Advanced

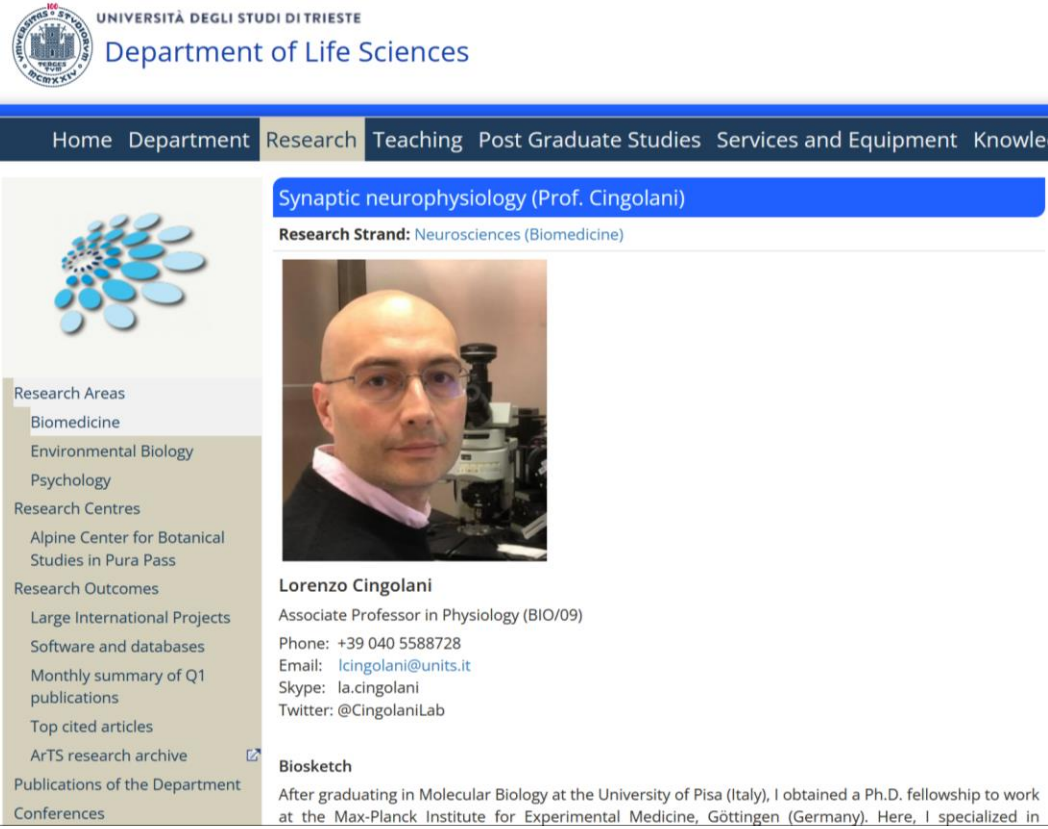
Electrophysiology

Lessons 1-2

26 February/ 5 March 2026

Course presentation

Equivalent electrical circuit of a neuron



UNIVERSITÀ DEGLI STUDI DI TRIESTE
Department of Life Sciences

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- Biomedicine
- Environmental Biology
- Psychology

Research Centres
- Alpine Center for Botanical Studies in Pura Pass

Research Outcomes
- Large International Projects
- Software and databases
- Monthly summary of Q1 publications
- Top cited articles
- ArTS research archive

Publications of the Department

Conferences

Synaptic neurophysiology (Prof. Cingolani)

Research Strand: Neurosciences (Biomedicine)

Lorenzo Cingolani

Associate Professor in Physiology (BIO/09)

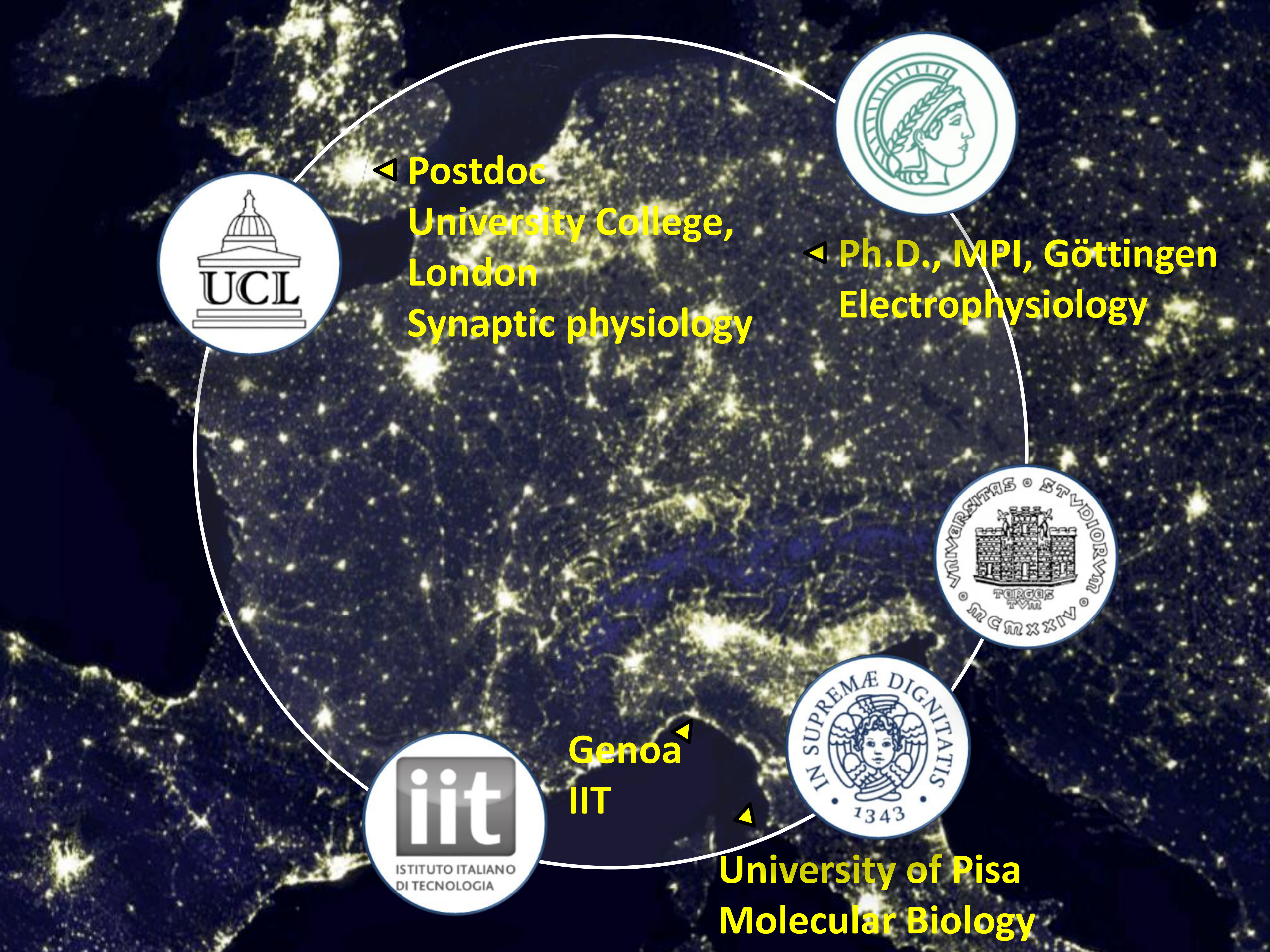
Phone: +39 040 5588728
Email: lcingolani@units.it
Skype: la.cingolani
Twitter: @CingolaniLab

Biosketch

After graduating in Molecular Biology at the University of Pisa (Italy), I obtained a Ph.D. fellowship to work at the Max-Planck Institute for Experimental Medicine, Göttingen (Germany). Here, I specialized in

