MEMRISTORS

Tea talk

13 May 2014

WHAT'S A MEMRISTOR?

- Memory-resistor:
  the missing 4th circuit element
- predicted by Leon Chua (1971)
  Einstein of Circuit Theory ?
- discovered by HP guys (2008)
- a big hype - we can now do a lot more with circuits! Really? (such as building brain-like computers!?)

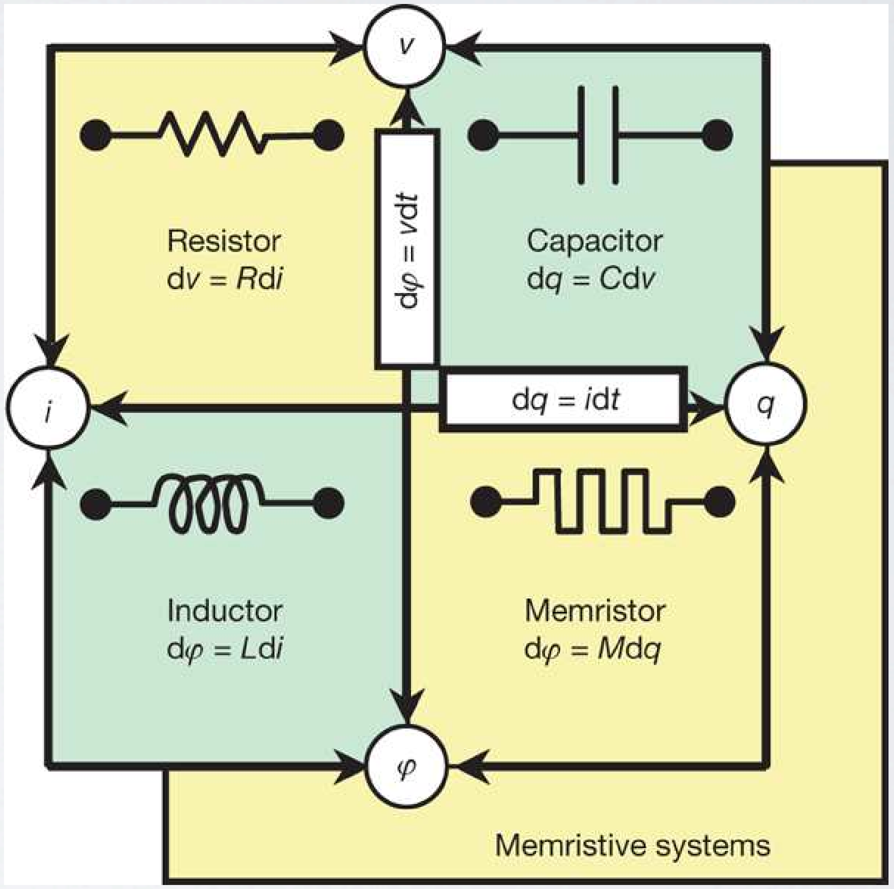


FIG. 1: Figure adapted from *Nature*.

4 BASIC CIRCUIT VARIABLES

- voltage v
- current i
- charge q
- magnetic flux ϕ

$$q = \int i \, dt \qquad \phi = \int v \, dt$$

CIRCUIT ELEMENTS

- A circuit element is:

  any device that imposes a relationship between two circuit variables

- Resistor: $v - i$
- Capacitor: $q - v$
- Inductor: $\phi - i$

4 BASIC CIRCUIT VARIABLES

4 FUNDAMENTAL CIRCUIT ELEMENTS?

- voltage v
- current i
- charge q
- magnetic flux ϕ

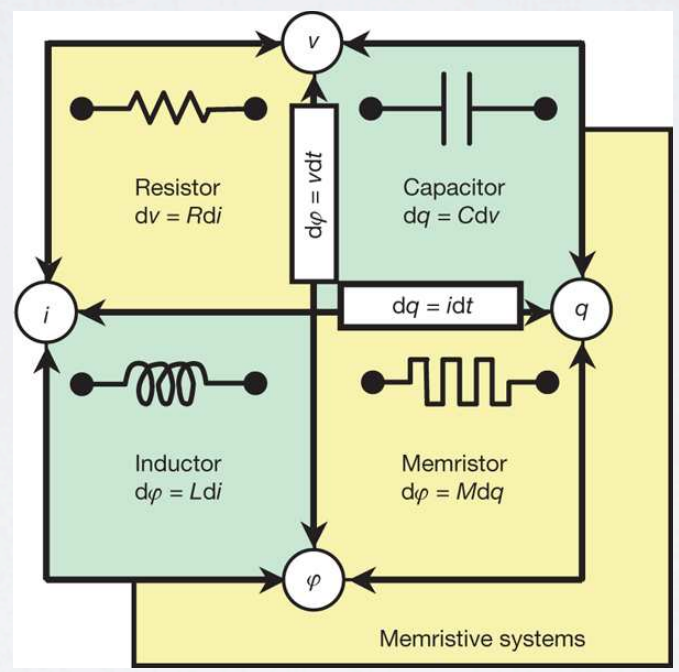


FIG. 1: Figure adapted from *Nature*.

- Resistor: $v - i$
- Capacitor: $q - v$
- Inductor: $\phi - i$

$$q = \int i \, dt \qquad \phi = \int v \, dt$$

4 BASIC CIRCUIT VARIABLES

- voltage v
- current i
- charge q
- magnetic flux ϕ

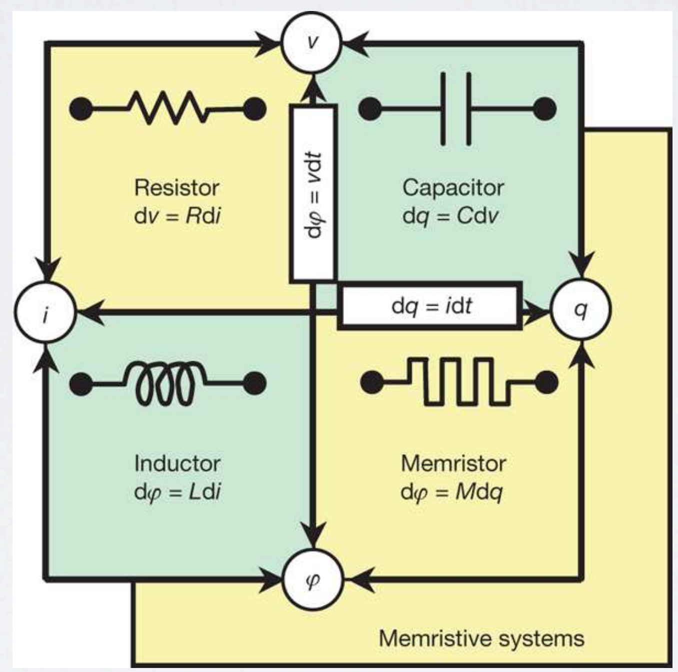


FIG. 1: Figure adapted from *Nature*.

