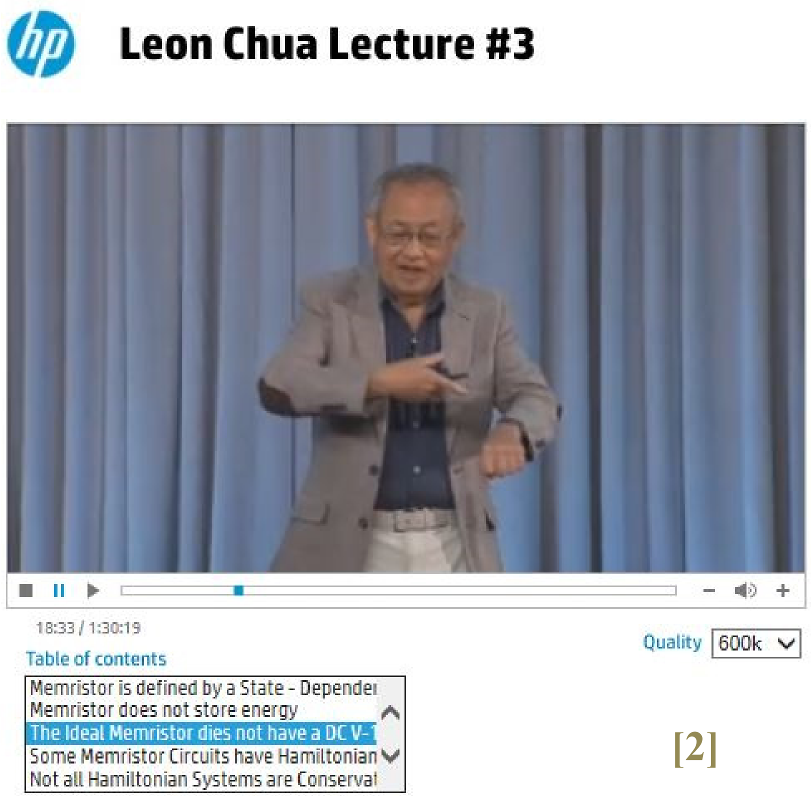
Introduction into the memristor and the non-linear electrical properties of human skin

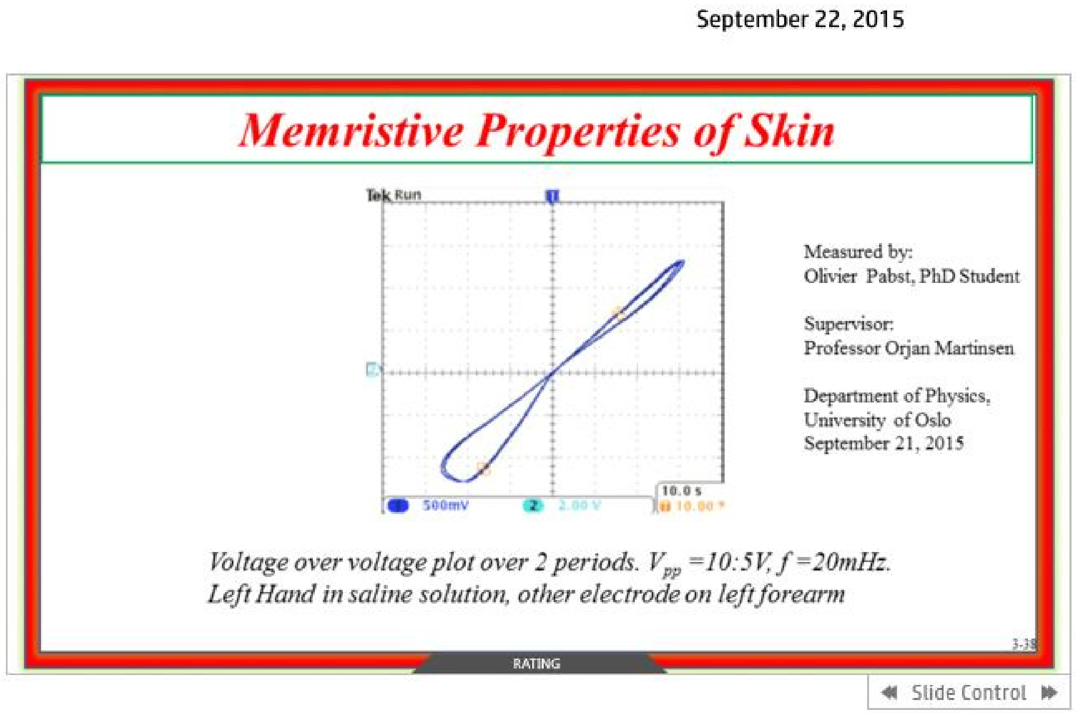
Oliver Pabst, Ørjan Grøttem Martinsen

UiO : Universitetet i Oslo

"If it's pinched it's a memristor" [1]



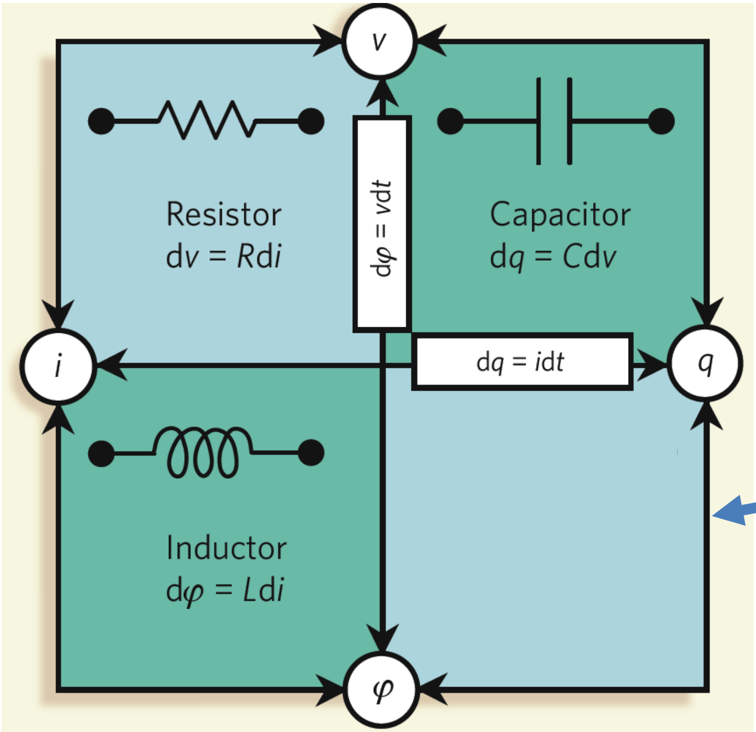
[2]



[1] **L. Chua**, "If it's pinched it's a memristor," in Memristors and Memristive Systems, pp. 17–90, Springer, 2014.

[2] **The Chua Lectures:** A 12-Part Series with Hewlett Packard Labs

The missing circuit element



The four passive elements [3]

Memristor - the missing circuit element [4]

?

$$v = M(Q)i$$

[3] **Tour, J. M., & He**, T. (2008). Electronics: the fourth element. *Nature*, *453*(7191), 42-43.

[4] **Chua, L. O.** Memristor - the missing circuit element. IEEE Trans. Circuit Theory 18, 507–519 (1971).

The missing circuit element

The term “memristor” is a combination of “**mem**ory” and “**res**i**stor**”.

Its memristance, *M(**x**)*, (in analogy to resistance) is dependent on one or more internal state variables states (expressed by **x**, a vector of internal state variables). For an ideal memristor, the memristance is a function of the charge, Q. However, **x** can be something else like, for example, the extension of a high conductive region vs. a low conductive region.

$$v = M(\mathbf{x})i$$

A memristor is described by its state-dependent Ohm’s law

[5]

and

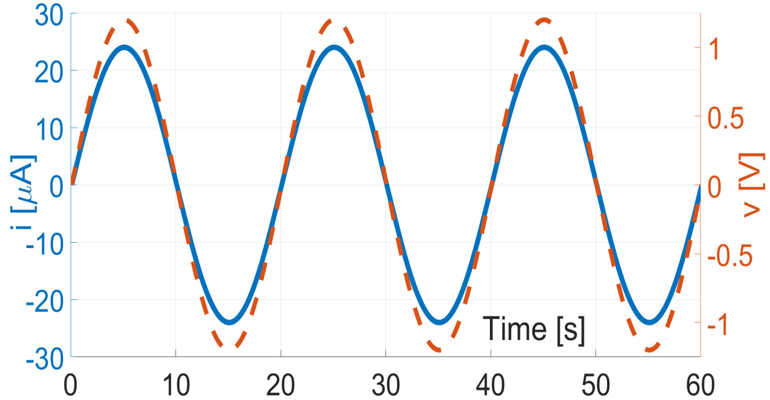
$$\frac{d\mathbf{x}}{dt} = f(\mathbf{x}, i) \cdot i$$

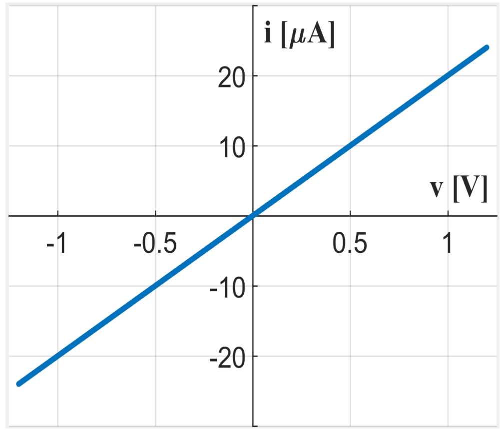
the state equation, that describes, how the internal state(s) changes with the current going through the memristor.

[5] **L. Chua**, "Everything you wish to know about memristors but are afraid to ask," *Radioengineering,* vol. 24, no. 2, p. 319, 2015.

Comparison of a resistor and a memristor

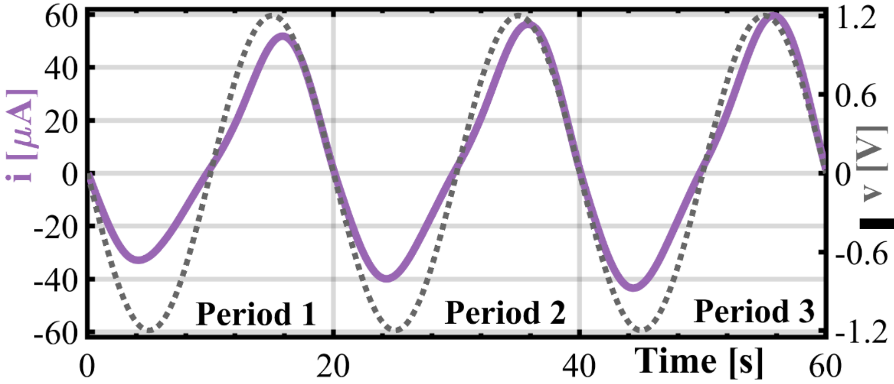
Resistor



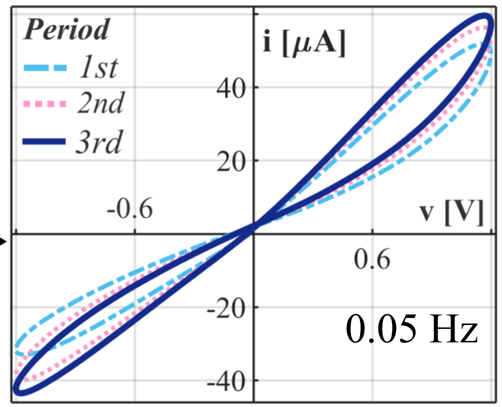


$v = R \cdot i$

Memristor



[6]



$v = M(\boldsymbol{x}) \cdot i$

$$\frac{d\boldsymbol{x}}{dt} = f(\boldsymbol{x}, i) \cdot i$$

[5]

[5] **L. Chua**, "Everything you wish to know about memristors but are afraid to ask," *Radioengineering,* vol. 24, no. 2, p. 319, 2015.

[6] **Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua.** "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Different memristor classes

We can also express the memristor in terms of its state-dependent conductance (memductance, in analogy to conductance). Furthermore, different memristor classes are defined and summarized in the table below.

