

An Electronic Version of Pavlov`s Dog

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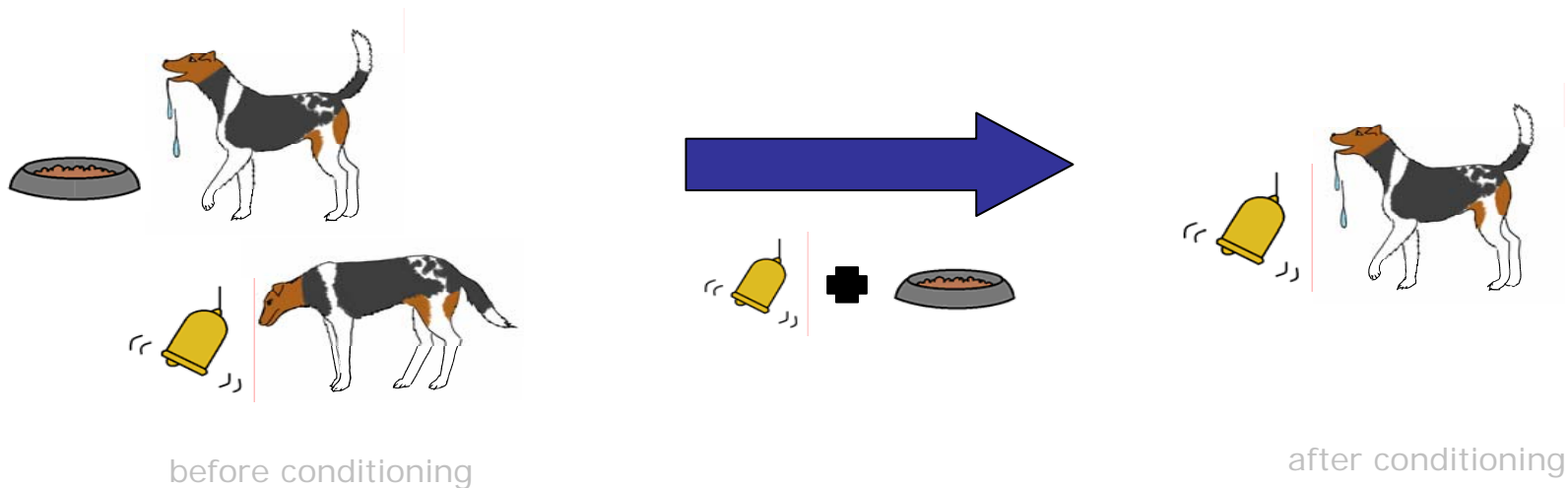
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Pavlov's dog: classical conditioning

IVAN PETROVICH PAVLOV (1905)

- Experiment to understand implicit learning in biological systems.



Experimental Psychology and Psychopathology in Animals, Vol. 1 p. 47-60, Ivan P. Pavlov, Lectures on Conditioned Reflexes, International Pub., New York 1928

- Neuromorphic engineering: Mimick of neural pathways

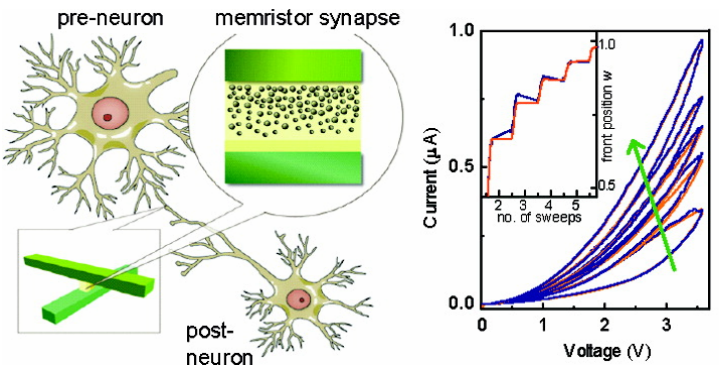
Which device could be used to close the gap from electronic to biological computing?