4 FUNDAMENTAL CIRCUIT ELEMENTS?

- Resistor: $v - i$
- Capacitor: $q - v$
- Inductor: $\phi - i$
- Memristor: $\phi - q$

$$q = \int i \; dt \qquad \phi = \int v \; dt$$

4 BASIC CIRCUIT VARIABLES

4 FUNDAMENTAL CIRCUIT ELEMENTS?

- voltage v
- current i
- charge q
- magnetic flux ϕ

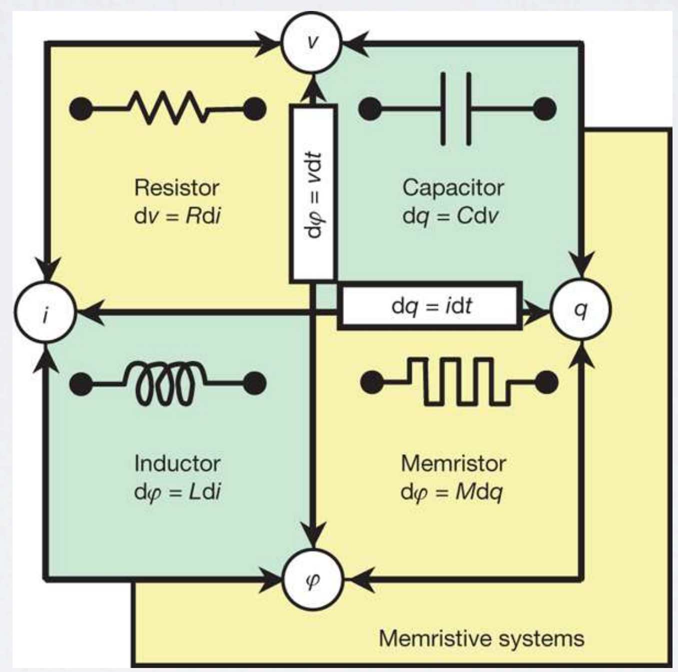


FIG. 1: Figure adapted from *Nature*.

$$R = \frac{dv}{di}$$

$$C = \frac{dq}{dv}$$

$$L = \frac{d\phi}{di}$$

$$M = \frac{d\phi}{dq}$$

$$q = \int i\ dt \qquad \phi = \int v\ dt$$

4 ELEMENT THEORY

- Chua

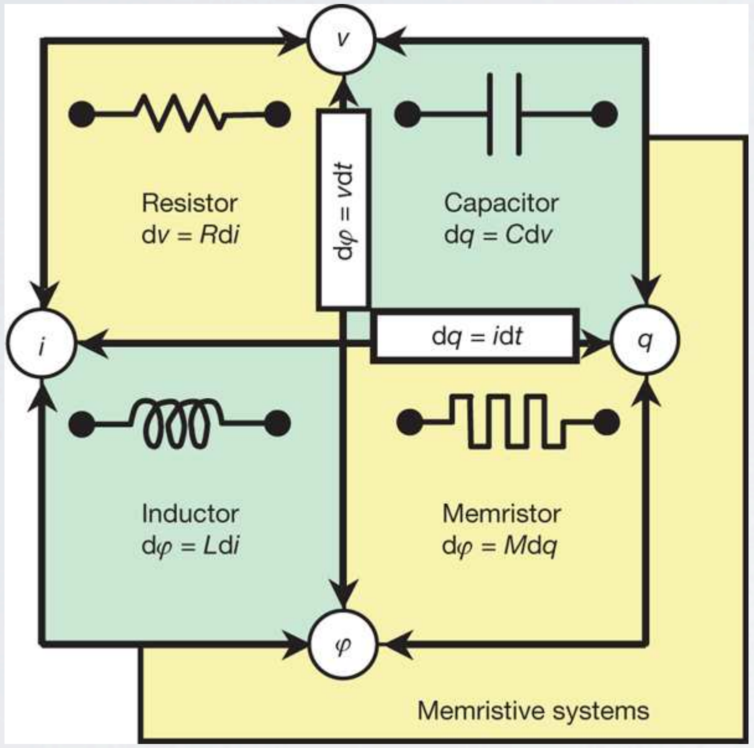


FIG. 1: Figure adapted from *Nature*.

- Aristotle

MEMRISTOR IS FUNDAMENTAL

- Because M cannot be replicated by combining other passive elements: R,L,C
- Transistor is not fundamental
- R,L,C are LTI (Linear-time-invariant). M is not.

- but M can be replicated with active elements (amplifier)

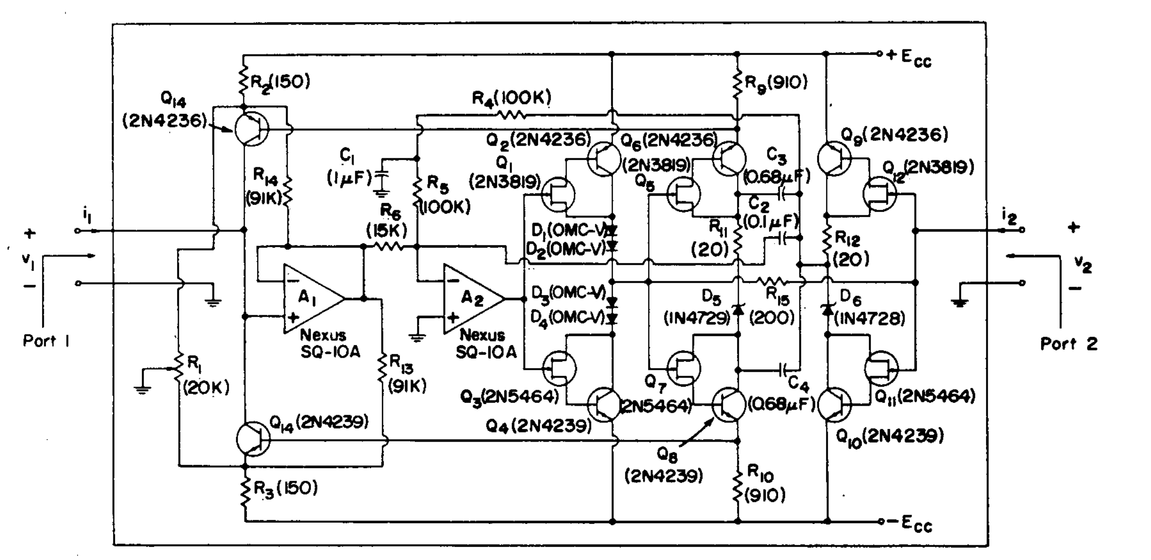


Fig. 2. Practical active circuit realization of type-1 *M–R* mutator based on realization 1 of Table I.