Memristor type	***Ideal***	***Ideal generic***	***Generic***	***Extended***
State dependent Ohms law	$i = G(\varphi) \cdot v$	$i = G(x) \cdot v$	$i = G(\mathbf{x}) \cdot v$	$i = G(\mathbf{x}, v) \cdot v$ $G(\mathbf{x}, 0) \neq \infty$
State equation	$\frac{d\varphi}{dt} = v$	$\frac{dx}{dt} = g(x)\, v$	$\frac{d\mathbf{x}}{dt} = \mathbf{g}(\mathbf{x}, v)\, v$	$\frac{d\mathbf{x}}{dt} = \mathbf{g}(\mathbf{x}, v)\, v$
Internal state variable	Flux φ	General variable x	Vector of internal state variables $\mathbf{x}$	
Indication	*1, *2, *3	*1, *3	*3	*4
	*1 Pinched hysteresis loop in the V-I plot is odd-symmetric. *2 φ-q plot results in a straight line. *3 V-I plot tends towards a straight line for $\lim f \to \infty$. *4 V-I plot tends towards a single valued curve for $\lim f \to \infty$.			

[5]

[5] **L. Chua**, "Everything you wish to know about memristors but are afraid to ask," *Radioengineering,* vol. 24, no. 2, p. 319, 2015.

Three fingerprints of memristors

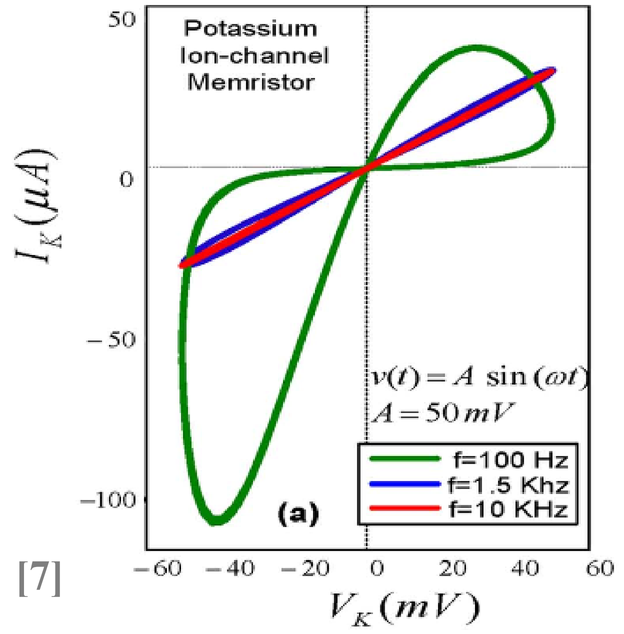
-> How to identify memristors?

1. **Pinched hysteresis loop in the V-I plot with pinched point in the origin**

   -> valid for any signal shape (periodic, non-periodic) and amplitude

2. **The lobe area of the pinched hysteresis loop is decreasing with increasing frequency**

3. **If the frequency tends to infinity, the pinched hysteresis loop should shrink to a single- valued function**



[7]

[7] Adhikari, Shyam Prasad, et al. "Three fingerprints of memristor." *IEEE Transactions on Circuits and Systems I: Regular Papers* 60.11 (2013): 3008-3021.

Breakthrough in memristor research

nature Vol 453|1 May 2008|doi:10.1038/nature06932

LETTERS

The missing memristor found

Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

Anyone who ever took an electronics laboratory class will be familiar with the fundamental passive circuit elements: the resistor, the capacitor and the inductor. However, in 1971 Leon Chua reasoned from symmetry arguments that there should be a fourth fundamental element, which he called a memristor (short for memory resistor)[1]. Although he showed that such an element has many interesting and valuable circuit properties, until now no one has presented either a useful physical model or an example of a memristor. Here we show, using a simple analytical example, that memristance arises naturally in nanoscale systems in which solid-state electronic and ionic transport are coupled under an external bias voltage. These results serve as the foundation for understanding a wide range of hysteretic current–voltage behaviour observed in many nanoscale electronic devices[2–19] that involve the motion of charged atomic or molecular species, in particular certain titanium dioxide cross-point switches[20–22].

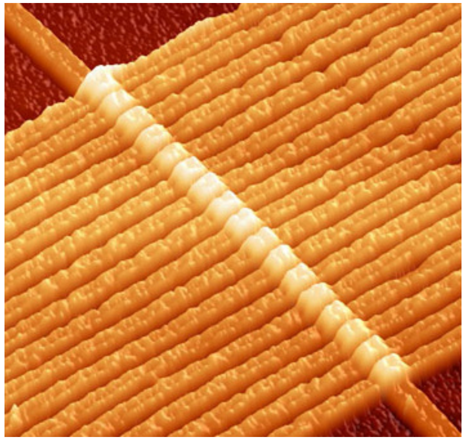
propose a physical model that satisfies these simple equations. In 1976 Chua and Kang generalized the memristor concept to a much broader class of nonlinear dynamical systems they called memristive systems[23], described by the equations

$$v = \mathcal{R}(w,i)i \tag{3}$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = f(w,i) \tag{4}$$

where w can be a set of state variables and $\mathcal{R}$ and f can in general be explicit functions of time. Here, for simplicity, we restrict the discussion to current-controlled, time-invariant, one-port devices. Note that, unlike in a memristor, the flux in memristive systems is no longer uniquely defined by the charge. However, equation (3) does serve to distinguish a memristive system from an arbitrary dynamical device; no current flows through the memristive system when the

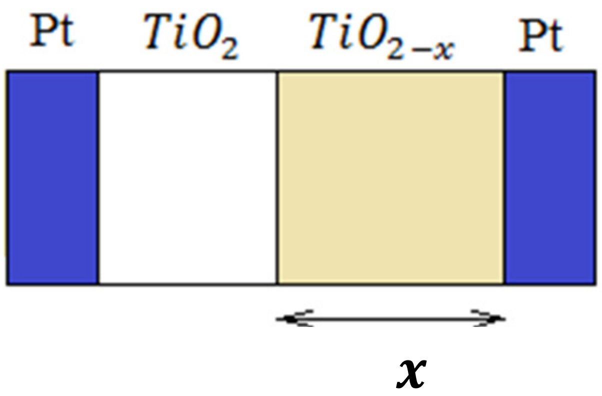
[8]



HP memristor Implementation [9]

[8] **Strukov, D. B.**, Snider, G. S., Stewart, D. R., & Williams, R. S. (2008). The missing memristor found. *nature*, *453*(7191), 80-83.
[9] **Bush, S.** (2 May 2008), "HP nano device implements memristor", Electronics Weekly

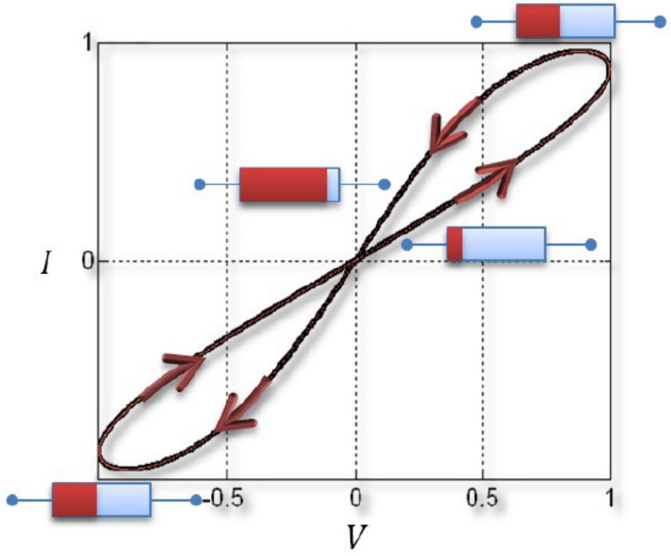
The Hewlett Packard (HP) memristor model



$$M(x) = 0.1 \cdot x + 16 \cdot (1 - x)\ [k\Omega]$$

$$\frac{dx}{dt} = \text{const} \cdot i \qquad [8]$$

The memristance in this example is a function of x, the extension of the doped titandioxide (TiO_{2-x}) region (high conductive) vs. the non-doped titandioxide (TiO_2) region (low conductive).



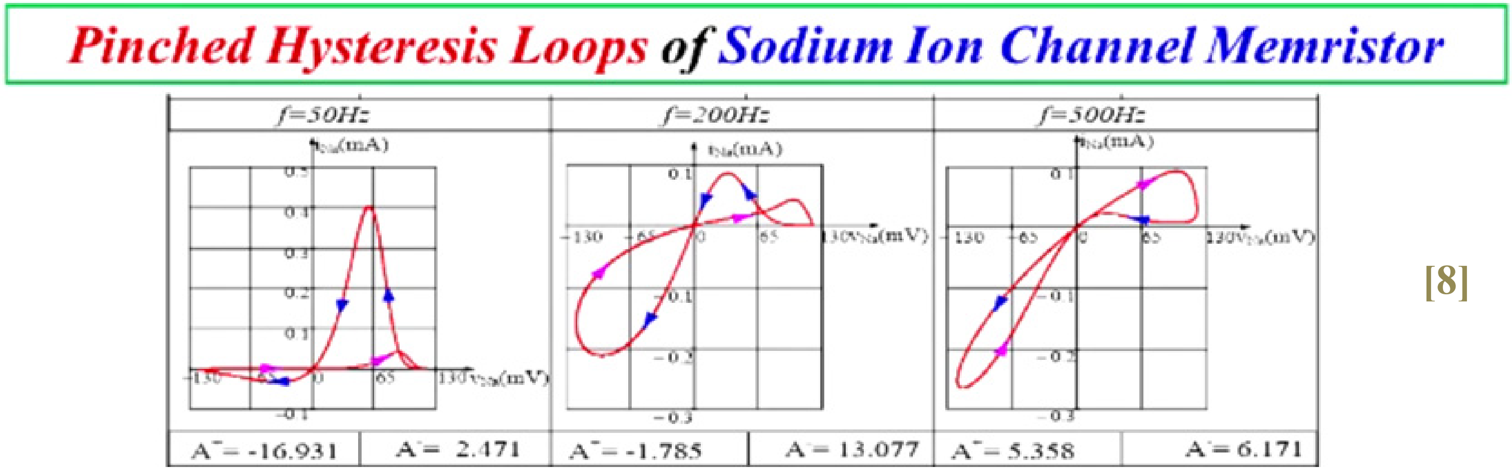
[10]

The red bar illustrates the extension, x, of the doped region. The results are obtained by simulation (using a sinusoidal voltage source).
With a positive voltage, x increases and the memristance, M(x), decreases concequently (see first quadrant). -> The current «on the way back» is larger than on the «way up».
With a negative voltage, x decreases and the memristance increases consequently. The resulting current decreases consequently.

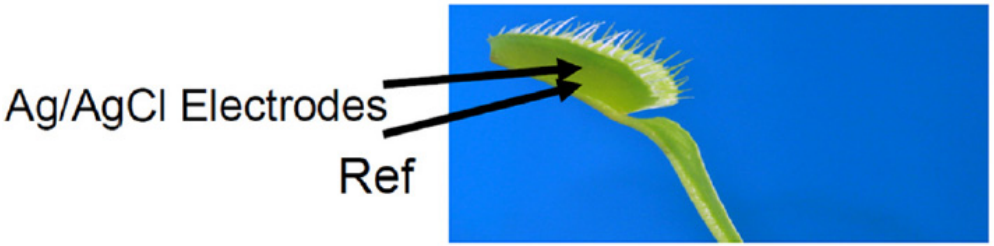
[8] Adapted from: **Strukov, D. B.**, Snider, G. S., Stewart, D. R., & Williams, R. S. (2008). The missing memristor found. *nature*, *453*(7191), 80-83.

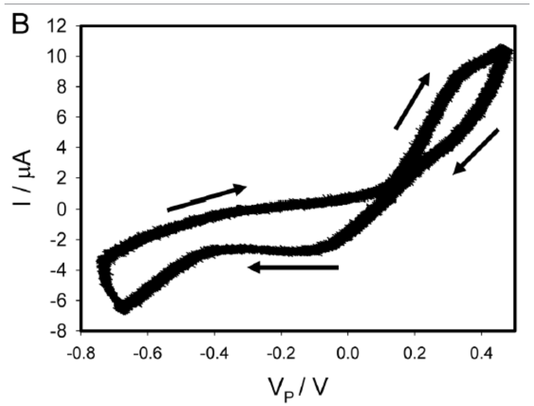
[10] **Tetzlaff, R., & Schmidt, T.** (2012, May). Memristors and memristive circuits-an overview. In *2012 IEEE International Symposium on Circuits and Systems* (pp. 1590-1595). IEEE.

