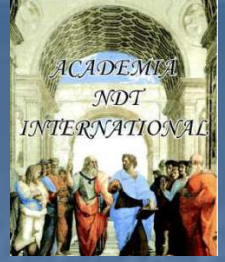
INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES CENTRE VAL DE LOIRE



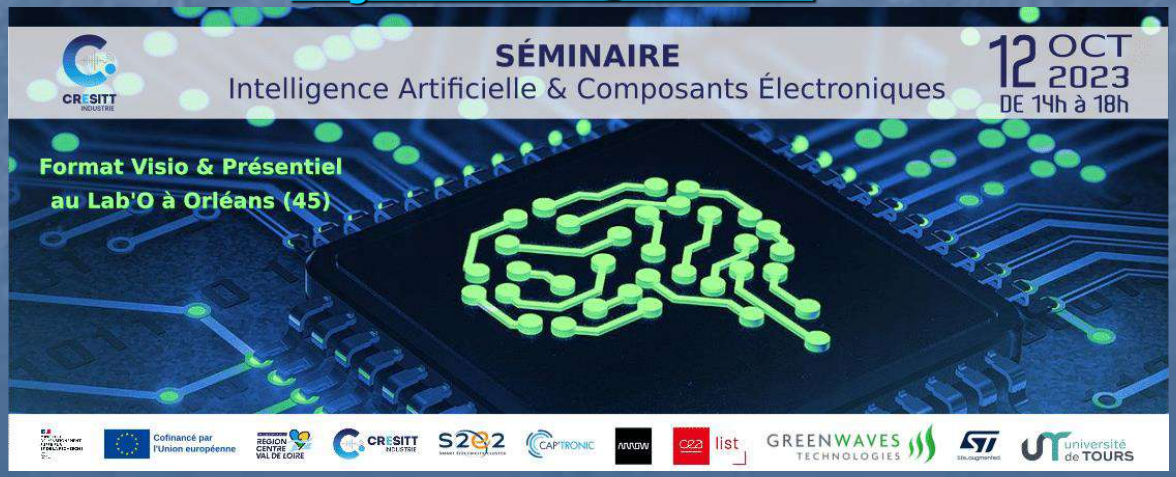
Instituts thématiques Inserm
Institut national de la santé et de la recherche médicale

Accès aux data: la piste des memristors

Serge Dos Santos, *PhD, Hab. Dir. Rech.*
Vice-President of Academia NDT International, Brescia, Italy
IEEE France Technical Activities Co-Chair, IEEE Senior Member

BRAKET Expertise, N° SIRET : 94832835600019 (Janvier 2023)

INSA Centre Val de Loire, UMR 1253 « Imaging and Brain », Inserm,
University of Tours, 3, Rue de la Chocolaterie CS 23410, F-41034 BLOIS cedex, France
serge.dossantos@insa-cvl.fr



Motivations

- Nouveau paradigme de traitement de l'information associé à la **signature non linéaire** d'un milieu **biologique**

- Problématique de la **Transition Numérique** (Industrie 4.0) dans le domaine du **Contrôle Non Destructif (CND)** portant sur le **vieillissement des structures**, utilisant des indicateurs multi-échelles complexes, des modalités d'imagerie complémentaires (US, X, THz), et nécessitant un **partage de données (IoT)** via des systèmes de **contrôle/monitoring** sensibles, autonomes et **intelligents (apprentissage)**

- **Design d'une nouvelle instrumentation TR-NEWS** associée à une imagerie harmonique avancée (imagerie médicale – CND)
  - Problématique de l'étalonnage des mesures (certification COFREND)
  - Problématique de l'hystérésis

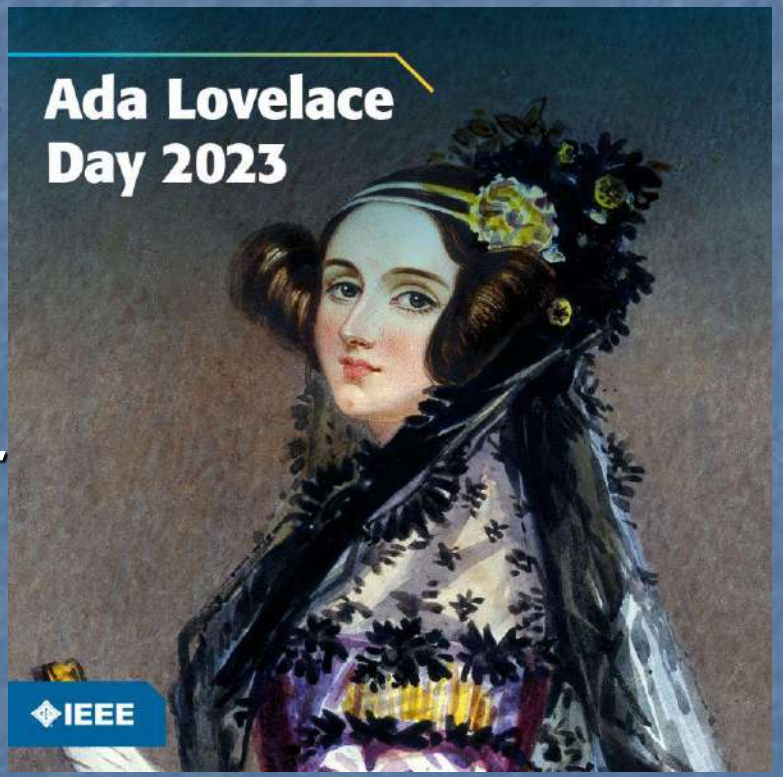
- Innovation dans la communauté de **l'imagerie ultrasonore**
  - Insertion contrôlée et étalonnée d'un **composant à mémoire memristive** modifiant délibérément et **de façon intelligente (optimisée)** la transduction ultrasonore

- Objectif : **mesurer et monitorer** le comportement **memristif** multi-échelles d'un milieu biologique en fonction de son **vieillissement**

Il y a 200 ans !

- Ada Lovelace, née le 10 Dec. 1815

"J'ai des espoirs, et des espoirs très distincts aussi, d'obtenir un jour des phénomènes cérébraux tels que je puisse les mettre en équations mathématiques, en bref, une ou plusieurs lois pour les actions mutuelles des molécules du cerveau. …. J'espère léguer aux générations un calcul du système nerveux."

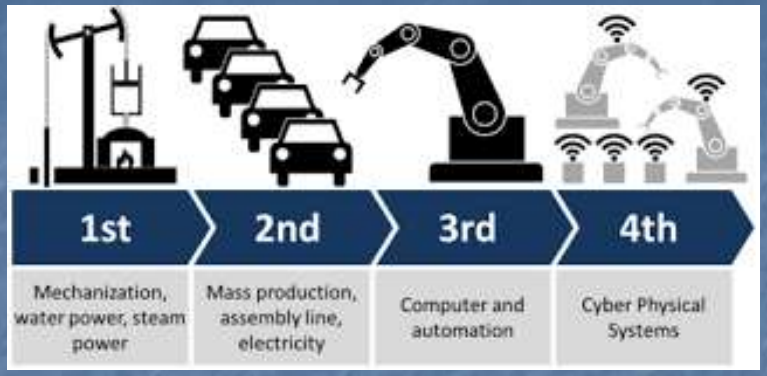


https://www.rigb.org/whats-on/ada-lovelace-day-live-0

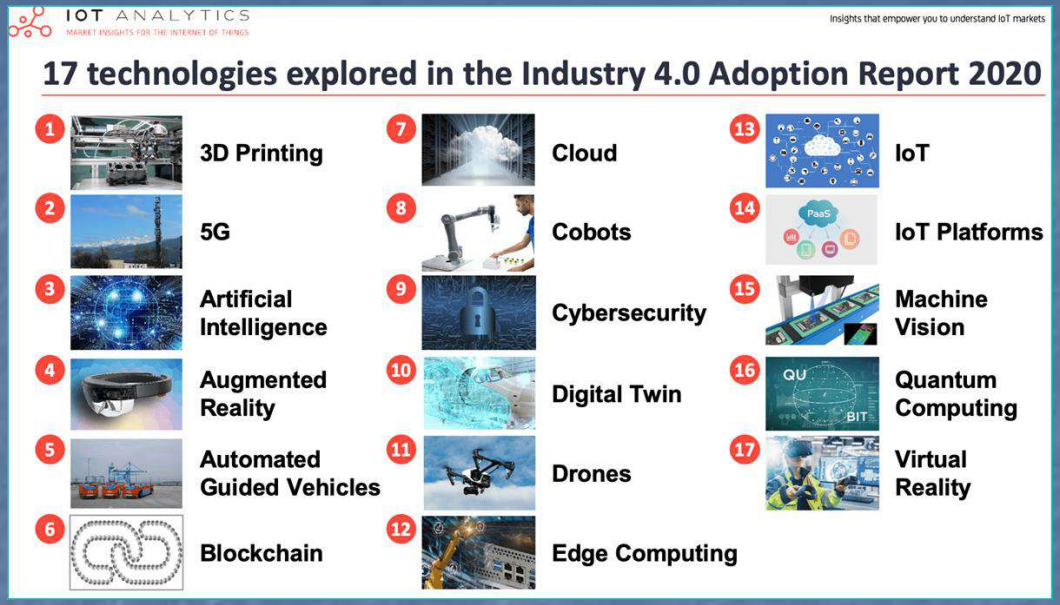
https://www.linkedin.com/posts/ieee_stem-activity-7117584608262541314-YY8p?utm_source=share&utm_medium=member_desktop

3

#data et IA pour le CND 4.0



https://en.wikipedia.org/wiki/Industry_4.0



https://iot-analytics.com/

2020

2021

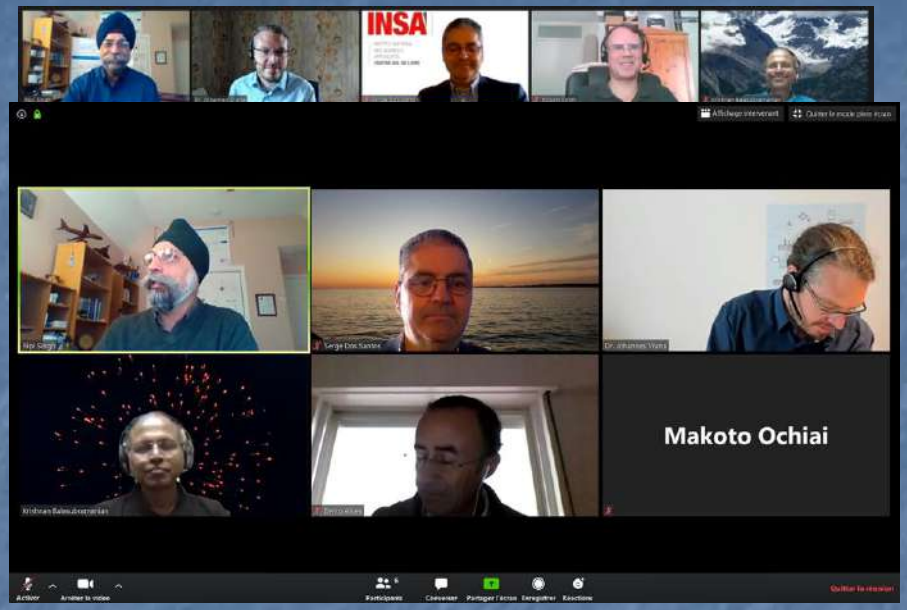
Digital Transformation of NDT :

- the process of using digital technologies to improve NDT processes : **NEW DATA is required**

Il est temps d'aborder la digitalisation du CND 4.0 !

See "NDT 4.0 – Overall Significance and Implications to NDT", R. Link and N. Riess, ECNDT, June 2018

NDE 4.0 at international level



Dear NDE 4.0 Enthusiast,

…

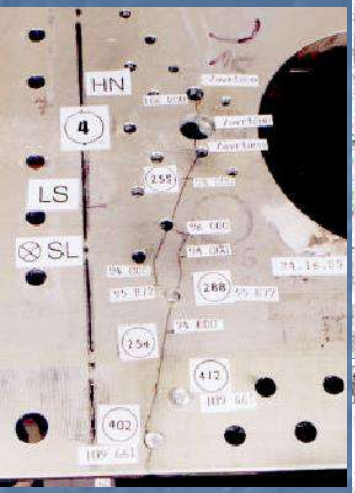
April 29, 2020

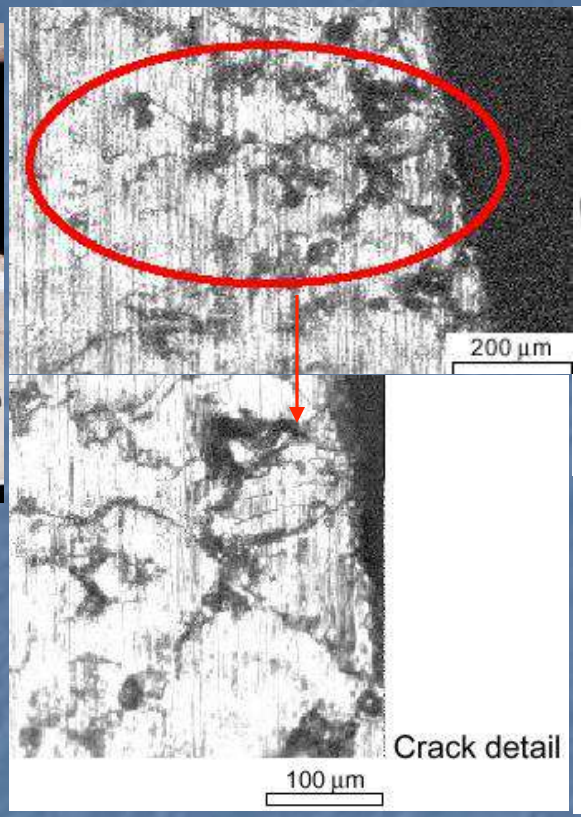
- **Ripi Singh & Johannes Vrana (Facilitators)**
- Alejandro García (Argentina)
- Anish Poudel (USA)
- **Bento Alves (Portugal)**
- Bernd Valeske (Germany)
- Casper Wassink (Netherlands)
- Don Andrews (Canada)
- Gao Xiaorong (China)
- Krishnan Balasubramanian (India)
- Luigi Feerigni (Italy)
- Makoto Ochiai (Japan)
- Pranay Wadyalkar (Australia)
- **Ramon Fernandez (Mexico)**
- Rafael Martínez-Oña (Spain)
- Nick Brierley (UK)
- **Serge Dos Santos (France)**
- Vladimir Syasko (Russia)
- Younho Cho (S Korea)

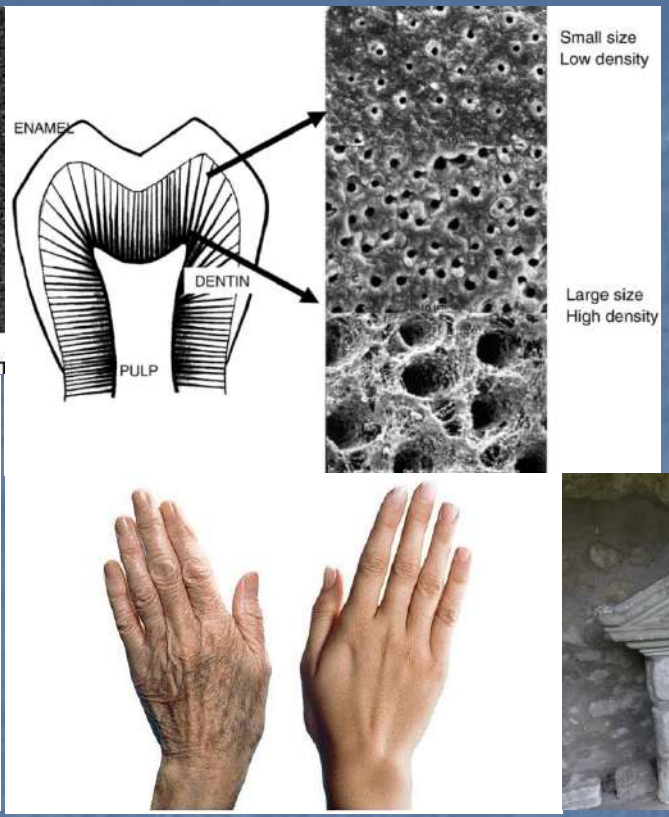
https://www.youtube.com/c/NDE40

https://www.linkedin.com/groups/12429385/members/

The (old) problem of aging !



