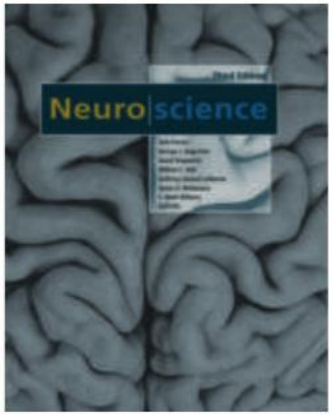
Action Potentials

Finally Something is Happening...

Topics I	Topics II
Introduction & Electrochemical Gradients	Synaptic Transmission
Passive Membrane Properties	Electrophysiology Techniques
Action Potentials	Basic Circuits (Spinal Cord)
Voltage-Gated Ion Channels	Sensory Systems Overview
Ligand-Gated Ion Channels	Synaptic Plasticity

Study Material

- NEUROSCIENCE Third Edition
  - Dale Purves
- Chapter 2 pages 31-46
  - In particular pages 43-45
- Chapter 3 pages 47-67



THE COVER
Dorsal view of the human brain.
(Courtesy of S. Mark Williams.)

Address inquiries and orders to
Sinauer Associates, Inc.
23 Plumtree Road
Sunderland, MA 01375 U.S.A.

www.sinauer.com
FAX: 413-549-1118
orders@sinauer.com
publish@sinauer.com

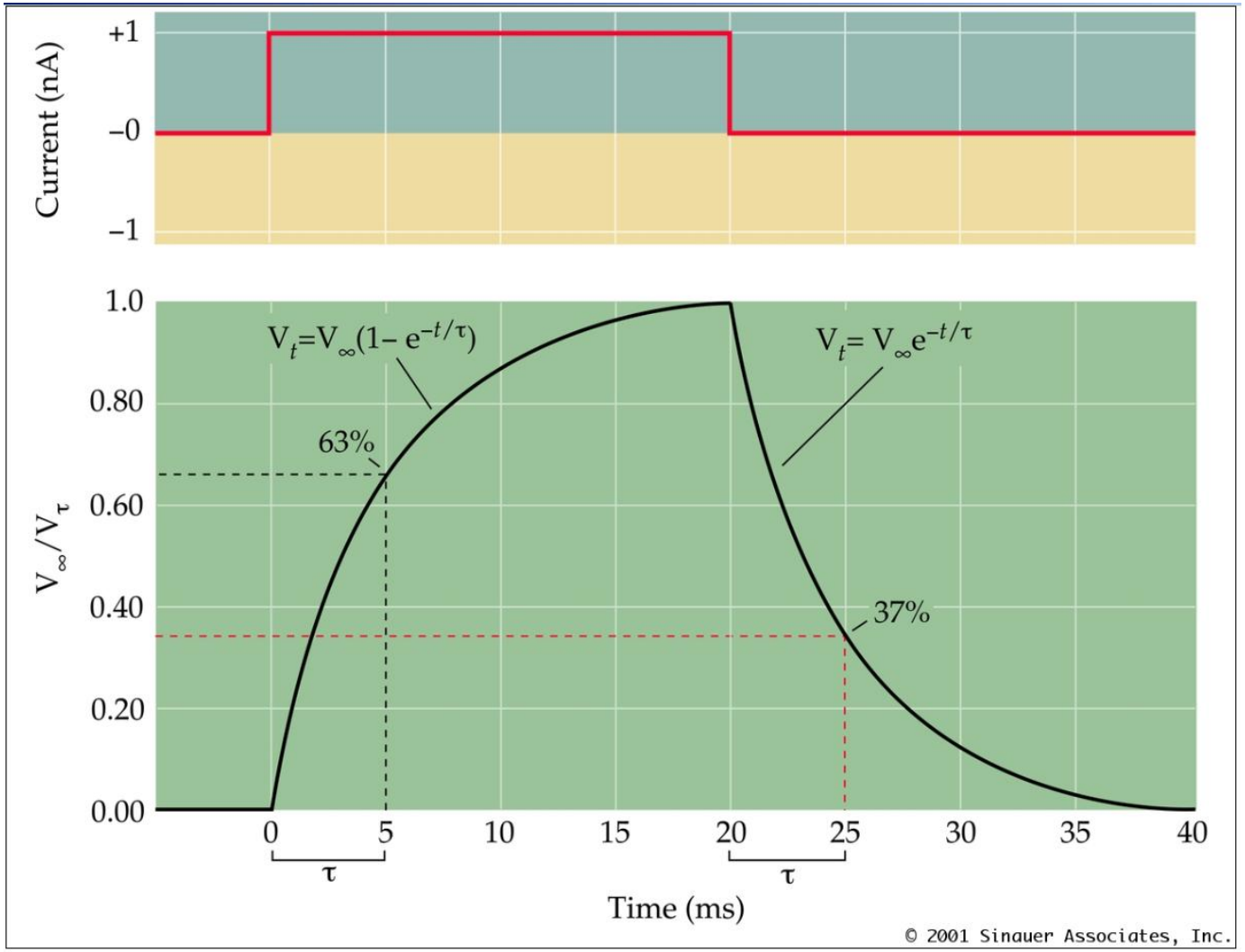
Aims for this Lecture

- Understand the action potential as an all-or-none signal with a threshold.
- Know the underlying ion conductances and their specific kinetics.
- Understand how positive and negative feedback mechanisms shape the action potential.
- Know how action potentials propagate.

Recapitulation L2

- Cell membranes are thin isolators separating conducting media. As such they behave as capacitors.
- Changing the voltage across the membrane therefore requires the movement of charges.
- These charges (ions) move trough channels with a certain resistance.

Recapitulation L2



Recapitulation L2

$$V(t) = V_{\infty}(1 - e^{-t/\tau})$$

$$\tau = RC$$

Tau is the membrane time constant. It is proportional to the capacitance of the neuron and the membrane resistance.

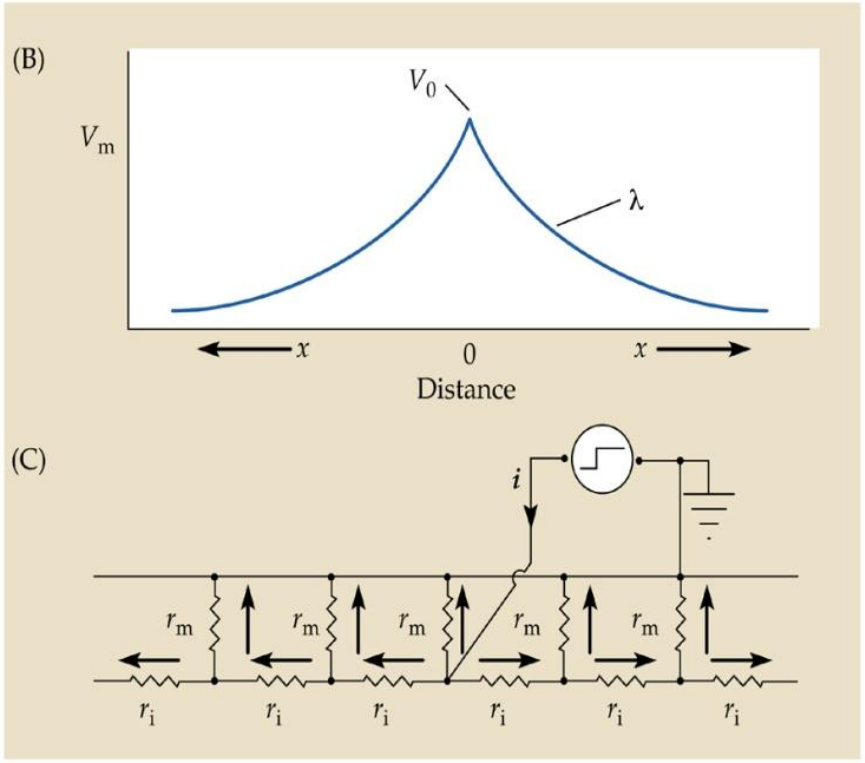
The capacitance is given by the amount of cell membrane and depends on the size (surface area) of the neuron.

The membrane resistance at rest is also likely a function of the size of the neuron (larger neuron -> smaller resistance), but it is very dynamic and can change, since channels can open and close.

Recapitulation L2

- Neuronal processes are not very good conductors.
- Neural membranes are not ideal isolators and the cytoplasm inside the process has a relatively high resistance.
- Moreover, if we want to change the membrane potential we again have to move charges just to charge the membrane capacitance.
- The hydraulic equivalent is a leaky, elastic garden hose.

