MEMRISTOR OPERATION AND APPLICATIONS

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MEMRISTOR – A RESISTOR WITH MEMORY

- The memristor is a device that contains memory and can remember its history even after it is removed from power.
- Its resistance is dependent on the voltage applied to it and the length of the voltage application.
- It functions like brain synapses do and can be used to emulate the human brain, which could help biomedical research topics regarding brain illnesses.
- It is a non-volatile random access memory (RRAM) and can remember its resistance until the next time it is turned on.
- That quality could be very useful as a form of memory storage for sensitive information on computers and other computing machinery.

MEMRISTOR OPERATION

HOW IT WORKS

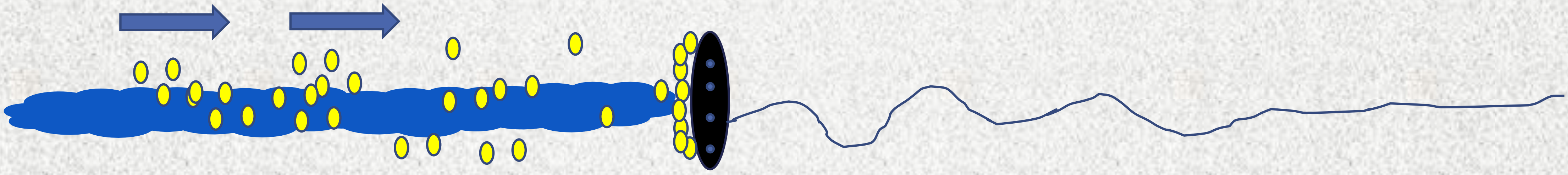
- The resistance in the memristor changes depending on the direction of the current that is traveling through the device.
- If charge flows in one direction, the resistance increases and if it flows in the opposite direction, the resistance decreases.
- If the voltage is turned off, the memristor remembers the resistance that it had when the voltage was on last.

IN SIMPLER TERMS

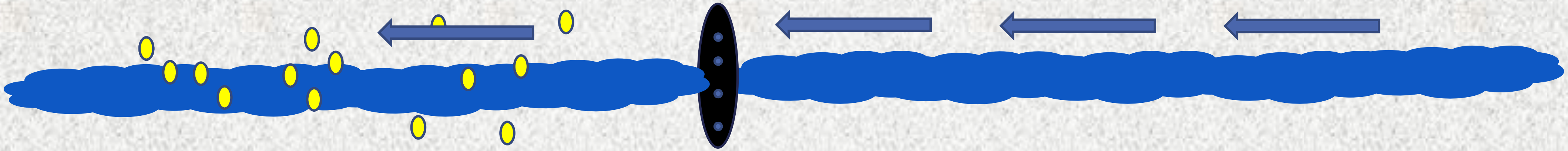
Electronic operation can be analogized to a hydraulic system.

- **Wire** → Pipe
- **Current** → Water Flowing In The Pipe
- **Voltage** → Pressure Controlling the Water
- **Memristor** → Sand Filter that catches sand as it flows through the water.
  - The accumulation of sand increases the resistance. Sending water the opposite way would clean out the sand and remove the resistance. The sand is held in the filter similar to how the memristor remembers its resistance. Even when sand stops coming (as voltage stops coming) the sand remains there, just as the memristor contains memory when the power is turned off.

MEMRISTOR AS A SAND FILTER



There is a higher resistance when sending water in one direction, and the stream of water making it through is very thin.



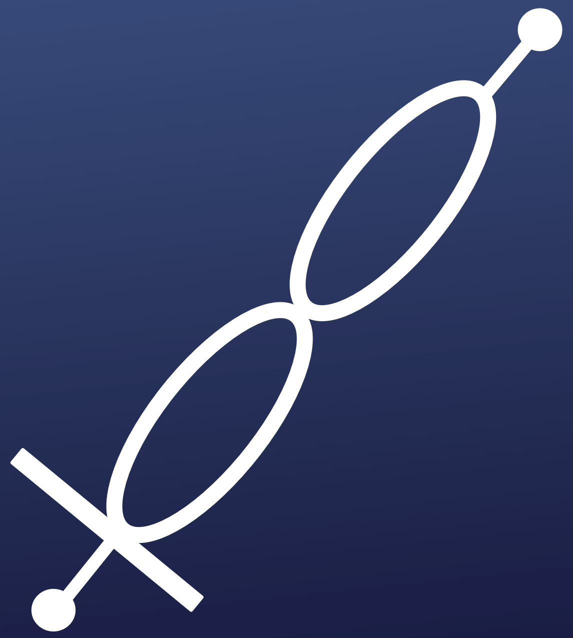
There is a lower resistance when sending water in the opposite direction as it pushes the sand out of the filter, and a full stream is able to flow.

When the water flow is stopped, the sand stays where it was in the filter and the amount stays the same. It does not disappear when the water is turned off.