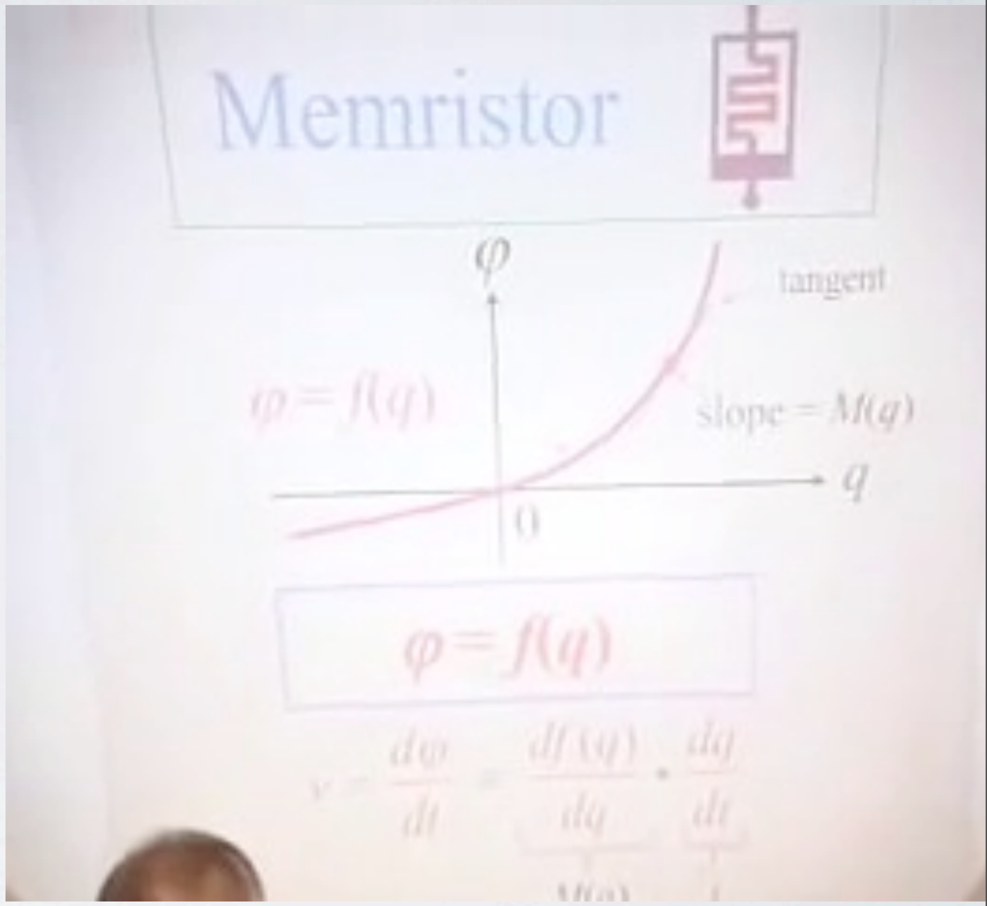
MEMRISTOR

- Charge - Flux relationship

$$\phi = f(q)$$

$$\frac{d\phi}{dt} = M(q)\frac{dq}{dt} \qquad\qquad M(q) = f(q)'$$

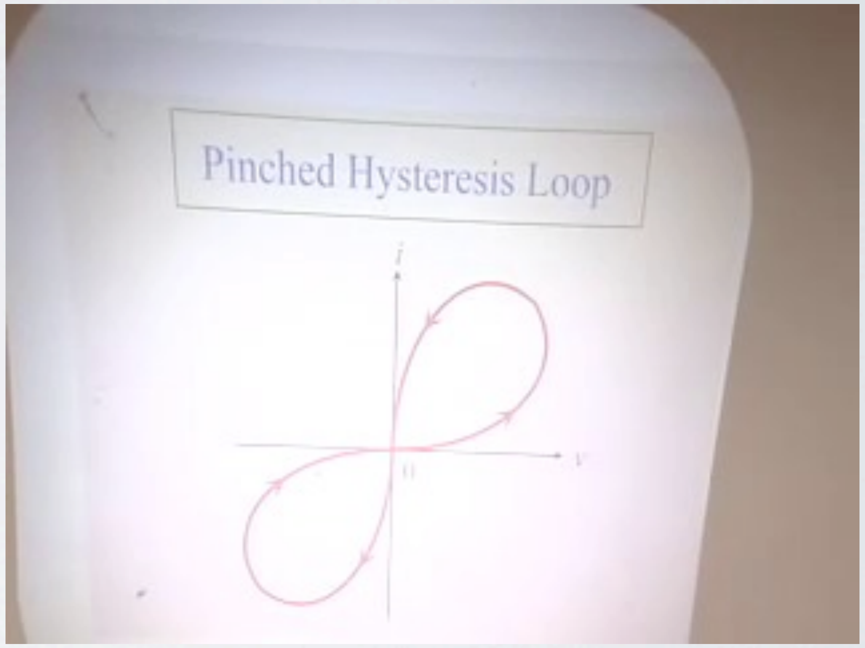
$$v = M(q)\ i$$

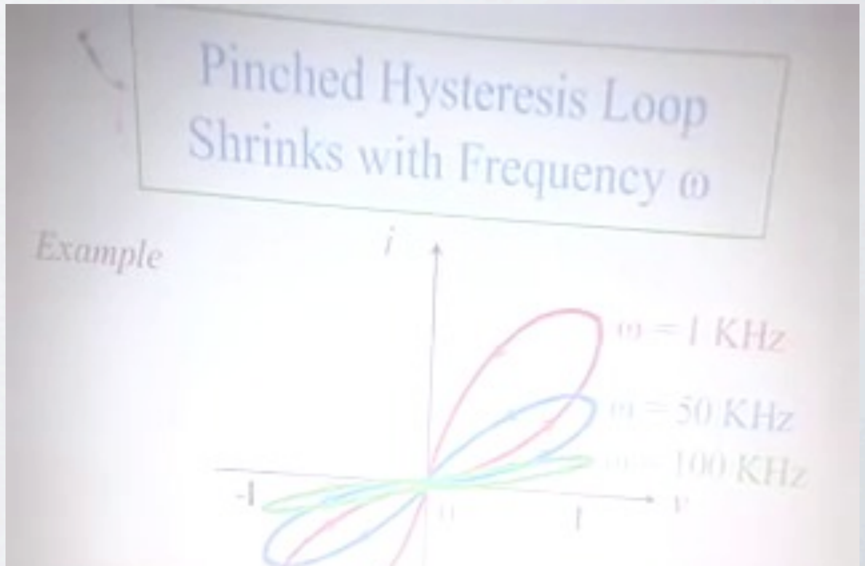


$$M = \frac{d\phi}{dq} = \frac{d\phi/dt}{dq/dt} = \frac{v}{i}$$

EXPERIMENTAL CHECK

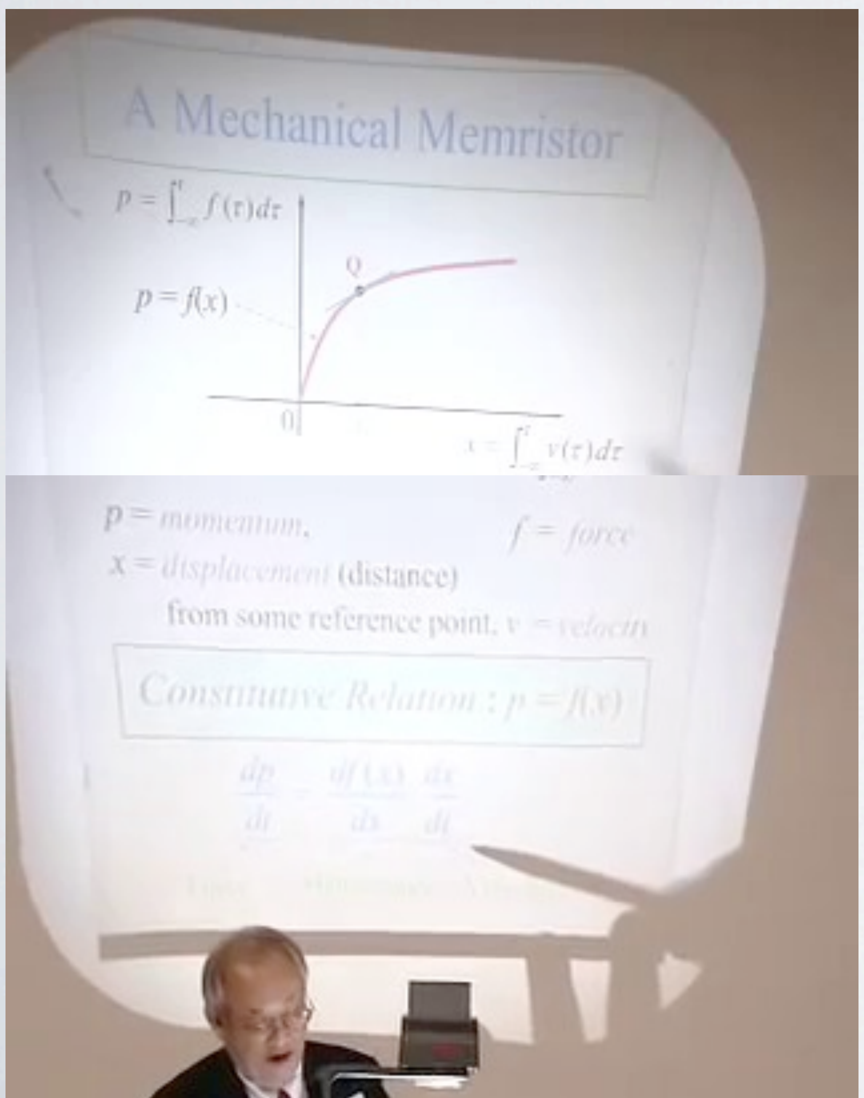
- You have a memristor if&f
  - it exhibits a pinched hysterisis loop,
  - the loop shrinks with freq, and
  - it shrinks to a straight line