Building Q - rooms 216 & 309

Lorenzo A. Cingolani


UCL
Postdoc
University College,
London
Synaptic physiology
Ph.D., MPI, Göttingen
Electrophysiology
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ISTITUTO ITALIANO
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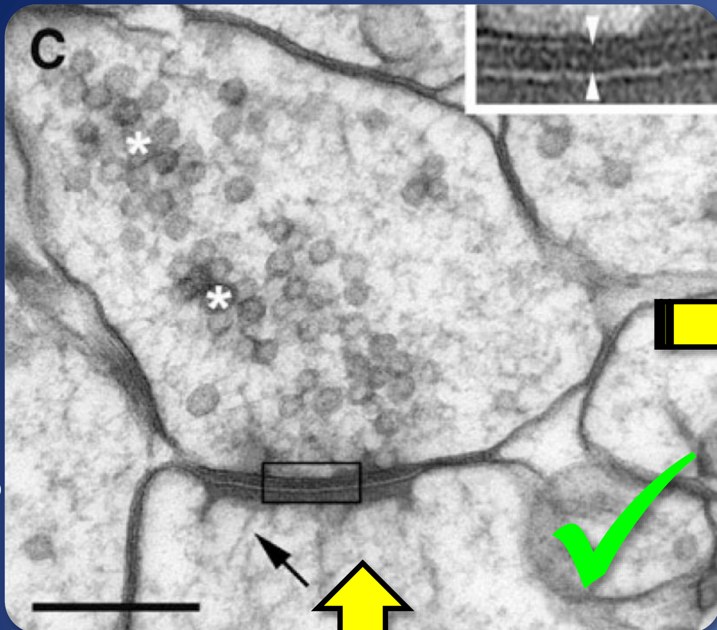
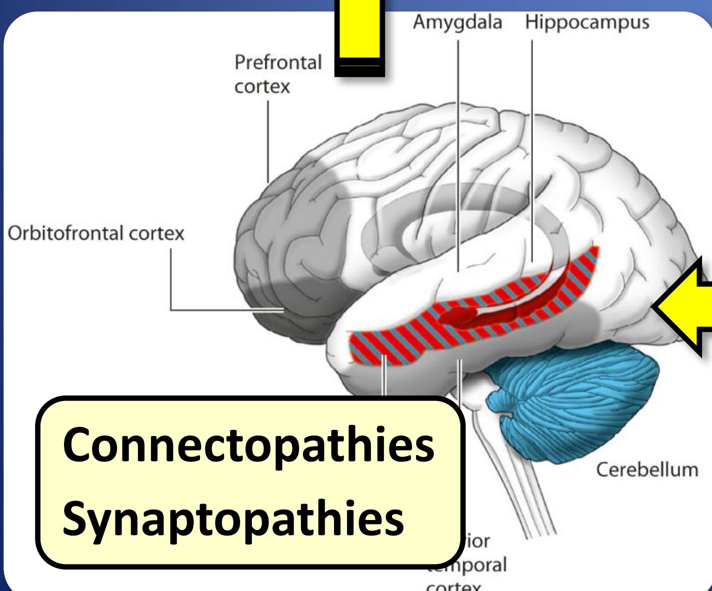
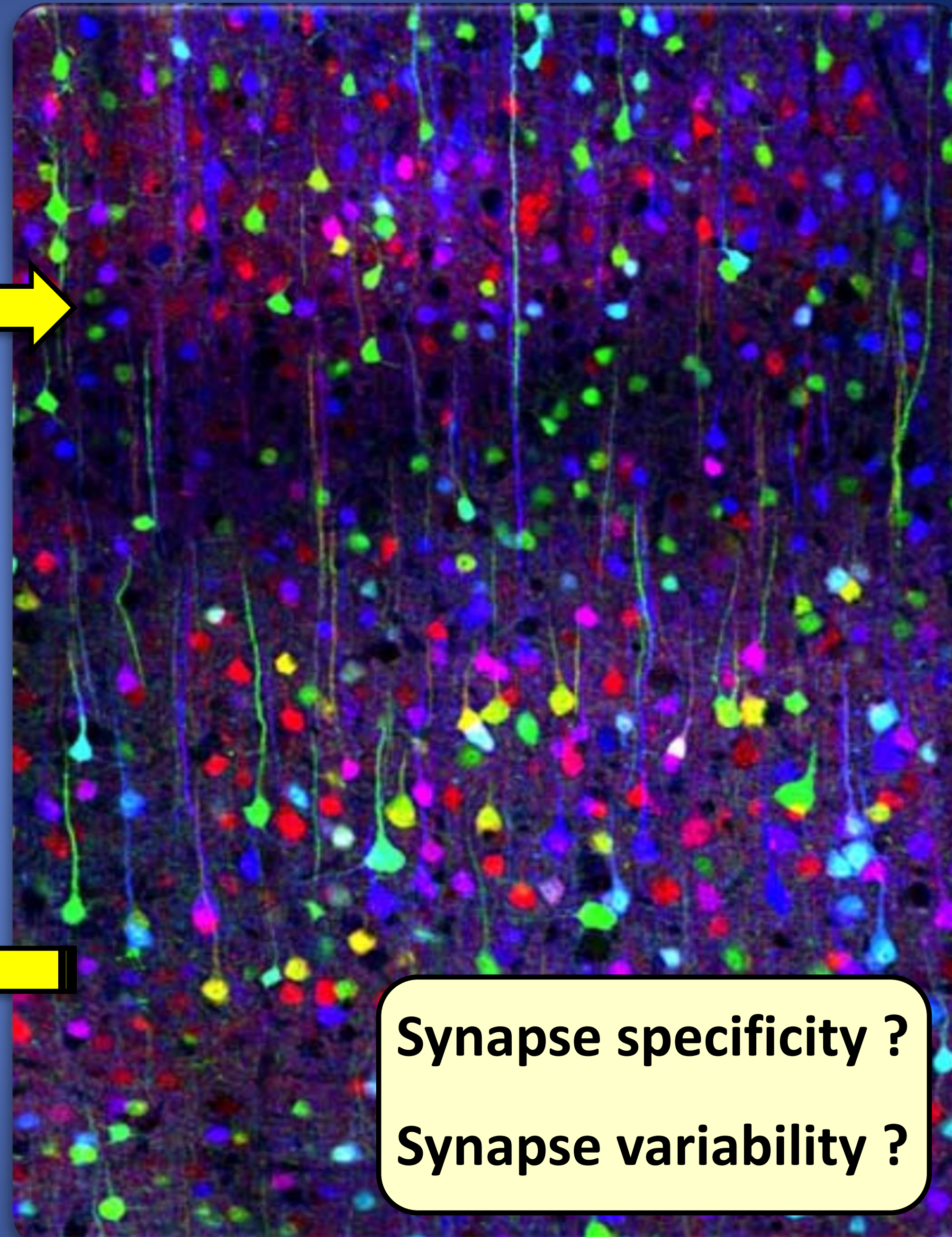
Molecular Biology