C. Zamarreño-Ramos et al., Front. Neurosci. 5, 26 (2011)
G. Indiveri et al., Front. Neurosci. 5, 118 (2011)

Memristive Devices for Neuromorphic Systems

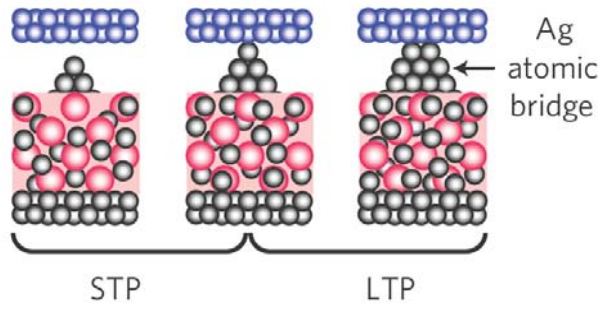
- **synaptic plasticity: spike timing dependent plasticity.**

Sung Hyun Jo et al., Nano Lett. 10, 1297-1301 (2010).



- **precondition of learning: long term potentiation**

T. Ohno et al., Nature Materials 10, 591-595 (2011).



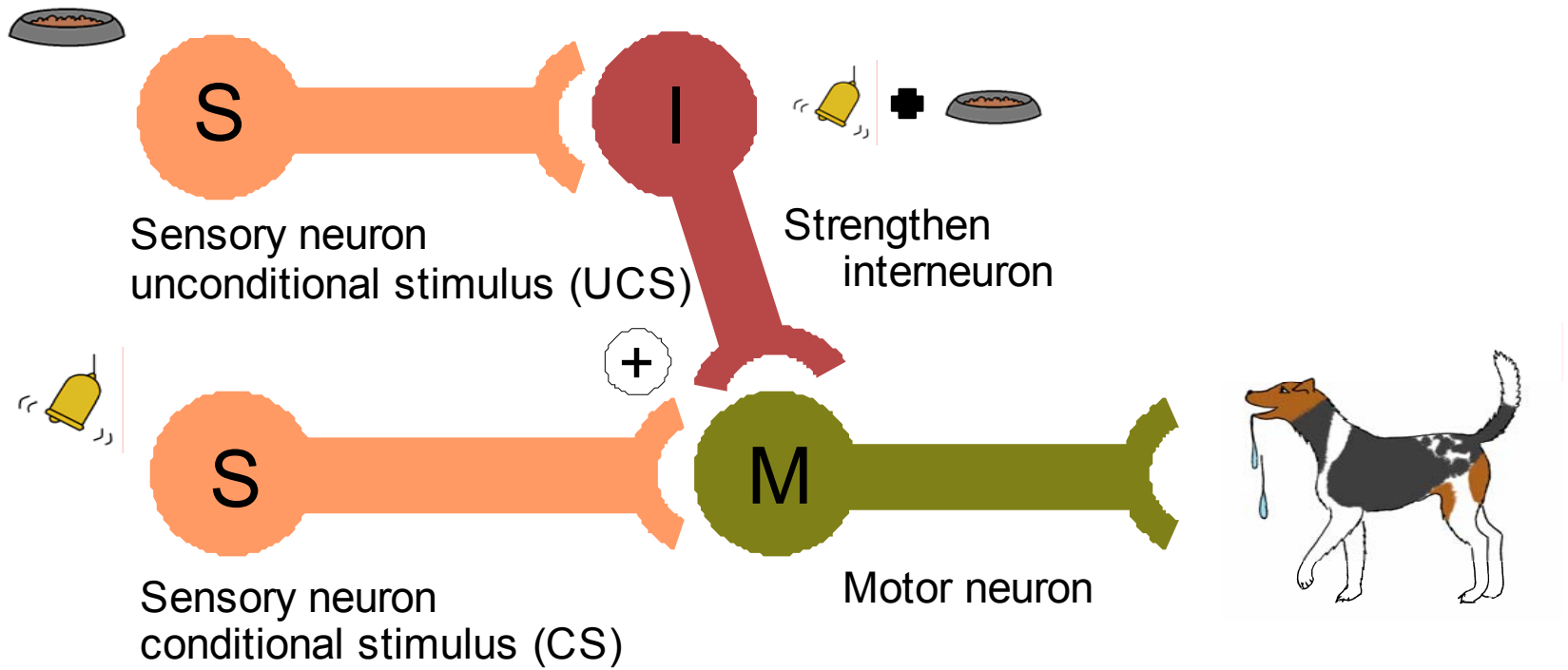
- **benefit for neuronal circuits:**

How can memristive devices learn to learn?