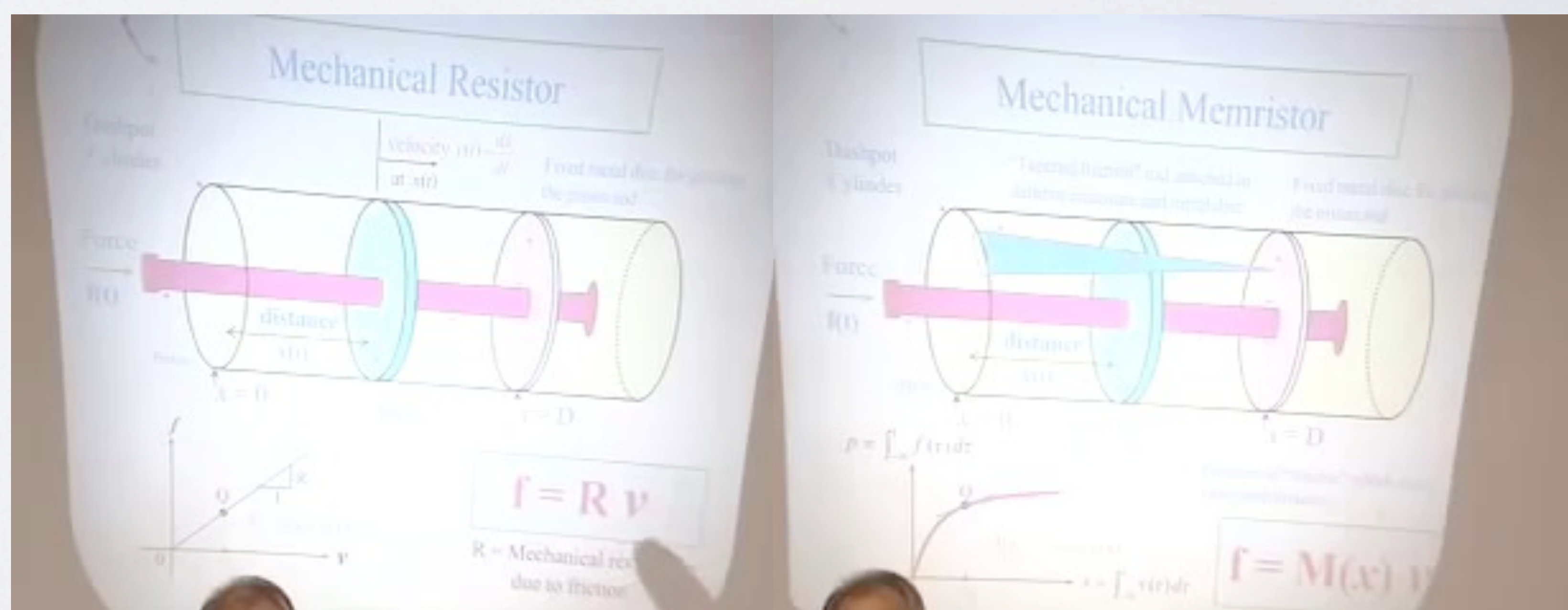




MECHANICAL MEMRISTOR

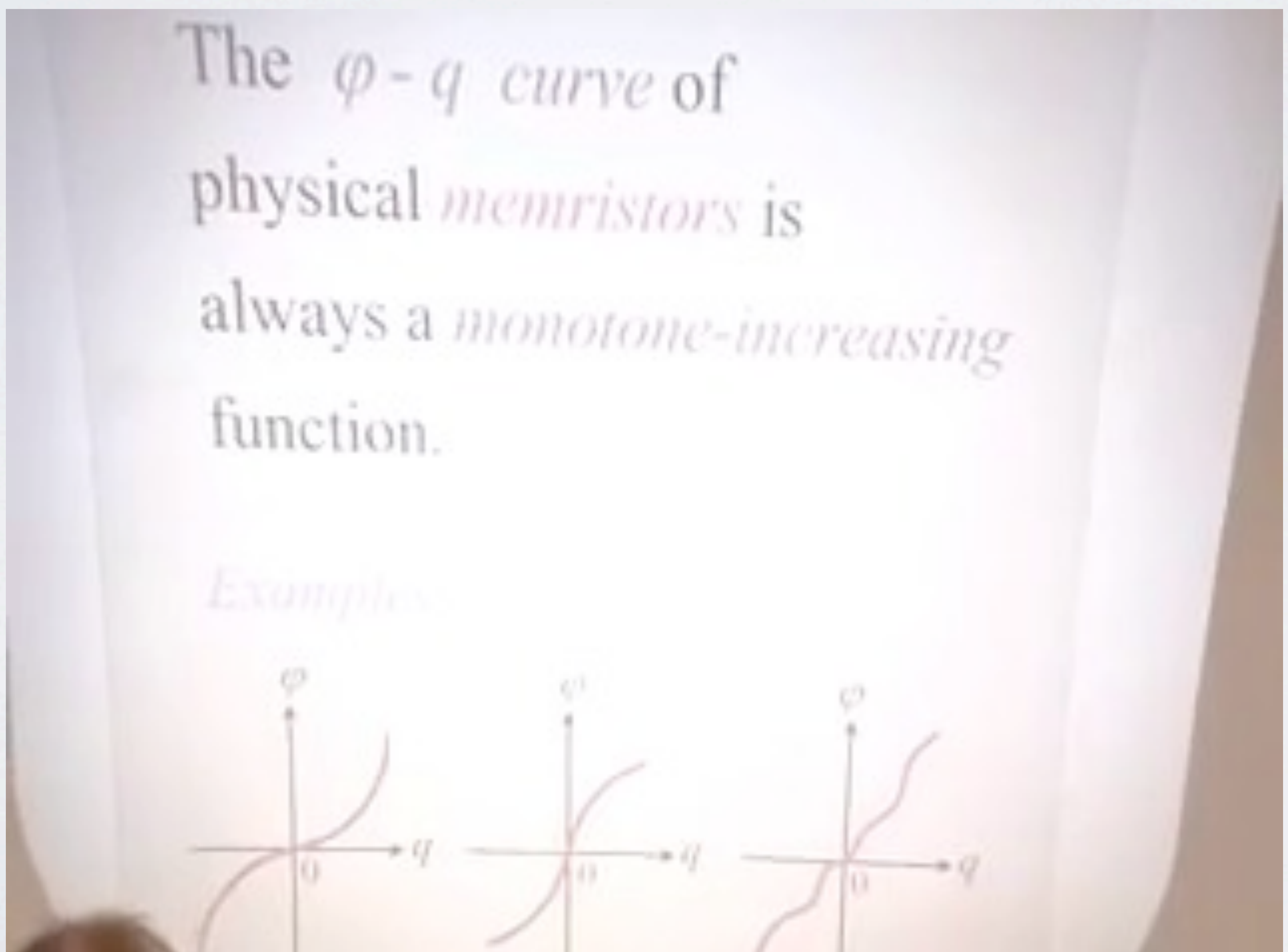
- just for illustration





THEOREM

- PASSIVE MEMRISTOR IS FEASIBLE
  - IF&F



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

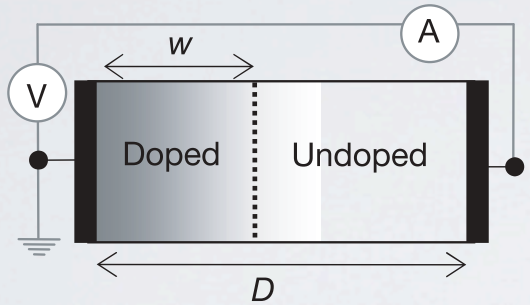
The missing memristor found

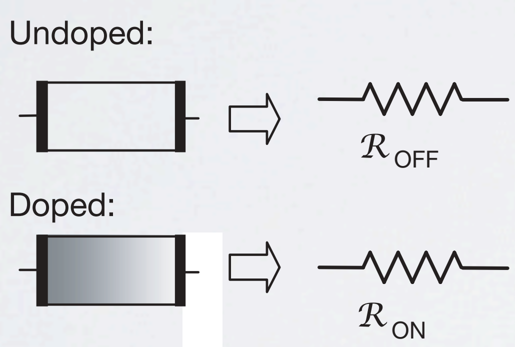
Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