Examples of pinched hysteresis loops



[8]



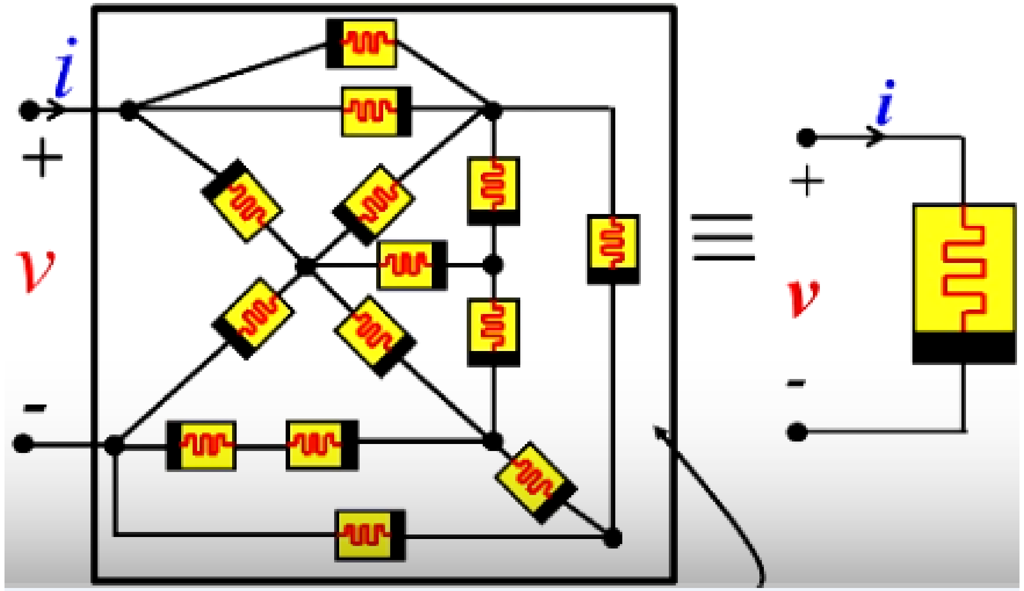


[9]

[8] **The Chua Lectures:** A 12-Part Series with Hewlett Packard Labs

[9] **Volkov, A. G., Tucket, C., Reedus, J., Volkova, M. I., Markin, V. S., & Chua, L.** (2014). Memristors in plants. *Plant signaling & behavior*, *9*(3), e28152.

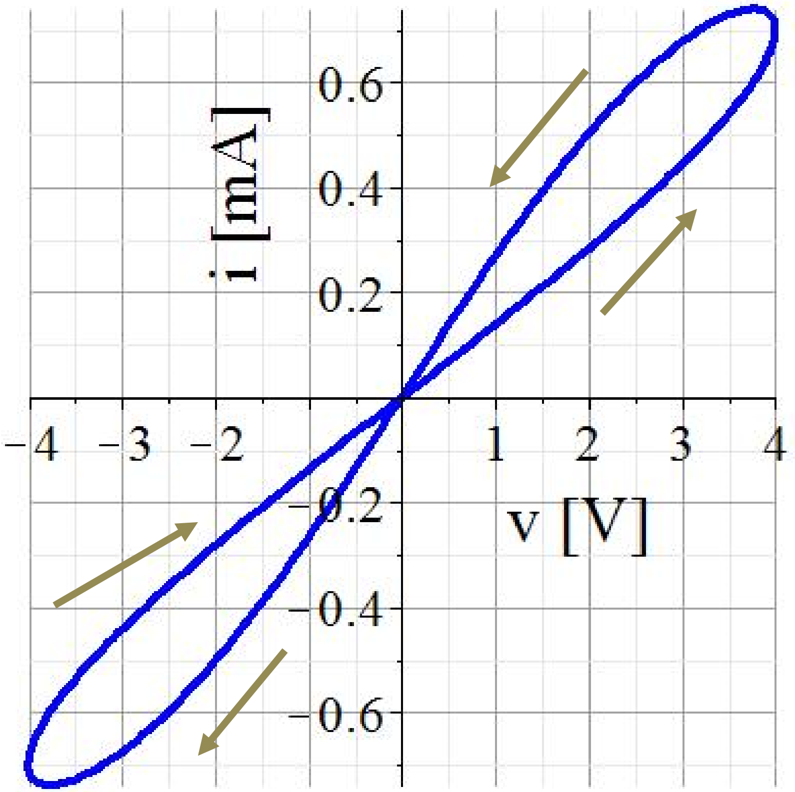
Closure theorem of memristors



[2]

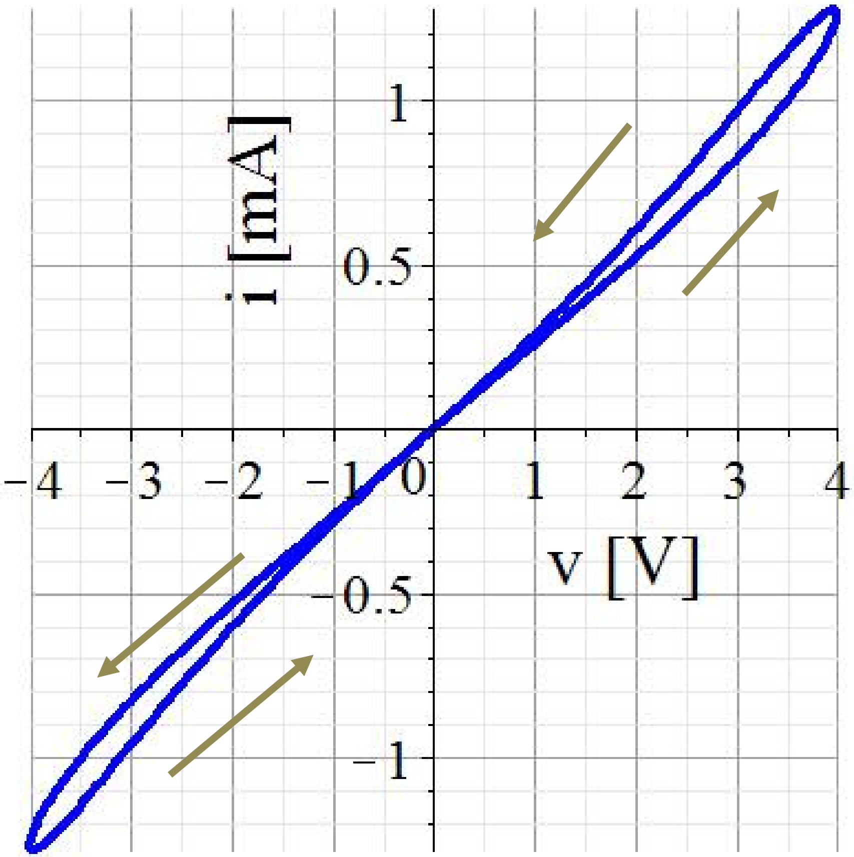
[2] **The Chua Lectures:** A 12-Part Series with Hewlett Packard Labs

Is this a memristor?



Yes:
This plot is obtained by simulation (based on an adapted version of the HP memristor).
The two branches of the loop are crossing the pinched point with different slopes.
We call this type of memristor a “transversal” memristor.

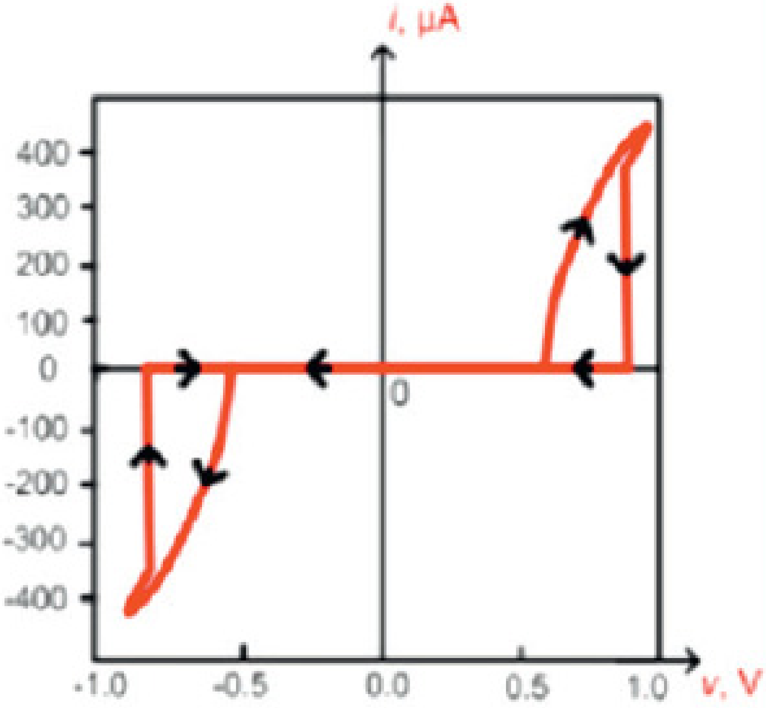
Is this a memristor?



Yes,
this plot is obtained by simulation of a memristor model presented in [11].
The two branches of the loop do not need to cross the pinched point but can also touch the pinched point with equal slopes.
We call this type of memristor a “tangential” memristor.

[11] M. P. Sah, C. Yang, H. Kim, B. Muthuswamy, J. Jevtic, and L. Chua, "A generic model of memristors with parasitic components," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 62, no. 3, pp. 891-898, 2015.

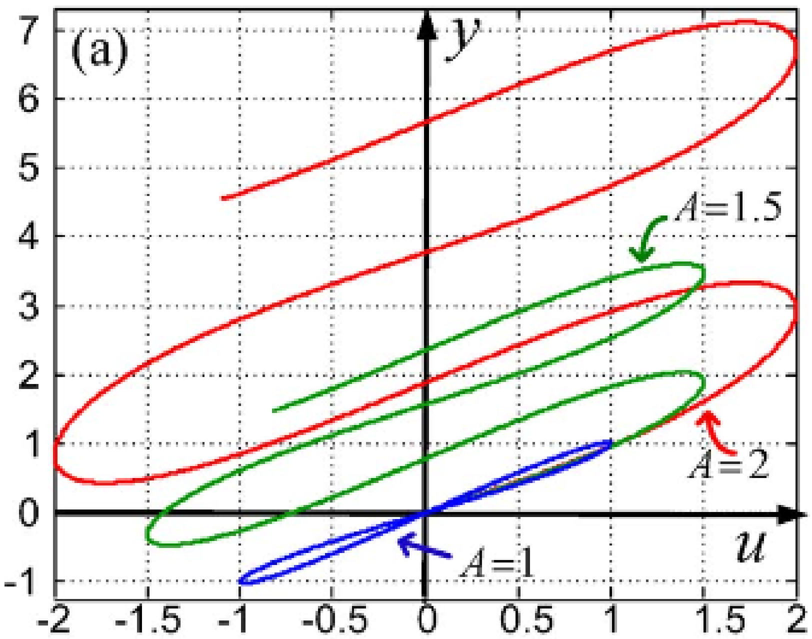
Is this a memristor?



Yes,
This is plot is obtained from some solid state memristor presented in [12].

[12] Pickett M D, Medeiros-Ribeiro G and Williams R S 2012 Nat. Mater. 12 114

Is this a memristor?

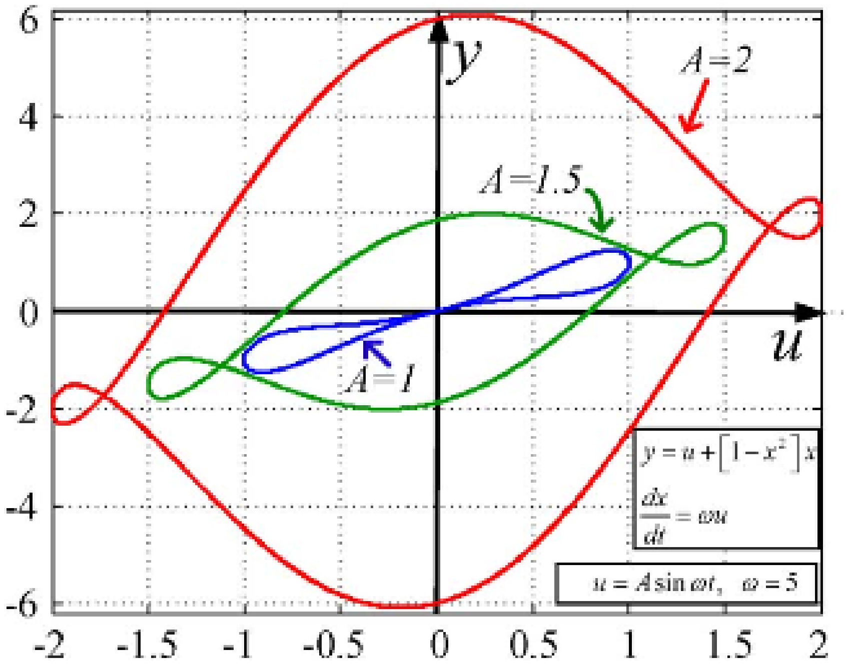


[7]

This is not a memristor, since we do not obtain pinched hysteresis loops for applied sinusoidal voltage with amplitudes, A, of 1.5 V and 2 V.

