Circuit Elements With Memory: Memristors, Memcapacitors, and Meminductors

Nanoscale devices, that store information without need for a power source, can be used for non-volatile memory, and promise to allow simulation of learning, adaptation and spontaneous behavior.

By Massimiliano Di Ventra, Yuriy V. Pershin, and Leon O. Chua, *Fellow IEEE*

ABSTRACT | We extend the notion of memristive systems to capacitive and inductive elements, namely, capacitors and inductors whose properties depend on the state and history of the system. All these elements typically show pinched hysteretic loops in the two constitutive variables that define them: current-voltage for the *memristor*, charge-voltage for the *memcapacitor*, and current-flux for the *meminductor*. We argue that these devices are common at the nanoscale, where the dynamical properties of electrons and ions are likely to depend on the history of the system, at least within certain time scales. These elements and their combination in circuits open up new functionalities in electronics and are likely to find applications in neuromorphic devices to simulate learning, adaptive, and spontaneous behavior.

KEYWORDS | Capacitance; dynamic response; hysteresis; inductance; memory; resistance

I. INTRODUCTION

Circuit elements that store information without the need of a power source would represent a paradigm change in electronics, allowing for low-power computation and storage. In addition, if that information spans a continuous range of values, analog computation may replace the present digital one. Such a concept is also likely to be at the origin of the workings of the human brain and possibly of many other mechanisms in living organisms so that such circuit elements may help us understand adaptive and spontaneous behavior, or even learning.

One such circuit element is the memory-resistor (memristor for short), which was postulated by Chua in 1971 by analyzing mathematical relations between pairs of fundamental circuit variables [1]. The memristor is characterized by a relation between the charge and the flux, defined mathematically as the time integral of the voltage, which need not have a magnetic flux interpretation. This relation can be generalized to include any class of two-terminal devices (which are called memristive systems) whose resistance depends on the internal state of the system [2].

Many systems belong to this class, including the thermistor [3] (whose internal state depends on the temperature), molecules whose resistance changes according to their atomic configuration [4], or spintronic devices whose resistance varies according to their spin polarization [5], [6], [23]. Recently, memristive behavior and memory storage have been reported in solid-state TiO_2 thin films [7], [8], where the change in resistance is realized by the ionic motion of oxygen vacancies activated by current flow. Additionally, memristive behavior has been demonstrated in VO_2 thin films, where the memory mechanism is related to the insulator-to-metal transition in these structures [9]. Lastly, memristive behavior has been identified by Di Ventra and Pershin as a possible mechanism in the adaptive behavior of unicellular organisms such as amoebas [10].

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M. Di Ventra is with the Department of Physics, University of California San Diego, La Jolla, CA 92093-0319 USA (e-mail: diventra@physics.ucsd.edu).
Y. V. Pershin is with the Department of Physics and Astronomy and USC Nanocenter, University of South Carolina, Columbia, SC 29208 USA (e-mail: pershin@physics.sc.edu).
L. O. Chua is with the Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720 USA (e-mail: chua@eecs.berkeley.edu).

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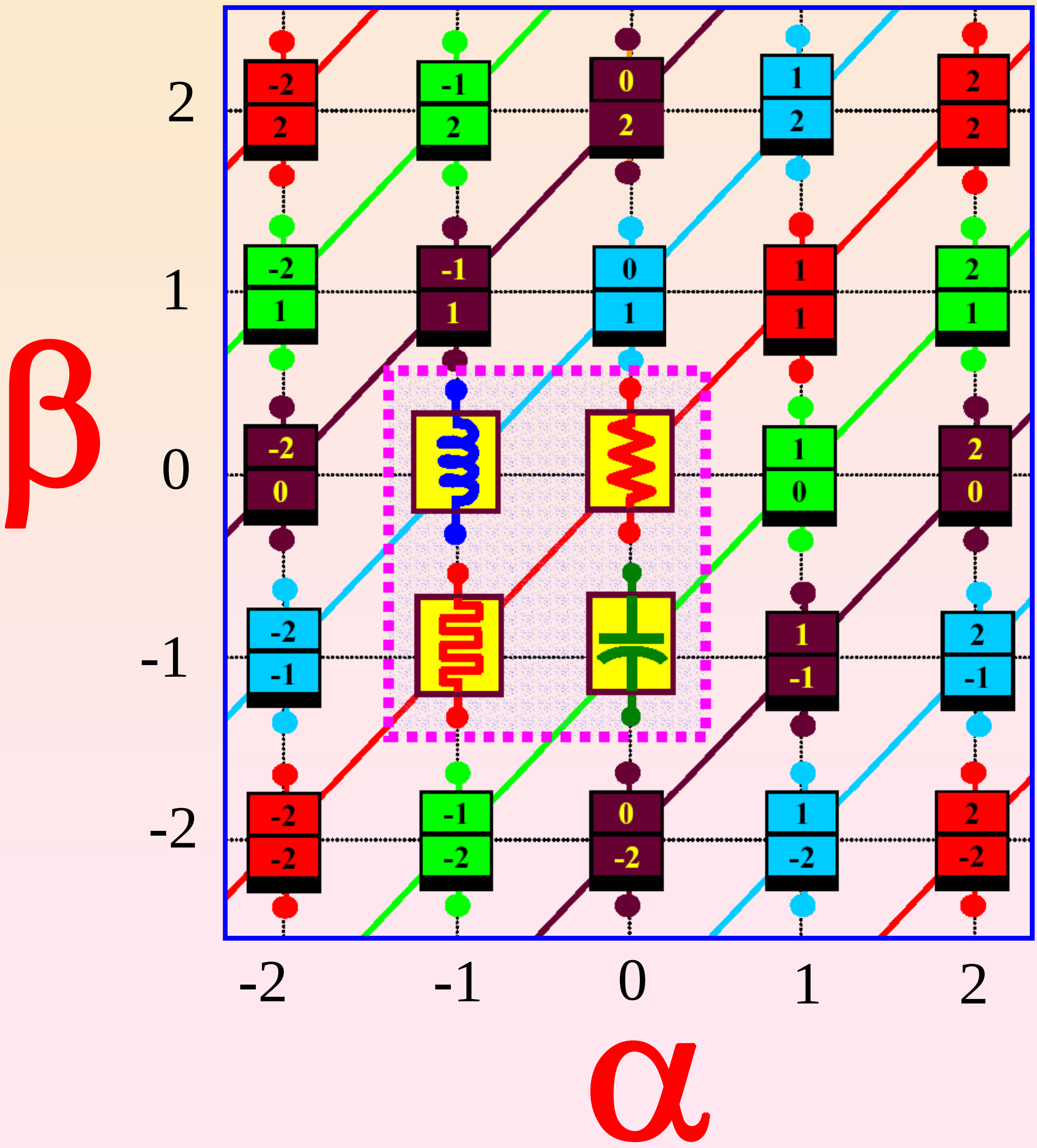
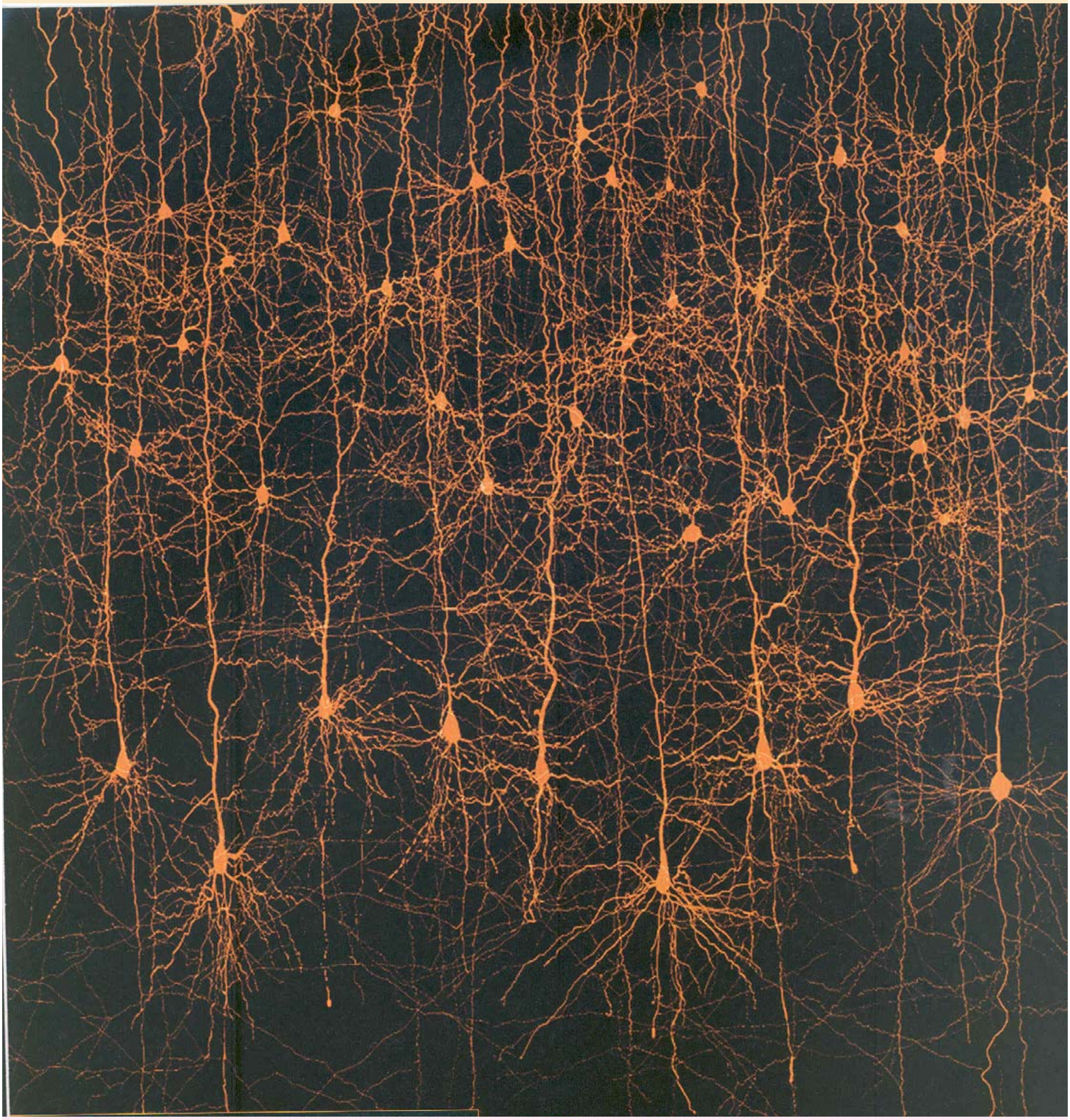
The First 25 Circuit Elements



