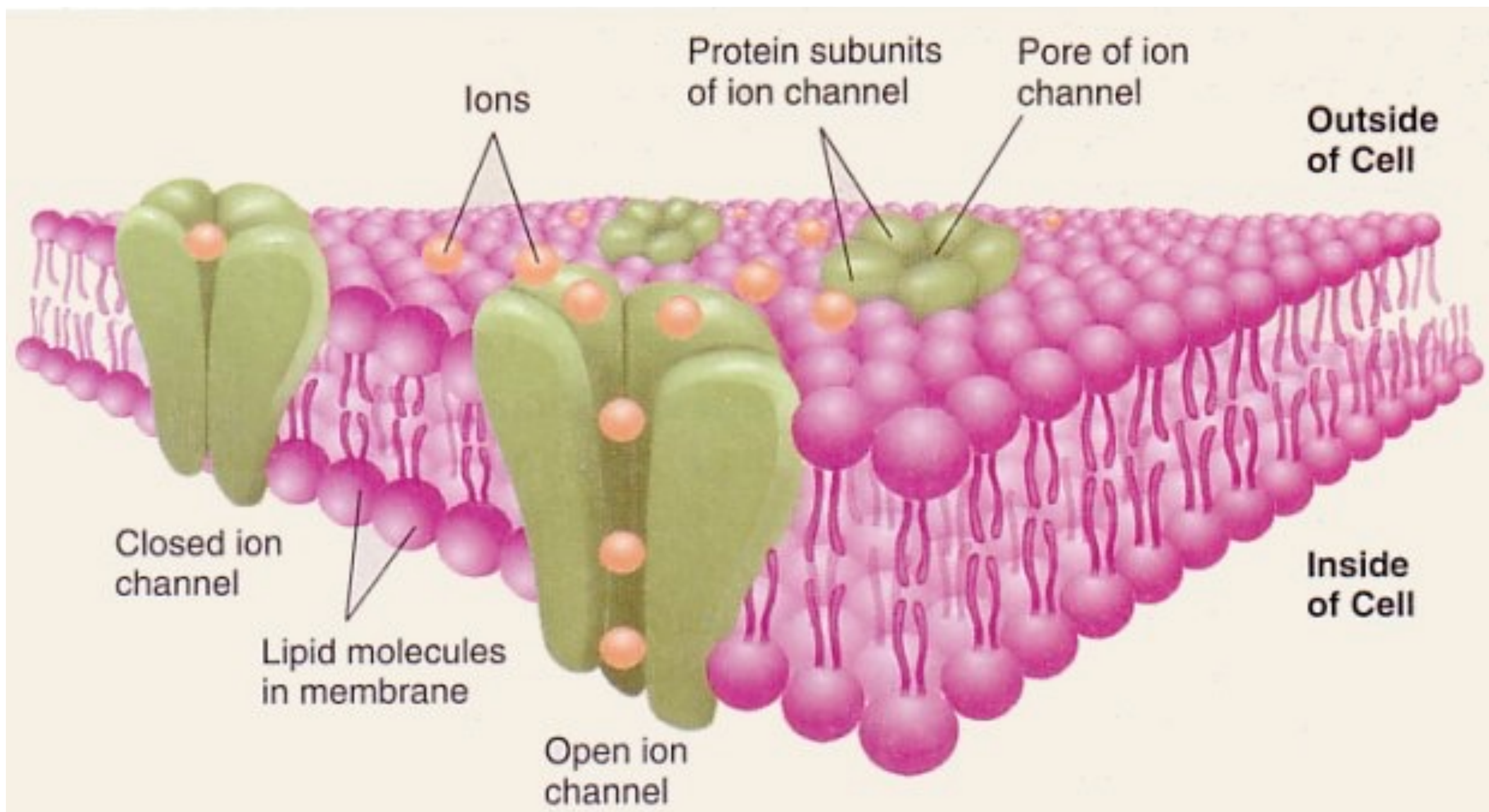
- Model of the Mind

Course Performance Evaluation:

- Homework: 70%
- Final: 30% (take-home exam)

Prerequisite:

- High school knowledge of biology and neuroscience

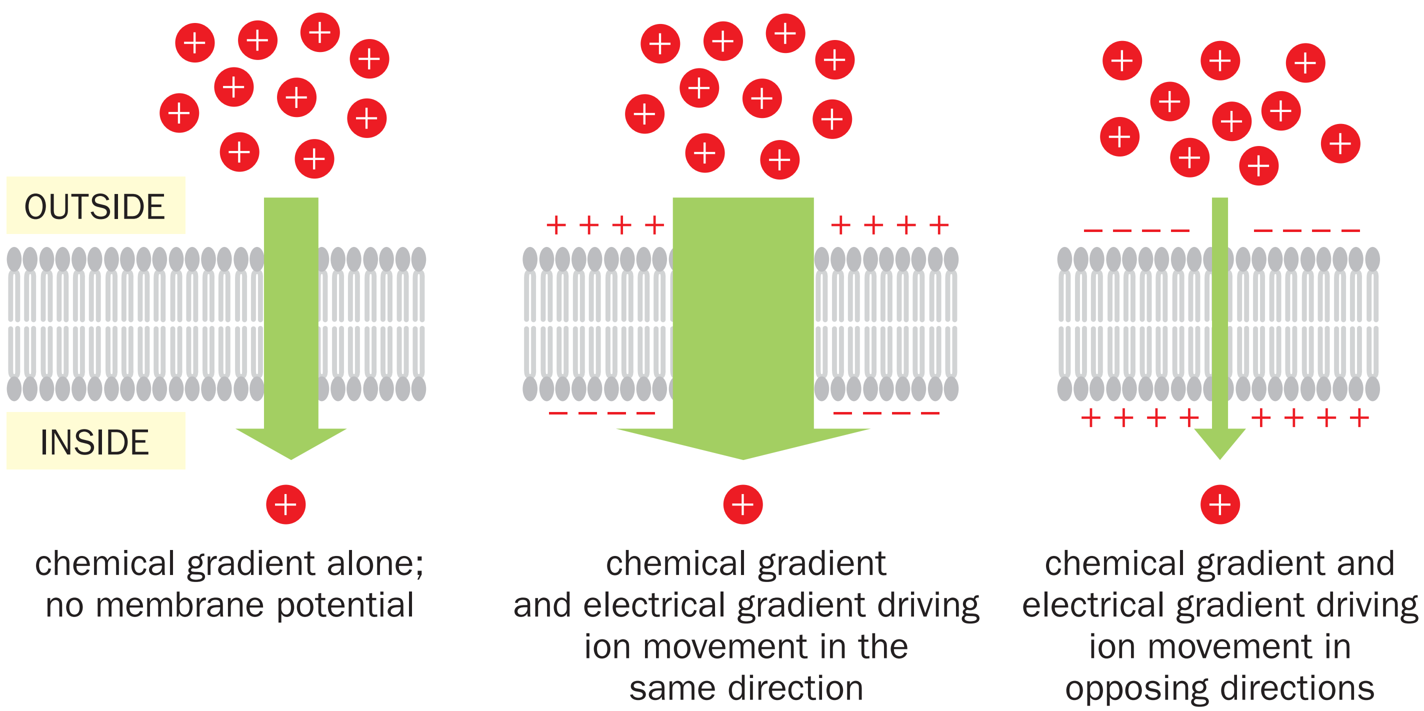


$$qV \sim k_B T$$

$$k_B = 8.6 \times 10^{-5} eV/K$$

$$T = 300\ K$$

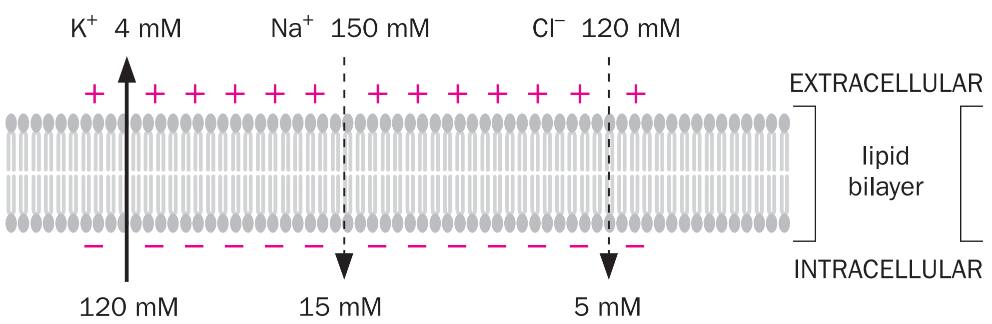
What determines the resting potential of a neuron?



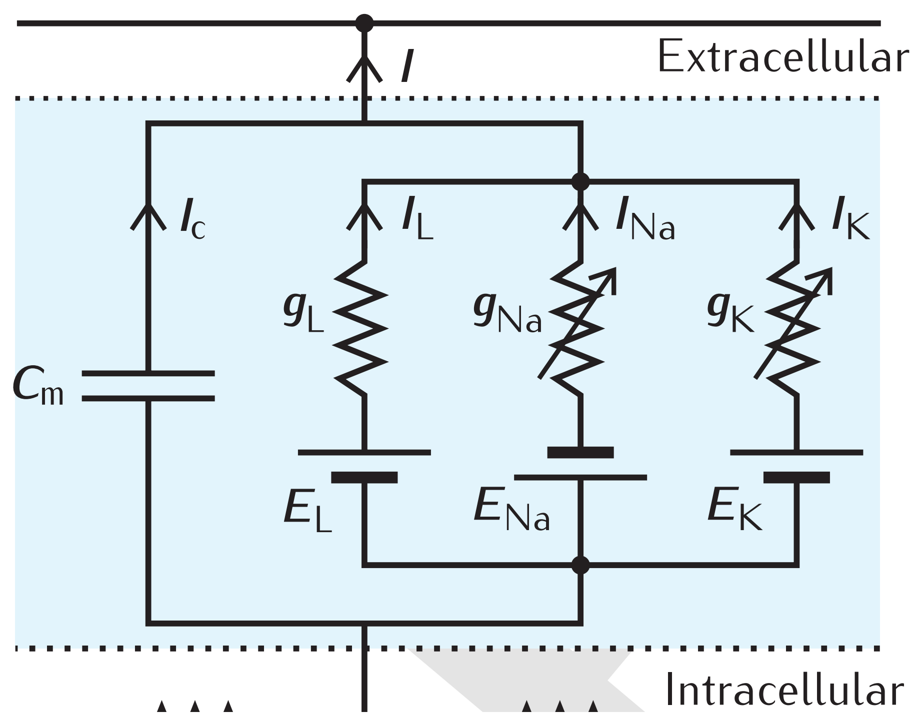
$$E = \frac{k_B T}{ze} \ln \frac{n_{out}}{n_{in}}$$