Reductionist strategy

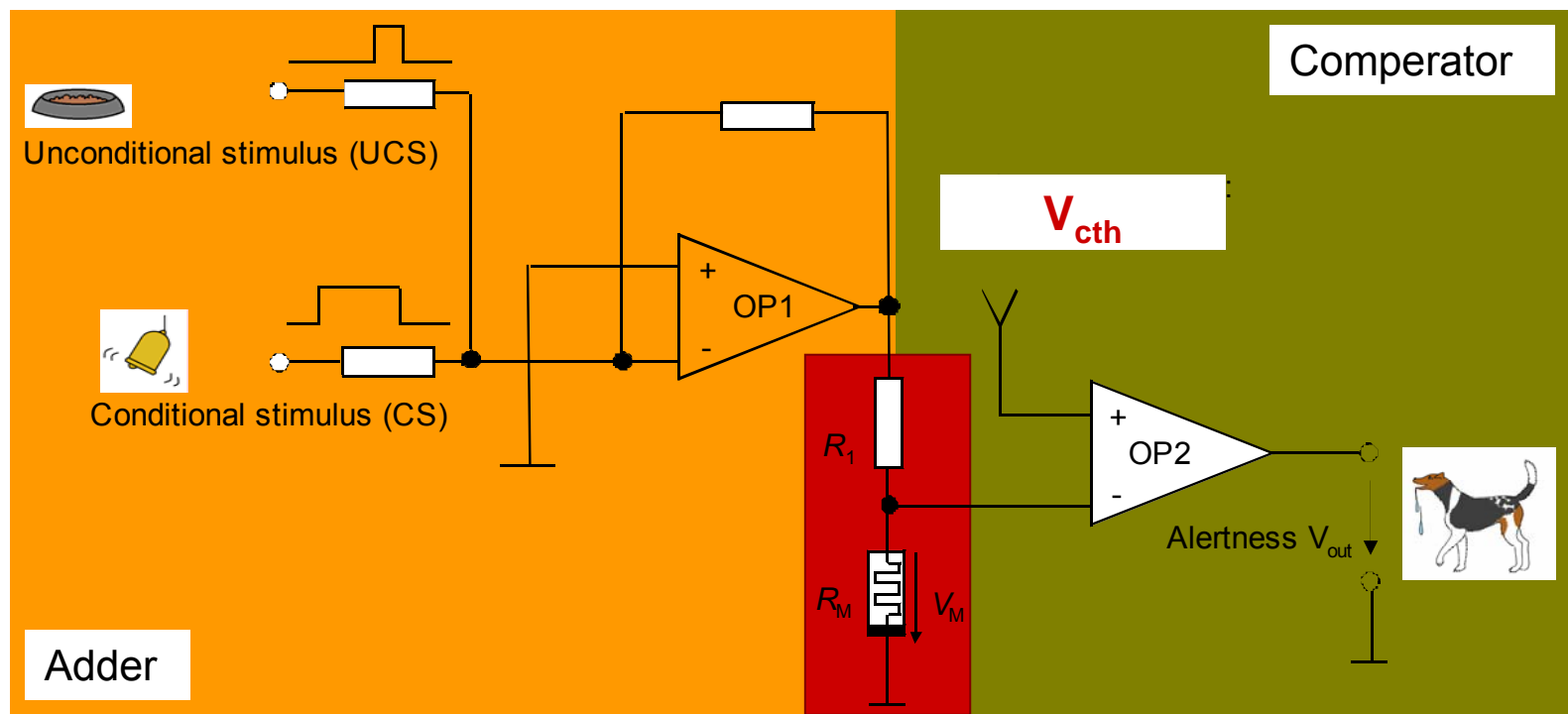
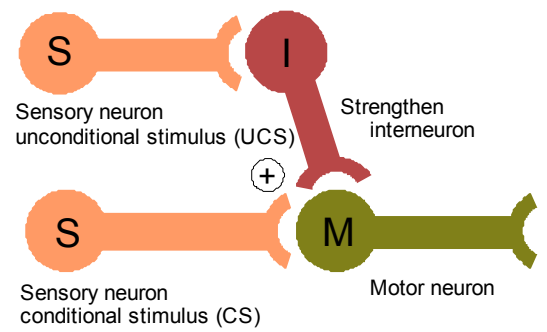
- Principles of **implicit learning** can be understood on **cellular level**