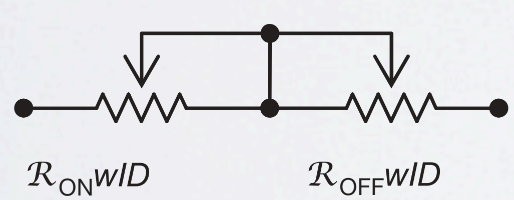
- Tungsten oxide semiconductor

$$v(t) = \left(\mathcal{R}_{\mathrm{ON}} \frac{w(t)}{D} + \mathcal{R}_{\mathrm{OFF}} \left(1 - \frac{w(t)}{D}\right)\right) i(t)$$

$$\frac{\mathrm{d}w(t)}{\mathrm{d}t} = \mu_{\mathrm{V}} \frac{\mathcal{R}_{\mathrm{ON}}}{D} i(t)$$

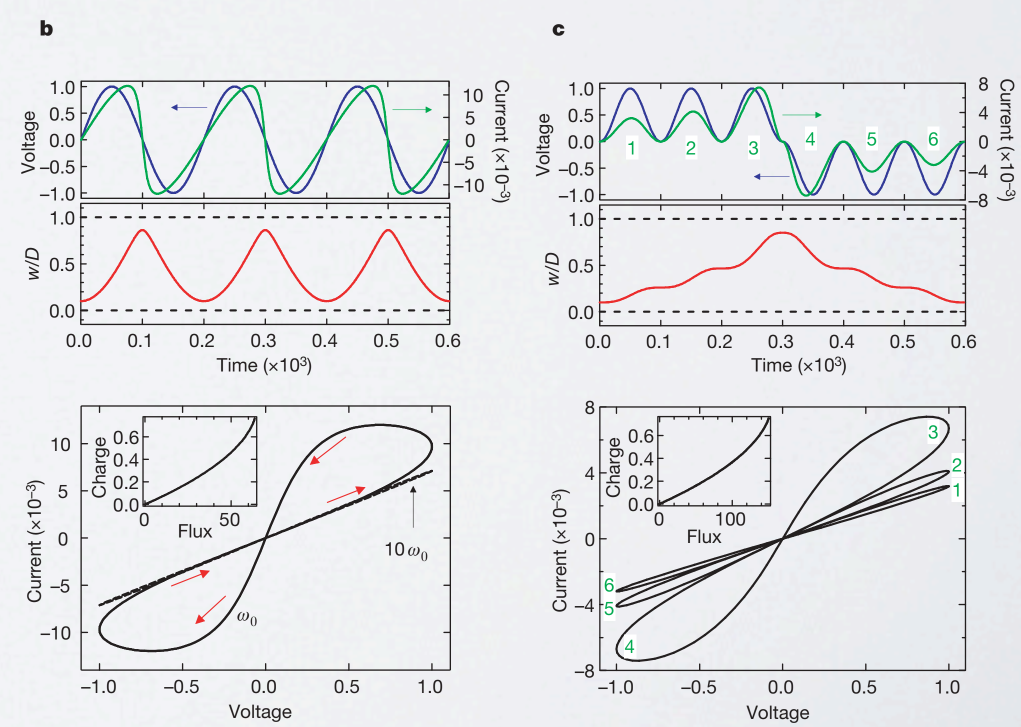






$$w(t) = \mu_{\mathrm{V}} \frac{\mathcal{R}_{\mathrm{ON}}}{D} q(t)$$

$$M(q) = \mathcal{R}_{\mathrm{OFF}} \left(1 - \frac{\mu_{\mathrm{V}} \mathcal{R}_{\mathrm{ON}}}{D^2} q(t)\right)$$



GENERALIZATION: MEMRISTIVE SYSTEMS

- any resistive system with internal state variables is memristive

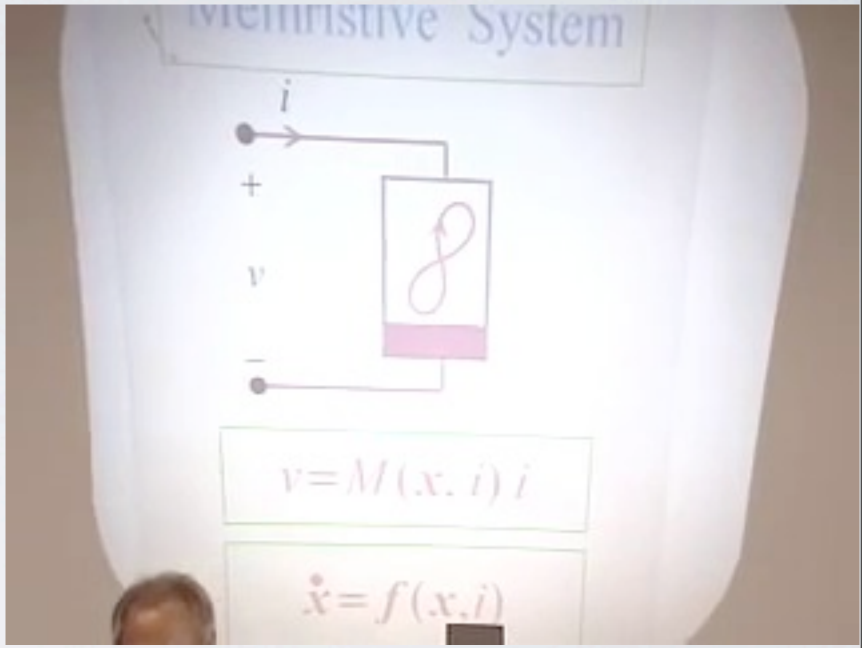
$$v(t) = M(\vec{x}, i)\ i(t) \qquad\qquad i(t) = M(\vec{x}, v)^{-1}\ v(t)$$

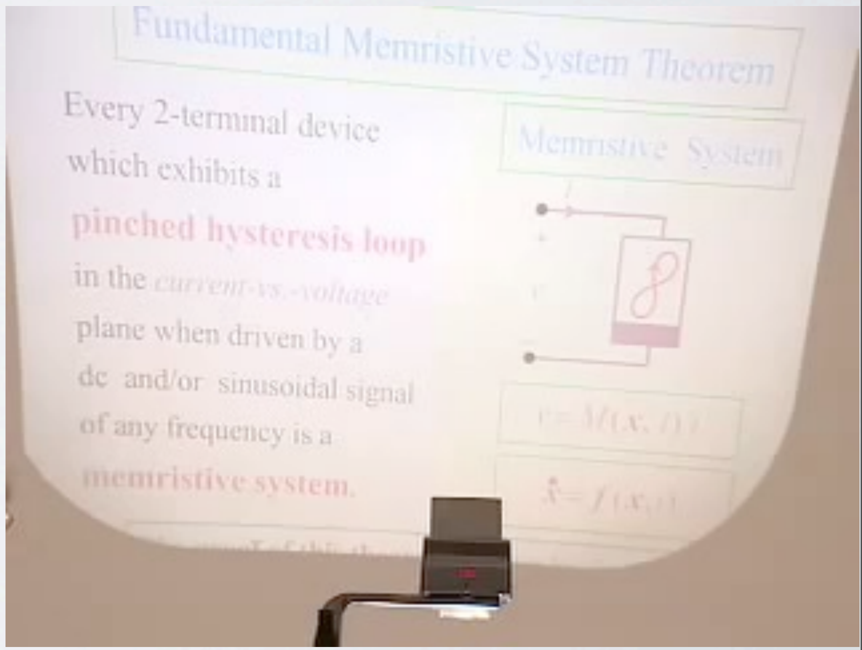
$$\dot{x} = g(\vec{x}, i) \qquad\qquad \dot{x} = g(\vec{x}, v)$$