Ion pump

(A)


K+ 4 mM
Na+ 150 mM
Cl− 120 mM
EXTRACELLULAR
lipid bilayer
INTRACELLULAR
120 mM
15 mM
5 mM

The Equivalent Electronic Circuit of a Neuron



$$C_m \frac{dV}{dt} = -\sum_i g_i(V)(V - E_i) - \bar{g}_L(V - E_L) - I_e$$

$C_m \approx 0.1 - 1$ nF

$r_m = 1/g \approx 10 - 100$ MΩ

$\tau_m = C_m r_m \approx 10 - 100$ ms

Squid Giant Axon

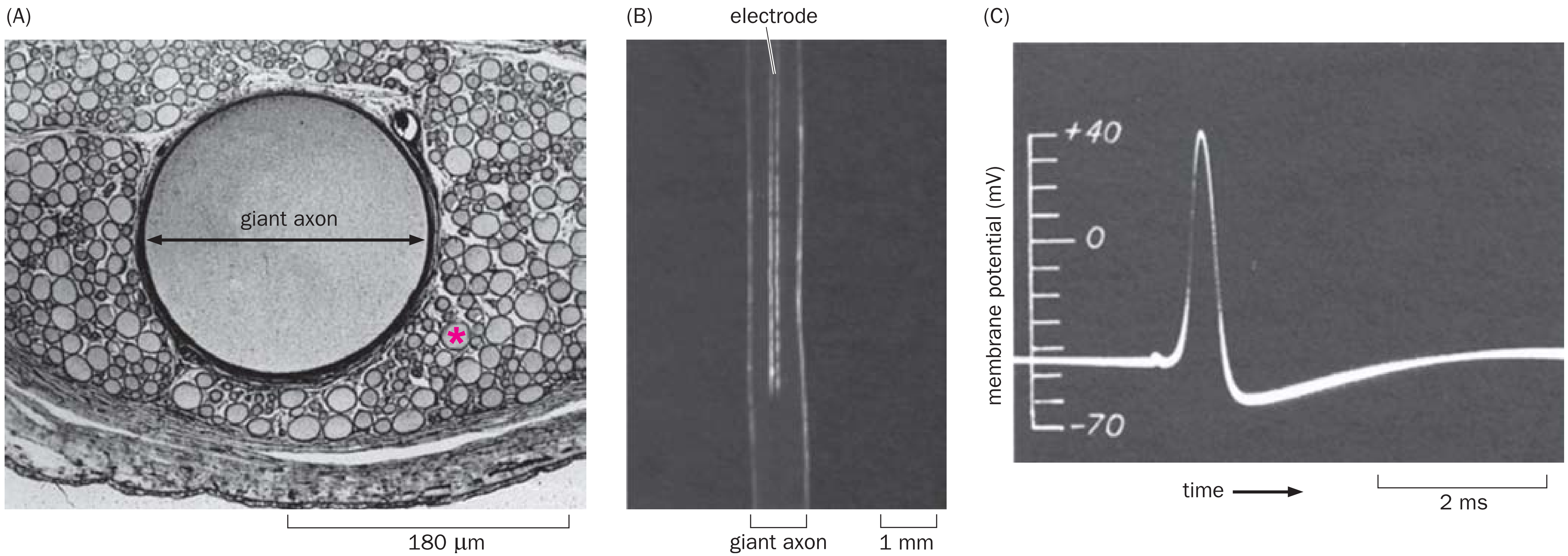
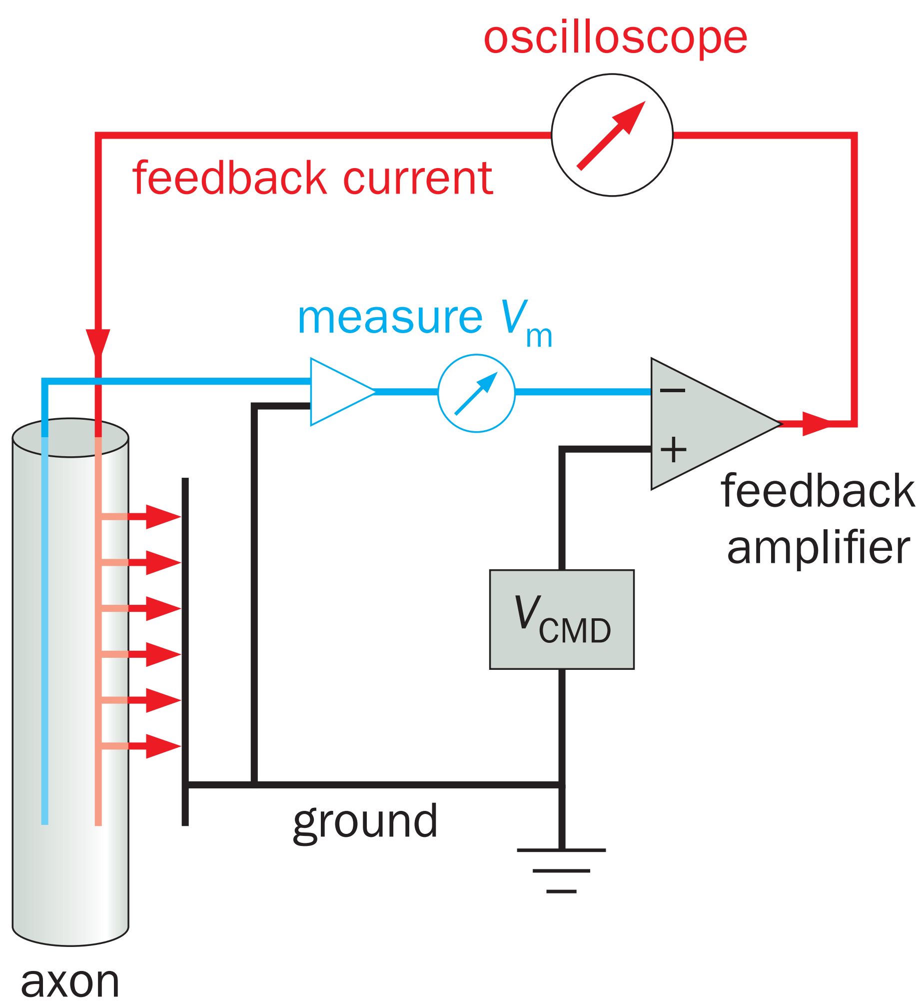
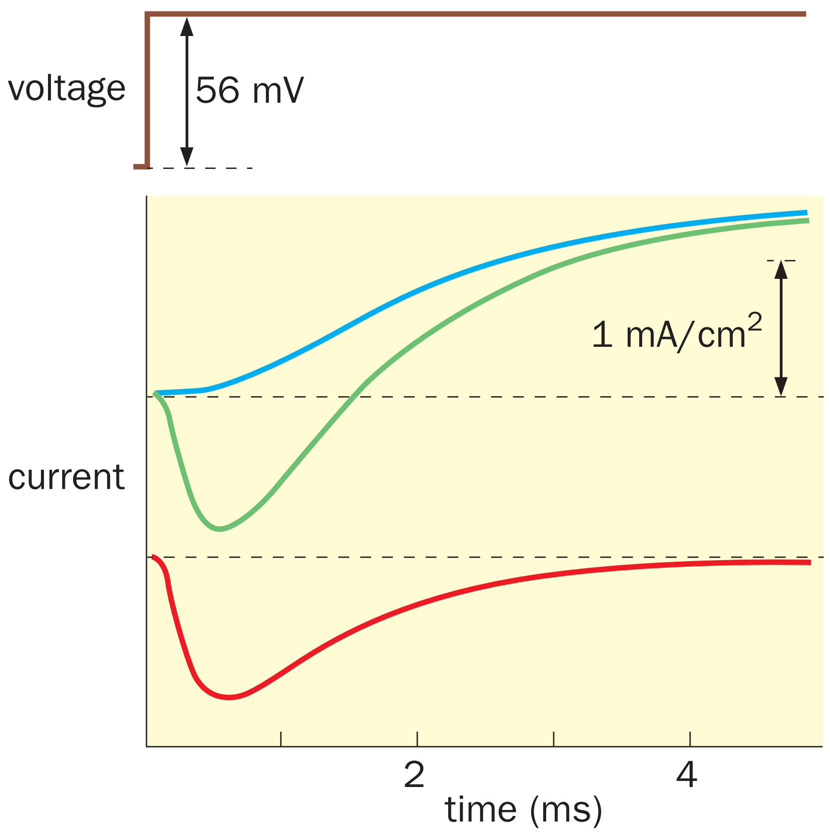