E. R. Kandel, Science 294, 1030 (2001).



Neural mediating circuit for associative learning

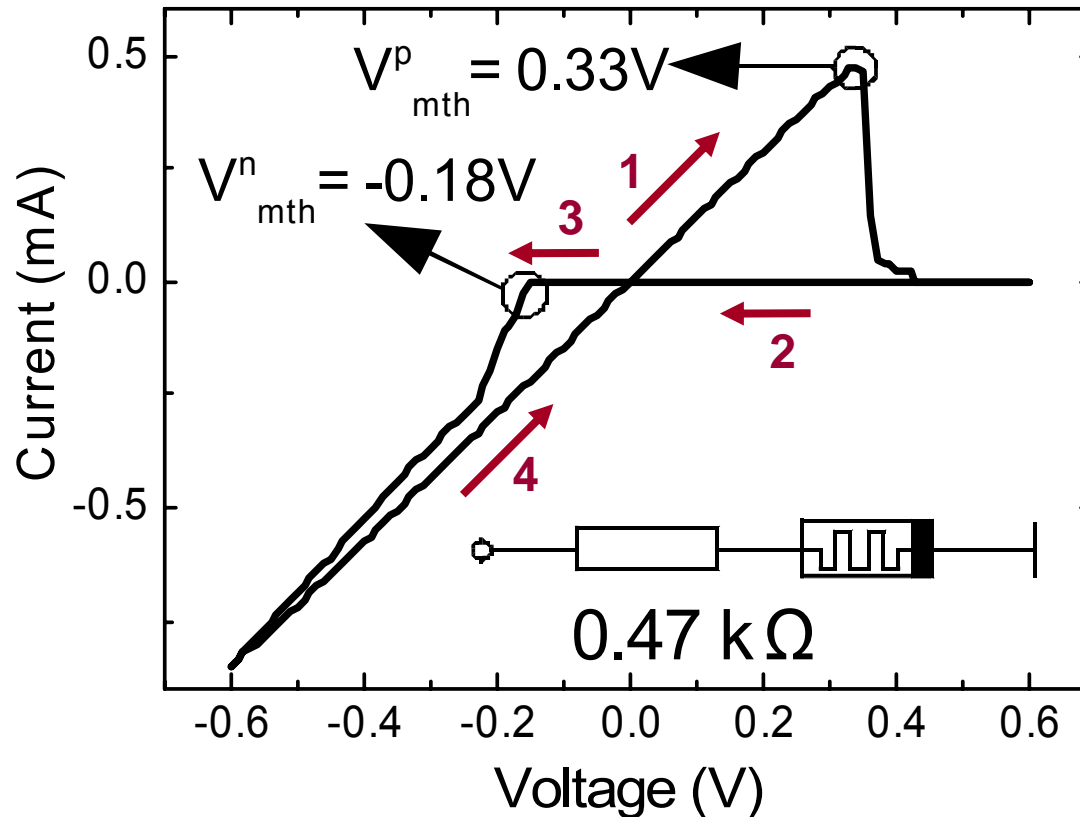
- Electrical circuit layout: single memristive device implemented in an analogue circuitry



