Exploiting Memristors and the Local Activity Principle

(FA 9550-18-1-0016)

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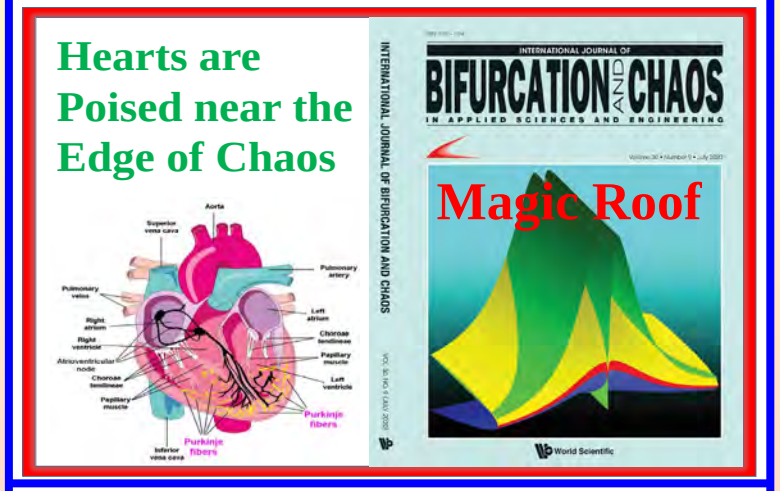
AFOSR Program Review:
Computational Cognition and Machine Intelligence Program
(6-8 October, 2020, Arlington, VA)

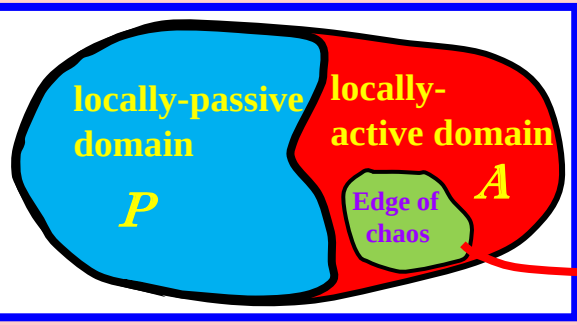
Exploiting Memristors and the Local Activity Principle

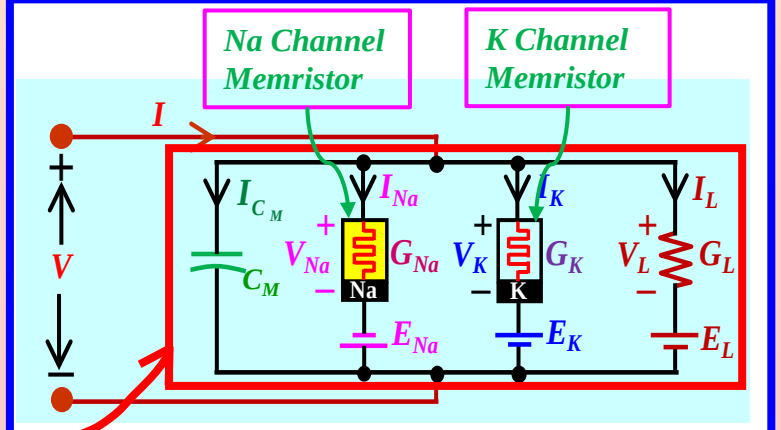
Leon Chua, University of California, Berkeley

- **Objectives:**
  - Revise the classic *Hodgkin-Huxley model* by modelling all *ion channels* with *memristors* and fine tuning their parameters.
  - Exploit *edge of chaos* for designing brain-like machines for emulating higher brain functions.
- **Approach:**
  - Exploit the nonlinear dynamics of *memristors*.
  - Apply the new universal *principle of local activity* and its pearl, the *edge of chaos*.
- **DoD Benefits:**
  - The *Memristive Hodgkin-Huxley model* can be used to design cognitive neuro-morphic systems for pattern recognition and associative memory.
  - The *edge of chaos* paradigm can be used to optimize agile and intelligent control systems for fighter jets and missiles.
- **Progress:**
  - We have derived the *edge-of-chaos* domain of the *Hodgkin-Huxley model* where *action potential*, *spiral waves*, and *chaotic riddled basin dynamics* can emerge.
  - We are designing compact and accurate *memristor* circuits for executing the computation-intensive dot-product operations for *deep learning*.



Edge of Chaos is the tiny Goldilocks zone where ***complex*** phenomena may emerge





Memristive Hodgkin-Huxley Model

List of Project Goals

1. Develop **memristor circuit models** of **time-varying conductances** exhibited by biological nano structures, such as **synapse** and **ion channels**.

2. Develop an in-depth characterization of the **nonlinear dynamics** of the ***Hodgkin-Huxley*** neuron at ***sub-critical*** *and* ***super-critical*** ***Hopf Bifurcation.***

3. Formulate the ***missing law of thermodynamics*** which **enables** ***non-monotonic entropy functions*** via the ***local activity principle***, thereby enabling formulation of patterns and structures, as well as high-speed information processing of ***big data***.

4. Investigate the exotic regime of **Edge of Chaos** **to** ***uncover*** the nonlinear dynamical mechanism responsible for the abrupt emergence of **the action potential (spikes),** and the unleashing of powerful mechanical forces, such as ***micro catapults***, as well as other ***extreme events*** such as earthquakes, tsunami, stock market crashes, etc.

Progress Towards Goals (or New Goals)

For over 60 years many distinguished researchers and scientists including Nobel Laureates ***B.D. Josephson*** (1973), ***N.F. Mott (1977)***, ***A. L. Hodgkin*** and ***A. F. Huxley*** (1961), and ***J. G. Bednorz*** (1987), had sought in vain to identify the mathematical mechanism and principle for devices exhibiting non-volatile memories, and time-dependent hysteretic dynamics. In particular, no one could explain why voltage pulses, or current pulses, can be used to turn on, or turn off, 2-terminal ***memristive*** devices, made from physically, or chemically-unrelated materials, including organic and inorganic elements and compounds. Many unexplained paradoxes and enigmas had remained unsolved until the recent publication of the following definitive paper:

L. Chua, "**Five non-volatile memristor enigmas solved**,"
Applied Physics A, July 25, 2018 (43 pages)

The above paper is destined to be a standard reference in future textbooks, as evidenced by the numerous invited keynote presentations that the PI (Leon Chua) had given since July 2018, including a high-profile **EDS Webinar** presented on September 26, 2018 (organized by the IEEE Electron Devices Society), and a keynote lecture at the ***Europe Supercomputing Frontier*** in Warsaw, Poland on March 11-14, 2019.

Presentation Slides

239-Year Old Mystery Resolved !

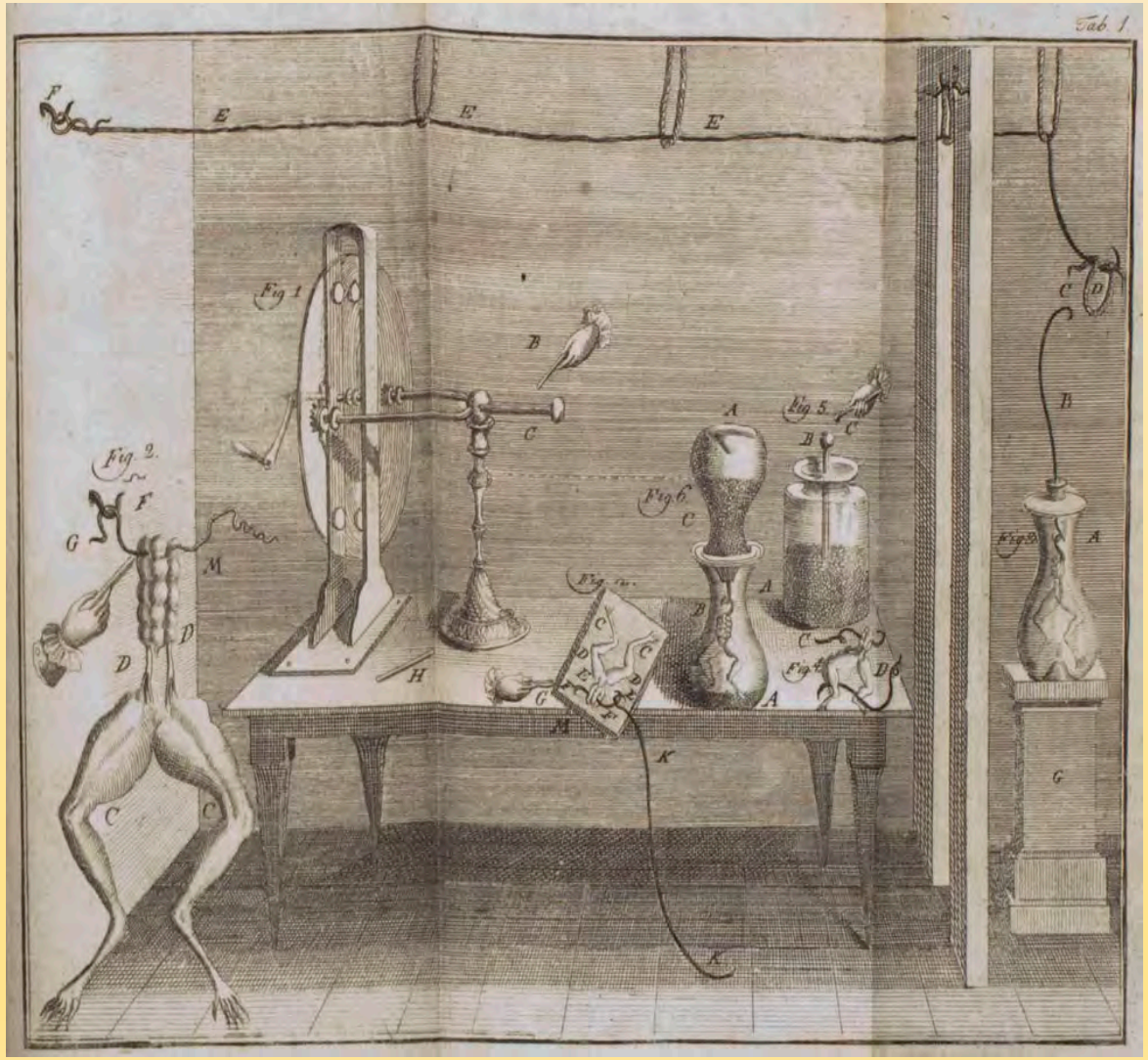
The **all or none phenomenon** was discovered by ***Luigi Galvani*** in ***1781***, the **father of electrophysiology**, via an accidental contact he made between the **nerve** from the **spinal cord** and the **muscle fiber** from a freshly skinned **frog leg**.

It's been **239 years** since **Galvani's discovery** and no one has succeeded to explain rigorously, the physical and nonlinear dynamical mechanism which give rise to the **action potential**.

We have finally proved **analytically** and **quantitatively**, that the **all or none phenomenon** is a direct consequence of the

Edge of Chaos Criterion

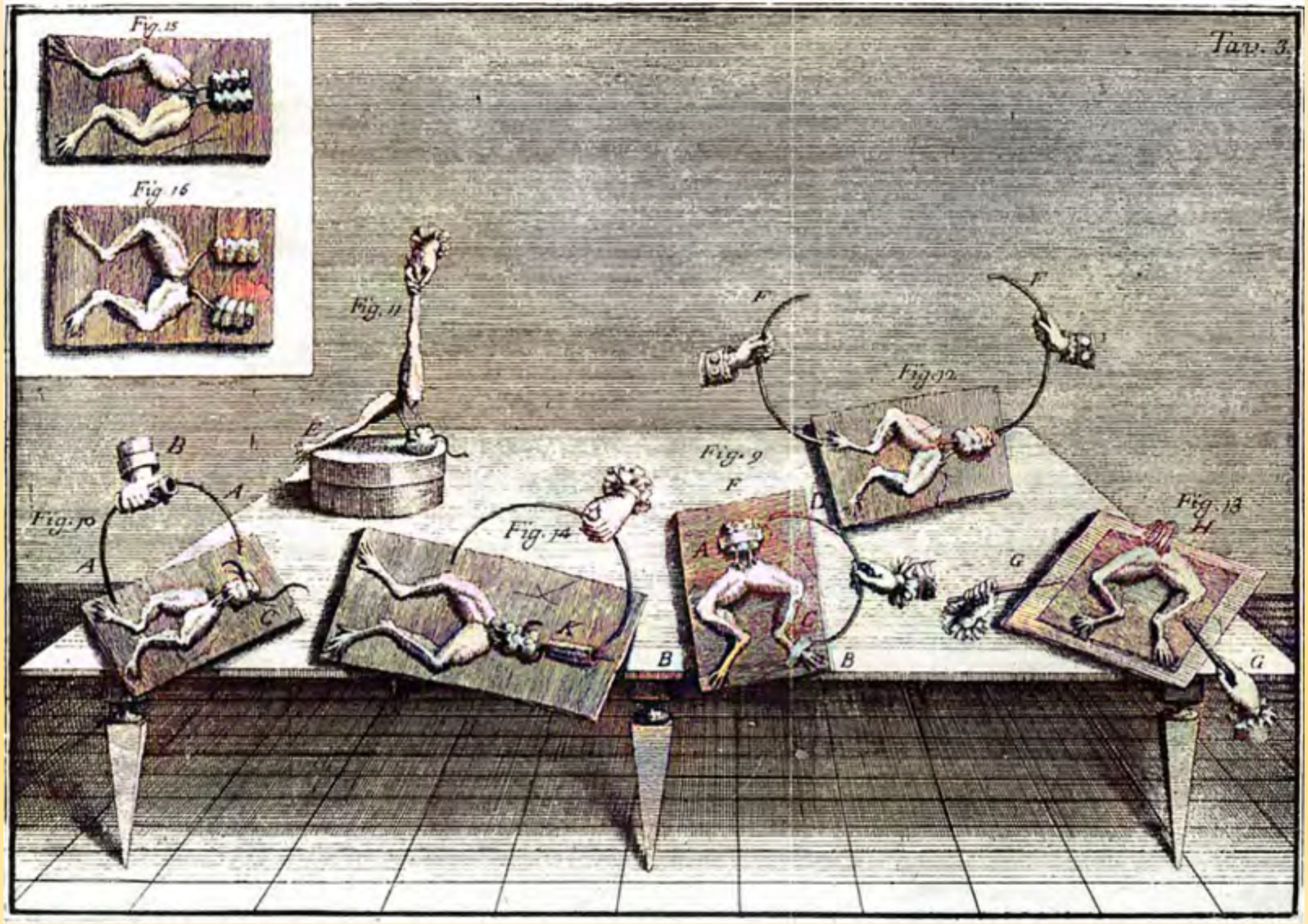
, the **pearl** of the ***local activity principle***.



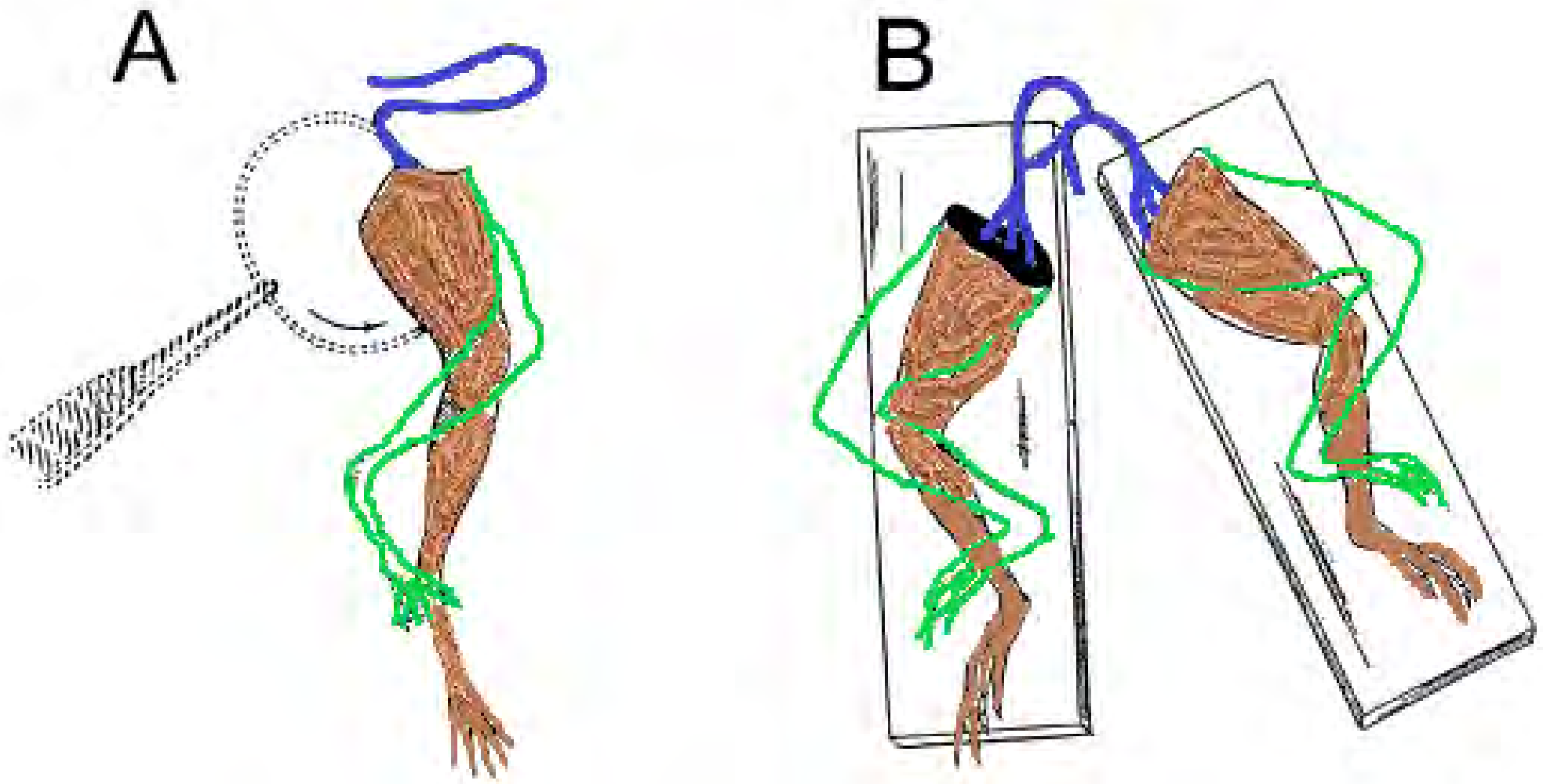
January 26, 1781

Luigi Galvani

1737-1798


Tav. 3.
Fig. 15
Fig. 16
Fig. 11
Fig. 10
Fig. 14
Fig. 9
Fig. 12
Fig. 13

LUIGI GALVANI AND ANIMAL ELECTRICITY



Animal Electricity

discovered by

Luigi Galvani

in 1791

Significance of Galvani's Discovery and Intuition

I. **Galvani's Animal Electricity** is the foundation of **Electrophysiology**

II. **Galvani's** intuition of an "***Extremely mobile principle***" is the ***Principle of Local Activity***

On the basis of these findings (and of the results of a multiplicity of studies in which experimental conditions were varied in an amazing number of ways), Galvani came to the conclusion that some form of intrinsic electricity was present in the animal, and that connective nerve and muscle together, by means of conductive materials, induced contractions by allowing for the flow of this internal electricity. Galvani will refer to such intrinsic electricity as "animal electricity" (*animal electricitas*).