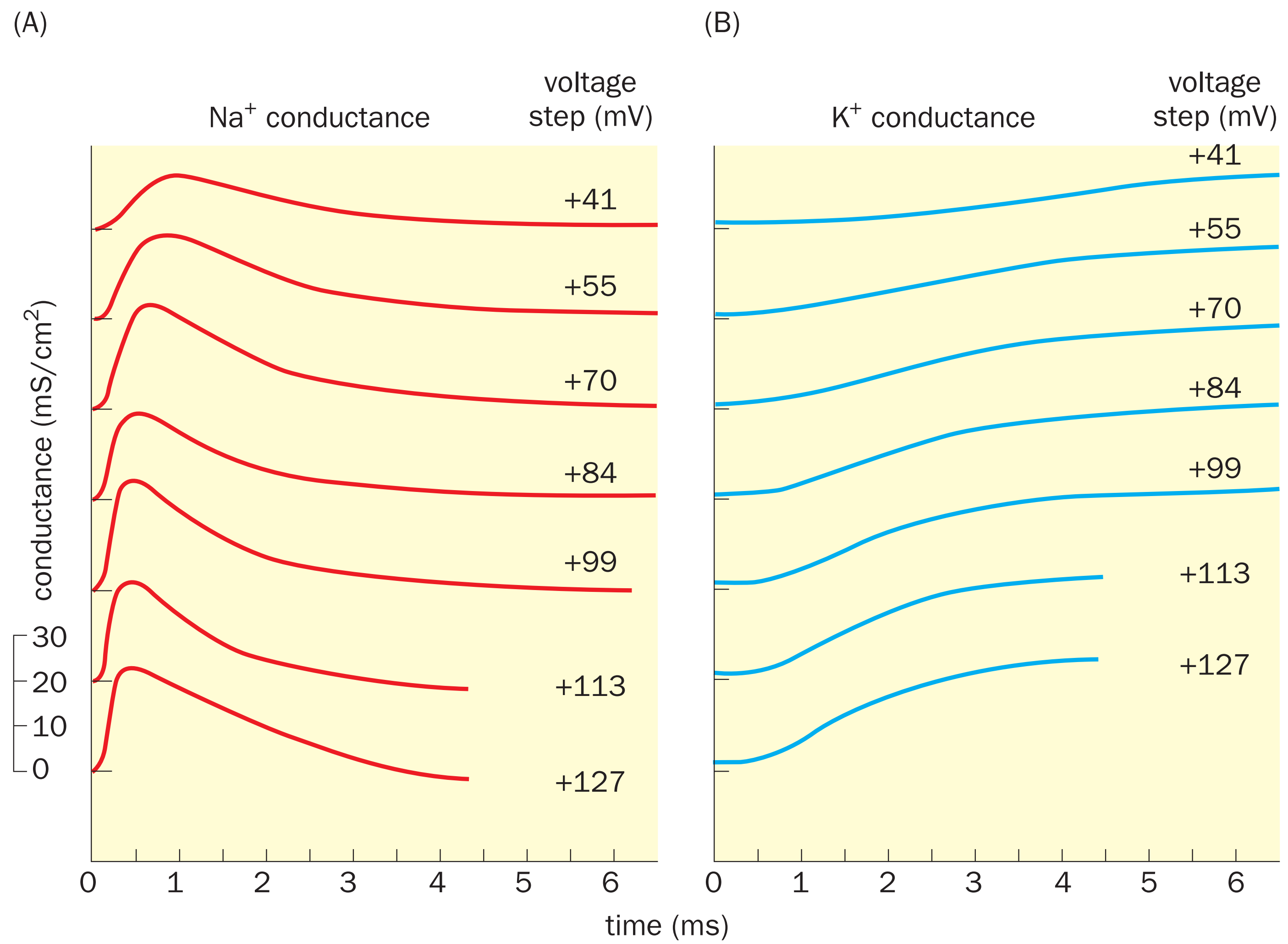
Figure 2–19 Studying action potentials in the squid giant axon. (A) Electron micrograph of a cross section of a squid giant axon showing its large diameter (~180 µm for this sample) as compared to neighboring axons (for example, the axon indicated by *). **(B)** Photograph of an electrode inserted inside a squid giant axon whose diameter is close to 1 mm. **(C)** An action potential recorded from the squid giant axon. (A, courtesy of Kay Cooper and Roger Hanlon; B, from Hodgkin AL & Keyes RD [1956] *J Physiol* 131:592–616; C, from Hodgkin AL & Huxley AF [1939] *Nature* 144:710–711. With permission from Macmillan Publishers Ltd.)

