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# Bioelectronic devices based on electrical-double-layers: Fundamentals, characterization, and design


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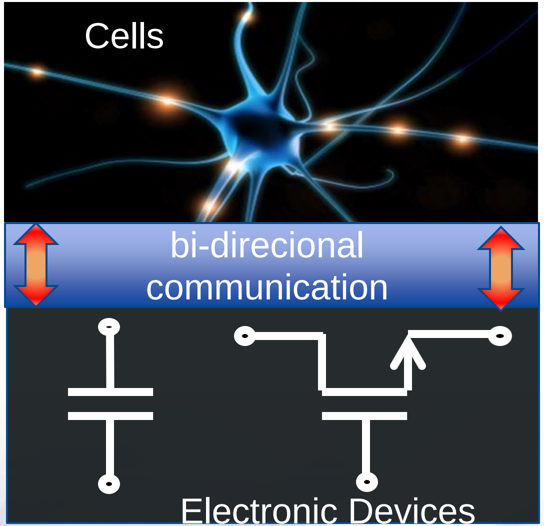

# Outline

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**The electrical double layer (EDL)s**

- **Part I: EDLs  in sensors that rely on impedance changes.**
- **Part II: EDLS in electrophysiological sensing,**
- **Part II EDLs in electrolyte-gated transistors**

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# Outline

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- **The electrical double layer (EDL);**
- **Electrical stimulation through electrical double-layers (tissues and cells);**
- **Electrolyte-gated transistor devices;**
- **Electrophysiological sensing devices;**
- **Applications.**

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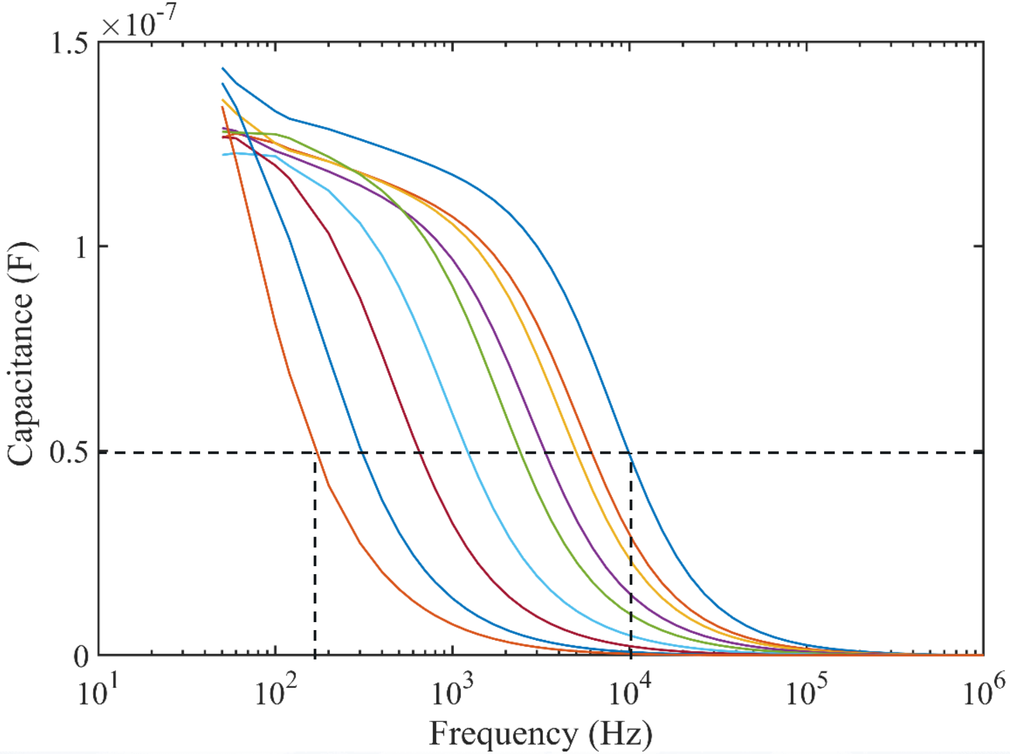
# Expected learning outcomes and competences to be acquired)



- Able to set-up an impedance measuring system.
- Know the basic rules to design microelectrodes arrays and field effect transistors to probe bio(chemicals) and living cells
- Learn how to use electrical noise based techniques to probe living cells
- Design an appropriate measuring system.
- Learn how to avoid artifacts.

# Real impedance data



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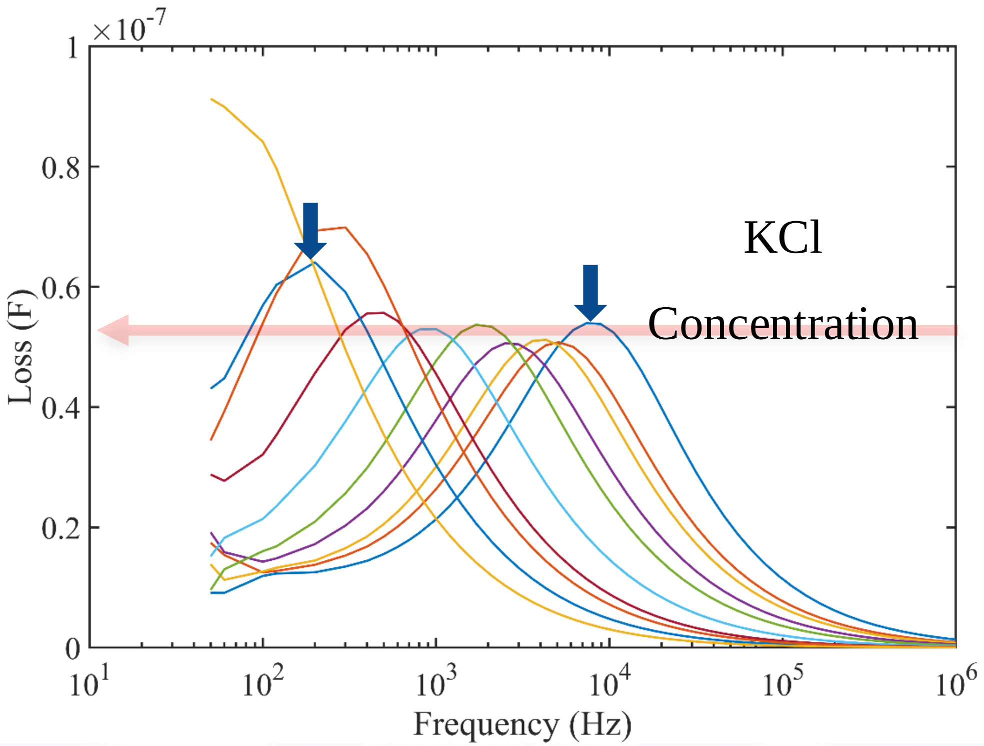
# Real impedance data



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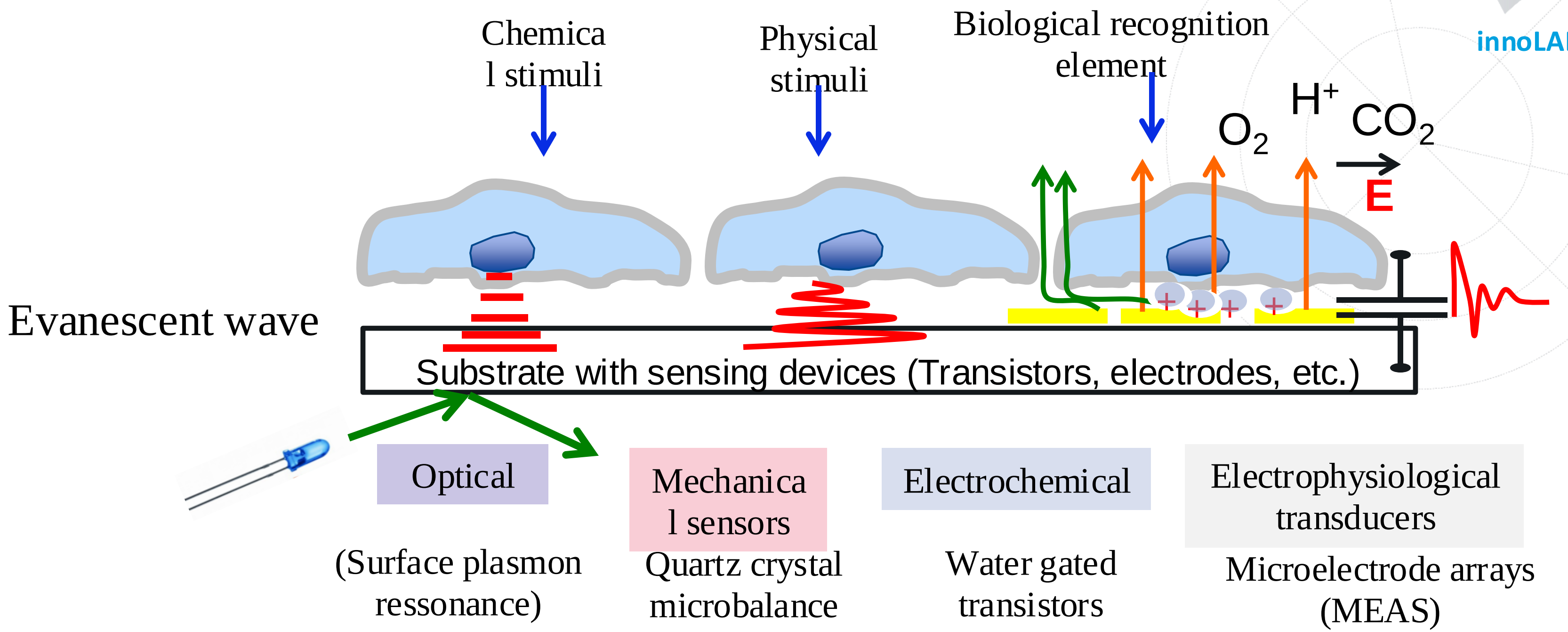
# Techniques to probe living cells on top of sensing electrodes