- Voltage divider compromising a memristive device

Synaptic potentiation

- $\text{Pt}/\text{SiO}_2/\text{Ge}_{0.3}\text{Se}_{0.7}/\text{Cu}$ memristive device in voltage divider
R. Soni et al., J. Appl Phys. 110, 054509 (2011).
- synaptic potentiation via transition LRS to HRS



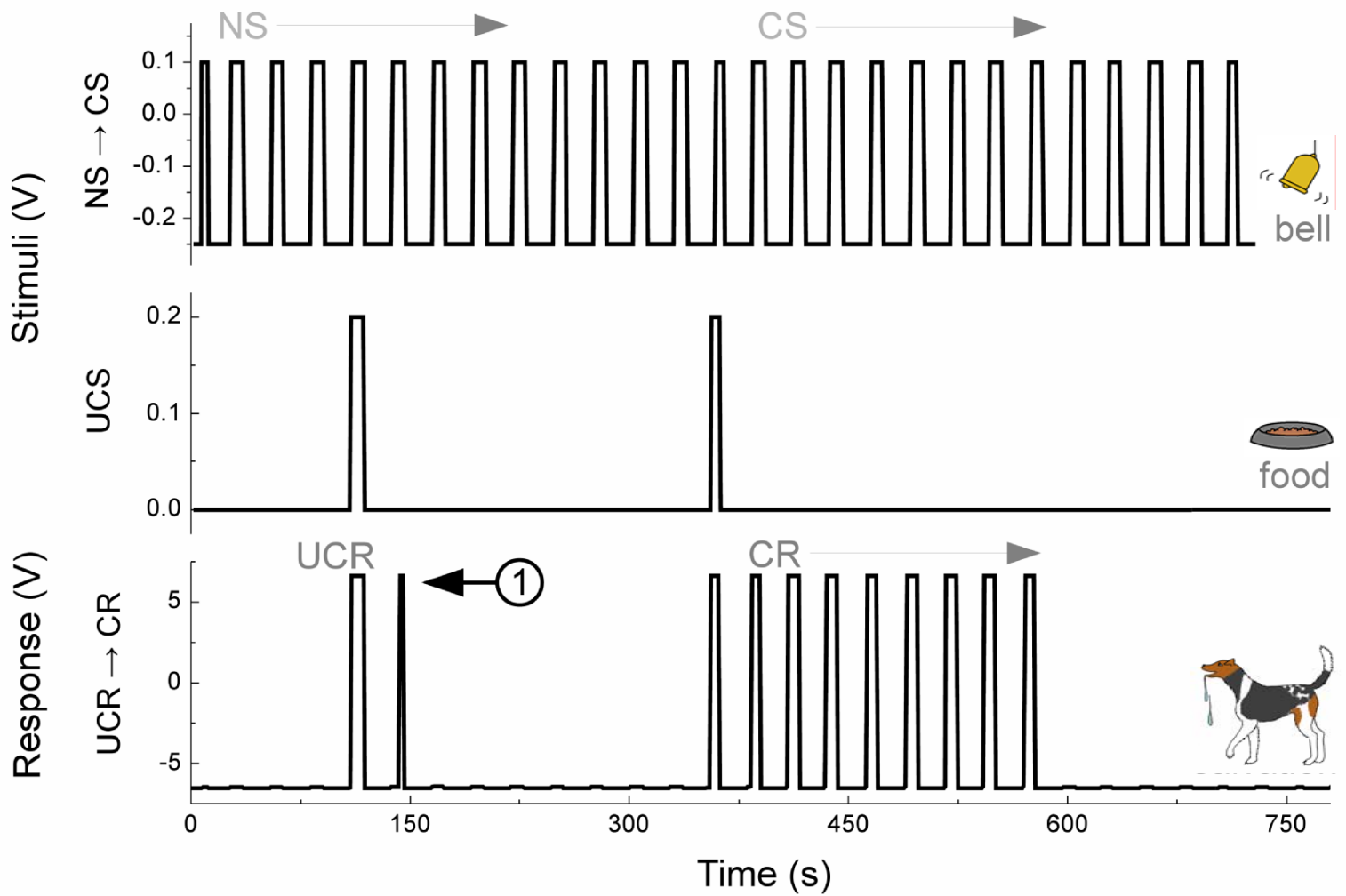
- effective **threshold voltage** of the device