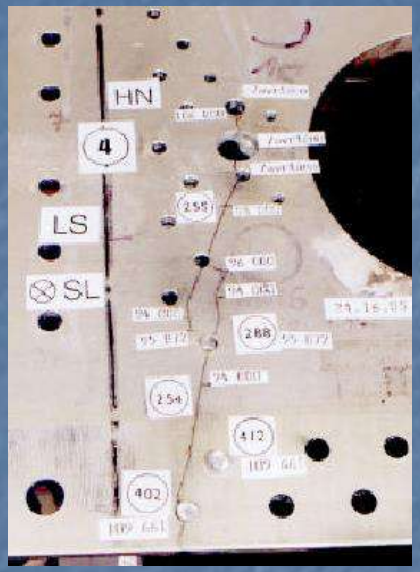


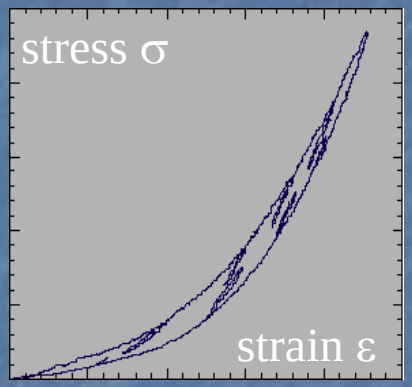


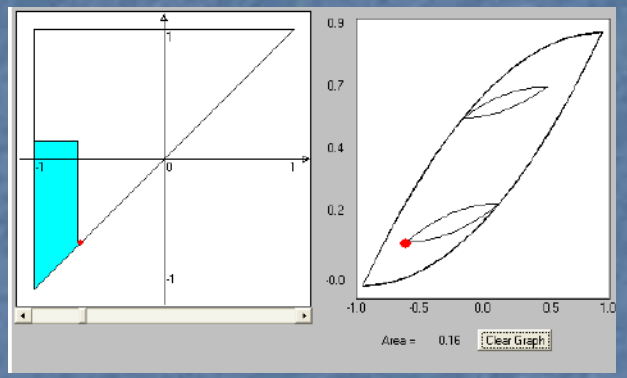
- What is the link between complex cracked structure from aeronautic industry, a human damaged tooth, the ancient stones, or skin …
- The internal complex structure …

The (old) problem of ageing / integrity

- NDT

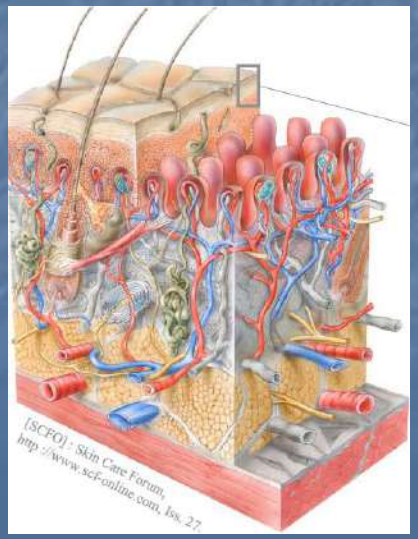


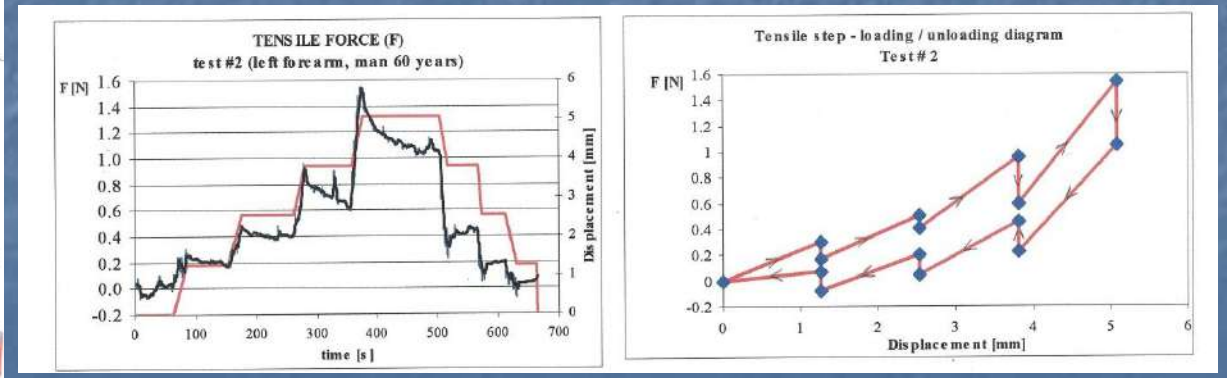




- Degradation ⇔ memory of the material

- skin

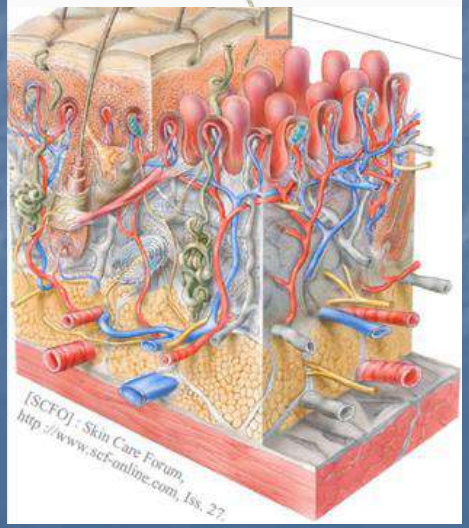


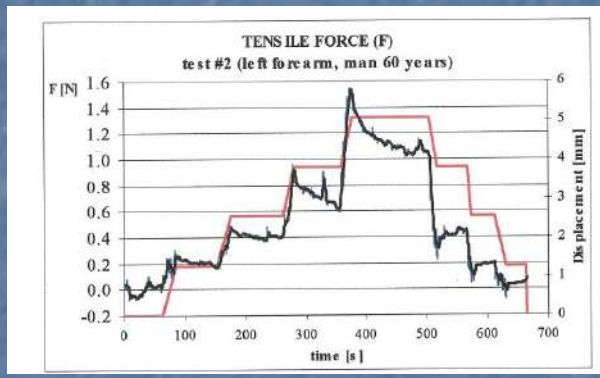


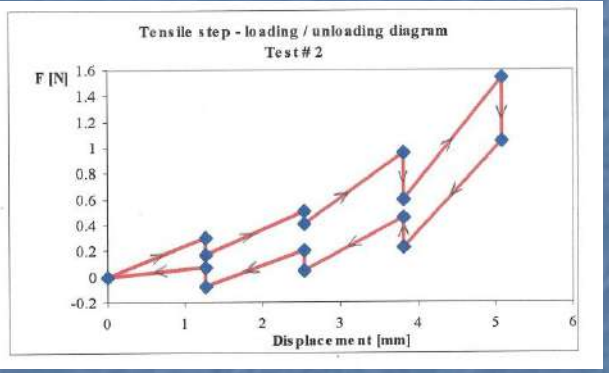
- Ageing ⇔ memory of the skin

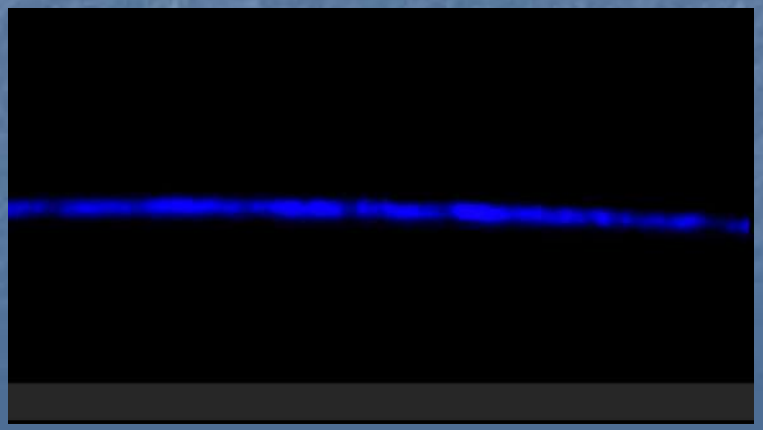
Applications en cosmétique

- Contexte : vieillissement des tissus (peau, etc.) et des systèmes
- Problématique : trop de paramètres physiques
- Hypothèses : approche statistique (hystérésis), multi-échelle
- Opportunité : émergence des composants neuromorphiques (memristors)







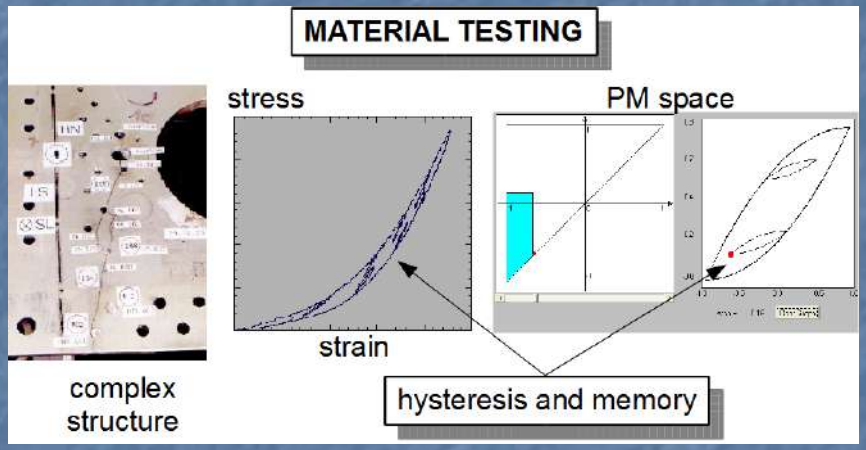


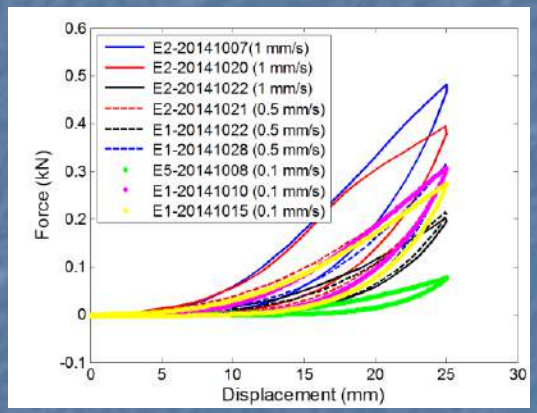
SkinFlex (Orion Concept, Tours)

Elasticité de la peau :
- Relaxation
- Hystérésis
- Effet mémoire

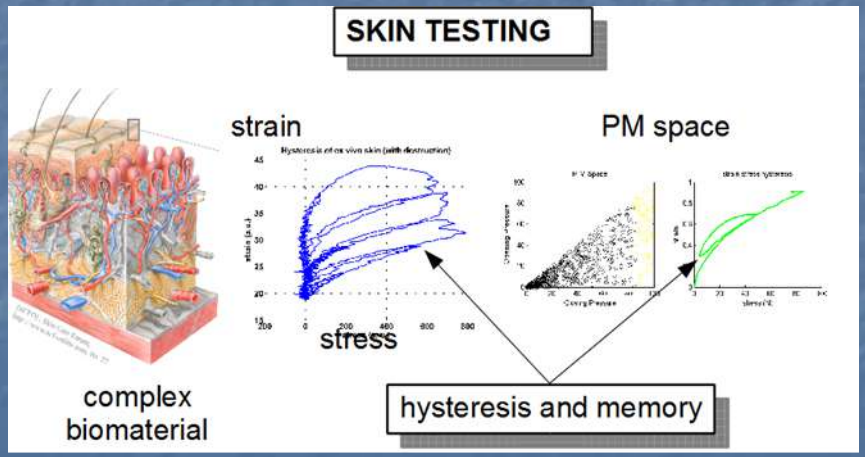
→ Outils de la Physique et du Traitement du **signal non linéaire**

Vieillissement, Mémoire, Nonlinéarité, et hystérésis

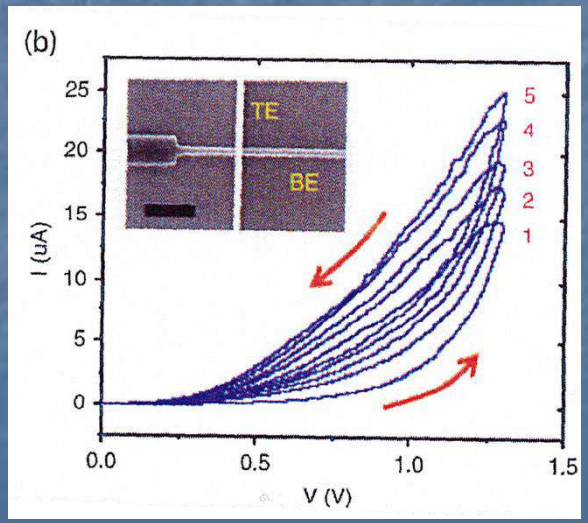




Plasticity and memory properties

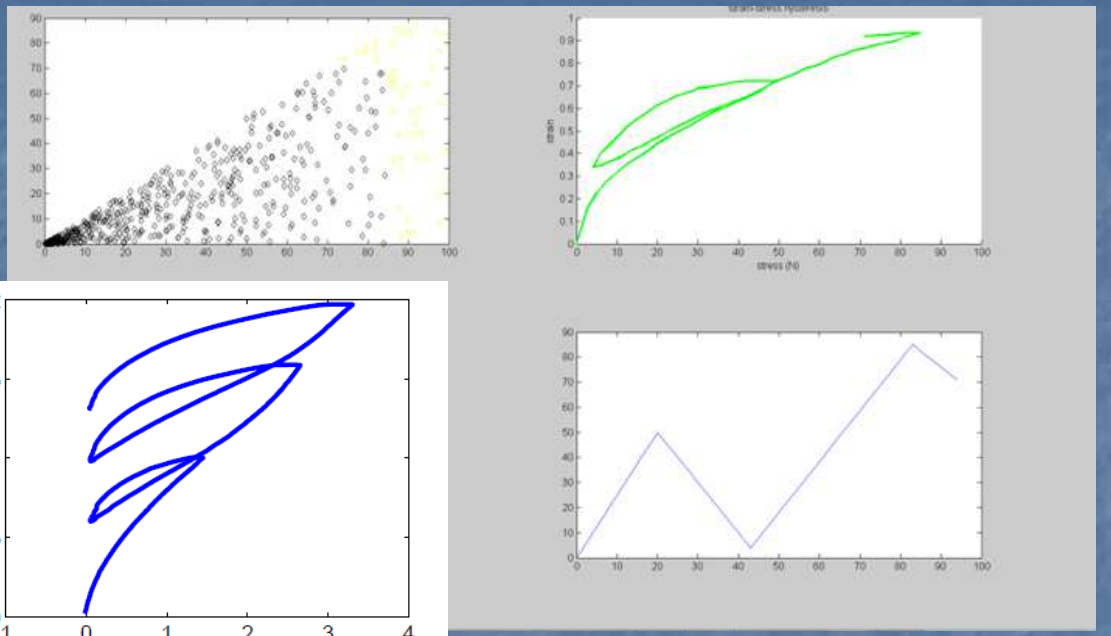


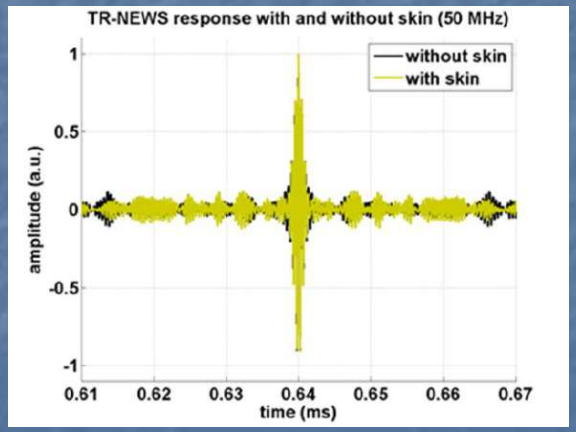
Serge Dos Santos *et al*, IFSCC 2014, Paris