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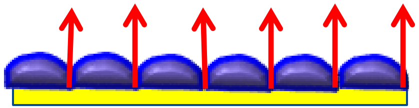
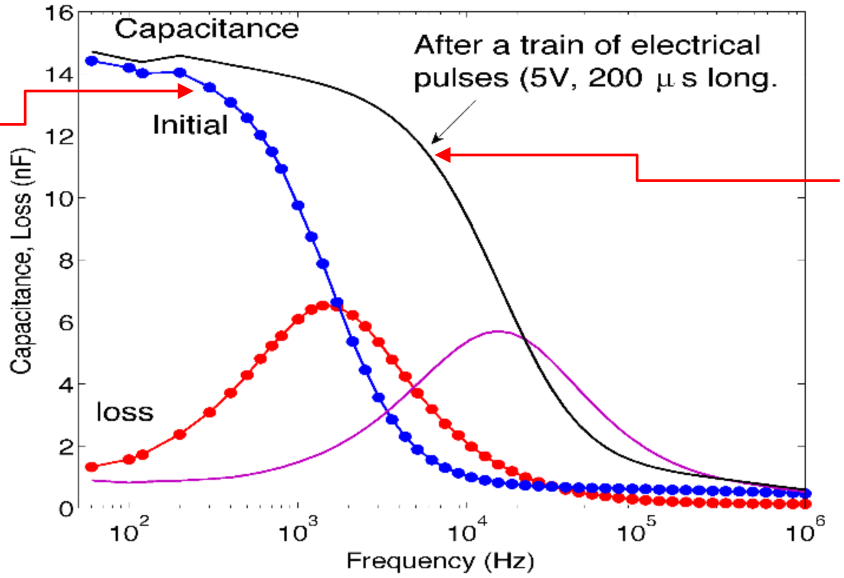
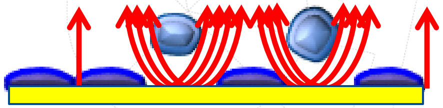
# Problem II: Design  a device for probe living cells  on top of electrodes





Confluent cell monolayer



Disrupted cell monolayer

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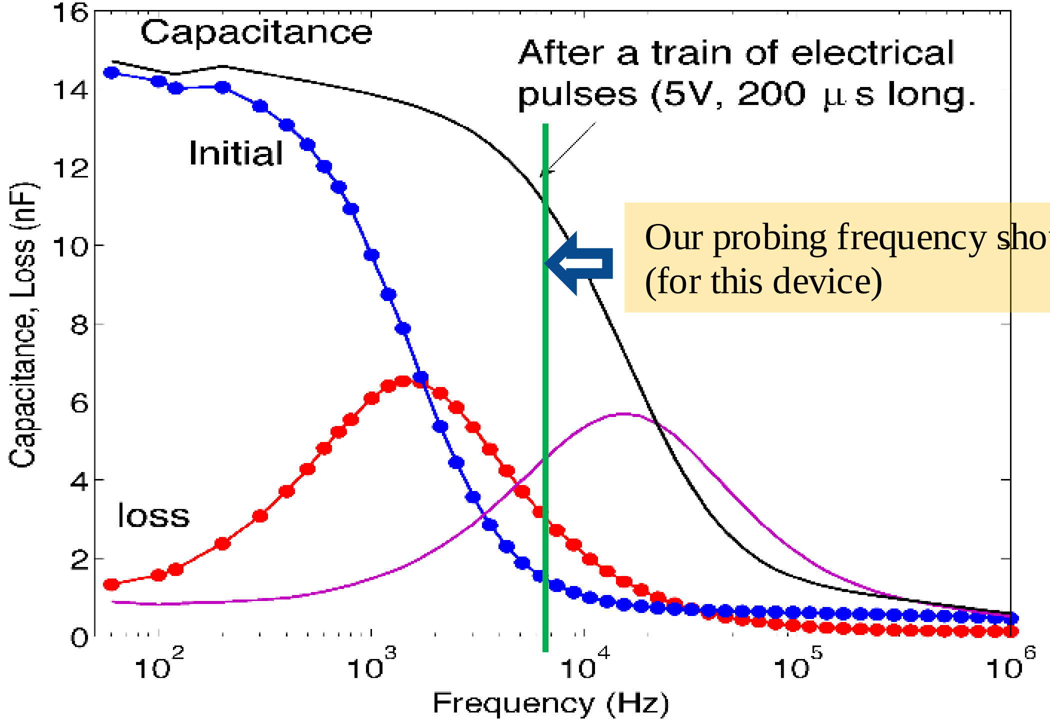
# Problem II: Design a device for probe living cells on top of electrodes






Our probing frequency should be here @ 6 kHz (for this device)

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# Applications of impedance measurements

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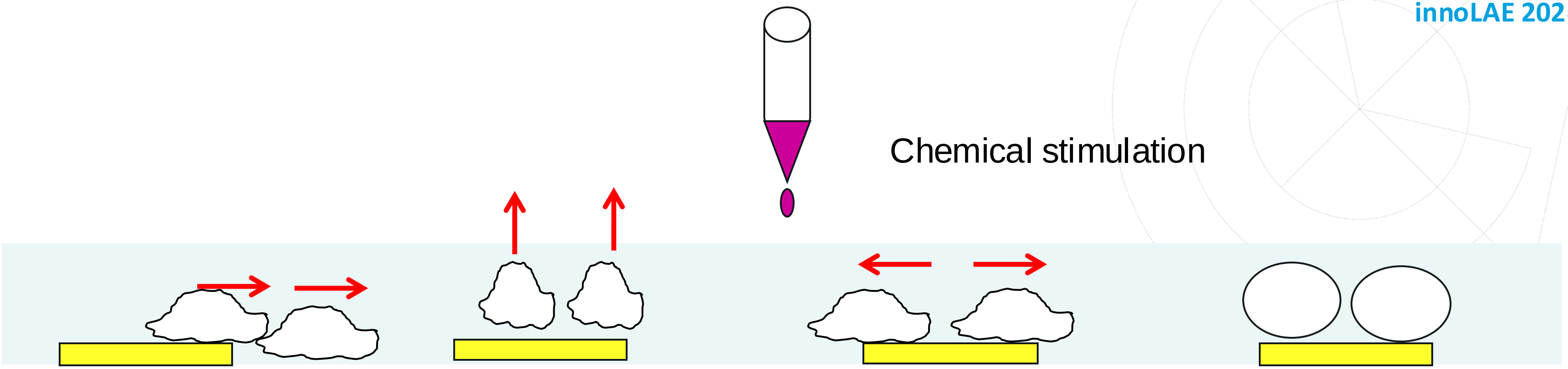


Cell movement and migration

Spreading attachment and motility

Morphological changes and cell detachment

Disruption of gap junctions

Apotheosis and cell death

Toxicological screening

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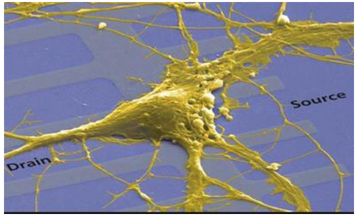
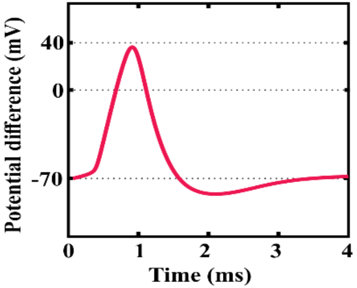
# Part II: EDLs in Electrophysiological sensing



Device requirements depend on the type of cells:

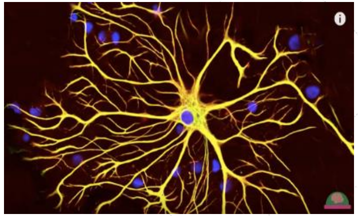
Neurons
Electrogenic cells

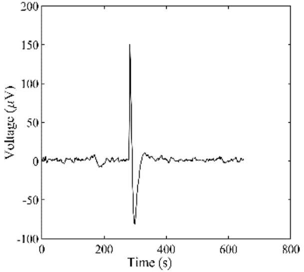



**Amplitude ≈ milivolts (mV)**
**Duration (Δt) ≈ miliseconds**

Skin Fibroblast, Astocytes
Non-electrogenic cells






**Amplitude < 5 μV**
**Durantion = several seconds**

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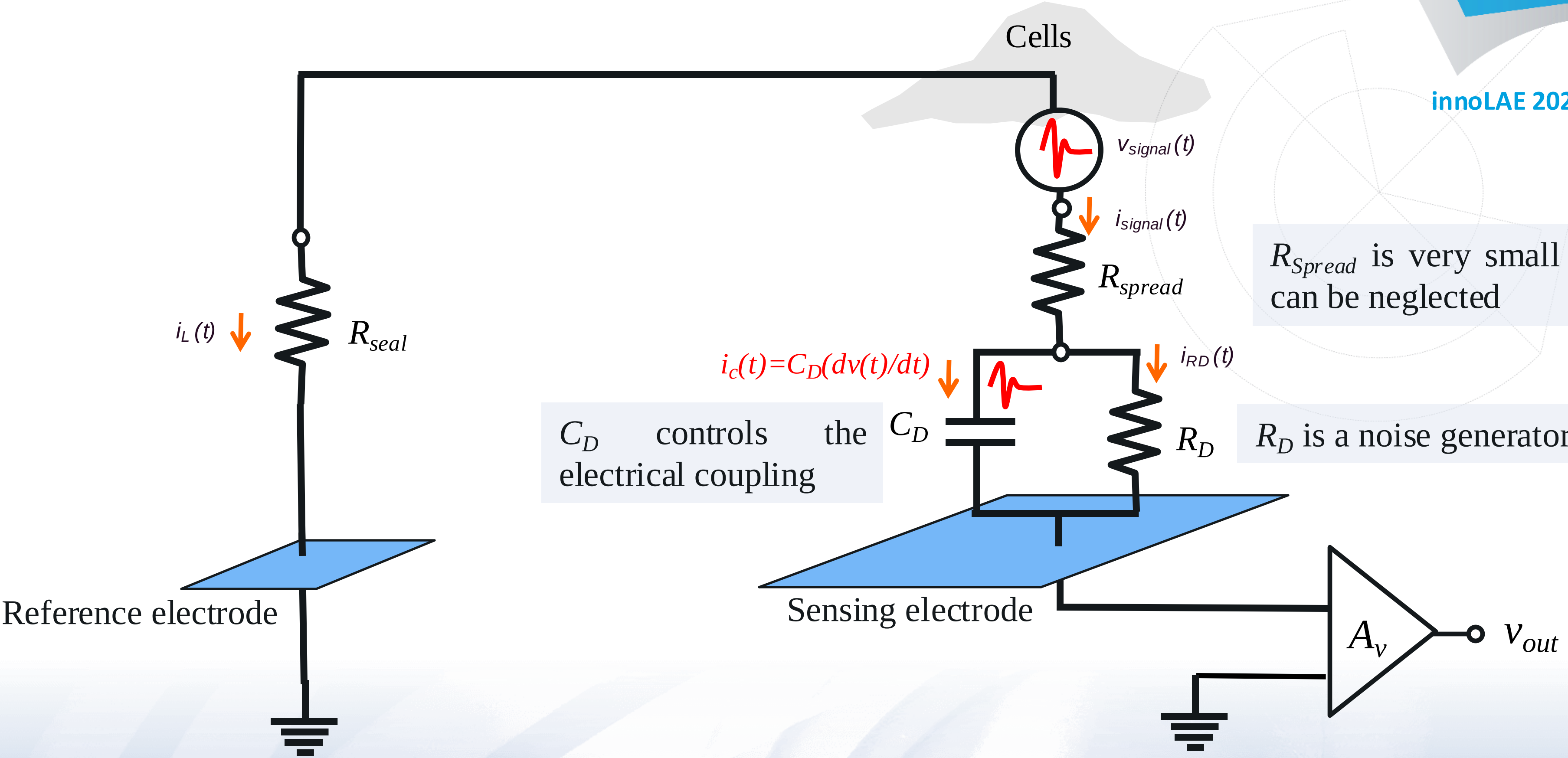
# The role of the impedance on the signal detection