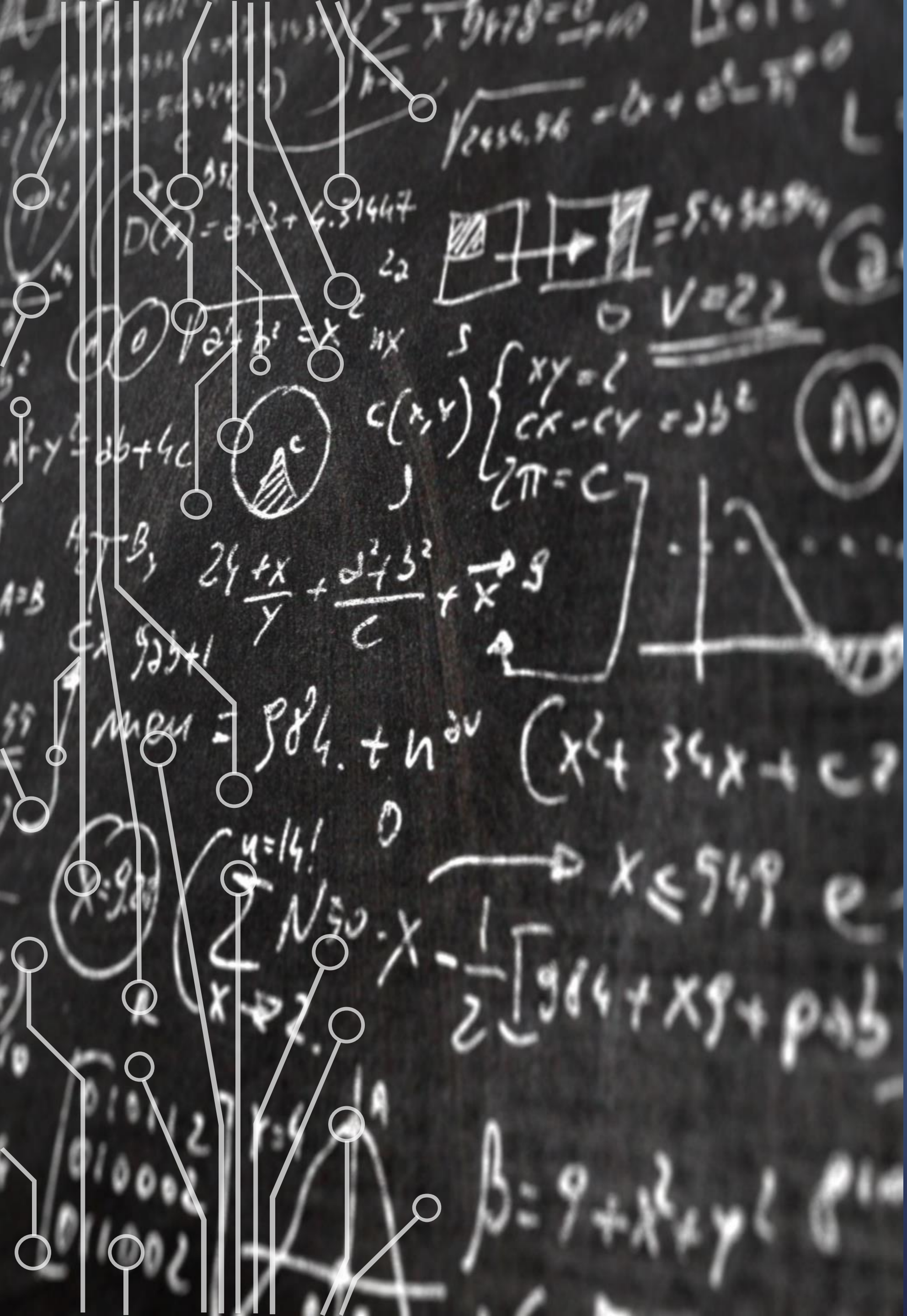
Memristor and Sand Filter Comparison Table

Sand Filter	Memristor
Sand	Charge
Water	Current
Filter	Memristor Device

THE FOURTH COMPONENT



- First theorized by Leon O. Chua at the University of California, Berkeley in 1971.
- The relationships between the quantities of current, charge, voltage and flux make up the basic equations of electrical components: resistors, capacitors and inductors. Chua realized that a combination of 4 components could make up 6 equations, rather than the 5 already used.
- He created a 6th equation and concluded that the equation would define the operation of the *memristor.*



THE 6 FUNDAMENTAL EQUATIONS

ACCORDING TO LEON O. CHUA

- <u>Memristance</u> → $M = \frac{\vartheta}{q}$
- <u>Capacitance</u> → $C = \frac{\varepsilon}{V}$
- <u>Resistance</u> → $R = \frac{V}{I}$
- <u>Inductance</u> → $L = \frac{\vartheta}{I}$
- <u>Flux & Voltage</u> → $V = \frac{d\vartheta}{dt}$
- <u>Charge & Current</u> → $i = \frac{dq}{dt}$

Where ϑ = flux, and q = charge

CHARGE & FLUX → CURRENT & VOLTAGE

Current and charge can be related to each other, although they are not the same.

Current is a measurement of the rate of flow of charge particles per second.	Charge is a physical quantity of the particles, electrons or protons.

Voltage and flux can be related to each other, although they are not the same.

Voltage is a quantity of electric potential difference, a force or pressure that drives the electrons through the conductor	Magnetic flux is a measurement of the electric field that passes through an area.