Recapitulation L2



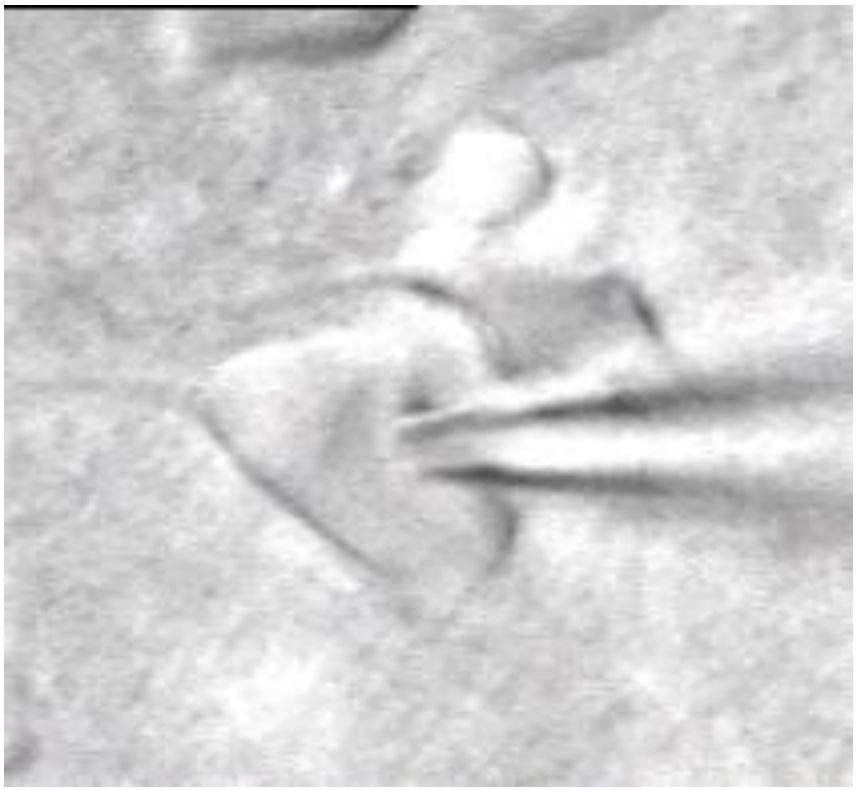
$$l = \sqrt{\frac{r_m}{r_i}}$$

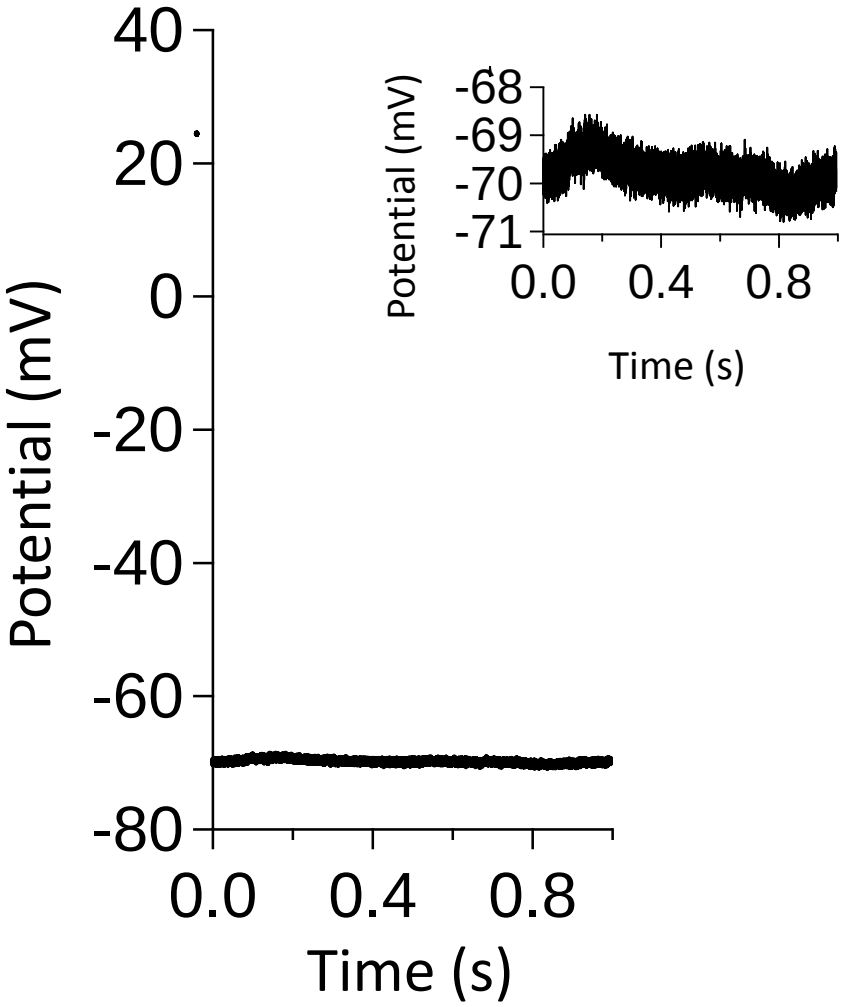
The length constant describes the signal loss along a neuronal process. After one length constant we only have 1/e or about 37% of the signal. Typical length constants range from 100 micrometers to a millimeter.

r_m is the membrane resistance (across).
r_i is the cytoplasmic resistance (lengthwise).

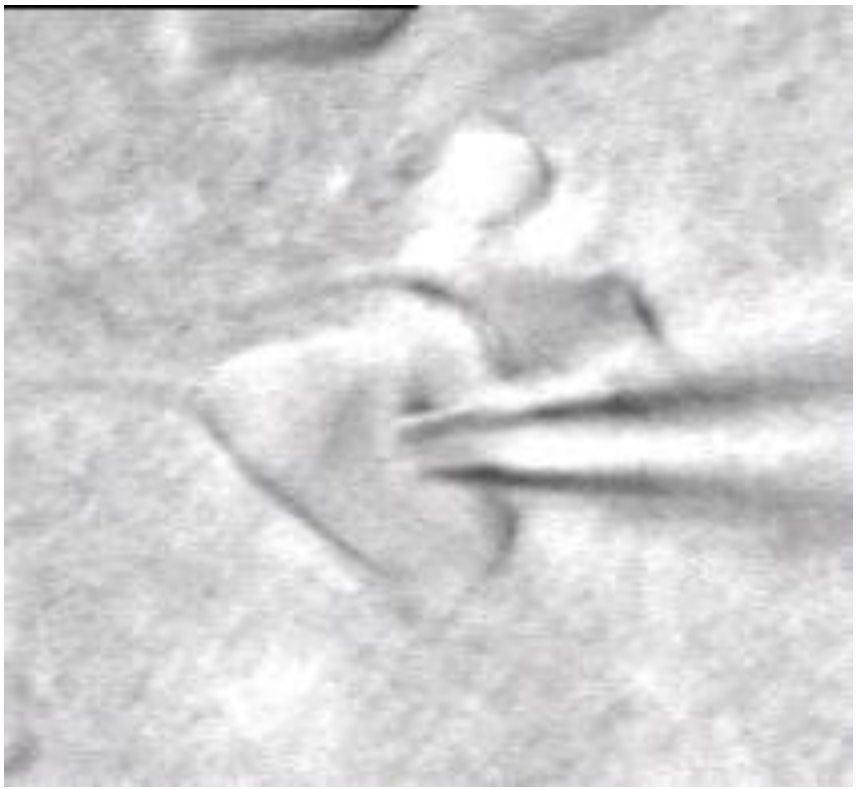
This simplified version is only valid for steady signals (and is the best case).