$R_{Spread}$ is very small and can be neglected

$C_D$ controls the electrical coupling

$R_D$ is a noise generator





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# Part II: EDLs in Electrophysiological sensing

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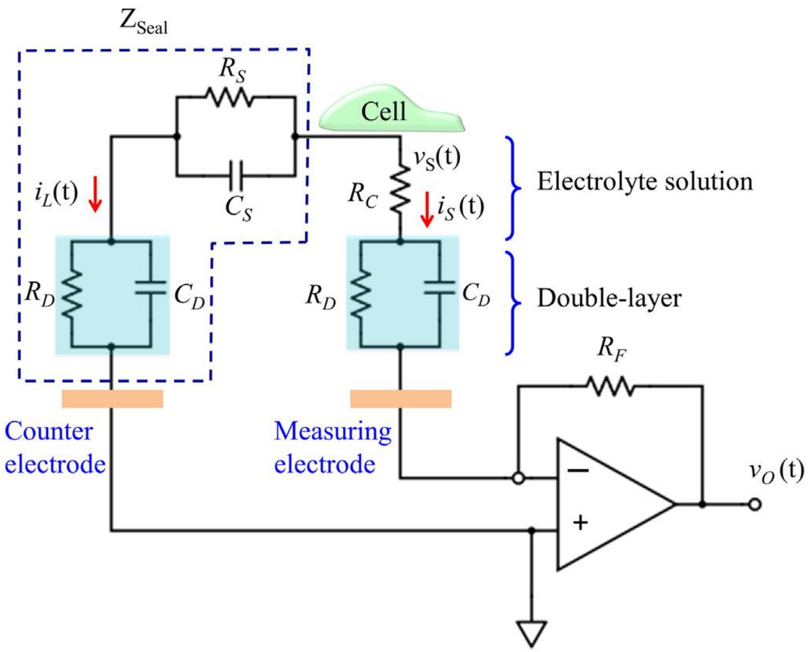


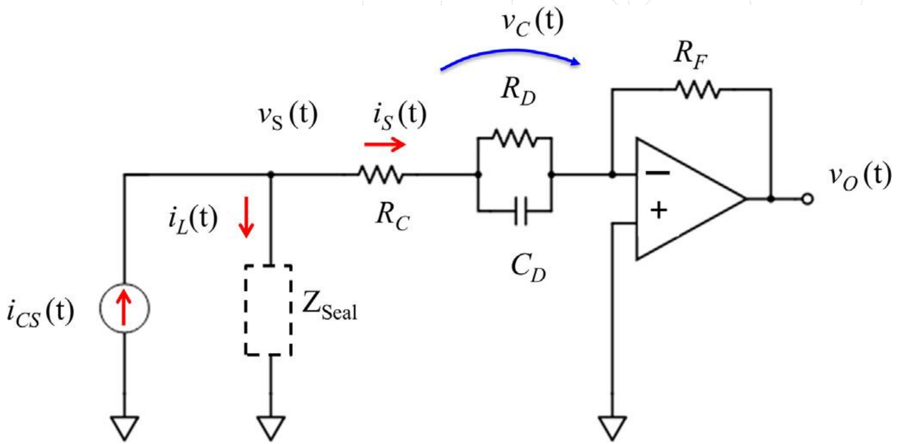


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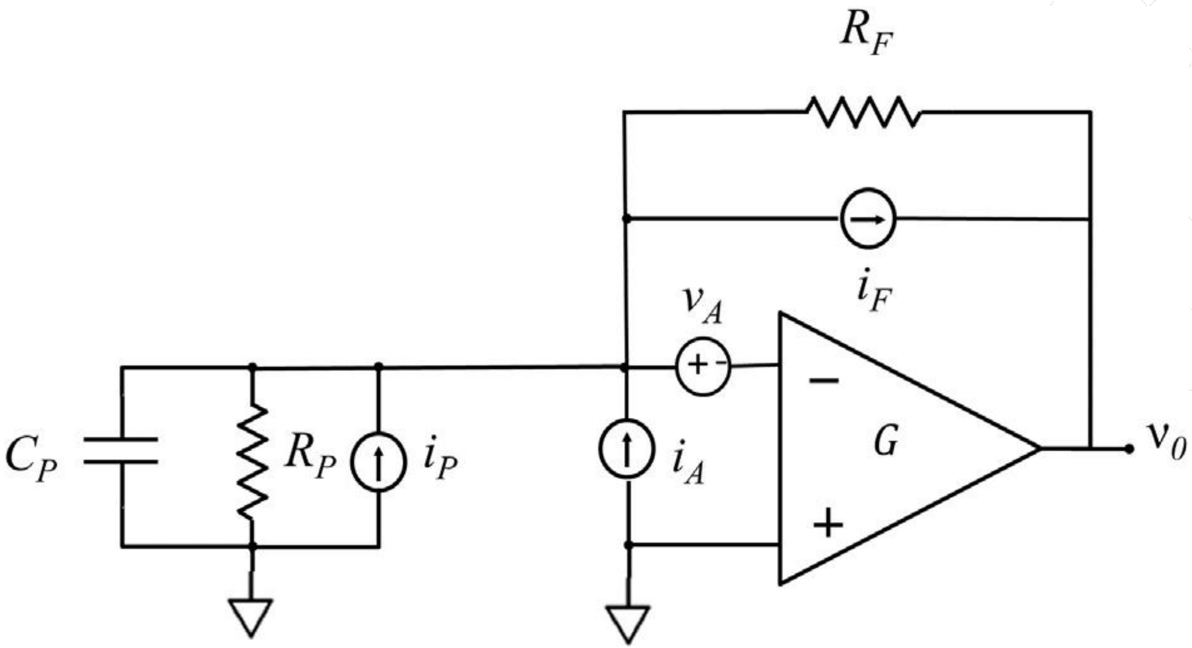
# Using impedance from a device physics point of view



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# Using impedance from a device physics point of view

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$$S_P(\omega) = 4kTRe\{Y_P(\omega)\} = \frac{4kT}{R_P(\omega)}\left[\frac{A^2}{Hz}\right]$$

$$S_{IeV_A}(\omega) = S_{V_A}(\omega)\frac{|1 + R_F Y_P(\omega)|^2}{R_F^2} = S_{V_A}(\omega) \times \left[\left(\frac{1}{R_F} + \frac{1}{R_P(\omega)}\right)^2 + \omega^2 C_p^2(\omega)\right]$$

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# Using impedance from a device physics point of view

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$$S(\omega)_{VT} = 4kTR_P(\omega) + S_{V_A}(\omega) + S_{I_A}(\omega)\left(\frac{R_P^2(\omega)}{1+\omega^2 R_P^2(\omega) C_P^2(\omega)}\right)$$

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# Using impedance from a device physics point of view

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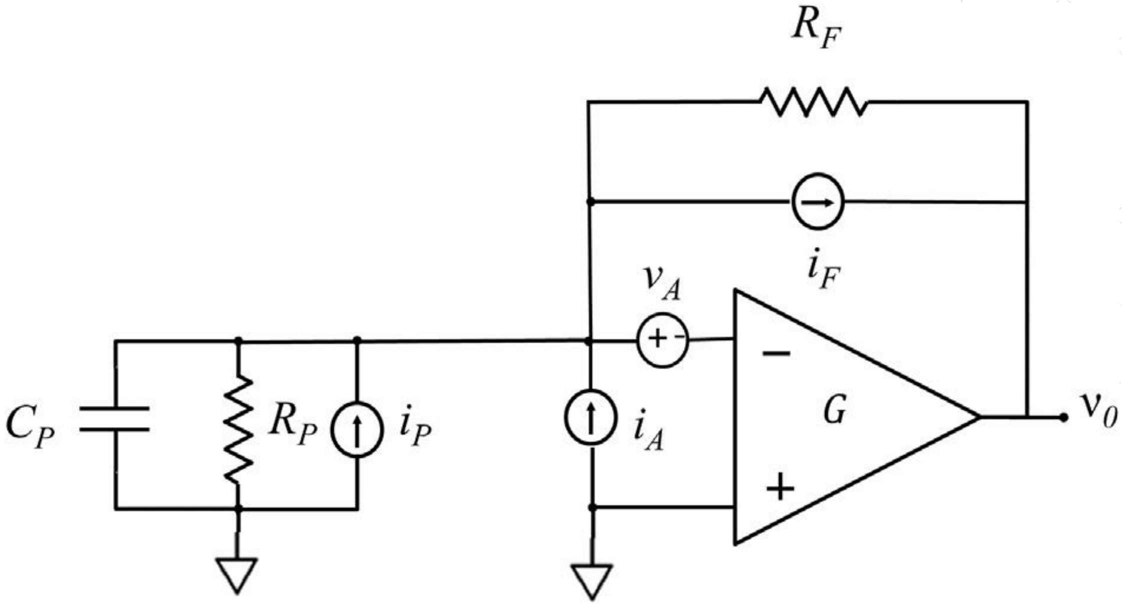