Voltage Clamp Recording

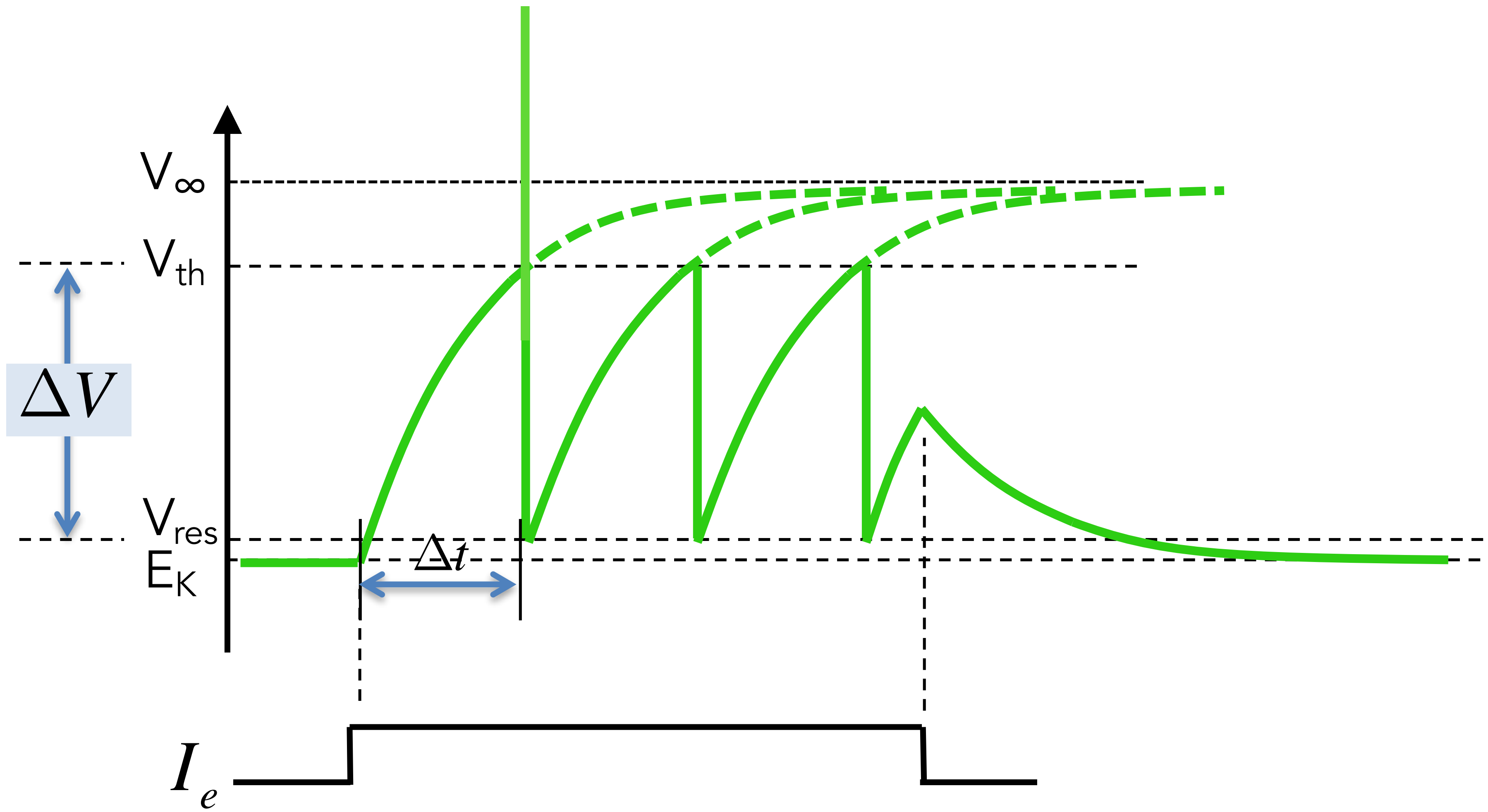




Voltage-gated Conductance



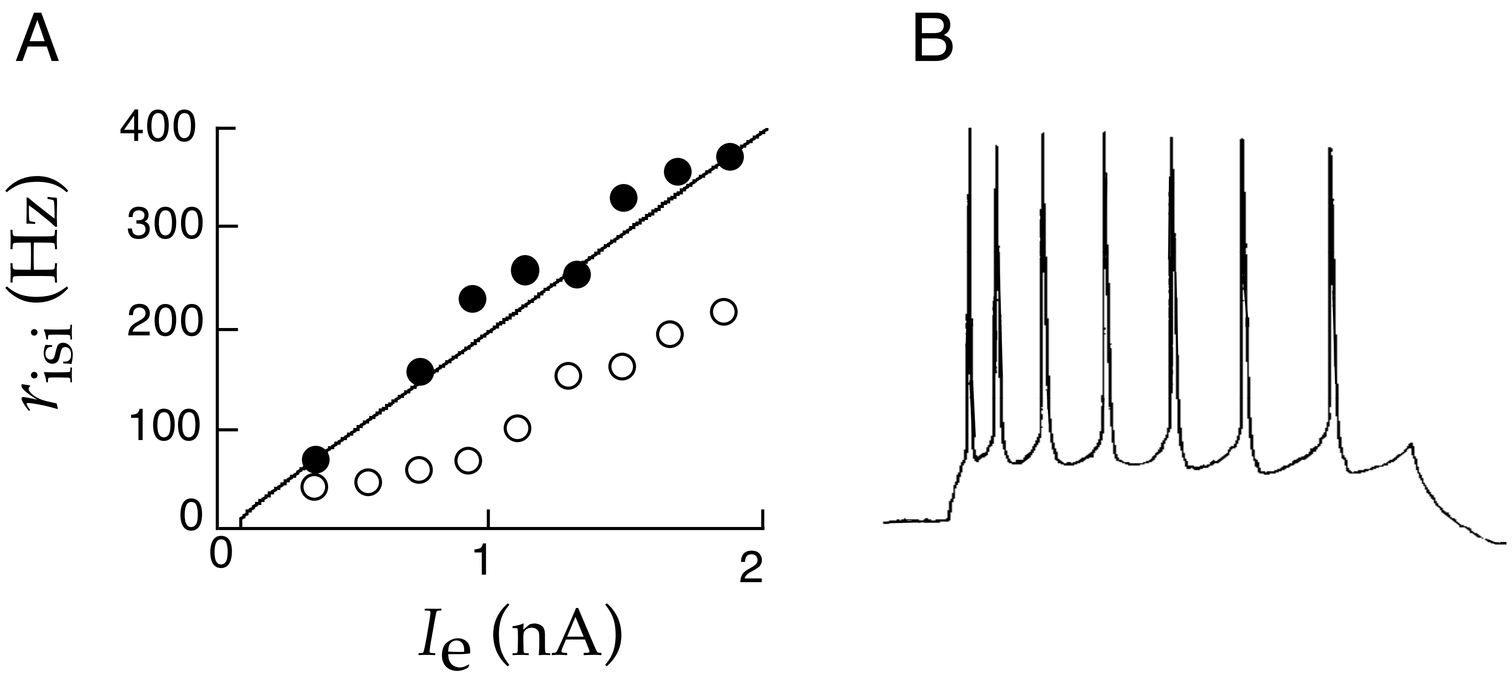
Integrate-and-Fire model



$$C\frac{dV}{dt} = -g(V - E_K) + I_e$$

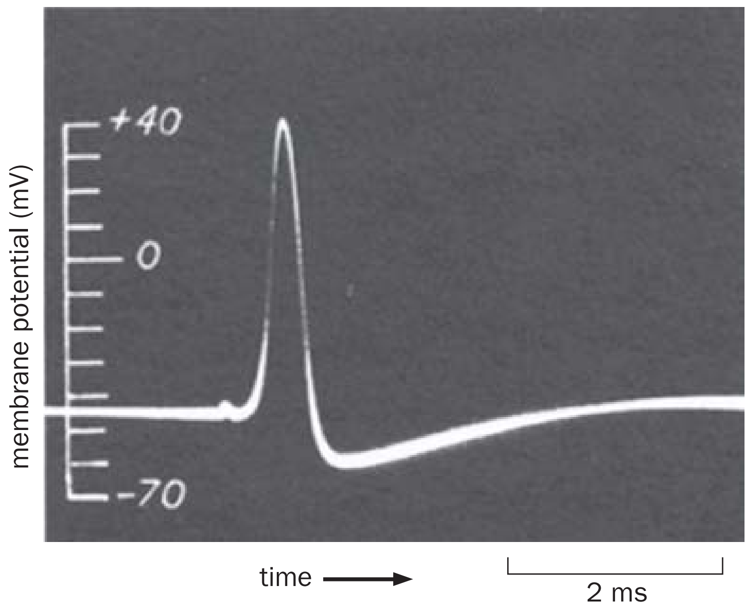
$$V(t^-_{spike}) = V_{th}$$

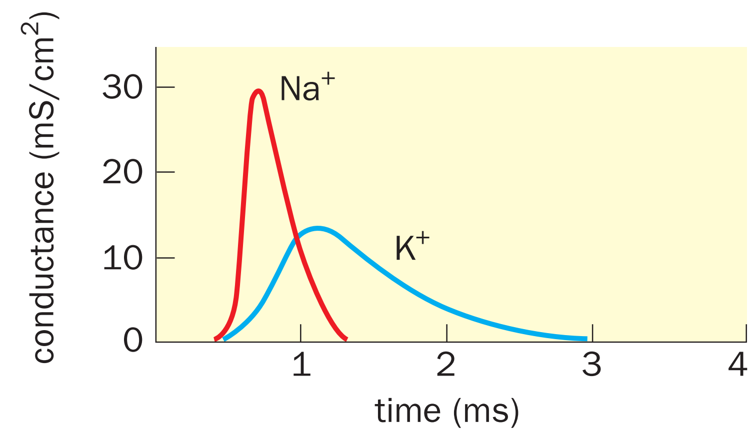
$$V(t^+_{spike}) = V_{res}$$



A
B
400
300
200
100
0
0
1
2
r_{isi} (Hz)
I_e (nA)

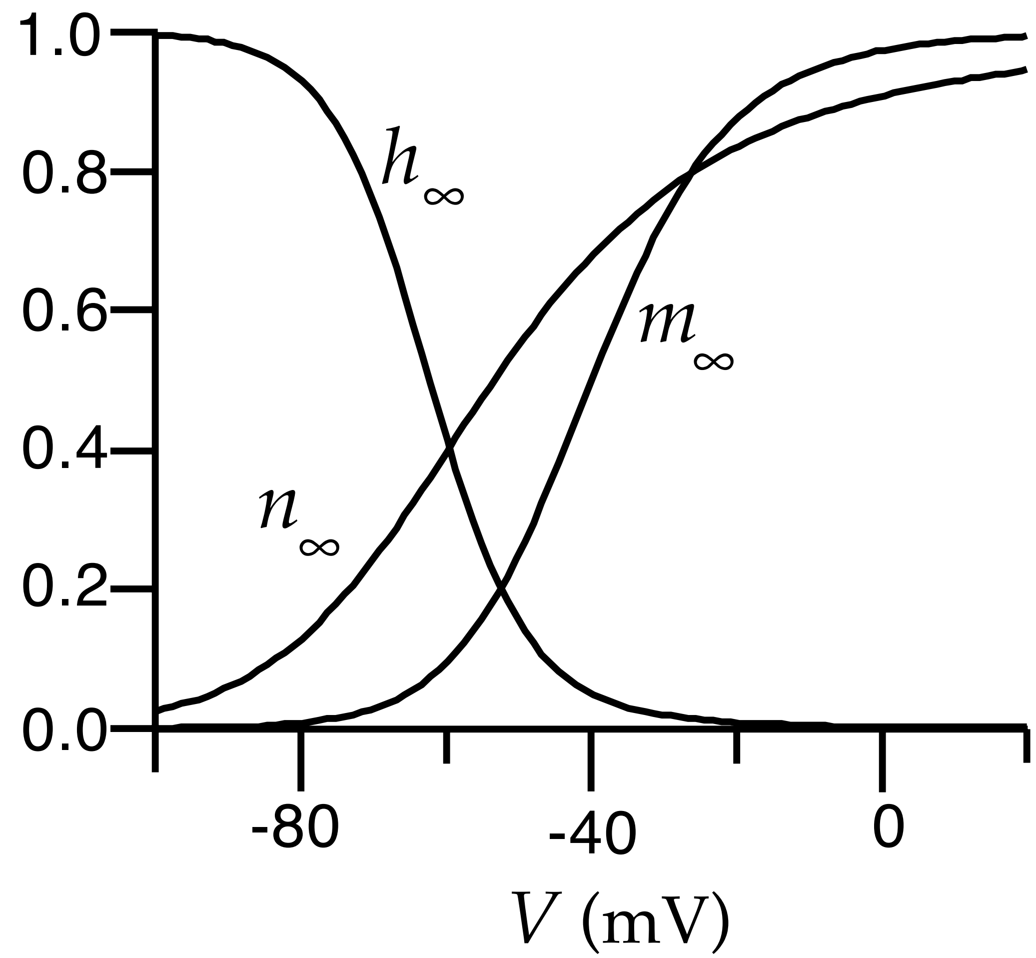
(C)





$$C\frac{dV}{dt} = -g_K n^4(V - E_K) - g_{Na} m^3 h(V - E_{Na}) - g_L(V - E_L) - I_e$$