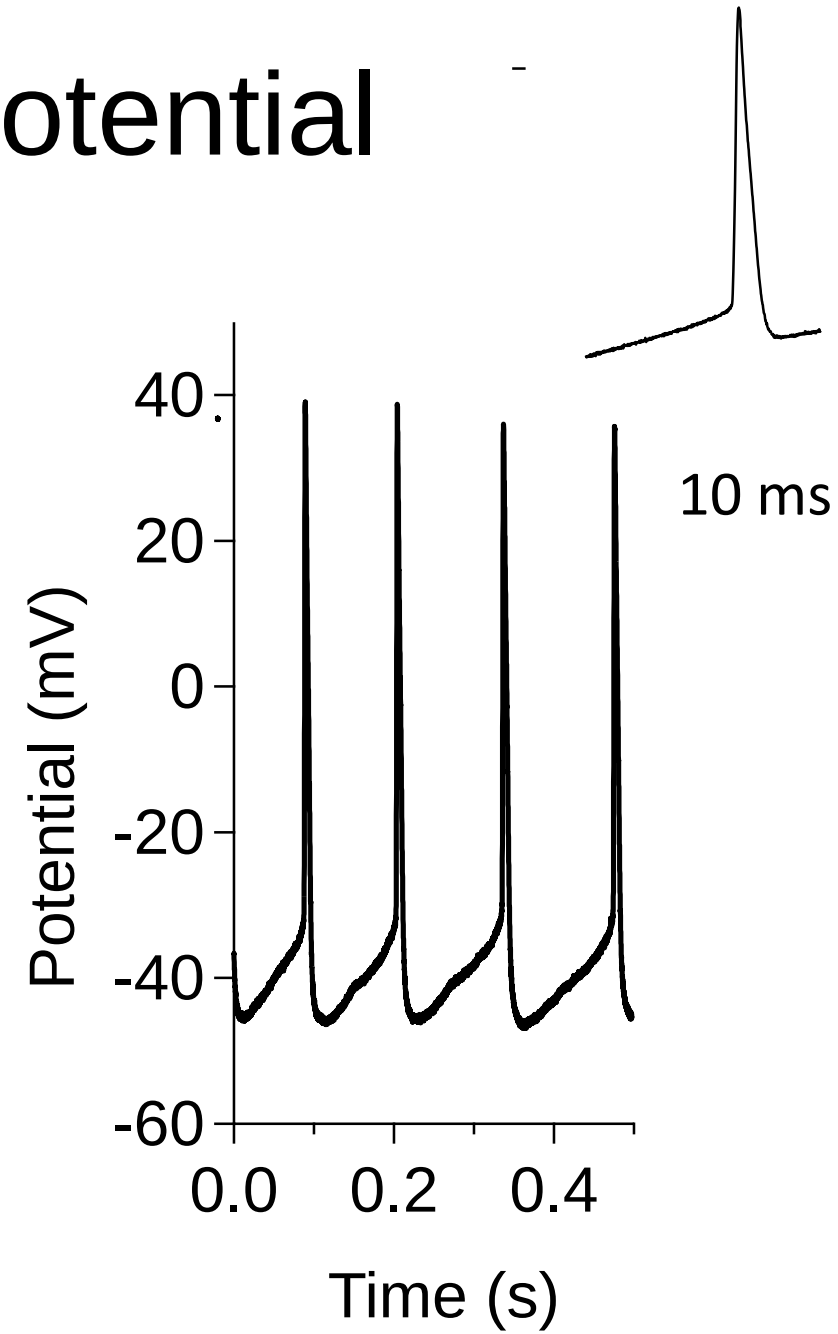
Resting Membrane Potential



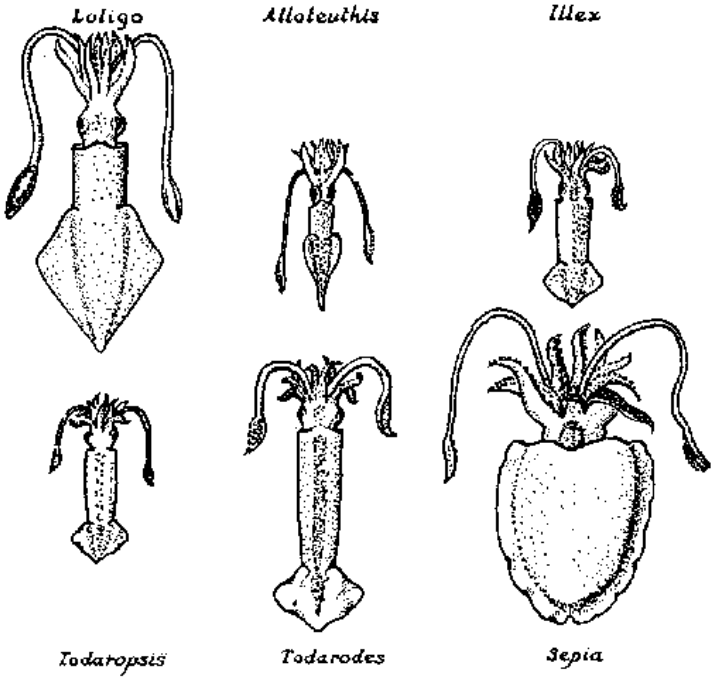


Action Potential





Loglio forbesi



Squid Giant Axon

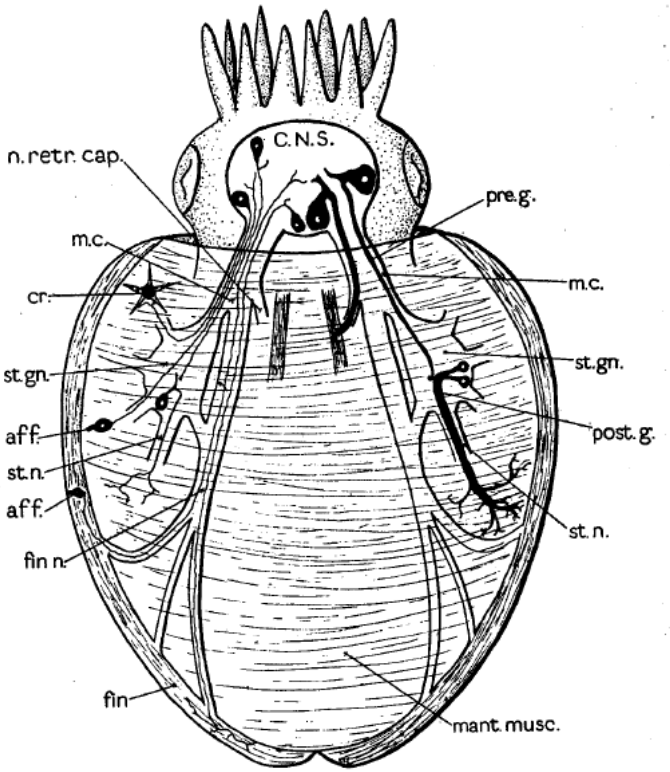
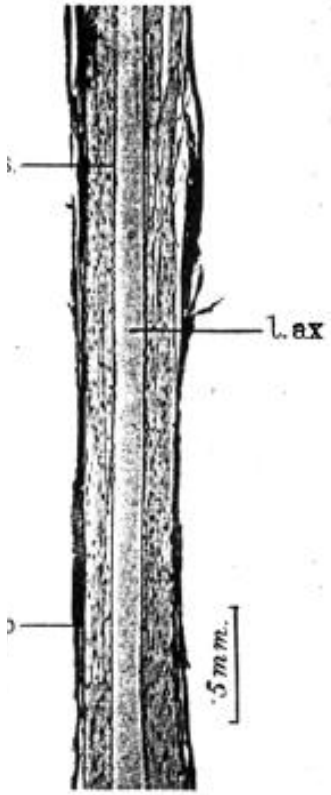


FIG. 1—Diagram of the innervation of the mantle in *Sepia officinalis*. The details of the connexions of the giant fibres are not known; *pre. g.*, represents the "pre-ganglionic" fibres, which arise in the palliovisceral ganglion; *post. g.*, the "post-ganglionic" fibres, which take origin from the fusion of the processes of several cells. For further explanation *see* text.



611 . 018 . 83 : 595 . 3
611 . 018 . 83 : 594 . 5

The Structure of Nerve Fibres in Cephalopods and Crustacea

By J. Z. YOUNG, Department of Zoology and Comparative Anatomy and Magdalen College, Oxford

(*Communicated by Sir Henry Dale, F.R.S.—Received* 20 *May*, 1936)

Intracellular Recording

NATURE OCT. 21, 1939, VOL. 144

Action Potentials Recorded from Inside a Nerve Fibre

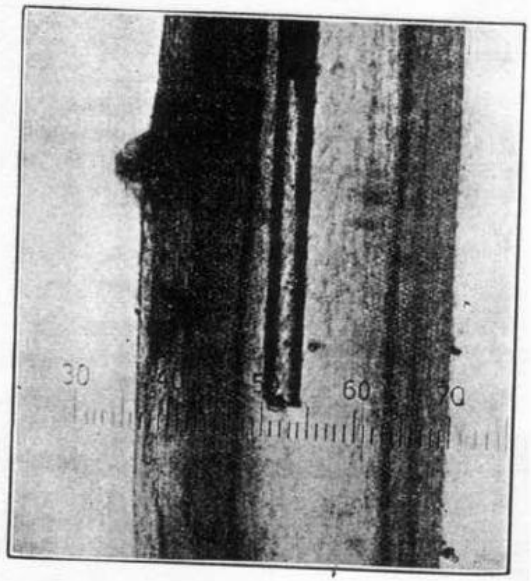


Fig. 1.

PHOTOMICROGRAPH OF ELECTRODE INSIDE GIANT AXON. 1 SCALE DIVISION = 33 μ.

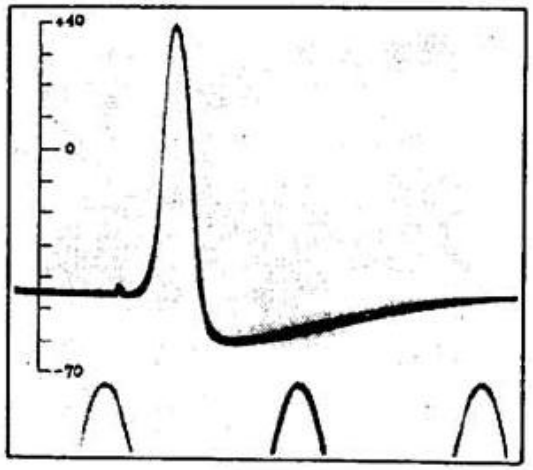
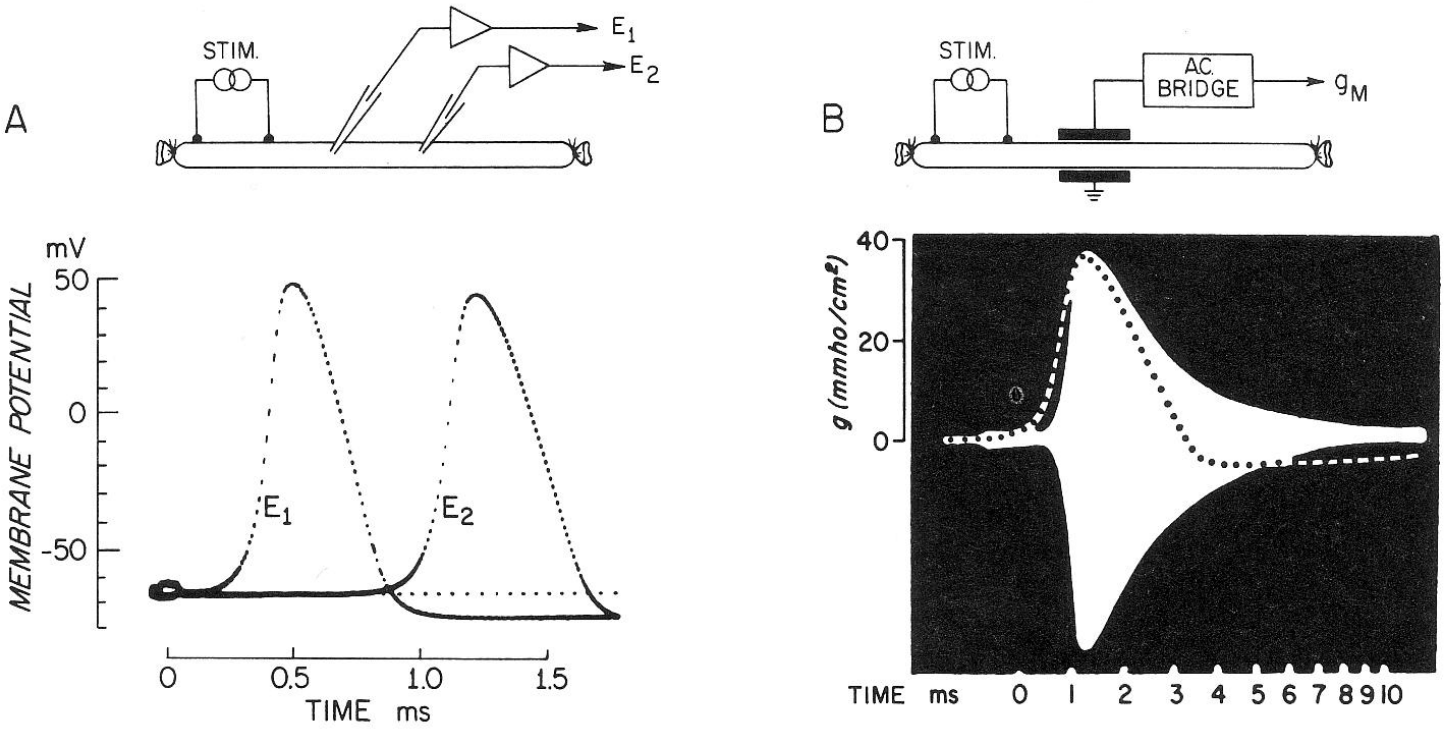


Fig. 2.