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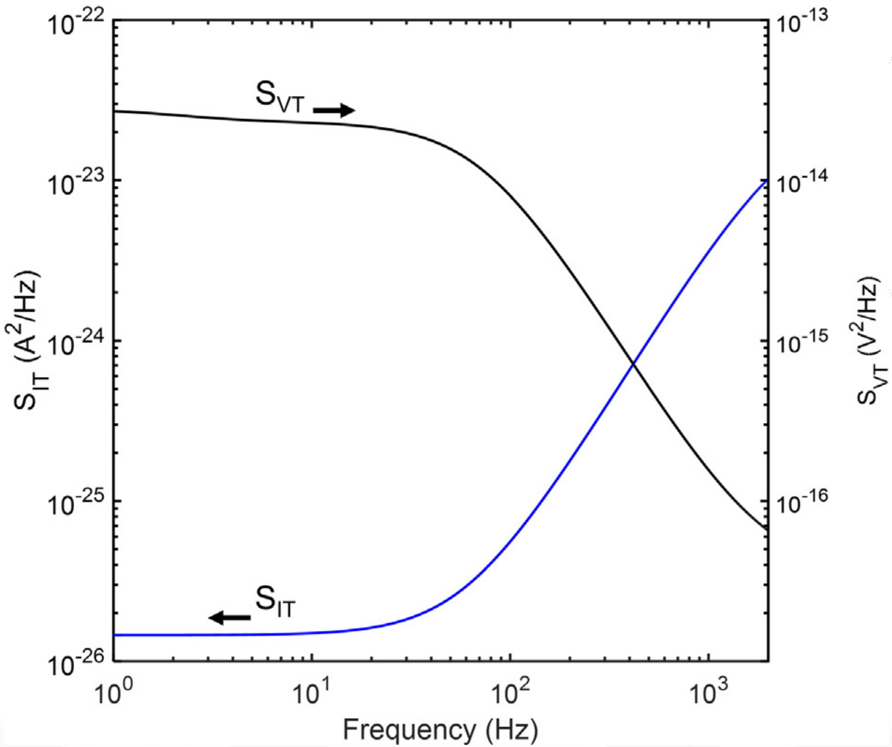
# Using impedance from a device physics point of view



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# To take away



- The higher $C_D$, the higher the SNR.
- Detection in current provides better SNR.
- Detection in current causes a derivative of the native signal (change in signal shape).
- For low frequencies is desirable to measure the bioelectrical signals in current detection mode, because the noise in current is low at low frequencies.
- For high frequencies is desirable to measure the bioelectrical signals in voltage, because the thermal noise decreases for high frequencies.

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# Somes concepts about signalling in non-excitable cells

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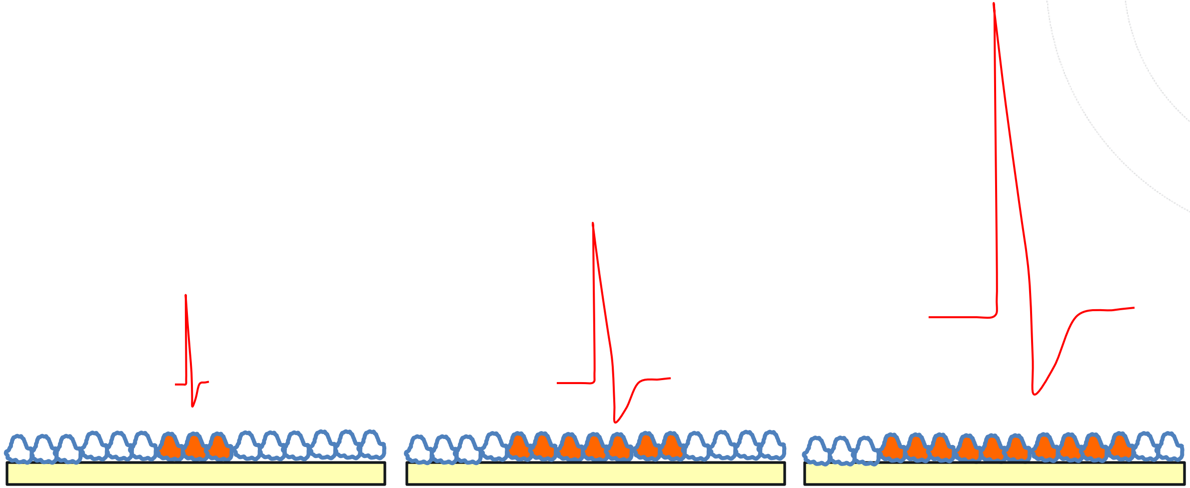

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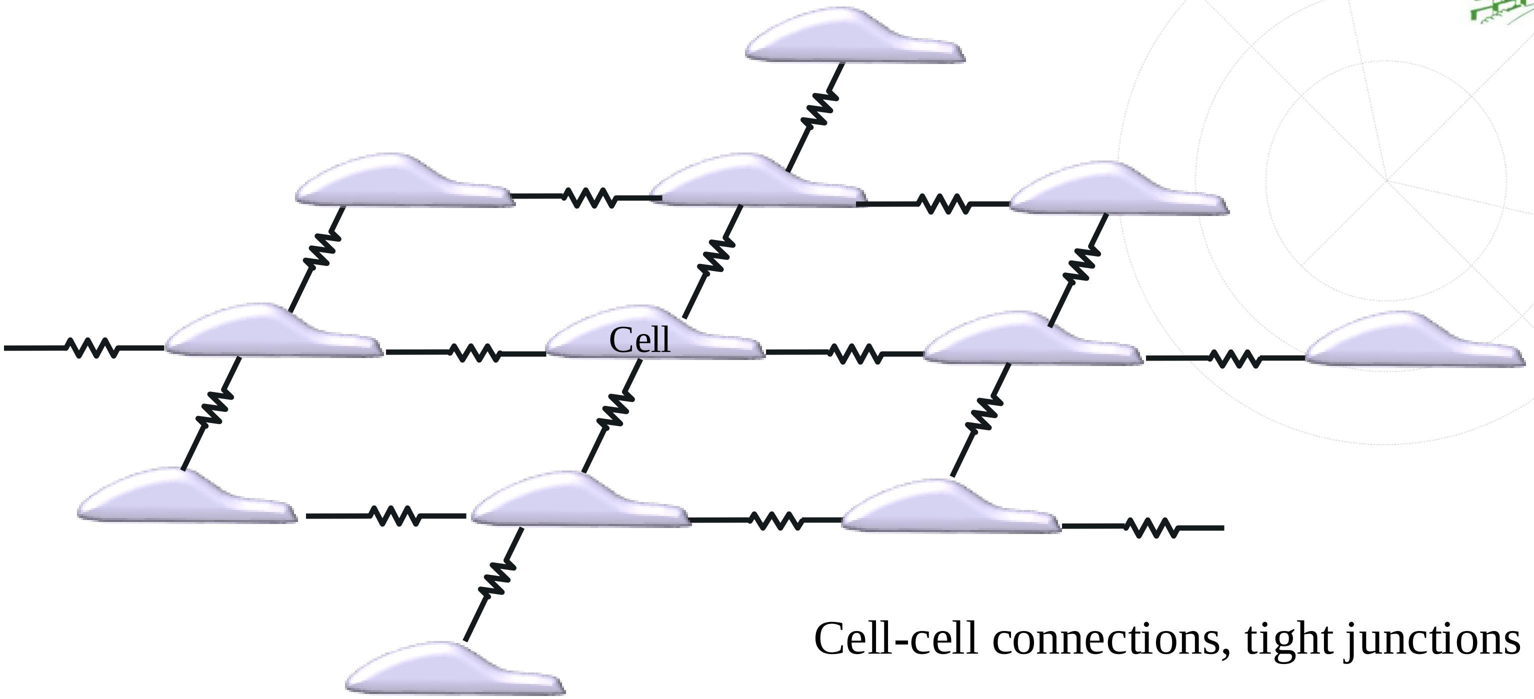
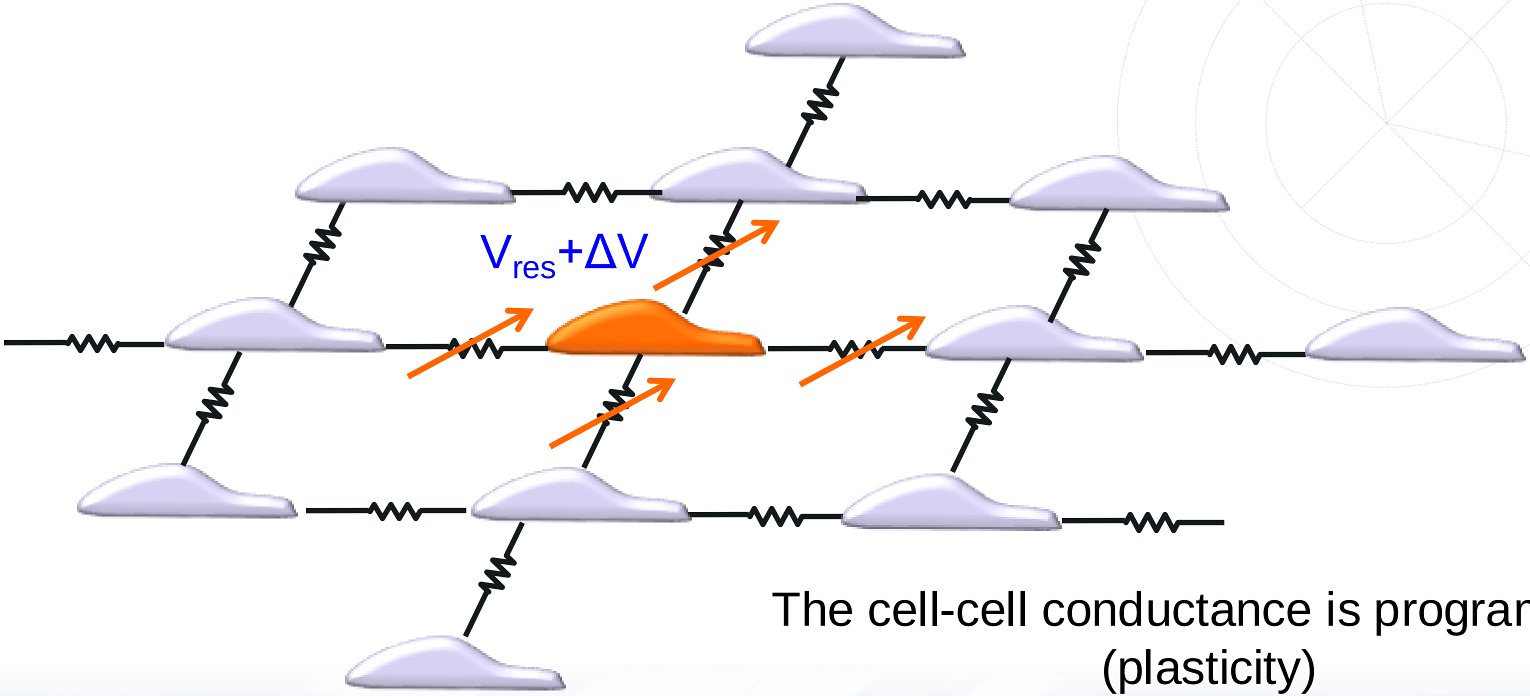
# Cell-cell communication