[7] Adhikari, Shyam Prasad, et al. "Three fingerprints of memristor." *IEEE Transactions on Circuits and Systems I: Regular Papers* 60.11 (2013): 3008-3021.

Is this a memristor?

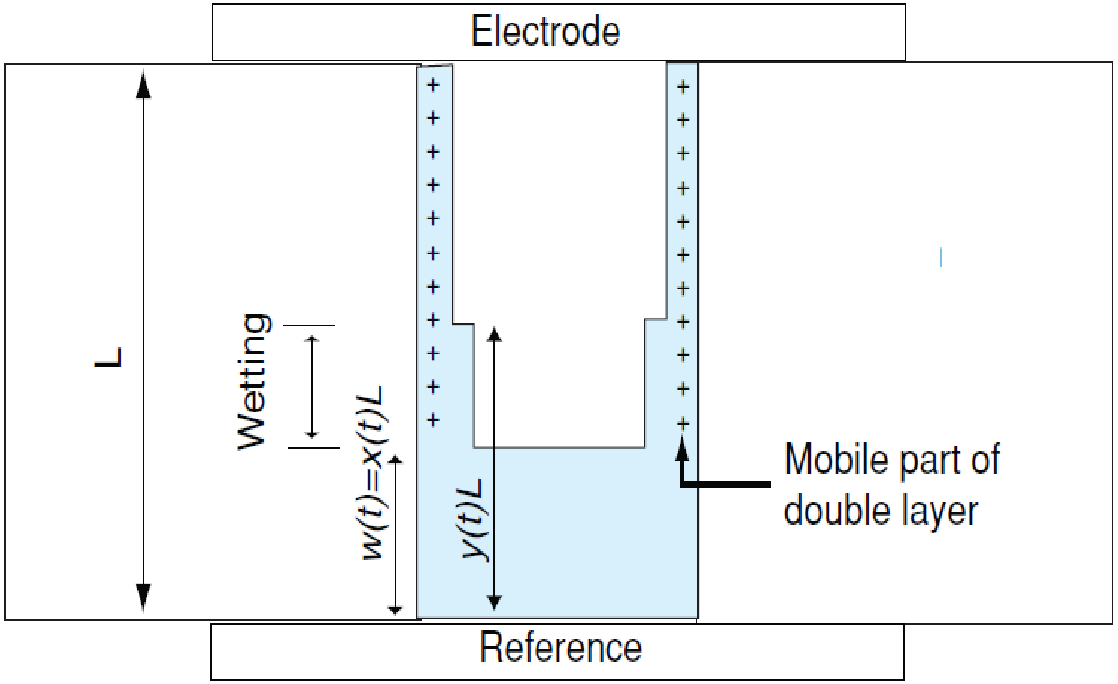


[7]

This is also not a memristor, since we do not obtain pinched hysteresis loops for applied sinusoidal voltage with amplitudes, A, of 1.5 V and 2 V.

[7] Adhikari, Shyam Prasad, et al. "Three fingerprints of memristor." *IEEE Transactions on Circuits and Systems I: Regular Papers* 60.11 (2013): 3008-3021.

Is this a memristor?

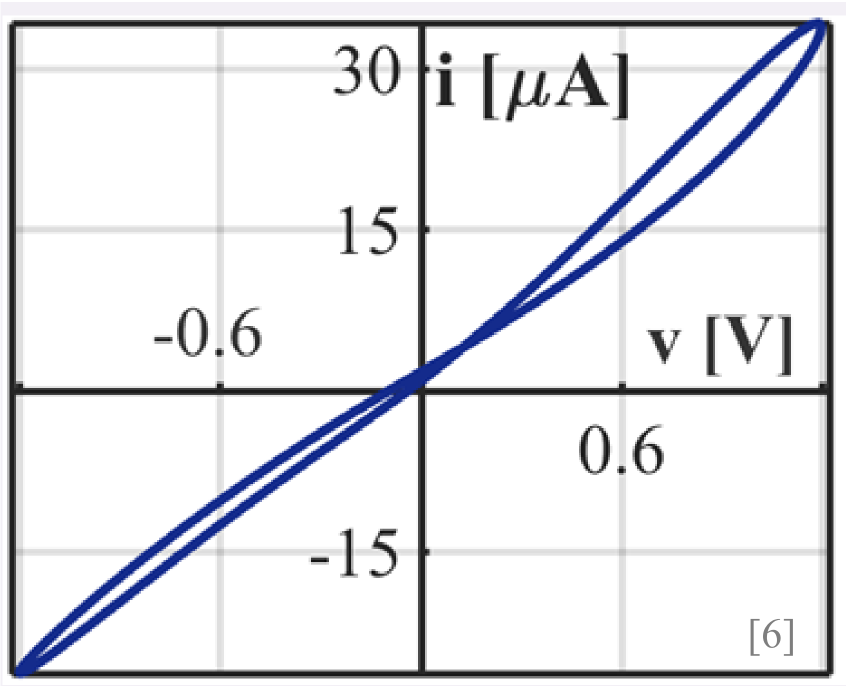


Yes,

This is a memristive model of human skin as presented in[13]. The sweat is moved by electro-osmosis resulting in a change of the state dependent conductance.

[13] Johnsen, G. K., et al. "Memristive model of electro-osmosis in skin." *Physical Review E* 83.3 (2011): 031916.

Is this a memristor?



Yes,
this is a recording from the human skin memristor (sinusoidal voltage with excitation frequency of 0.25 Hz).
However, measurements on human skin and other biological tissues (like apples) are affected by parasitic elements like, a capacitance. That is why the pinched point is slightly shifted from the origin of coordinates.

[6] **Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua.** "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

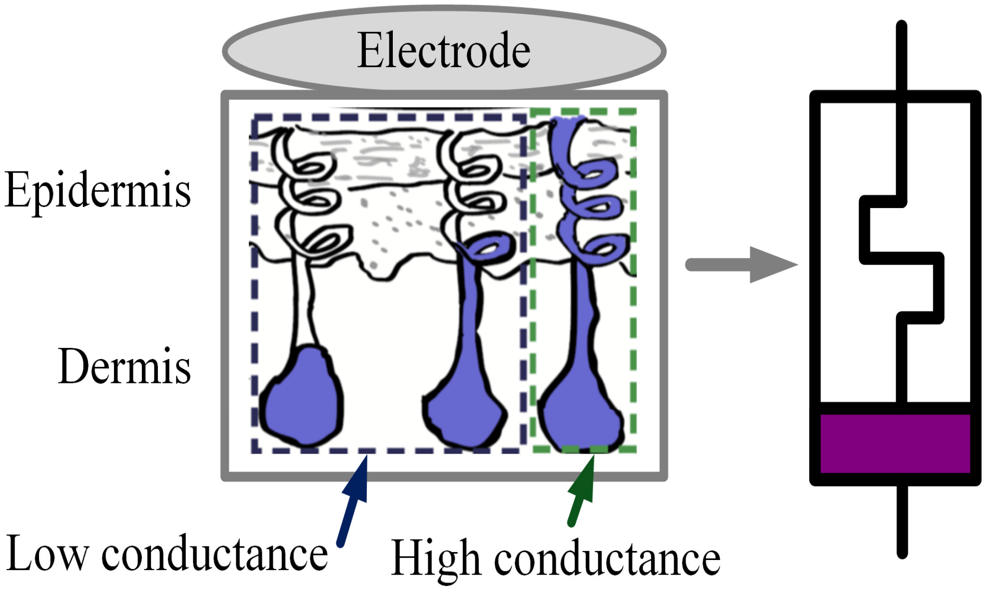
Questions

If you want to design an experiment to find out whether a material or tissue is a memristor, what do you need to test?

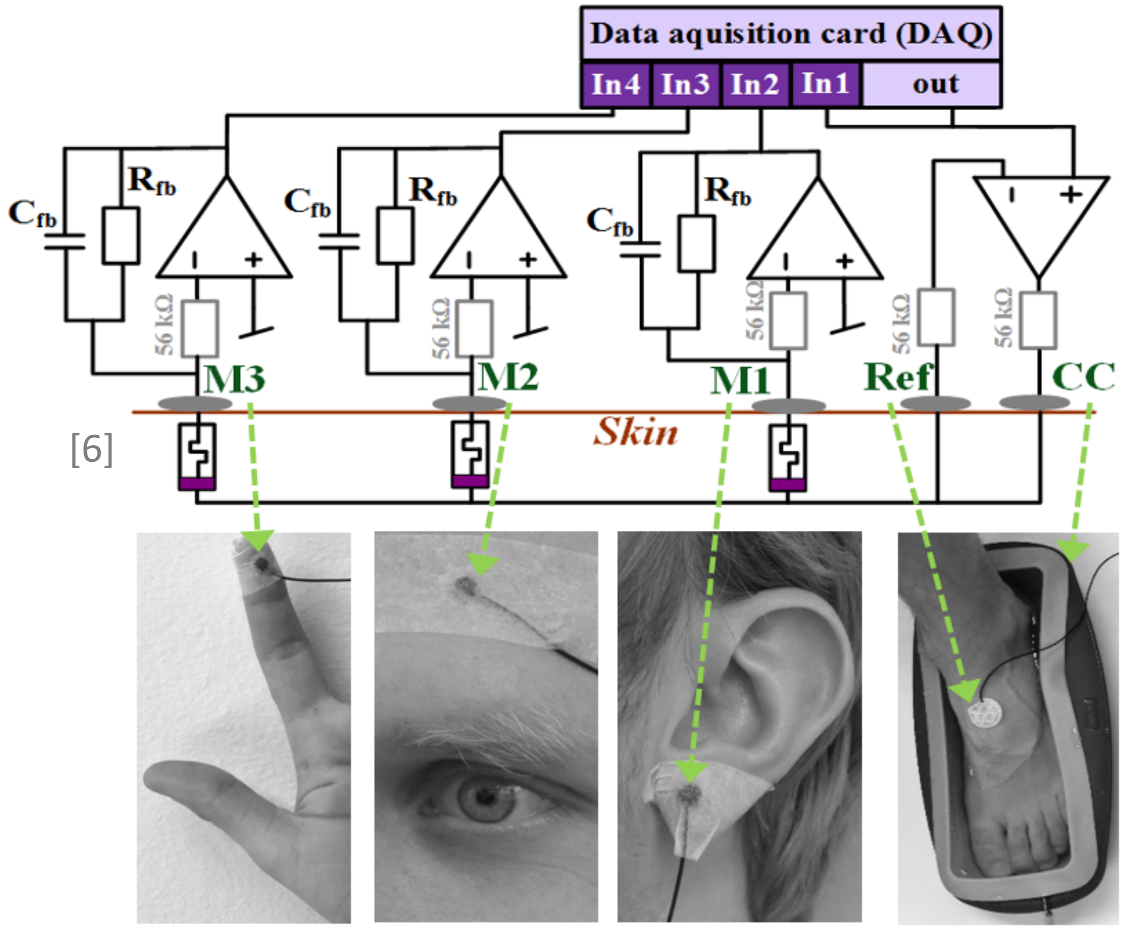
-> Remember what the three fingerprints of a memristor are.