Therefore, at some moment of his intellectual elaboration, Galvani became fully convinced that the "extremely mobile principle" necessary to explain the contractions in the spark experiment is in fact of an electrical nature.

Macro Piccolino, Animal electricity and the birth of electrophysiology
Brain Research Bulletin, vol. 46, no.5, 381-407, **1998**

Galvani's Vision of
Action Potential

In Galvani's view, similar to the physical device, the animal is indeed capable of storing the electrical fluid and to maintain it in a state of "disequilibrium," ready to be set in motion by means of the ***conductive arc*** (or follow other external or internal influences). In the case of the physical device, the motion of the electric fluid is capable of producing a series of effects (e.g., sparks, luminescence, "electrical wind," heating) . In an analogous way, ***the motion of the animal electricity from the internal to external surface of the muscle, through the nerve fibers, would normally produce muscle contraction.***

AF-9 b

Macro Piccolino
Animal electricity and the birth of electrophysiology
Brain Research Bulletin, vol. 46, no.5, 381-407, **1998**

Galvani's Irritability Property

Edge of Chaos

Galvani was well aware of the ***doctrine of "irritability,"*** one of the most important conceptual elaborations of 18th century physiology. Implicit in the notion of ***irritability*** was the idea that the way an organism reacted to an external influence was an expression of its ***internal functional organization***, and was in some way independent of the specific nature of external influence that acted as an "***irritation***." According to ***Galvani***, in the framework of ***doctrine of irritability***, external electricity was acting as an ***excitatory stimulus***. (as a trigger we would say now) for the contraction, and not as the direct "efficient" cause of the observed phenomena.

Galvani's suspicion that external electricity was setting into motion some specific internal force responsible for the contraction was supported by the results of other experiments in which he established how small was the minimal quantity of electrical force of an effective stimulus. Contraction could be obtained by using a Leyden jar almost completely discharged so as to be undetectable with the most sensitive electroscope.

How could it be that such a tiny electrical force would produce muscle contraction if it were not setting in motion some internal force, and commoting some extremely ***mobile principle*** existing in nerves ***excites the action*** of the nervo-muscular force?

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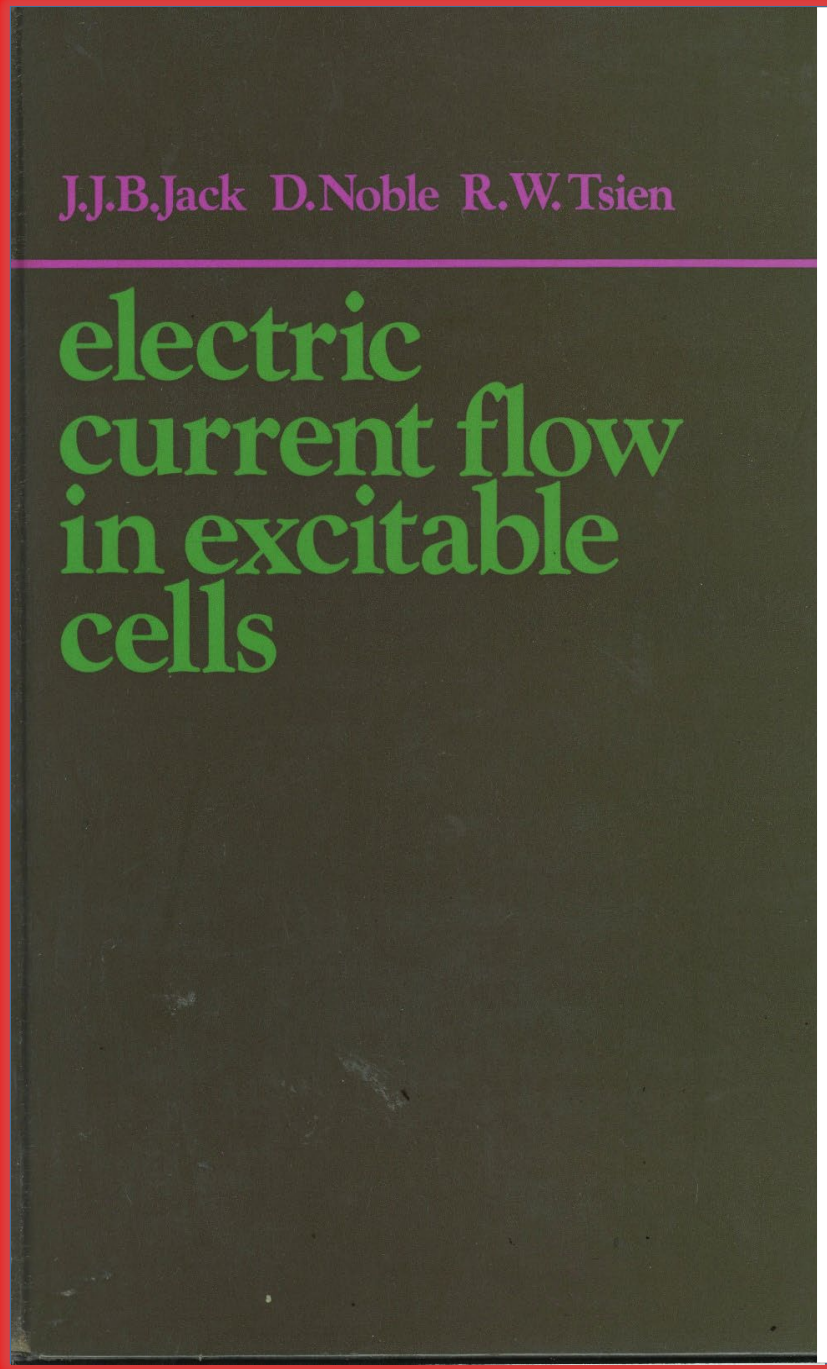
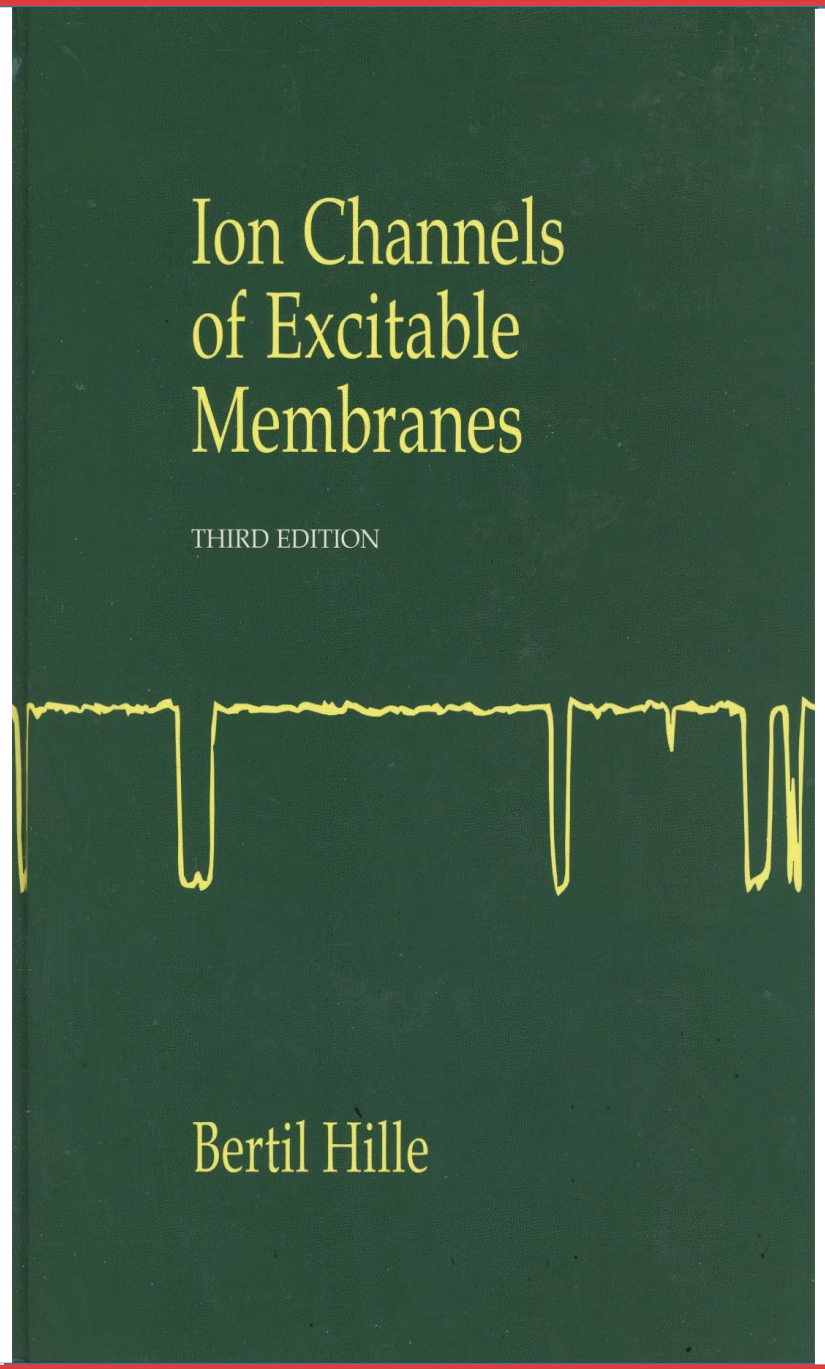
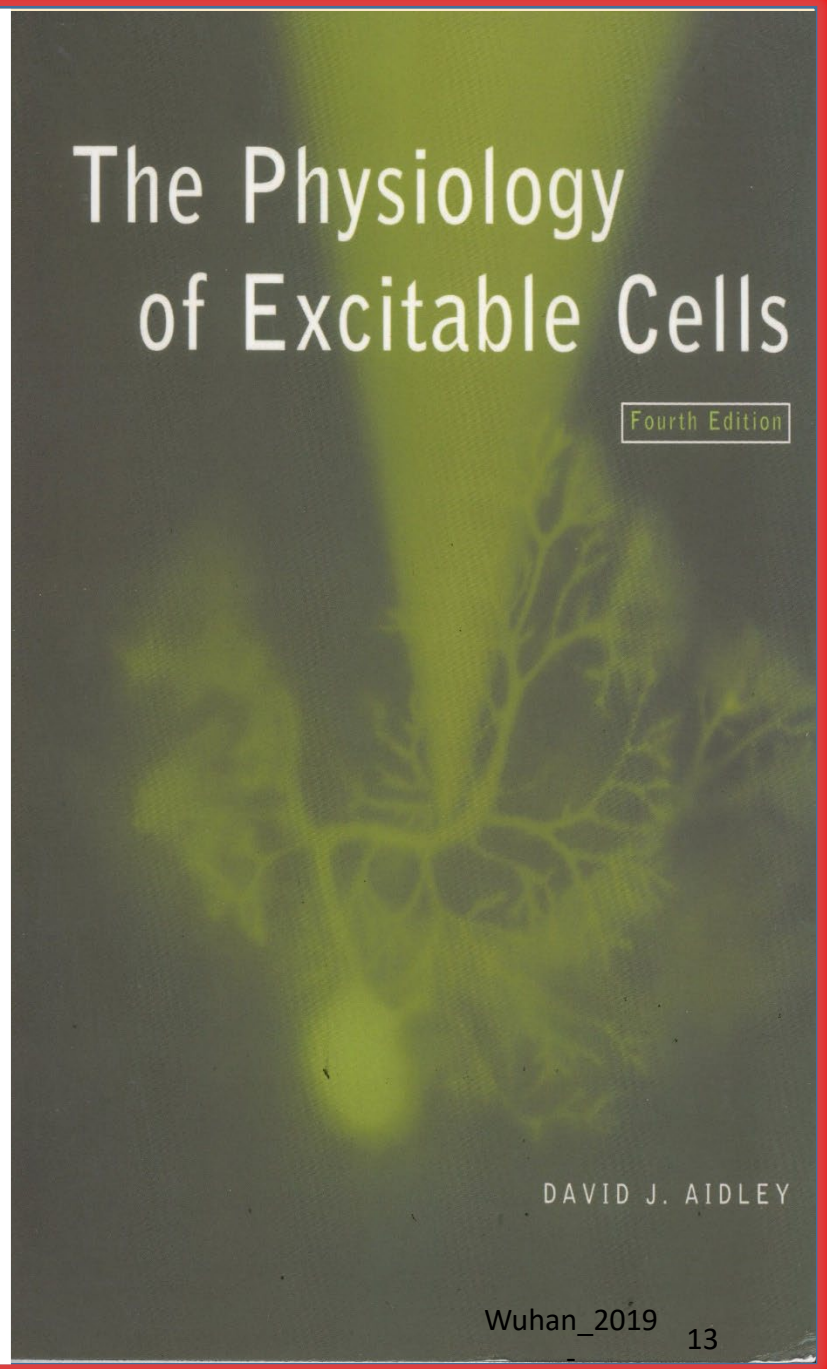
Macro Piccolino
Animal electricity and the birth of electrophysiology
Brain Research Bulletin, vol. 46, no.5, 381-407, **1998**


J.J.B.Jack D.Noble R.W.Tsien
electric current flow in excitable cells


Ion Channels of Excitable Membranes
THIRD EDITION
Bertil Hille


The Physiology of Excitable Cells
Fourth Edition
DAVID J. AIDLEY

What does

Excitable

mean ?

Excitable

Answer :

There is presently no Definition !

Excitable

means

Edge of Chaos

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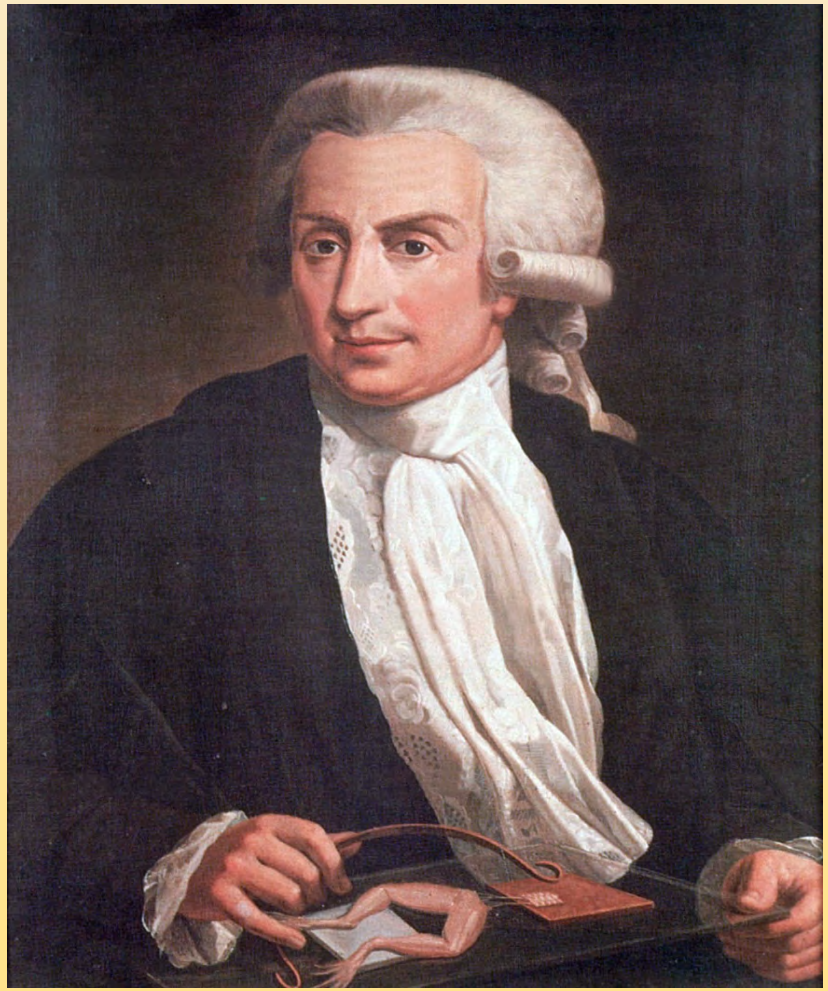


Luigi Galvani

1737-1798

Alessandro Volta

1745-1827

Alessandro Volta

Volta explains the principle of the "*electrode column*" to Napoleon

In honor of his invention Volta was made a *count* by Napoleon in **1801**.