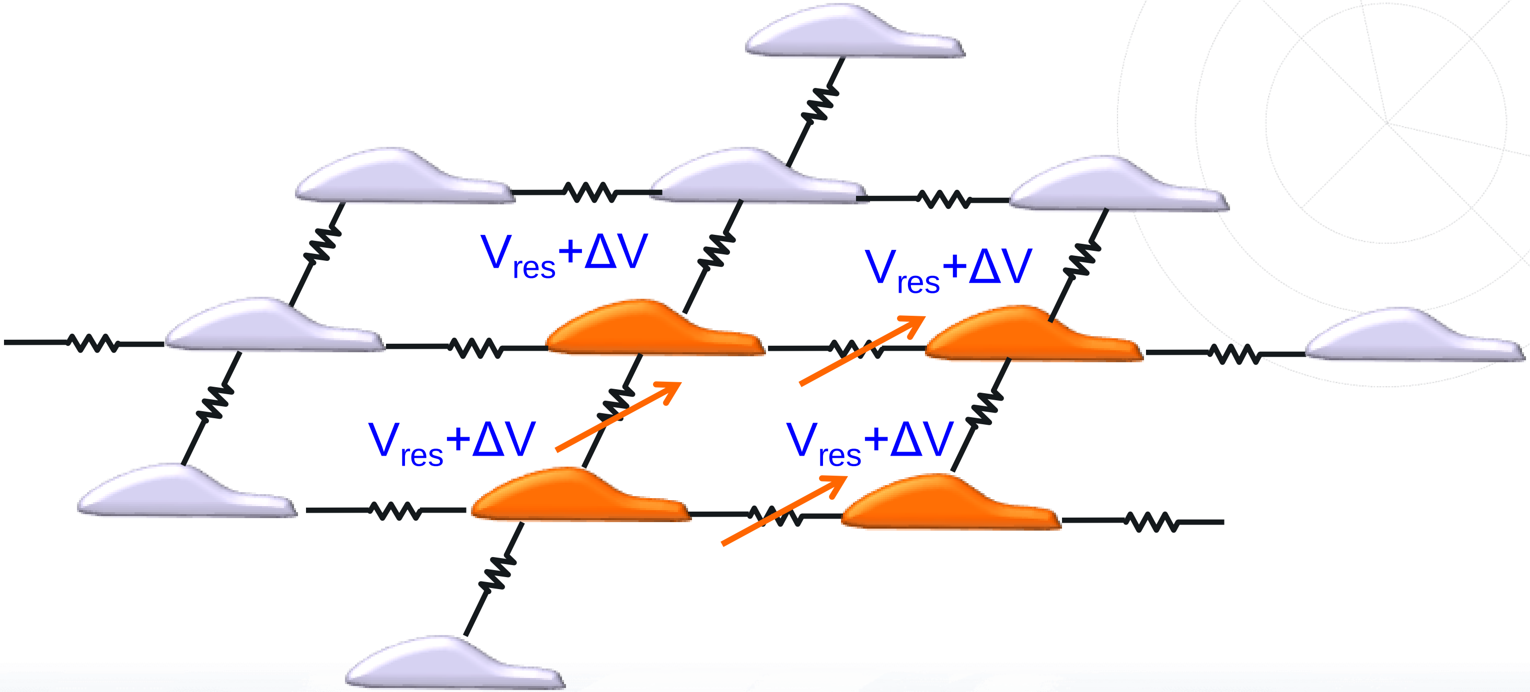

Cell-cell connections, tight junctions

# Waves in a programmable medium

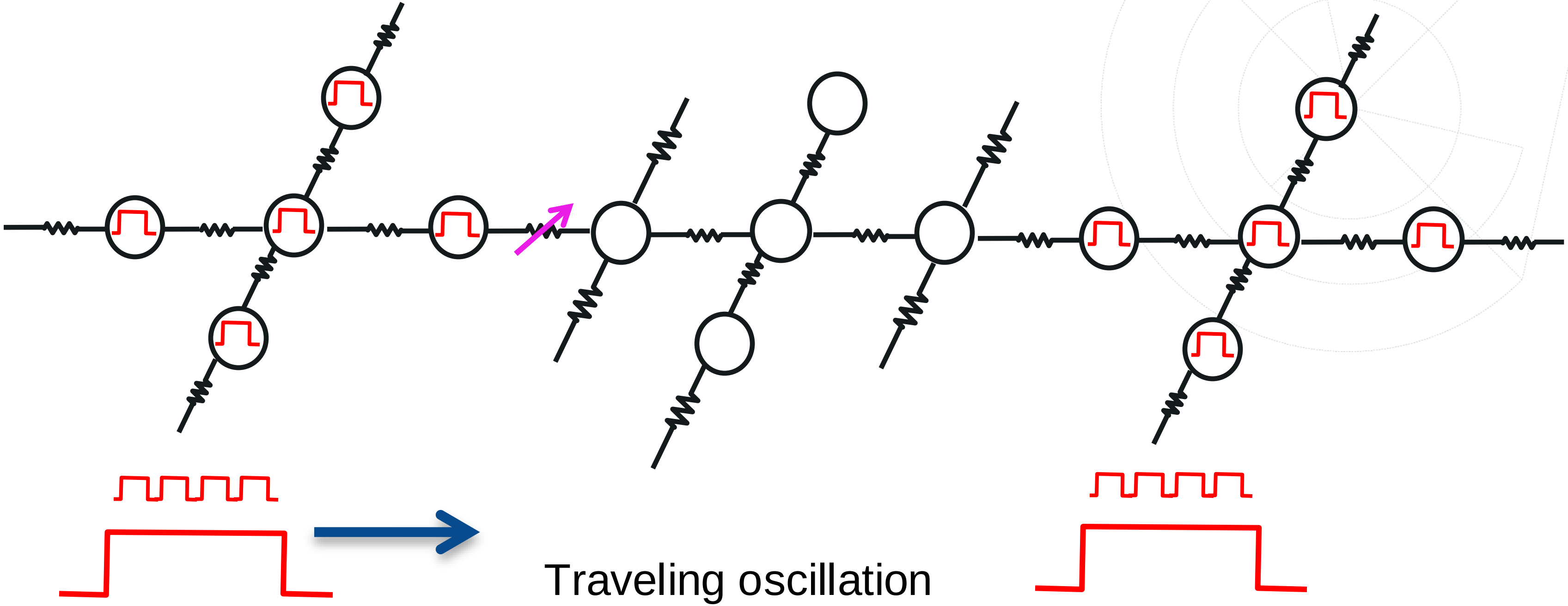



The cell-cell conductance is programmed
(plasticity)

# Synchronization



# Traveling oscillations in a programmable medium



Traveling oscillation

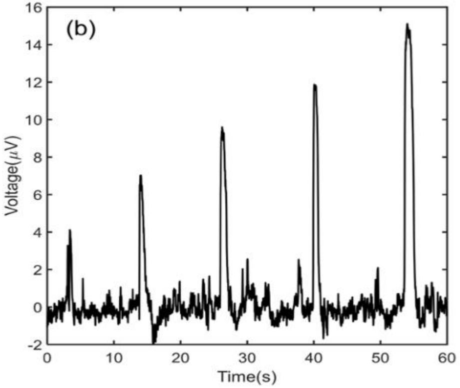
# Summary: A very simplistic view of communication in biology

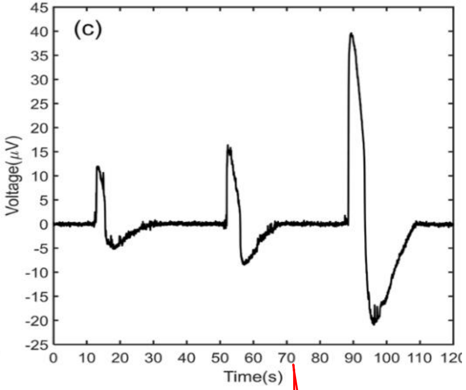
The transmission of signals in non-excitable cells requires:

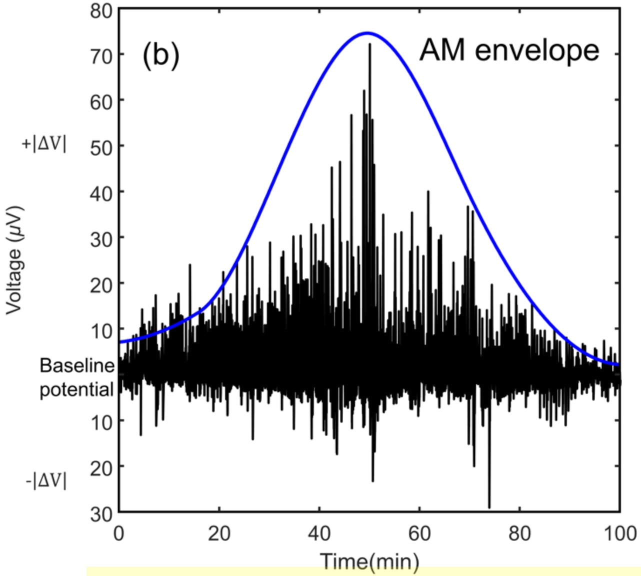
- a **chemical wave** (similar to a action potential)