Rostaing et al., 2006

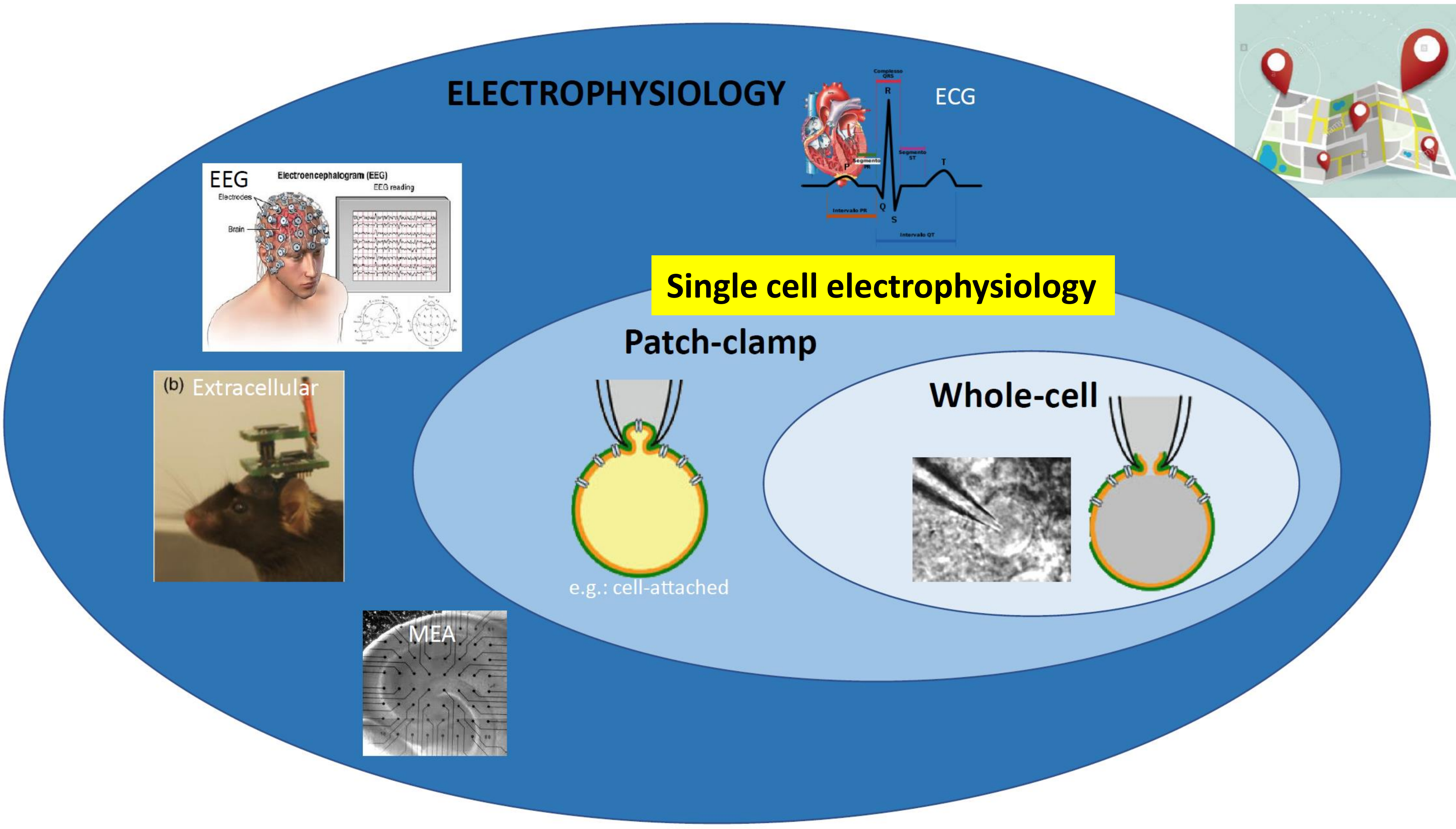


Wang et al., 2014

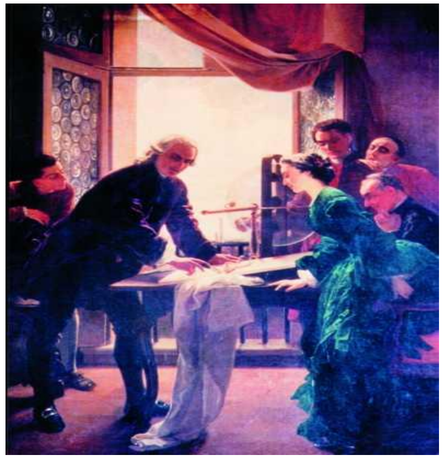


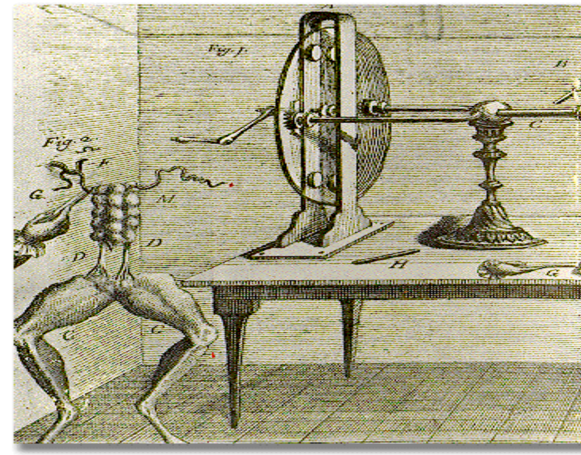
What is electrophysiology?

Electrophysiological techniques



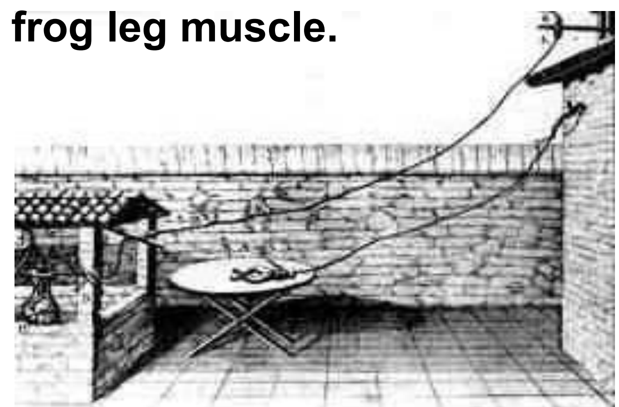
The origins of bioelectricity



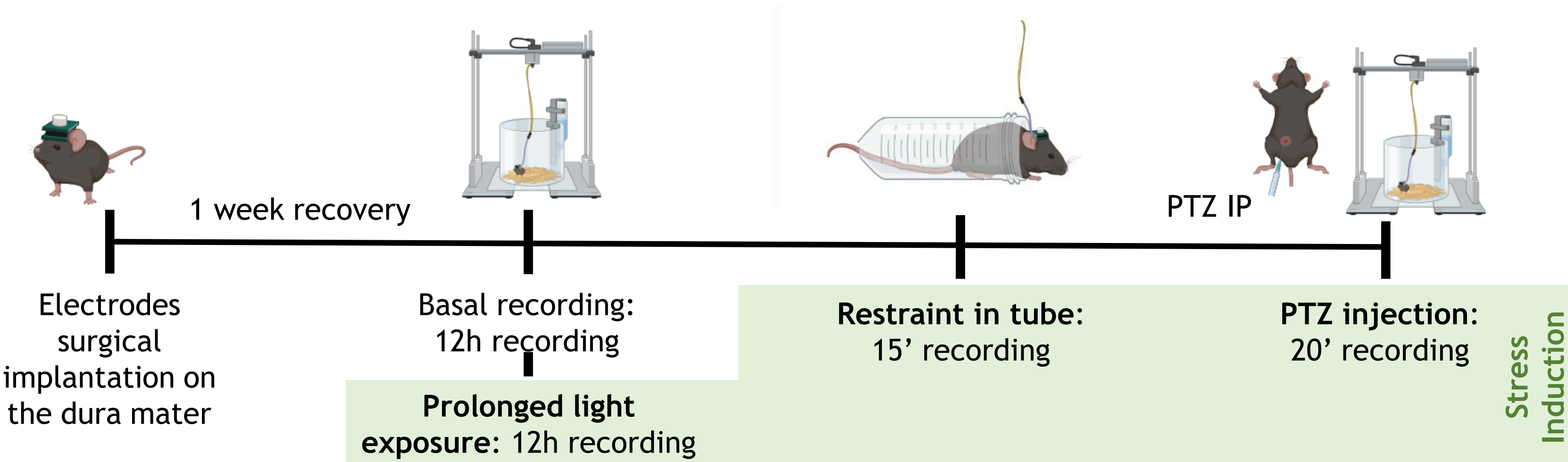


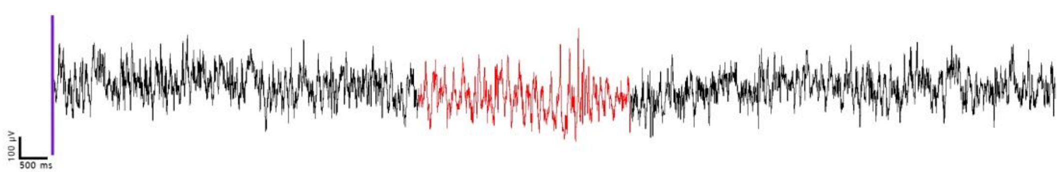
Luigi Galvani (1737-1798), working at the University of Bologna, discovered that nerve conduction and muscle contraction are electrical phenomena. Galvani published his results in 1791 in "De Viribus Electricitatis in Motu Muscolari Commentarius".

Galvani, demonstrated that the application of an electric current caused the contraction of the frog leg muscle.



Electroencephalographic (EEG) recordings in freely moving mice





Course goals

- Understand the basic biophysics of synapses, neurons and neuronal networks, and the principles and potential of electrophysiological techniques
- Become accustomed to performing electrophysiological experiment (patch-clamp and MEA recordings)
- Become proficient at data analysis using dedicated software

Structure of the course

- **Face-to-face course**
- **Work at the computer**
- **Laboratory**

- **Lessons will be recorded and available on MT**
- **Materials (presentations, papers, articles, book chapters) loaded on Moodle before lessons (password: electro)**

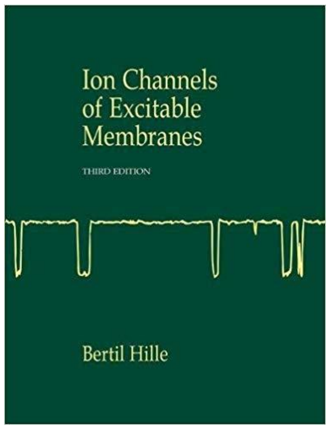
Structure of the exam

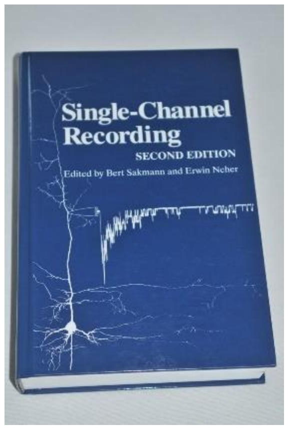
1. **A homework assignment, consisting in the analysis, figure preparation and interpretation of a set of electrophysiological data.**
   Weight in the final score: 60%

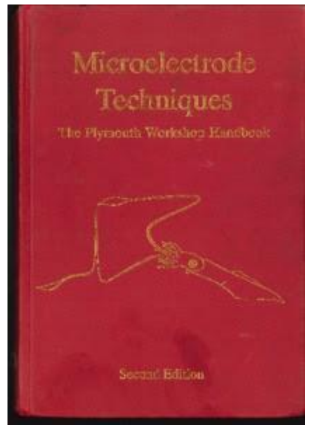
2. **Practicum at the electrophysiological setups. Students will be judged for their propensity for experimental work.**
   Weight in the final score: 10%

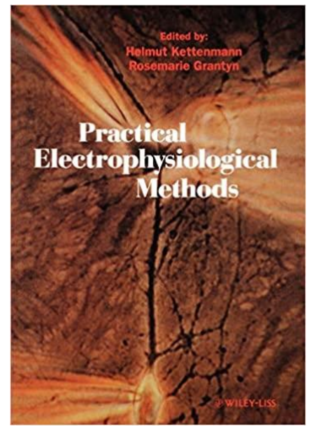
3. **Questionnaire on the Moodle platform. 10 multiple choice questions. Each question has only one correct answer, and each correct answer is awarded 1 point.**
   Weight in the final score: 30%