Transient Na^+ channel conductance

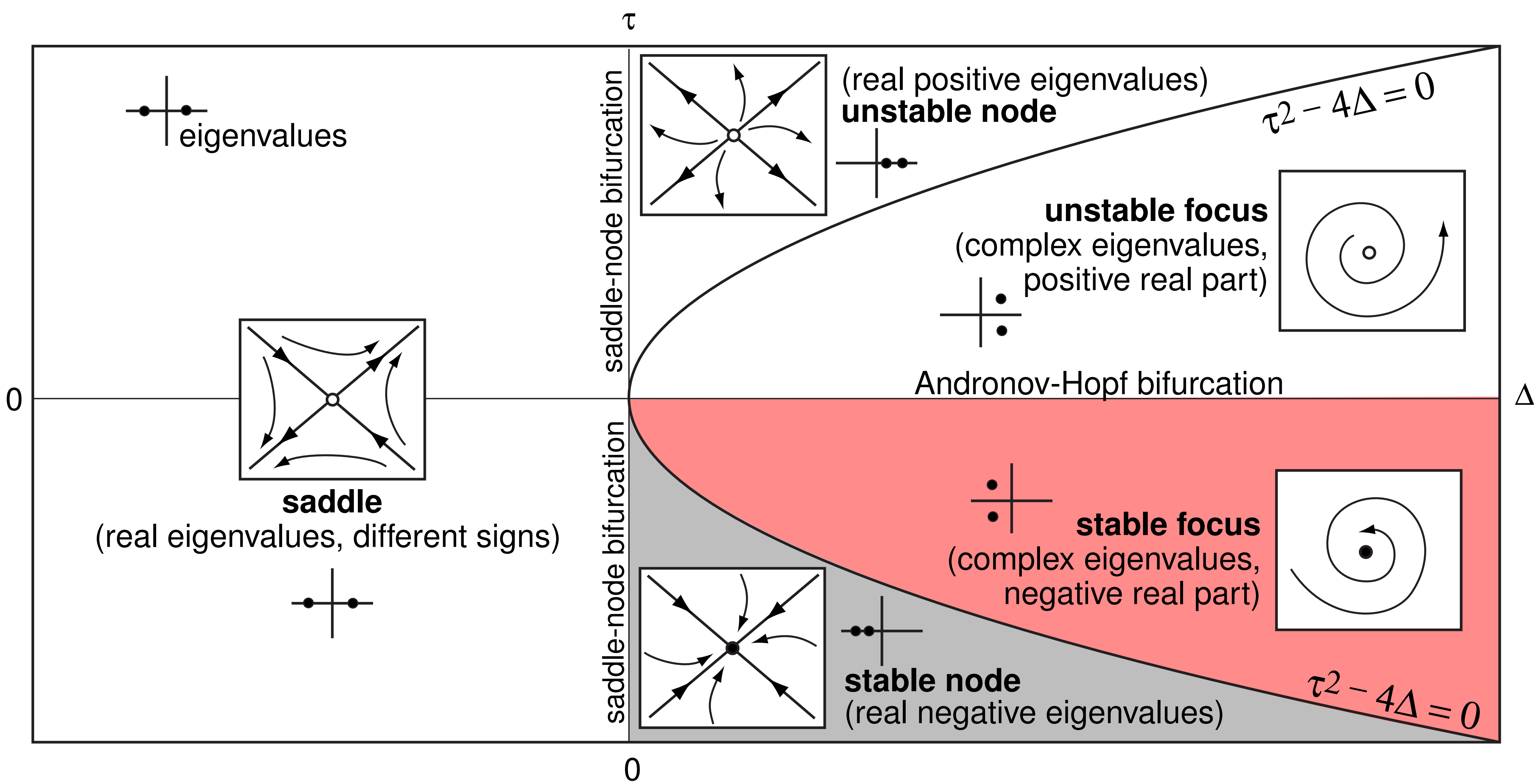


Fix Point one dimension

$$\frac{dV}{dt} = F(V)$$

$$F(V^*) = 0$$

Fix Point in two dimensions

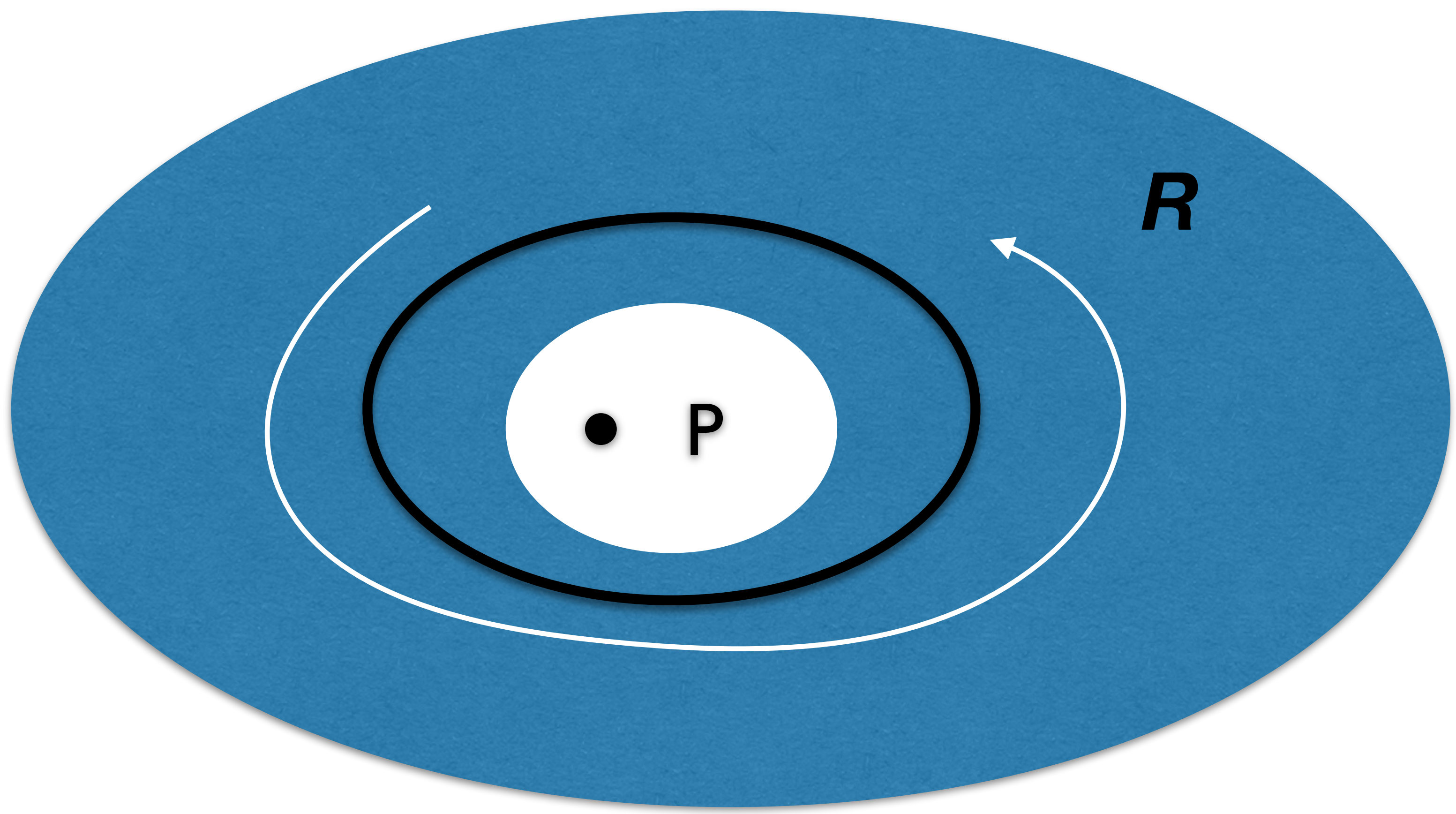


Poincare-Bendixson Theorem (2D)

- *R* is a closed, bounded subset of the plane;
- $\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x})$ is a continuously differentiable vector field on an open set containing *R*;
- *R* does not contain any fixed points; and
- There exists a trajectory *C* that is "confined" in *R*, in the sense that it starts in *R* and stays in *R* for all future time

Then either *C* is a closed orbit, or it spirals toward a closed orbit at $t \to \infty$. In either case, *R* contains a closed orbit.

Poincare-Bendixson Theorem (2D)



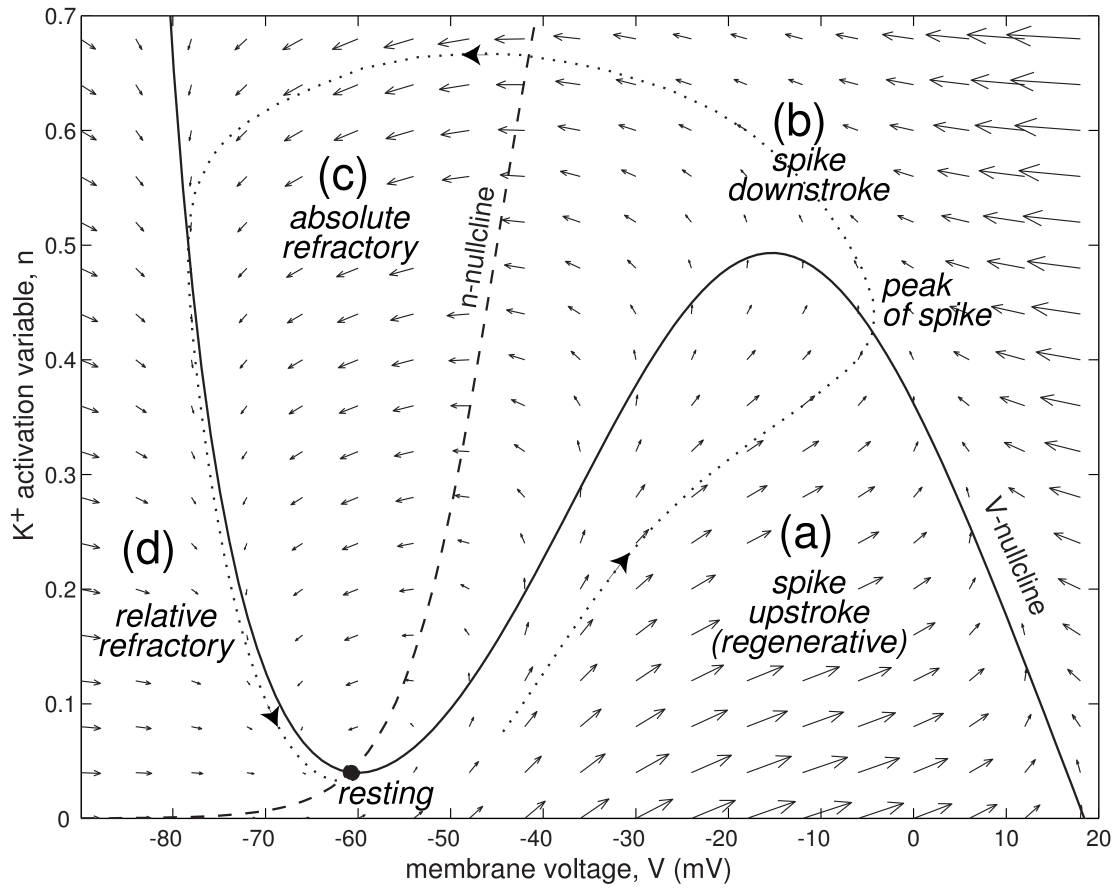


Figure 4.4: Nullclines of the $I_{\mathrm{Na,p}}+I_{\mathrm{K}}$-model (4.1, 4.2) with low-threshold K^+ current in Fig.4.1b. (The vector field is slightly distorted for the sake of clarity of illustration).