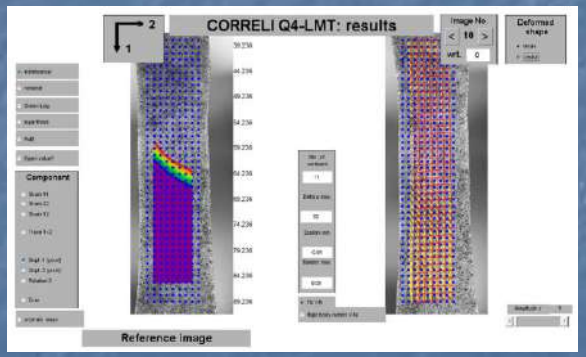


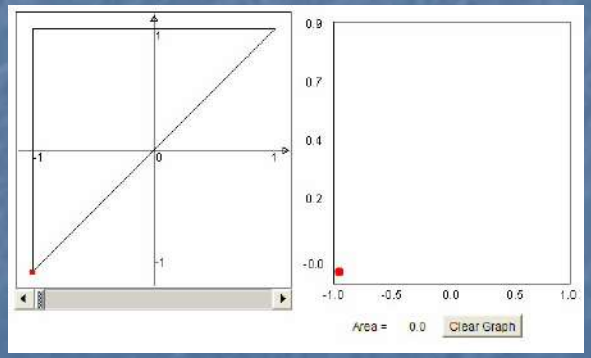
Memristor networks :
T. Chang, Y. Yang, W. Lu, IEEE Circuits and Systems Magazine 13, 56 (2013)

Caractérisation multi-échelles des comportements à hysérésis de la peau (PM space)







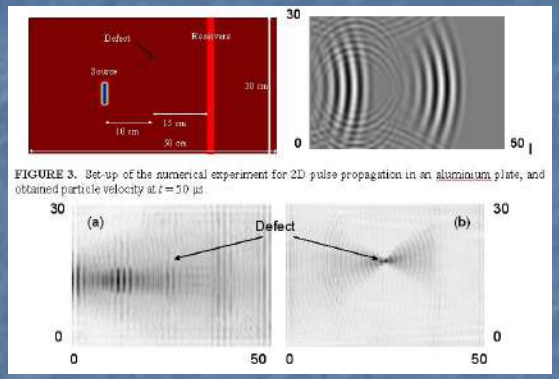


TR-NEWS signature | Image correlation | PM space

S. Dos Santos *et al*, *Viscoelastic and hysteretic properties of the skin : Acousto-mechanical evaluation using nonlinear time reversal imaging*, IFSCC, Oct. 2014, Paris

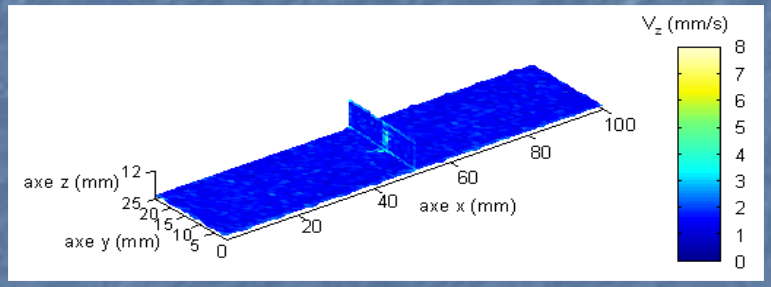
TR-NEWS

2D simulations : ISNA17 2005



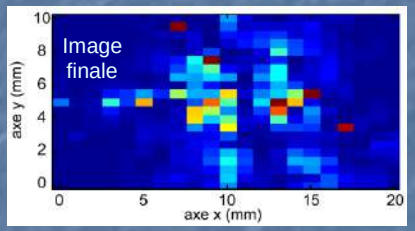
Google TR-NEWS nonlinear

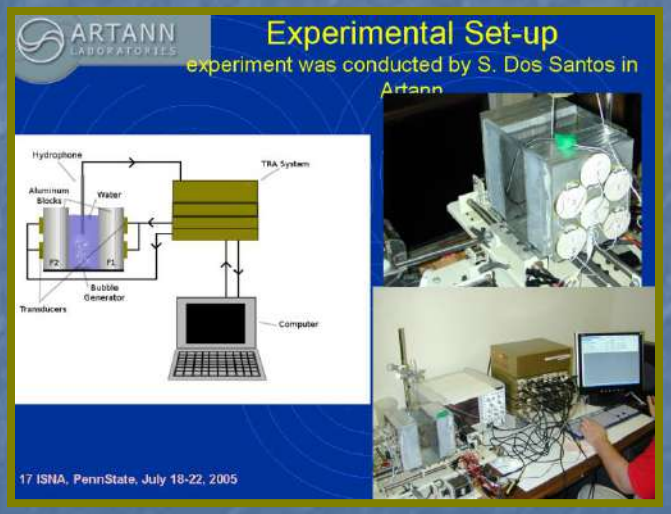
3D simulations : T. Goursolle *et al*, JASA 2007



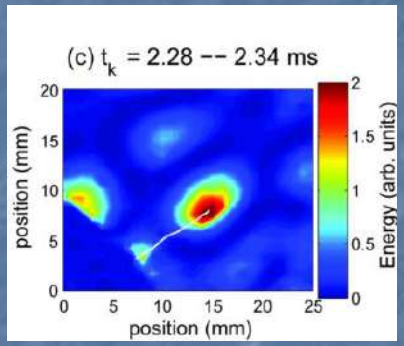
ECNDT 2006

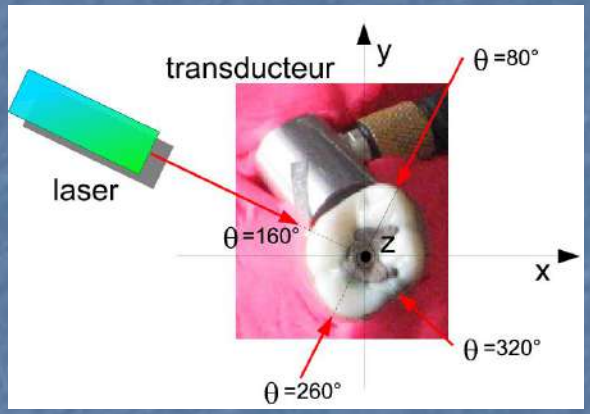
AERONEWS 6

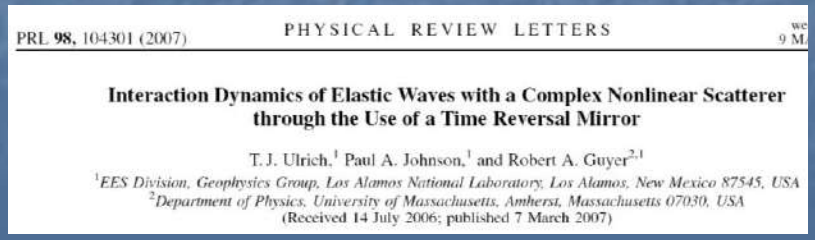




A. Sutin *et al., ISNA17, PennState, 2005*



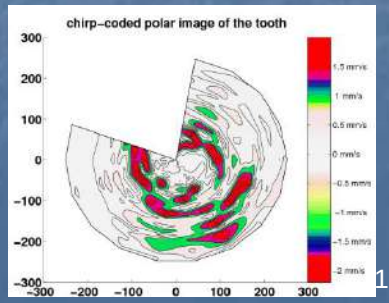



PRL 98, 104301 (2007) PHYSICAL REVIEW LETTERS

Interaction Dynamics of Elastic Waves with a Complex Nonlinear Scatterer through the Use of a Time Reversal Mirror

T. J. Ulrich,[1] Paul A. Johnson,[1] and Robert A. Guyer[2,1]

[1]*EES Division, Geophysics Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Department of Physics, University of Massachusetts, Amherst, Massachusetts 07030, USA*
(Received 14 July 2006; published 7 March 2007)



Strategies for TR-NEWS focusing improvement and nonlinear measurements : the memosducer, a memristance within the US transducer

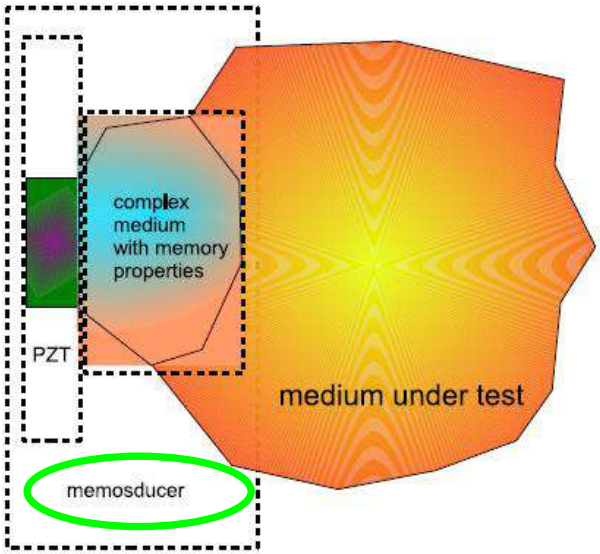


Figure 2: *Principle of the memory based transducer. Putting memory into transducer induce the possibility of breaking any symmetry in the excitation device leading to a unambiguous superfocusing properties needed for TR-NEWS based experiments[12, 13]*

S. Dos Santos *et al*, *proc of the* SPMS2010 (http://gams.fjfi.cvut.cz/index.html) *Stochastic and Physical Monitoring Systems, Decin, Czech Republic, ISBN 978-80-01-04641-8, pages 11–24, 2010*

Ø G Martinsen and S Grimnes and C A Lütken and G K Johnsen, Memristance in human skin, Journal of Physics: Conference Series, 224,1, pp. 012071, 2010

The memristor : a new standard for the human skin aging

- *Prof. Orjan G. Martinsen, keynote lecture, BEC 2018, october 2018*

Hystérésis

réponse
$y(x)$

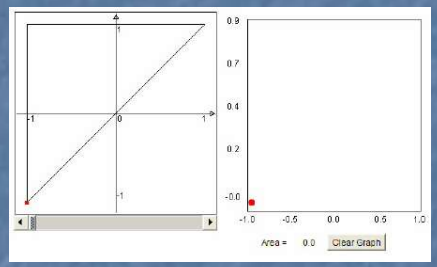
réponse
γ

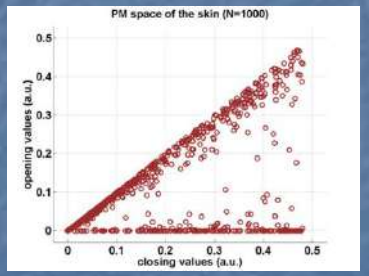
$P_o \neq P_c$

stimulus

P_{off} P_{on}

hystéron :
"particule" élémentaire





Hystérésis réel :
distribution statistique
multi-échelle d'hystérons

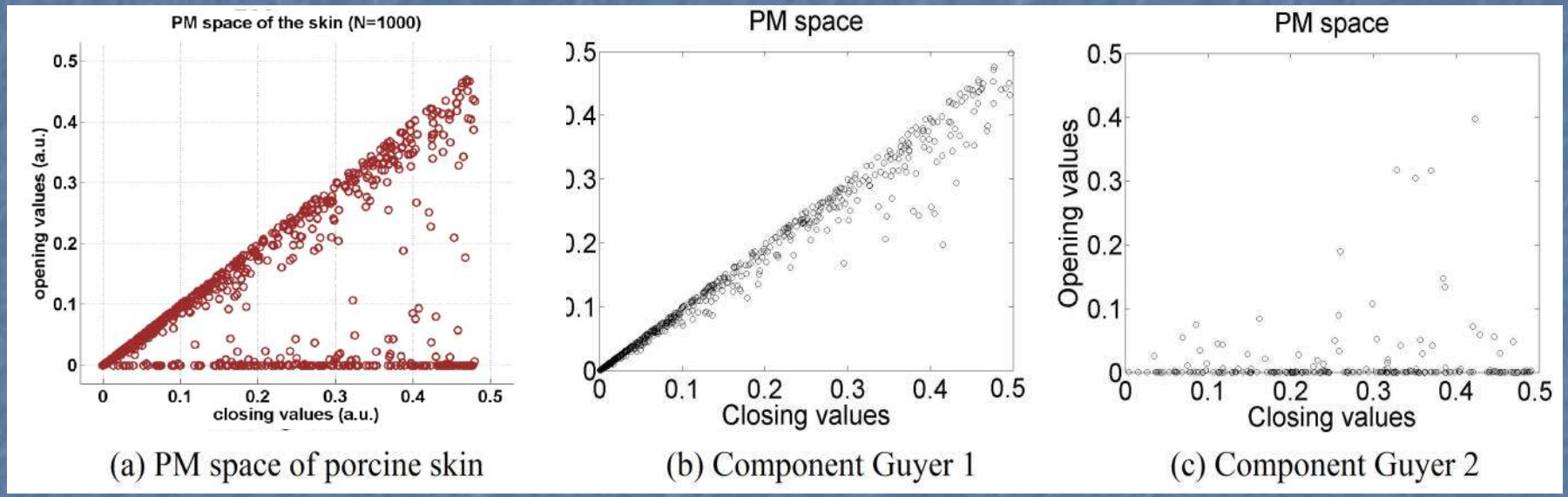
S. Dos Santos *et al*, IEEE COMET 2017

stimulus

Analyse des #data : signatures non linéaire, multi-échelle et stochastique

- Ageing monitoring

D. Remache, M. Caliez, M. Gratton, S. Dos Santos, *The effects of cyclic tensile and stress-relaxation tests on porcine skin*, In Journal of the Mechanical Behavior of Biomedical Materials, 2017, , ISSN 1751-6161, https://doi.org/10.1016/j.jmbbm.2017.09.009 (Open Access paper, IF 2016 : 3.11)



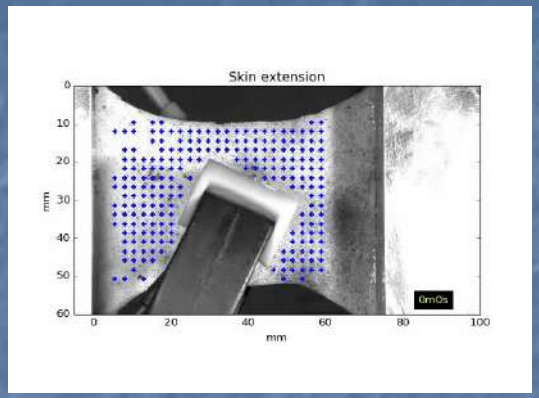
(a) PM space of porcine skin (b) Component Guyer 1 (c) Component Guyer 2