current controlled or voltage controlled

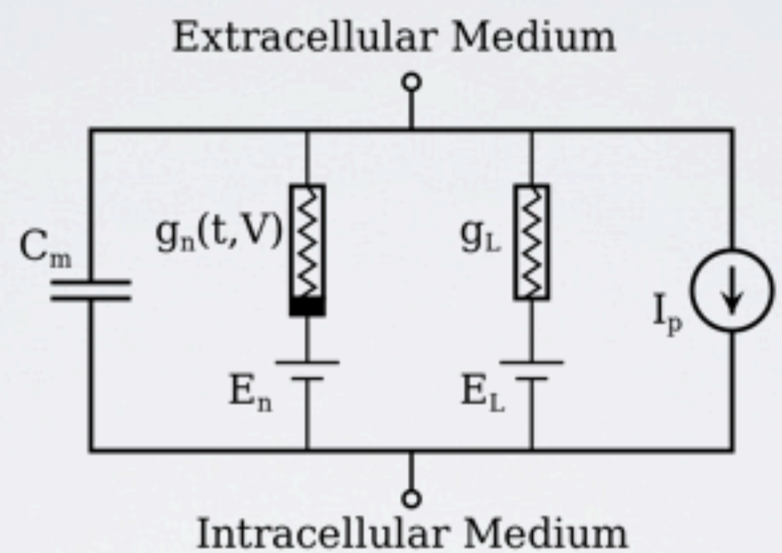
- e.g. thermistor (x = temperature)

- **Theorem**: every system with a pinched hysteresis is memristive





HH NEURON MODEL IS MEMRISTIVE or memductive



$$I = C_m \frac{\mathrm{d}V_m}{\mathrm{d}t} + \bar{g}_K n^4 (V_m - V_K) + \bar{g}_{Na} m^3 h (V_m - V_{Na}) + \bar{g}_l (V_m - V_l),$$

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

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

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

APPLICATIONS

Neural Net Application:

Neuromorphic engineering of synapses http://www.artificialbrains.com/darpa-synapse-program#memristor-chip

Williams' solid-state memristors can be combined into devices called crossbar latches, which could replace transistors in future computers, given their much higher circuit density.

They can potentially be fashioned into non-volatile solid-state memory, which would allow greater data density than hard drives with access times similar to DRAM, replacing both components.[56] HP prototyped a crossbar latch memory that can fit 100 gigabits in a square centimeter,[9] and proposed a scalable 3D design (consisting of up to 1000 layers or 1 petabitper cm^3).[57] In May 2008 HP reported that its device reaches currently about one-tenth the speed of DRAM.[58] The devices' resistance would be read with alternating current so that the stored value would not be affected.[59] In May 2012 it was reported that access time had been improved to 90 nanoseconds if not faster, approximately one hundred times faster than contemporaneous flash memory, while using one percent as much energy.[60]

Memristor patents include applications in programmable logic,[61] signal processing,[62] neural networks,[63] control systems,[64] reconfigurable computing,[65] brain-computer interfaces[66]and RFID.[67] Memristive devices are potentially used for stateful logic implication, allowing a replacement for CMOS-based logic computation. Several early works in this direction are reported.[68] [69]

Memristor definition and criticism

According to the original 1971 definition, the memristor was the fourth fundamental circuit element, forming a non-linear relationship between electric charge and magnetic flux linkage. In 2011 Chua argued for a broader definition that included all 2-terminal non-volatile memory devices based on resistance switching. Williams argued that MRAM, phase change memory and RRAM were memristor technologies. Some researchers argued that biological structures such as blood and skin fit the definition. Others argued that the memory device under development by HP Labs and other forms of RRAM were not memristors but rather part of a broader class of variable resistance systems [19] and that a broader definition of memristor is a scientifically unjustifiable land grab that favored HP's memristor patents.[20]

Meuffels and Schroeder noted that one of the early memristor papers included a mistaken assumption regarding ionic conduction.[21] Meuffels and Soni discussed issues and problems in the realization of memristors.[4] They claimed that the physics behind the HP memristor model conflicts with fundamentals of solid state electrochemistry as the coupling of electronic/ionic diffusion currents was not considered. Additionally, they pointed to issues concerning fundamentals of non-equilibrium thermodynamics: the dynamic state equations set up for memristors like the HP memristor imply the possibility of violating Landauer's principle of the minimum amount of energy required to change "information" states in a system.[4] This critique was endorsed by Di Ventra and Pershin.[5]

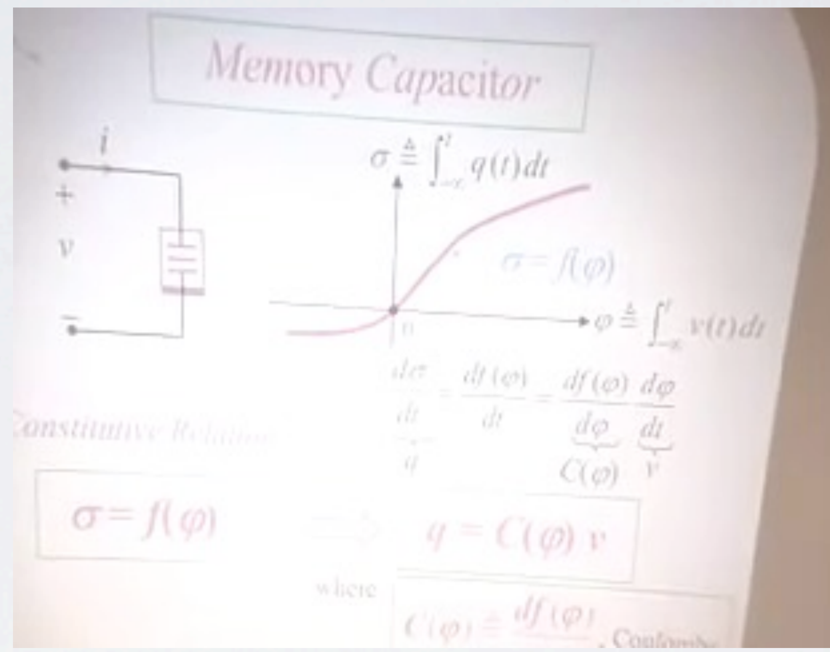
Nonvolatile information storage requires the existence of energy barriers that separate distinct memory states from each other.[4][5] Memristors whose resistance (memory) states depend only on the current (like the HP memristor) or voltage history would be unable to protect their memory states against unavoidable fluctuations and thus permanently suffer information loss: the proposed hypothetical concept provides no physical mechanism enabling such systems to retain memory states after the applied current or voltage stress is removed. Such elements can therefore not exist, as they would always be susceptible to a so-called "stochastic catastrophe".[5]