Voltaic Pile
(Invented by Volta **1800**)

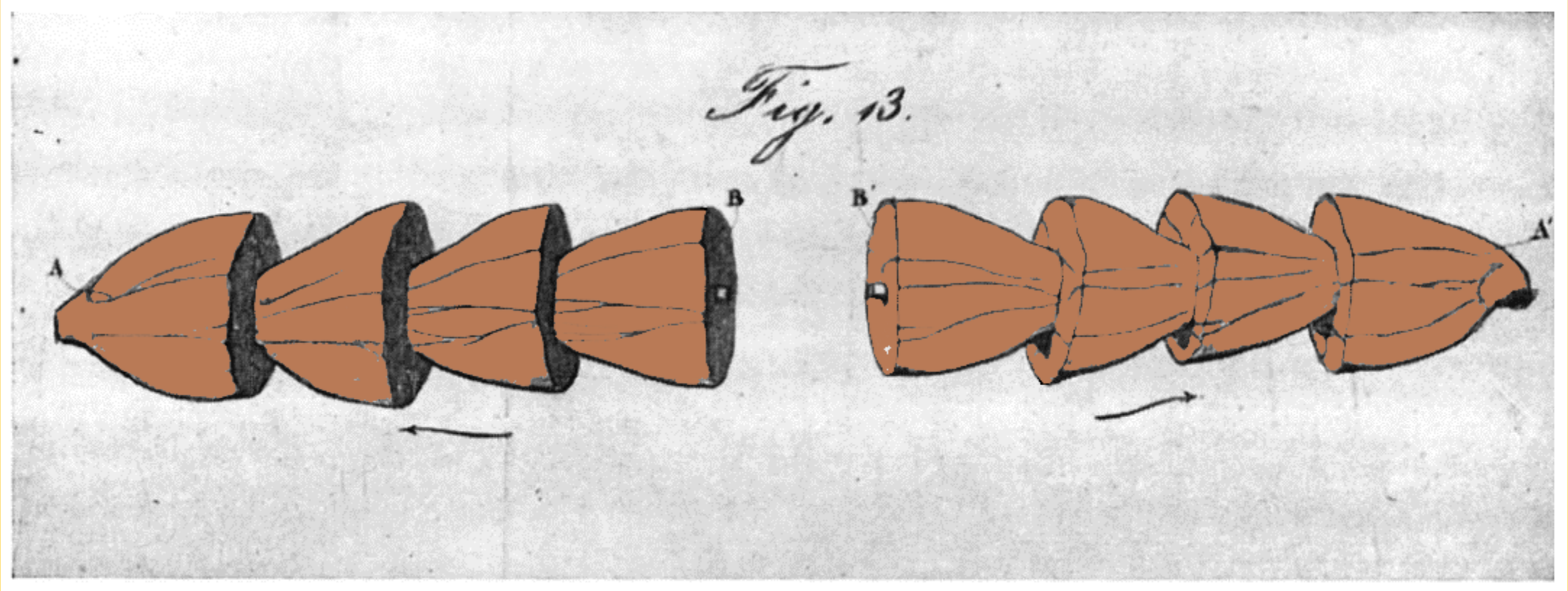
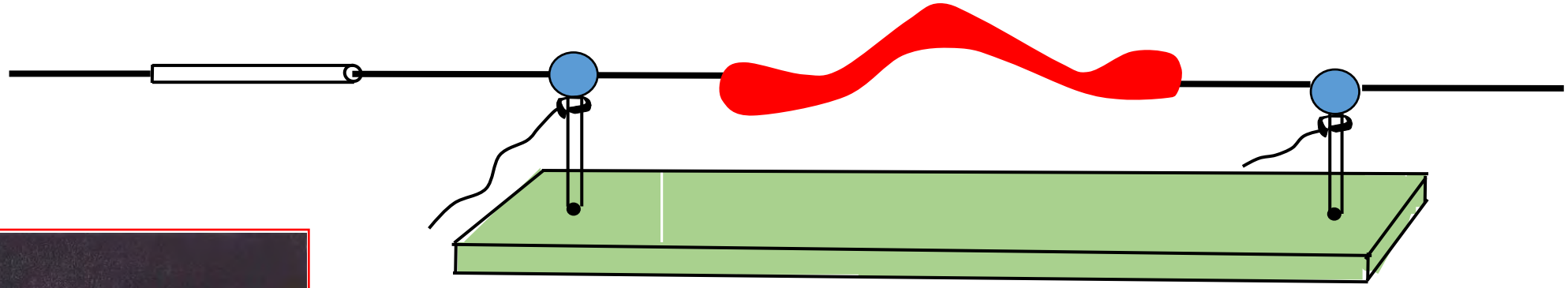


Fig. 13.
A
B
B'
A'

The First Man-Made Memristor



Sir Humphry Davy

ELEMENTS
of
CHEMICAL PHILOSOPHY

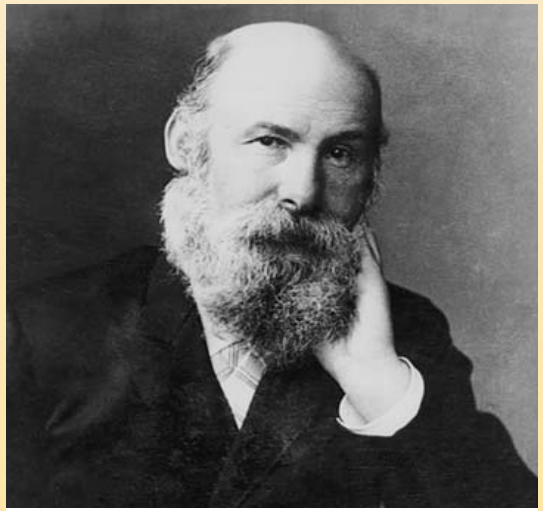
^^^^^^^^^^^^^^^^^^

BY

SIR HUMPHRY DAVY, LL D.

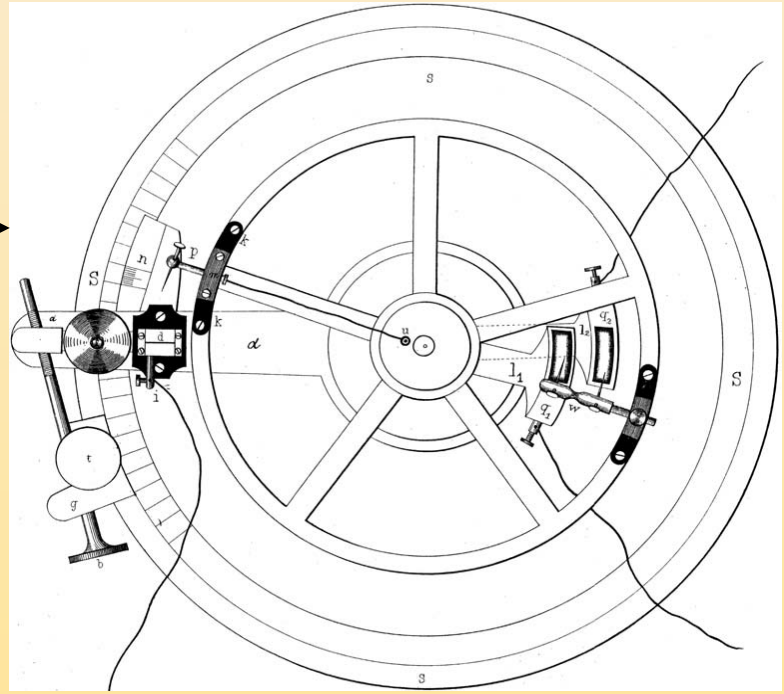
First Successful Demonstration of Continuous arc Memristor :

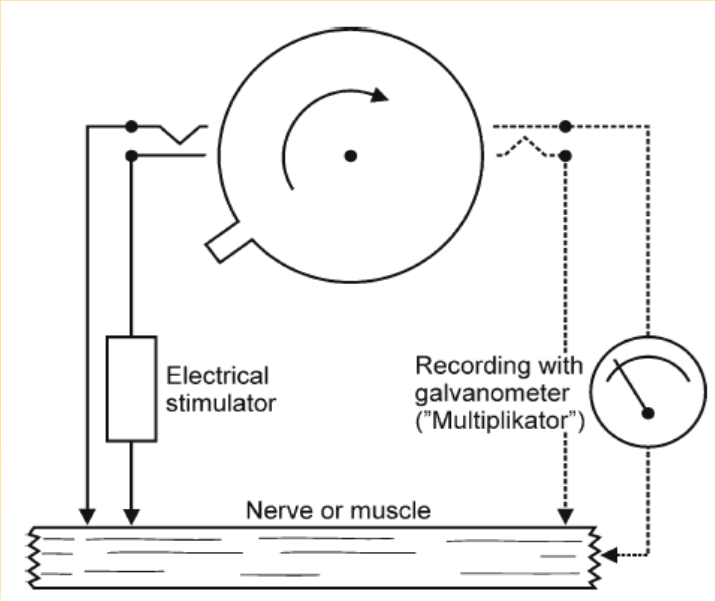
1801



Julius Bernstein (1839-1917)

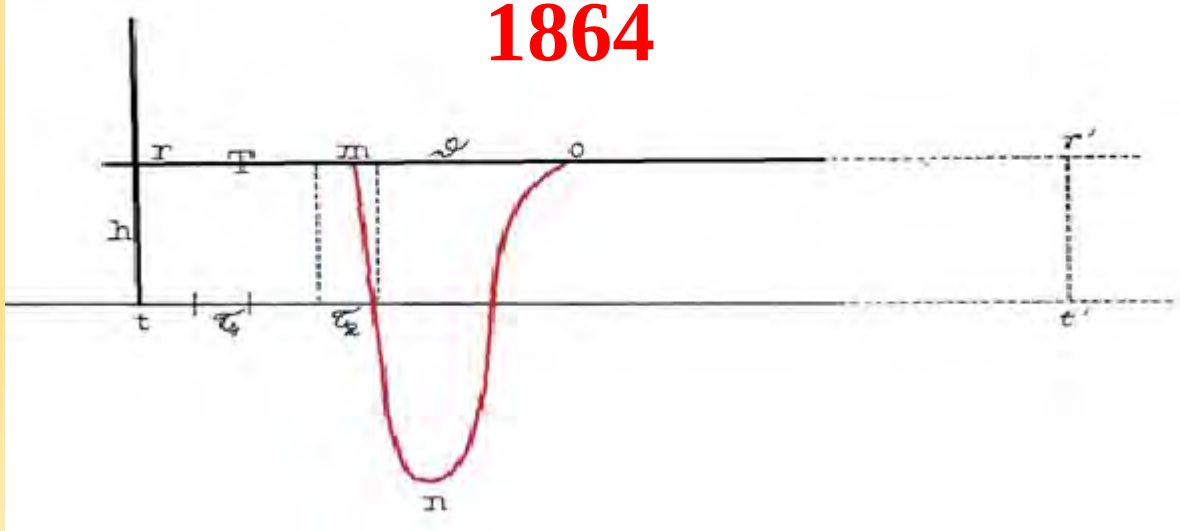
Differential Rheotome



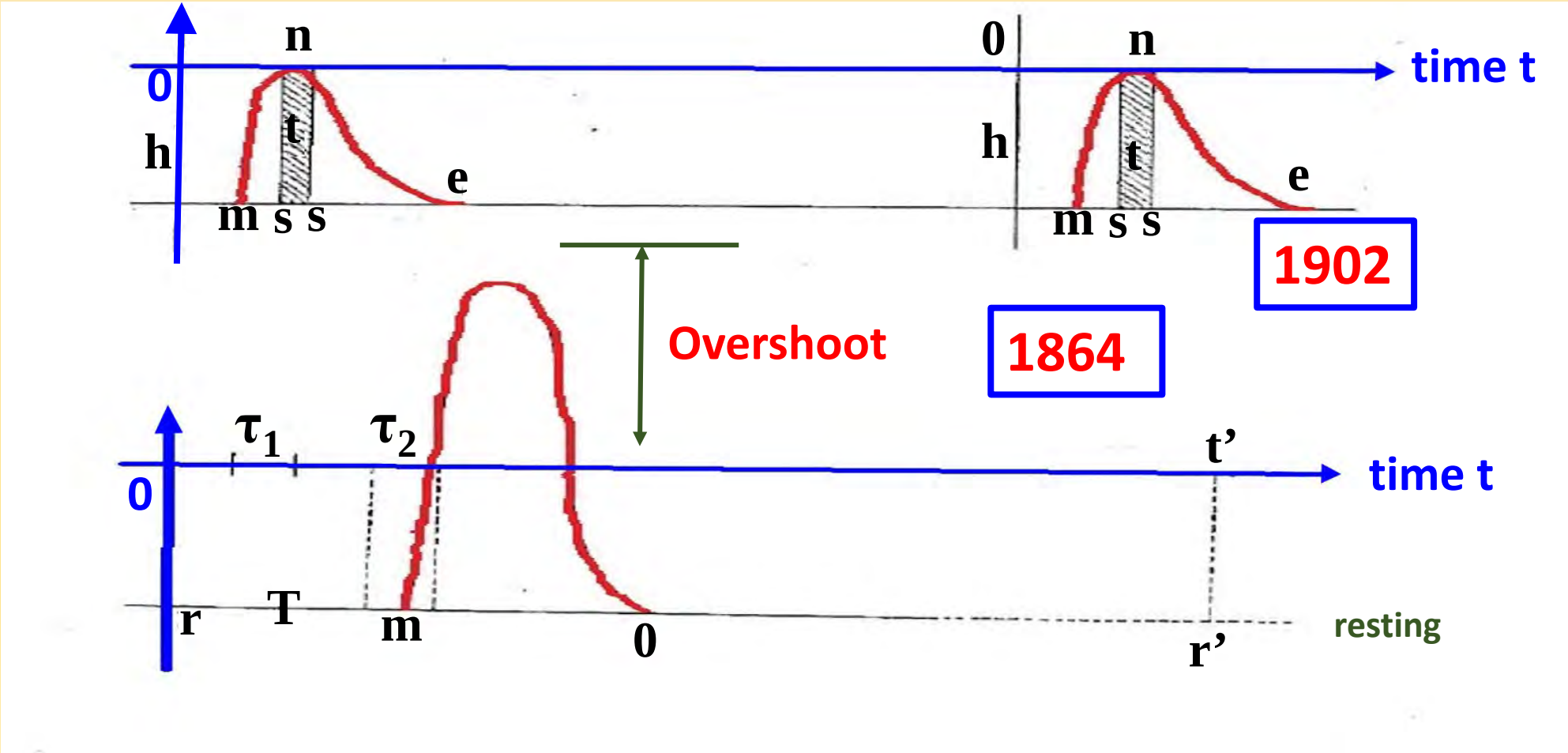


First Measured Action Potential in *frog nerve*

1864



Action Potential measured from Bernstein's Differential Rheotome Instrument



Most Fundamental Unsolved Problem :

Find the Dynamical Mechanism Responsible for generating

all or none Action Potential

The most well-known Mechanism was proposed by ***Julius Bernstein*** in **1902**

Bernstein's Membrane Hypothesis

Axons are surrounded by a membrane selectively permeable to **K^+ ions** at rest, but during **excitation**, the membrane permeability to other **ions** (**Na^+**, **Cl^-** , etc.) increases.

Bernstein's Wrong Hypothesis was Taught in Physiology for over 50 years !

Bernstein's hypothesis, which curiously ignored or discounted one of his own major results – the overshoot of the action potential – ***misled an entire generation of neurophysiologists***. It was not until about 1940 that this error was corrected and the overshoot of the action potential became firmly established.

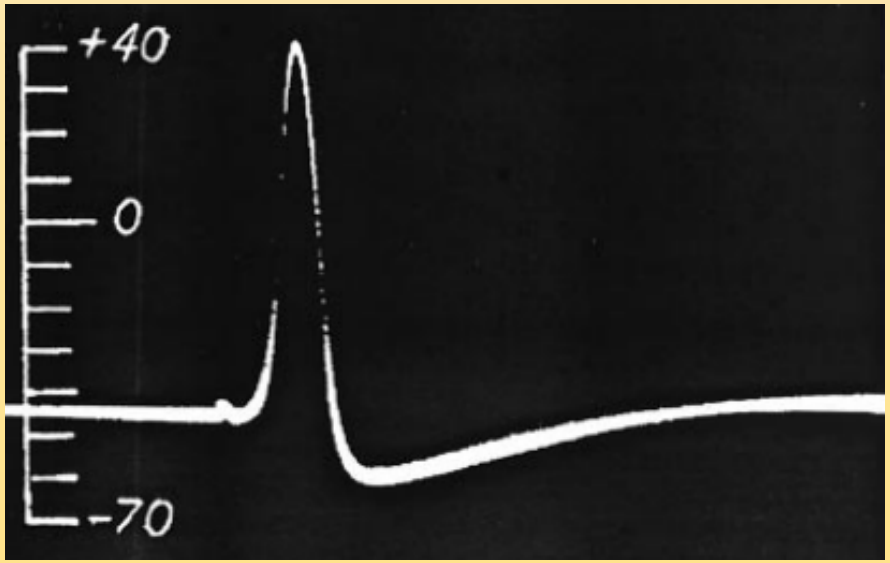
From: S.M. Schuetze

The discovery of the action potential.

Trends in neuroscience,

vol. 6, pp. 164-168, 1983

All or None Signal
aka
Action Potential



A.L. Hodgkin and **A.F. Huxley**

Nature, vol. 144, 710-711, **1939**

The first published intercellular recording of the action potential in the squid axon. Time course of the difference between the internal and external potential, in the resting state and during the discharge of an action potential. Notice the large positive overshoot of the membrane potential during the action potential, which contrasted with the expectation of the Bernstein's theory.

All *action potentials* along a **nerve axon**, or a **muscle fiber**, have **identical shape and height**. There is no such thing as $\frac{1}{2}$, or $\frac{1}{5}$, of an ***action potential***. It is either **all or none !**

The Hodgkin-Huxley Circuit Model

The ***giant squid*** has nothing to do with the work of Hodgkin and Huxley on ***squid giant axon !***

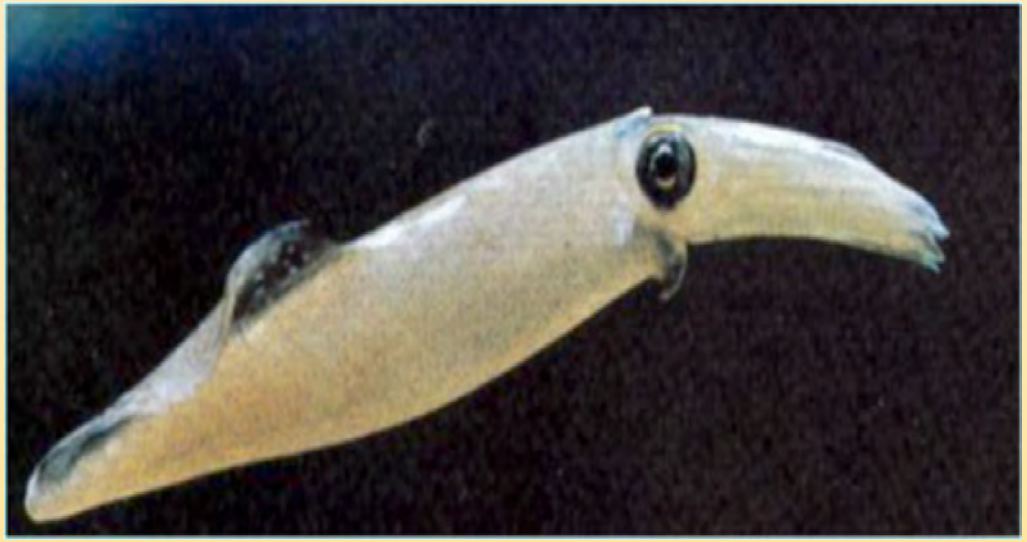
Physiologists had struggled for more than
100 years to invent an
electrical circuit model
that could generate an action potential,
until Hodgkin and Huxley
published their classic
Hodgkin-Huxley Circuit and Equations
in 1952