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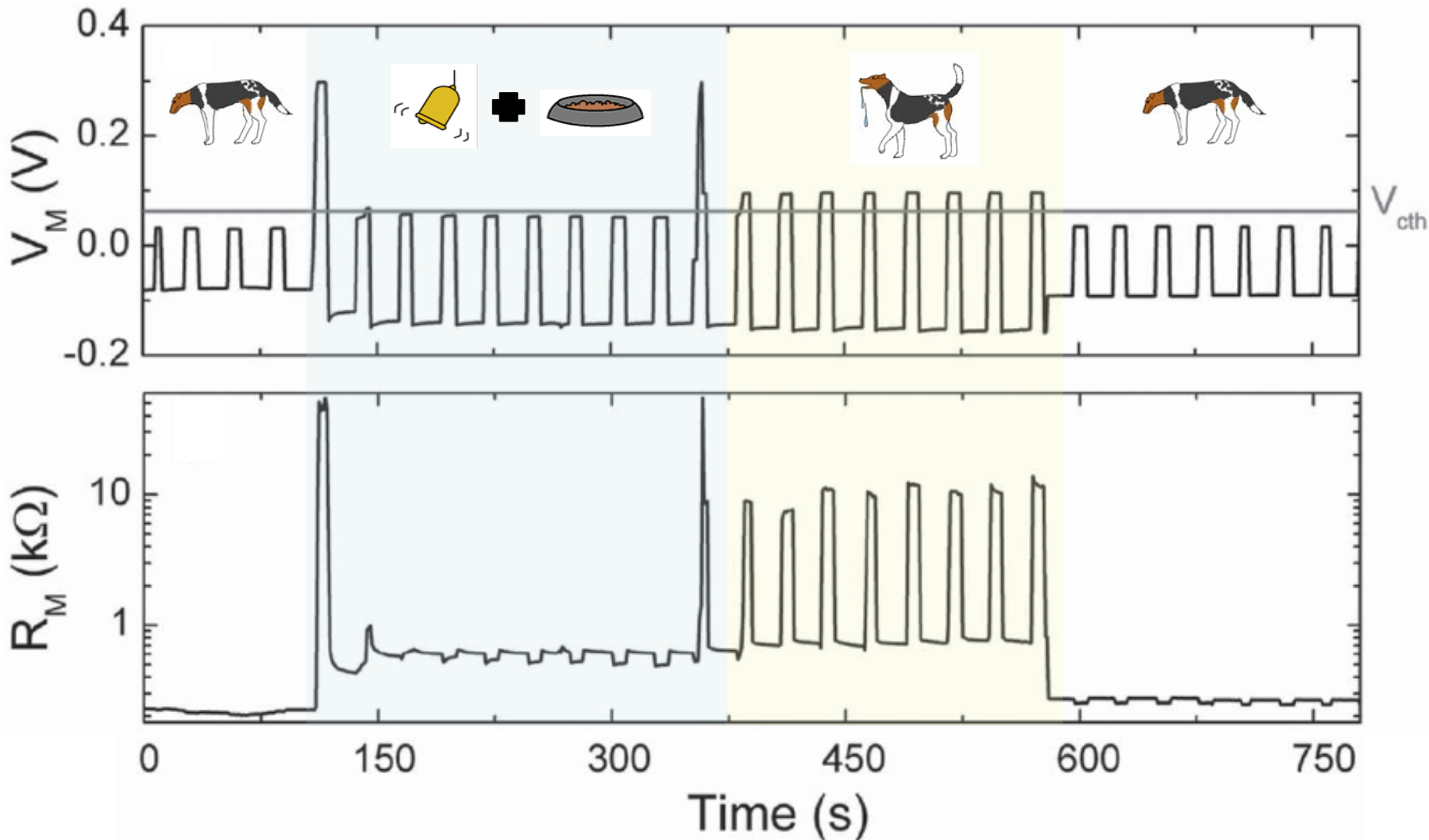
- circuit with threshold voltages for the comparator and mem device

$$V_{\text{bell}} < V_{\text{cth}} \ \& \ V_{\text{food}} > V_{\text{cth}}$$

$$V_{\text{bell}} + V_{\text{food}} > V_{\text{p_mth}} \ (\text{before conditioning}) \ \& \ V_{\text{bell}} > V_{\text{cth}} \ (\text{after conditioning})$$