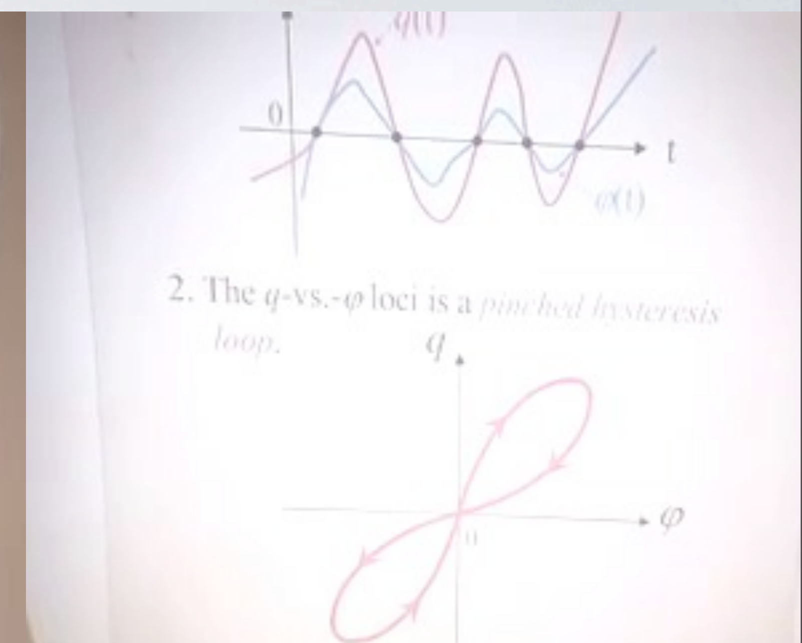
Other researchers noted that memristor models based on the assumption of linear ionic drift do not account for asymmetry between set time (high-to-low resistance switching) and reset time (low-to-high resistance switching) and do not provide ionic mobility values consistent with experimental data. Non-linear ionic drift models have been proposed to compensate for this deficiency.[22]

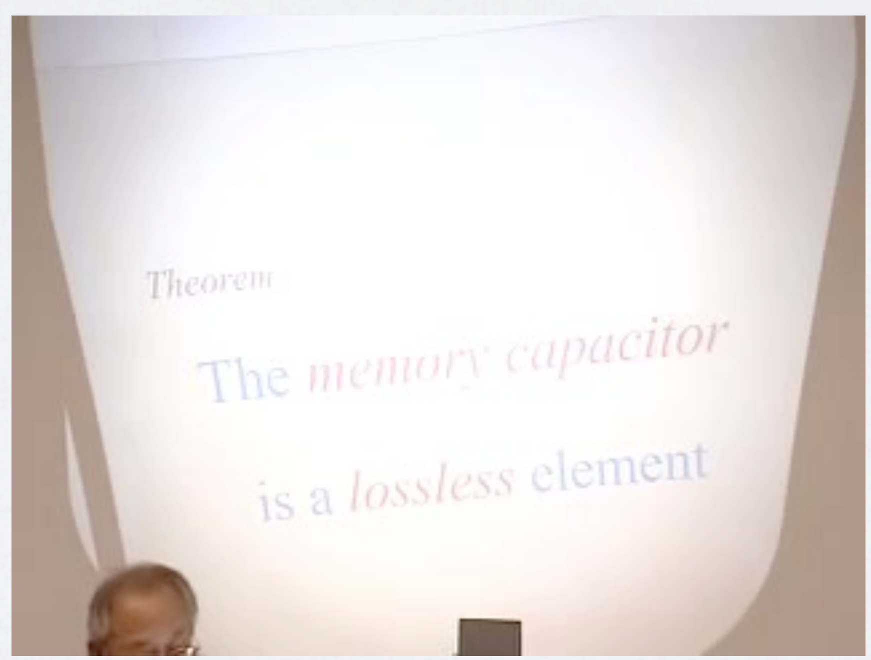
Yet another article from researchers of ReRAM concluded that "If the basic equations do not reflect the actual device physics well, as we see for the basic memristor equations, with or without window functions, low predictivity is given..".[23]

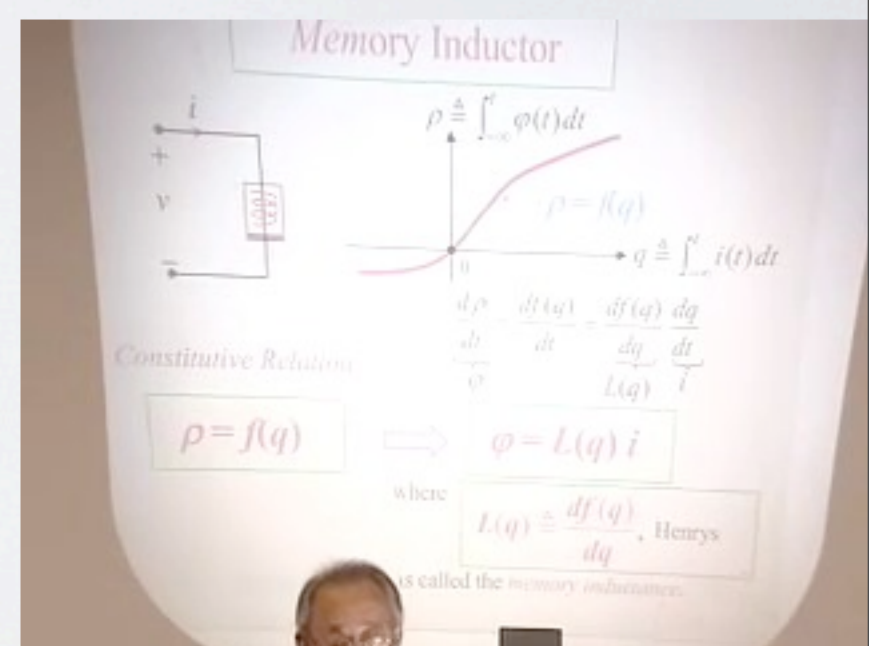
Martin Reynolds, an electrical engineering analyst with research outfit Gartner, commented that while HP was being sloppy in calling their device a memristor, critics were being pedantic in saying it was not a memristor.[24]

MEM-CAPACITORS, MEM-INDUCTORS..