Dynamic systems in Neuroscience

Eugene Izhikevich 2007

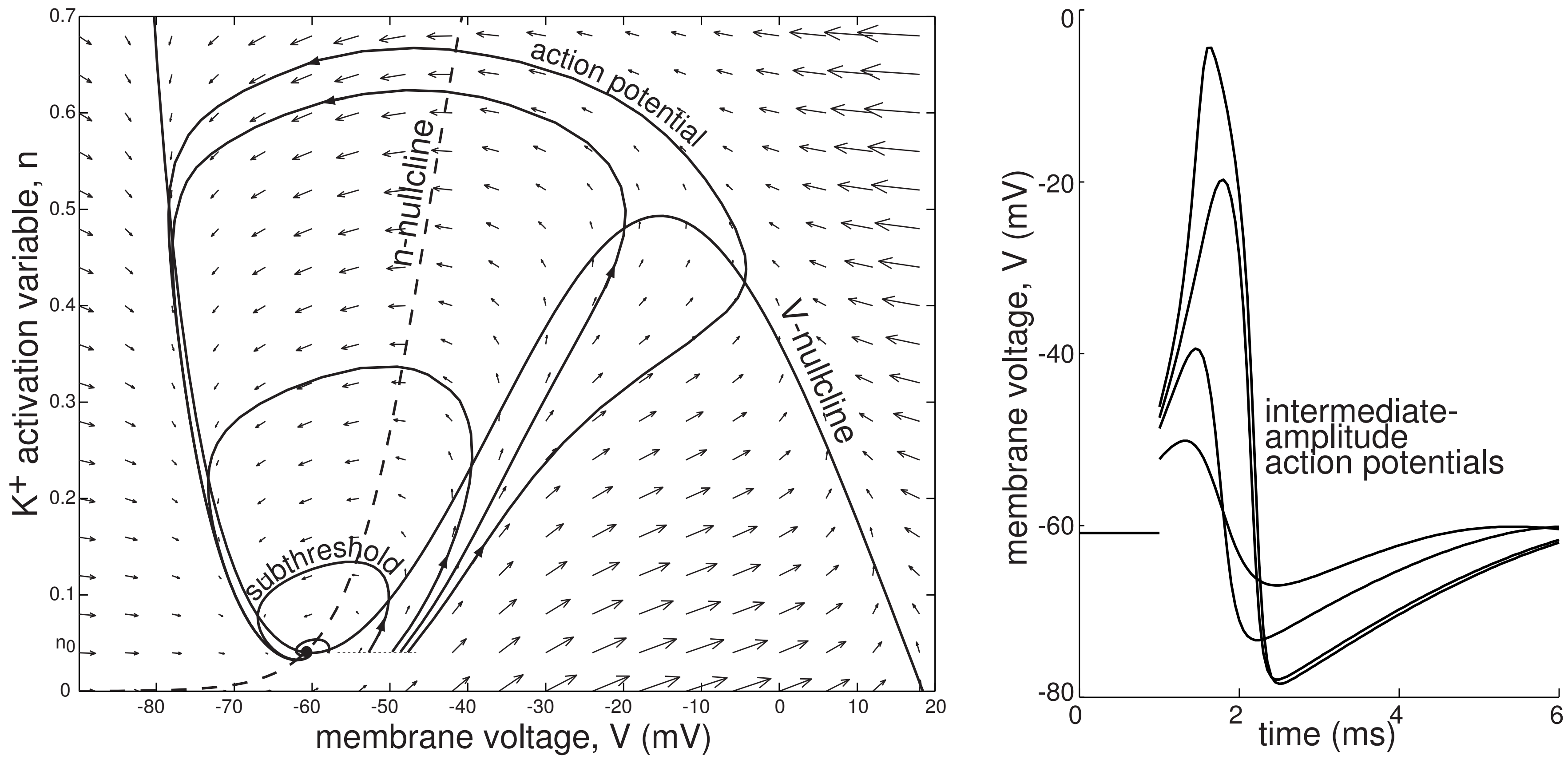
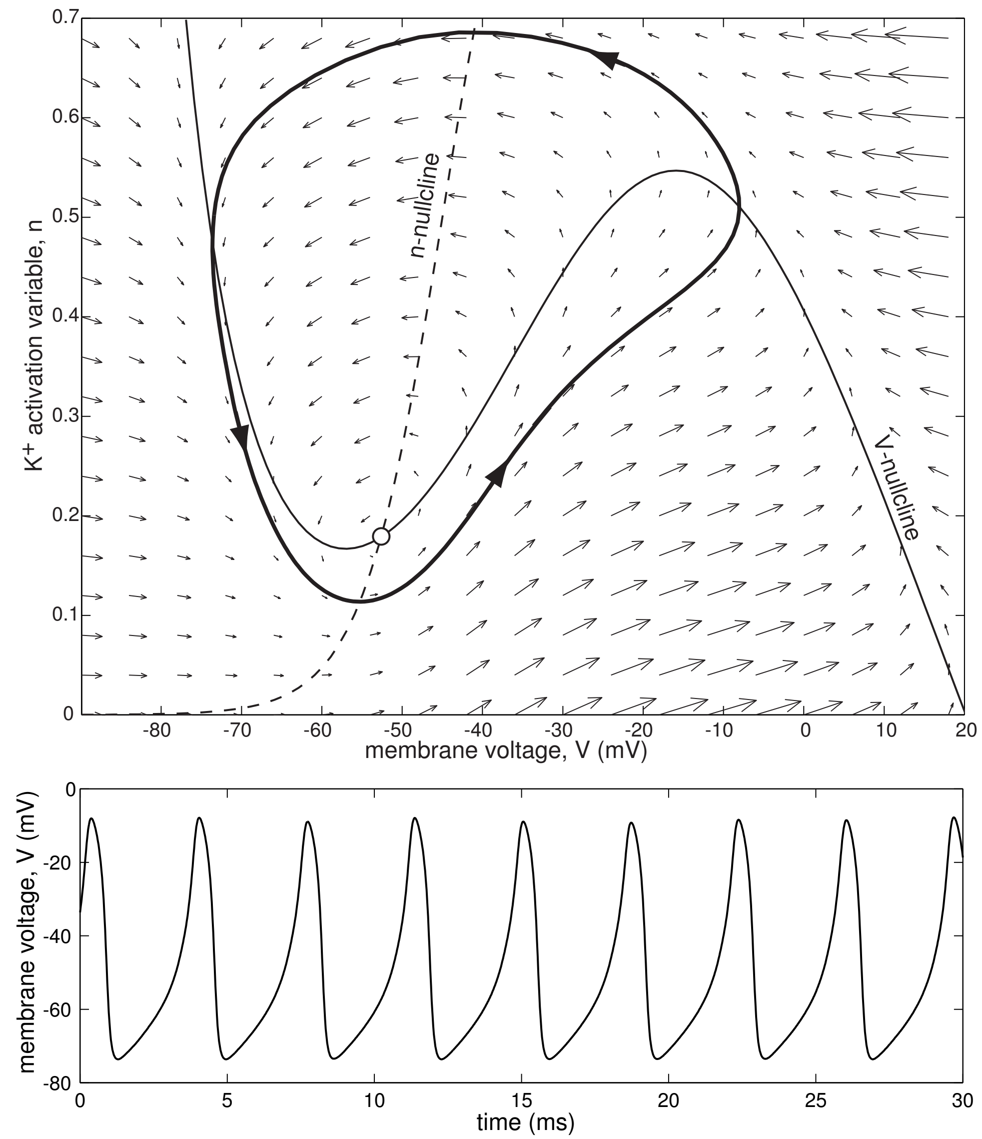


Figure 4.7: Failure to generate all-or-none action potentials in the $I_{\mathrm{Na,p}}+I_{\mathrm{K}}$-model.

Dynamic systems in Neuroscience

Eugene Izhikevich 2007

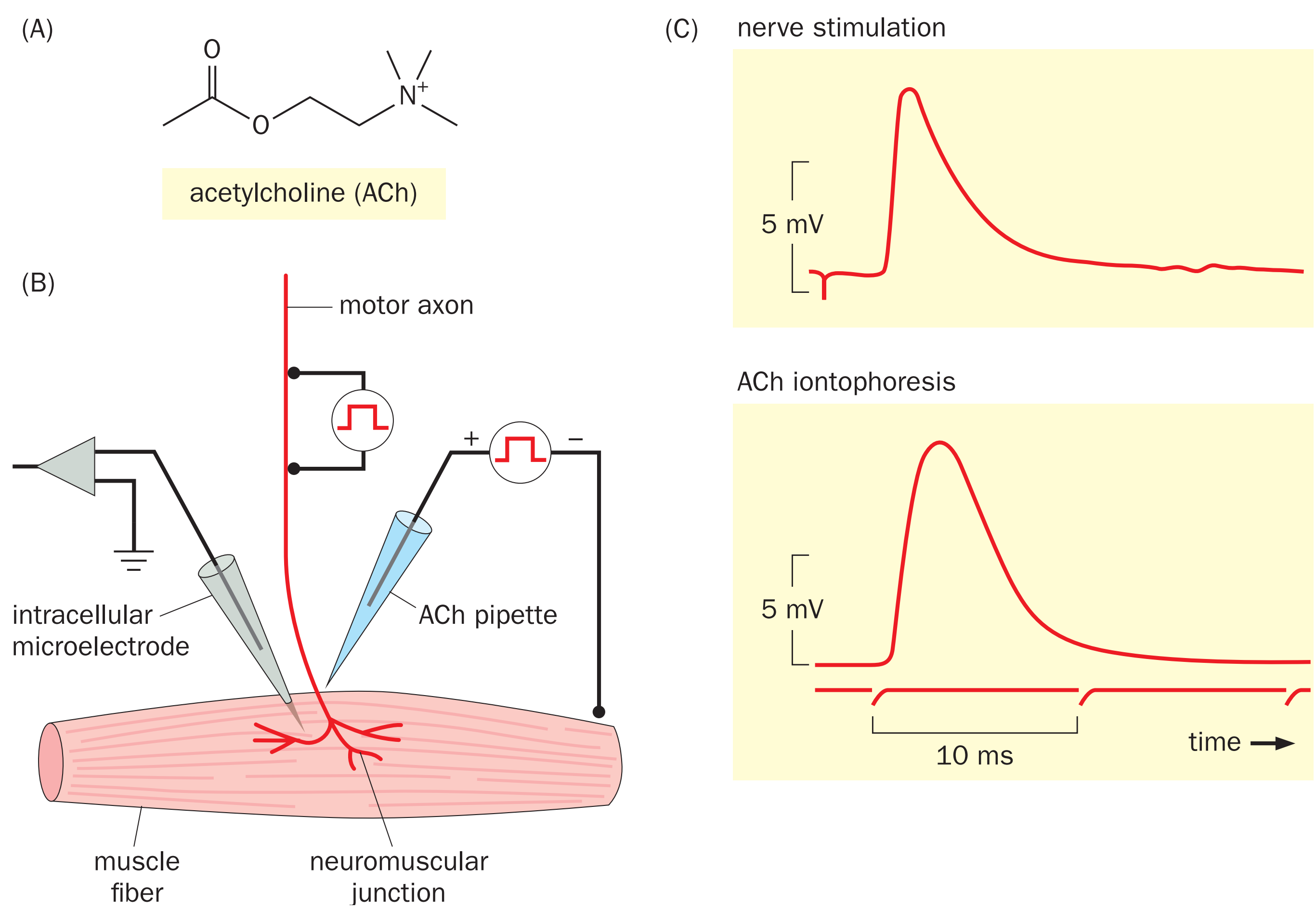


Dynamic systems in Neuroscience

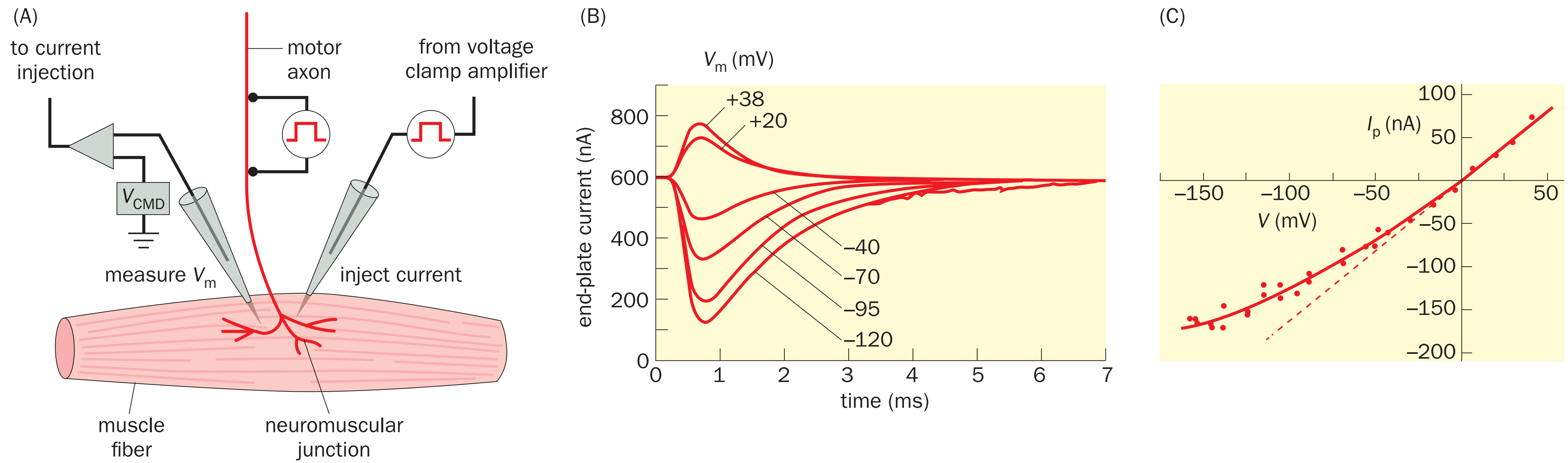
Eugene Izhikevich 2007

Synaptic Transmission

Neurotransmitter release evokes membrane potential change in the postsynaptic neuron