MEMRISTOR EQUATION - AS A FUNCTION OF CHARGE

- The memristor equation resembles that of Ohm's law: V=IR.
- The portion of the equation for resistance, R, is a function in the memristor equation.
- M(q) is a function of charge that flows through the memristor.
- M(q) is still measured in Ohms, resembling the R value in the Ohm's law equation.
- ***V= I * M(q)***
  - ***V is measured in Volts***
  - ***I is measured in Amperes***
  - ***M(q) is measured in Ohms***

Ohm's Law	Memristor Equation
V = I * R	V = I * M(q)
R is scalar and is measured in Ohms	M(q) is a variable and is measured in Ohms

TYPES OF MEMRISTORS

Ionic Thin Film & Molecular

- **Titanium dioxide – titanium dioxide in between 2 platinum metal plates.**
- Polymeric/ Ionic – use doping of dielectric materials to create hysteresis behaviors.
- Resonant-tunneling diode – use quantum-well diodes with doping between source and drain
- Manganite – use bilayer oxide films instead of titanium dioxide

Magnetic and Spin Memristors – use the electron spin polarization to create hysteresis.

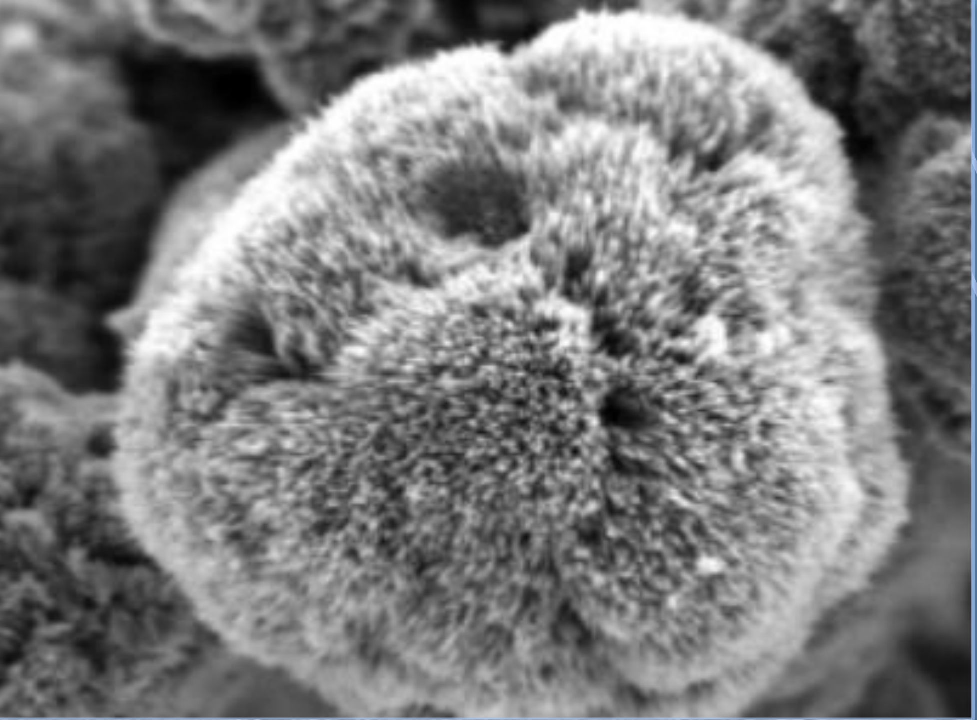
- Spin Torque Transfer (STT) MRAM – the spin valve allows for state change and the spin torque can give off magnetic and ionic properties.
- Spintronic – magnetization is used to change the direction in which the electrons spin and the partition in between the two spin directions which controls the resistance.