Alan L. Hodgkin

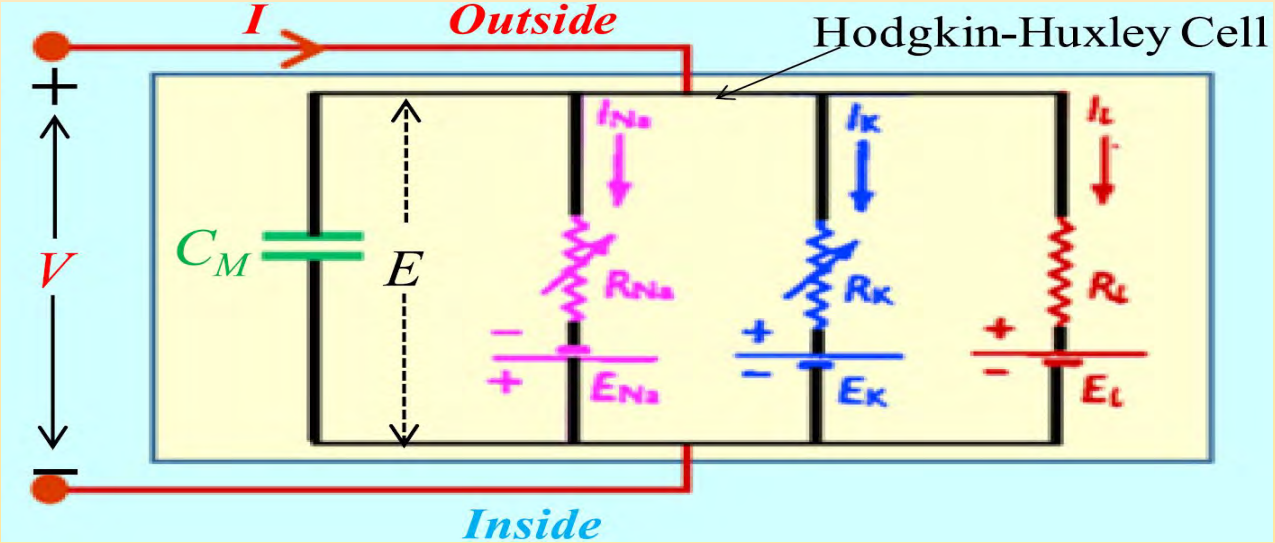
Andrew F. Huxley

1961 Nobel Prize in Physiology

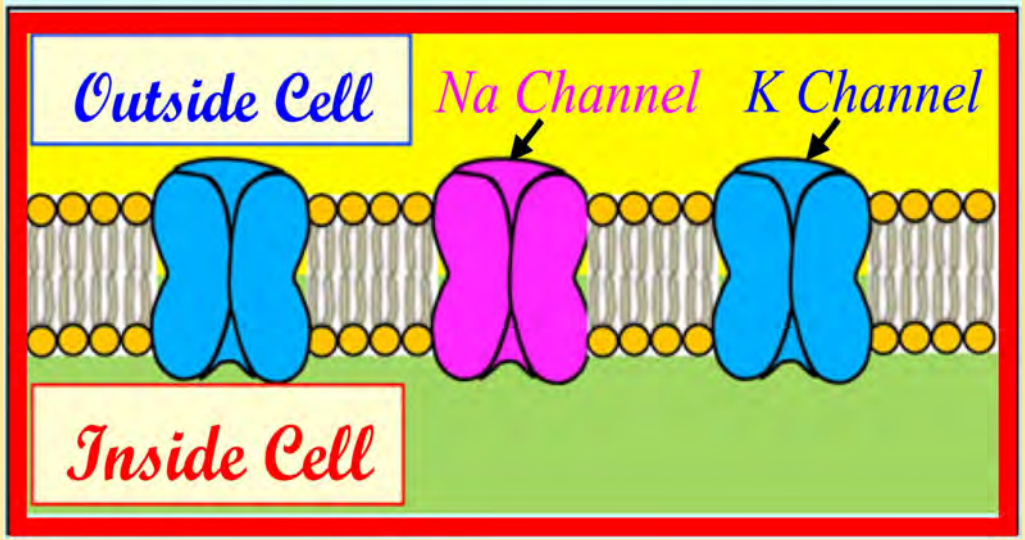
Squid with giant axon



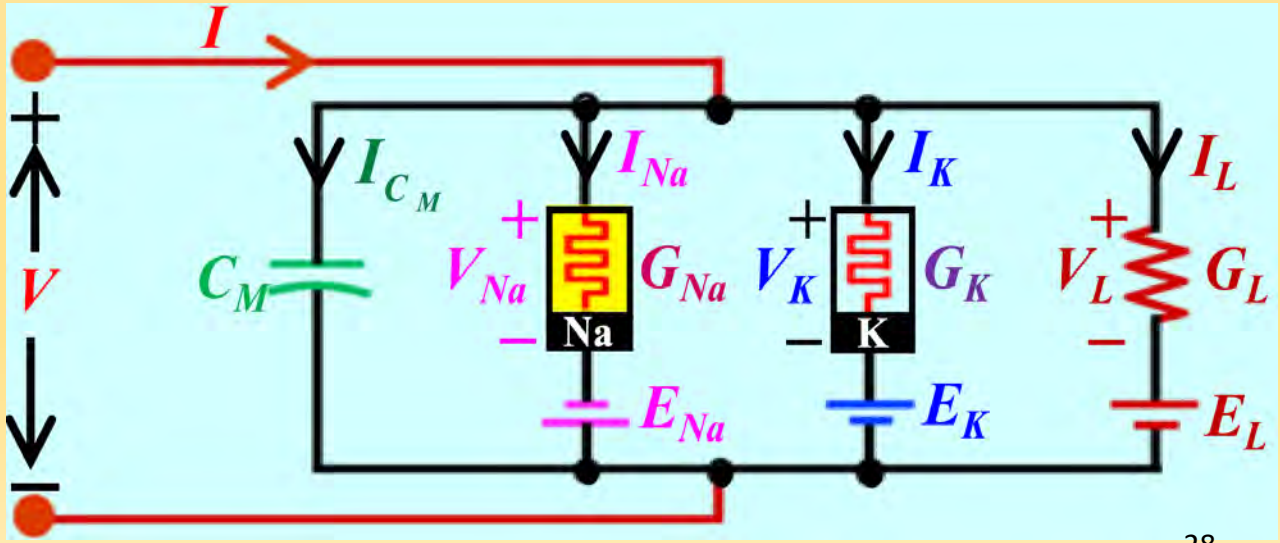
Hodgkin-Huxley Model with Time-Varying Resistance



Membrane of axon



Hodgkin-Huxley Model with Memristors



Hodgkin-Huxley Equations

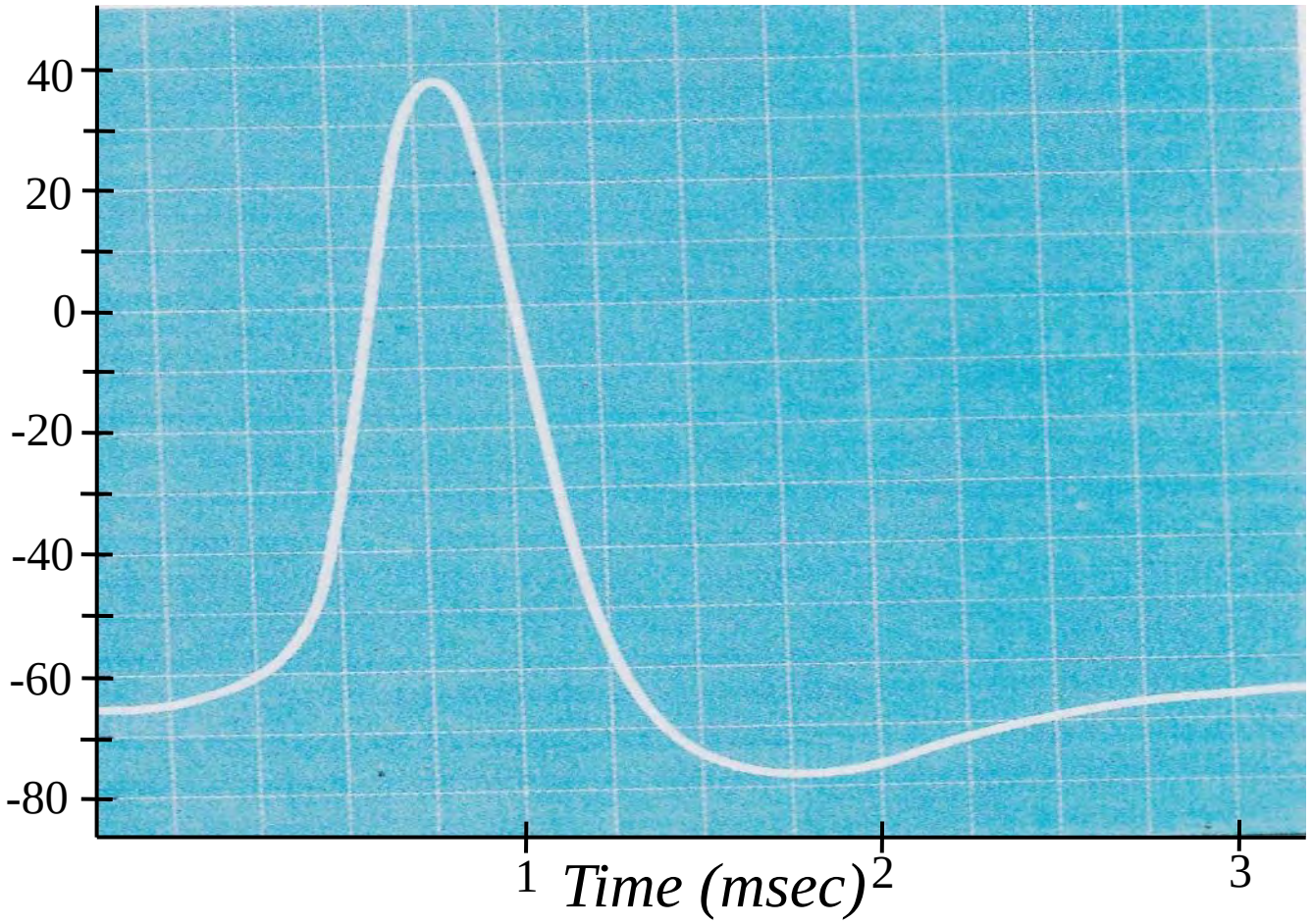
$$\frac{dV}{dt} = -\frac{1}{C_M}\left[\bar{g}_K n^4 (V - E_K) + \bar{g}_{Na} m^3 h (V - E_{Na}) + \bar{g}_l (V - E_l) - I\right]$$

$$\frac{dn}{dt} = \left[\frac{0.01\,(V + 10)}{\left(\exp\frac{V + 10}{10} - 1\right)}(1 - n)\right] - \left[0.125\,\exp\left(\frac{V}{80}\right) n\right]$$

$$\frac{dm}{dt} = \left[\frac{0.1\,(V + 25)}{\left(\exp\frac{V + 25}{10} - 1\right)}(1 - m)\right] - \left[4\,\exp\left(\frac{V}{18}\right) m\right]$$

$$\frac{dh}{dt} = \left[0.07\,\exp\left(\frac{V}{20}\right)(1 - h)\right] - \left[\frac{1}{\left(\exp\frac{V + 30}{10} + 1\right)} h\right]$$

Action Potential

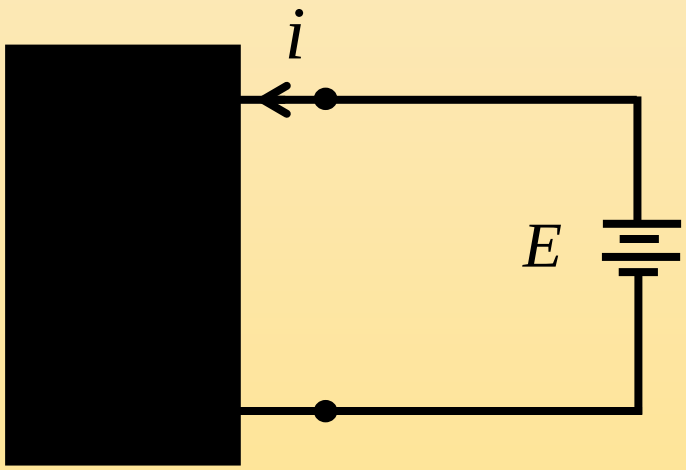


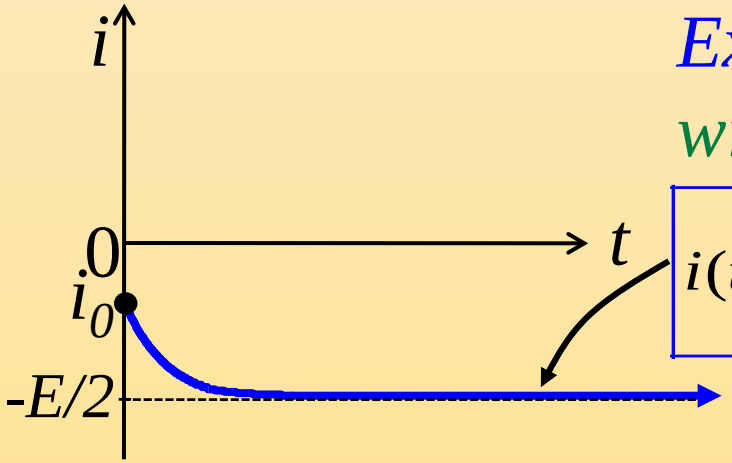
239-Year Unsolved Mystery

Find the physical, computable, and mathematically-rigorous mechanism of the Action Potential.

Chua's Riddle

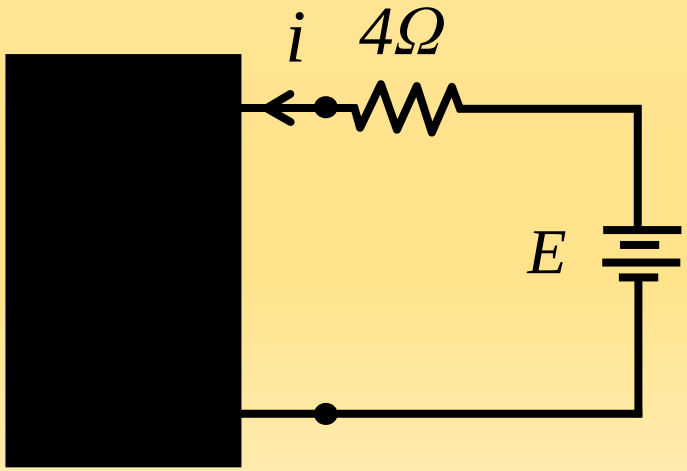
Chua's Riddle

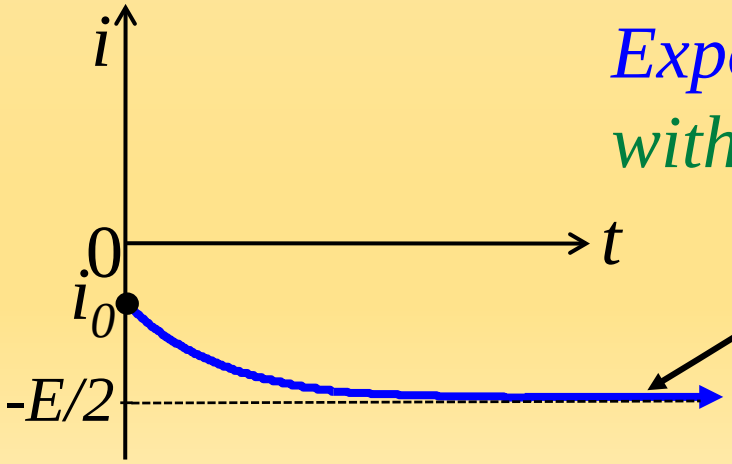




Exponential waveform with time constant $\tau = 1$

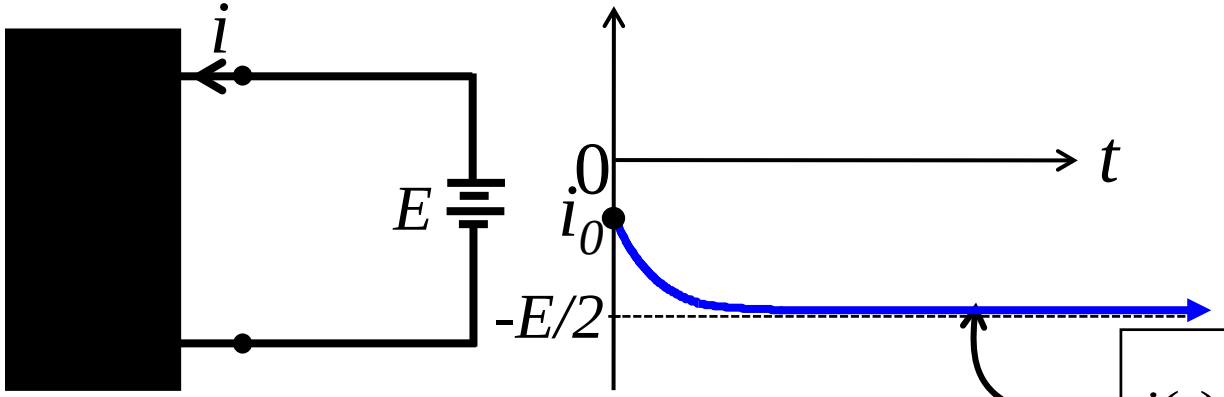
$$i(t) = -\frac{E}{2} + \left[i_0 + \frac{E}{2} \right] e^{-t}$$





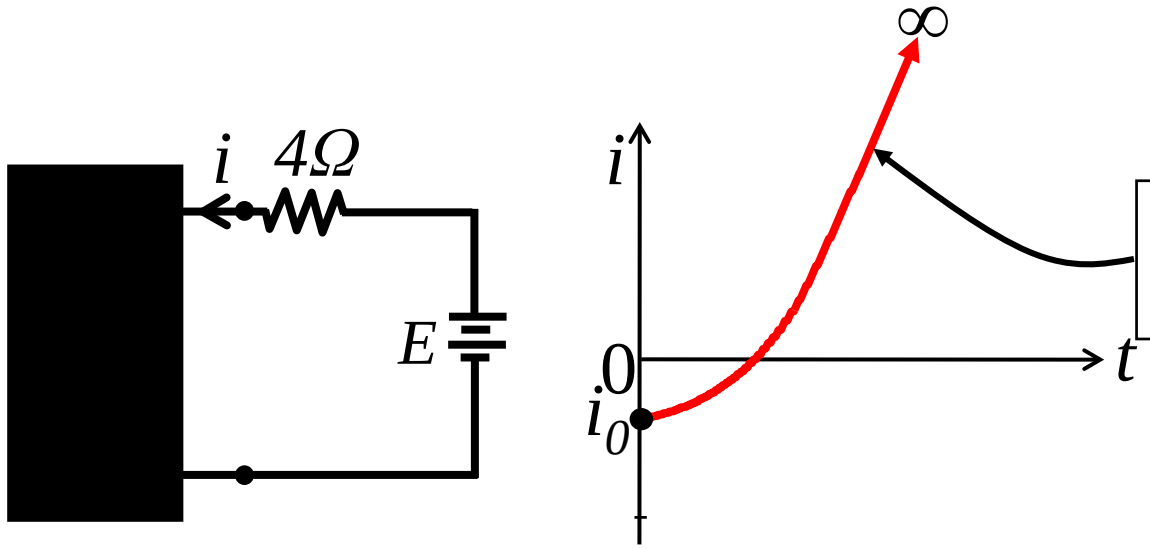
Exponential waveform with time constant $\tau >> 1$