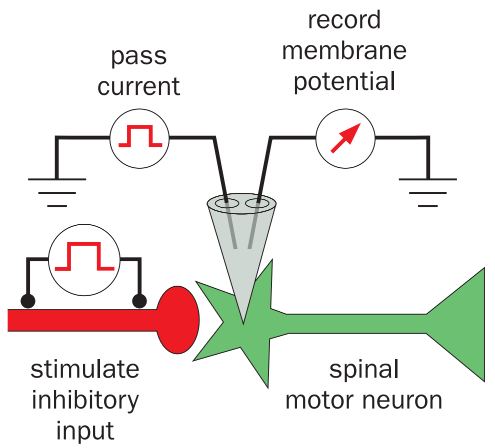
Reversal potential of a synapse

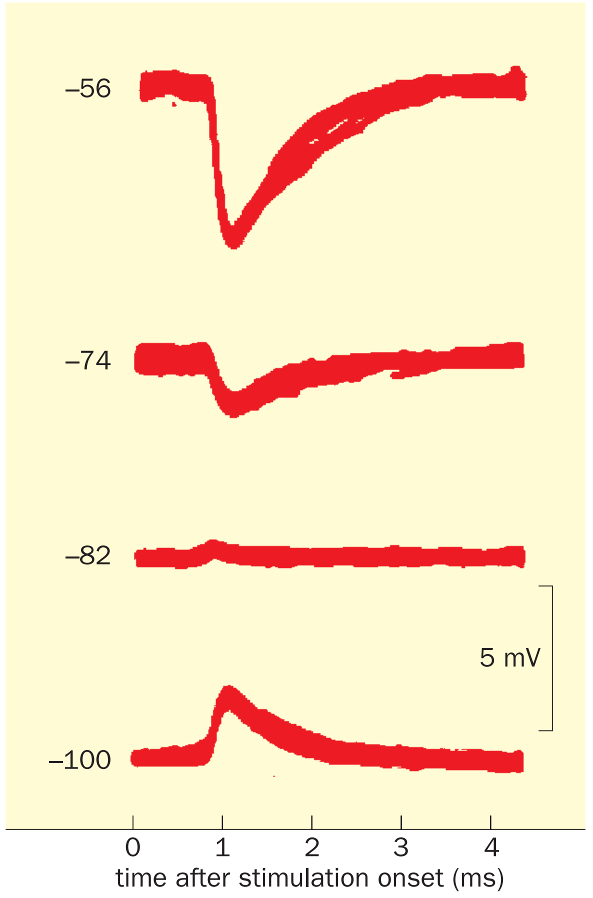


Excitatory and Inhibitory Synapses

Table 3–2: Commonly used neurotransmitters

Neurotransmitter	Major uses in the vertebrate nervous system[1]
Acetylcholine	motor neurons that excite muscle; ANS[2] neurons; CNS excitatory and modulatory neurons
Glutamate	most CNS excitatory neurons; most sensory neurons
GABA	most CNS inhibitory neurons
Glycine	some CNS inhibitory neurons (mostly in the brainstem and spinal cord)
Serotonin (5-HT)	CNS modulatory neurons
Dopamine	CNS modulatory neurons
Norepinephrine	CNS modulatory neurons; ANS[2] neurons
Histamine	CNS modulatory neurons
Neuropeptides	usually co-released from excitatory, inhibitory, or modulatory neurons; neurosecretory cells



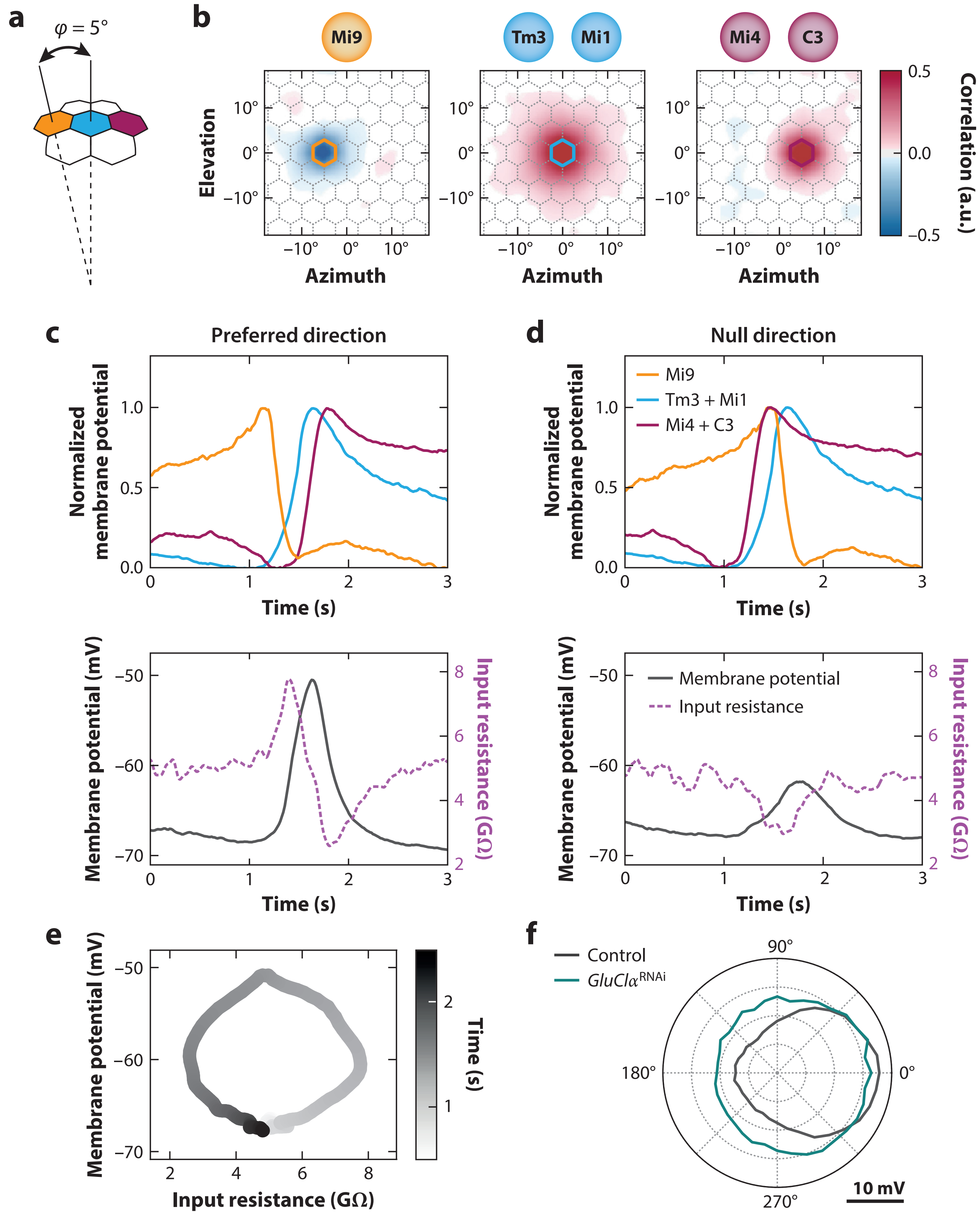


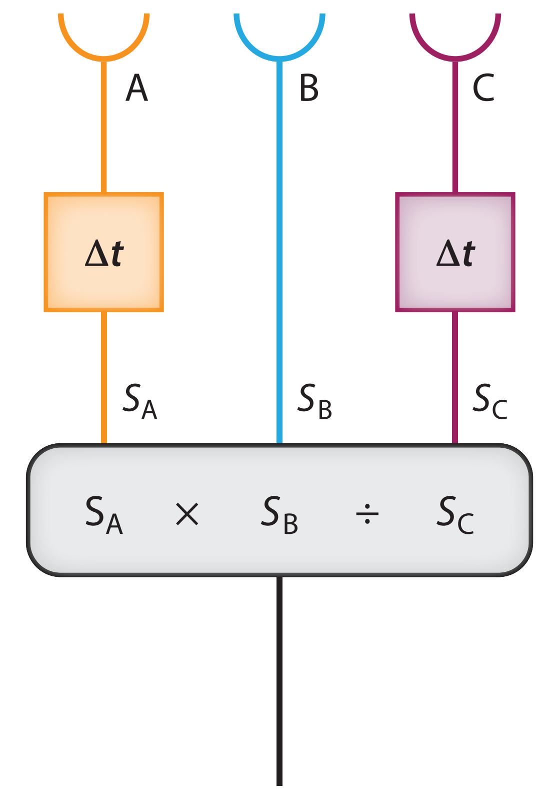
Shunting inhibition and divisive operation