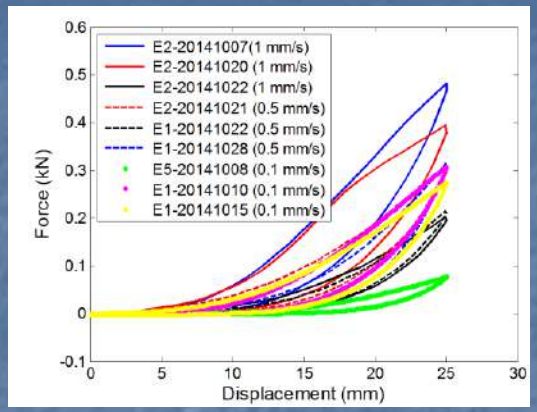
S. Dos Santos *et al.*, "*Acousto-Mechanical Instrumentation of Multiscale Hysteretic Memristive Properties of the Skin with Nonlinear Time Reversal Imaging*," 2017 Cosmetic Measurements And Testing (COSMETIC), 2017, pp. 1-4 (2017)

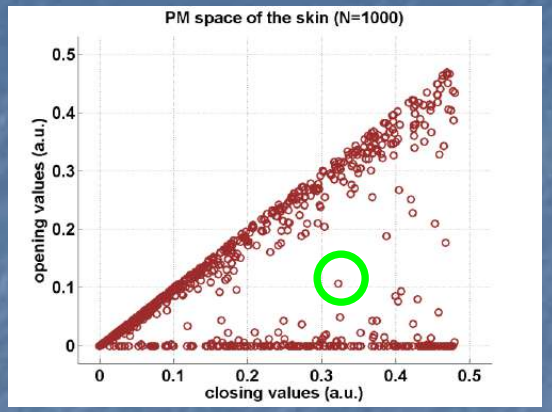
https://ibrain.univ-tours.fr/caracterisation-des-proprietes-de-la-peau-par-ultrasons-662500.kjsp?RH=U930_FR

https://ieeexplore.ieee.org/document/8521466

Accès à l'hystérésis : la piste des memristors

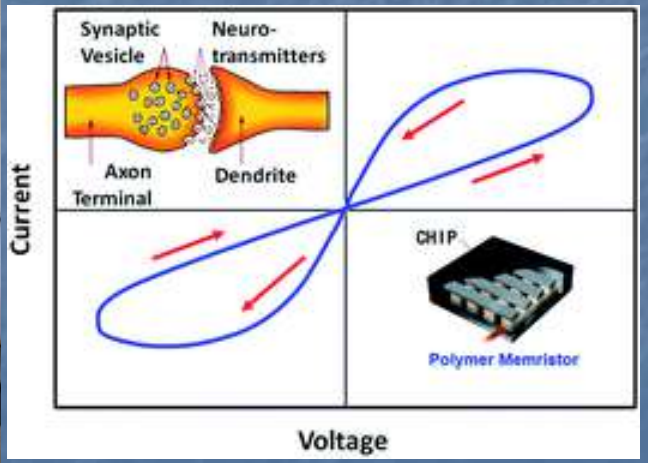




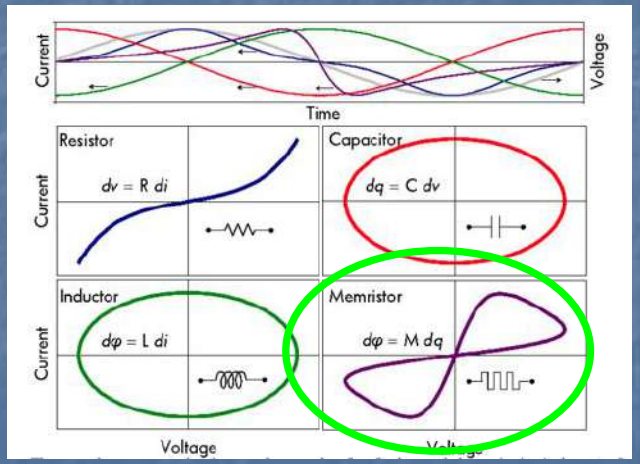


D. Remache, M. Caliez, M. Gratton, **S. Dos Santos**, *The effects of cyclic tensile and stress-relaxation tests on porcine skin*, In Journal of the Mechanical Behavior of Biomedical Materials, 2017 , ISSN 1751-6161, https://doi.org/10.1016/j.jmbbm.2017.09.009 (Open Access paper, IF 2016 : 3.11)

Leon Chua, Séminaire iBrain, juin 2019, Faculté de Médecine, Tours



Chen, Materials Horizon, 2014

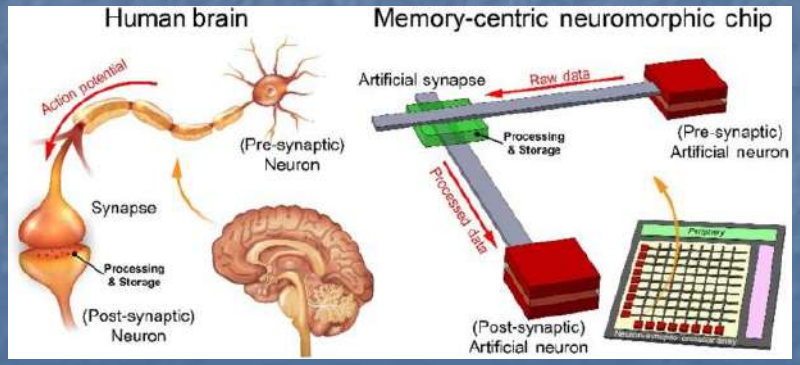


- Memristor : composant découvert par Leon Chua, Berkeley, USA

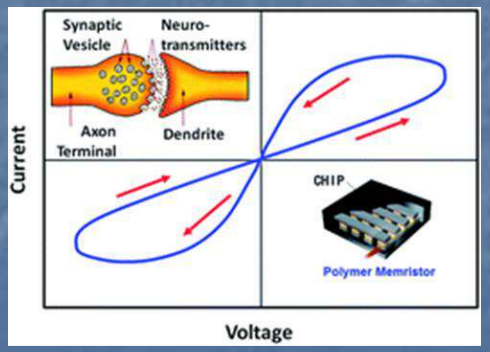
Accès aux propriétés du cerveau : la piste des memristors

- Analyse de Données Multivariées et Multimodales (multi-échelles)
- Extractions de nouveaux paramètres statistiques, signature du vieillissement/dégradation d'un bio-matériau (peau, dent, cerveau)
  - Traitement du Signal / Traitement des Données

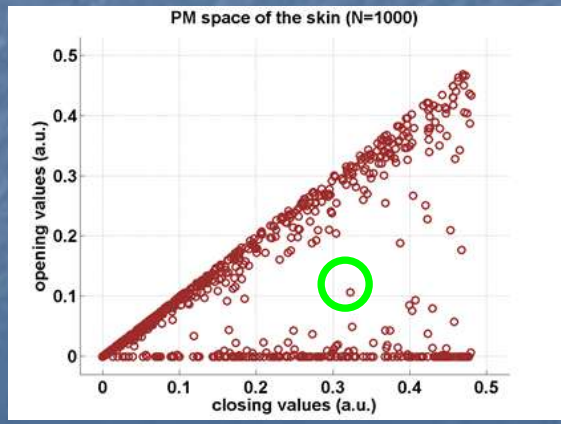
Neuromorphic systems



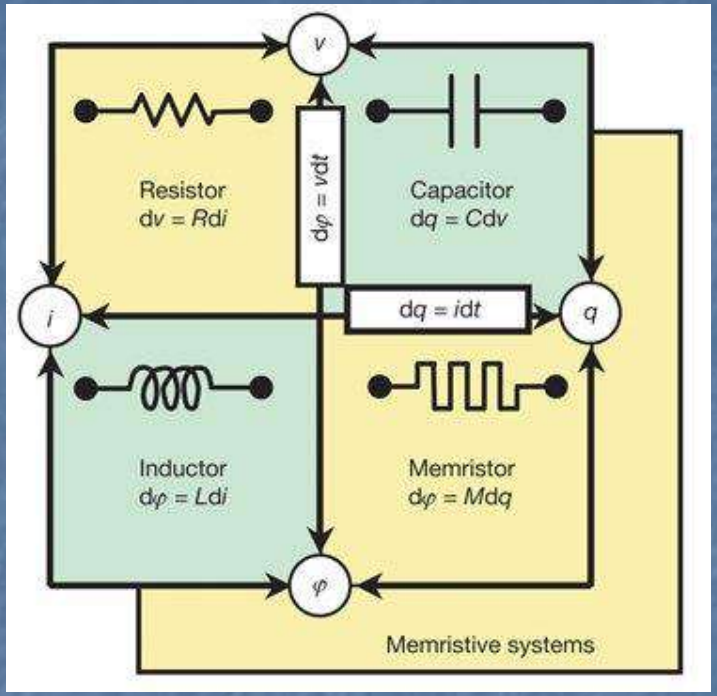
Sung, S.H., et al., Nano Res. 14, 3126–3142 (2021)

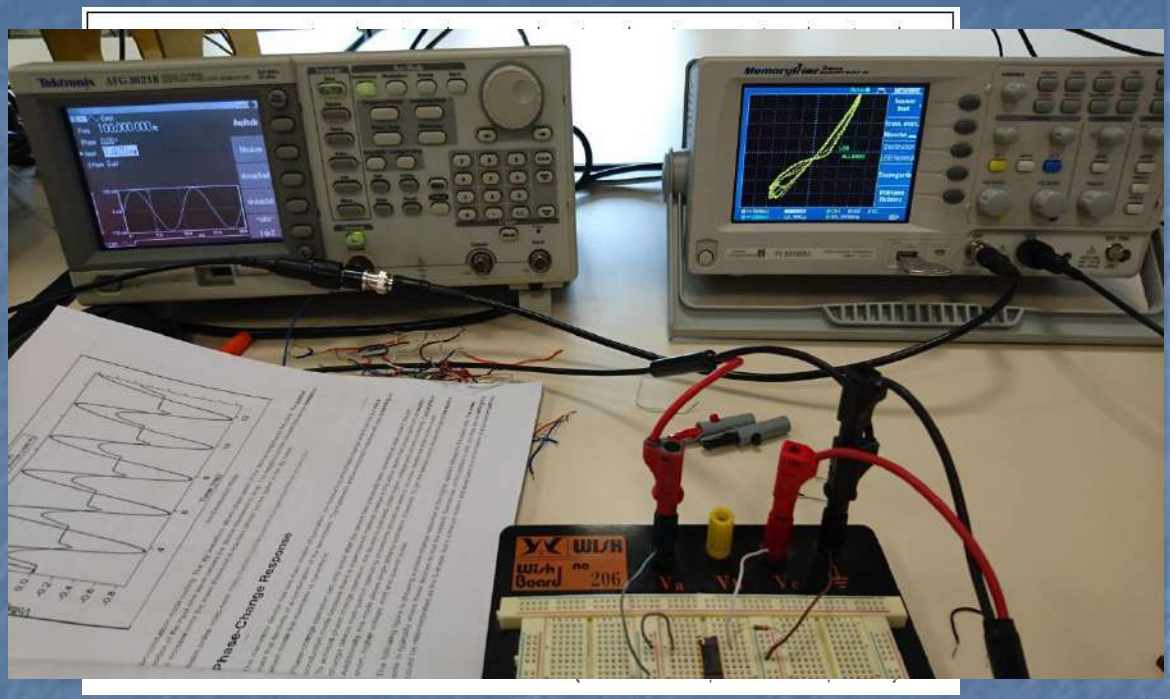


Chen, Materials Horizon, 2014



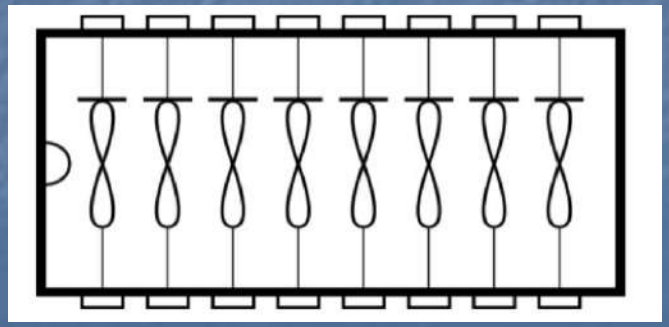
Les memristors Knowm Inc





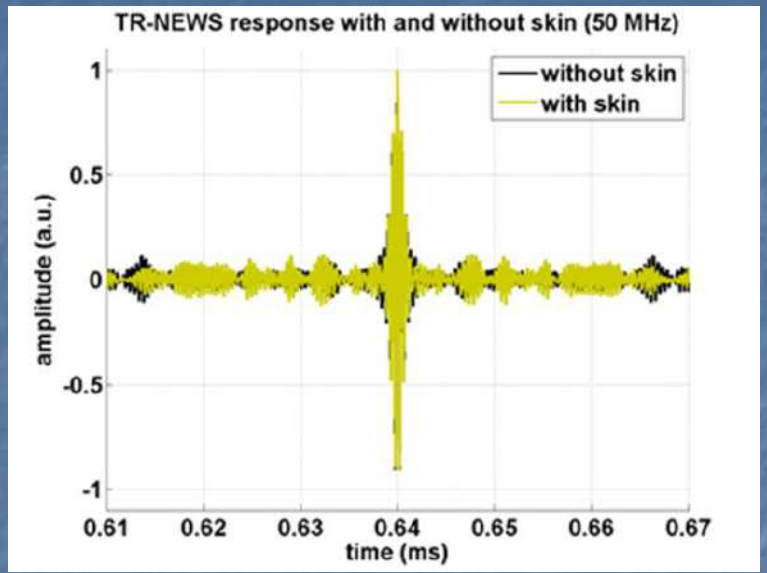
Chua, L. O., "Memristor-the missing circuit element," IEEE Transactions on Circuit Theory, vol. 18, no. 5, pp. 507-519, 1971

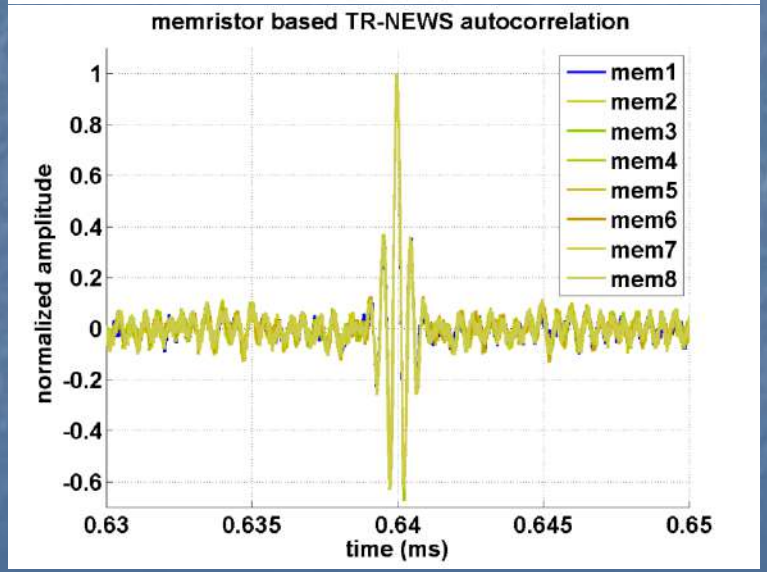
Strukov, D.B., Snider, G. S., Stewart, D. R. and Williams, R. S. "The missing memristor found," Nature 453, pp. 80-83, 2008