Chua's Riddle



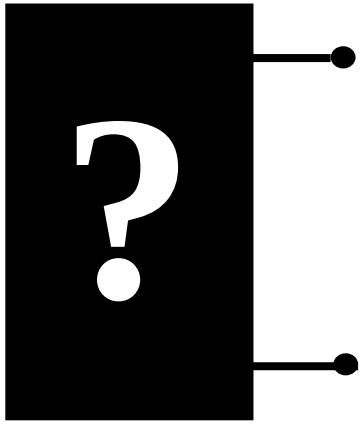
Exponential waveform with time constant $\tau = 1$

$$i(t) = -\frac{E}{2} + \left[i_0 + \frac{E}{2} \right] e^{-t}$$

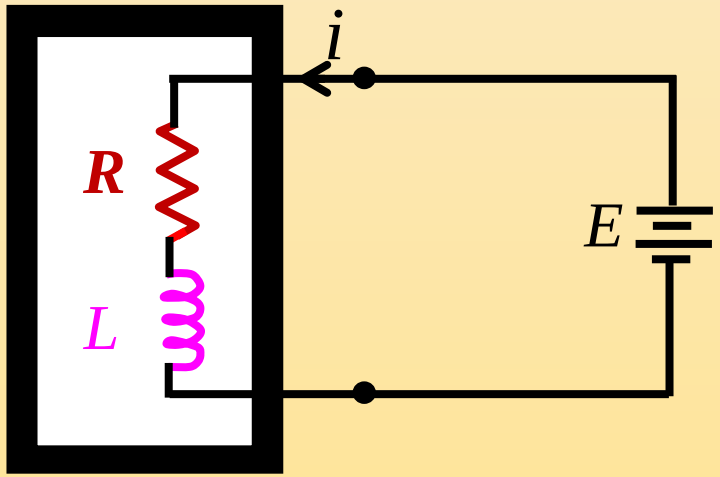


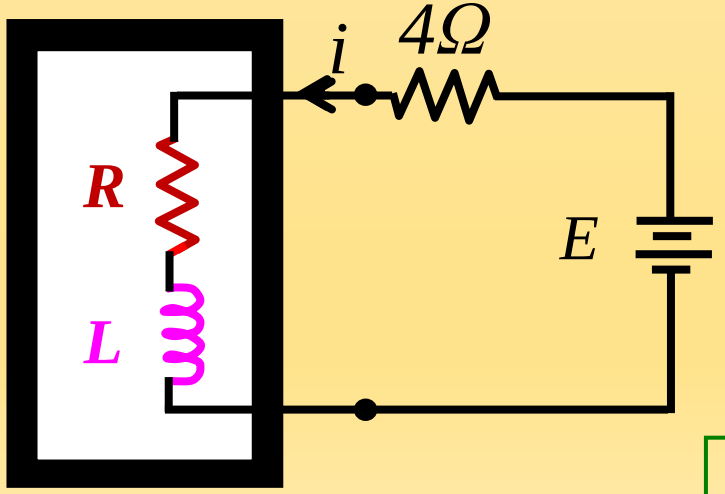
$$i(t) = \frac{E}{2} + \left[i_0 - \frac{E}{2} \right] e^{t}$$

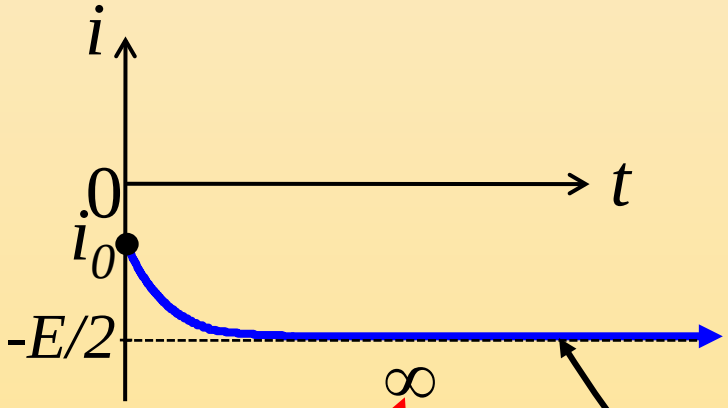
What is inside the Black Box



Hint to Chua's Riddle

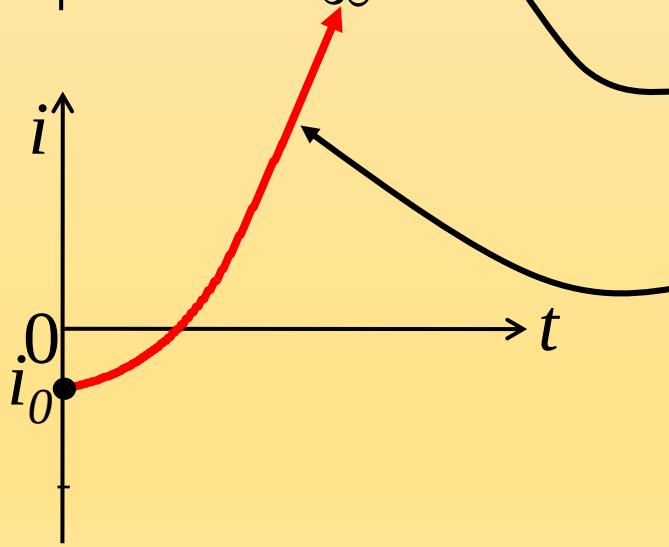






Exponential waveform with time constant $\tau = 1$

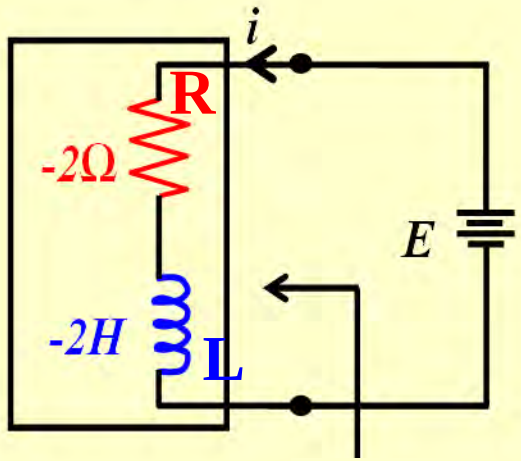
$$i(t) = -\frac{E}{2} + \left[i_0 + \frac{E}{2} \right] e^{-t}$$

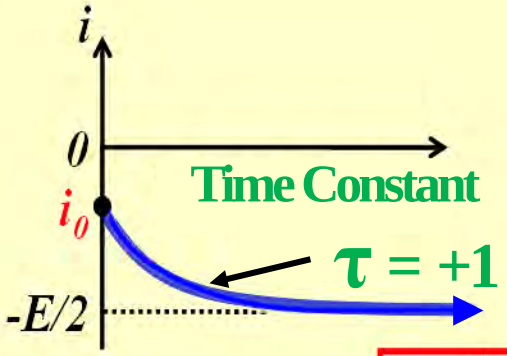


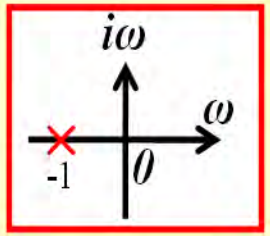
$$i(t) = \frac{E}{2} + \left[i_0 - \frac{E}{2} \right] e^{t}$$

What value of **R** and **L** would **blow up** this circuit ?

$$\text{Time Constant} = \tau = \frac{L}{R} = \frac{-2}{-2} = 1$$







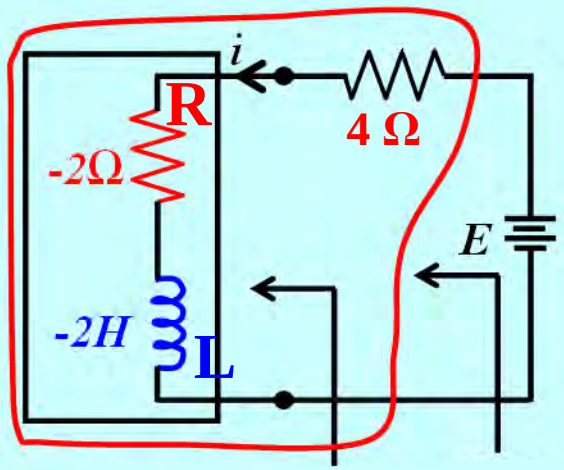
Admittance $Y(s)$

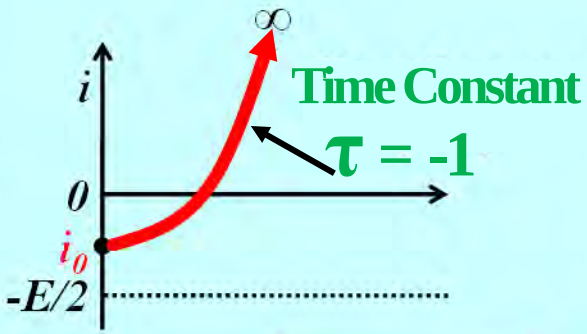
$$Y(s) = \frac{I(s)}{V(s)} = \frac{1}{(-2-2s)} = \frac{-1}{2(s+1)}$$

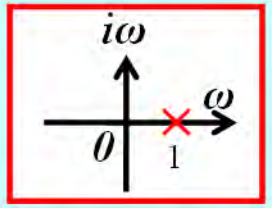
$$Y(i\omega) = \frac{-1}{2(1+i\omega)} = \frac{-(1-i\omega)}{2(1+i\omega)(1-i\omega)} = \frac{-1}{2(1+\omega^2)} + i\frac{w}{2(1+\omega^2)}$$

$$\text{Re } Y(i\omega) = \frac{-1}{2(1+\omega^2)} < 0, \quad \infty < \omega < \infty$$

$$\text{Time Constant} = \tau = \frac{L}{R} = \frac{-2}{-2+4} = \frac{-2}{+2} = -1$$







Admittance $Y(s)$ $Y'(s)$

$$Y'(s) = \frac{I(s)}{V(s)} = \frac{1}{(2-2s)} = \frac{-1}{2(s-1)}$$

$$Y'(i\omega) = \frac{-1}{2(-1+i\omega)} = \frac{-(-1-i\omega)}{2(-1+i\omega)(-1-i\omega)} = \frac{1}{2(1+\omega^2)} + i\frac{\omega}{2(1+\omega^2)}$$

$$\text{Re } Y'(i\omega) = \frac{-1}{2(1+\omega^2)} < 0, \quad \infty < \omega < \infty$$

The *Answer*

to

Chua's Riddle

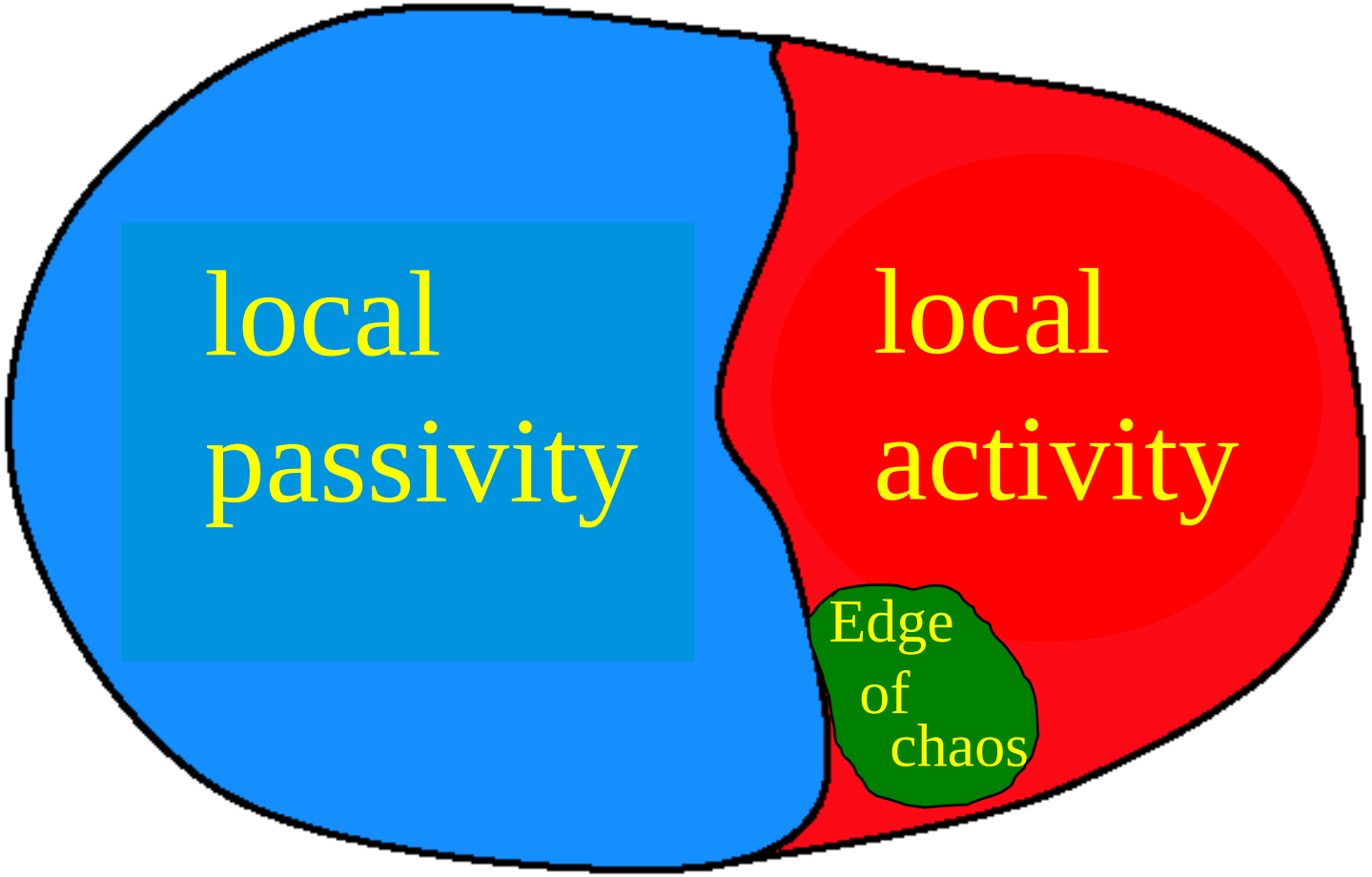
is the essence of the

Edge of Chaos

The Local Activity Principle

All 2-terminal electrical devices can be classified into either "***locally passive***", or "***locally active***". Occasionally, a tiny subset of "***locally active***" devices is blessed with an "***edge of chaos***" domain capable of exhibiting fascinating phenomena and attributes, such as "***learning***", "***artificial intelligence***", and even "***life***" itself.

Three Fundamental Concepts



Edge of Chaos

is the

"pearl"

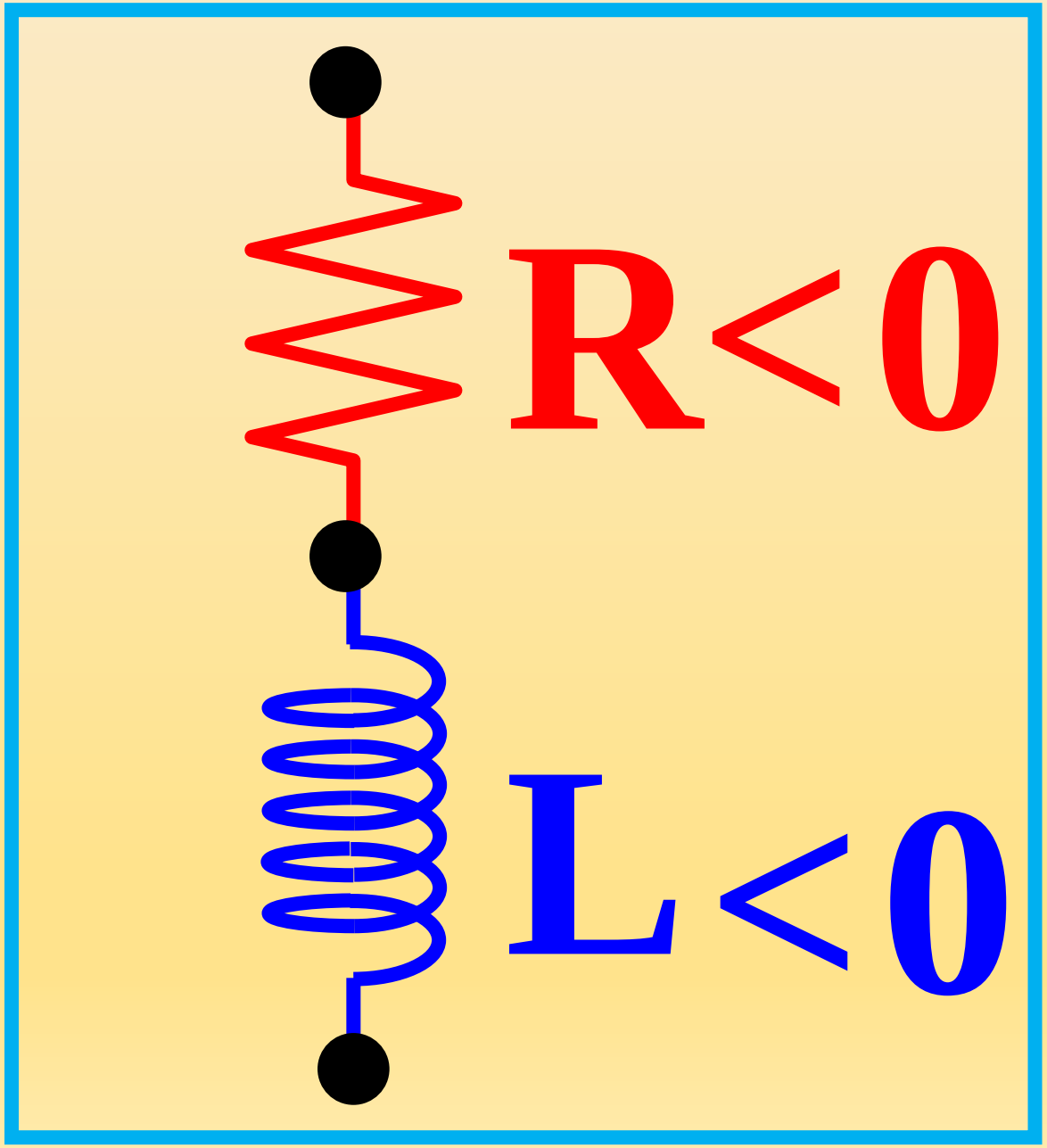
Imbedded within

the domain of

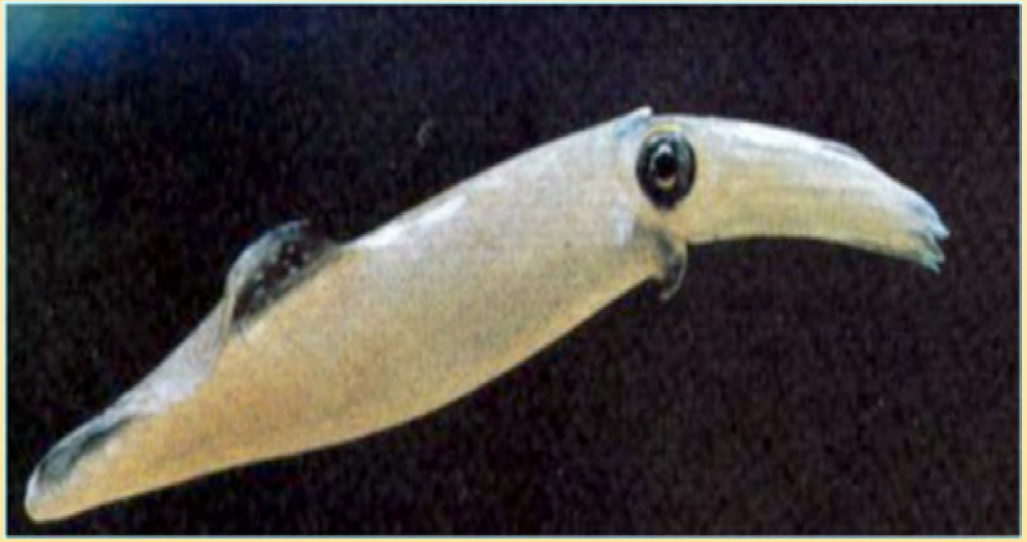
local activity

The "*Edge of Chaos*" is the "**Oyster**" amidst the "***locally active domain***"