THERE'S MORE

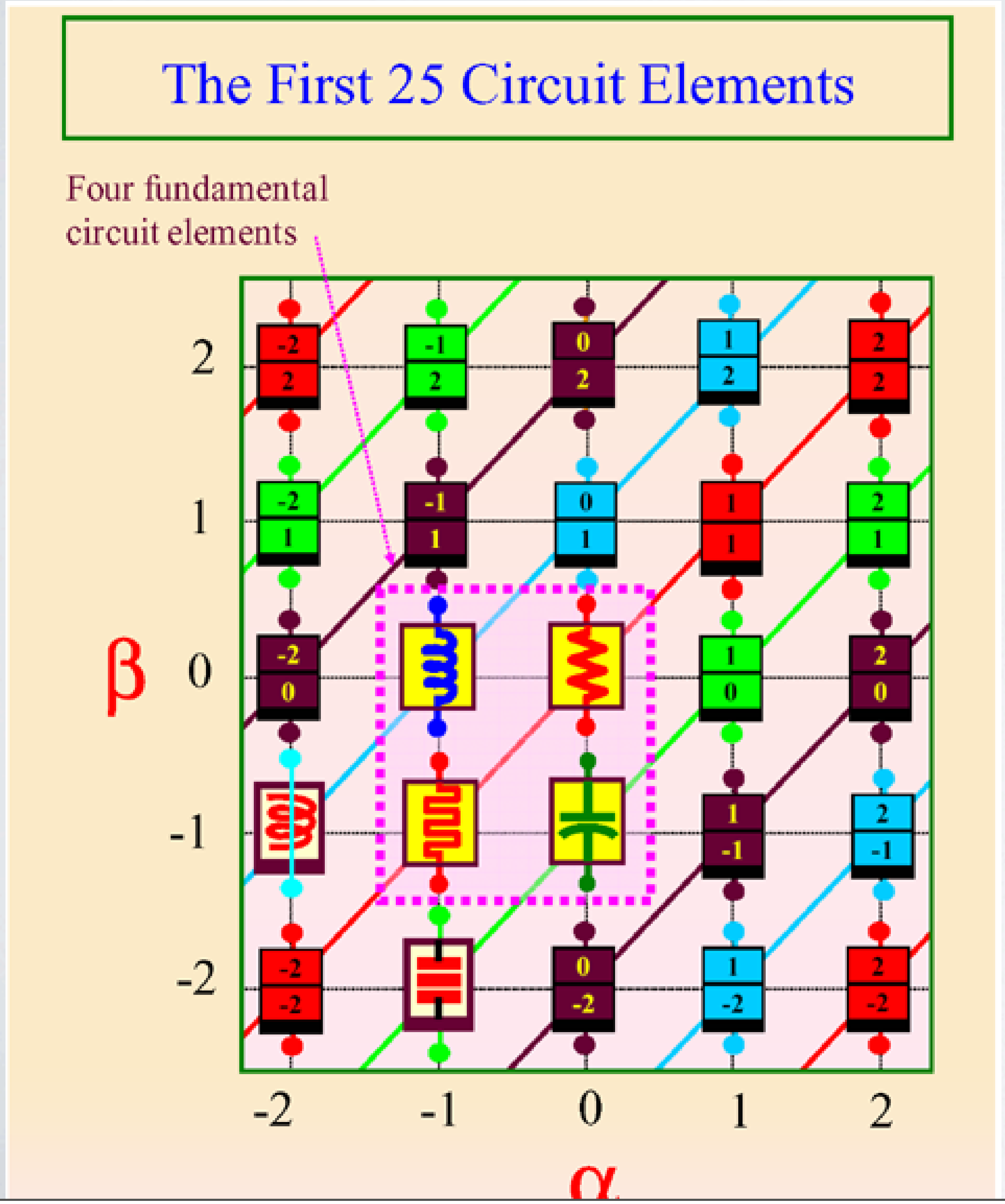


Fig. 11 An enlargement of the first 25 axiomatically defined circuit elements from the periodic table of circuit elements (Fig. 31 of [3]) where the four basic circuit elements (resistor, capacitor, inductors and memristor) are replaced by their symbols. The ***memcapacitor*** is located at (a, b) = (−1, −2) and the ***meminductor*** is located at (a, b) = (−2, −1). Observe that since these two elements require double time integrals of voltage and current, their dynamics are of a higher order than those of the four basic circuit elements enclosed inside the dotted *red box*

REFERENCES

- **Memristor**-the **missing circuit element**
  L Chua - **Circuit** Theory, IEEE Transactions on, 1971
  http://www.ufpi.br/subsiteFiles/zurita/arquivos/files/Memristor_chua_article.pdf

- The **missing memristor** found
  DB Strukov, GS Snider, DR Stewart, RS Williams - Nature, 2008
  http://www.ece.ucsb.edu/~strukov/papers/2008/Nature2008.pdf

- **Memristor for Introductory Physics**
  F Wang http://arxiv.org/pdf/0808.0286.pdf

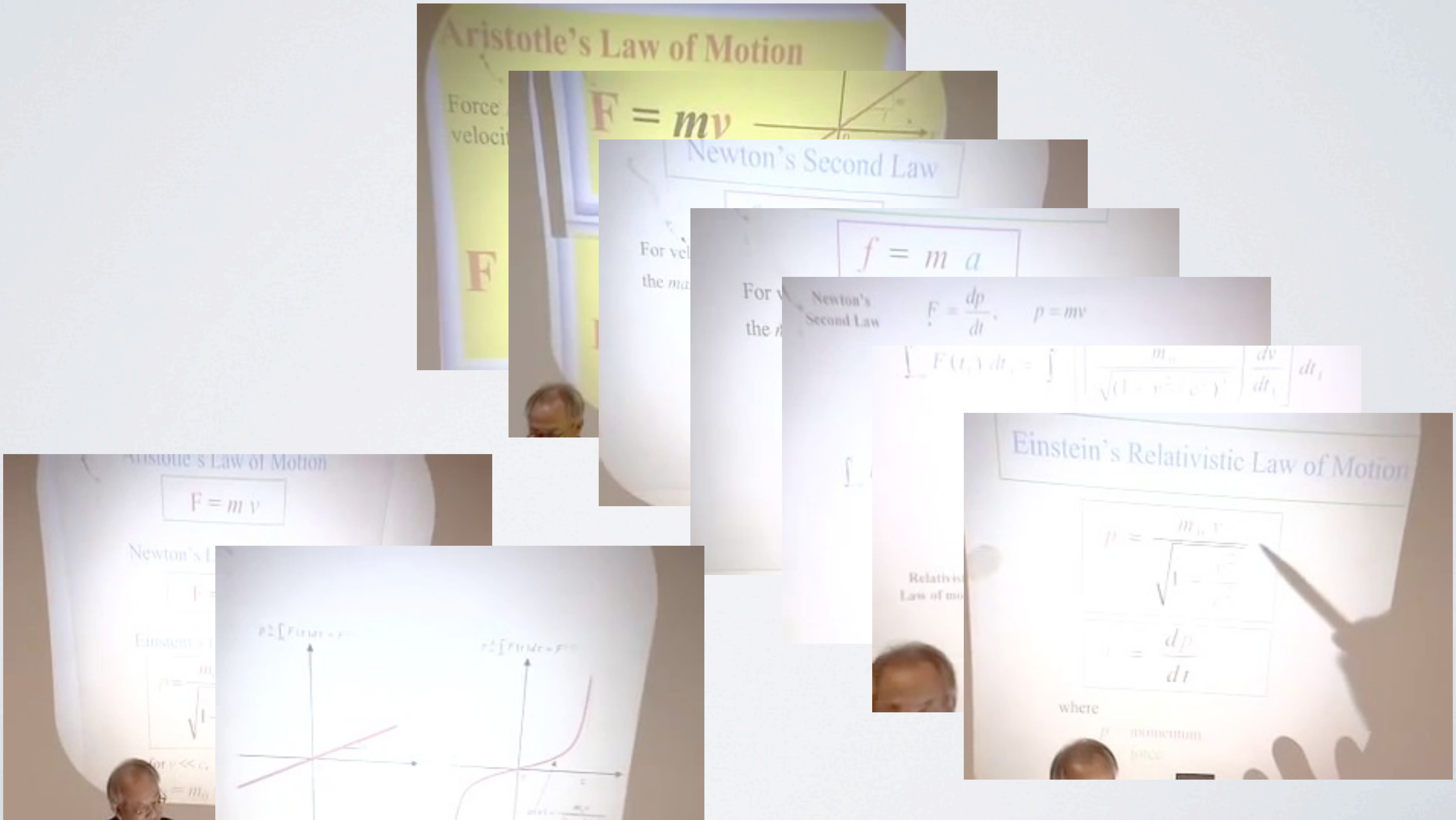
- **Resistance switching memories are memristors**
  Leon Chua http://goo.gl/k9Yn5N

How we found the **missing memristor**
R Williams - Spectrum, IEEE, 2008 - ieeexplore.ieee.org
http://dat175-memristor.googlecode.com/svn/trunk/Papers/MemristorSpectrum.pdf

- Circuit elements with memory: memristors, memcapacitors and meminductors
  Massimiliano Di Ventra, Yuriy V. Pershin, and Leon O. Chua, Fellow, IEEE
  http://arxiv.org/pdf/0901.3682.pdf

Memristor and Memristive Systems Symposium
http://youtu.be/QFdDPzcZwbs
http://youtu.be/o9u9o_ToQwM
http://youtu.be/h7cX_m5IKxk
http://youtu.be/PSnC_6U5tKI

http://www.artificialbrains.com/darpa-synapse-program#memristor-chip


Aristotle's Law of Motion
F = mv
Newton's Second Law
f = m a
Newton's Second Law
p = mv
Einstein's Relativistic Law of Motion
where
Aristotle's Law of Motion
F = m v