Non-linear electrical properties of human skin

Instrumentation



[14]

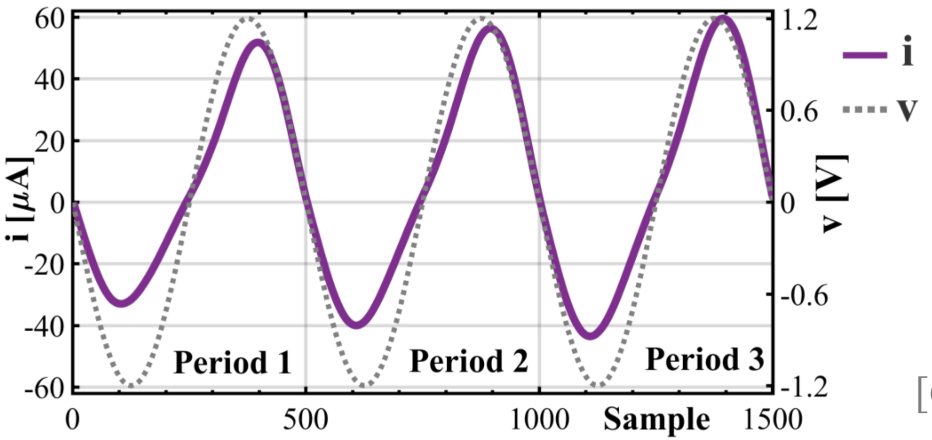


[6]

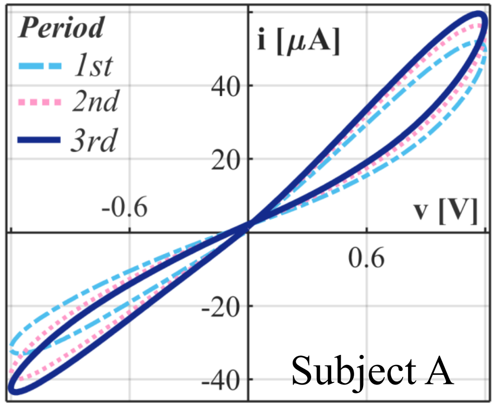
[14] Pabst, Oliver, Christian Tronstad, and Ørjan G. Martinsen. "Instrumentation, electrode choice and challenges in human skin memristor measurement." *Engineering in Medicine and Biology Society (EMBC), 2017 39th Annual International Conference of the IEEE*. IEEE, 2017.[

[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Non-linear AC characteristics

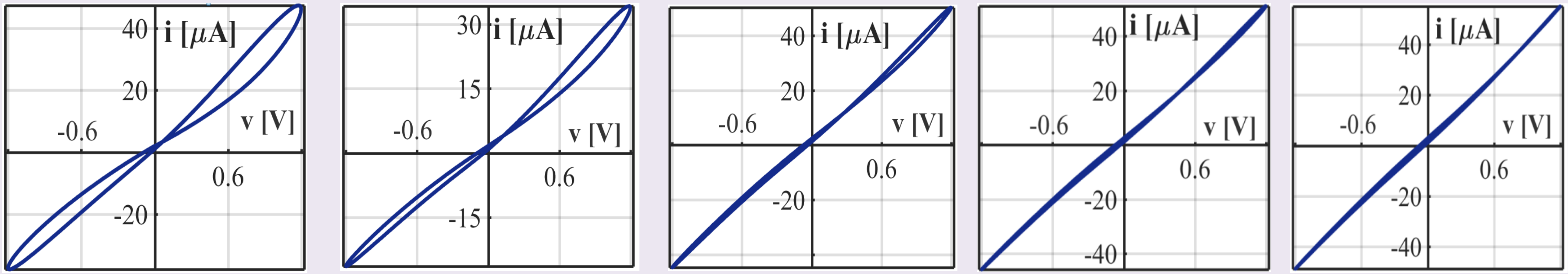


[6]



0.05 Hz

Different signal frequencies



0.1 Hz

0.25 Hz

0.5 Hz

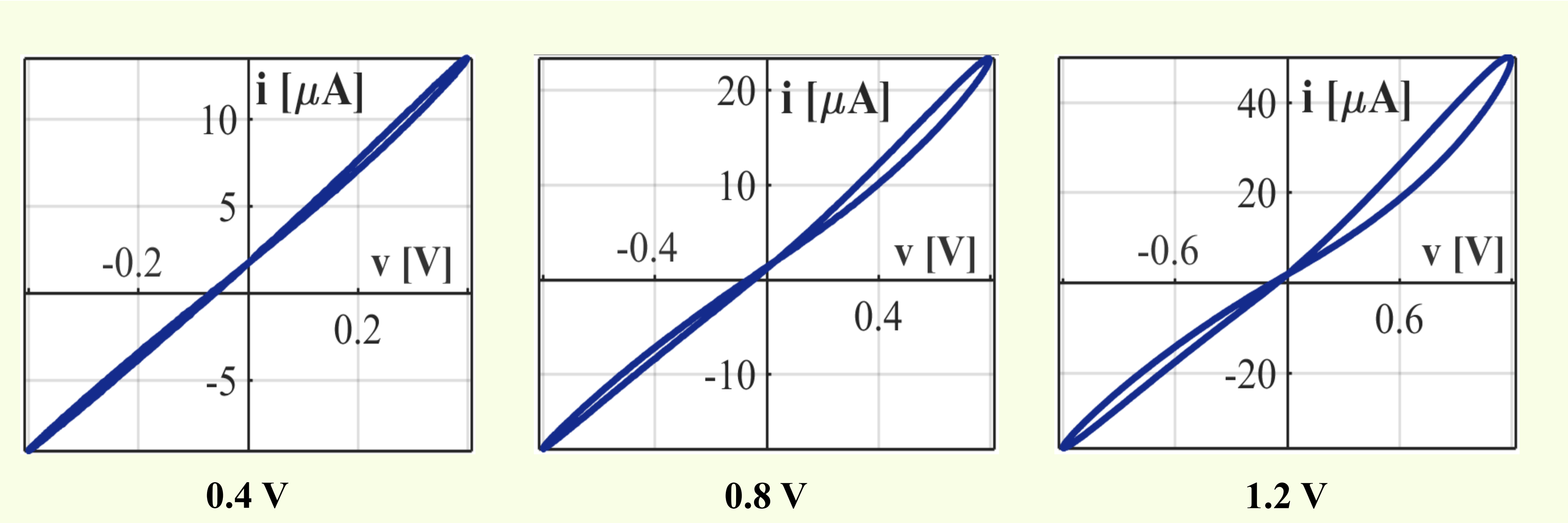
1 Hz

2.5 Hz

[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Non-linear AC characterisrics

Different amplitudes



[6]

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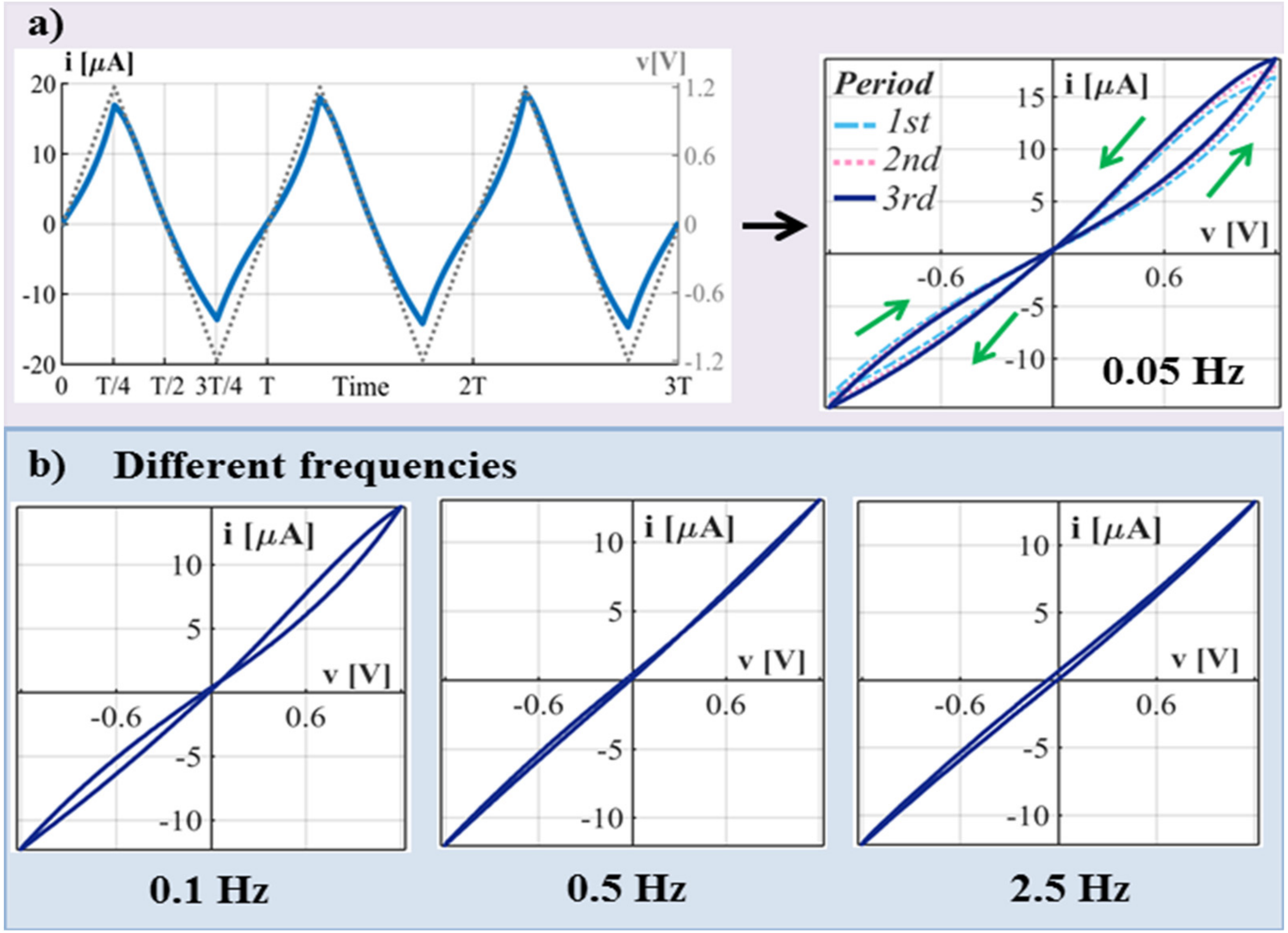
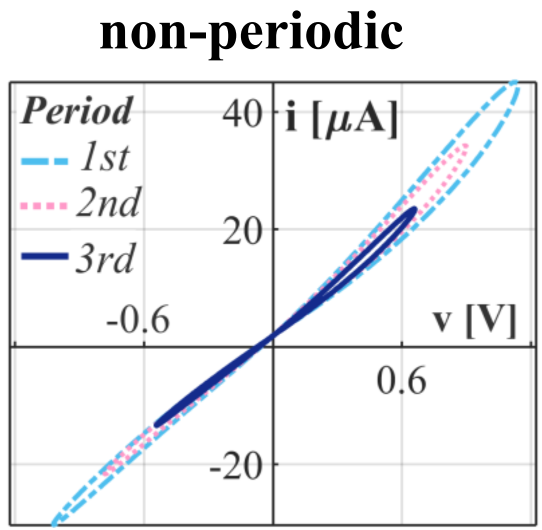
Non-linear AC characterisrics



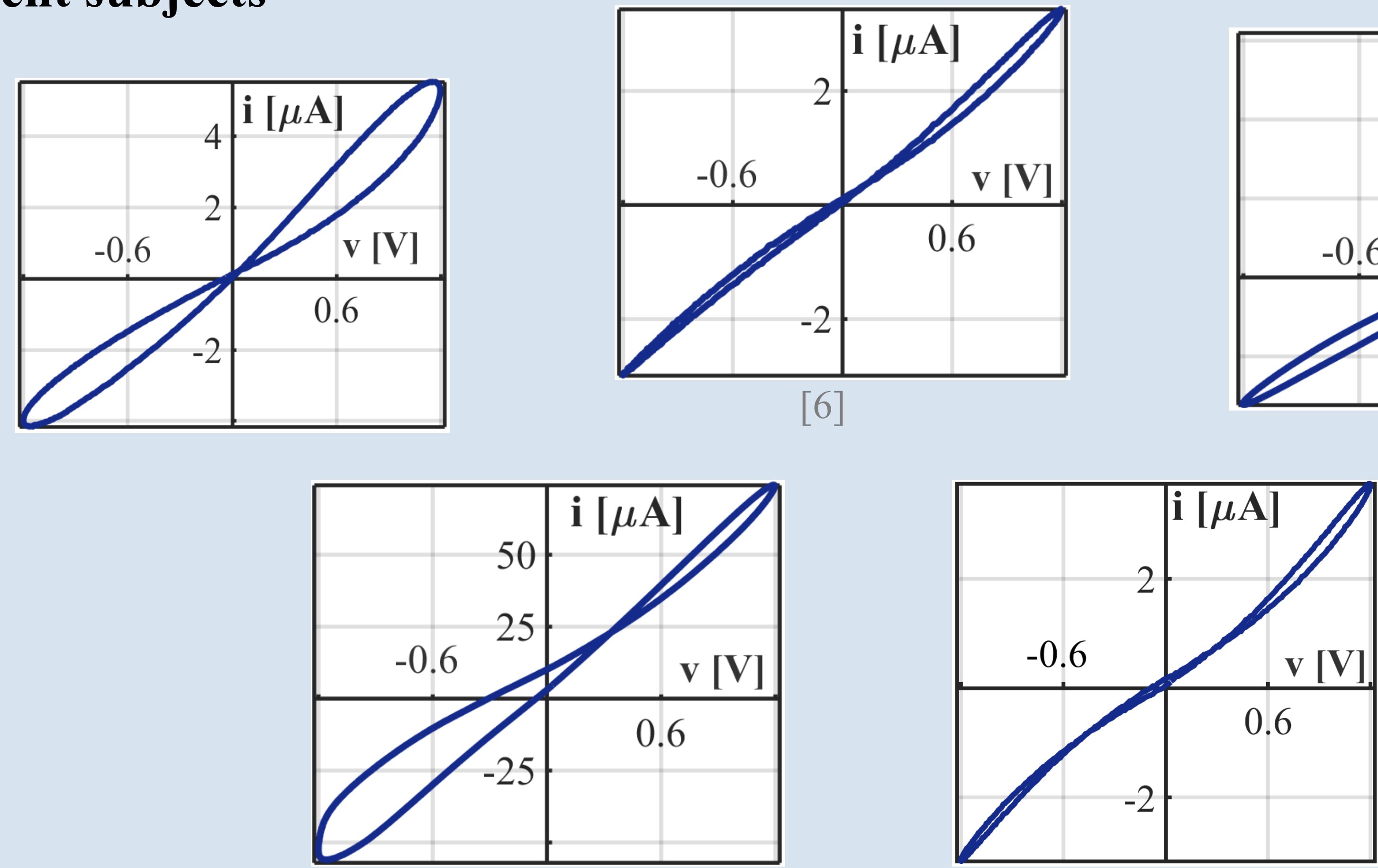


[6]