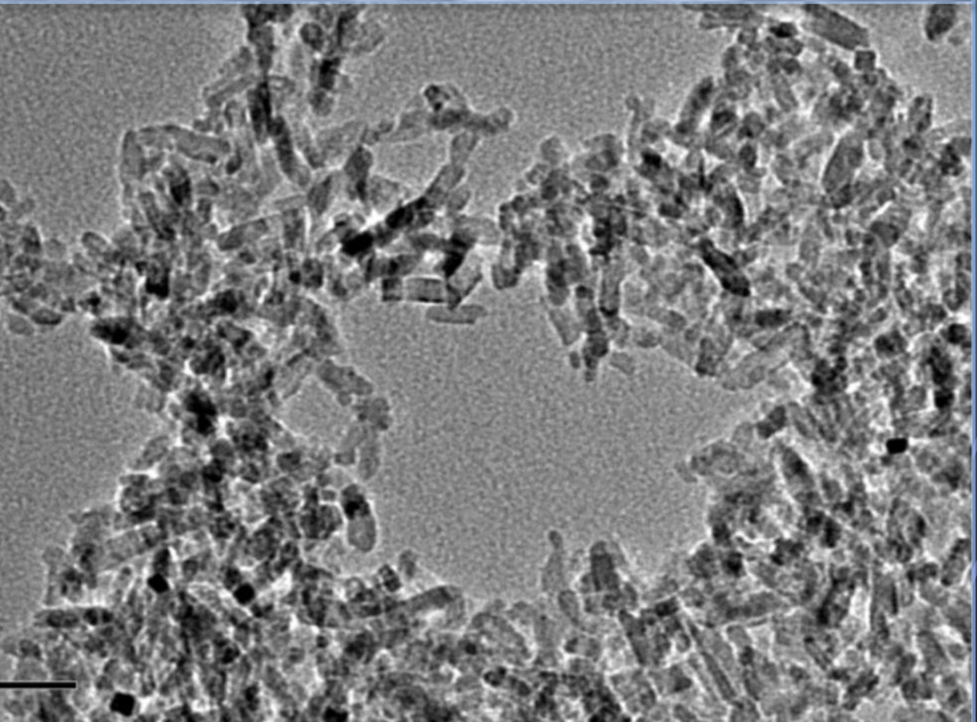
3 Terminal Memristors

- The gate is used to control the device to allow for constant tuning

STAN WILLIAMS' HEWLETT PACKARD RESEARCH

- Stan Williams and his research group at HP Research Labs were influenced by the Teramac, a supercomputer built with mostly defective parts and wanted to create a device that would also work if portions of it were defective.
- They experimented with a crossbar architecture (large storage system) containing many switches and wanted to be able to allow the device to work by closing switches to the defective parts and being able to select what opens.
- They attempted to open and close switches by applying voltages and wanted to be able to change the distance between two wires in the crossbar to get the switching ratio of 1000:1 that they were looking for.
- In the process of trying to find reduce the wire distance in the crossbar, they created the titanium dioxide memristor.
- The "switches" they made were made of two platinum electrodes, where one wire was ionized to become platinum dioxide and allow it to become more conducting. In between the wires was a film of switching molecules covered in titanium.
- The devices didn't work as planned however they were memristors and had useful qualities such as:
  - The resistances stayed the same for years.
  - The on and off resistance ratios were much larger than 1000:1 that they were initially looking for.