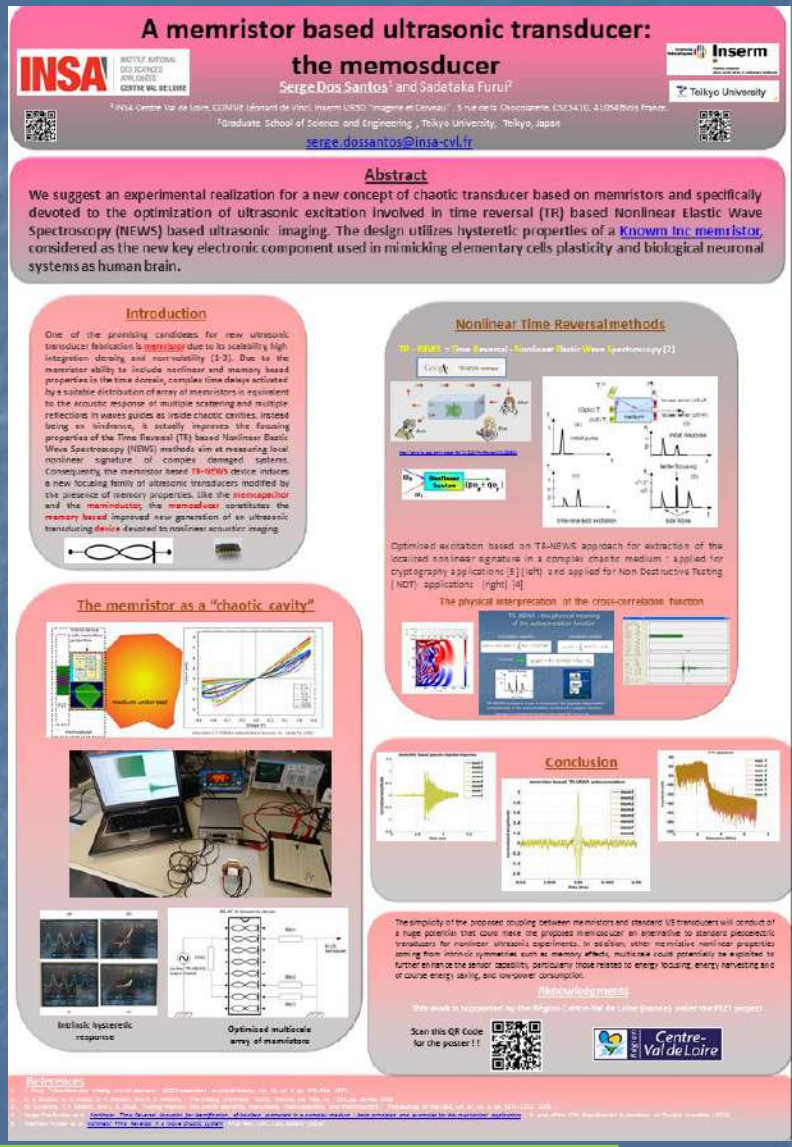


http://knowm.org/

Objective : a memristor based calibrated hysteretic measurement of the skin aging







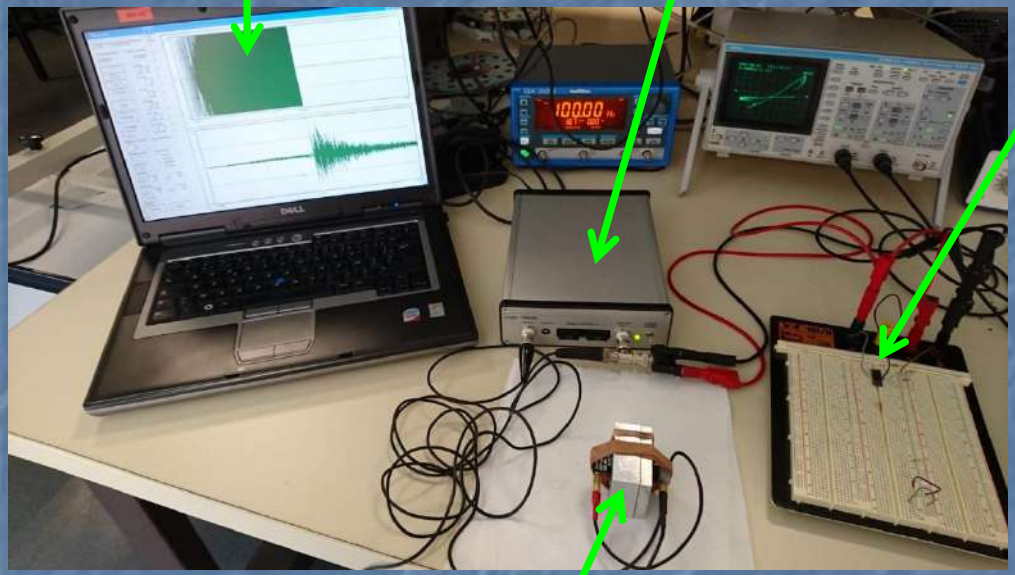
IEEE International Ultrasonic Symposium IUS 2016, Tours (France), Dos Santos and Furui (link here)

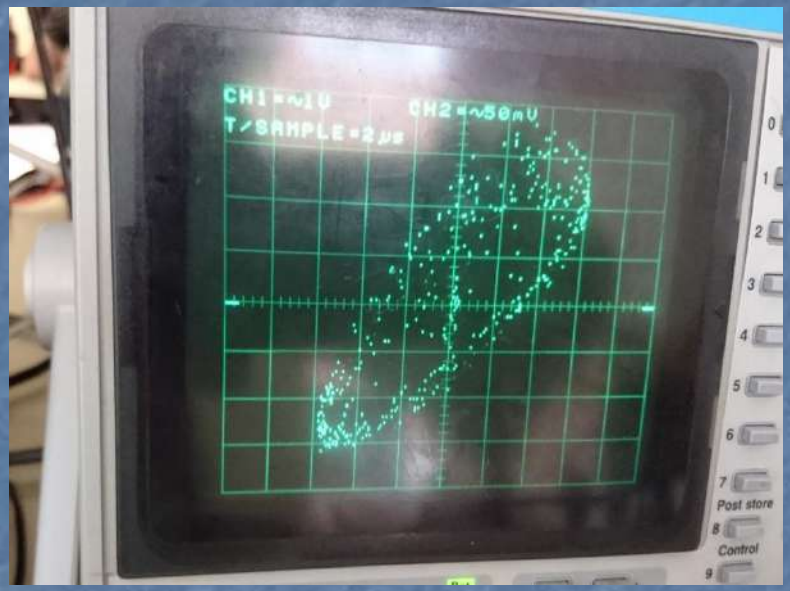
Le memosducer pour TR-NEWS

chirp-coded excitation

TR-NEWS system

Knowm memristor





sample under test

The memristor is inserted in order to change the transducing process during ultrasonic testing (UT) of bounding in aluminum sample

During the chirp-coded excitation, the memristor properties are activated in order to generate complex behavior like a chaotic cavity

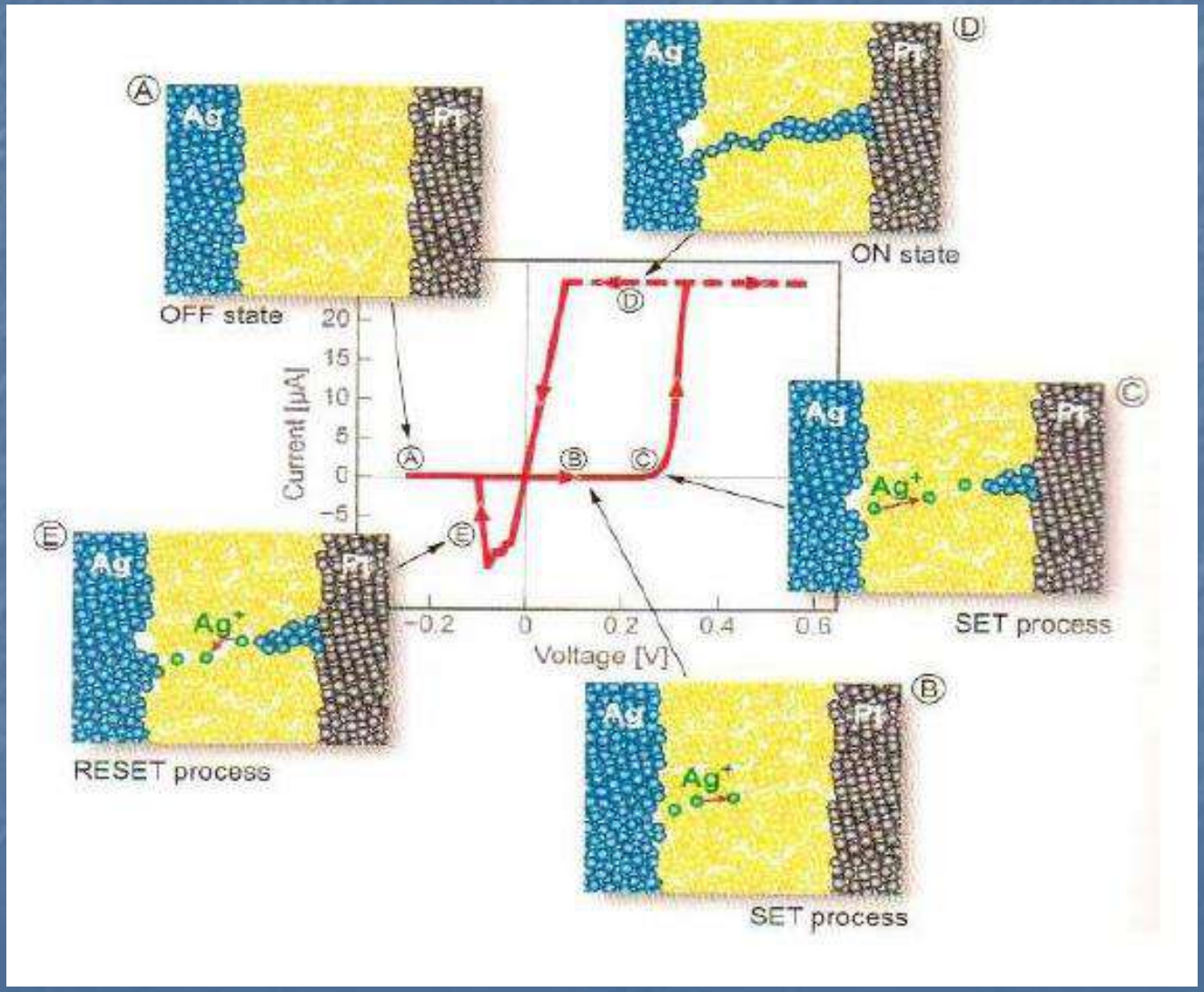
A memristor based ultrasonic transducer : the memosducer, S. Dos Santos and S. Furui, in the proc of the 2016 IEEE IUS Symposium, Tours, France

Le Memristor : composant non linéaire

Le modèle de dérive ionique non linéaire dans un memristor décrit la variation de la résistance en fonction du flux de charges à travers un matériau ionique. Il repose sur des phénomènes non linéaires de migration d'ions, influencés par des champs électriques. Ces interactions dynamiques entre les ions et la structure cristalline du matériau permettent au memristor de stocker et de rappeler des informations.

L'hystérésis dans un memristor est due à l'effet de dérive ionique. Lorsqu'un courant est appliqué, les ions se déplacent à travers le matériau, modifiant sa résistance. Cette modification est non linéaire, ce qui signifie que la résistance varie de manière différente selon que le courant augmente ou diminue. Cette caractéristique d'hystérésis permet au memristor de conserver un état de résistance même après la cessation du courant, ce qui est crucial pour son utilisation en tant que composant de mémoire.

Le Memristor : composant non linéaire

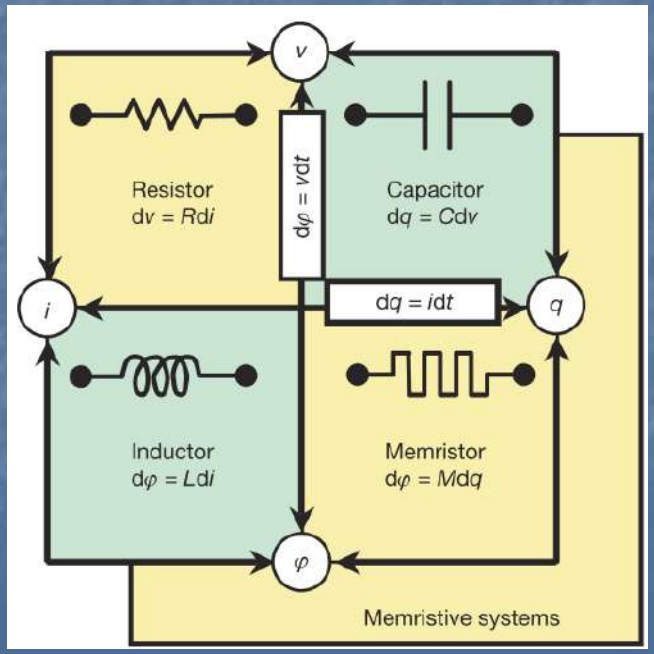


Définition du Memristor

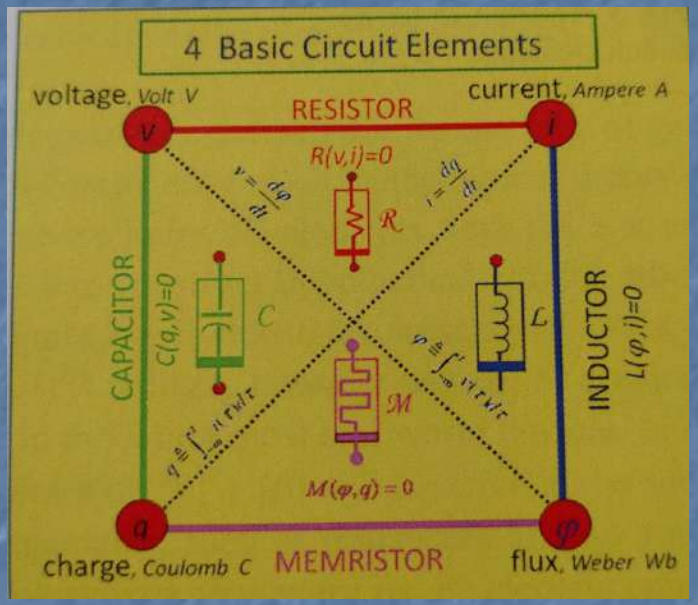
- Résistance variable et mémorisée
- 4ème élément de base des circuits (passif)
  - Conceptualisé en 1971 (Leon Chua)
  - Réalisé en 2008 par HP

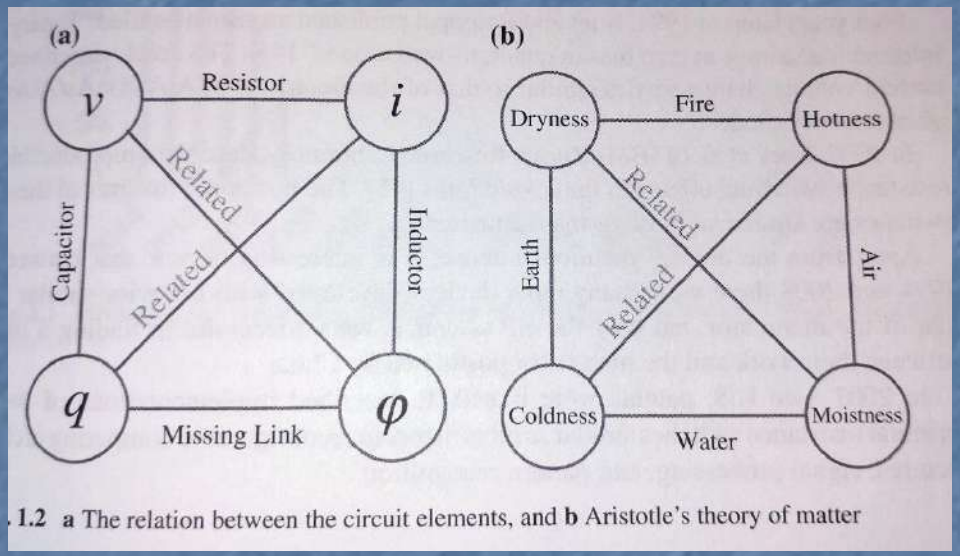
$$v = \mathcal{R}(w,i)\,i$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = f(w,i)$$