[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Non-linear AC characterisrics

Different subjects

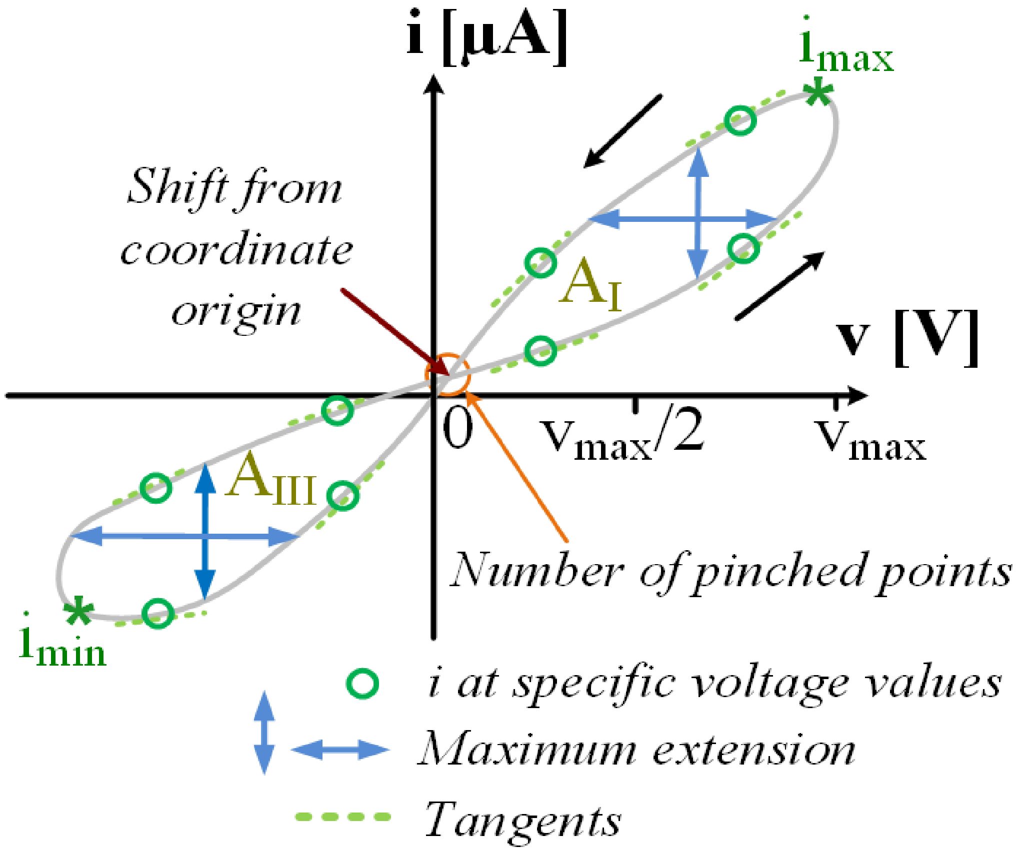


[6]

[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

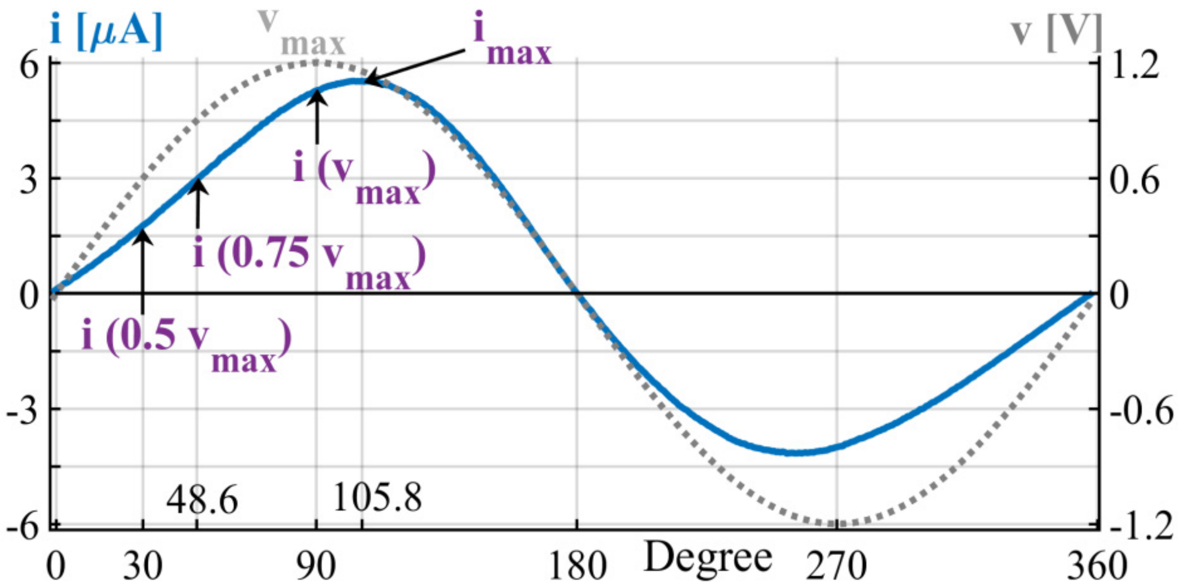
Parameterization

How to evaluate the recordings of several subjects?

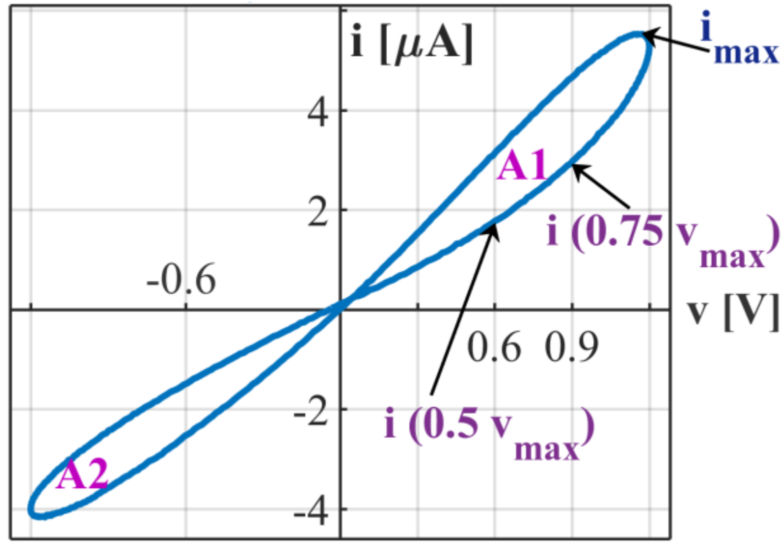


First idea is to use the geometry of the pinched hysteresis loop (see plot on the left).
However, what are the parameters that are meaningful?

Parameterization



[6]

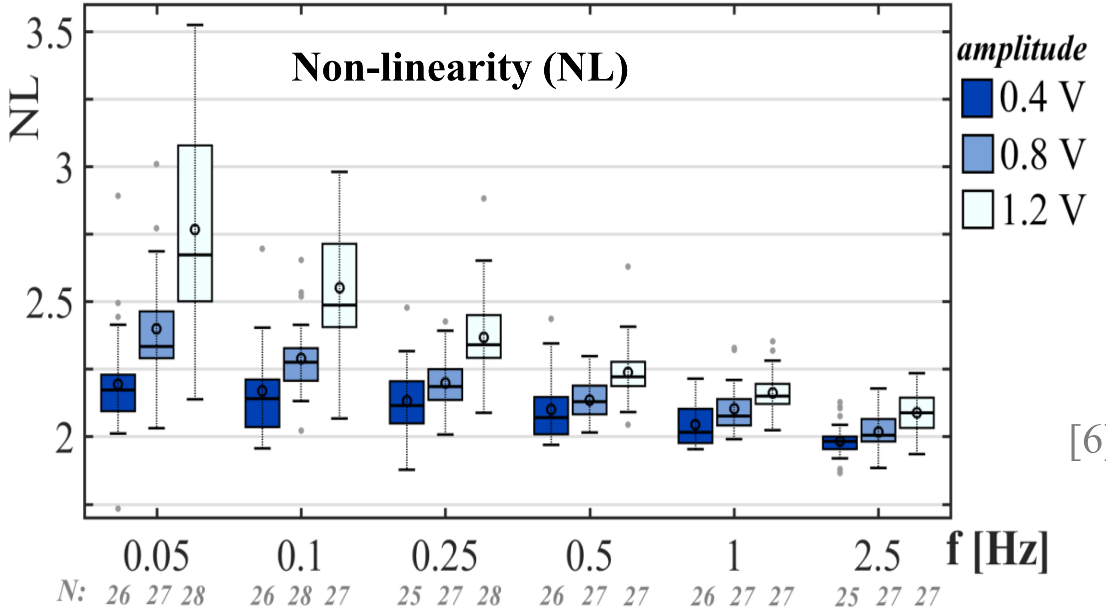


Non-linearity (adapted from [14])

[14] Joshua Yang, J., et al. "Engineering nonlinearity into memristors for passive crossbar applications." *Applied Physics Letters* 100.11 (2012): 113501.

[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Evaluation over several test subjects



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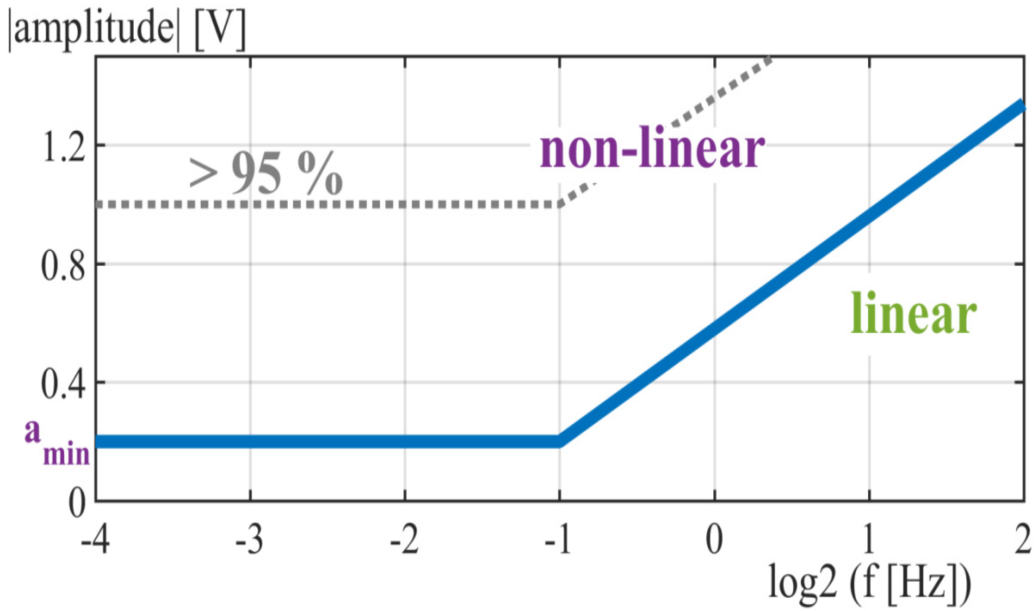
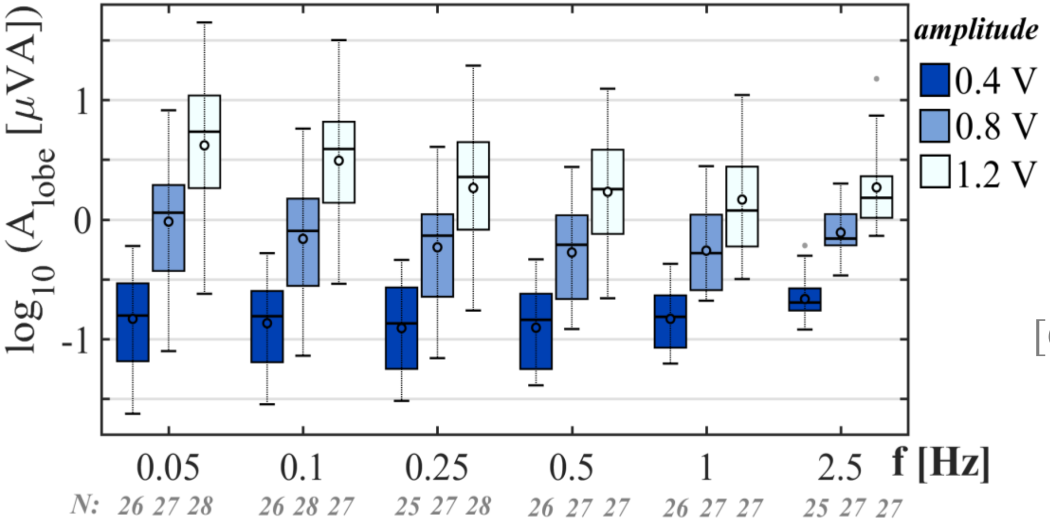