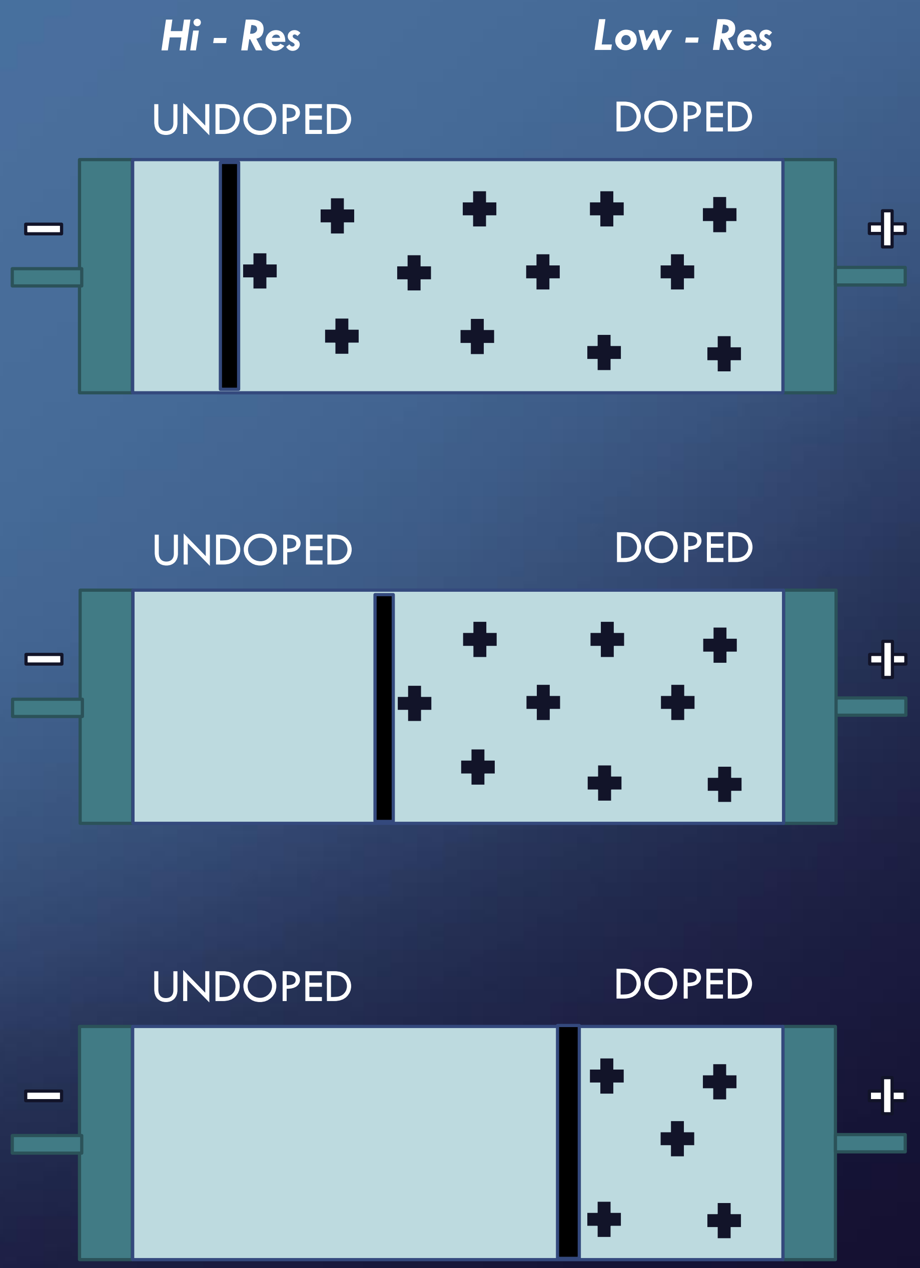


TITANIUM DIOXIDE MEMRISTOR

- The memristor is made up of 2 platinum metal electrodes & a thin film of ***titanium dioxide (TiO_2)***. It is also known as Titania.
- TiO_2 has a high natural resistance and is an electrical insulator.
- The resistance of titanium dioxide can be changed based on its exposure to oxygen.
- Mobile electrons then can carry the current that moves through the memristor.

VARIABLE RESISTANCE

- The undoped part of the TiO_2 film keeps its high resistance.
- The other part is doped & starved of oxygen to reduce the resistance which allows mobile electrons to carry current.
- The current travels through the entirety of the TiO_2 film.
- The resistance is found by adding those of the doped and undoped sections of the TiO_2 film.
- Since the doped and undoped portions have different resistance values, the thickness of each side is important.
- The partition between the two sections can move.
- ***As the thicknesses of the doped and undoped sections change,*** ***<u>the overall resistance changes which causes the characteristic variable resistance of a memristor.</u>***



CALCULATING MEMRISTANCE

- **An equation that can be used to find the memristance of a device is:**
- $M(t) = Rmin * \frac{w(t)}{L} + Rmax * (1 - \frac{w(t)}{L})$

Where w(t) = thickness of conductive doped regions as a function of time

L = thickness of memristor

Rmin = minimum memristance

Rmax = maximum memristance

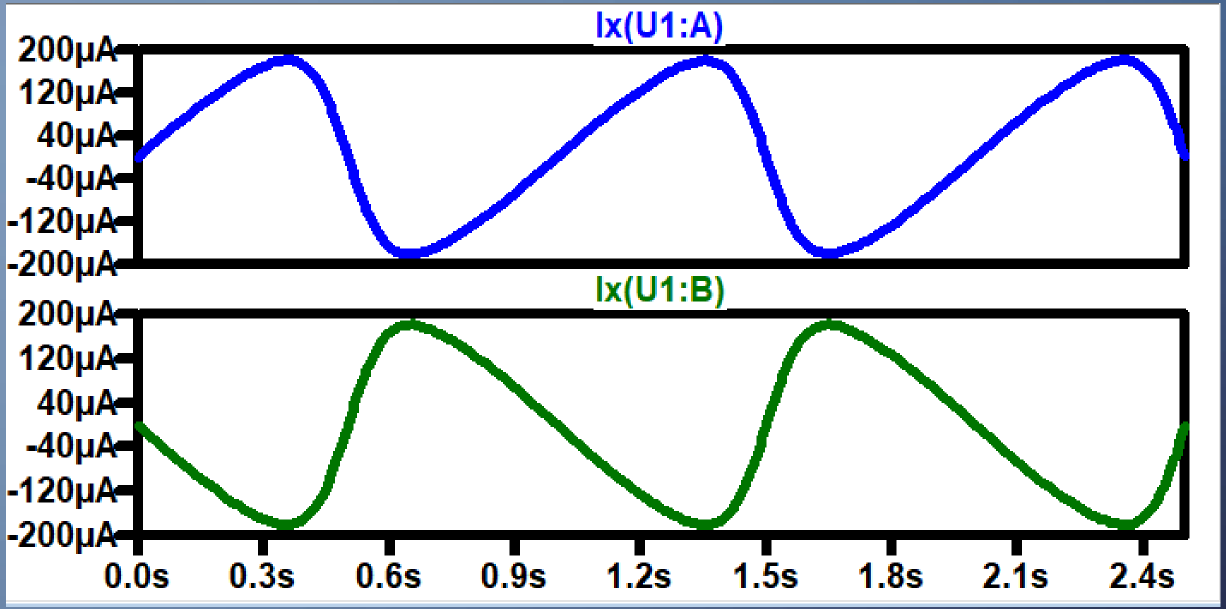
<u>Equation credited to the authors in the following article:</u>

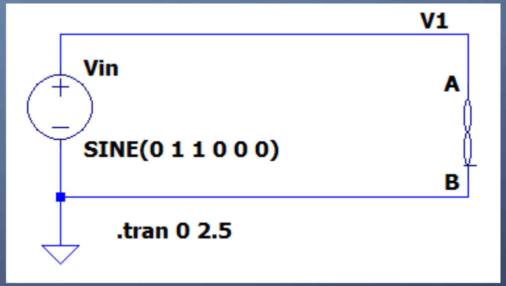
Zangeneh, Mahmoud & Joshi, Ajay. (2012). Performance and energy models for memristor-based 1T1R RRAM cell. 10.1145/2206781.2206786.