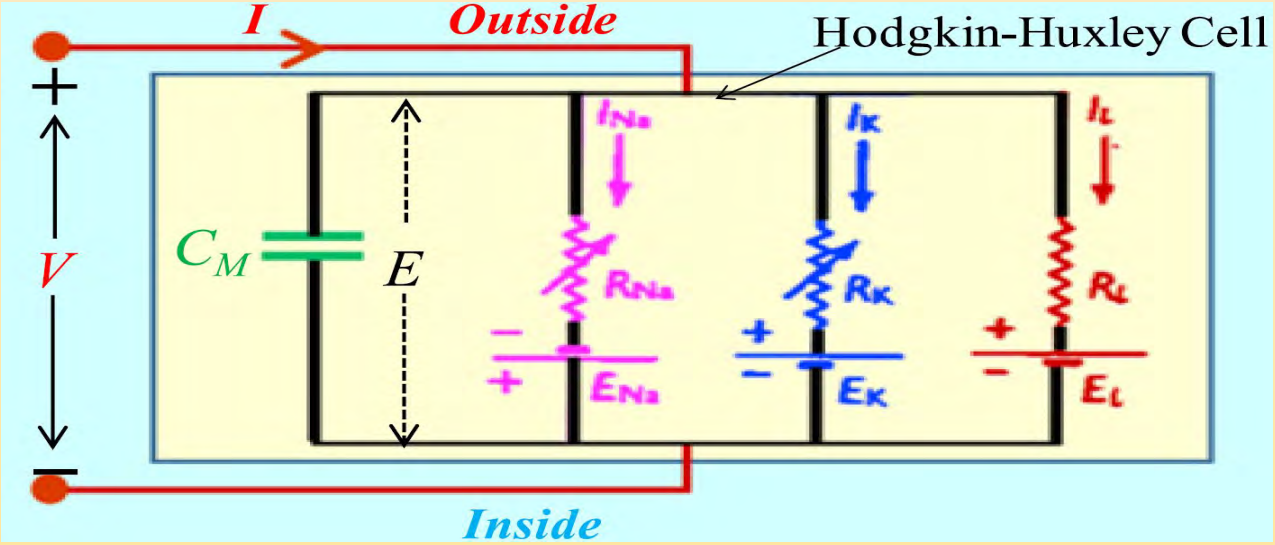
A Signature of Edge of Chaos



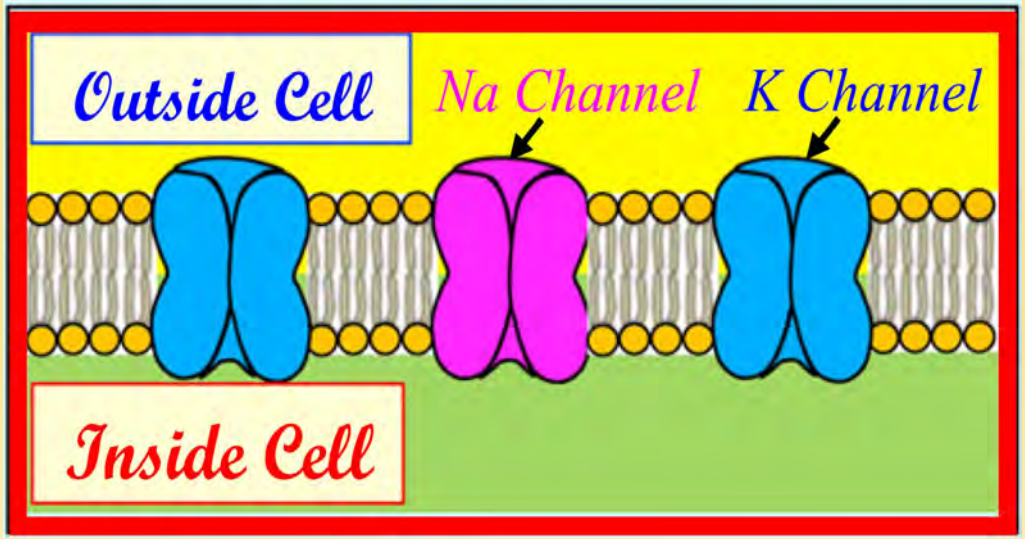
Squid with giant axon



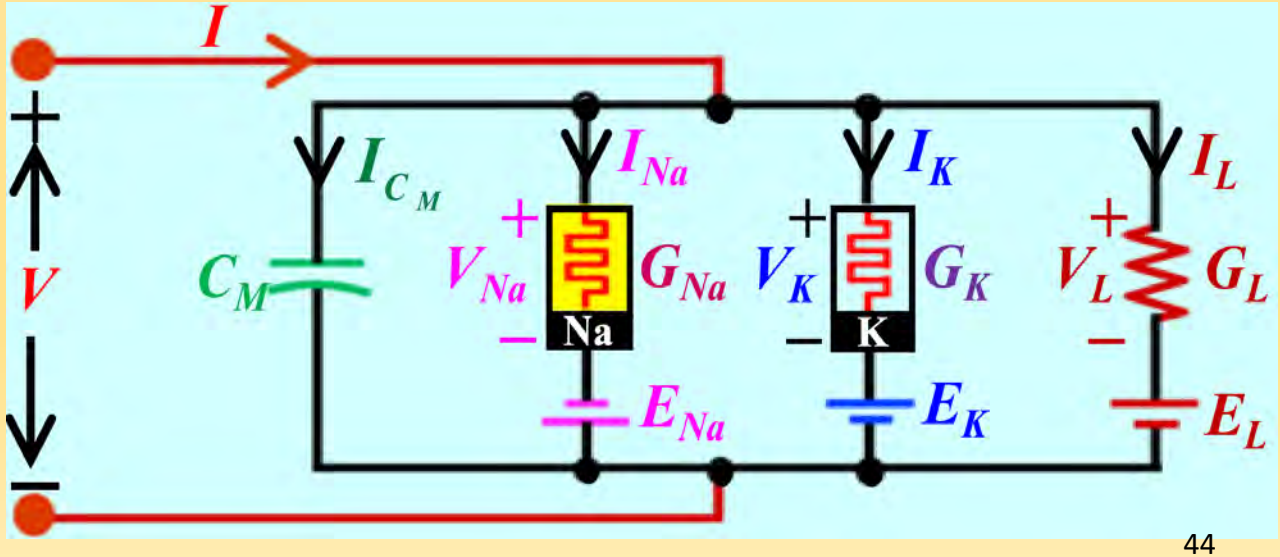
Hodgkin-Huxley Model with Time-Varying Resistance



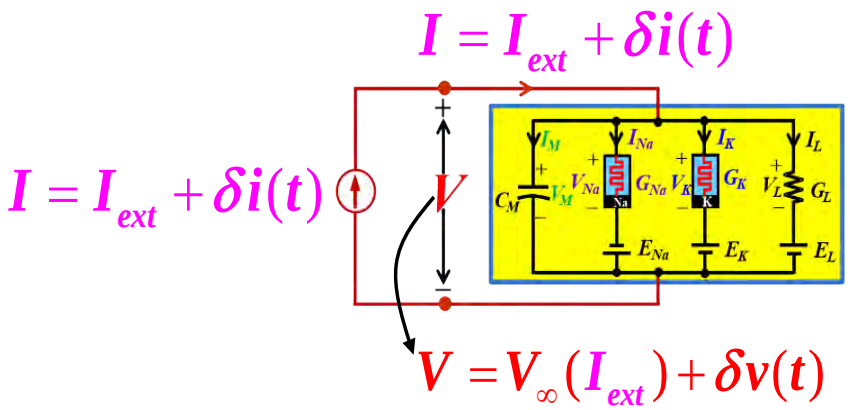
Membrane of axon



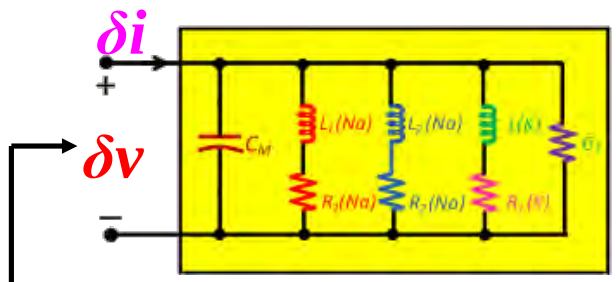
Hodgkin-Huxley Model with Memristors



Hodgkin-Huxley Axon Circuit



Small-Signal equivalent circuit at DC (equilibrium point) (I_{ext}, V_∞)



Admittance: $Y(s\,;\,I_{ext}) \equiv \dfrac{L\{\delta v(t)\}}{L\{\delta i(t)\}}$

Hodgkin-Huxley Edge of Chaos Criterion:

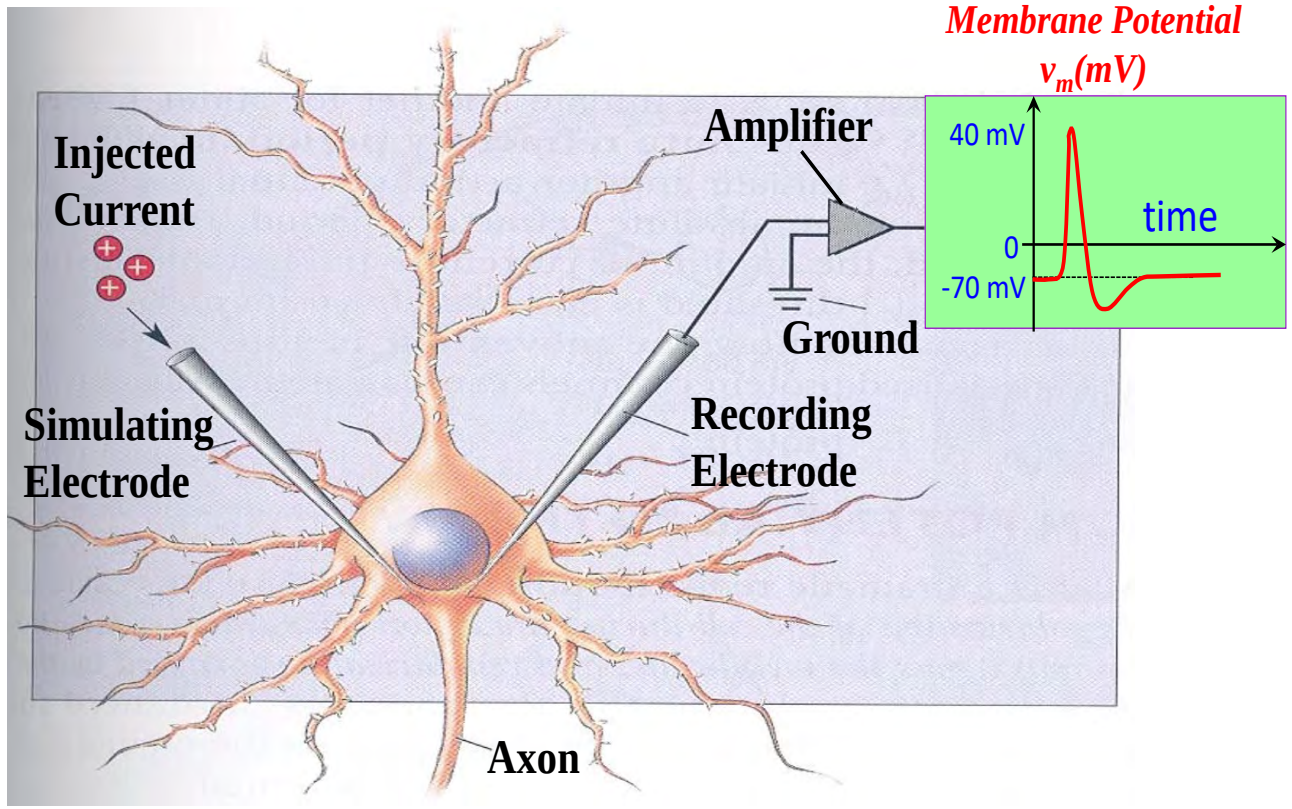
The *Hodgkin-Huxley Neuron* under synaptic input I_{ext} is on the *edge of chaos* if, and only if,

1. All zeros of $Y(s;\,I_{ext})$ are in the *open left half plane*,

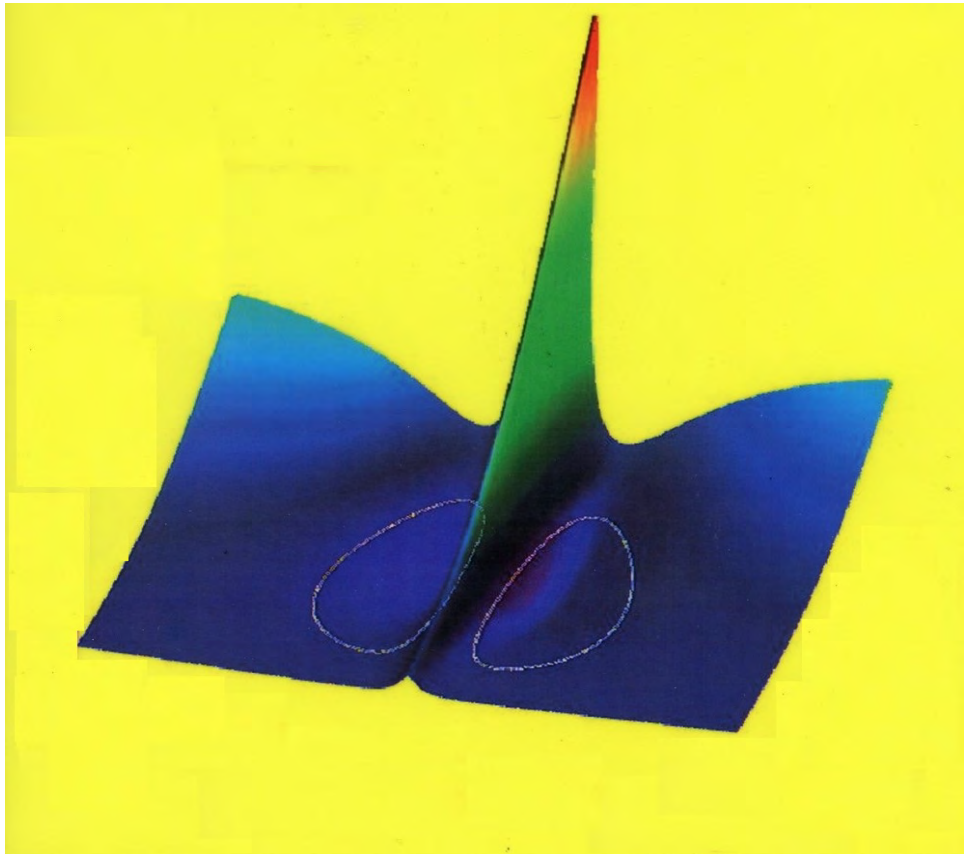
   i. e. $Re\ z_k(I_{ext}) < 0 \quad k = 1,\ 2,\ 3,\ 4$

2. $Re\ Y(i\omega; I_{ext}) < 0$ for at least *one frequency* $\omega = \omega_0$

Neurons are Poised Near The Edge of Chaos

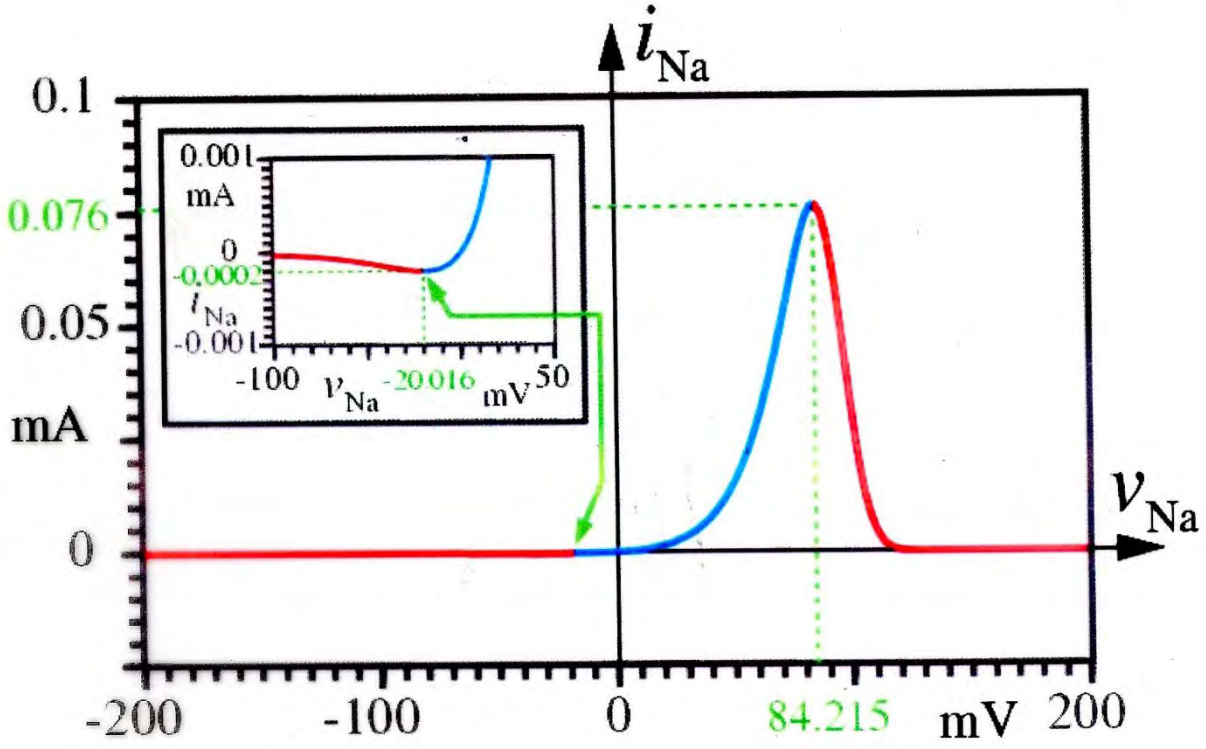


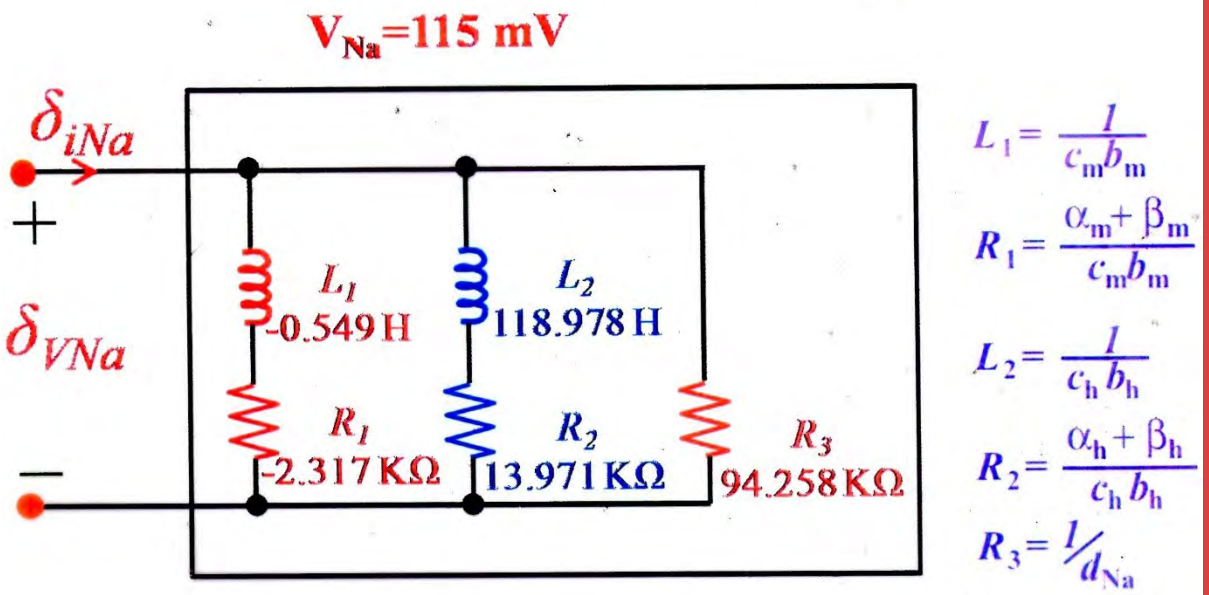
Real Part of Complex Admittance



DC v_{Na} - i_{Na} curve of the Sodium Memristor for Hodgkin-Huxley Axon circuit model