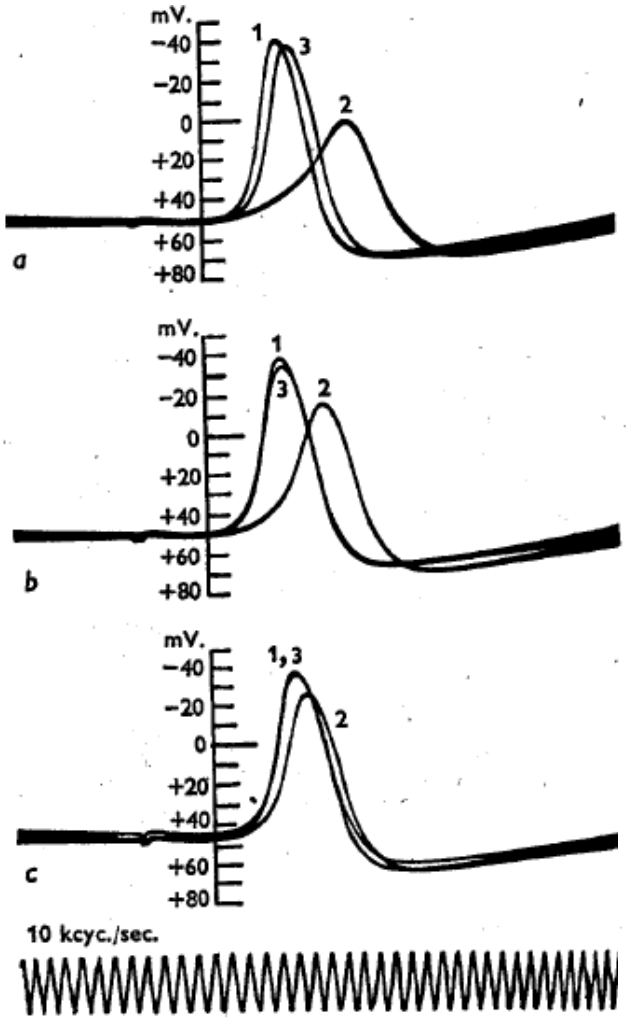
ACTION POTENTIAL RECORDED BETWEEN INSIDE AND OUTSIDE OF AXON. TIME MARKER, 500 CYCLES/SEC. THE VERTICAL SCALE INDICATES THE POTENTIAL OF THE INTERNAL ELECTRODE IN MILLIVOLTS, THE SEA WATER OUTSIDE BEING TAKEN AT ZERO POTENTIAL.

These results are important for two reasons. In the first place they prove that the action potential arises at the surface, and in the second, they give the absolute magnitude of the action potential as about 90 mv. at 20° C. Previous measurements have always been made with external electrodes and give values which are reduced by the short-circuiting effect of the fluid outside the nerve fibre.

Increased Permeability



Depolarization is Na-dependent



J. Physiol. (1949) 108, 37–77 612.813

THE EFFECT OF SODIUM IONS ON THE ELECTRICAL ACTIVITY OF THE GIANT AXON OF THE SQUID

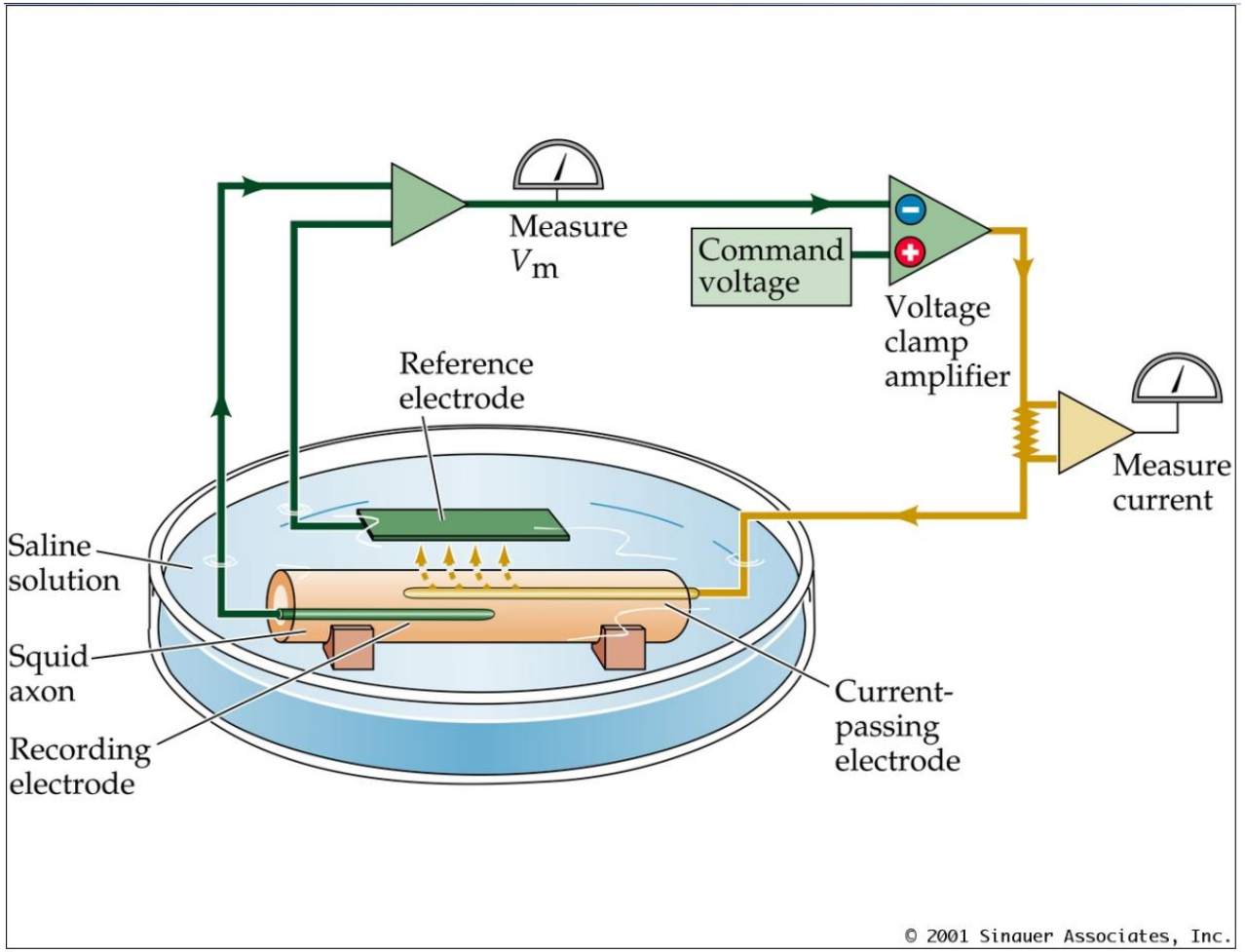
BY A. L. HODGKIN AND B. KATZ

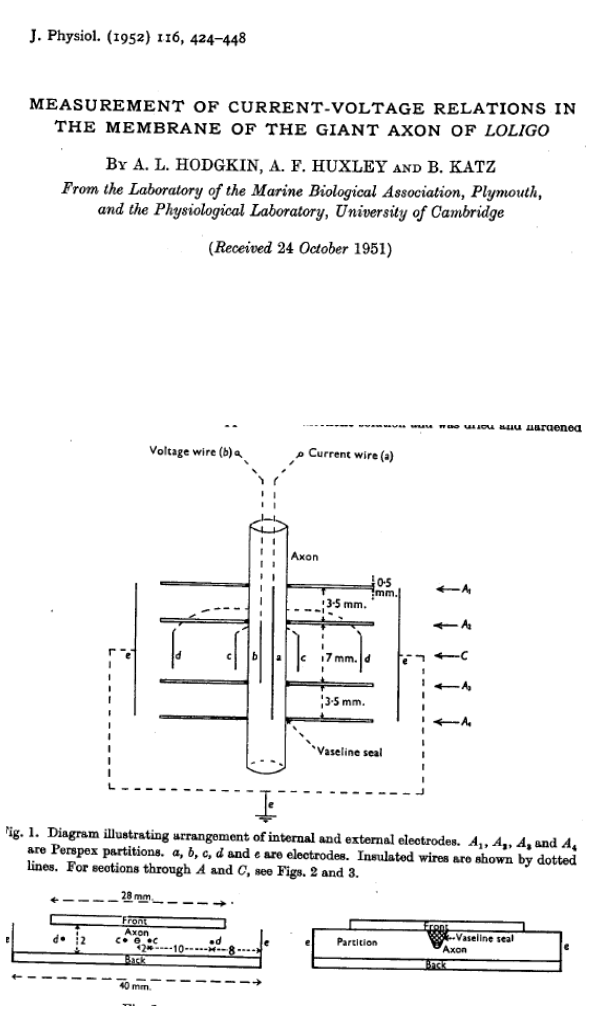
From the Laboratory of the Marine Biological Association, Plymouth, and the Physiological Laboratory, University of Cambridge

Replacing Na-Ions in the extracellular solution with impermeant ions reduces the action potential amplitude.

Fig. 4. Action of sodium-deficient solutions on the resting and action potential. *a* 1, response in sea water; *a* 2, after 16 min. in 33% sea water, 67% isotonic dextrose; *a* 3, 13 min. after reapplication of sea water. *b* 1, response in sea water, *b* 2, after 15 min. in 50% sea water, 50% isotonic dextrose; *b* 3, 6 min. after reapplication of sea water. *c* 1, response in sea water; *c* 2, after 16 min. in 71% sea water, 29% isotonic dextrose; *c* 3, 7 min. after reapplication of sea water. The scale gives the potential difference across the nerve membrane (outside – inside) with no allowance for the junction potential between the axoplasm and the sea water in the microelectrode.

Voltage Clamp





J. Physiol. (1952) 116, 424–448

MEASUREMENT OF CURRENT-VOLTAGE RELATIONS IN THE MEMBRANE OF THE GIANT AXON OF *LOLIGO*

BY A. L. HODGKIN, A. F. HUXLEY AND B. KATZ

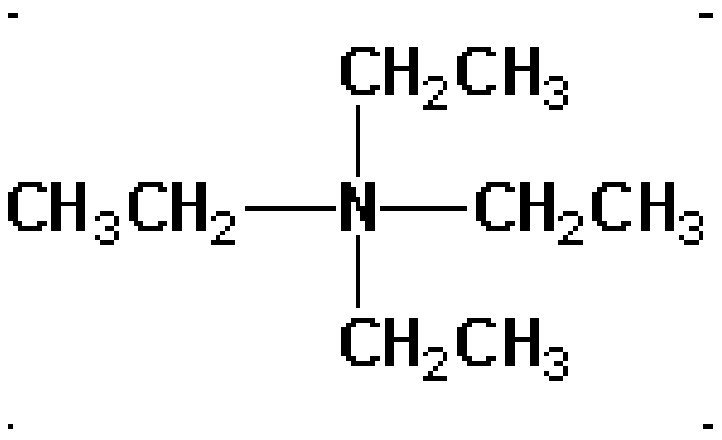
From the Laboratory of the Marine Biological Association, Plymouth, and the Physiological Laboratory, University of Cambridge

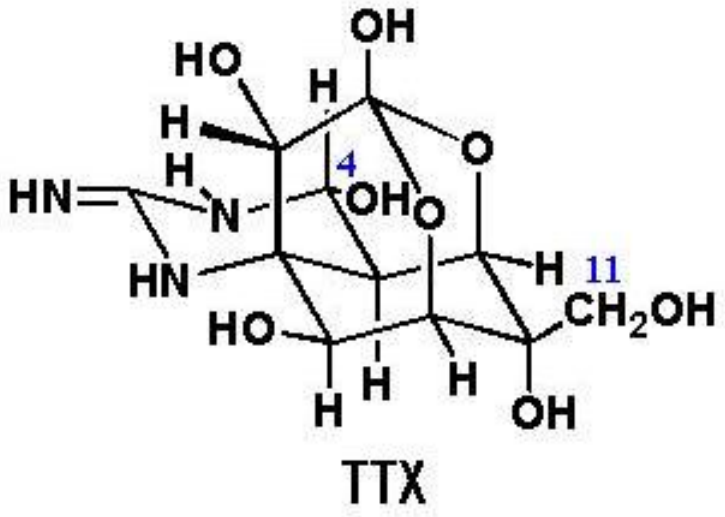
(*Received* 24 *October* 1951)

ig. 1. Diagram illustrating arrangement of internal and external electrodes. A_1, A_2, A_3 and A_4 are Perspex partitions. *a*, *b*, *c*, *d* and *e* are electrodes. Insulated wires are shown by dotted lines. For sections through *A* and *C*, see Figs. 2 and 3.