Brains are made of memristors



Synapses

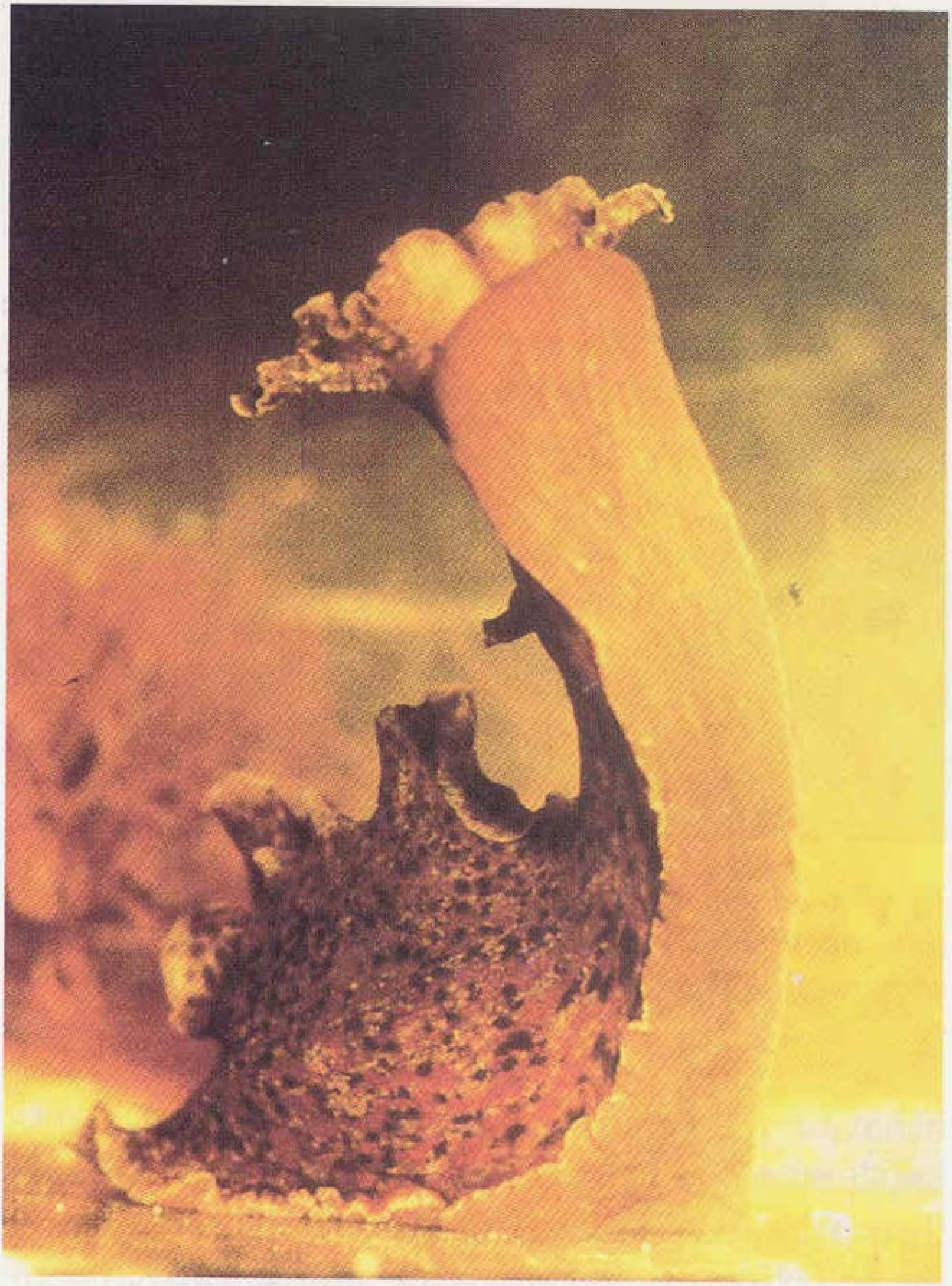
are

memristors !