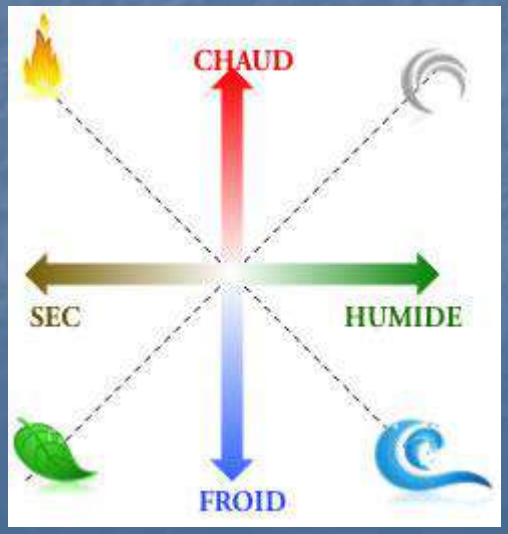
Définition du Memristor (Leon Chua)



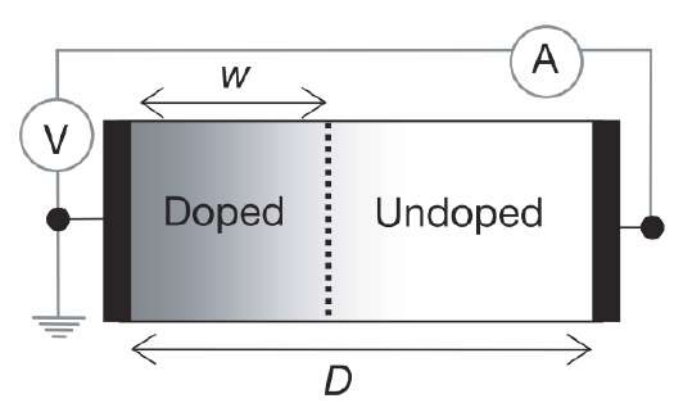


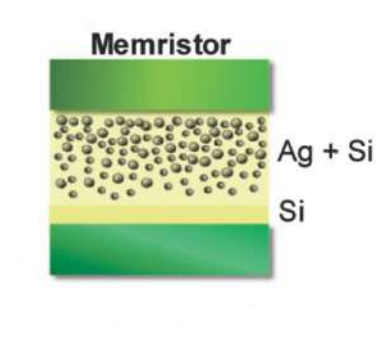
1.2 a The relation between the circuit elements, and b Aristotle's theory of matter

- Memristance M(q)
  - Existence prédite par des considérations de symétrie de la représentations des composants électroniques



Définition de la Memristance

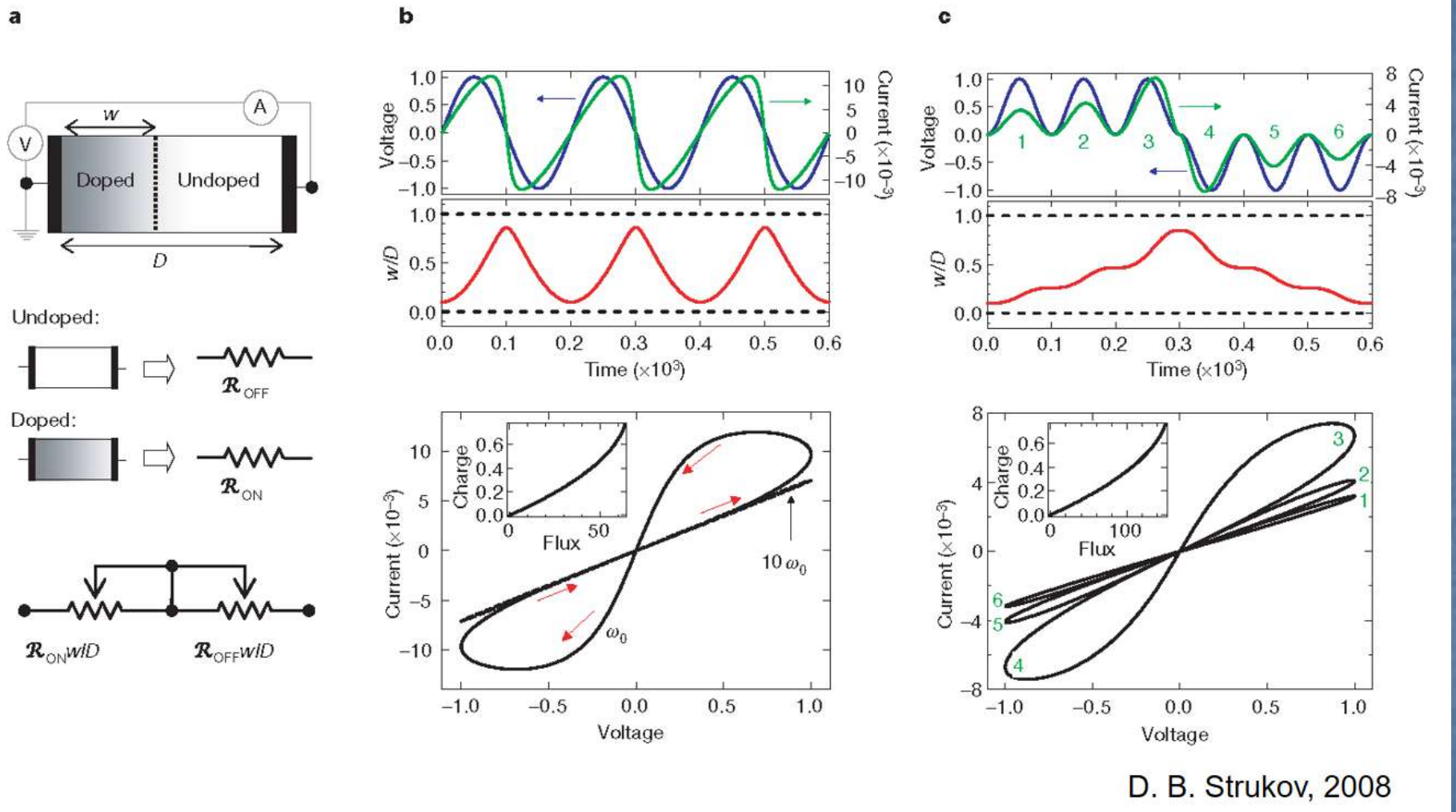




$$M(q) = \mathcal{R}_{OFF}\left(1 - \frac{\mu_V \mathcal{R}_{ON}}{D^2} q(t)\right)$$

- **Memristance** : résistance variant avec la charge ayant traversé le matériaux
  - *Effet mémoire*
  - *Exacerbé pour des dimensions nanométriques*

Hystérésis du memristor



Langage naturel de la Symétrie – Théorie des Groupes

Une goutte d'eau qui tombe possède une symétrie circulaire...mais après l'impact, une "couronne" apparaît et ne possède que 24 rotations possibles

Nombre infini de rotations et de réflexions SO(2)

groupe continu

24 rotations et 12 réflexions D_{24}

groupe ponctuel

Lien entre symétrie d'un système, son excitation et sa réponse ?

Lien entre l'équation modélisant le système et ses solutions ?

Analyse des Symétries (B. J. Cantwell, *Introduction to Symmetry Analysis*, 2002)

Symétries des Équations

$$\mathcal{E}(u, u') = 0 \text{ or } u' = f(u) \qquad u' = \frac{du}{dt} = u_t$$

- Solutions obtenues par quadrature (séparation des variables)
- Point de vue théorique: invariance par rapport à la transformation

$$\bar{t} = t + a, \bar{u} = u.$$

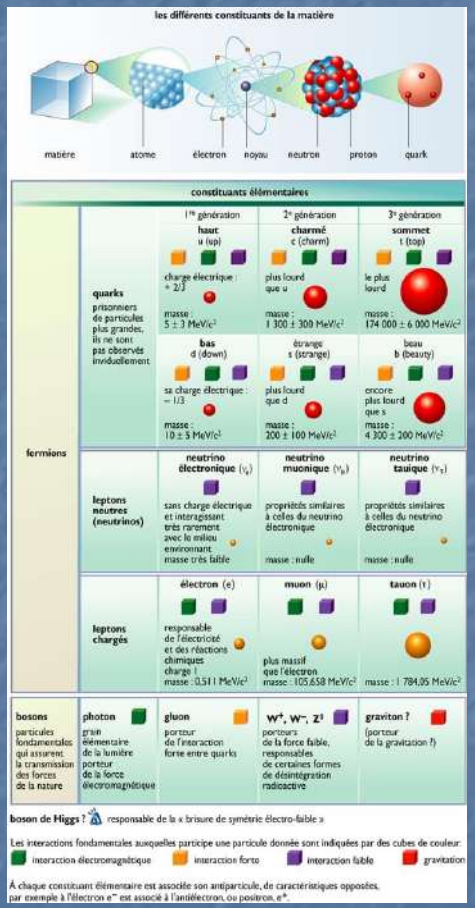
- Il s 'agit d 'une transformation définissant un groupe de Lie continu de paramètre *a*

Groupes de Lie, symétries et invariants

- Propriétés :
  - les solutions possèdent la signature de la symétrie
  - c 'est applicable aux **systèmes non linéaires**
  - la symétrie révèle des **quantités invariantes**
  - la symétrie permet d'accéder à de « bonnes représentations des solutions (signaux) »
- Exemples

Symétrie de l équation	Quantités conservées (invariants)	Propriétés
Invariance par translation du temps	Energie	homogénéité du temps
Invariance par translation de l 'espace	Moment	homogénéité de l 'espace
Invariance par rotation	Moment angulaire	isotropie de l 'espace

Symétries en physique nucléaire



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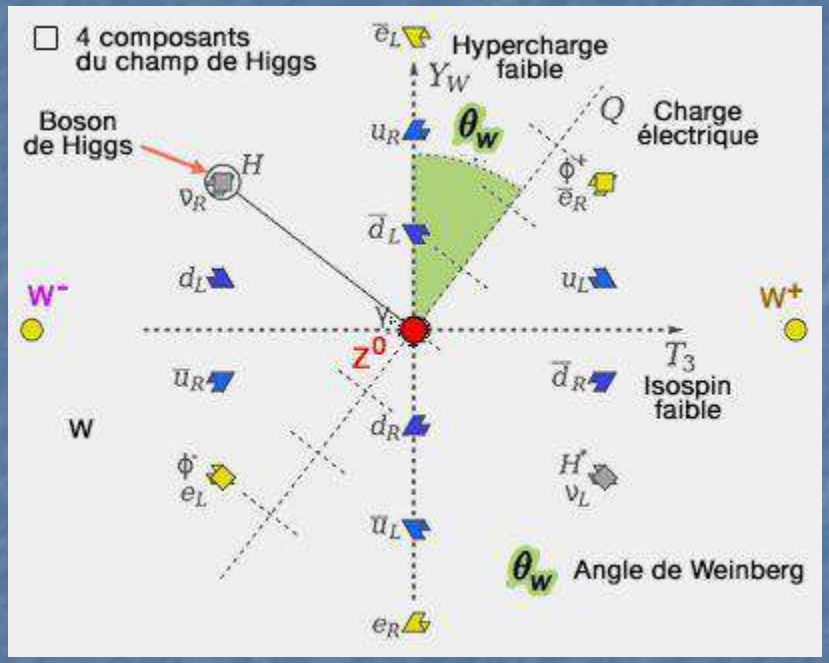


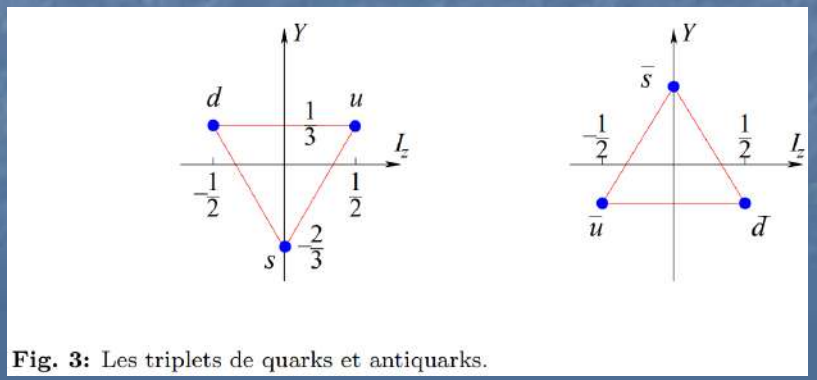


Fig. 3: Les triplets de quarks et antiquarks.

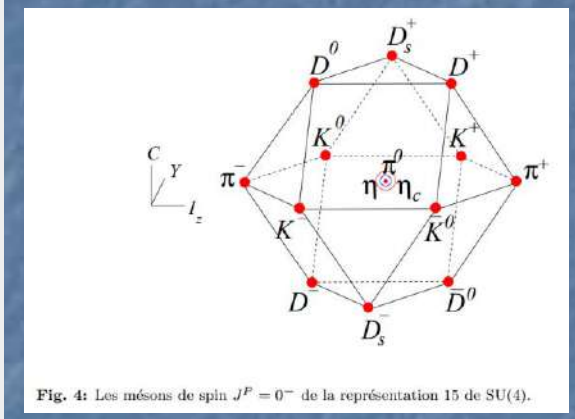
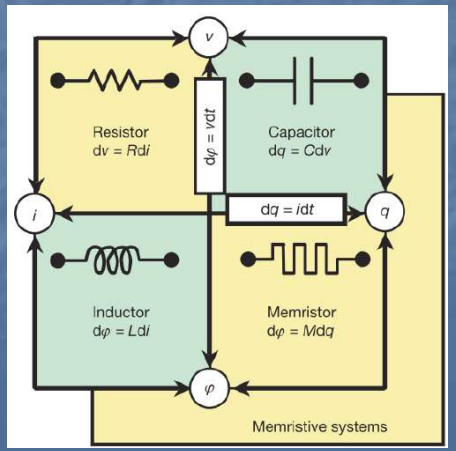
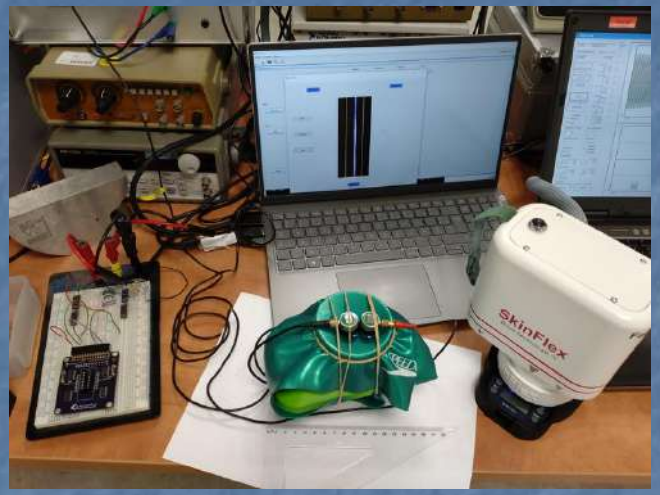
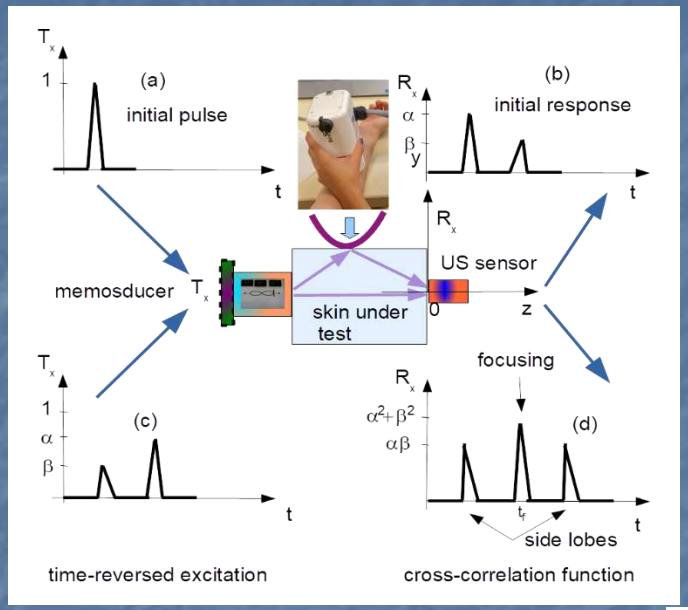


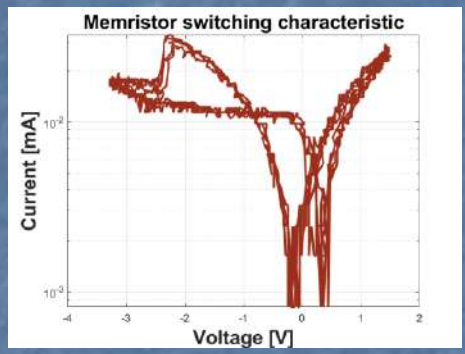
Fig. 4: Les mésons de spin $J^P = 0^-$ de la représentation 15 de SU(4).