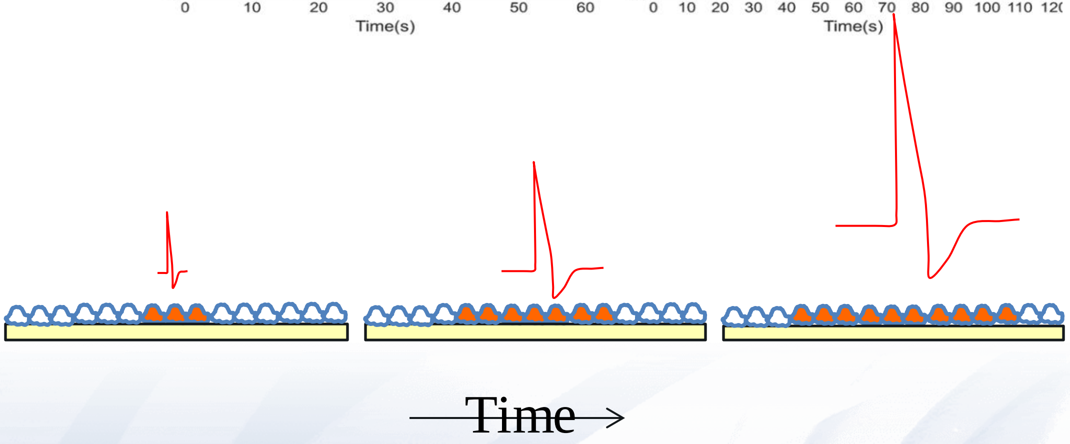
- a **medium** with a programmable conductance to define the signal path (similar to a synapse)

# Coding information in waves (Amplitude Modulation)



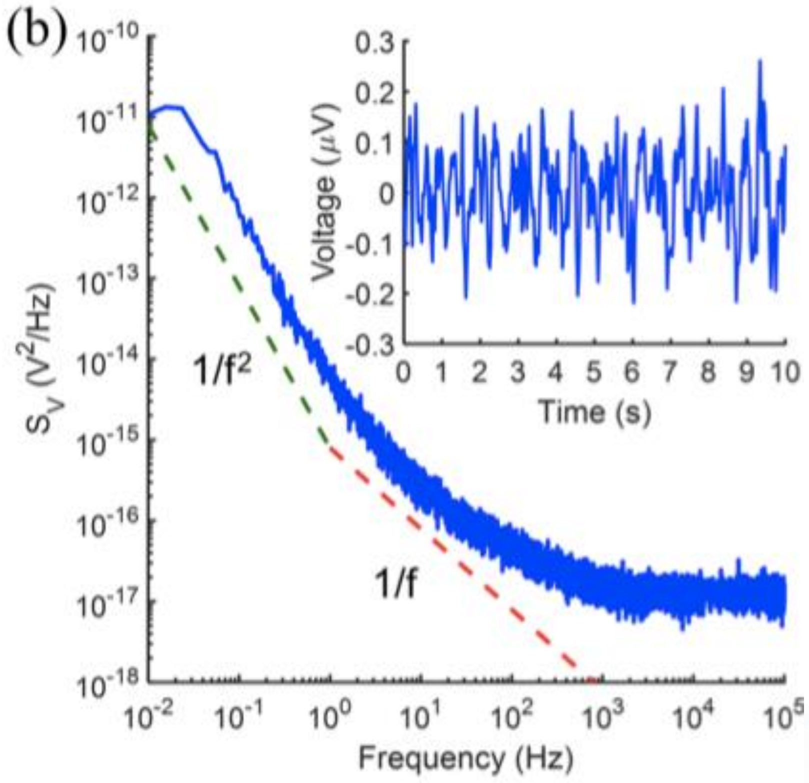




The power of the signal is proportional to the number of cells synchronized

# Noise is important




Noise=0.3 μV pp

Thermal noise

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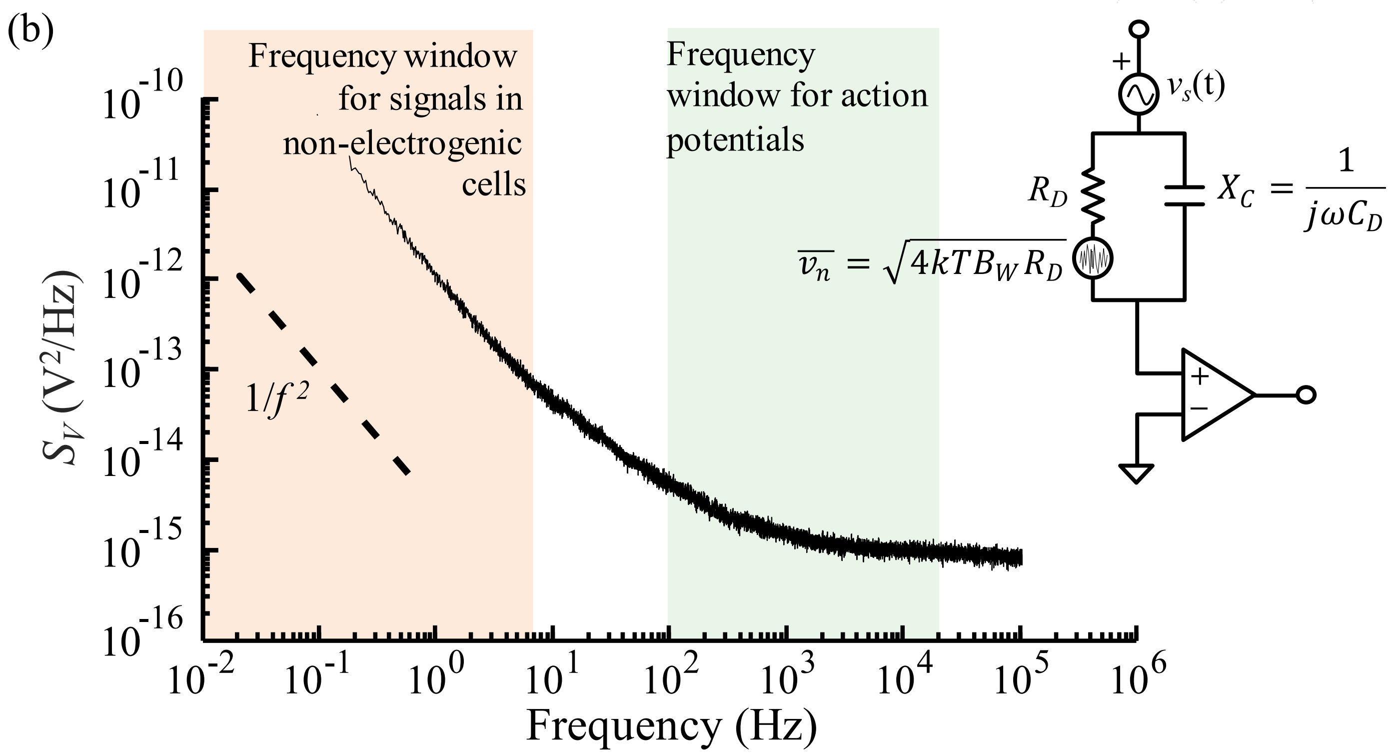
# The importance of thermal and 1/*f* noise



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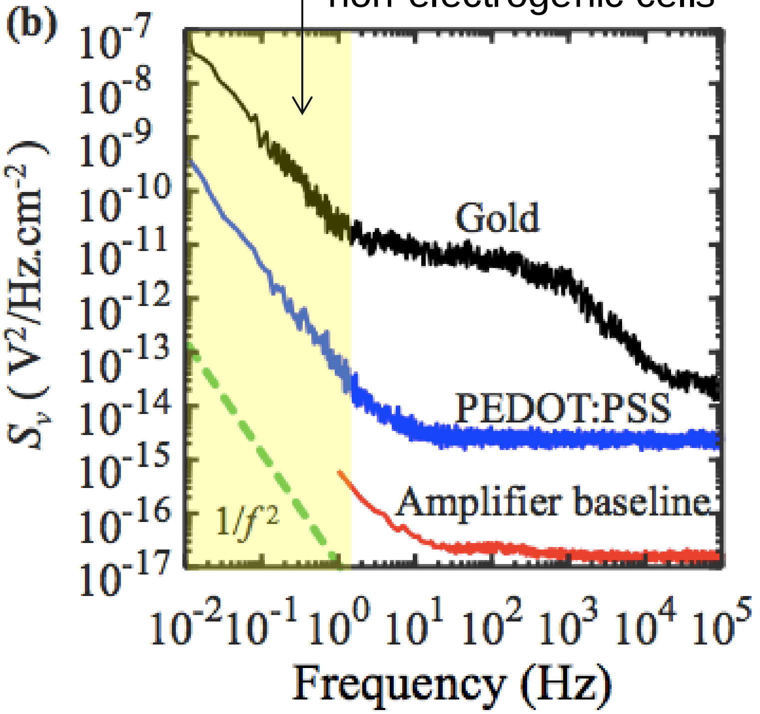
# Electrical noise

Electrophysiological frequency window for non-electrogenic cells



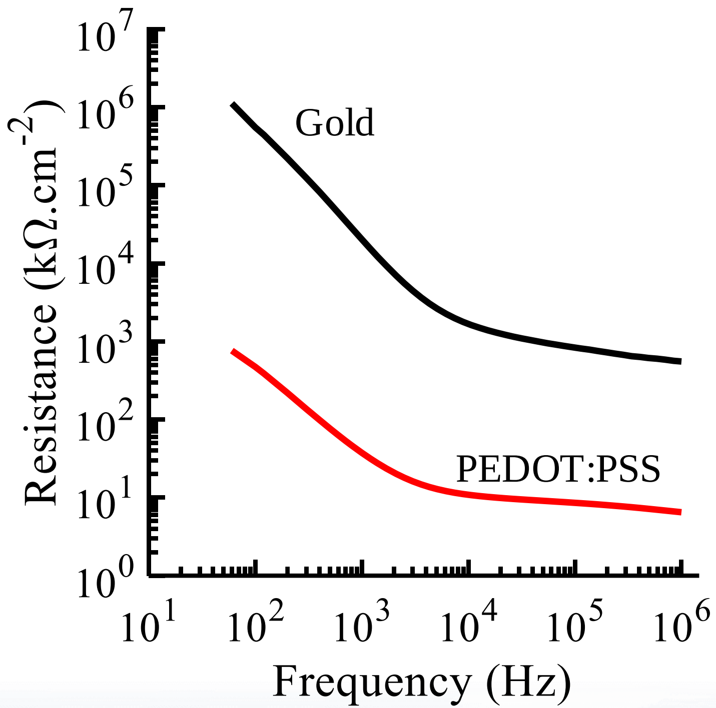

Conducting polymers generate significant less noise than metal based electrodes.