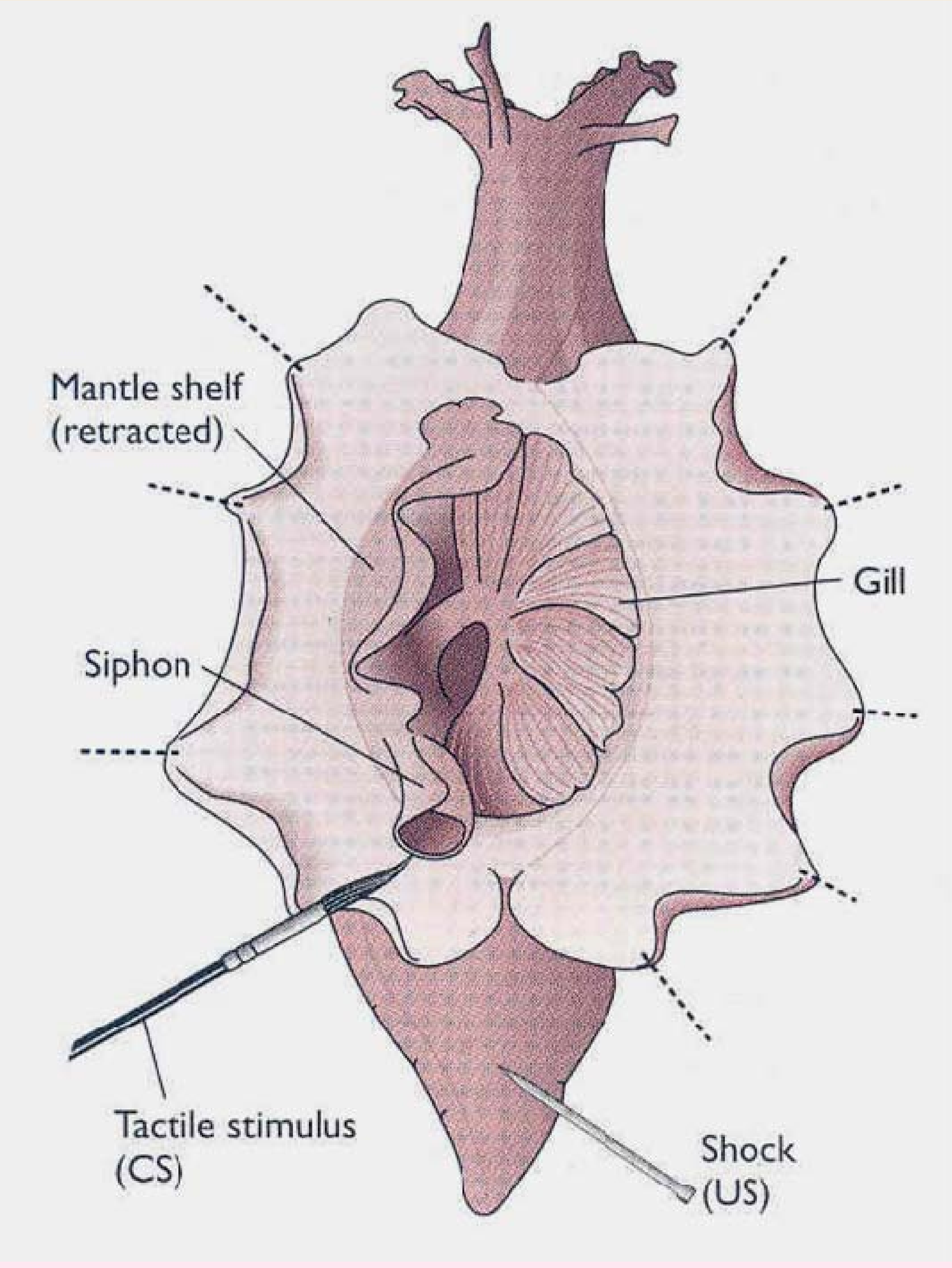
Axons

are made of

memristors



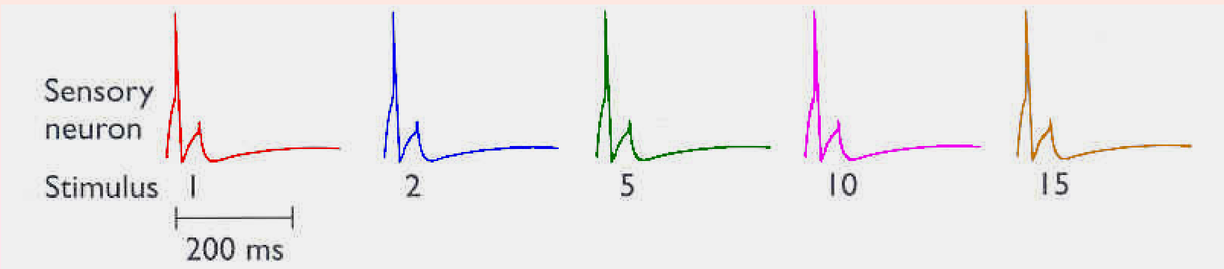
The sea hare (Aplysia californica). *The relatively simple nervous system of this animal makes it amenable to cellular and molecular studies of learning and memory.*


Mantle shelf
(retracted)
Gill
Siphon
Tactile stimulus
(CS)
Shock
(US)