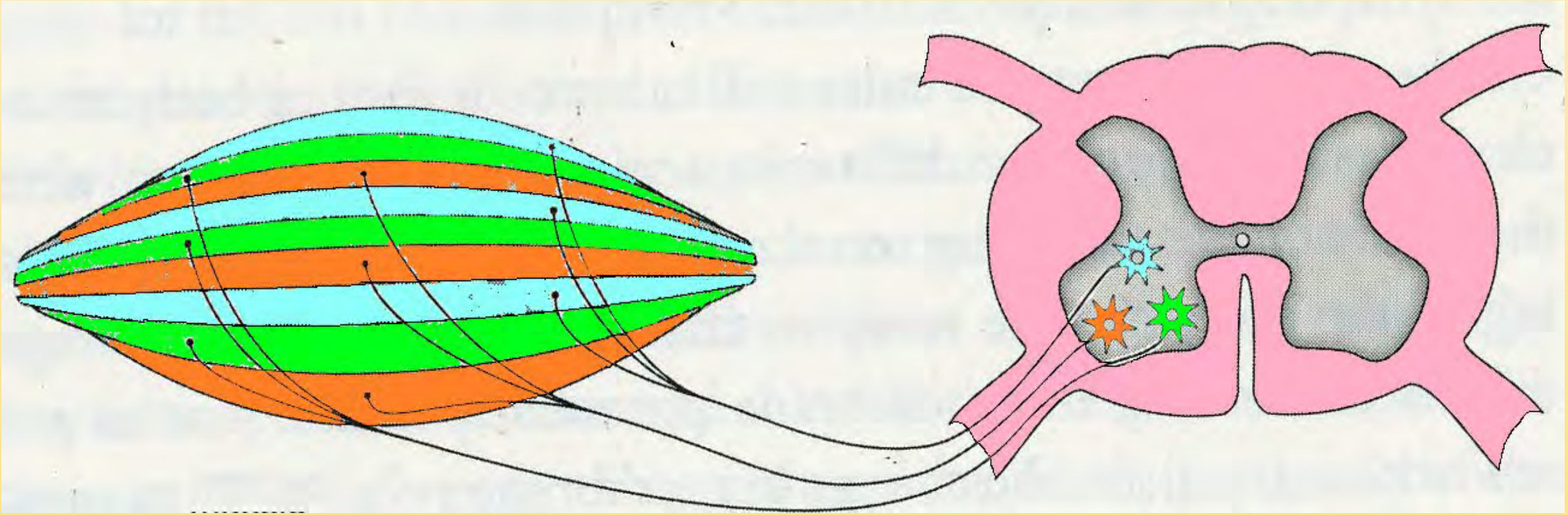
Small-Signal Equivalent Circuit About An Operating Point of the Hodgkin-Huxley Sodium memristor





$$L_1 = -0.549\ H$$

$$R_1 = -2.317\ K\Omega$$

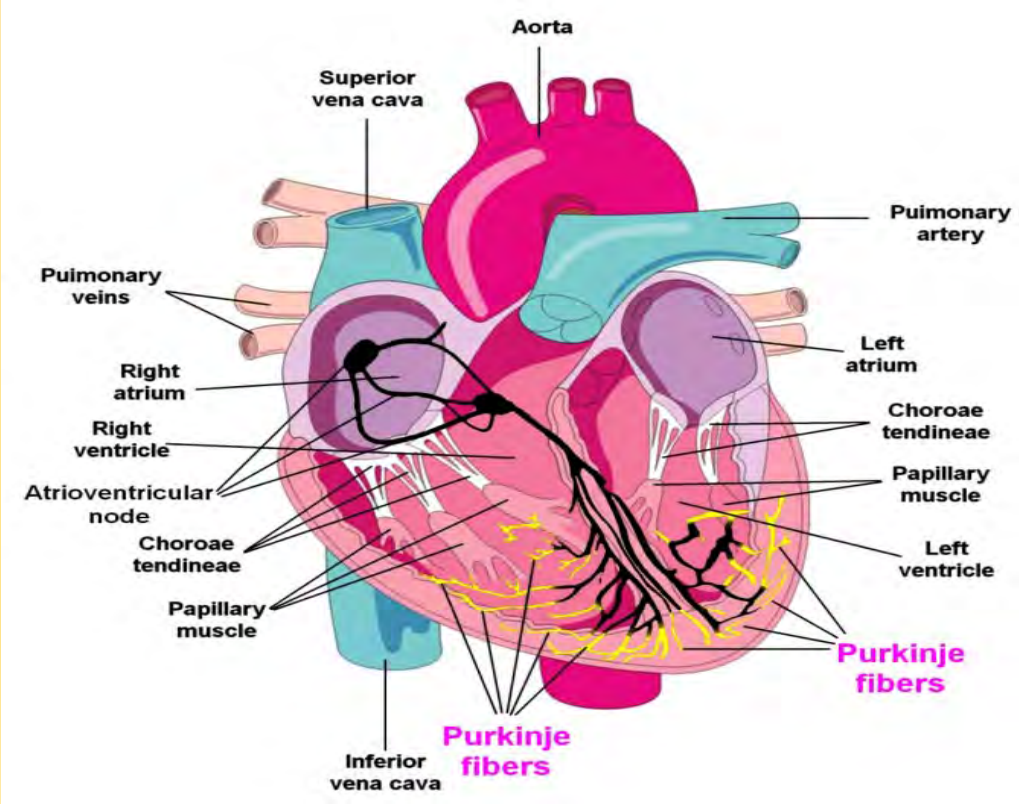


Muscle

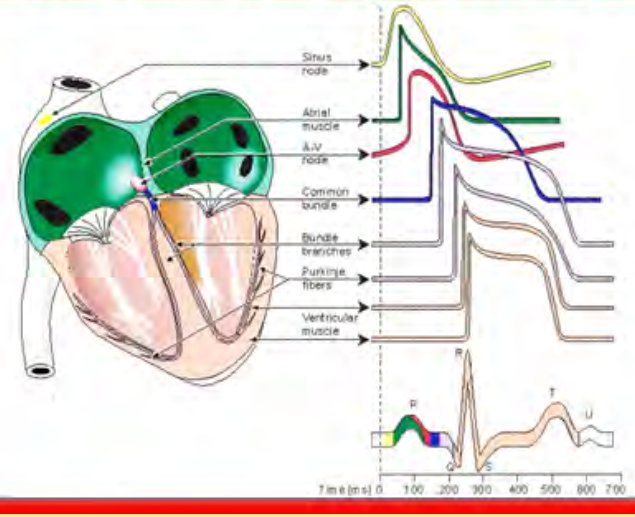
Spinal Cord

X. Zhang, Z. Wu, and L. Chua
Int. Journal of Bifurcation and Chaos
Vol. 30, July 2020.

Hearts are Poised near the Edge of Chaos



Action Potentials from the Heart Are Generated by Memristors



Hodgkin-Huxley "Cardiac" Equations

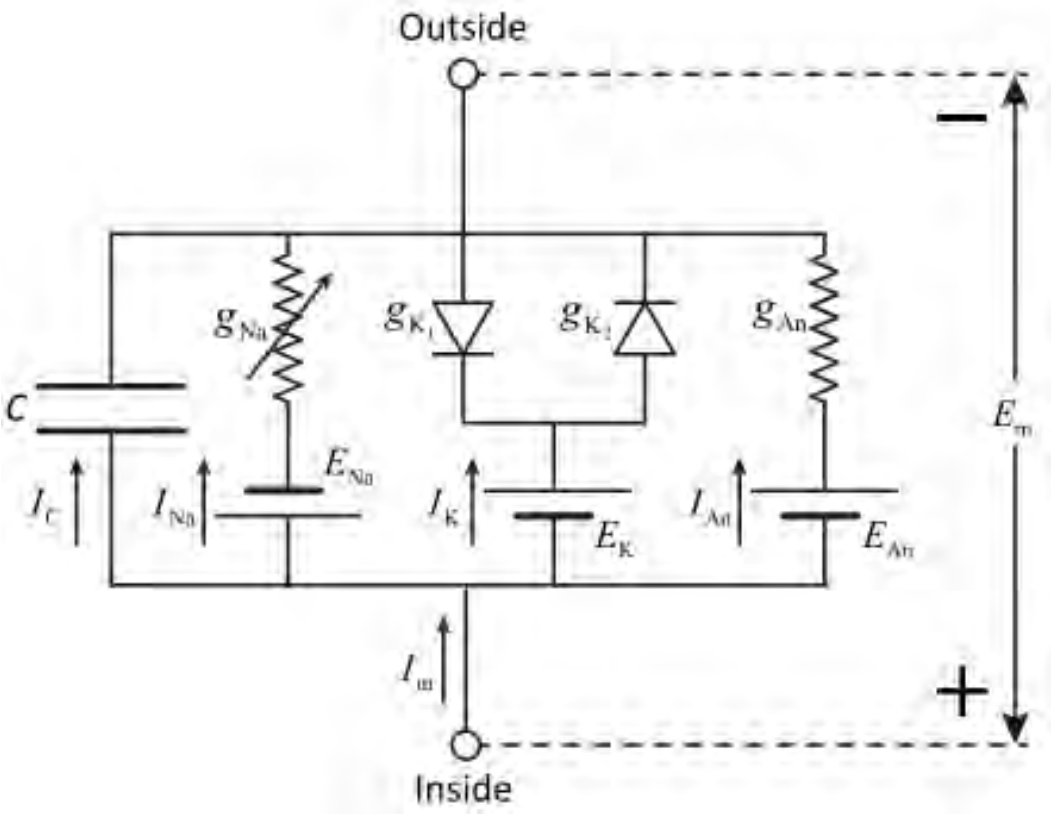
$$\frac{dV}{dt} = -\frac{1}{C_m}\Big\{[400m^3h + 0.14](V - a) + \big[1.2\exp((-V-90)/50) + 0.015\exp((V+90)/60) + 1.2n^4\big](V + b)\Big\} + D\nabla V$$

$$\frac{dm}{dt} = \alpha_m(V)(1-m) - \beta_m(V)m$$

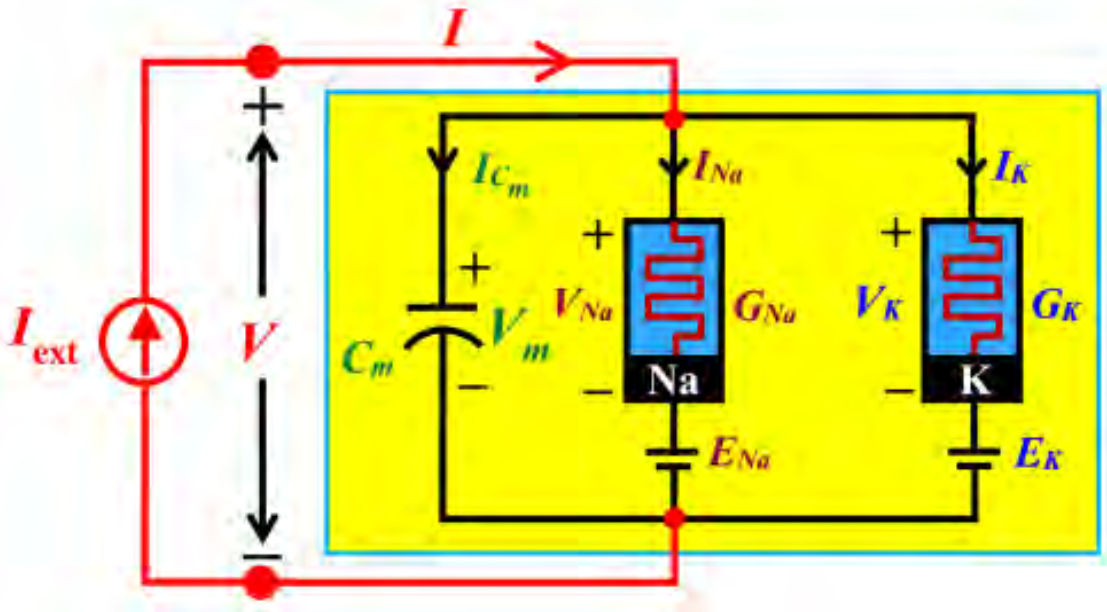
$$\frac{dh}{dt} = \alpha_h(V)(1-h) - \beta_h(V)h$$

$$\frac{dn}{dt} = \alpha_n(V)(1-n) - \beta_n(V)n$$

D: Noble, D. [1962] A modification of the Hodgkin-Huxley equations applicable to Purkinje fibre action and peacemaker potentials, *J. Physiol.* 160, 317-352.

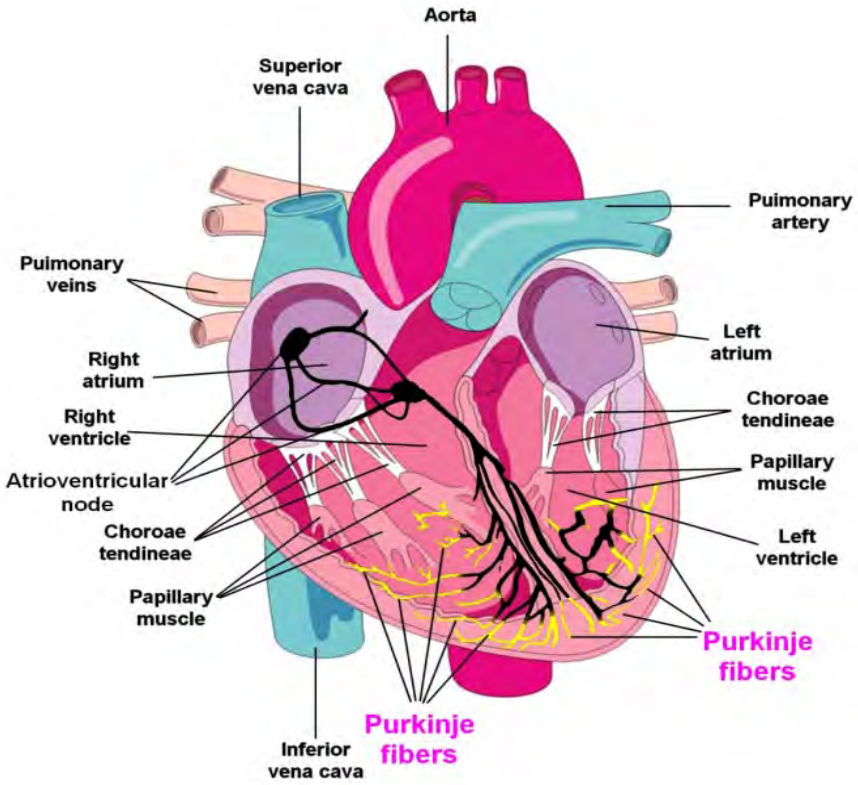


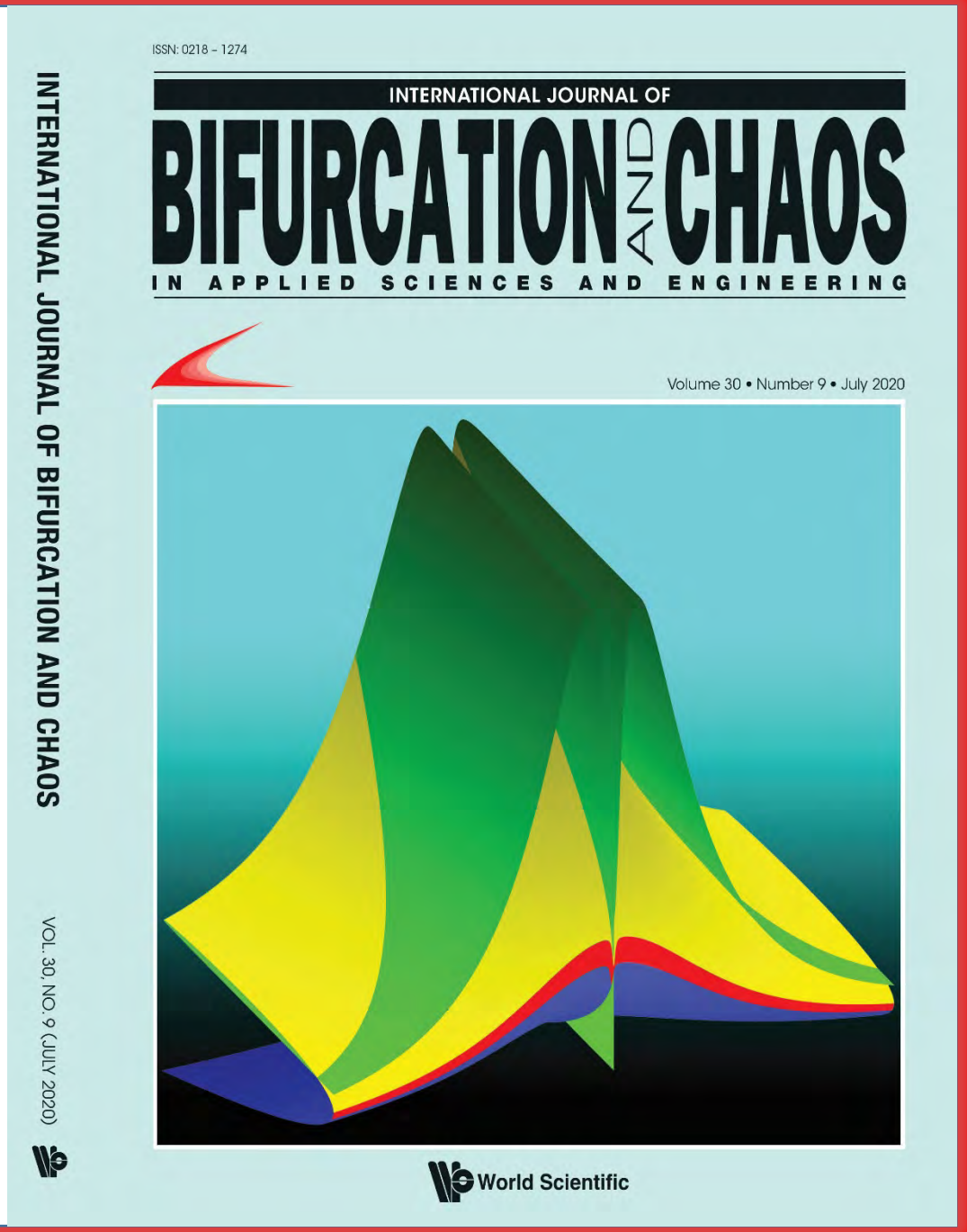
A Modified Hodgkin-Huxley circuit model of cardiac (Purkinje Fiber) Heart Muscle Reproduced from D. Noble [1962]