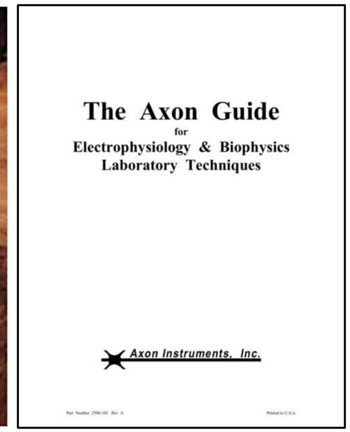
Textbooks

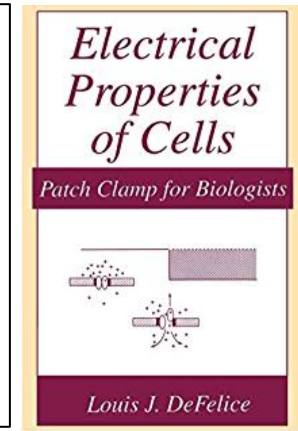


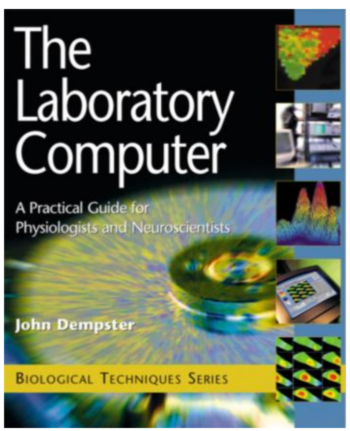


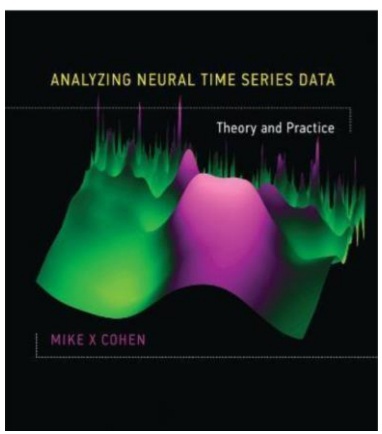


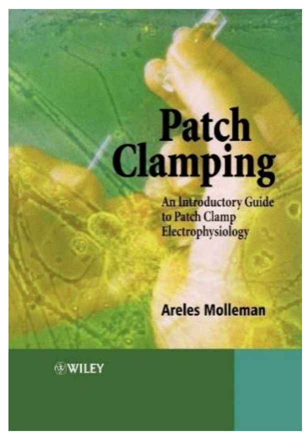


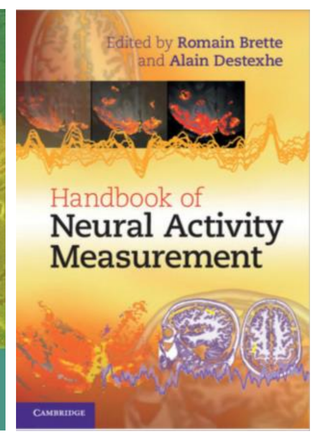












.... and others

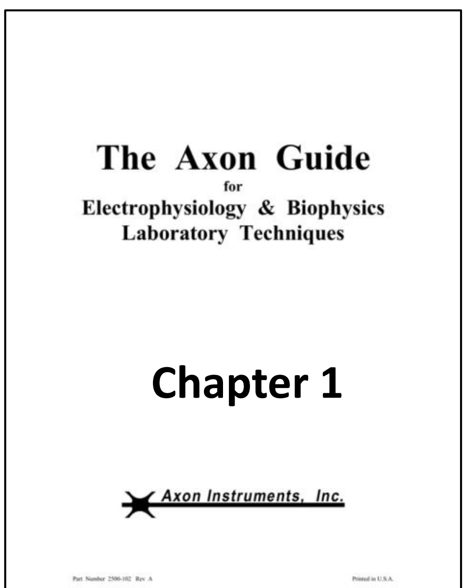
Calendar

- Th 26 February (14:00-16:00): Frontal lesson (ex-Cla)
- Th 26 February (16:00-18:00): Data analysis project (ex-Cla)
- F 27 February (14:00-18:00): Acute brain slice preparation (Room 309, Building Q)
- Th 5 March (14:00-16:00): Frontal lesson (ex-Cla)
- Th 5 March (16:00-18:00): Data analysis project (ex-Cla; Bring a laptop!)
- F 6 March (14:00-18:00): Patch-clamp (group 1; Room 309, Building Q)
- Th 12 March (14:00-16:00): Frontal lesson (ex-Cla)
- Th 12 March (16:00-18:00): Data analysis project (ex-Cla; Bring a laptop!)
- F 13 March (14:00-18:00): Patch-clamp (group 2; Room 309, Building Q)
- F 20 March (14:00-18:00): Patch-clamp (group 3; Room 309, Building Q)

Bioelectricity

Learning objective:

To understand the equivalent electrical circuit of a neuron


The Axon Guide
for
Electrophysiology & Biophysics
Laboratory Techniques

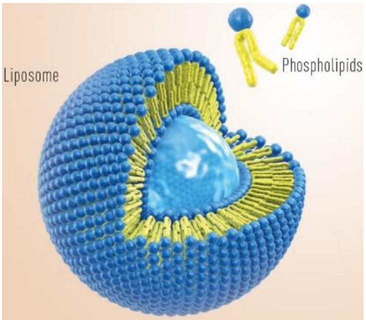
Chapter 1

Axon Instruments, Inc.

Foolish assumptions:

We know what the membrane potential (ΔV_m) and Nernst equation are

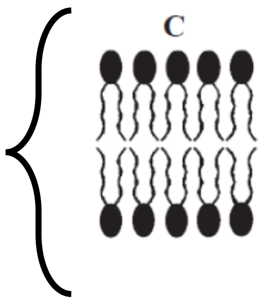
Principles of electrical circuits - Capacitance



C 

$$C = \frac{\Delta Q}{\Delta V_m}$$

ΔV_m



$$\Delta Q_{total} = \Delta Q_1 + \Delta Q_2 = C_1 \Delta V_m + C_2 \Delta V_m = \Delta V_m \,(C_1 + C_2)$$

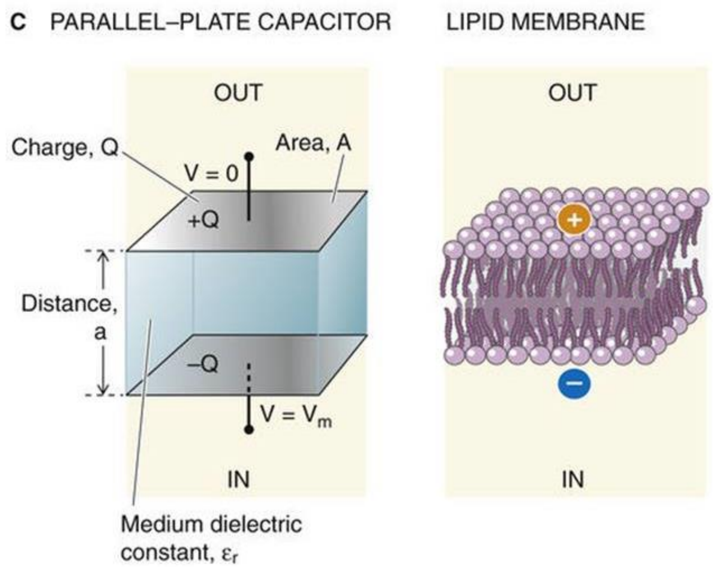
$$C_{total} = C_1 + C_2$$

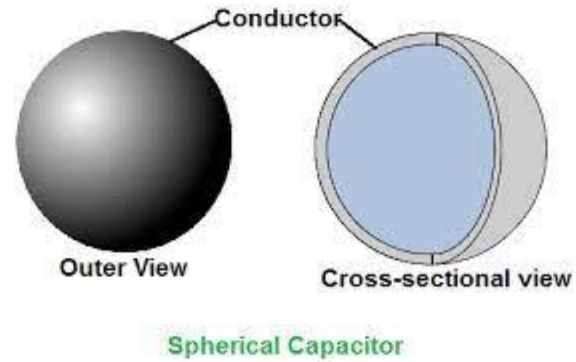
$$C_{total} = \sum_i^n C_i$$

ΔQ is charge imbalance (Coulombs, C)
C is capacitance (Farads, F)

Principles of electrical circuits - Capacitance

$$C = \varepsilon_m \frac{A}{d}$$





d_m = 10 nm = 10^{-8} m

ε_m = 10^2 pF / m (ε_0 = 8.85 pF / m)

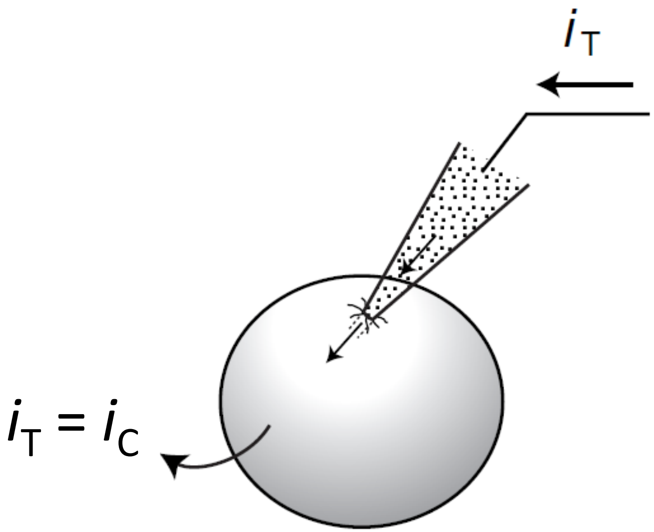
C_m / A = ε_m / d = Specific C_m = 10^{10} pF / m^2