Example of Déjà vu Response of the Aplysia

Response

Excitation



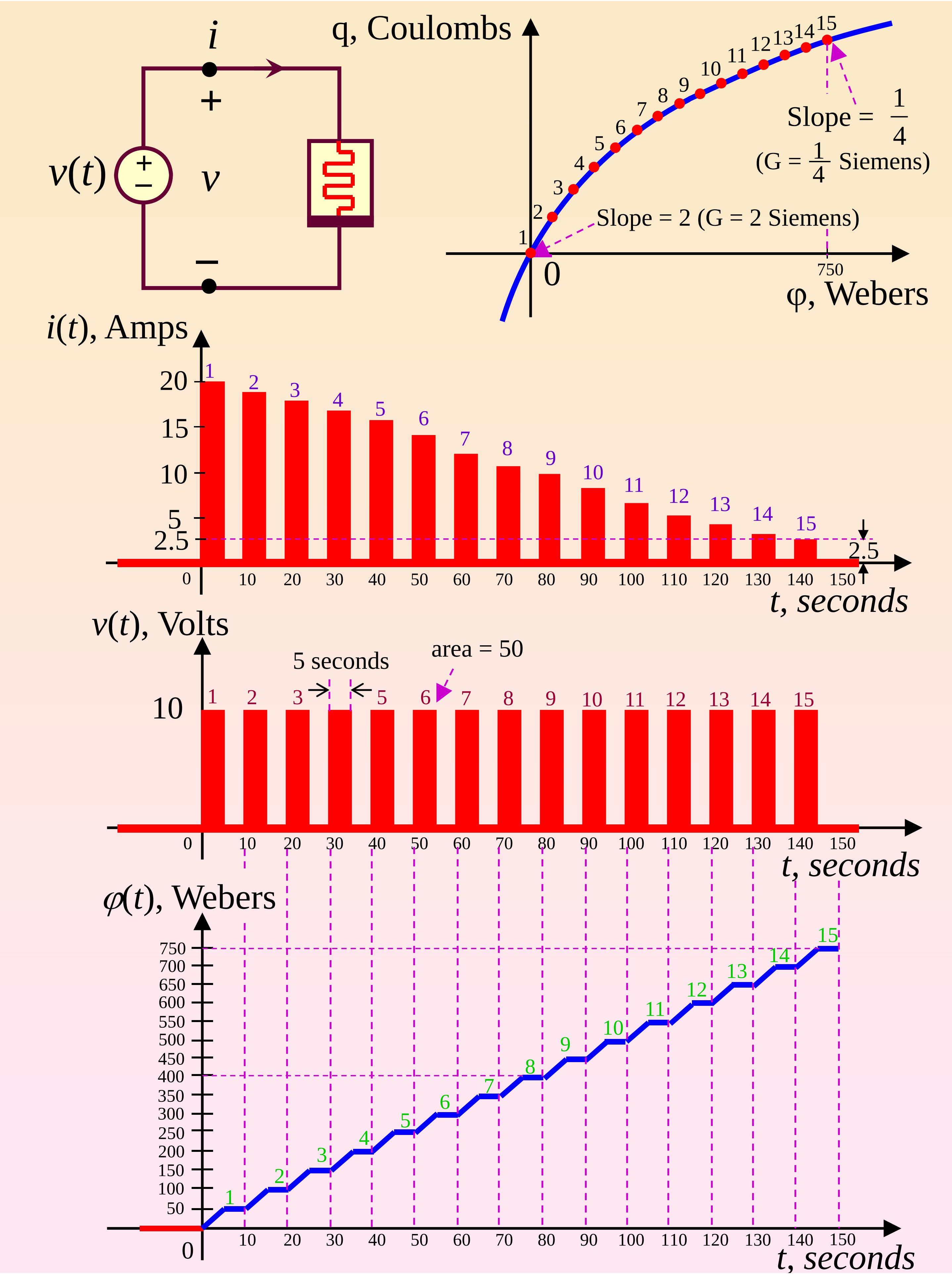
Déjà vu response

Déjà vu response is

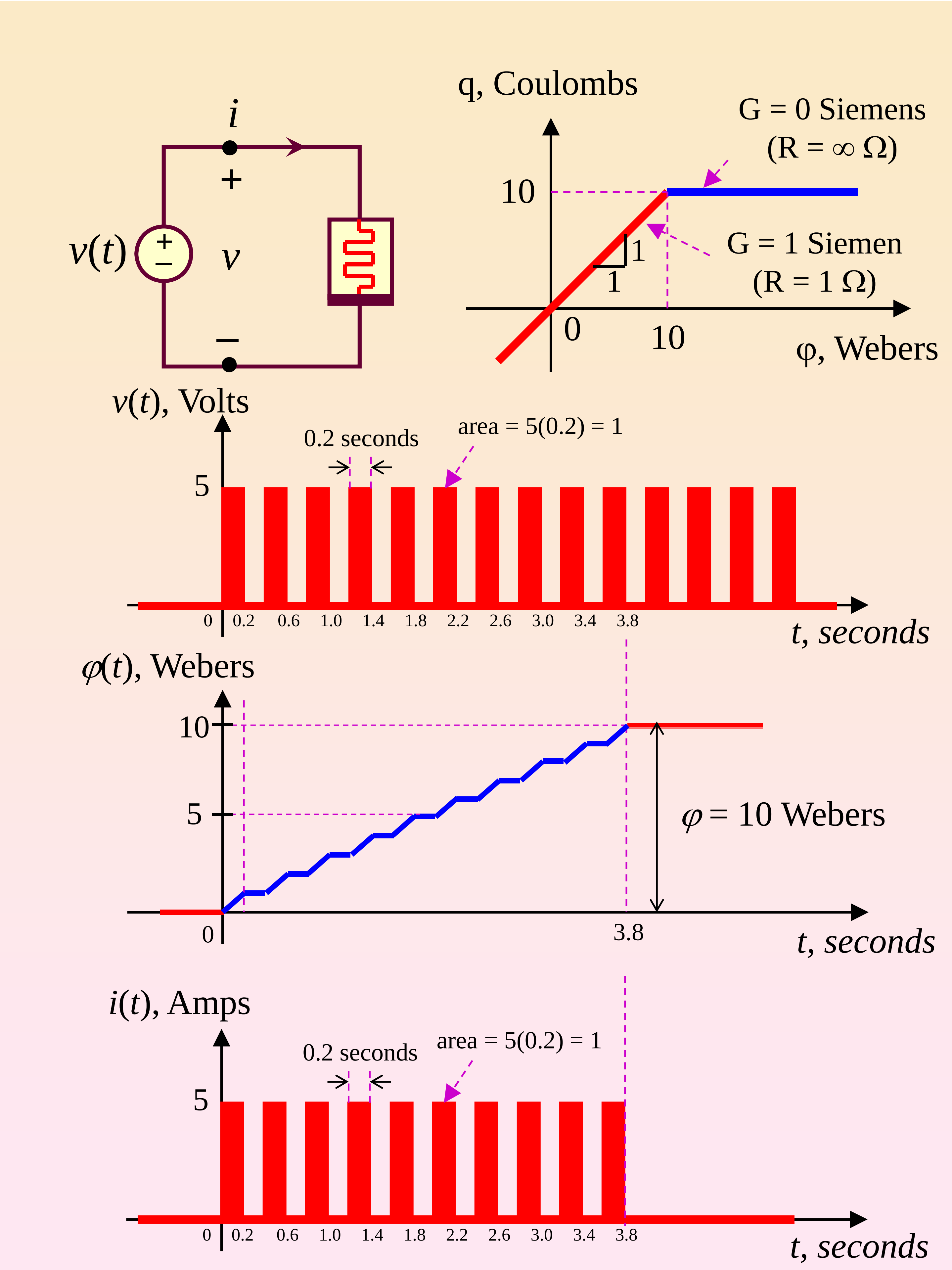
learning to *recognize*

and *ignore* benign

and boring stimulus.



i
v(t)
v
q, Coulombs
φ, Webers
750
Slope = 1/4
(G = 1/4 Siemens)
Slope = 2 (G = 2 Siemens)
i(t), Amps
2.5
t, seconds
v(t), Volts
5 seconds
area = 50
t, seconds
φ(t), Webers
t, seconds

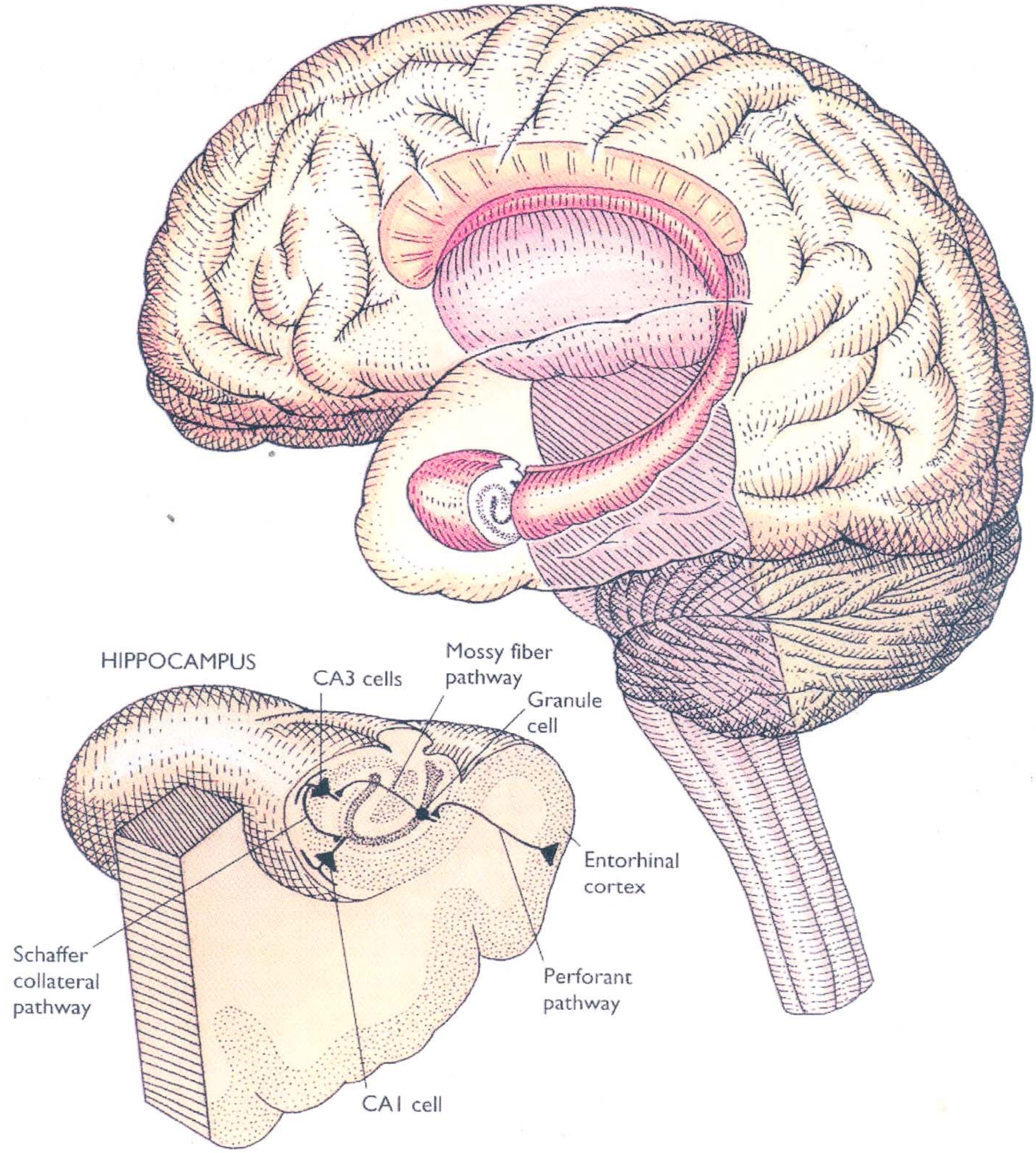


i
v(t)
v
+
−
q, Coulombs
G = 0 Siemens
(R = ∞ Ω)
G = 1 Siemen
(R = 1 Ω)
10
1
1
0
10
φ, Webers
v(t), Volts
0.2 seconds
area = 5(0.2) = 1
5
0 0.2 0.6 1.0 1.4 1.8 2.2 2.6 3.0 3.4 3.8
t, seconds
φ(t), Webers
10
5
0
3.8
φ = 10 Webers
t, seconds
i(t), Amps
0.2 seconds
area = 5(0.2) = 1
5
0 0.2 0.6 1.0 1.4 1.8 2.2 2.6 3.0 3.4 3.8
t, seconds

Henry Molaison, a man without memories, died on December, 2008, aged 82

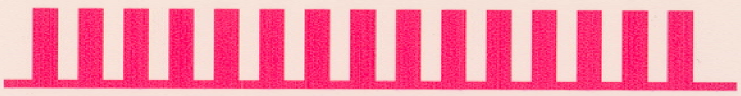
The Man Who Couldn’t Remember

When asked how old he is, HM invariably responds “about thirty.” In HM’s world, *Harry Truman* is always president, *black and white television* is a novelty, and *furniture* made out of chrome and vinyl still seems like a good idea.