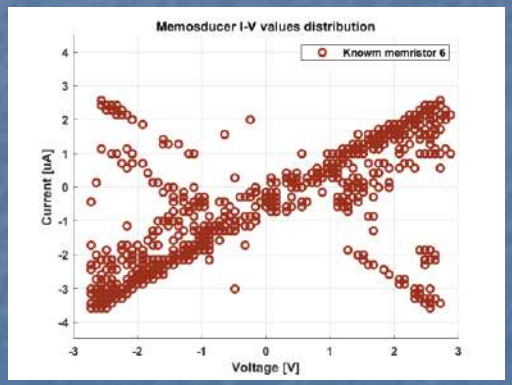


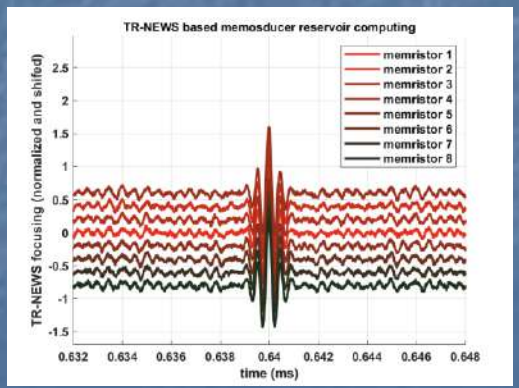
Memristors et hystérésis de la peau

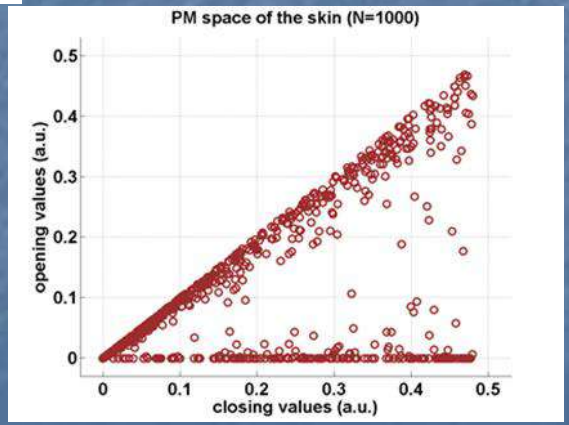






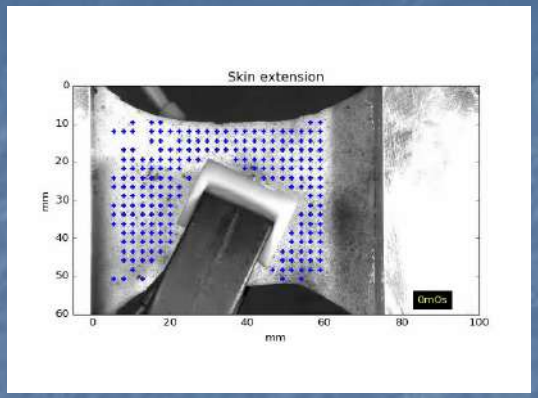


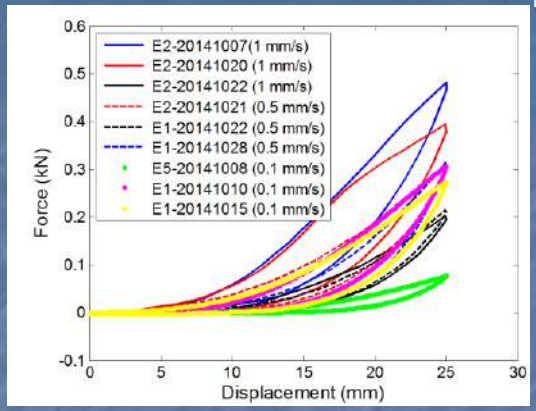


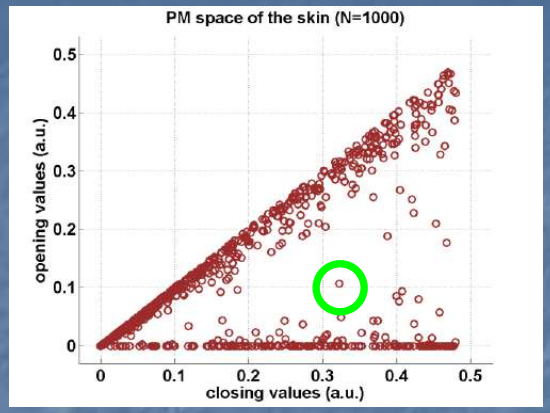


S. Dos Santos, P. Hemmati and S. Furui, *Memristor based ultrasonic optimized excitations for mesoscopic nonlinear characterization of biomedical tissues*, in Proc of the IEEE 18th Biennial Baltic Electronics Conference, Tallinn, Estonia, 2022, doi: 10.1109/BEC56180.2022.9935594.

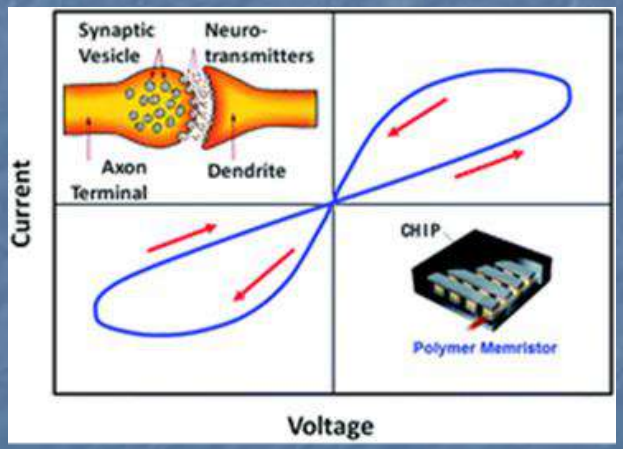
Memristors et hystérésis de la peau



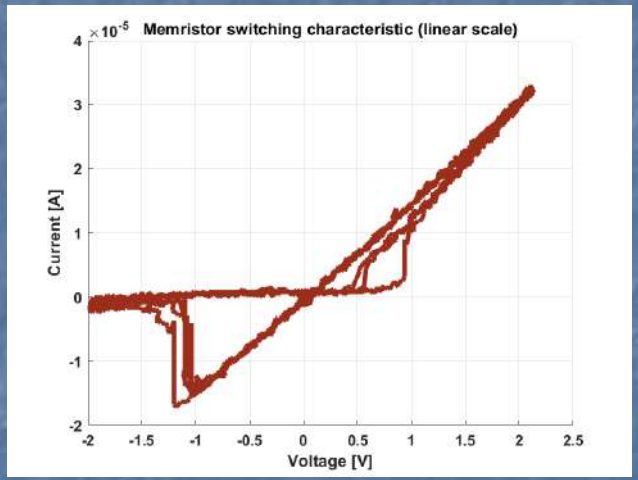




D. Remache, M. Caliez, M. Gratton, **S. Dos Santos**, *The effects of cyclic tensile and stress-relaxation tests on porcine skin*, In Journal of the Mechanical Behavior of Biomedical Materials, 2018 , ISSN 1751-6161, https://doi.org/10.1016/j.jmbbm.2017.09.009 (Open Access paper, IF 2016 : 3.11, 62 citations)



Chen, Materials Horizon, 2014



S. Dos Santos, P. Hemmati and S. Furui, "*Memristor based ultrasonic optimized excitations for mesoscopic nonlinear characterization of biomedical tissues,"* 2022 18th IEEE Biennial Baltic Electronics Conference (BEC), 2022

S. Dos Santos, P. Hemmati and S. Furui, "*Optimization of memristor based ultrasonic transducers for mesoscopic characterization of biomaterials*," 2022 IEEE International Symposium on Applications of Ferroelectrics (ISAF), 2022

1ère Visite de Leon Chua (2009)

…et d'en trouver des innovations …

Exemple : le memristor (Leon O Chua, Berkeley University)

Visite de Leon O Chua

le lundi 8 juin 2009, ENI Val de Loire

COVER STORY

Memristor milestones

1971

Leon Chua (EE, University of California, Berkeley) publishes "Memristor — the Missing Circuit Element," (IEEE Transactions of Circuit Theory, Vol. 18, No. 5), but never builds one.

Memristor $d\varphi = Mdq$

1976

Leon Chua publishes "Memristive Devices and Systems" (Proceedings of the IEEE, Vol. 64, No. 1), but ultimately builds only an oscillator.

1980

Leon Chua publishes "Dynamic Nonlinear Networks: State of the Art" (IEEE Transactions on Circuits, Vol. 27, No. 11), which models all nonlinear circuit elements, including the memristor.

es will require at least five more years of research," Stewart said. HP Labs estimates that commercial applications are about a decade out.

The fundamentals

Technically, a memristor is a passive circuit element that relates flux to charge in the same way resistors relate voltage to current, capacitors relate voltage to charge and inductors relate flux to current. The fact that this fourth combination has been ignored in electronic-circuit theory was discovered by EE professor Leon Chua at the University of California, Berkeley, who wrote a seminal paper about the memristor in 1971.

"Memristors represent a fundamental change in electronic-circuit theory," said Sung-Mo Kang, chancellor of the Engineering School and an EE professor at the University of California at Merced. The most important items in electronics are the voltage, the current, the electrical charge and the flux linkage, he said. "If you consider those four variables as constitutive relations, then you get the equations that describe the resistor, inductor and capacitor."

But there is a fourth combination that everybody had overlooked, said Kang. "Chua's genius was realizing that combination defined a new passive device type — the memristor," he said. "Chua's argument was mathematical, but what he was saying is that the memristor had just as much a fundamental right as resistors, inductors and capacitors."

Chua called his discovery a memristor because of its behavior: The device acts as a variable resistance that "remembers" how much current has flowed through it by changing the voltage across its terminals. Thus, it can serve as a memory element that can be flipped "on," with a current in one direction, and "off," with a current in the reverse direction.

"A resistor relates voltage to current and the memristor relates flux to charge," said Notre Dame's Perod. "However, if you sum up flux over time, it becomes a voltage, and if you sum up charge over time it becomes a current. So a device that relates flux to charge, like the memristor, will over time relate voltage to current like a variable resistor that changes its value depending on how much, and in which direction, current has flowed through it."

For 35 years, only Chua and a handful of his former students taught fledgling engineers about the concept of a memristor. In lab classes, using resistors, inductors, capacitors and transistors, Chua had circuit boards built that emulated a memristor. He also wrote many papers providing detailed characterizations for EEs — effectively telling them how to recognize a memristor when they saw one.

Nevertheless, the idea remained an academic matter for 35 years, until HP chemist Stanley Williams (now a senior fellow) realized he had discovered an electronic circuit element that exhibited the behavior Chua described.

"The fingerprint by which EEs can recognize a memristive circuit element is by its voltage-current relationship," Chua said. He described that relationship as "a hysteresis loop that goes through the origin — what I call a pinched hysteresis loop."

Many such pinched hysteresis loops have cropped up in the literature on nanoelectronics over the past 35 years, said Chua, "but these devices have been incorrectly identified by the authors of these papers." It took Williams' multidisciplinary team of physicists, chemists, mathematicians and EEs at

1995

HP Labs forms "Quantum Structures Research Initiative" led by chemist Stanley Williams to develop molecular-scale alternative to transistor-based switches.

2002

Leon Chua publishes "Nonlinear Circuit Foundation for Nanodevices" (Proceedings of IEEE, Vol. 91, No. 11), which positions memristors within his nonlinear circuit theory.

2005

Leon Chua receives IEEE Gustav Robert Kirchhoff Award, which recognizes him as the father of both nonlinear circuit theory and cellular neural networks.

32 Electronic Engineering Times August 18, 2008

ENI Val de Loire
Ecole Nationale d'Ingénieurs

Serge Dos Santos - Cours de Traitement du Signal - Année 2009-2010

UNIVERSITÉ FRANÇOIS - RABELAIS TOURS

Avis de Conférence

MEMRISTOR : 37 years later from Nonlinear Physics to Nanoelectronics

Leon O. CHUA
University of California, Berkeley

Mardi 9 juin 2009, 14h
Amphithéâtre 22, bâtiment F, Faculté des Sciences
Université François Rabelais, Parc de Grandmont
2 Avenue Monge, Tours

Résumé :

On the May 1, 2008 issue of Nature scientists from the Hewlett-Packard Company unveils a nano-scale device called the memristor, a hypothetical circuit element postulated in 1971. This Nature paper has generated unprecedented worldwide interests because, among many applications, memristors can be used as super-dense non-volatile memories for building instant turn-on computers. Even more exciting is the recent suggestions from many brain-research scientists that the memristor's continuous (analog) memory can be used to build ultra-small brain-like learning machines with nano-scale memristive synapses having a density of more than 50,000 synapses per neuron on a single chip. This lecture will provide an introduction to memristors and its potential applications, along with some historical and philosophical perspectives.

The circuit-theoretic foundation of the memristor, and its generalizations to a lossless memory capacitor, and a lossless memory inductor, will be presented along with the devices' constitutive relations. Their identifying fingerprints consist of a pinched hysteresis loop when plotted in the voltage-vs.-current plane, flux-vs.-integrated-charge plane, and charge-vs.-integrated-flux plane, respectively. All three devices are nonlinear and their underlying physical mechanisms are expected to dominate and manifest their memory character as the device size scales below 20 nanometers, when electrons and ions are coupled strongly under intense electric and/or magnetic fields. While all three devices are ideal candidates for non-volatile nano memories, the long-term significance lies in their enabling potentials for designing intelligent nano machines, with learning and adaptive capabilities. Even more fundamental is their memristive nonlinear dynamics, which underpins the biological basis of life itself, where ion channels, with their complex biochemical synaptic dynamics, are essentially memristors.

Brief Technical Biography

Prof. Leon O. Chua is known as a pioneer in 3 research areas, namely, nonlinear circuits, neural networks, and chaos. His work in these areas has been recognized through many awards, including 11 honorary Doctorates from major Universities in Europe and Japan, and 7 USA patents. He was elected as Fellow of IEEE in 1974, a foreign member of the European Academy of Sciences (Academia Europea) in 1997, and a foreign member of the Hungarian Academy of Sciences in 2007. He was honored with many major IEEE prizes, including the IEEE Browder J. Thompson Memorial Prize Award in 1972, the IEEE W. R. G. Baker Prize Award in 1978, the Frederick Emmons Award in 1974, twice winner of the IEEE M.E.Van Valkenburg Award (1993 and 1998). He is also a Recipient of the top 15 most cited authors Award in 2002 from all fields of engineering published during the 10-year period 1959 to 2001, from the Current Contents (ISI) database, the IEEE Neural Networks Pioneer Award in 2000, the IEEE Gustav Kirchhoff Award in 2005, and the IEEE Vitold Belevitch Award in 2007.