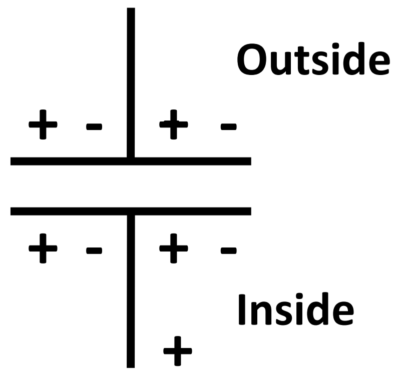
C_m is proportional to A_m

Specific C_m = 1 μF / cm^2

ε is dielectric constant of the insulator (Farad / m)
A is area of the capacitor (m^2)
d is distance between conducting plates (m)

Principles of electrical circuits - Capacitive current

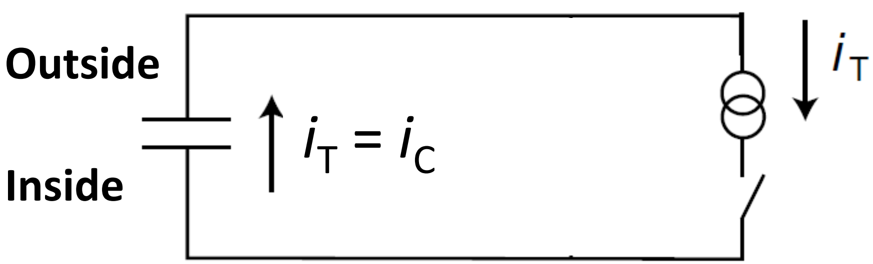




$$\Delta Q = C\,\Delta V_m$$

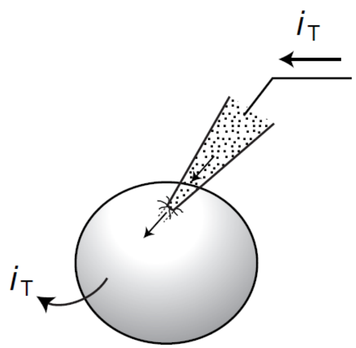
$$i_T = i_C = \frac{dQ}{dt} = C\,\frac{dV_m}{dt}$$

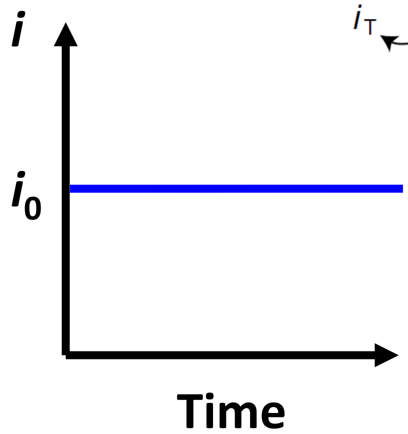
i_C is C times the time rate of change (d/dt) of V_m

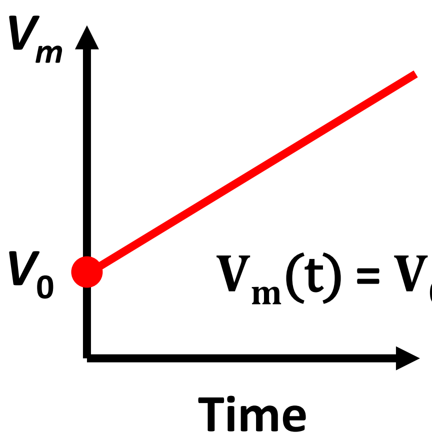


What happens when we inject current into this simple neuron?

Principles of electrical circuits - Capacitive current







$$V_m(t) = V_0 + \frac{i_0}{C}\, t$$

$$i_T(t) = C\,\frac{dV_m}{dt}$$

We can integrate this differential equation over time starting with initial voltage V_0 at time 0

$$dV_m = \frac{1}{C}\, i_T(t)dt$$

$$\int_{V_0}^{V_t} dV_m = \frac{1}{C}\int_0^t i_T(t)dt$$

$$V_m(t) = V_0 + \frac{1}{C}\underbrace{\int_0^t i_T dt}_{\Delta Q}$$

$$V_m(t) = V_0 + \frac{\Delta Q}{C}$$

V_m is the initial V_m at time 0 plus the integral over time of the injected current (=ΔQ) divided by C

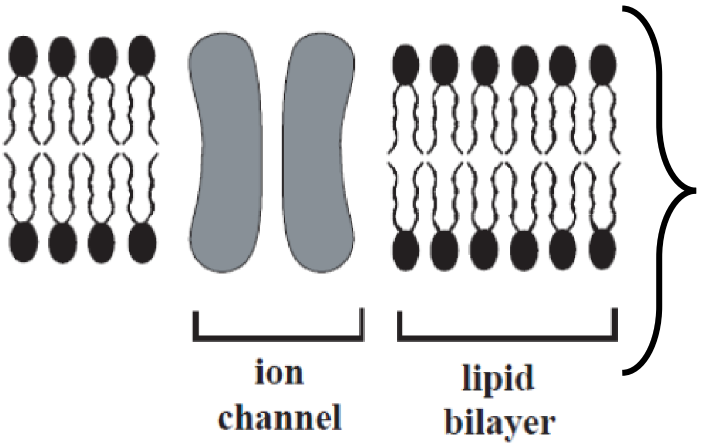
Principles of electrical circuits - Resistance

Ohm's (first) law

$$i = \frac{\Delta V_m}{R}$$

$$i = G\,\Delta V_m$$

$$R = \frac{1}{G}$$



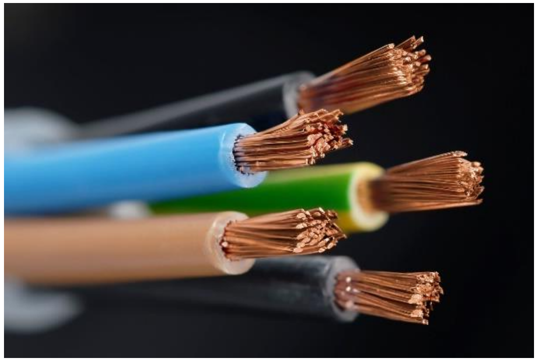
$$i_1 = \frac{\Delta V_m}{R_1} \qquad i_2 = \frac{\Delta V_m}{R_2} \qquad i_{total} = \frac{\Delta V_m}{R_{total}} = \Delta V_m \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \frac{1}{R_{total}} = \sum_i^n \frac{1}{R_i}$$

$$G_{total} = G_1 + G_2 \qquad G_{total} = \sum_i^n G_i$$

ΔV is voltage (Volts, V)
i is current (Amperes, A)
R is resistance (Ohms, Ω)
G is conductance (Siemens, S)

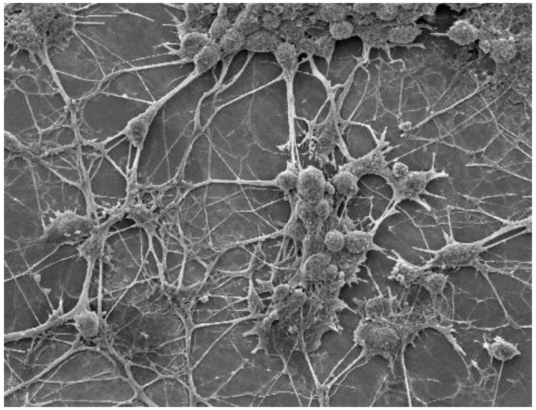
Principles of electrical circuits - Resistivity



ρ_{copper} = 1.7 µΩ cm

Ohm's second law

$$R = \rho \frac{L}{A}$$



ρ_{CSF} = 60 Ω cm

(More than 10 million higher)

The brain is made of lousy conductors → You need huge ΔV to produce tiny currents (i = ΔV/R), that's why you need special gimmicks like action potentials to send electrical signals

ρ is resistivity of the material (Ω m)
L is length of the conductor (m)
A section of the conductor (m^2)

The equivalent electrical circuit of a neuron

$$i_T = \frac{V_m}{R} + C\frac{dV_m}{dt}$$ (first order liner differential equation)

$$Ri_T = V_m + RC\frac{dV_m}{dt}$$

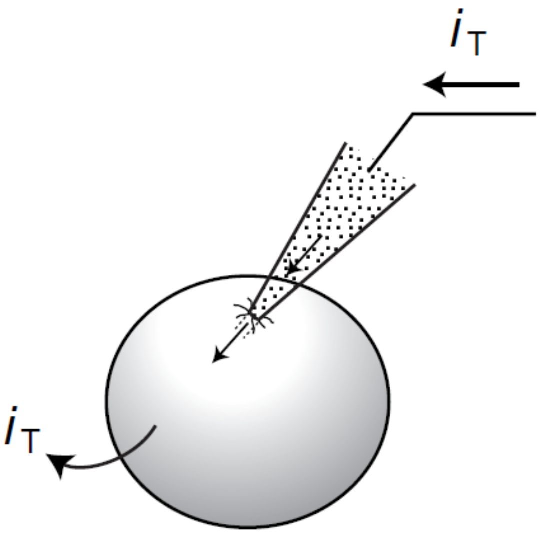
What is the steady-state solution of this equation?