[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

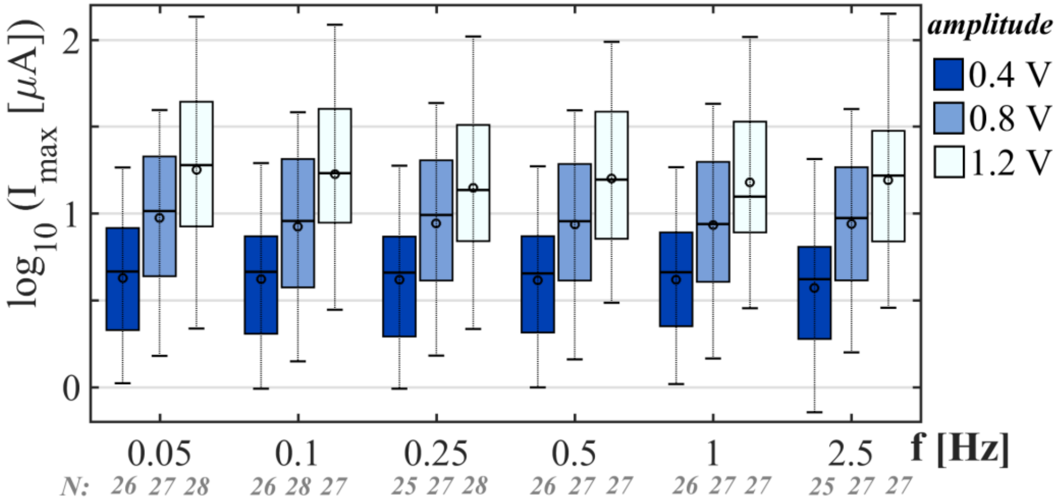
Evaluation over several test subjects

Lobe area



[6]

Maximum current



[6] Pabst, Oliver, Ørjan G. Martinsen, and Leon Chua. "The non-linear electrical properties of human skin make it a generic memristor." *Scientific reports* 8.1 (2018): 15806.

Outlook and Motivation

Undeveloped research field

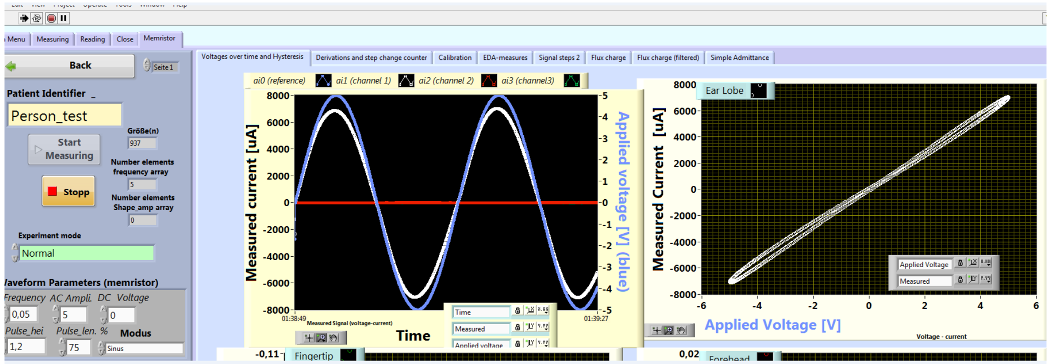
New insights

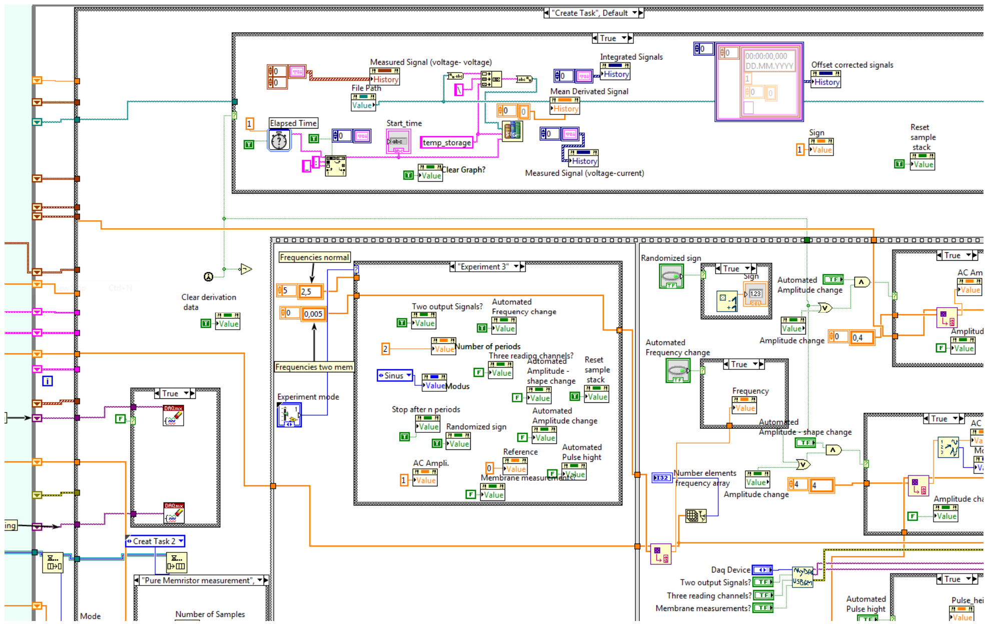
Sensor applications

Diagnostics?