$$C_m \frac{dV}{dt} = -g_L(V - E_L) - g_{inh}(V - E_L) - g_{exc}(V - E_0)$$

$$V = \frac{(g_L + g_{inh})E_L + g_{exc}E_0}{g_L + g_{inh} + g_{exc}}$$

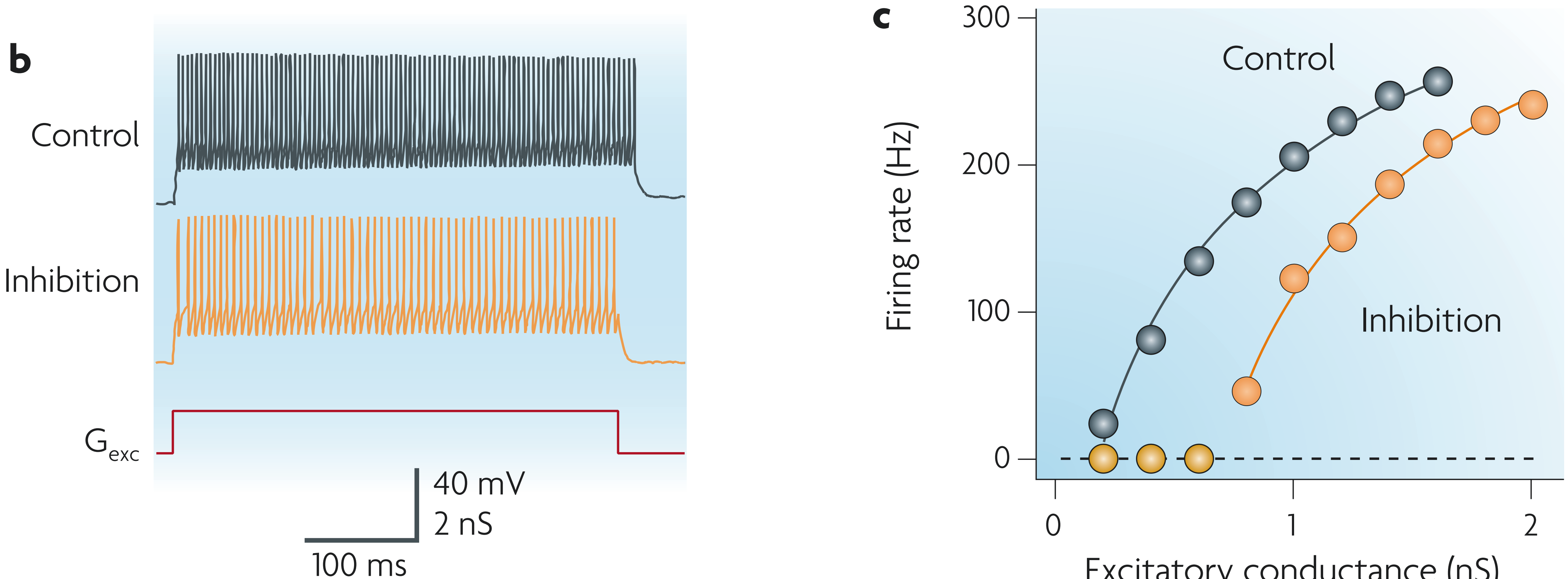
$$g_{inh} \gg g_L + g_{exc} \qquad V \approx E_L + \frac{g_{exc}}{g_{inh}} E_0$$





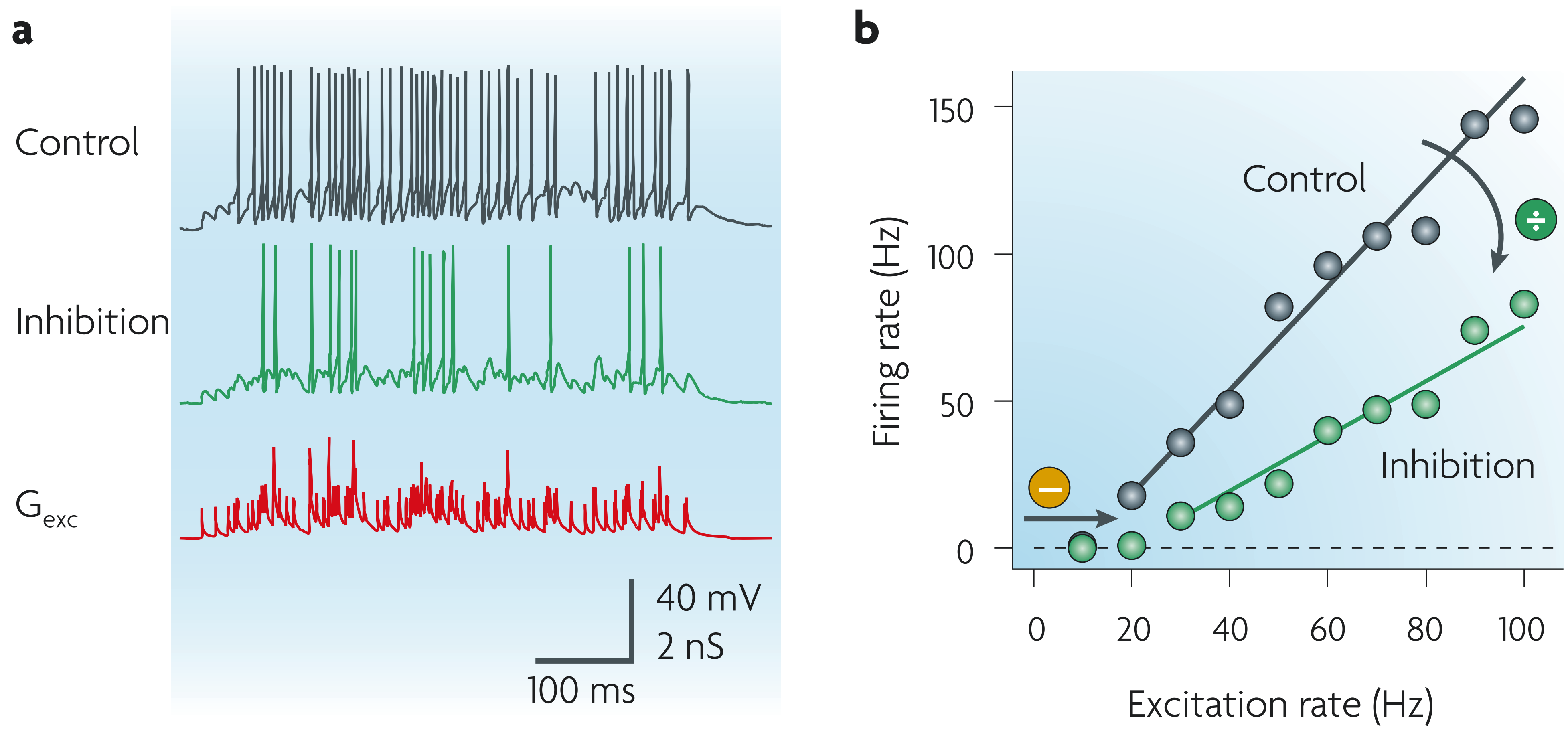
Gonzalez-Suarez AD et. al.,
Current Biology 2022

However, shunting inhibition becomes subtractive for firing rate

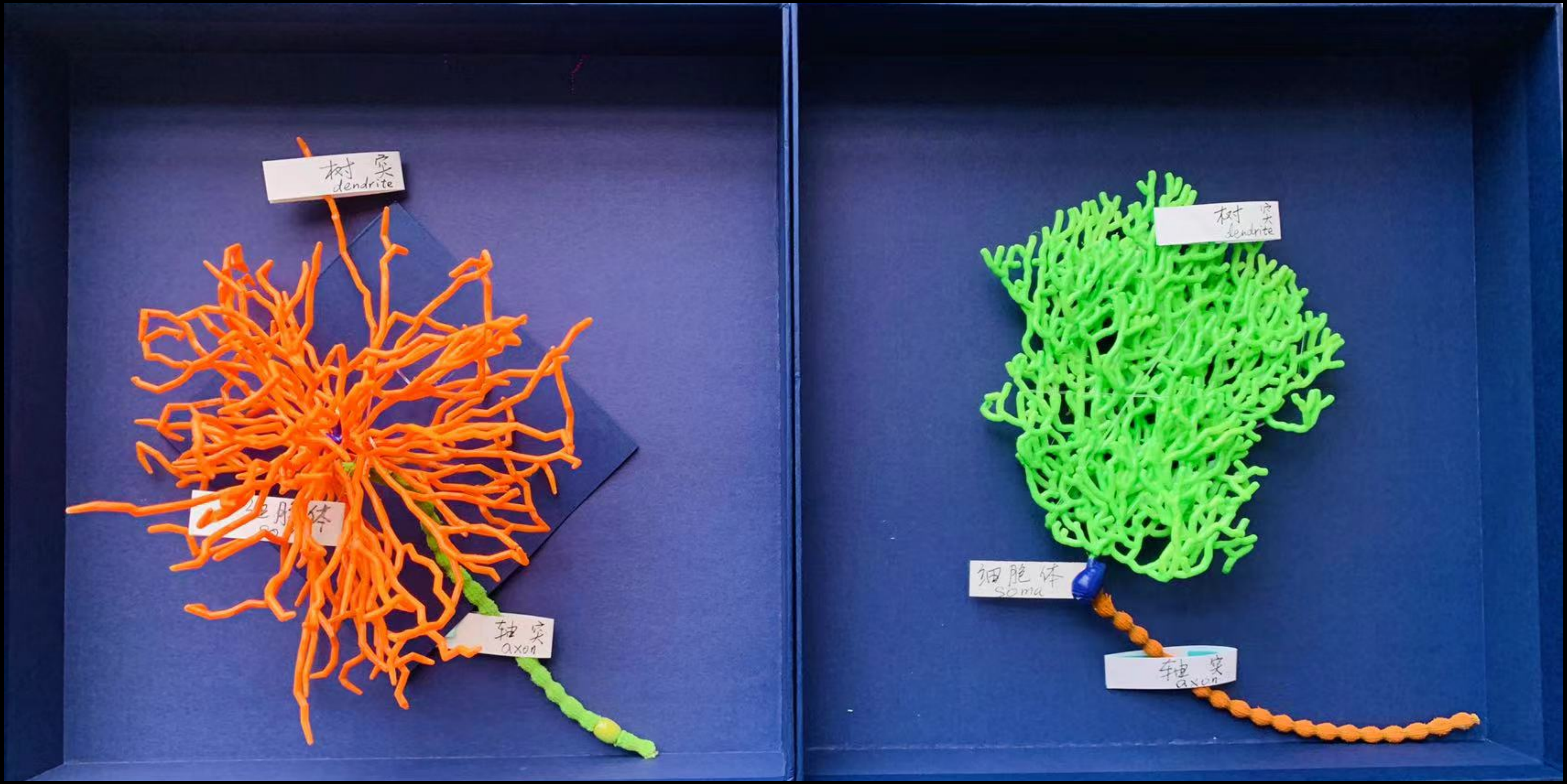


Why? (Your homework)

But Shunting inhibition can become divisive in the presence of large synaptic input noise



Angus Silver Nature Review Neuroscience 2010


树突
dendrite
胞体
轴突
axon
树突
dendrite
细胞体
soma
轴突
axon