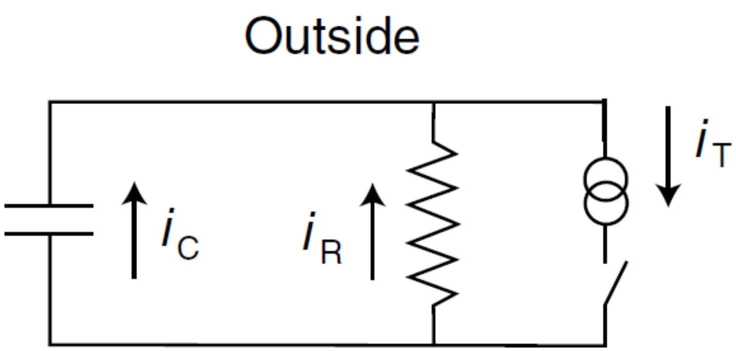
Set $\frac{dV_m}{dt} = 0$

$$V_{ss} = Ri_T$$

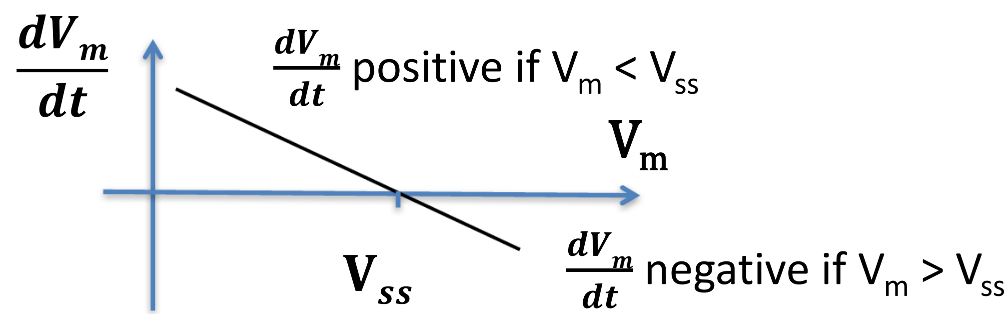
$$V_{ss} = V_m + \tau\frac{dV_m}{dt}$$ **where τ = RC**

$$\frac{dV_m}{dt} = -\frac{1}{\tau}(V_m - V_{ss})$$



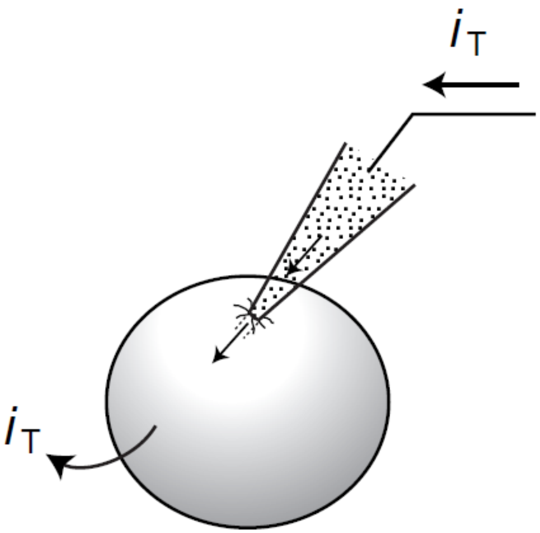


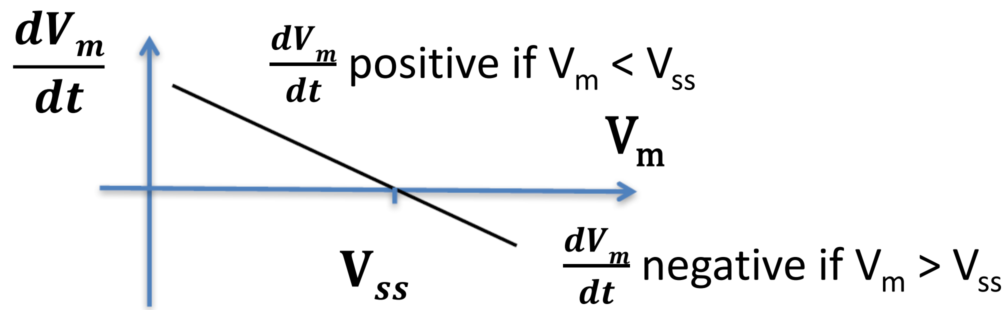
$i_C = C\frac{dV_m}{dt}$ Inside $i_R = \frac{V_m}{R}$



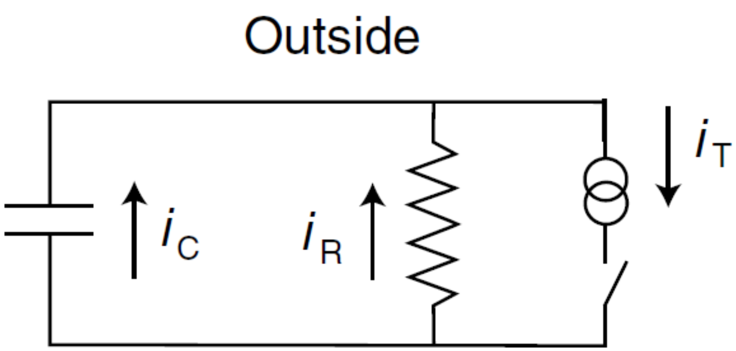
The equivalent electrical circuit of a neuron

$$\frac{dV_m}{dt} = -\frac{1}{\tau}(V_m - V_{ss})$$





- V_m is always approaching (relaxing towards) V_{ss}
- V_m approaches V_{ss} at a rate ($\frac{dV_m}{dt}$) proportional to how far away it is from V_{ss}