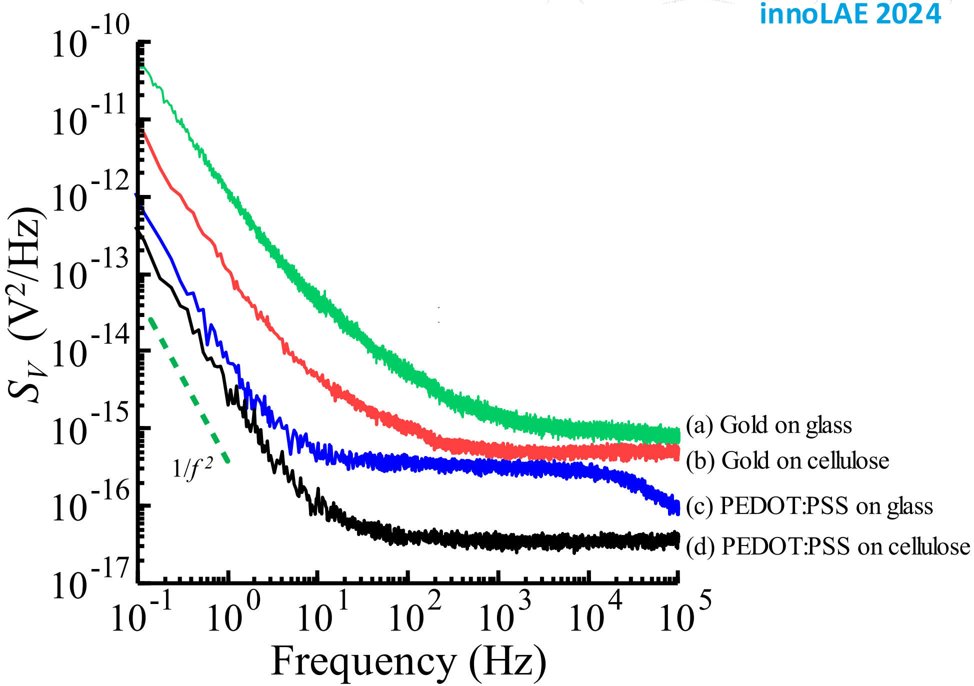
Chemical Papers 72 (7)

1597-1603

# Interfacial resistance and intrinsic noise





# Electrical stimulation of astrocytes populations

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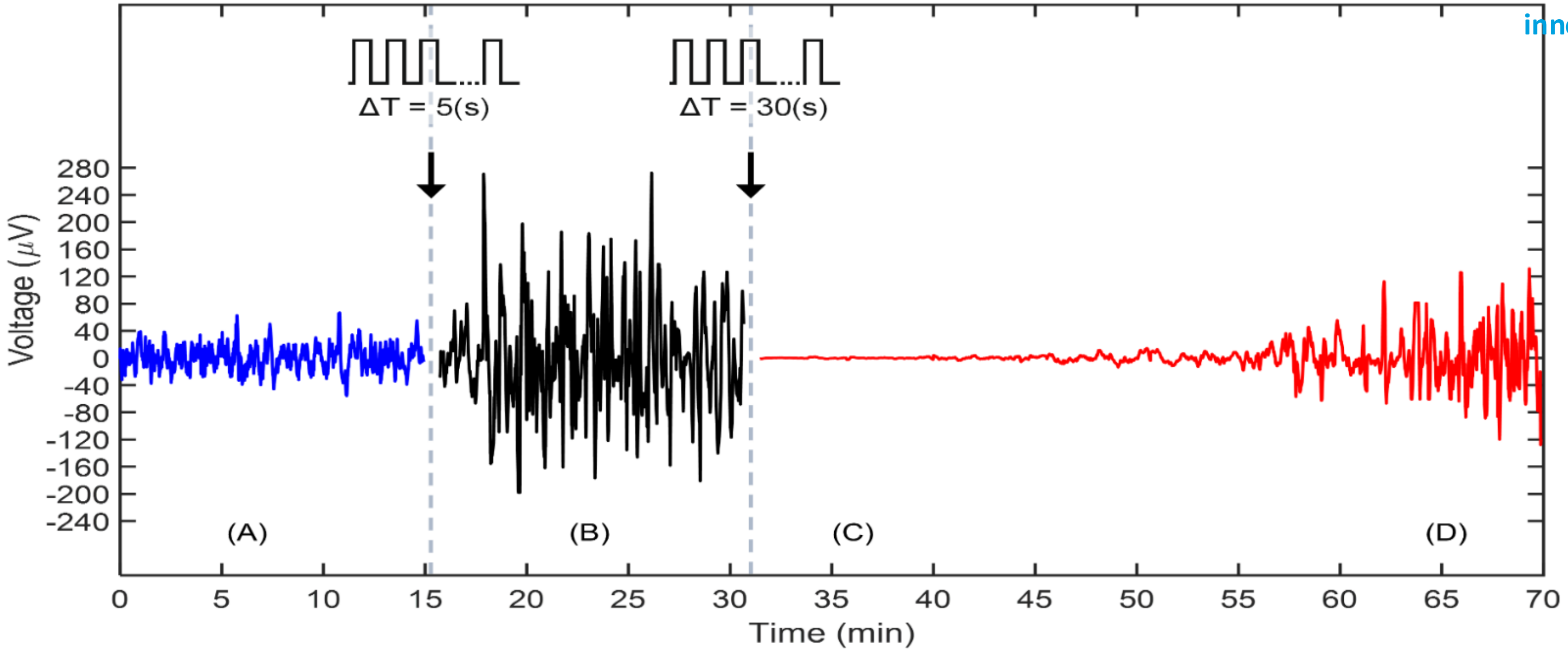


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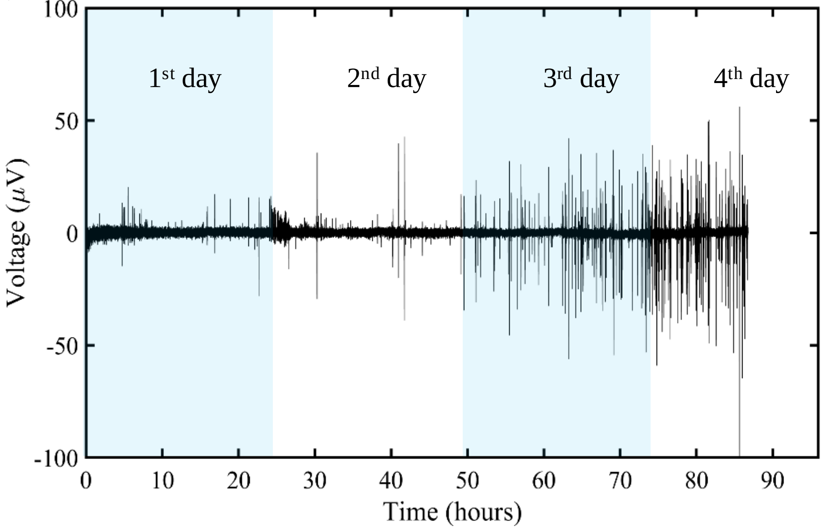
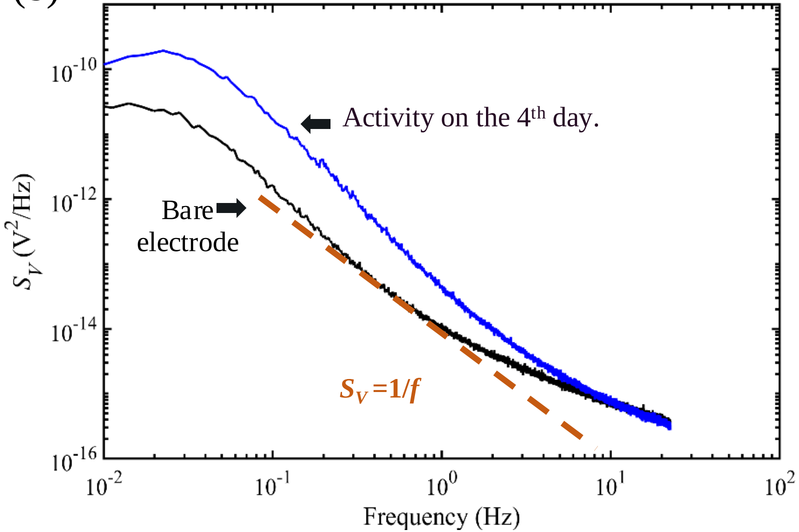
# Spontaneous activity of dermal cells

(a)

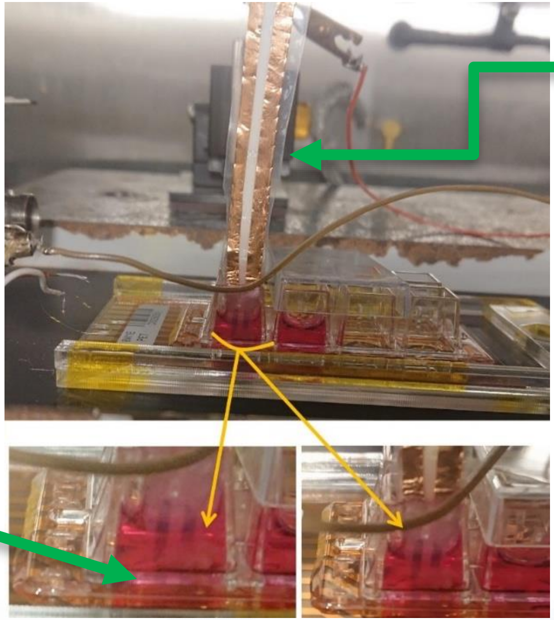



(b)