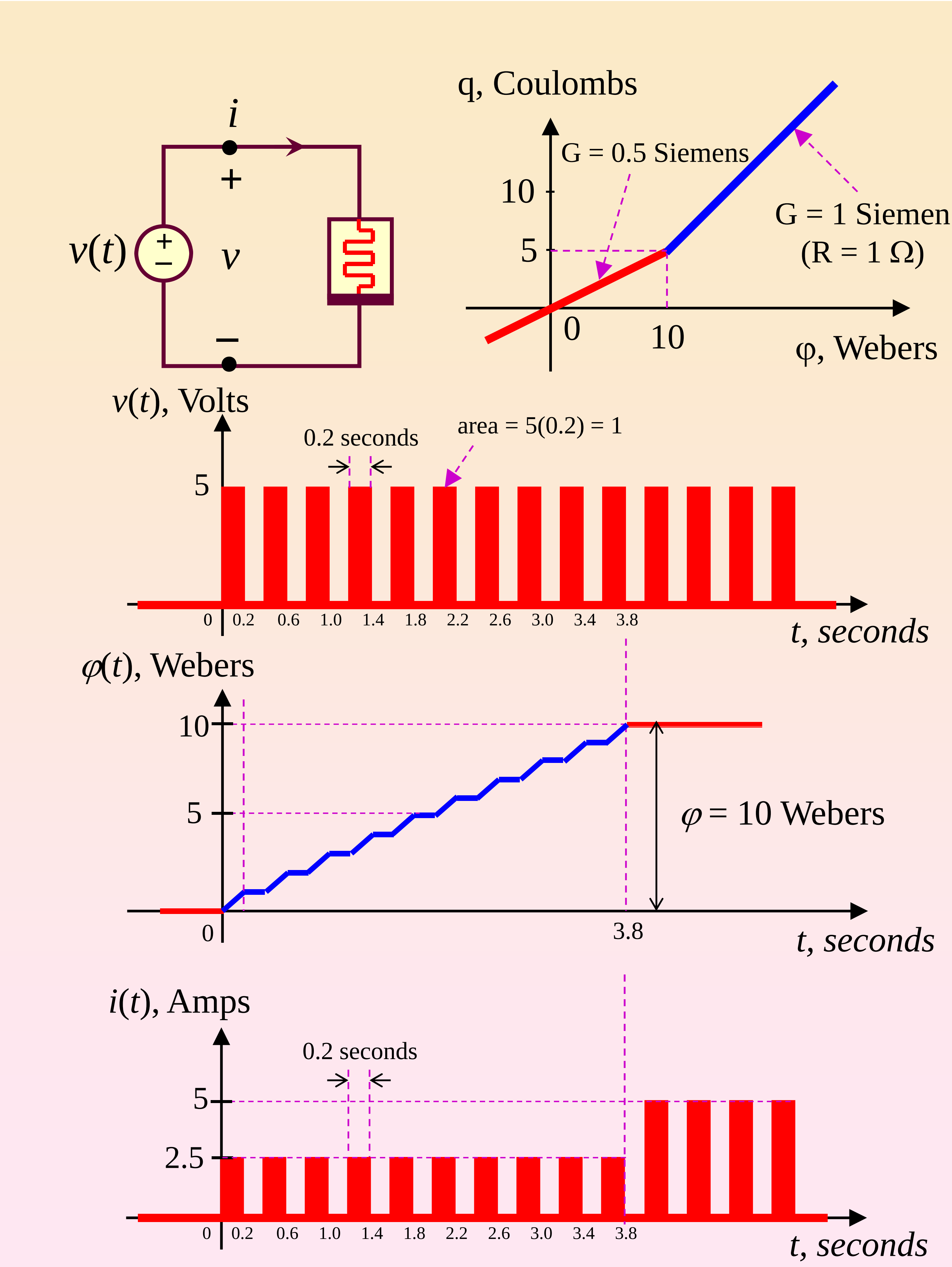

HIPPOCAMPUS
CA3 cells
Mossy fiber pathway
Granule cell
Entorhinal cortex
Schaffer collateral pathway
Perforant pathway
CA1 cell

LTP

In 1973, Bliss and Lomo found that a ***tetanus*** (a short high-frequency pulse train)



excitation at the hippocampus enhances the *synaptic* response to a single input pulse.



i
+
v(t)
v
−
q, Coulombs
G = 0.5 Siemens
10
5
0
10
G = 1 Siemen
(R = 1 Ω)
φ, Webers
v(t), Volts
0.2 seconds
area = 5(0.2) = 1
5
0
0.2
0.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
t, seconds
φ(t), Webers
10
5
0
3.8
φ = 10 Webers
t, seconds
i(t), Amps
0.2 seconds
5
2.5
0
0.2
0.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
t, seconds

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Amoebae Anticipate Periodic Events

Tetsu Saigusa
Graduate School of Engineering, Hokkaido University, N13 W8, Sapporo 060-8628, Japan

Atsushi Tero* and Toshiyuki Nakagaki†
Research Institute for Electronic Science, Hokkaido University, Sapporo, 060-0812, Japan