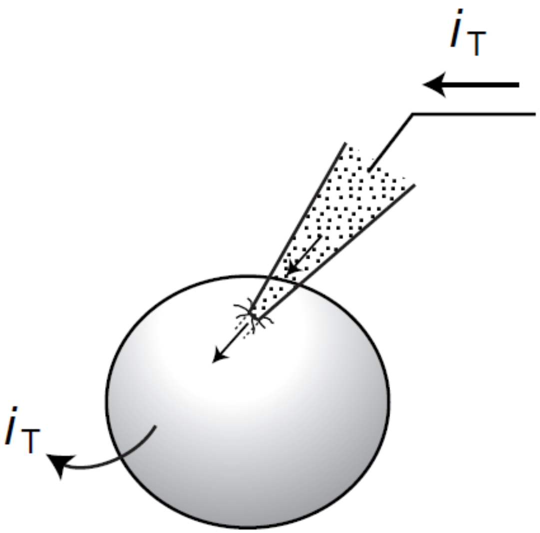


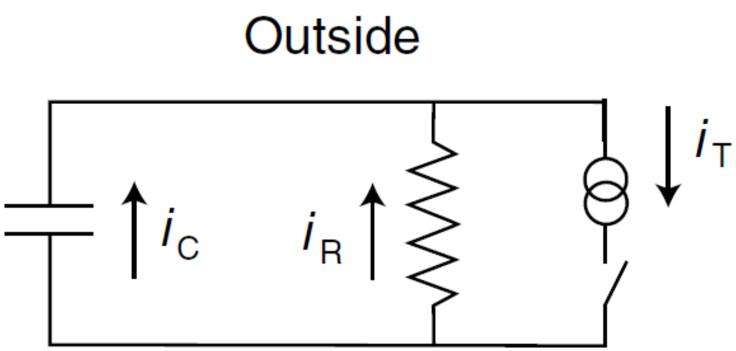
$i_C = C\frac{dV_m}{dt}$

Inside

$i_R = \frac{V_m}{R}$

The equivalent electrical circuit of a neuron





$$i_C = C\frac{dV_m}{dt}$$

Inside

$$i_R = \frac{V_m}{R}$$

$$\frac{dV_m}{dt} = -\frac{1}{\tau}(V_m - V_{ss})$$

$$\frac{dV_m}{V_m - V_{ss}} = -\frac{dt}{\tau}$$

$$\int_{V_0}^{V_t} \frac{dV_m}{V_m - V_{ss}} = -\frac{1}{\tau}\int_0^t dt$$

$$\int \frac{dx}{x+c} = \ln(x+c)$$

$$\ln\frac{V_m - V_{ss}}{V_0 - V_{ss}} = -\frac{t}{\tau}$$

$$\frac{V_m - V_{ss}}{V_0 - V_{ss}} = e^{-\frac{t}{\tau}}$$

If $V_0 < V_{ss}$ → exponential rise
If $V_0 > V_{ss}$ → exponential decay

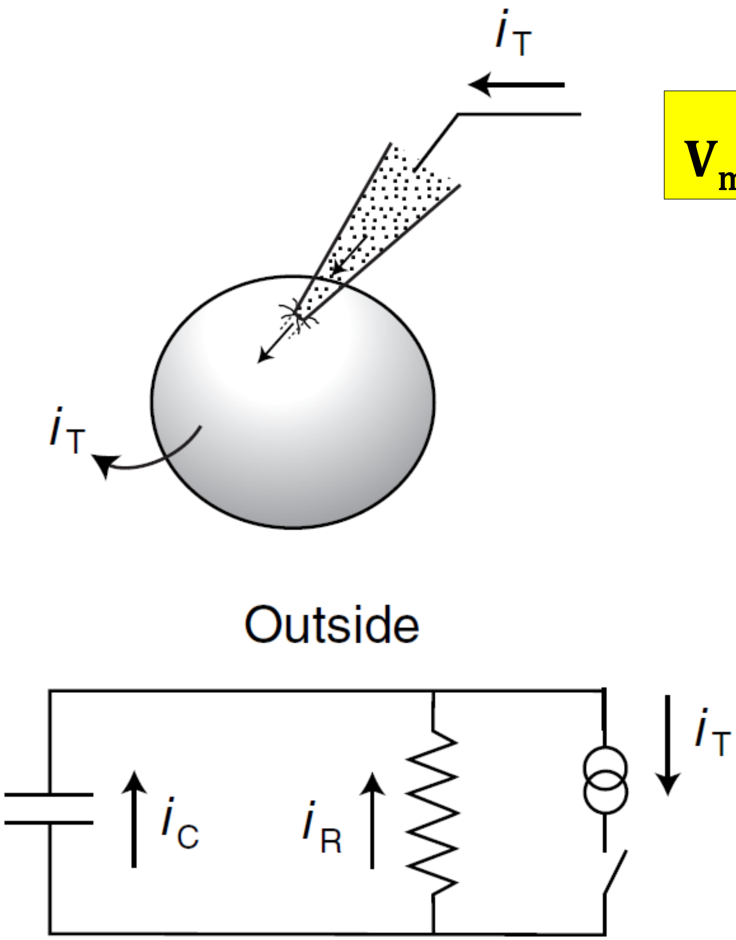
$$V_m - V_{ss} = (V_0 - V_{ss})\, e^{-\frac{t}{\tau}}$$

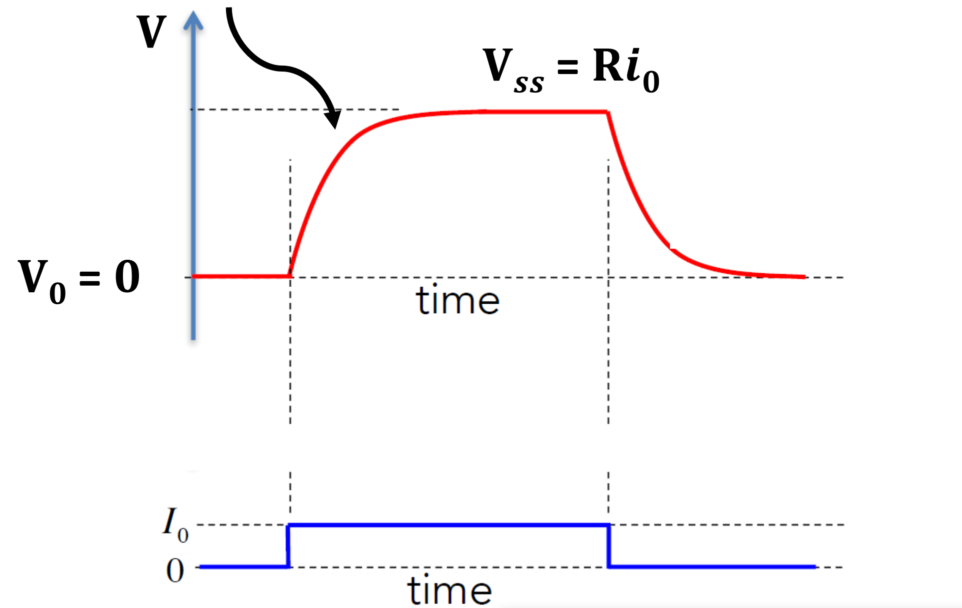
General solution for constant current

What is relaxing exponentially towards V_{ss} is the difference between V_m and V_{ss}

Response to current injection

$$V_m = V_{ss}\,(1 - e^{-\frac{t}{\tau}})$$





$$i_C = C\,\frac{dV_m}{dt}$$

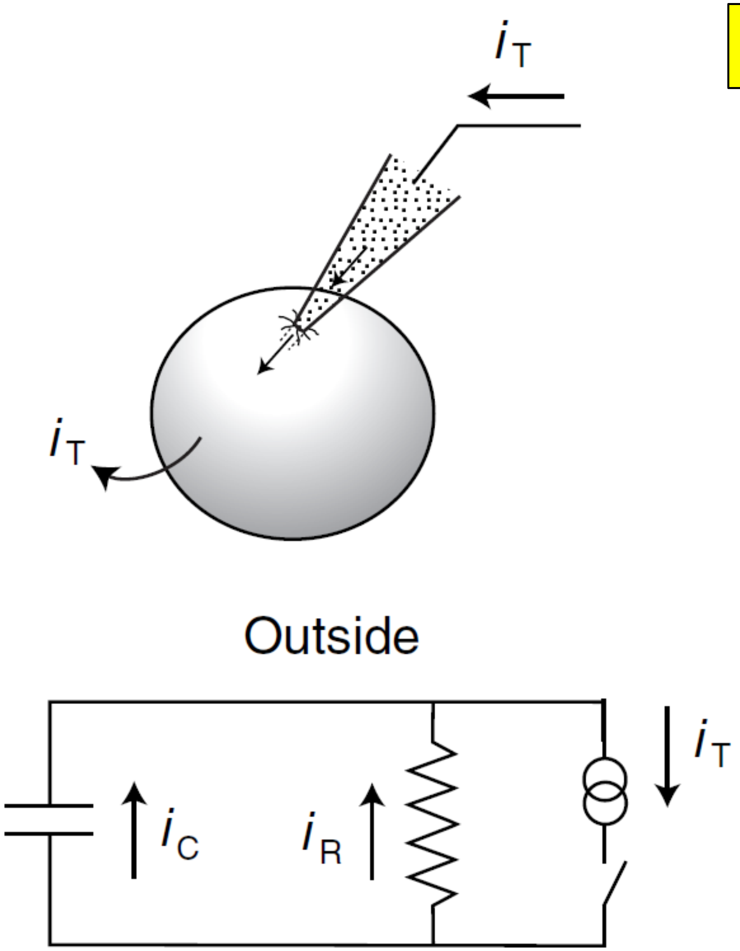
Inside

$$i_R = \frac{V_m}{R}$$

$$V_m - V_{ss} = (V_0 - V_{ss})\,e^{-\frac{t}{\tau}}$$

Response to current injection

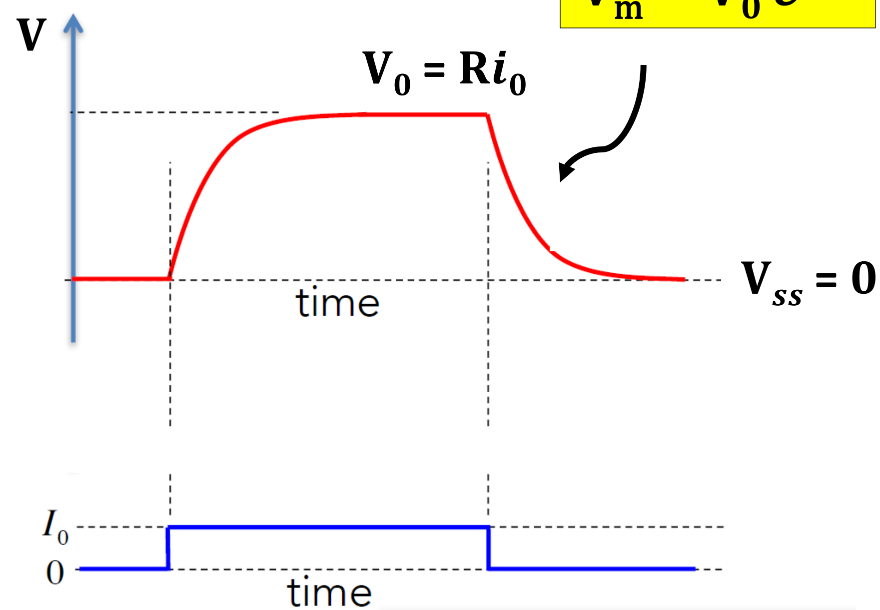
V_m is always relaxing toward V_{ss} exponentially



$$i_C = C\frac{dV_m}{dt}$$

$$i_R = \frac{V_m}{R}$$

$$V_m = V_0\, e^{-\frac{t}{\tau}}$$



$$V_m - V_{ss} = (V_0 - V_{ss})\, e^{-\frac{t}{\tau}}$$

An RC neuron acts as a low pass filter

(it allows low-frequency signals to pass through while attenuating high-frequency components)