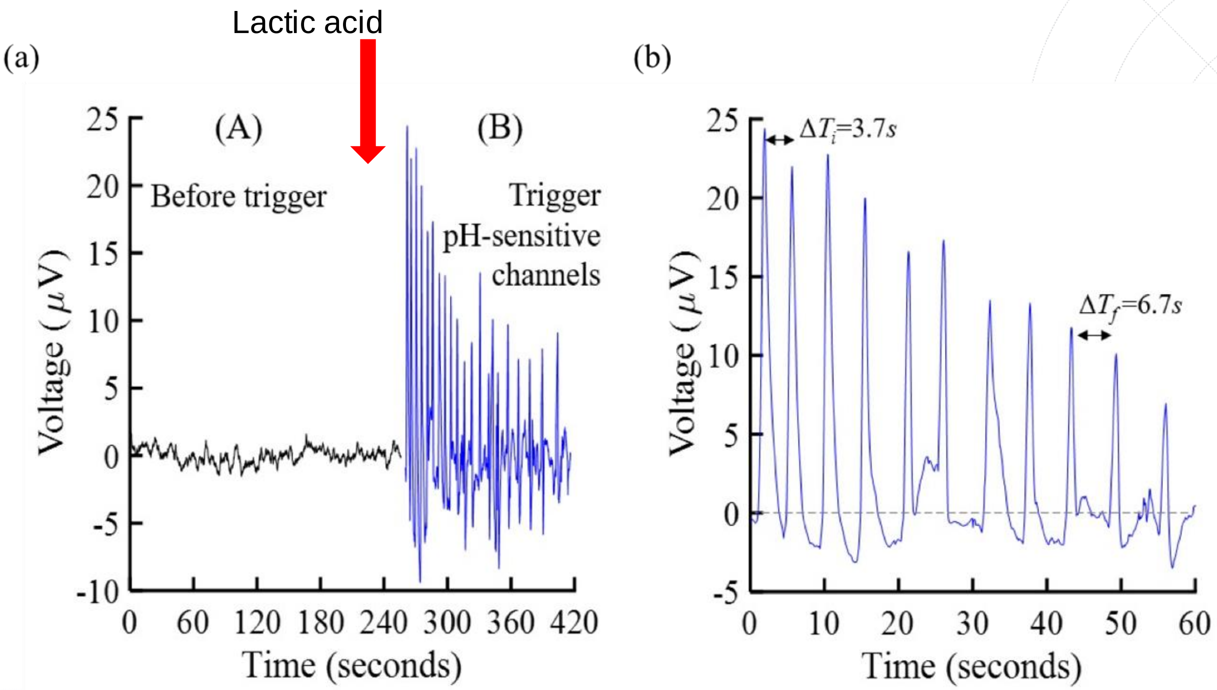
# Application:
# bioelectrical activity of a glioblastoma (ex-vivo)

PEDOT:PSS on bacterial cellulose



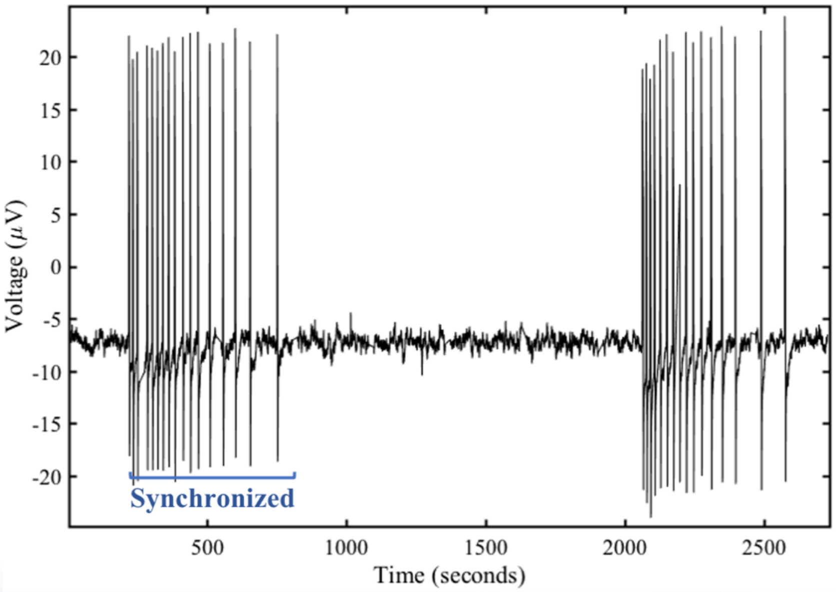
Resected *ex-vivo* human glioblastoma tumour

# Application:
# Bioelectrical activityof a glioblastoma (ex-vivo)



# Application;
# bioelectrical activity of a glioblastoma (ex-vivo)

(a)

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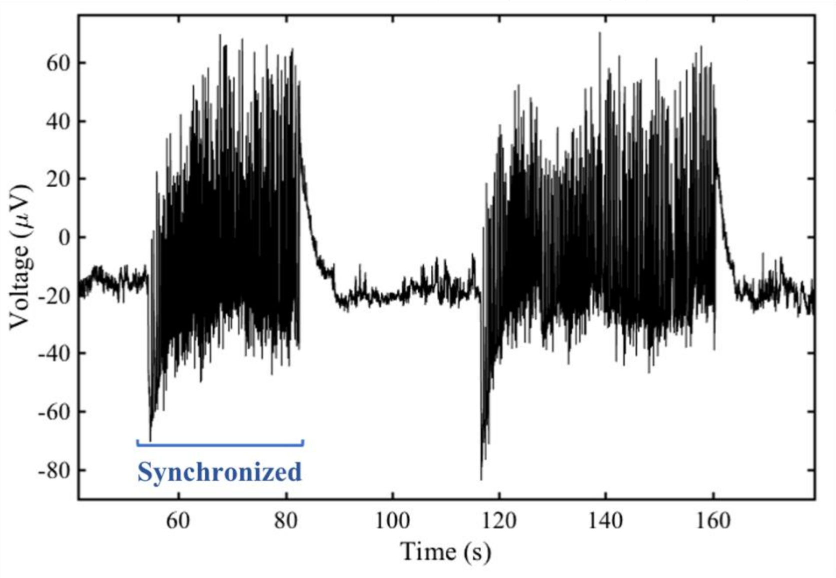
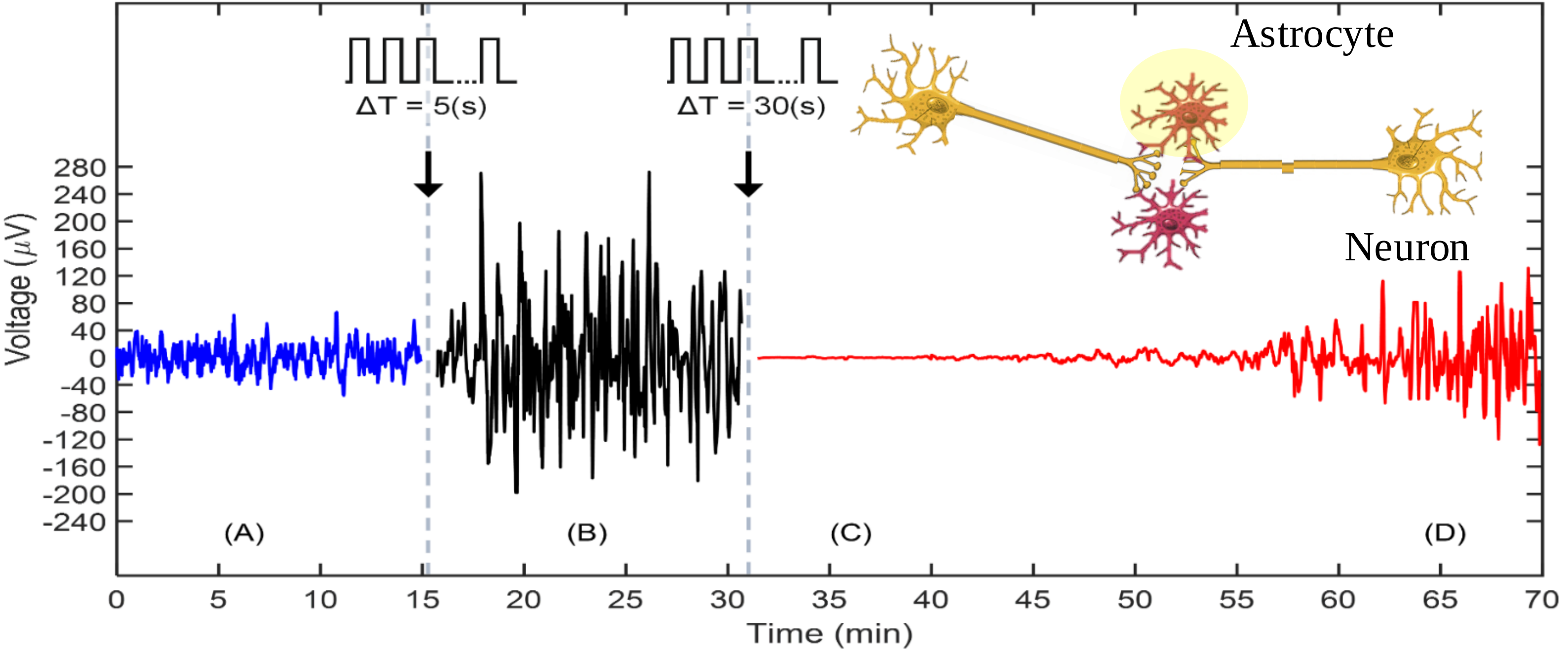


# Electrical stimulation of astrocytes populations



# Acknowledgements

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