NONLINEARITY

- The memristor is a nonlinear device and is not a passive element like the resistor, inductor and capacitor.
- The nonlinearity results from the increase and decrease of memristance.
- Current flowing through the memristor makes the resistance decrease by making the doped layer larger in one direction, but current flowing in the opposite direction increases the resistance.
- When the voltage is zero, the current is also zero because it does not store energy.

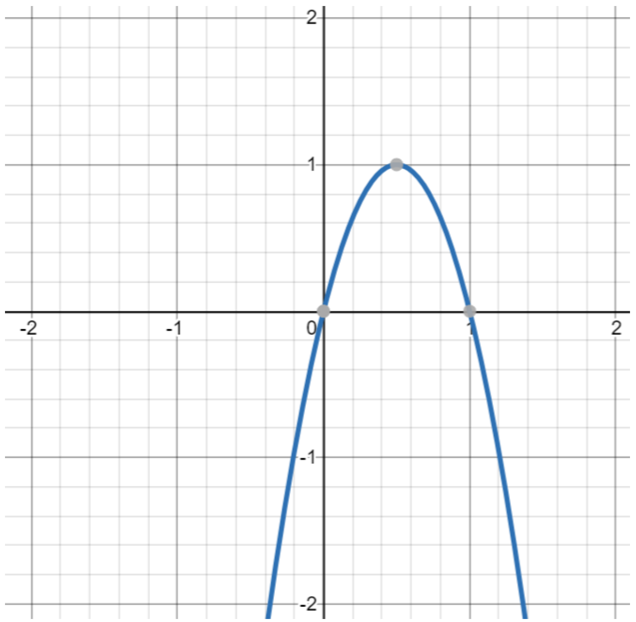
Memristor – Current vs. Time





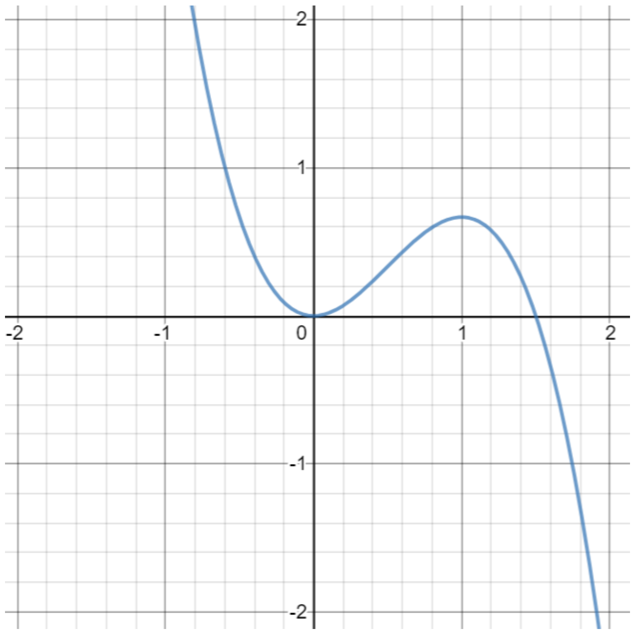
In this memristor LTspice simulation of the current with respect to time, the nonlinearity of the component is evident. Measuring the current through memristor at the opposite end reverses the polarity and shows a reflected output.

MEMRISTOR LTSPICE MODELS



$$f(x) = 1 - (2x - 1)^{2p}$$

where p=1



The integral is

$$g(x) = -\left(\frac{4}{3}\right)x^3 + 2x^2$$

- The LTspice models used in the simulations are based on the Joglekar models from the paper “The elusive memristor: properties of basic electrical circuits” by Joglekar YN and Wolf SJ in the European Journal of Physics.
- The spice models are based on the equation:

$f(x) = 1 - (2x - 1)^{2p}$ where p=1

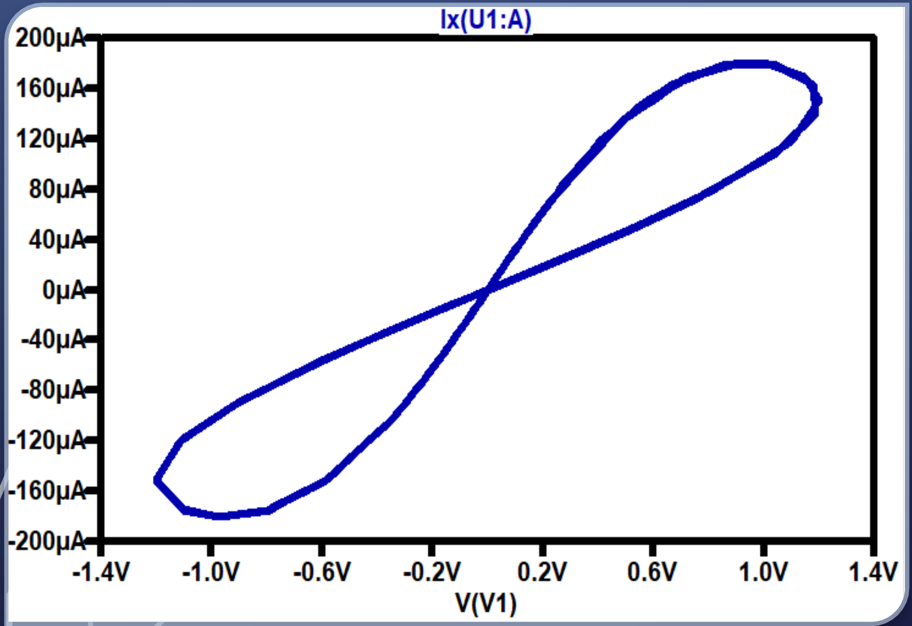
And its integral:

$$g(x) = -\left(\frac{4}{3}\right)x^3 + 2x^2$$

Spice models used belong to Tim Molter and the Knowm Company and can be found at:
https://knowm.org/the-joglekar-resistance-switch-memristor-model-in-ltspice/

HYSTERESIS & MEMORY IN IV CURVES

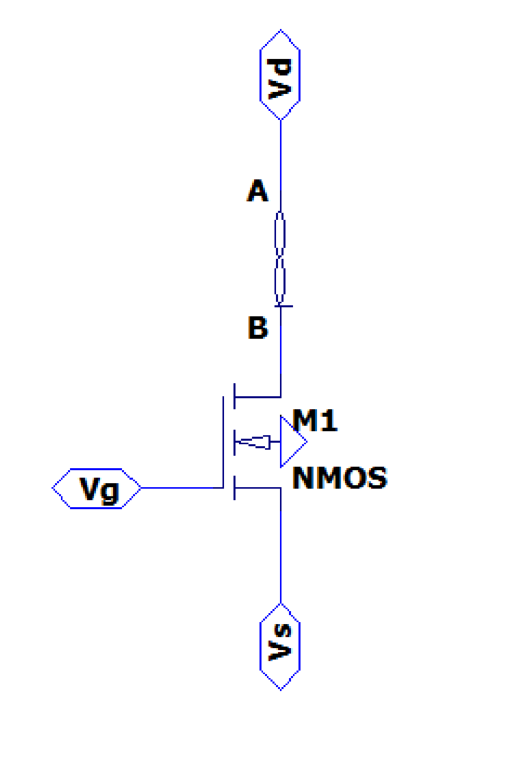
- Hysteresis is when the output depends on both the input and the previous inputs, associating memory with a device.
- Hysteresis shows that the device knows its history and contains memory.



- The IV curves of the memristor are measured by sending a sinusoid into the memristor model and sweeping the current through terminal 'A' versus the voltage 'V1.'
- In a regular resistor IV curve, each voltage corresponds to a specific current, whereas the memristor remembers the history of previous inputs and exhibits those qualities.
- The IV curve of the memristor shows hysteresis and memory because there are two current values for one voltage value, showing that the output exhibits that of many different inputs.
- This shows that the curve exhibits the outputs of previous inputs that may not have been sine waves.
- The "pinched" hysteresis designation refers to the origin where 0 volts correspond to 0 Amps, showing a pinch in the loop.

MEMRISTOR APPLICATIONS

ONE TRANSISTOR ONE MEMRISTOR (1T1R) MEMORY CELL



- Could potentially replace flash memory as the primary source of non-volatile memory.
- It has a high density and low power operation.
- It is a smaller memory cell and mimics the design of the 1T1C DRAM cell.
- Density can be increased by using multiple bits per cells.
- It takes about 30% longer time to write a 1 than to write a logic zero.
- It dissipates the same amount of energy when writing a logic zero or a logic one.
- The bitline is shared by many 1T1R cells and the wordline selects the row, the same way a DRAM cell is selected.
- It dissipates about 65% less energy when reading than when writing.
- A disadvantage is that it needs to be refreshed after a few read operations because it has a low threshold voltage.

READING AND WRITING TO THE 1T1R MEMORY CELL

- **Read operation:**
  - Pre-charge the bitline to 0
  - Send VDD to the wordline and to a node Vd
  - The bitline charges to either a logic 1 or 0 depending on the value it is reading and if it is above or below the threshold voltage.
  - A sense amplifier with two inputs: the bit line voltage and the threshold voltage, is used to find the value that is stored in the memory cell.
  - The sense amplifier does not consume much power because it does not require a large gain and can read voltages of at least 50mV.
  - The noise margin is also larger in the sense amplifier.
- **Write operation:**
  - The wordline is charged to VDD
  - A positive voltage on the memristor corresponds to writing a logic 1
  - A negative voltage on the memristor corresponds to writing a logic 0
  - Vd is charged to VDD/2
  - The memristance is reduced from the large current flowing while writing a logic 1
  - The memristance is increased when the current is decreased while writing a logic 0

MEMRISTORS IN SRAM

- SRAM is not an ideal form of energy because it uses significant energy and power when it is not being used because of leakage.
- It is also a volatile form of memory which is not ideal because the memory won't be retained when the system loses power.
- By including a memristor in the SRAM topology, memory can be stored after the power is lost.
- This transforms the conventional 6T SRAM into a form of non-volatile memory.
- There are many different topologies of the SRAM including memristors:
  - 9T2R
  - 8T2R
  - 7T1R

HYBRID CMOS-MEMRISTOR MEMORY CELL

- This cell operates much faster than flash memory, as titanium dioxide allows memristors to consume much less energy than flash and some RAM.
- This combination of memristors and transistors aims to reduce sneak – path problems found in crossbar topologies, where current travels parallel to the path intended.
- Combining memristors and CMOS transistors reduces the problems associated with the crossbar topologies and instead includes active transistor components that can restore signals.
- The goal would be to use the memristor as a memory cell and use the CMOS transistors for sensing, decoding, driving and other functions that would give some additional functions to the memory device.
- Adding the CMOS transistors allows for more control of the memory cell function and allows for more flexibility.