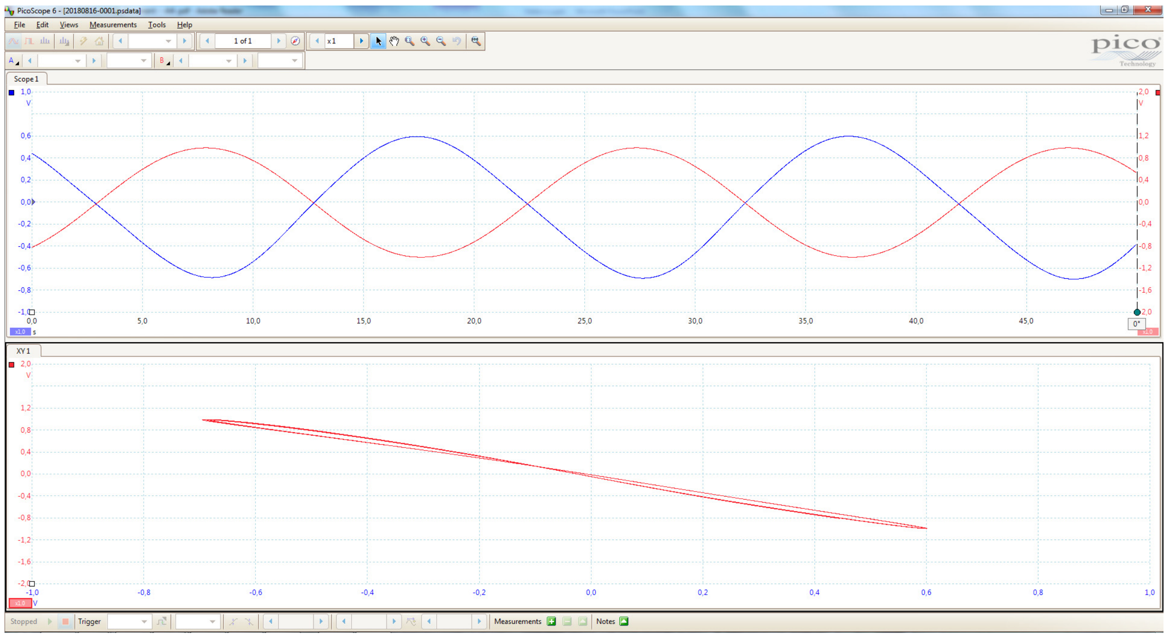
Sensorama 2018

Data acquisition box





Picoscope



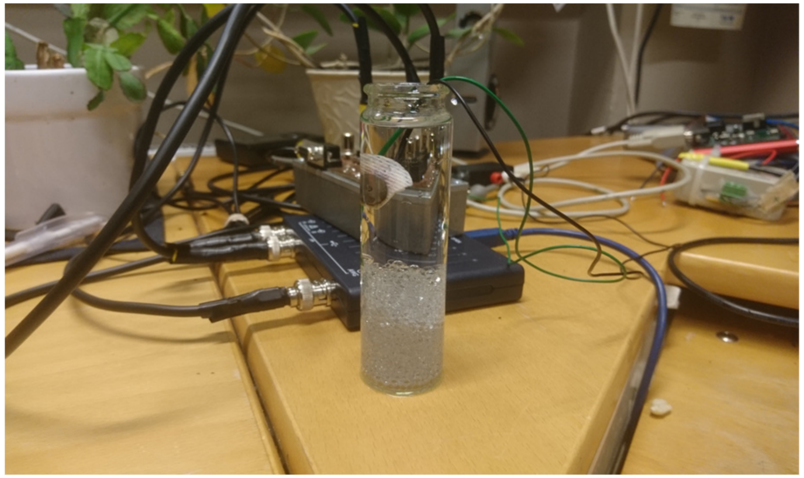
Advantage

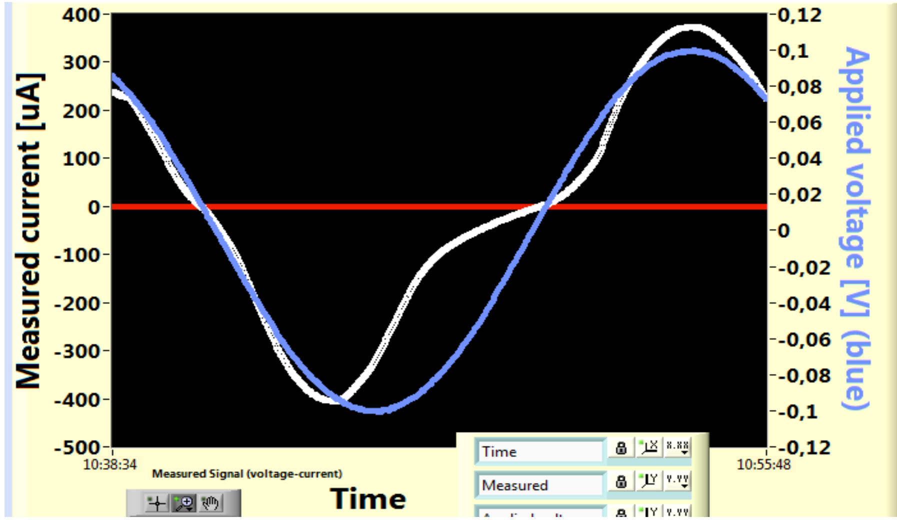
-easy to set up

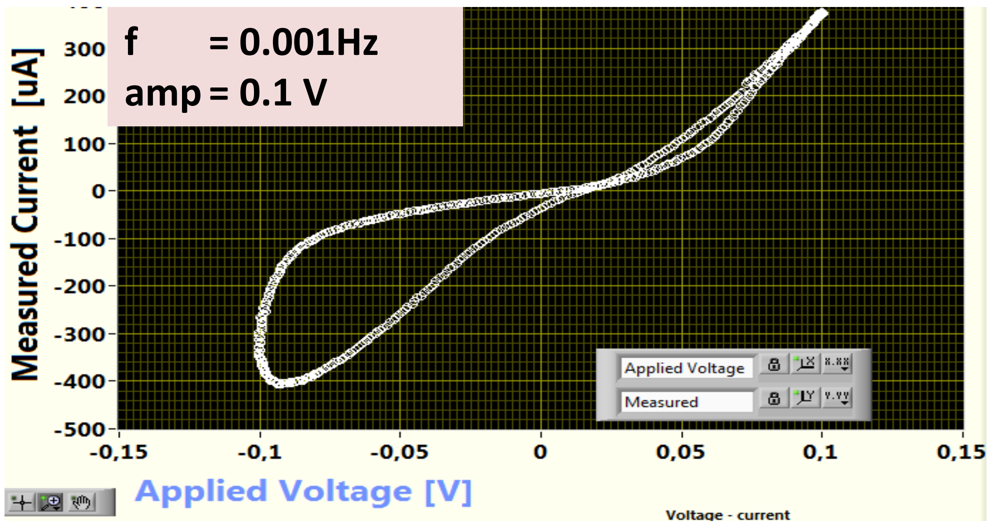
Disadvantages

- less automation
- output voltage limited to ±2

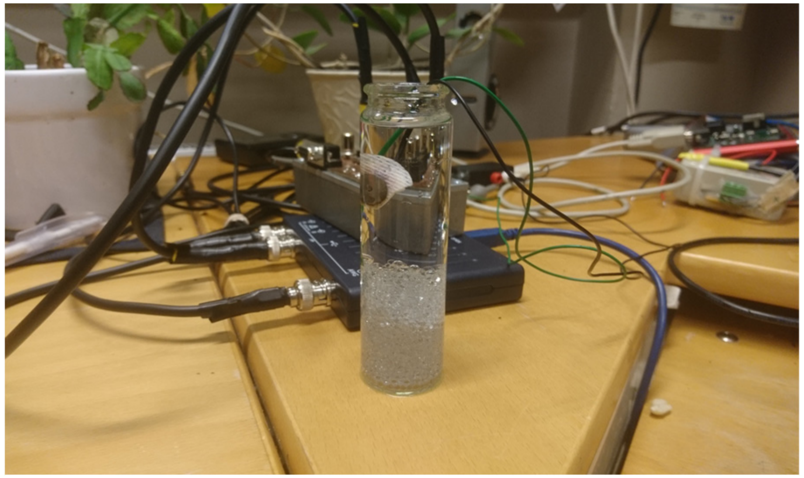
Electrodes in saline solution

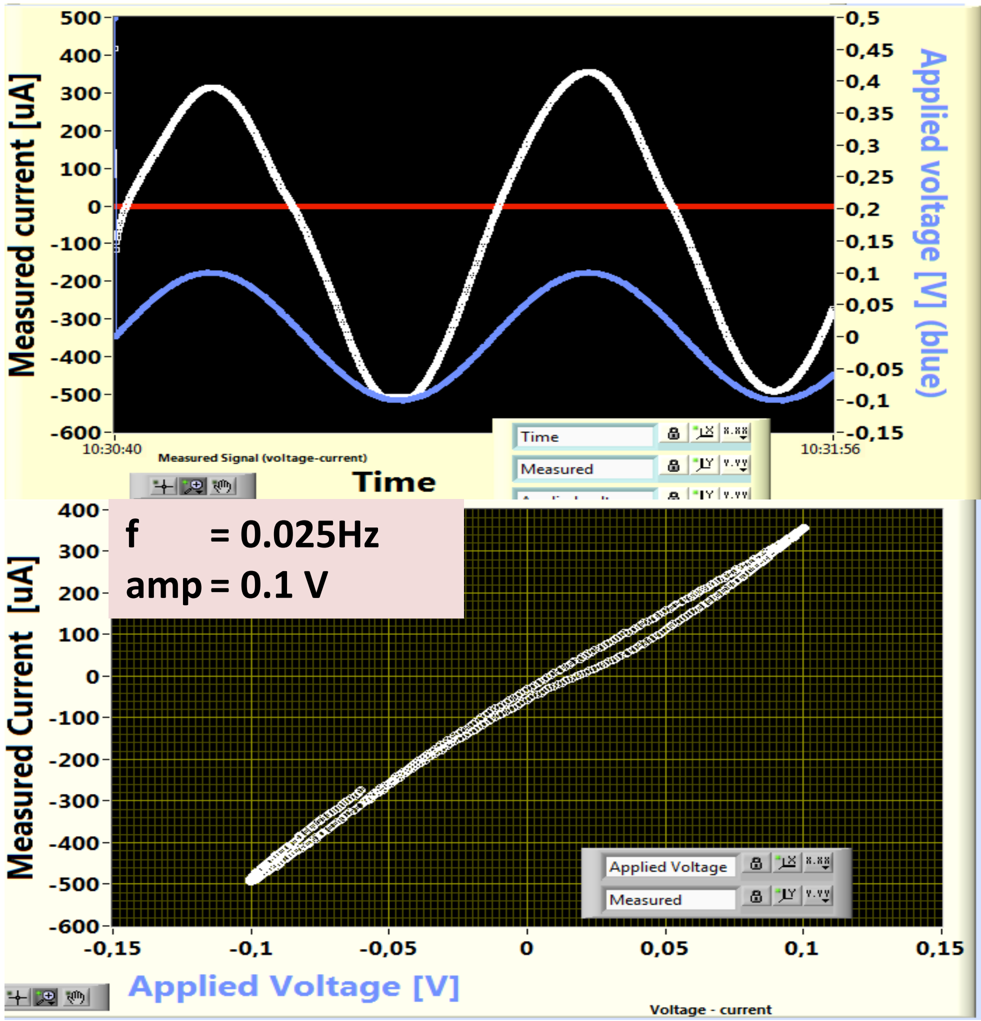




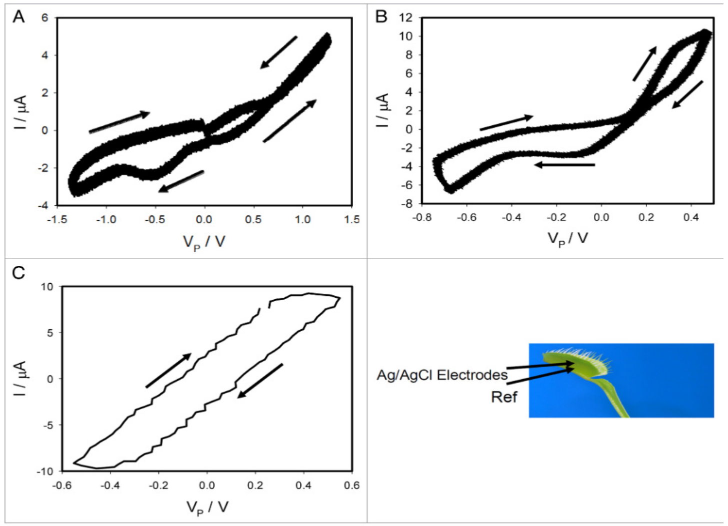


Electrodes in saline solution

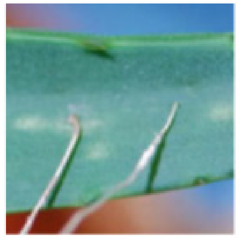




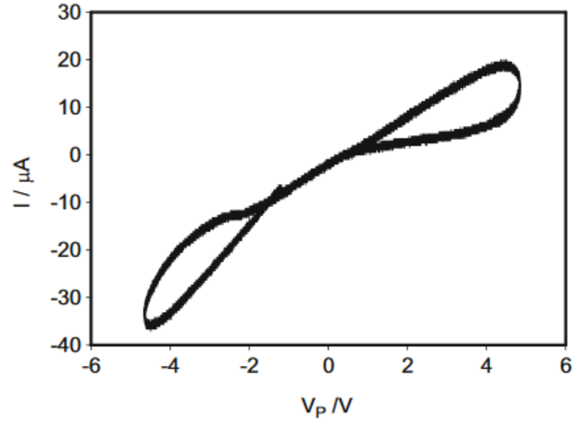
Measuring on plants with a three-electrode system

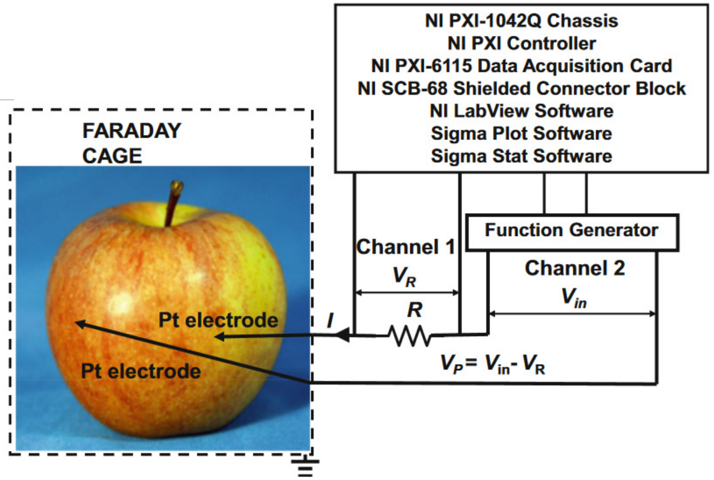


[2]



Aloe vera



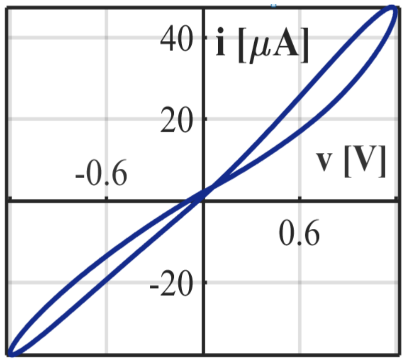


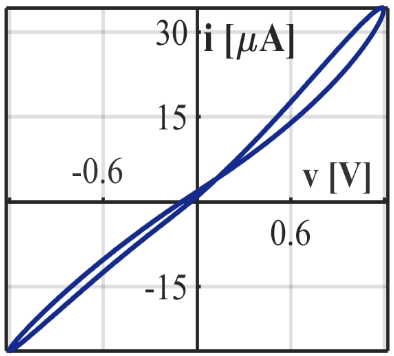
[1]

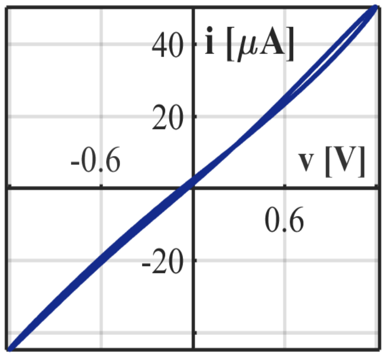
[1] Volkov, Alexander G. "Memristors and Electrical Memory in Plants." *Memory and Learning in Plants* (2018): 139-161.
[2] Volkov, Alexander G., et al. "Memristors in plants." *Plant signaling & behavior* 9.3 (2014): e28152.

Design of the studies

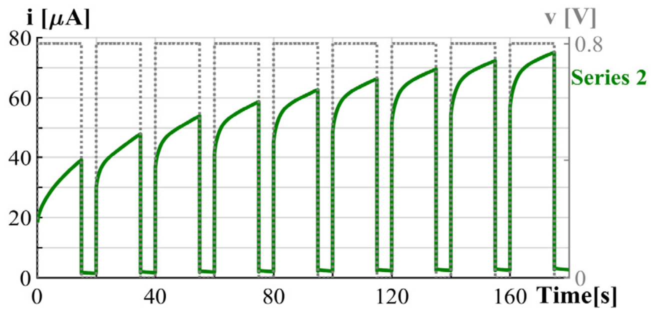
- Different frequencies
- Different amplitudes
- Different excitation signals







- DC pulses?

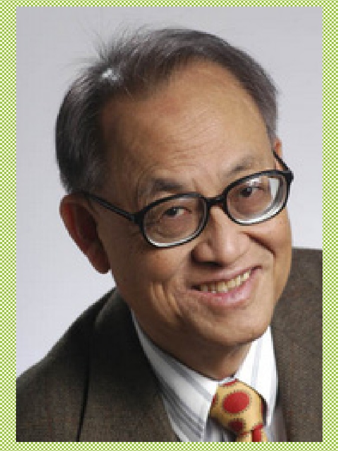


Design of the studies

- **Duration of the experiments: Think of excitation frequency of 0.001 Hz**

- **Need of a good experiment protocol**

„*Where there is ion, there is memristor.*“ [11]



[15] **The Chua Lectures:** A 12-Part Series with Hewlett Packard Labs, Part 5: Brain

The Chua lectures

If you are interested in learning more about memristors, the Chua lectures (1 to 5 out of 12) are quite useful. You can find them on YouTube.