Membrane voltage is held constant and the current is measured.

Channel-Blockers





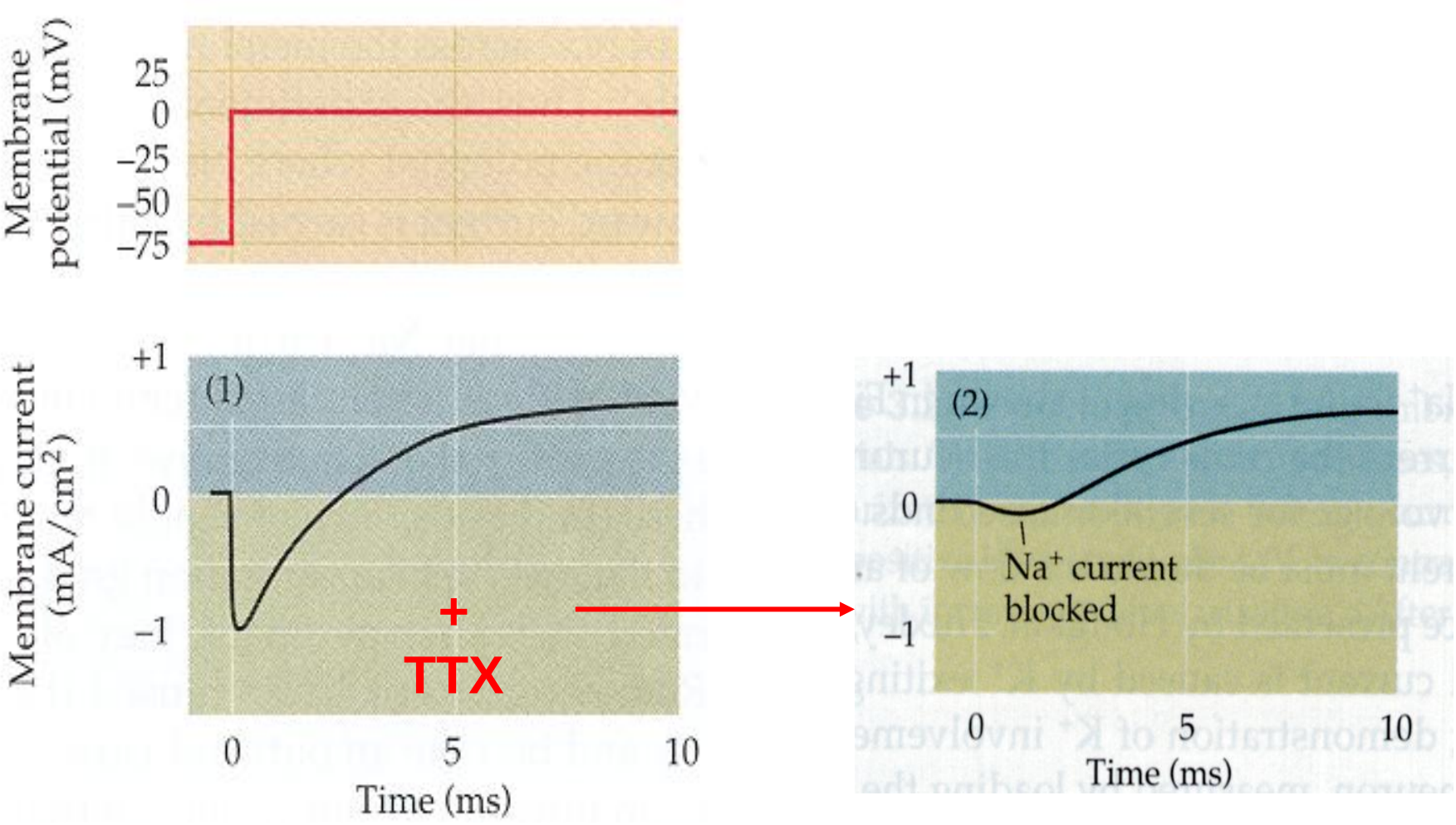
TTX

Sodium (Na) channels

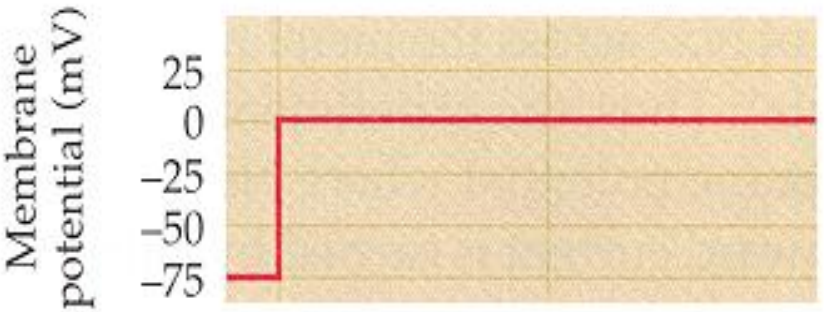
TEA
Tetraethylammonium

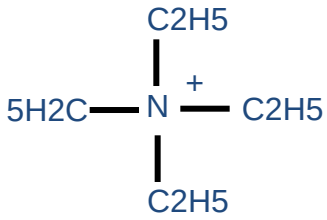
Potassium (K) channels

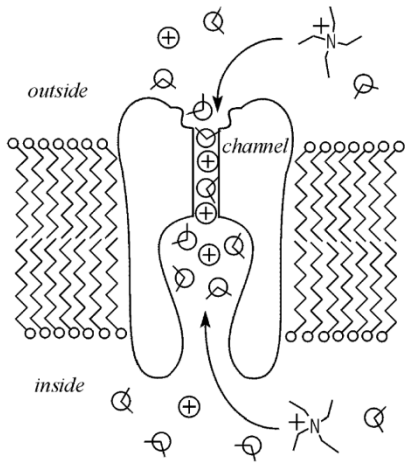
After Block of Na-Channels

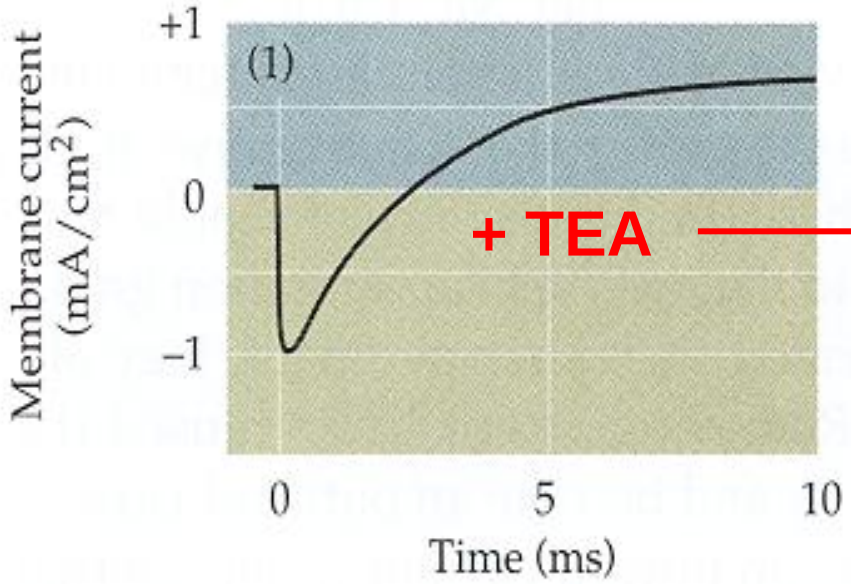


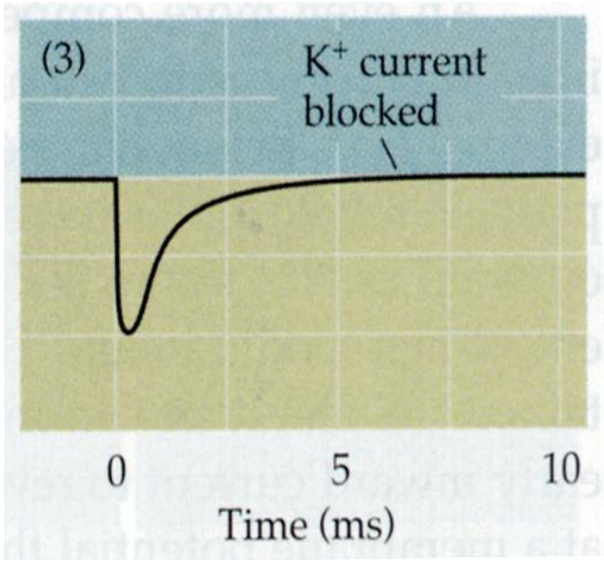
After Block of K-Channels







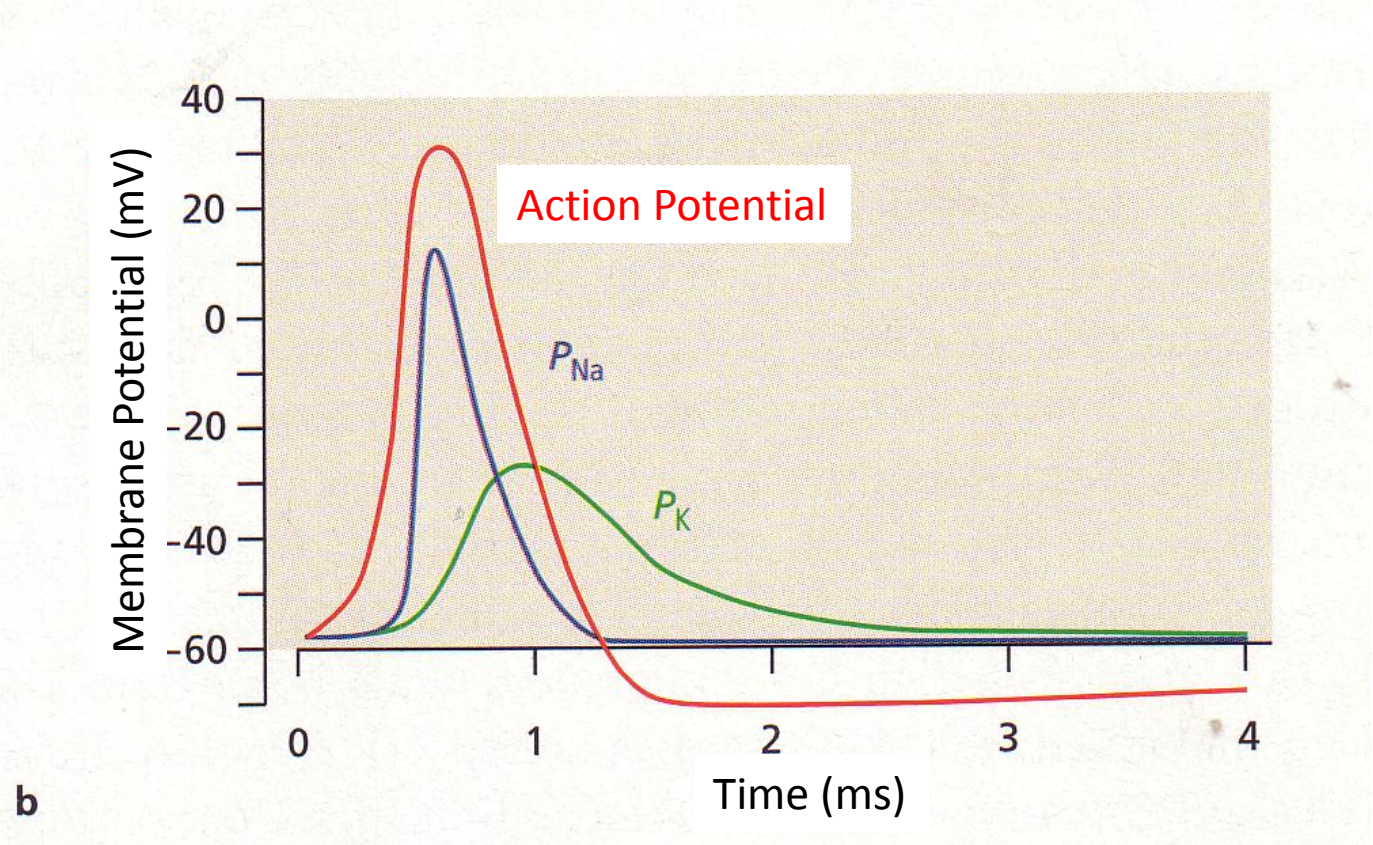




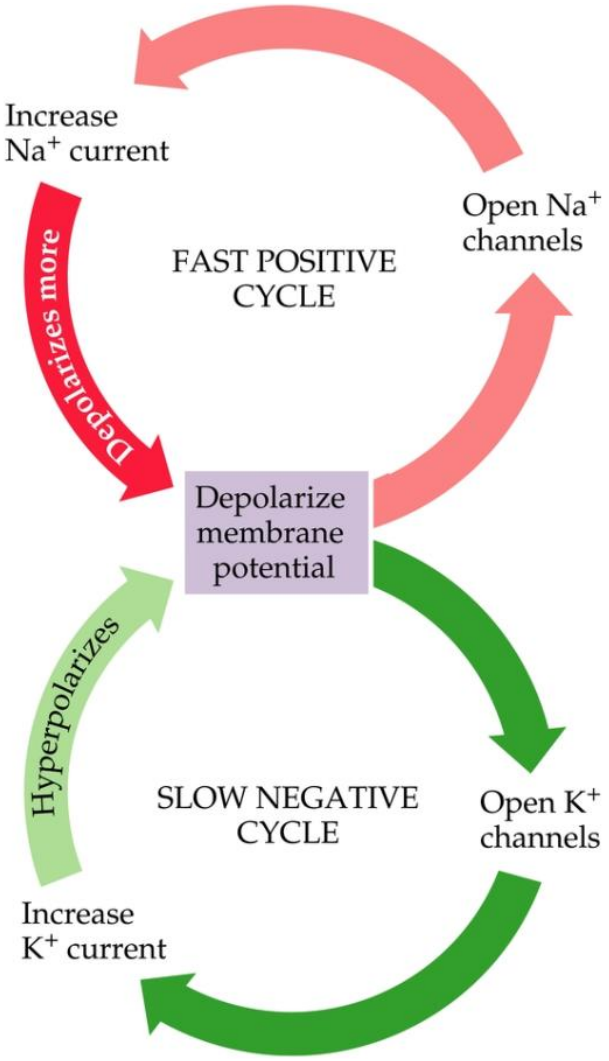
Conductances

Goldmann, Hodkin, Katz

$$E_i = \frac{RT}{F} \ln\left(\frac{P_K[K^+]_a + P_{Na}[Na^+]_a}{P_K[K^+]_i + P_{Na}[Na^+]_i} \right)$$