MEMRISTORS AS ARTIFICIAL SYNAPSES

- Memristor devices can be used as an artificial synapse for neuromorphic computing.
- Artificial Neural Networks (ANNs) have been used to test artificial intelligence.
- The device's bipolar analog- resistive switching behavior allows it to mimic brain synapses and can allow better research regarding brain functions and illnesses.
- It has been possible to use a three terminal ferroelectric memristor on which to program a synapse function on.
- The memristor's switching capabilities can emulate functions relating to synapses such as:
  - Long term depression / potentiation
  - Paired pulse facilitation
  - Spike timing depending plasticity

MEMRISTORS IN LOGIC CIRCUITS

- Since memristors are small, they are good candidates to be used in architectures aiming to reduce layout size. They have been recently used in logic circuit topologies.
- Some research groups have been able to show that they can even be used to create Boolean functions using K-maps, the same way that other components have been able to.
- This is highly beneficial because of the size and speed of the memristor, allowing for higher density in topologies and potentially faster integration.
- The nonlinearity of the devices do not negatively influence the logic gates.
- Some groups have integrated memristors into designs using transistors while others have pursued memristor-only logic topologies.

MEMRISTOR - AIDED LOGIC (MAGIC)

- Memristor-only logic creates stability in the circuit and only requires a single voltage pulse at the input.
- A logic ‘1’ and logic ‘0’ are characterized by the resistance found in the memristor devices.
- They need two separate memristors for the input and the output of the circuit.
- Sometimes the circuit will have two or more inputs, but the output memristor must be added onto however many inputs there are.
- The nonlinearity of the memristor is used to ensure correct operation of the circuit.
- To operate a MAGIC gate, first set the output memristor to a known logic state then apply a voltage across the logic gate.
- The most common logic gates such as NAND, NOR, AND and OR can all be designed using memristors only.
- Example: A MAGIC NOR gate is made up of 2 input memristors in parallel and an output memristor.
  - If the input memristors have a high resistance meaning they are operating at a logic ‘0’ the current exhibited by the memristor at the output is too low to cause a change in the output’s logic state.
  - If the input memristors have logic values other than the that above, the current will be larger than the threshold voltage and current of the memristor which allows the logic state on the output to change.

MEMRISTOR CROSSBARS AND SIGNAL PROCESSING

- Many researchers are using the memristor crossbar topology in collaboration with transistors in the 1T1R formation to speed up signal processing, specifically vector multiplication, and provide a more energy and power efficient alternative to the current solution.
- Because of the small size of the memristor, the crossbar can be a large array and a high density.
- The topology contributes to stable and accurate reading and writing when signal processing.
- The array has been proven to be capable of creating linear transformations, discrete cosine as well as performing convolution.
- Convolution error filtering can be used when image processing and has shown that the crossbar can produce a smooth image by using many different, commonly used convolution filters such as Gaussian, Laplacian, and more.
- The signal Is not perfect but displays a insignificant amount of output error.
- An issue is that there is less precision as the crossbar array is increased as a result of a large wire resistance so the tradeoff between high density and bit precision must be considered.

A REVOLUTION IN MEMORY DESIGN?

THE IMPORTANCE

- Memristors are important in new waves of memory because of their low energy and power dissipation as well as their non-volatility.
- They are very small and can be packed into an array in a similar capacity as the DRAM cell, however, they can store data after power is lost which makes it more reliable as a memory storage source.
- Stan William's research group concluded that the memristor can hold its memory for years with very little change, which is quite advantageous compared to flash. Flash wears away over time and is not reliable as a source of long term non-volatile memory.
- Not only is flash memory not long-lasting, but it is also very large and not concerned with speed.
- Memristors or RRAM could very well replace all flash memory because of its size, speed, power efficiency, and long lasting memory storage.
- The integration of memristors with volatile memories, such as SRAM, provides designers with the capability to choose the advantageous traits of both volatile and non-volatile sources and create a more ideal design.
- RRAM also have a greater capacity, area efficiency and readability than DRAM.
- It also rivals DRAM in its long term memory storage.

REJECTIONS

- Some researchers reject the concept of the memristor as a fourth fundamental element.
- The memristor has been known to read incorrect information at times and it is not commercially available.
- RRAM is also only a fraction as fast as DRAM.
- Although it has some shortcomings and is continually being researched, the potential benefits of using memristors within other forms of existing memory could open the door to a collaboration of the advantages of volatile and non-volatile memory systems.

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ADDITIONAL READING

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