Yoshiki Kuramoto
Department of Nonlinear Science, ATR Wave Engineering Laboratories,
2-2-2 Hikaridai, Seika-Cho, Soraku-gun, Kyoto 619-0288, Japan
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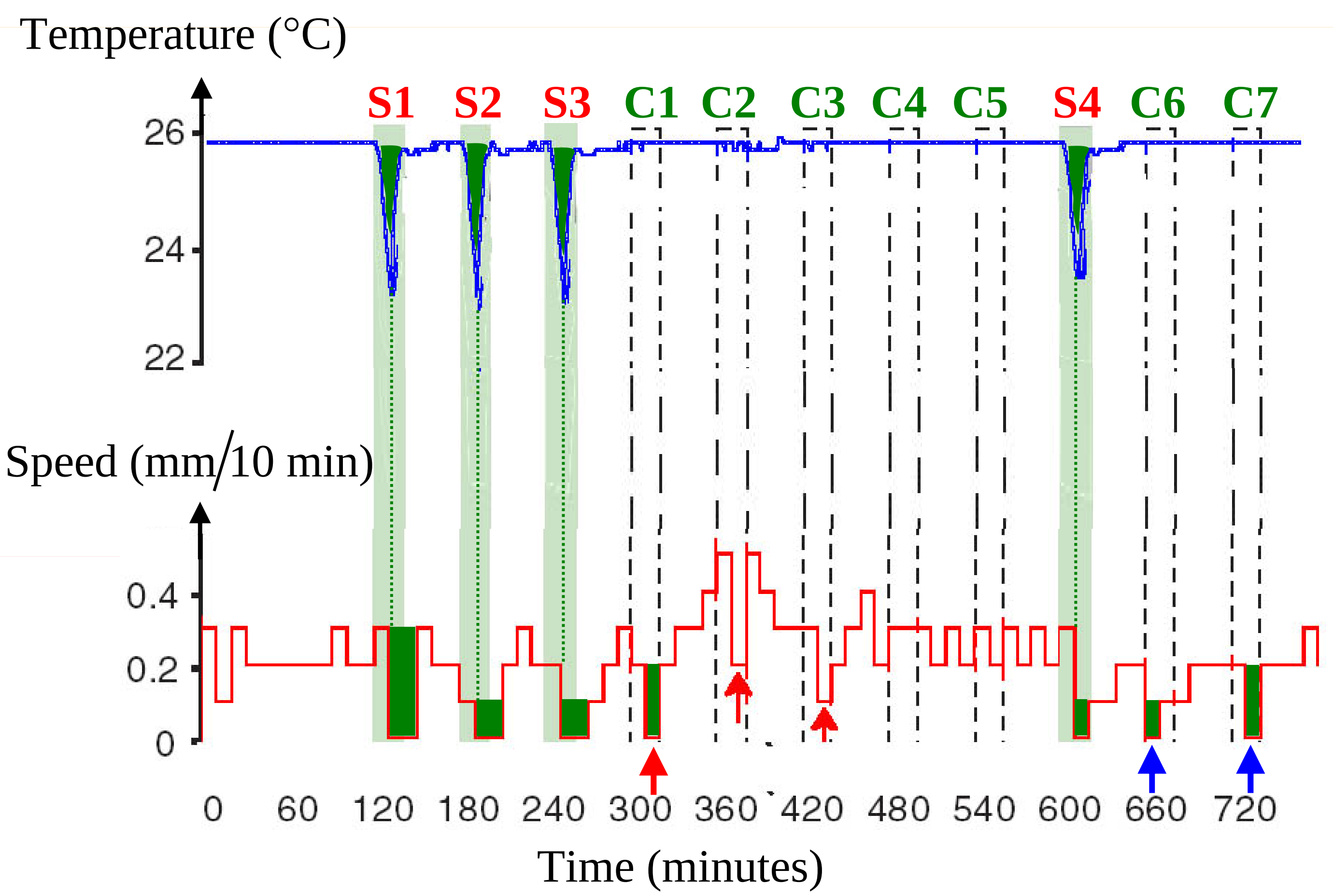
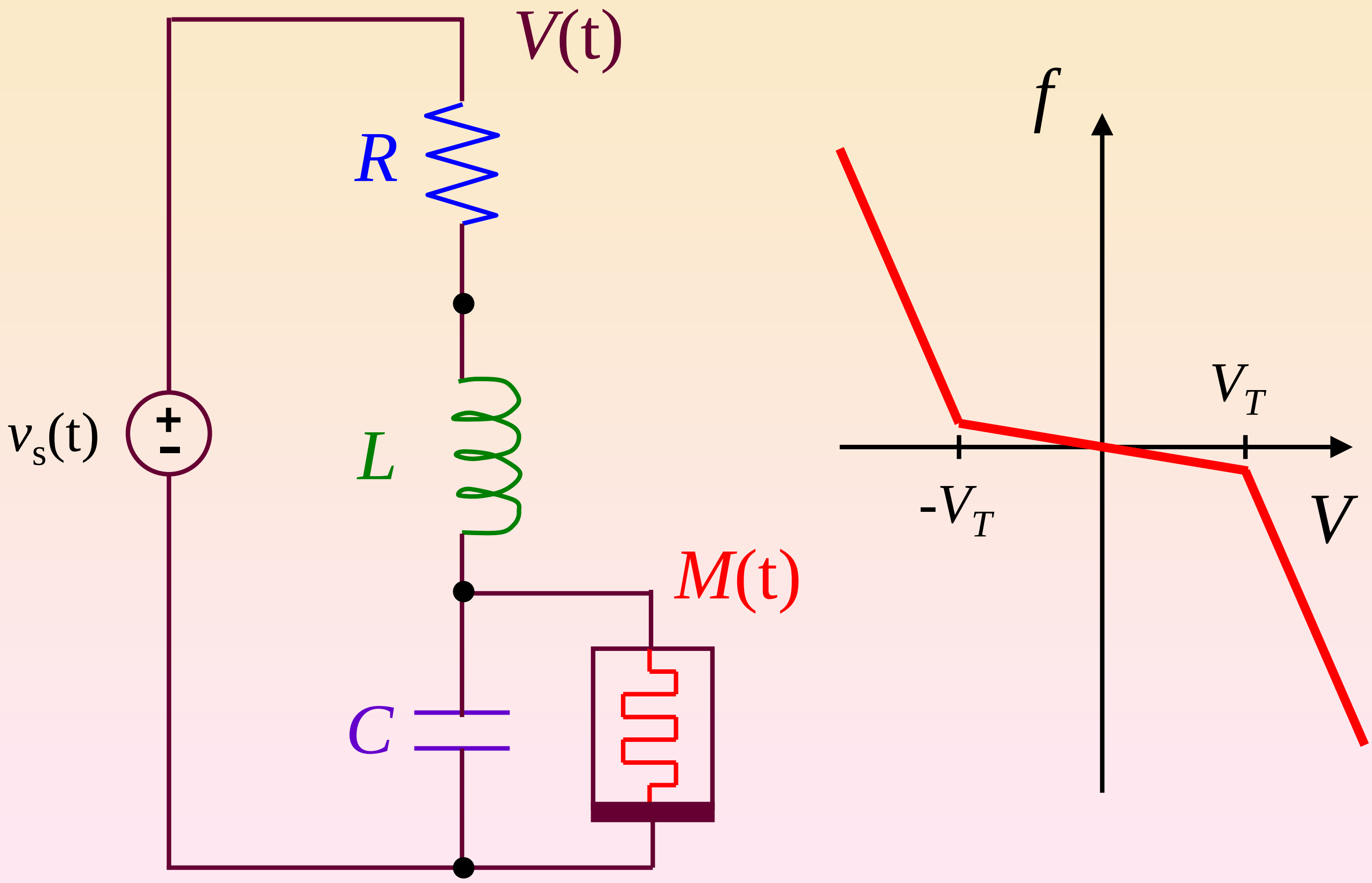
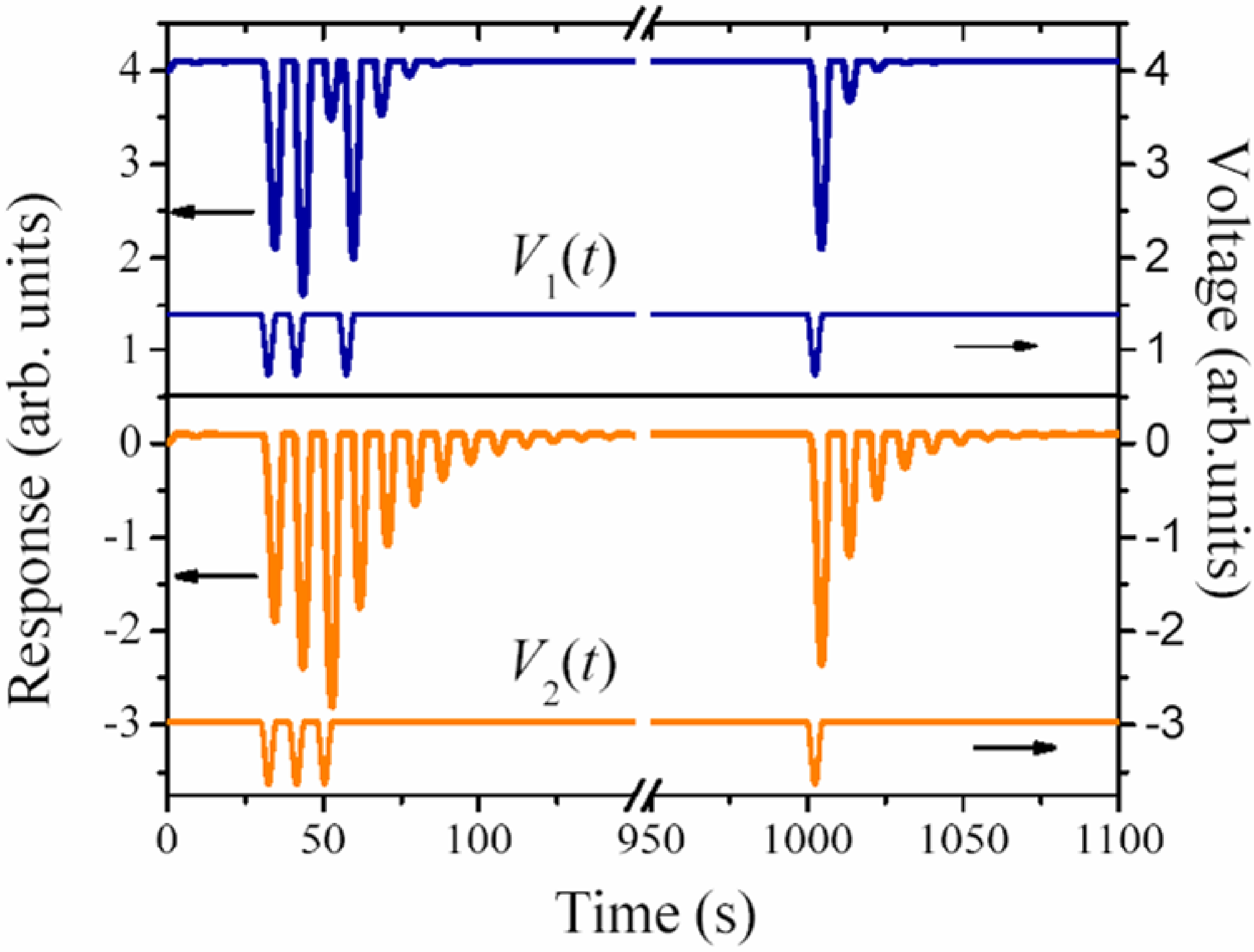