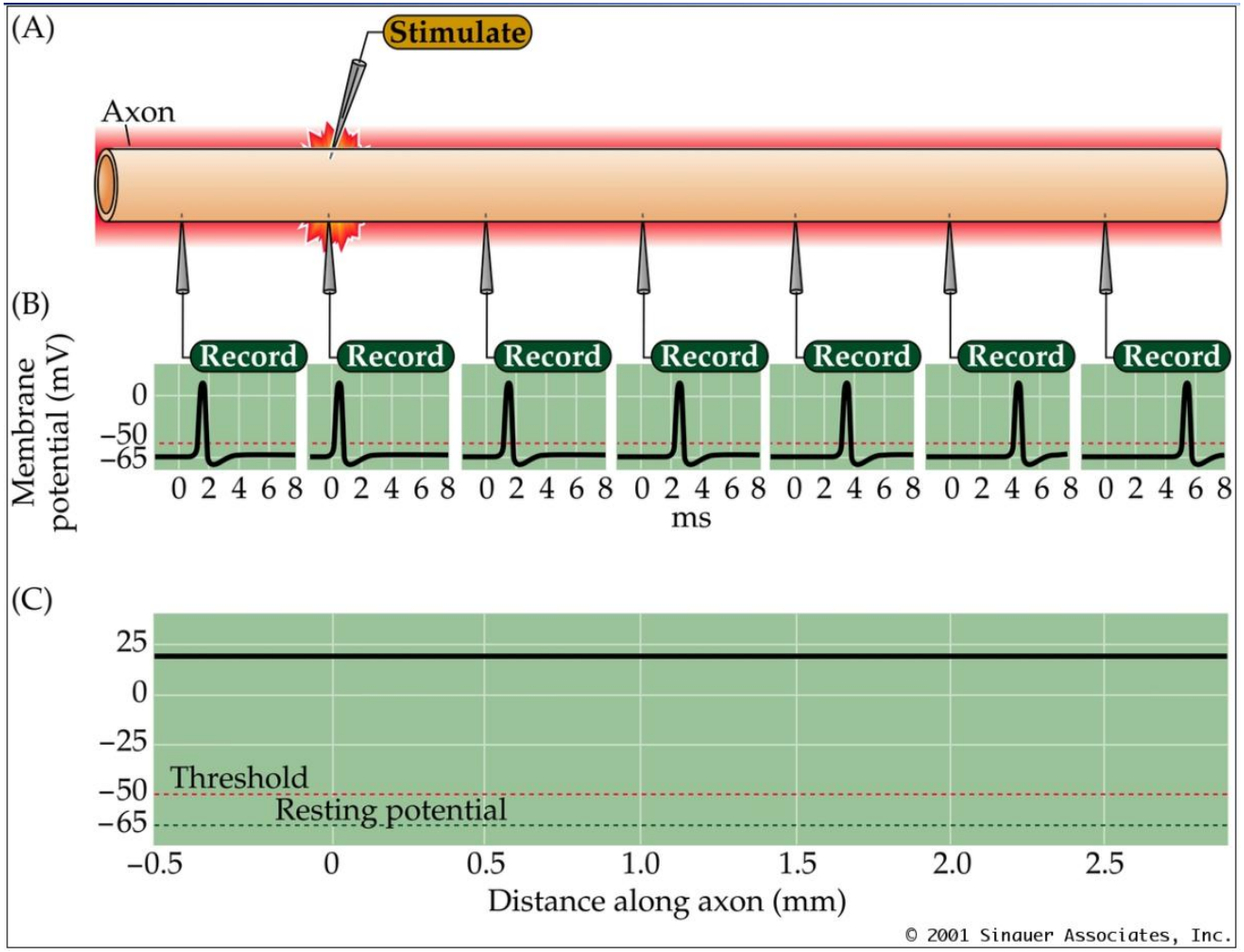
Feedback Mechanisms



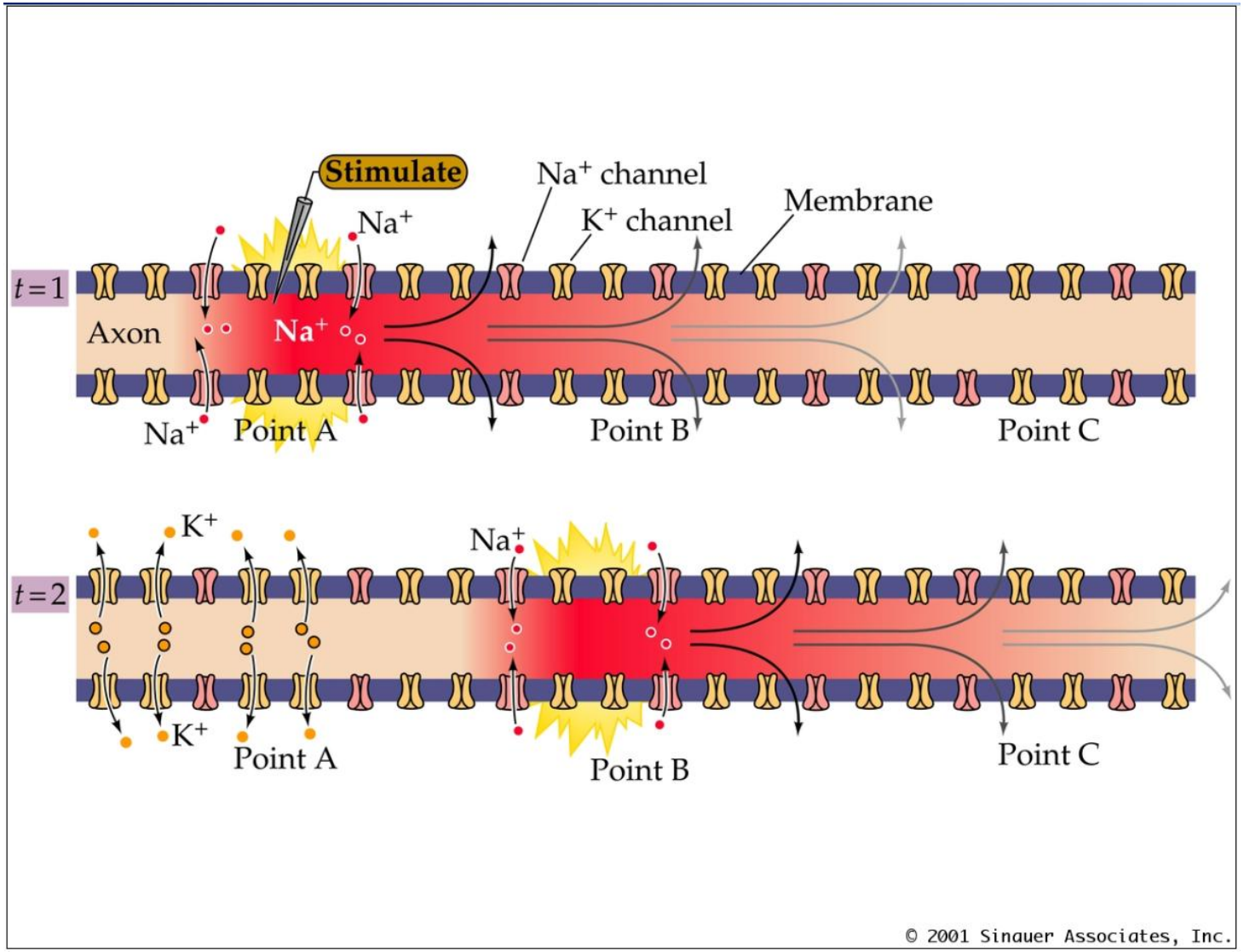
- Positive feedback of voltage dependent Na-conductance
- Negative feedback of voltage dependent K-conductance

- Explosive depolarization and subsequent repolarization