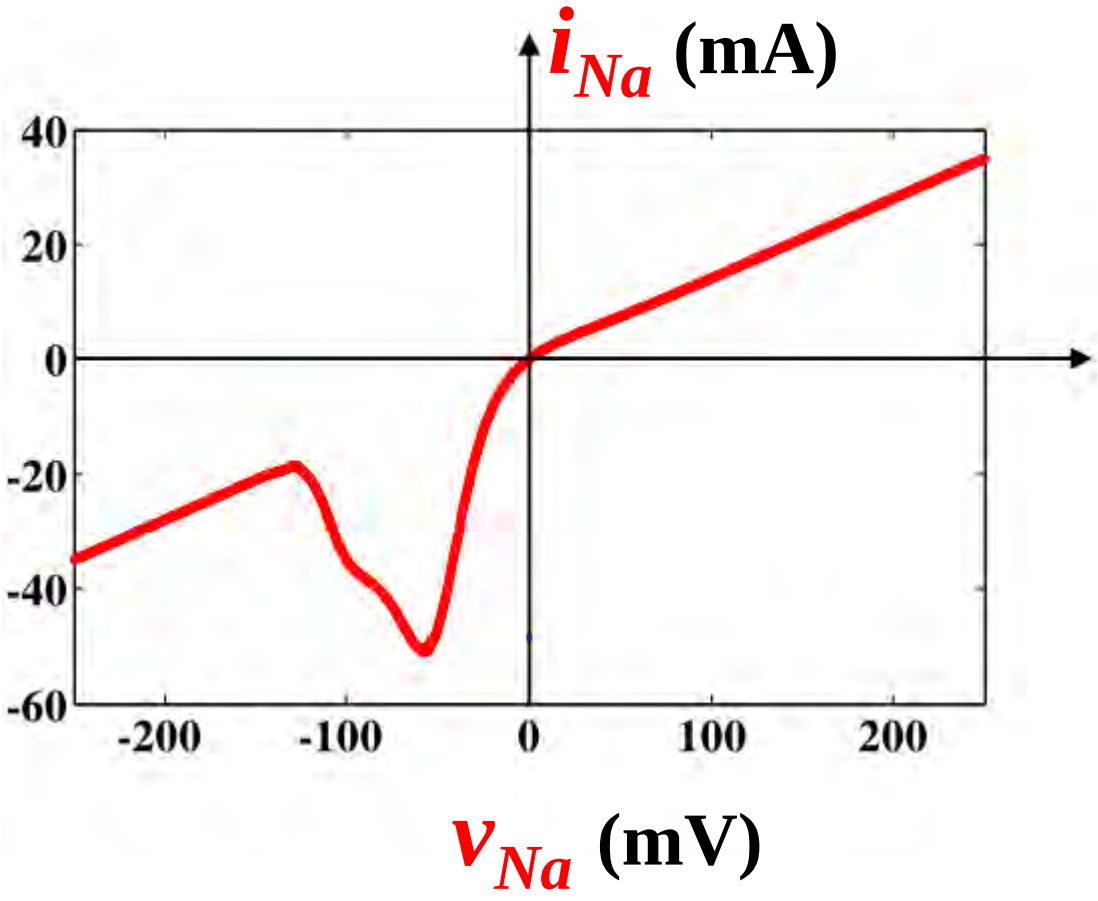
A modified Hodgkin-Huxley Memristive circuit model of Cardiac Heart Muscle driven by an external current source I_{ext}.

Hearts are Poised near the Edge of Chaos

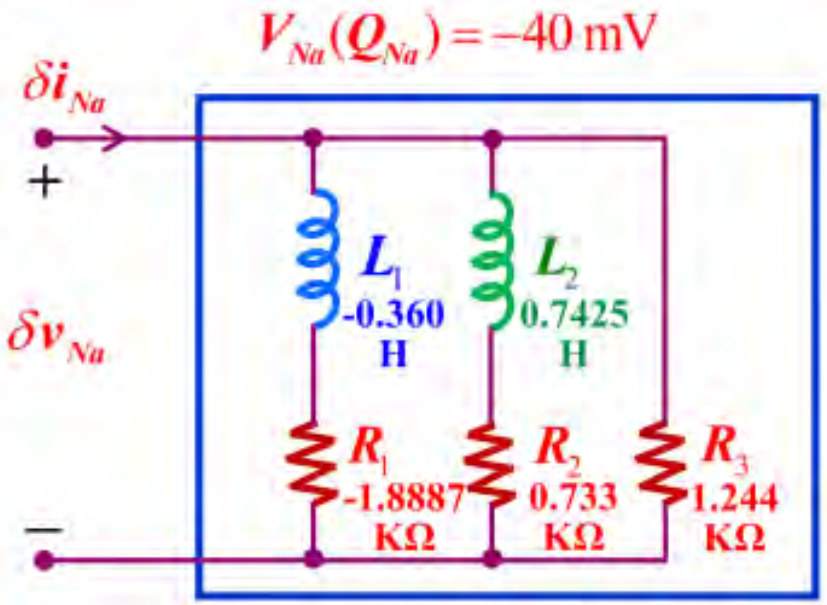




DC v_{Na} - i_{Na} curve of the Sodium Memristor for Cardiac Heart Muscle circuit model



Small-Signal Equivalent Circuit About An Operating Point of the Heart Muscle Sodium memristor



$$L_1 = -0.360\ H$$

$$R_1 = -1.8887\ K\Omega$$

239-Year Old Mystery Resolved !

The **all or none phenomenon** was discovered by ***Luigi Galvani*** in ***1781***, the **father of electrophysiology**, via an accidental contact he made between the **nerve** from the **spinal cord** and the **muscle fiber** from a freshly skinned **frog leg**.

It's been **239 years** since **Galvani's discovery** and no one has succeeded to explain rigorously, the physical and nonlinear dynamical mechanism which give rise to the **action potential**.

We have finally proved **analytically** and **quantitatively**, that the **all or none phenomenon** is a direct consequence of the

Edge of Chaos Criterion

, the **pearl** of the ***local activity principle***.

Opening Keynote Lecture at
ECCTD 2020 Sofia, Bulgaria,
Sept. 7-10, 2020

Edge of Chaos:

The *elan vital* of Complex Phenomena

Elan Vital

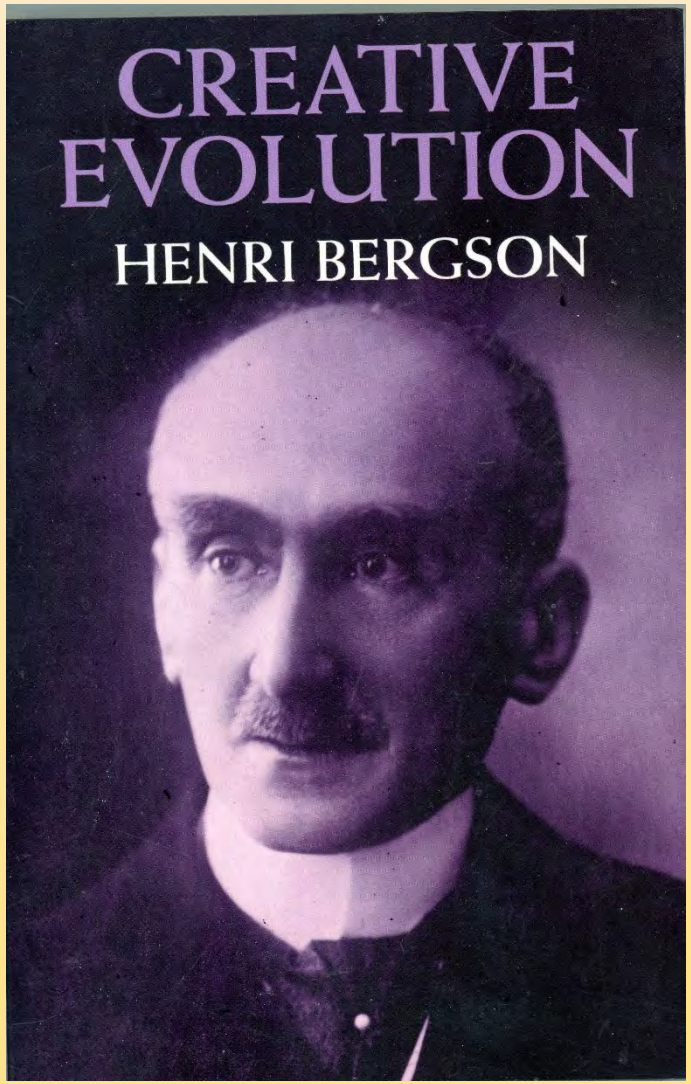
or

Vital Impetus

is an abstract, deep philosophical concept conceived

by the French philosopher

Henri Bergson in 1907.



Henri Bergson

1927 Nobel Prize

The Local Activity Principle

is the

Scientific Interpretation of
Bergson's Abstract Concept of

Elan Vital

List of the Publications Attributed to the Grant (May 2019-April 2020)

1. Xiaohong Zhang, Zhengze Wu and Leon Chua, "**Hearts are Poised Near the Edge of Chaos**," *International Journal of Bifurcation and Chaos*, vol. 30, no. 9, 2020.
2. A. Ascoli, I. Messaris, R. Tetzlaff, and L.O. Chua, "**Theoretical Foundations of Memristor Cellular Nonlinear Networks: Stability Analysis with Dynamic Memristors**," *IEEE Trans. on Circuits and Systems–I: Regular Papers*, vol. 67, no. 4, pp. 1389-1401, April 2020.
3. Eunhye Baek, Nikhil Ranjan Das, Carlo Vittorio Cannistraci, Taiuk Rim, Gilbert Santiago Cañón Bermúdez, Khrystyna Nych, Hyeonsu Cho, Kihyun Kim, Chang-Ki Baek, Denys Makarov, Ronald Tetzlaff, Leon Chua, Larysa Baraban & Gianaurelio Cuniberti, "**Intrinsic plasticity of silicon nanowire neurotransistors for dynamics memory and learning functions**," *Nature Eectronics*, no. 3, pp. 398-408, June 2020.
4. Ronald Tetzlaff, Alon Ascoli, Ioannis Messaris, Leon O. Chua, "**Theoretical Foundations of Memristor Cellular Nonlinear Networks: Memcomputing with Bistable-Like Memristors**," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 67, no. 2, pp. 502-515, Feb 2020.

List of the Publications Attributed to the Grant (May 2019-April 2020)

5. Zubaer Ibna Mannan, Hyongsuk Kim, "**Nonlinear Dynamics, Switching Kinetics and Physical Realization of the Family of Chua Corsage Memristors**," *Electronics* vol. 9, no. 2, pp. 369-388, February 2020.
6. Zubaer Ibna Mannan, Shyam Prasad Adhikari, Hyongsuk Kim, "**Global dynamics of Chua Corsage Memristor circuit family: fixed-point loci, Hopf bifurcation, and coexisting dynamics attractors**," *Nonlinear Dynamics*, vol. 99, pp. 3169-3196, February 2020.
7. JackA.Tuszynski, Douglas Friesen, Holly Freedman, Valery I. Sbitnev, Hyongsuk Kim, Iara Santelices, Aarat P. Kalra, Sahil D. Patel , Karthik Shankar and Leon O. Chua, "**Microtublues as Sub-Cellular Memristors**," *Scientific Reports* 10, 2108, February 2020.
8. O. Pabst, Ø.G. Martinsen and Leon Chua, "**Information can be stored in the human skin Memristor which has non-volatile memory**," *Scientific Reports* 9, 19260, December 2019.

List of the Publications Attributed to the Grant (May 2019-April 2020)

9. Mauro Di Marco, Mauro Forti, Fernando Corinto, Leon Chua, "**Unfolding nonlinear dynamics in computing systems with mem-elements**," *2019 26th IEEE International Conference of Electronics, Crcuits and Systems (ICECS),* Genova Italy, November 27-29, 2019.

10. Leon Chua, Georgios Sirakoulis and Andrew Adamatzky **(Eds.)** , **Handbook of Memristor Networks**, Springer, 2019 (ISBN 978-3-319-76375-0), (1386 Pages).

11. Leon Chua, "-The Fourth Element", in Chua et al. (eds.), **Handbook of Memristor Networks, Springer**, 2019, pp. 1-14.

12. Leon Chua, "If It's Pinched It's a Memristor", in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 15-88.

13. Leon Chua, "Everything You Wish to Know About Memristor but Are Afraid to Ask", in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 89-158.

List of the Publications Attributed to the Grant (May 2019-April 2020)

14. Shyam Parasad Adhikari, Maheshwar Pd. Sah, Hyongsuk Kim, Leon Chua, “Three Fingerprints of Memristor”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 165-196.
15. Leon Chua, “Resistance Switching Memories are Memristors”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 197-230.
16. Gaurav Gandhi, Vann Aggarwal, Leon Chua, “The Detectors Used in the First Radios were Memristors”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 231-246.
17. Shyam Parasad Adhikari, Hyongsuk Kim, “Why Are Memristor and Memistor Different Devices”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 247-266.
18. Leon Chua, “Memristor, Hodgkin-Huxley and Edge of Chaos”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 287-314.

List of the Publications Attributed to the Grant (May 2019-April 2020)

19. Maheshwar Pd. Sah, Hyongsuk, Leon Chua, “Brains Are Made of Memristors”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 315-350.
20. Hyongsuk Kim, Maheshwar Pd. Sah, Changju Yang, Tamas Roska, Leon Chua, “Memristor Bridge-Based Artificial Neural Weighting Circuit”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 619-636.
21. Ram Kaji Budhathoki, Maheshwar Pd. Sah, Shyam Prasad Adhikari, Hyongsuk Kim, Leon Chua, “Behavior of Multiple Memristor Circuits”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 913-940.
22. Makoto Itoh, Leon Chua, “Memristor Cellular Automata and Memristor Discrete-Time Cellular Neural Networks”, in Chua et al. **(Eds.)** , ***Handbook of Memristor Networks***, Springer, 2019, pp. 1289-1362.
23. Fernando Corinto, Mauro Di Marco, Mauro Forti, Leon Chua, “**Nonlinear Networks with MemElements: Complex Dynamics via Flux-Charge Analysis Method**,” *IEEE Transactions on Cybernetics*, April 3, 2019 (Early Access).

List of the Publications Attributed to the Grant (May 2019-April 2020)

24. Olga Krestinskaya, Alex Pappachen James, Leon Ong Chua, "**Neuromemristive circuits for edge computing: A review**," *IEEE Transactions on Neural Networks and Learning Systems*, March 14, 2019 (Early Access).

25. Zubaer Ibna Mannan, Shyam Prasad Adhikari, Changju Yang, Ram Kaji Budhathoki, Hyongsuk Kim, Leon Chua, "**Memristive Imitation of Synaptic Transmission and Plasticity**," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 30, no. 11, pp. 3458-3470, Feb 11, 2019.

26. Frank Z Wang, Ling Li, Luping Shi, Huaqiang Wu, Leon O Chua, "**Φ memristor: Real memristor found**," *AIP Journal of Applied Physics*, vol. 125, no. 5, pp. 054504 , February 7, 2019.

27. Arturo Buscarino, Claudia Corradino, Luigi Fortuna, L.O. Chua, "**Taming Spatiotemporal Chaos in Forced Memristive Arrays**," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 26, no. 12, pp. 2947-2954, December 2018.

28. Oliver Pabst, Ørjan G. Martinsen, Leon Chua, "**The non-linear electrical properties of human skin make it a generic Memristor**," *Scientific Reports*, 8: 15806, pp. 1-9, 2018.

List of Honors Attributed to the Grant

1. Recipient of the IEEE Devices Society "**2019 Celebrated Member Award**". This is the most prestigious award from the EDS Society, which includes 3 Nobel laureates(George Smith in 2010, Herb Kroemer in 2011, and Leo Esaki in 2012), and several luminaries, including Robert Dennard in 2015 and Gordon Moore in 2017.

2. Recipient of the 2020 Julius Springer Prize for Applied Physics.

Opening Keynote Lectures

1. **Edge of Chaos: The *elan vital* of complex phenomena** , International Virtual Conference on ECCTD 2020, September 7-10, 2020, Sofia, Bulgaria.
2. **Memristor: Remembrance of things Past and Missed Opportunities**, Inaugural Chua Memristor Institute Conference on Theory, Devices and Applications, November 11-14, 2019, Wuhan, China.
3. **Shocking Phenomena Uncovered from Hodgkin-Huxley Equations**, International Conference on Memristive Materials, Devices and Systems, July 8-11, 2019, Dresden, Germany.
4. **Memristor: Remembrance of things Past**, Supercomputing Frontiers Europe, March 11-14, 2019, Warsaw, Poland.

Opening Keynote Lectures

5. **2018 12th Spanish Conference on Electron Devices (CDE),** November 11-14, 2018, Hospedería del Colegio Fonseca, Salamanca, Spain.
6. **MemoCIS 8th Workshop And MC Meeting on Memristors – Devices, Models, Circuits**,
   Systems and Applications, September 20-21, 2018, Technische Universität Dresden, Germany.
7. **Advances in Neural Networks and Applications 2018 (ANNA' 18),** September 15-17, 2018, Frederic Joliot-Curie International House of Scientists St. Konstantin and Elena Resort,
   Bulgaria.
8. **International Symposium " Volga Neuroscience Meeting-2018"**
   20 things You Didn't know about Memrisotrs
   Nizhny Novgorod, Russia, July 22-27, 2018.