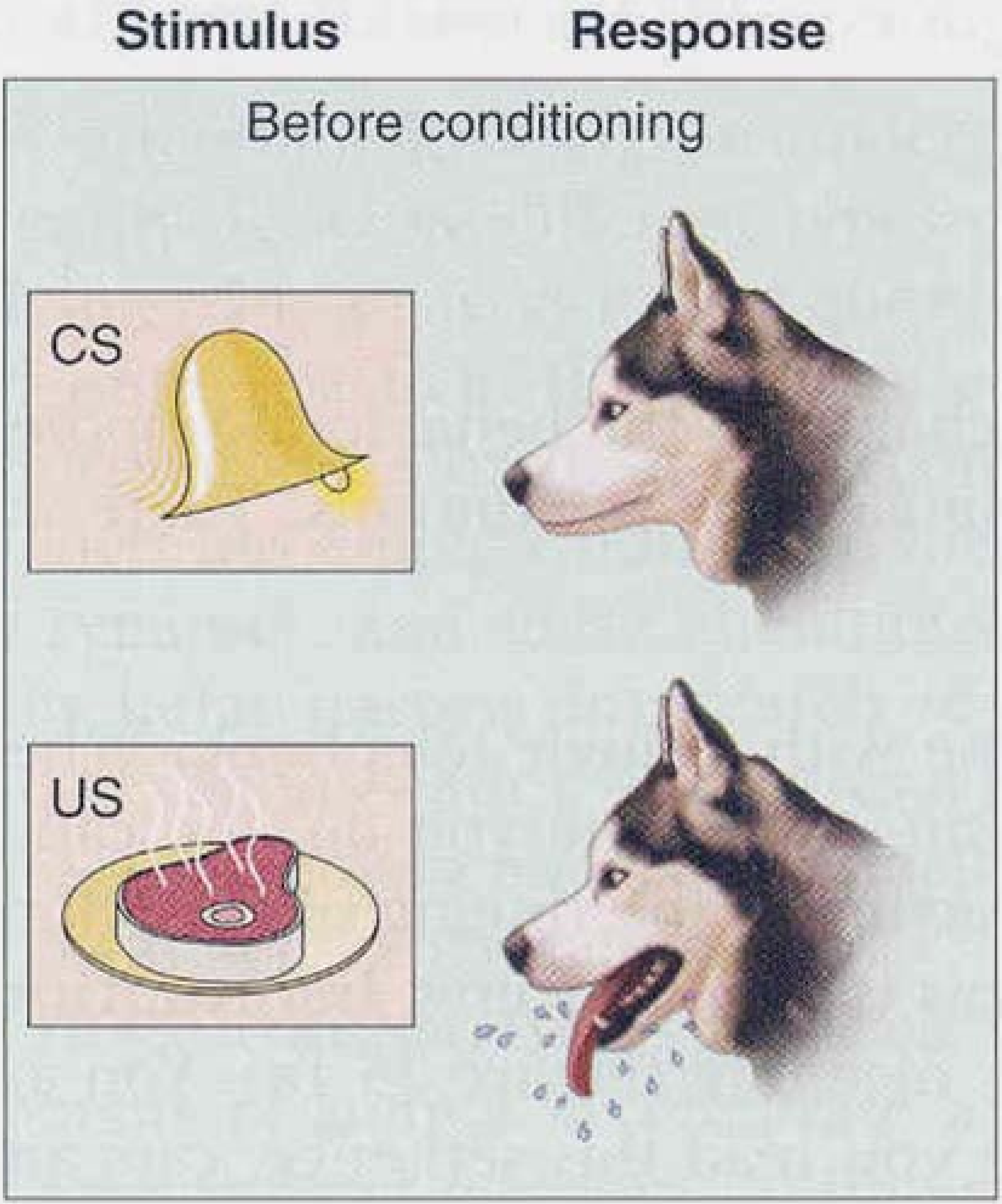
Temperature (°C)
S1
S2
S3
C1
C2
C3
C4
C5
S4
C6
C7
26
24
22
Speed (mm/10 min)
0.4
0.2
0
0
60
120
180
240
300
360
420
480
540
600
660
720
Time (minutes)