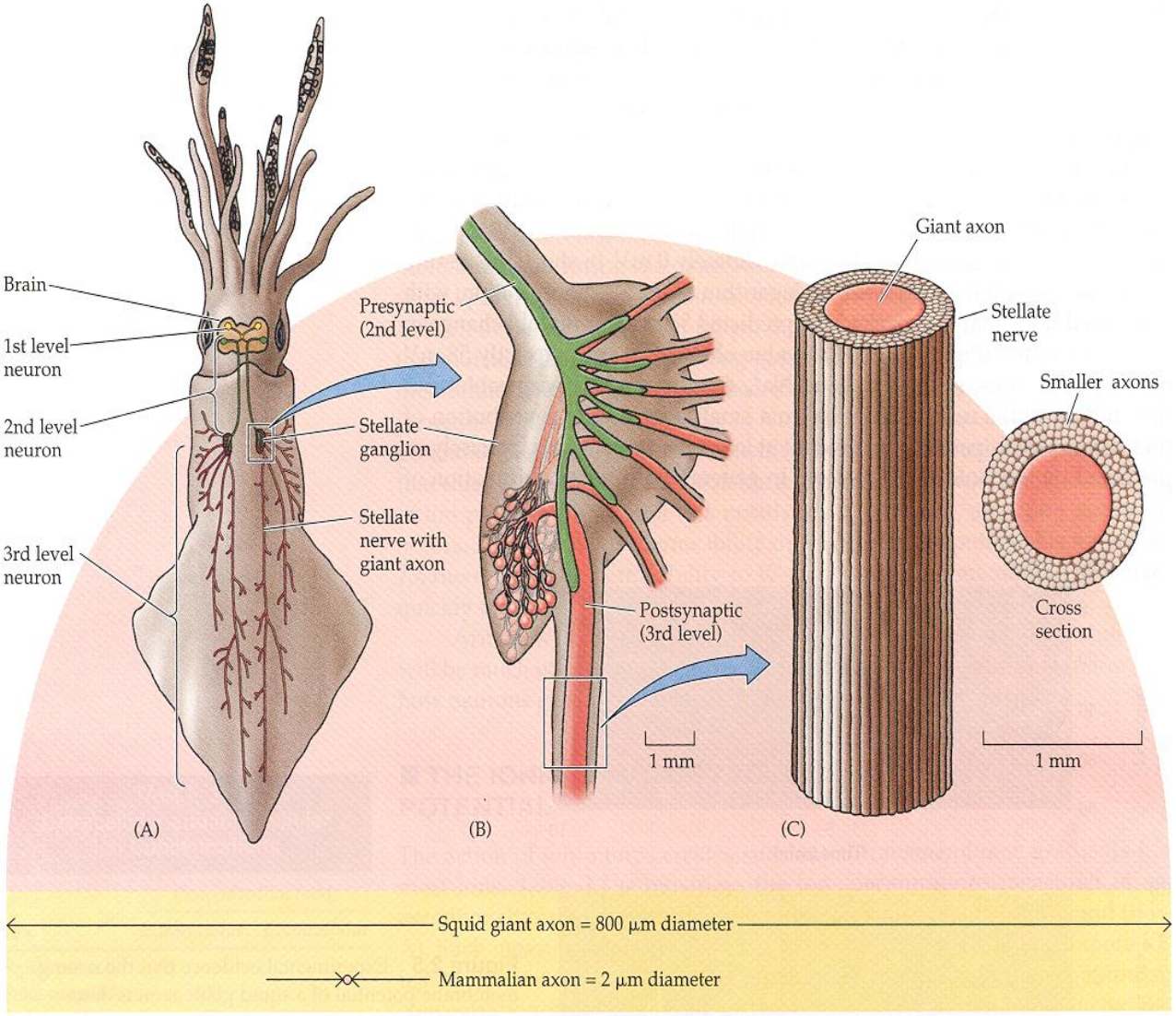
Action Potentials Propagate



AP Propagation



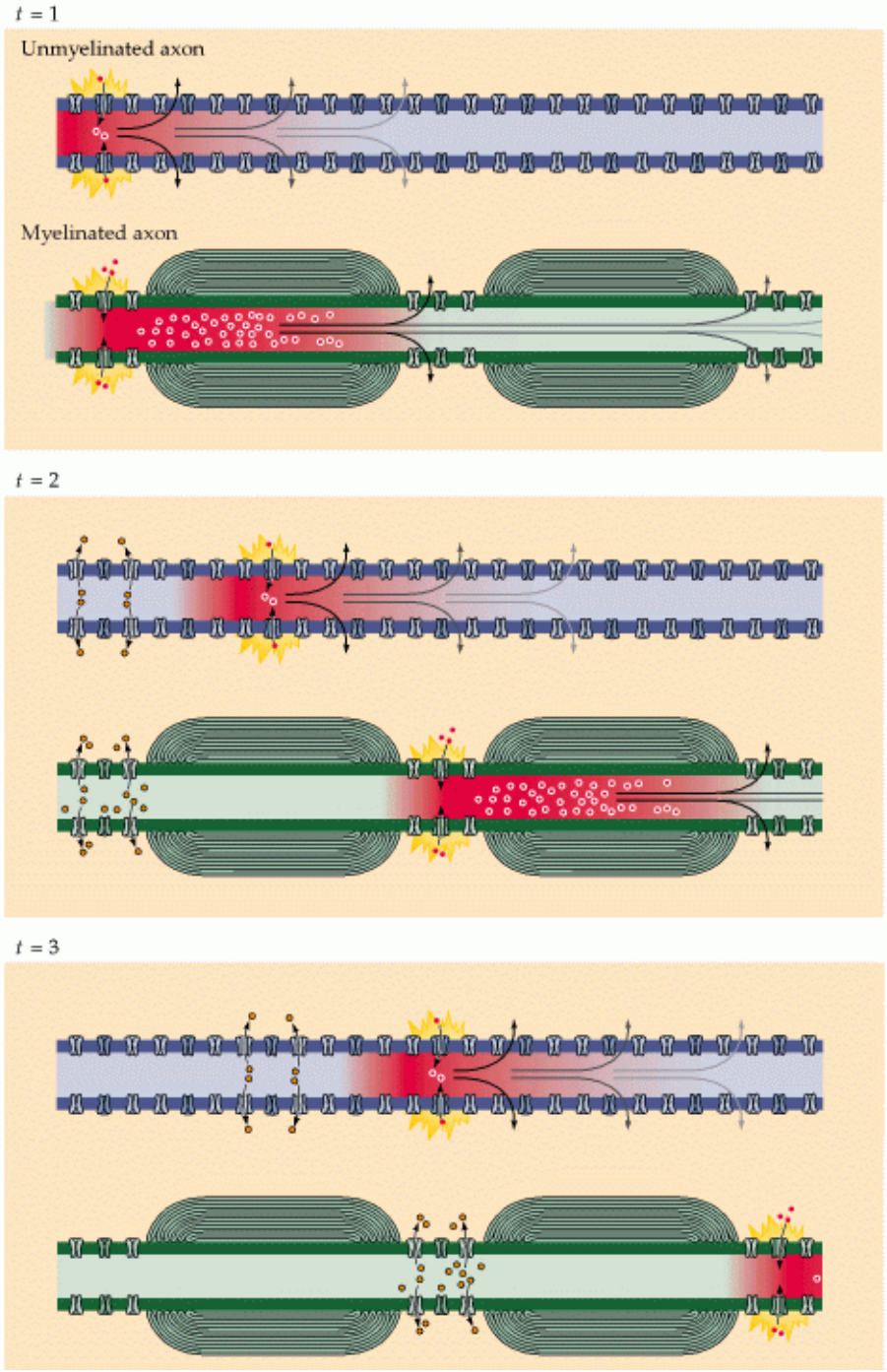
Make It Fast



$$l = \sqrt{\frac{r_m}{r_i}}$$

r_m scales linearly with the diameter, while r_i scales with the square of the diameter