Synaptic plasticity within the memristive cell



Conclusions



- a single Pt/SiO₂/Ge_{0.3}Se_{0.7}/Cu **memresistive device** implemented in an analog circuitry enables to mimic **implicit learning**.
- for Pavlovian conditioning, different **threshold voltages** for the memresistive device and the comparator were essential.
- effective threshold voltages are **fundamental design parameters**.

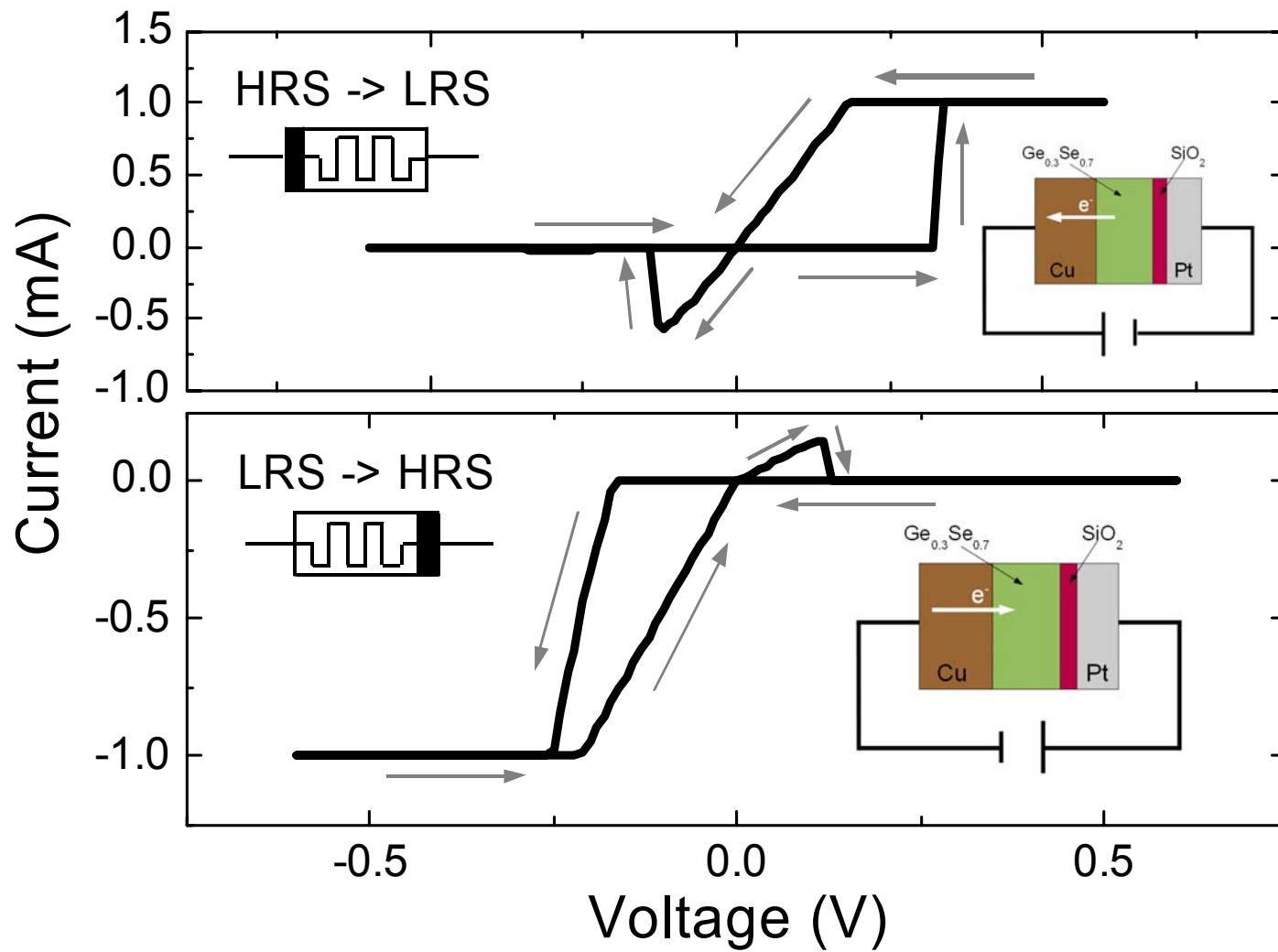
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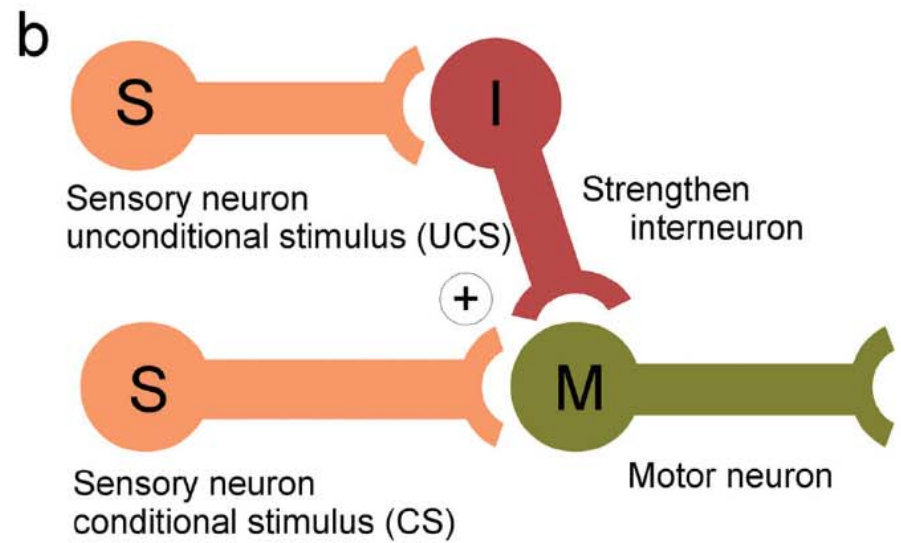
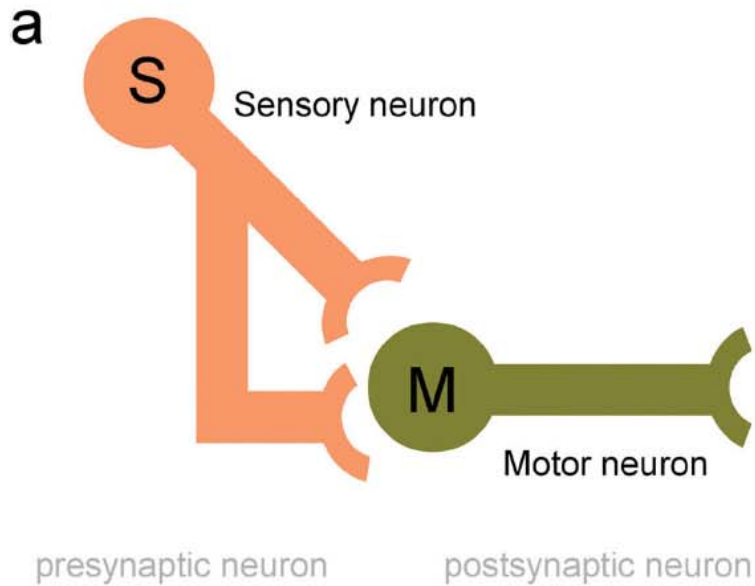
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Thanks for your attention!!!

Back-up





UCS (food)	CS (bell)	Response (before conditioning)	Response (after conditioning)
1	0	1	1
1	1	1	1
0	1	0	1
0	0	0	0