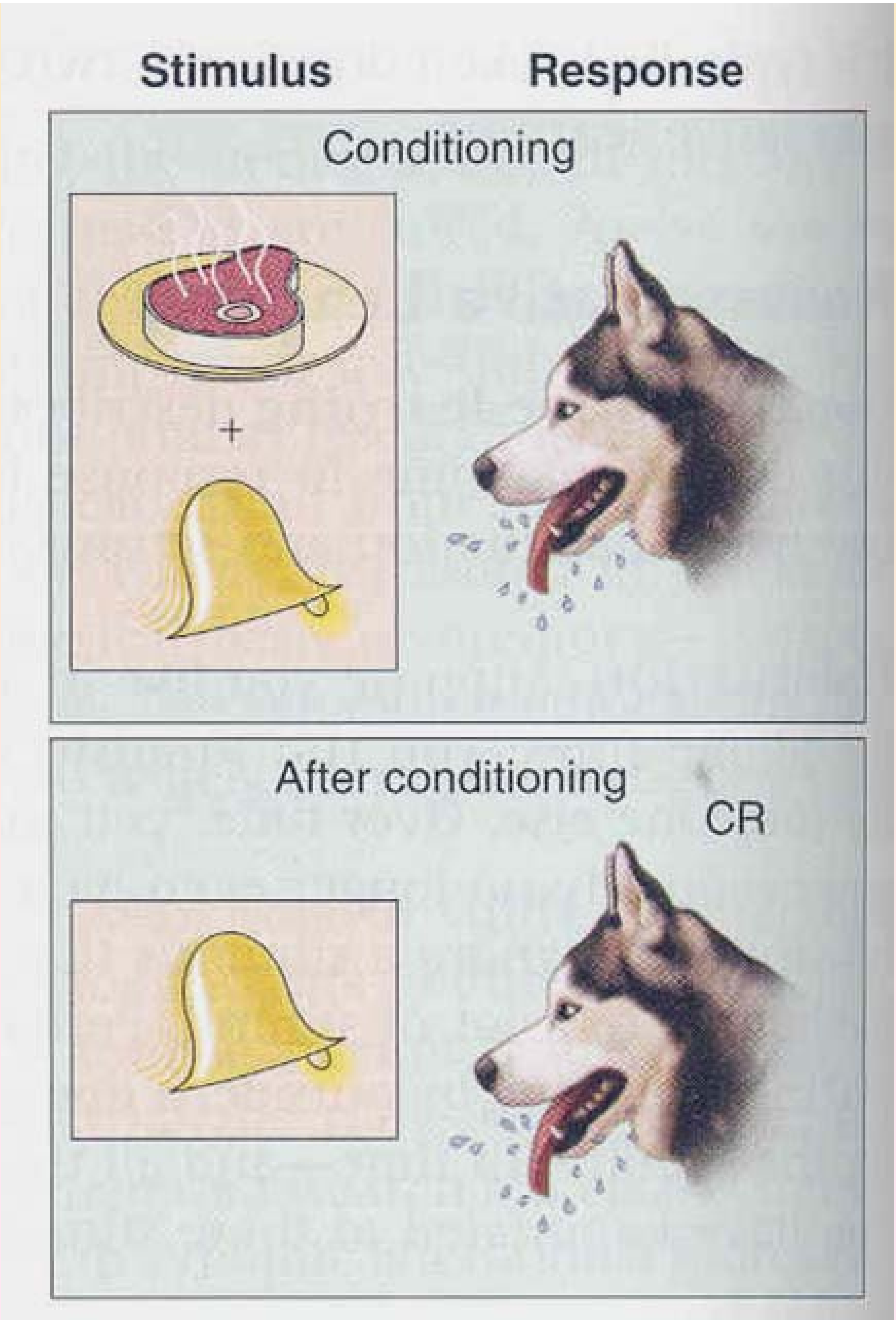


V(t)
R
L
C
M(t)
vs(t)
f
V
VT
-VT



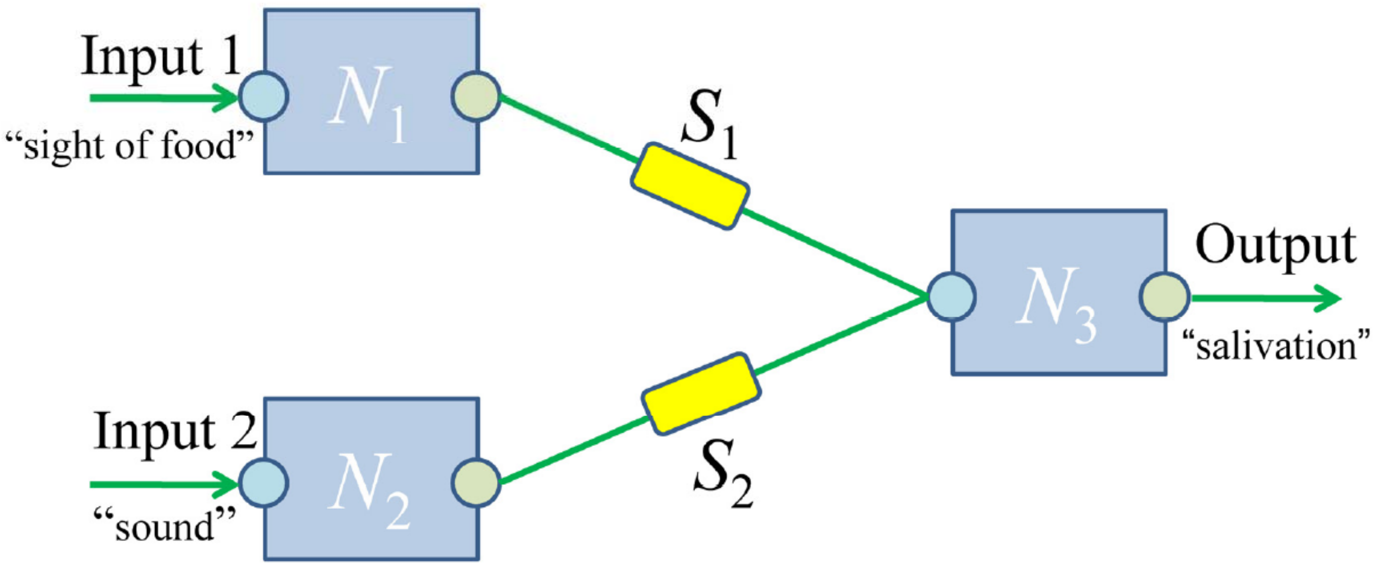
Response (arb. units)
Voltage (arb.units)
Time (s)
$V_1(t)$
$V_2(t)$
4
3
2
1
0
-1
-2
-3
0
50
100
950
1000
1050
1100


Stimulus
Response
Before conditioning
CS
US

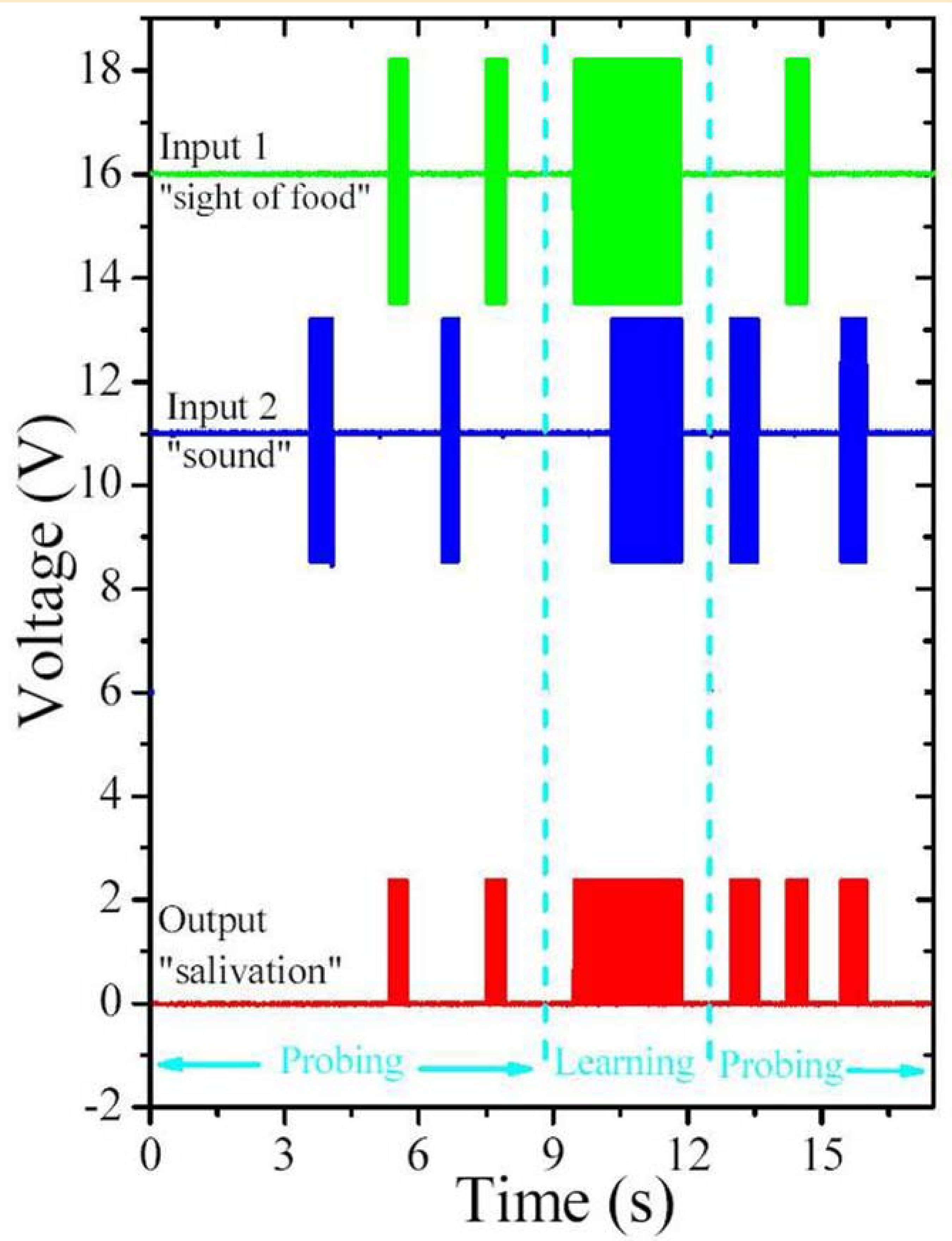

Stimulus
Response
Conditioning
+
After conditioning
CR

Experimental Demonstration of Associative Memory with Memristive Neural Networks

Yuriy V. Pershin and Massimiliano Di Ventra



Input 1
"sight of food"
N_1
S_1
Input 2
"sound"
N_2
S_2
N_3
Output
"salivation"


Voltage (V)
Time (s)
Input 1
"sight of food"
Input 2
"sound"
Output
"salivation"
Probing
Learning
Probing
18
16
14
12
10
8
6
4
2
0
-2
0
3
6
9
12
15

Long Range Memristive Circuit Potentials

Memristive Circuits has the potential of creating a new market for *intelligent* hardware capable of *adaptive interaction* with a changing and uncertain environment. The demand for cheap, energy-efficient, *intelligent hardware that could learn* would make such memristor circuitry *ubiquitous*.

Greg Srider
hp, 2009

A circuit element that could store information without the need for a power source would represent a momentous shift in electronics, enabling a new generation of low-power computers and storage devices as well as a new class of neuromorphic devices that simulate learning.