Big axons are faster

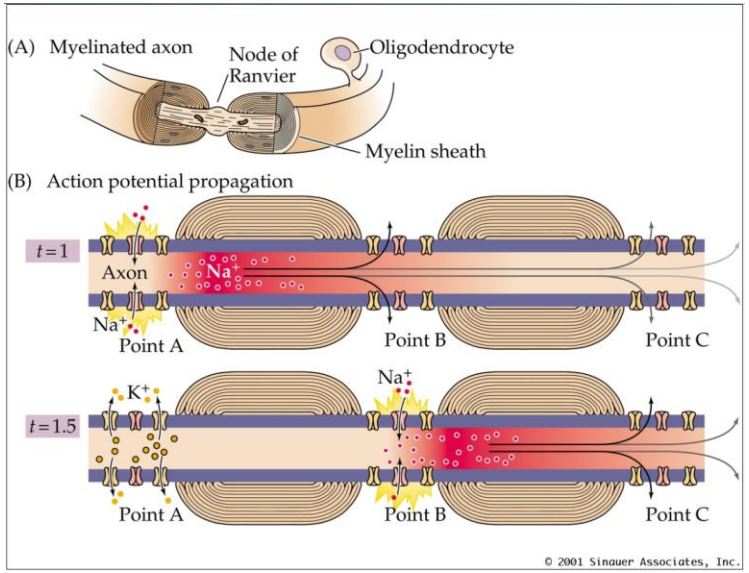


Myelin

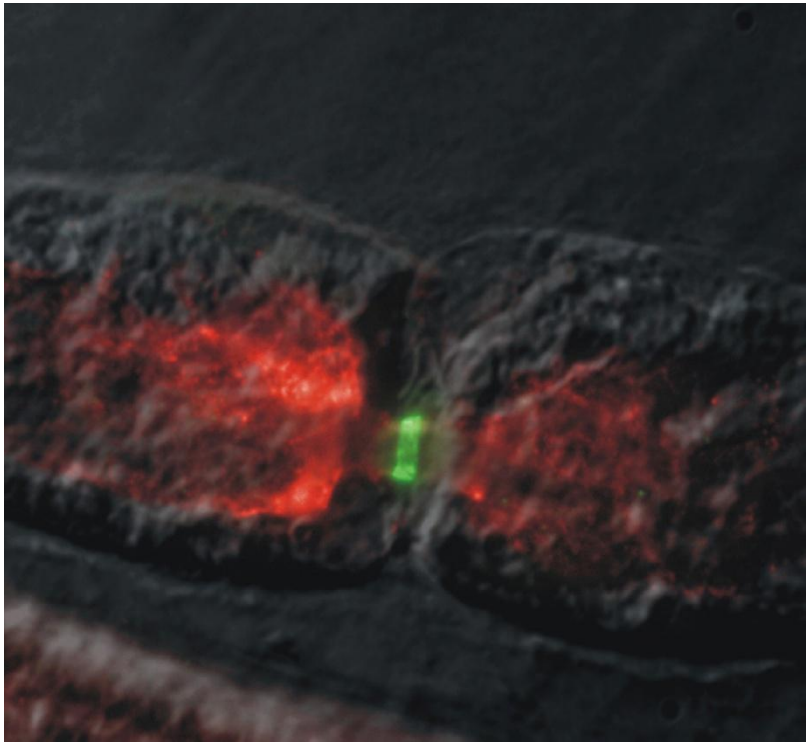
Myelinization reduces both r_m and the capacitance of the membrane. This greatly improves the performance of the ‘leaky flexible garden hose’.

The trigger signal can reach more distant channels more quickly.

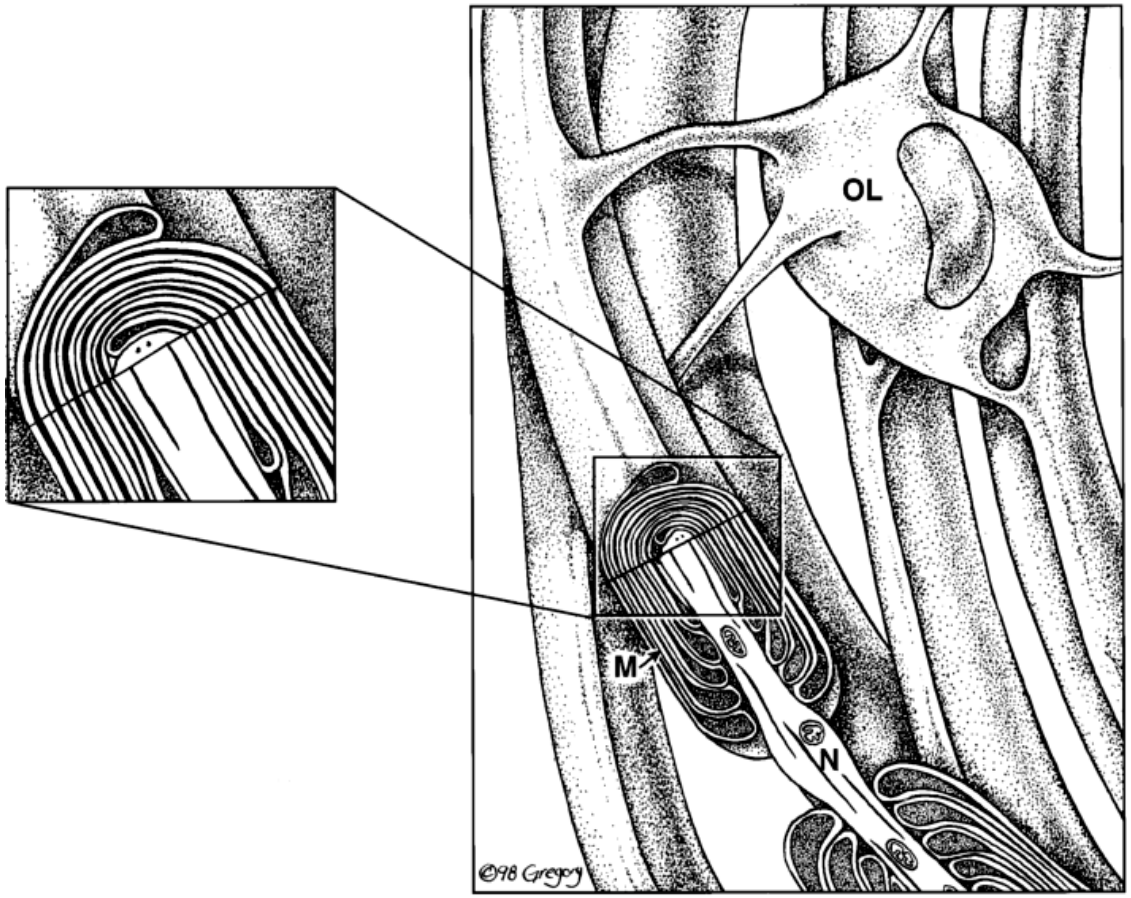
Channels are Strategically Enriched



Sodium channels are enriched at nodes of Ranvier -> Saltatory propagation of the AP.

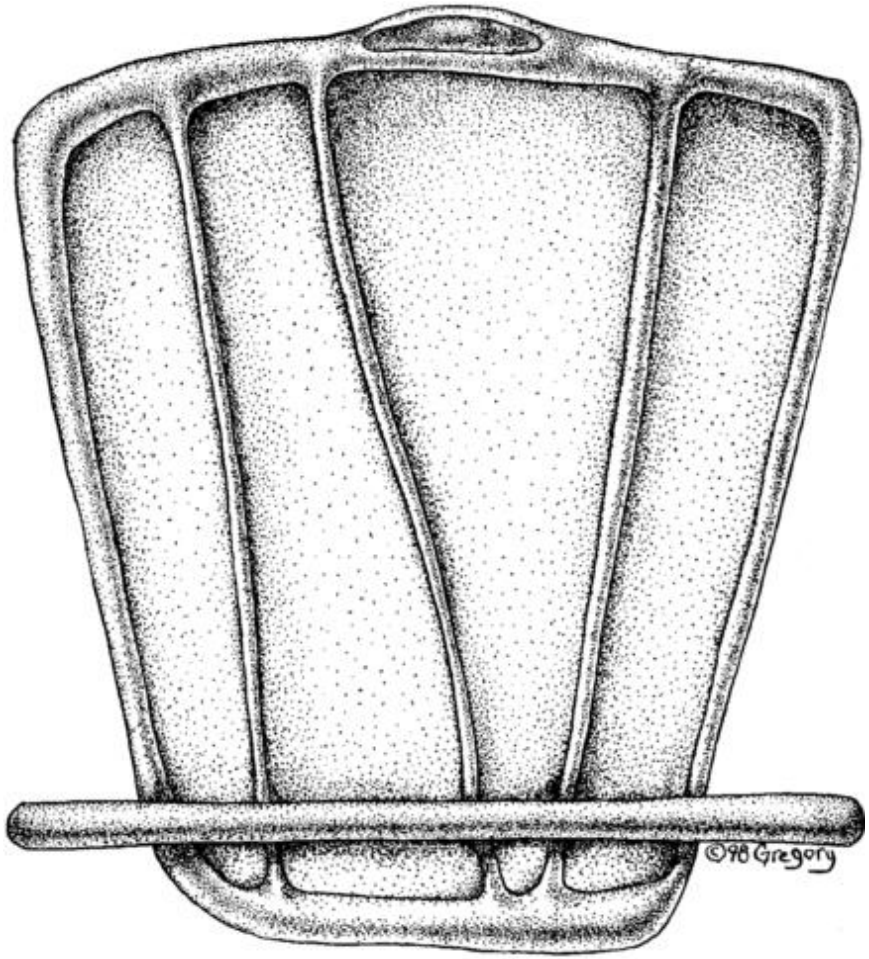


CNS Myelin



- A single oligodendrocyte forms myelin sheath around many (50) axons.
- Segment length: ca. 1 mm

PNS Myelin



- An unrolled Schwann cell in the peripheral nervous system (PNS).
- Each Schwann cell only surrounds one axon.