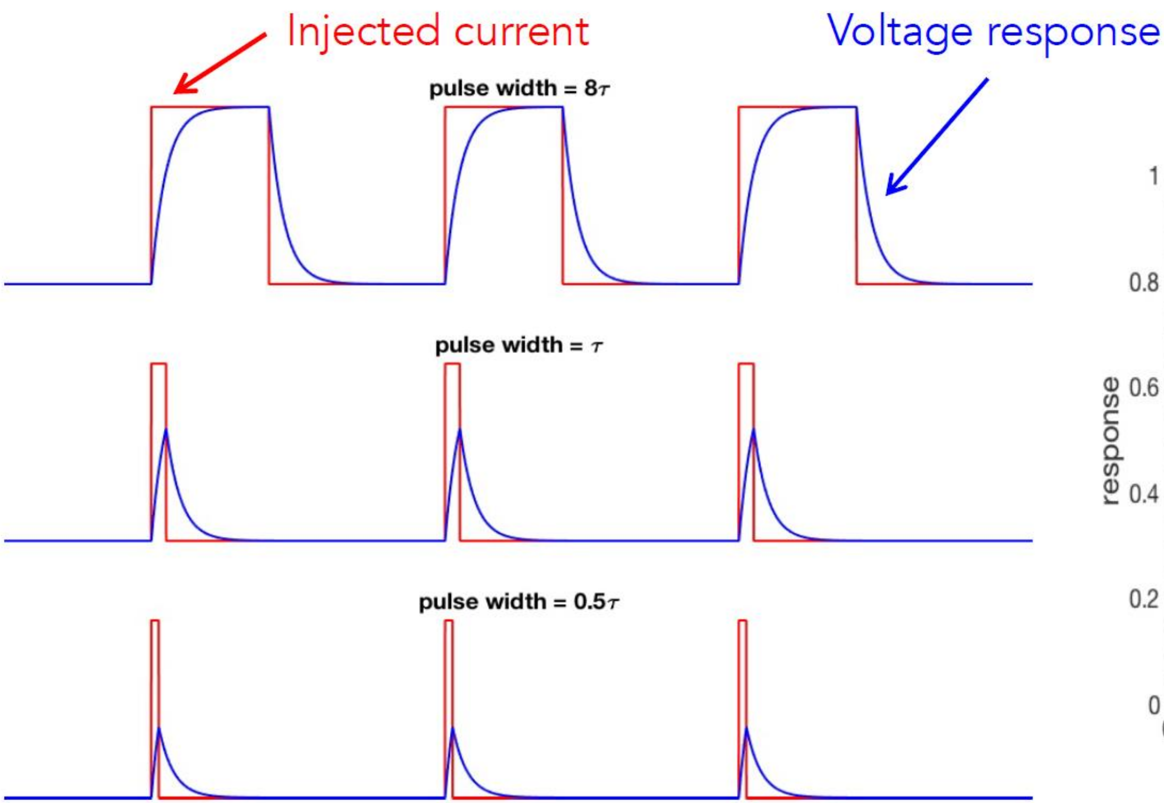
$$V_m = V_{ss}\left(1 - e^{-\frac{t}{\tau}}\right)$$

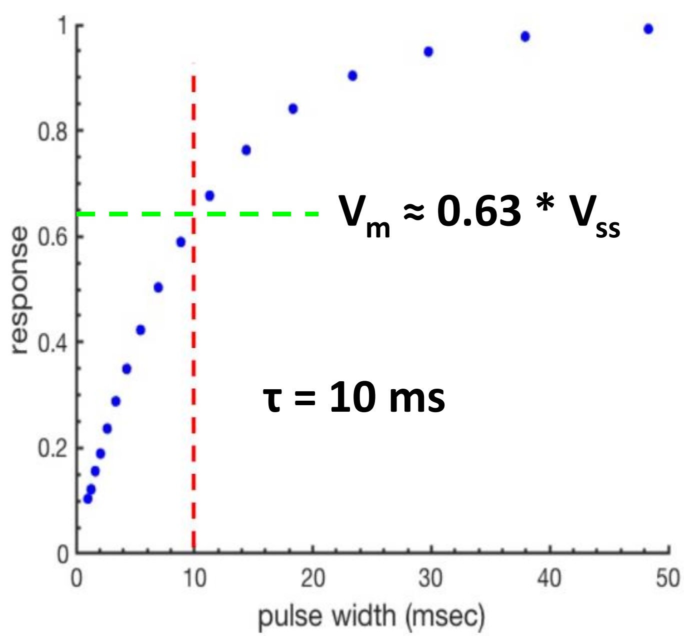
$\tau = RC$

$R \approx 10^8\ \Omega = 100\ M\Omega$

$C \approx 10^{-10}\ F = 100\ pF$

$\tau = RC \approx 10^{-2}\ s =$ **10 ms**





Learning objectives

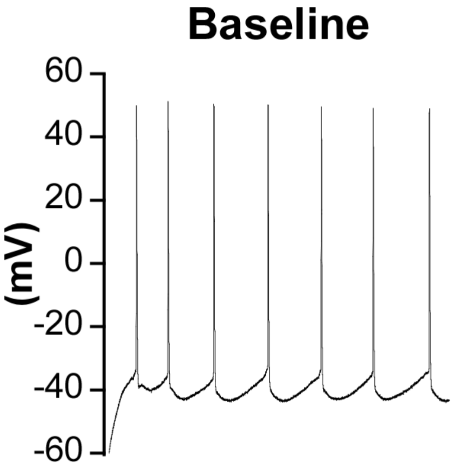
1. To understand what membrane capacitance is from both biological and electrical perspectives

2. To understand what membrane resistance is from both biological and electrical perspectives

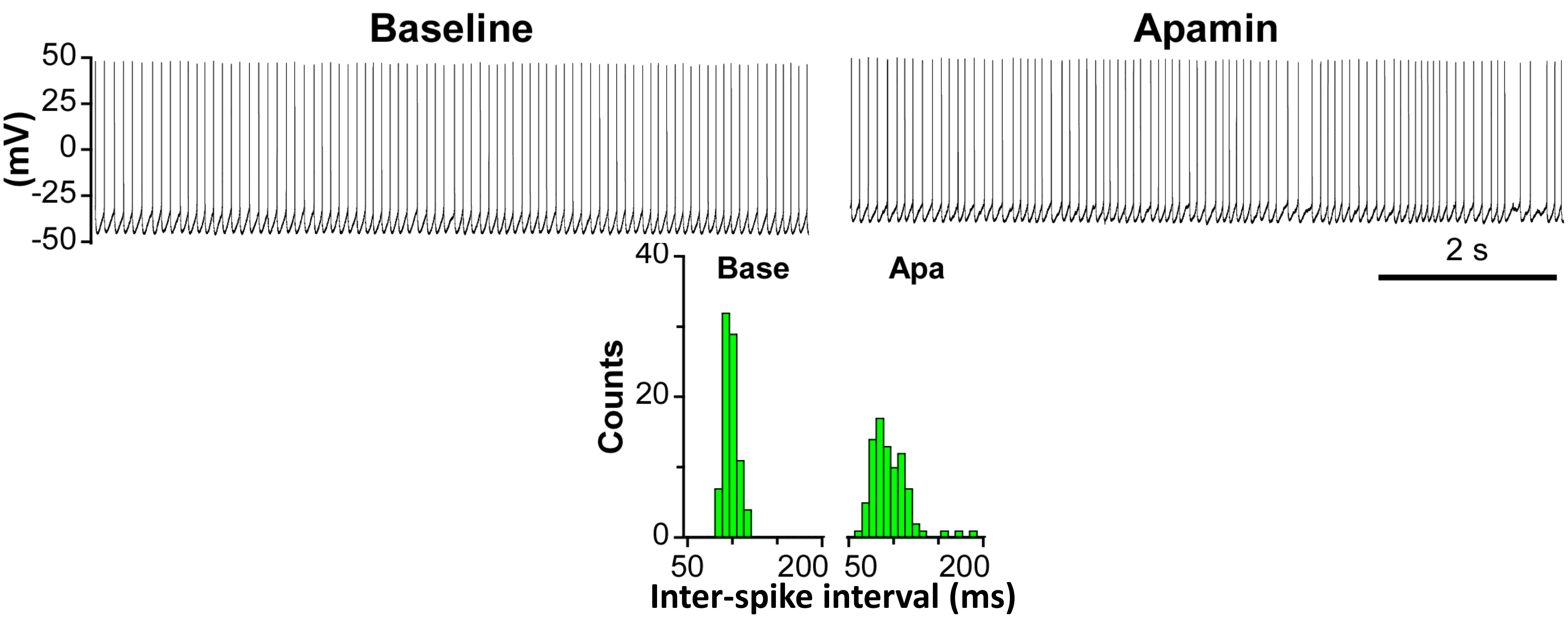
3. To understand the equivalent electrical circuit of a neuron

4. To be able to predict the response of a neuron to different current injections

A neuron with active ion channels - action potentials



1. Frequency
2. Adaptation/acceleration
3. Precision



A neuron with active ion channels beyond action potentials