Prof. Chua is widely recognized as the father of nonlinear circuit theory and cellular neural networks (CNN). Prof. Chua also invented a five-element electronic circuit for generating chaotic signals, known as the Chua Circuit. It has become a standard paradigm for teaching chaos in textbooks on nonlinear dynamics.

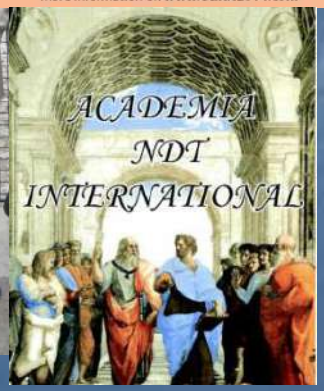
Contacts :
Serge DOS SANTOS, UMR 930 « Imagerie et Cerveau » INSERM-CNRS FRE 3106-Université François Rabelais, ENIVL, Rue de la Chocolaterie, 41034 BLOIS, serge.dossantos@univ-tours.fr

Laurent VENTURA, Daniel AUQUE, Laboratoire de Microélectronique de Puissance (FA 5246)
Site Polytech'Tours, 7 avenue Marcel Dassault, 37200 Tours, laurent.ventura@univ-tours.fr

Jean-Claude SORET, Laboratoire d'Electroélectronique des Matériaux Avancés (LEMA)
UMR Université - CNRS 6157, Parc de Grandmont 37200 Tours, soret@delphi.phys.univ-tours.fr

http://www.dr8.cnrs.fr/CNRS-Hebdo/Documents/117/Document.aspx

Leon Chua, Prague 2014



Le memristor comme sujet d'examen INSA CVL ...

Institut National des Sciences Appliquées
Centre Val de Loire - Blois - Bourges
Département Sciences et Technologies Pour l'Ingénieur

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES CENTRE VAL DE LOIRE

Electromagnetism exam

June 2018, 8th
Duration : 3 hours

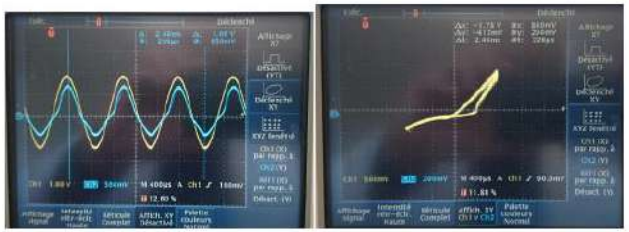
- **The 3 exercises (R, L, C) must be written on separate copies (different correctors).**

Exercise R (8 points) : the memristor (from Mines Physique MP 2017)

This exercise focuses on a new (resistive) component that could soon revolutionize inform tion storage capabilities: the memristor, a kind of resistance with a memory effect, predic by Leon Chua in 1971 and manufactured by HP Laboratories in 2008.

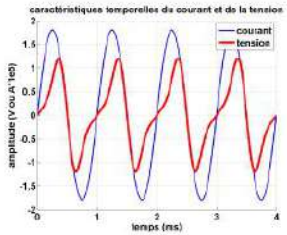
Course questions and hypotheses

1. Recall the expression of Faraday's law relating to the presence of an electromotive force induced e_{ind} to the variation of a magnetic flux ϕ.
2. Recall the expression of the circulation $\mathcal{C}_{AB}$ of the electrostatic field $\overrightarrow{E_0}$ between points A and B of a circuit ($AB = l$), and its dependence on potential V such that $u = u_{AB} = V(A) - V(B)$.
3. Assuming that the memristor is studied in receptor convention, it can be shown that the two quantities above e_{ind} et $\mathcal{C}_{AB}$ are related by $e_{ind} = -\mathcal{C}_{AB}$. Deduce that the potential u across the memristor is given by $u = \frac{d\phi}{dt}$.

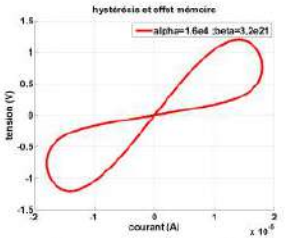


(a) memristor current and voltage

(b) Lissajous plot showing hysteresis



(c) simulated curves $i(t)$ et $u(t)$



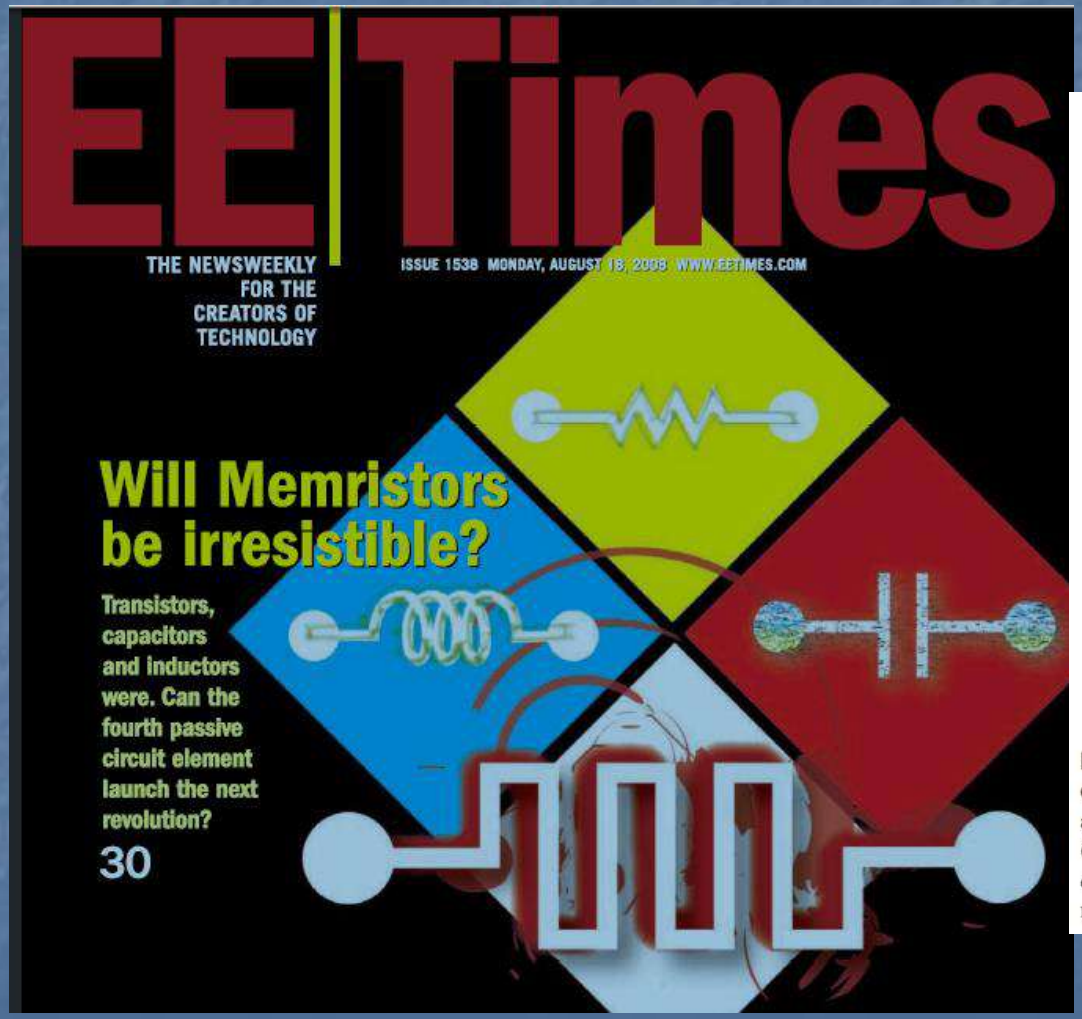
(d) Lissajous parametric plot $u(i)$

Figure 7.7: *Experimental memristor characteristics* $f = 1kHz$, $I_{max} = 0.018mA$, $\alpha = 1,6.10^4$S.I., $\beta = 3,2.10^{21}$S.I. *from the measurements given by figure (a) and (b). The variable resistance of the memristor is calculated from the "slope" of the curves (b) et (d).*

https://celene.insa-cvl.fr/pluginfile.php/12945/mod_resource/content/15/cours_EMAG_2023_STPI_INSACVL.pdf page 176

...pour en trouver des innovations ...

- Exemple : le memristor



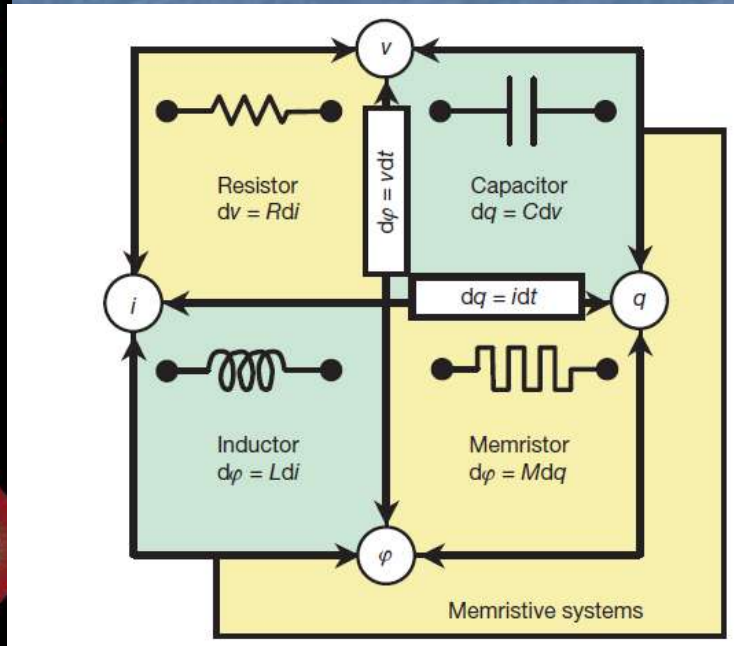


Figure 1 | The four fundamental two-terminal circuit elements: resistor, capacitor, inductor and memristor. Resistors and memristors are subsets of a more general class of dynamical devices, memristive systems. Note that R, C, L and M can be functions of the independent variable in their defining equations, yielding nonlinear elements. For example, a charge-controlled memristor is defined by a single-valued function $M(q)$.

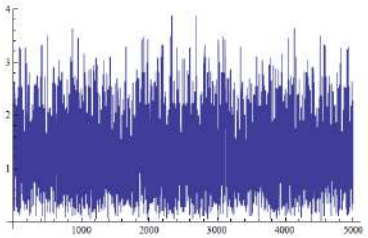
https://celene.insa-cvl.fr/pluginfile.php/84126/mod_resource/content/2/CoursTS2_2010b.pdf

… pour en trouver des innovations …

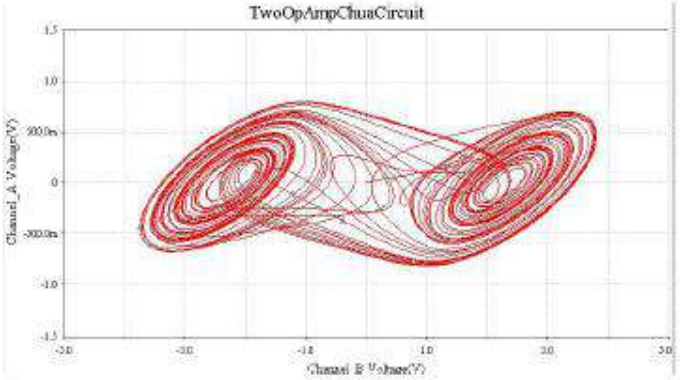
Exemple : le memristor (Leon O Chua, Berkeley University)

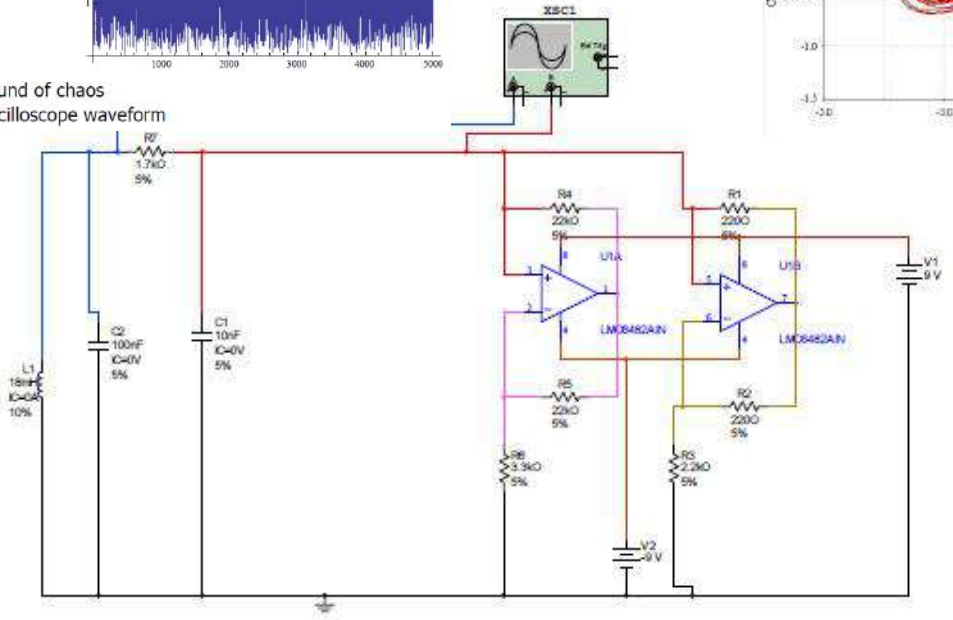
Chua's Circuit: MultiSim Circuit Simulation and Physical Implementation

Power Spectra of $v_{C1}(t)$



Sound of chaos
Oscilloscope waveform





NOEL : Nonlinear Electronics Lab
Dr. Leon O Chua – Director 151M Cory Hall University of California, Berkeley
http://nonlinear.eecs.berkeley.edu

July 9th 2008

…e years of …s estimates …are about a … …assive circuit …arge in the …ge to current, …rge and induc… …fact that this …gnored in elec… …vered by EE …iversity of Cal… …seminal paper … …damental …eory," said …he Engineer… …r at the Univer… …he most … …are the volt… …charge and the …nsider those …relations, then …cribe the resis… … …sation that …d Kang. …hat combina… …rice type — …a's argument …e was saying … as much a …, inductors … …memristor …vice acts as a …mbers" how …ugh it by … terminals. … element that …rent in one …rent in the … … current and …harge," said

Notre Dame's Porod. "However, if you sum up flux over time, it becomes a voltage, and if you sum up charge over time it becomes a current. So a device that relates flux to charge, like the memristor, will over time relate voltage to current like a variable resistor that changes its value depending on how much, and in which direction, current has flowed through it."

For 35 years, only Chua and a handful of his former students taught fledgling engineers about the concept of a memristor. In lab classes, using resistors, inductors, capacitors and transistors, Chua had circuit boards built that emulated a memristor. He also wrote many papers providing detailed characterizations for EEs — effectively telling them how to recognize a memristor when they saw one.

Nevertheless, the idea remained an academic matter for 35 years, until HP chemist Stanley Williams (now a senior fellow) realized he had discovered an electronic circuit element that exhibited the behavior Chua described.

"The fingerprint by which EEs can recognize a memristive circuit element is by its voltage-current relationship," Chua said. He described that relationship as "a hysteresis loop that goes through the origin — what I call a pinched hysteresis loop."

Many such pinched hysteresis loops have cropped up in the literature on nanoelectronics over the past 15 years, said Chua, "but these devices have been incorrectly identified by the authors of these papers." It took Williams' multidisciplinary team of physicists, chemists, mathematicians and EEs at

2002
Leon Chua publishes "Nonlinear Circuit Foundation for Nanodevices" (Proceedings of IEEE, Vol 91, No. 11), which positions memristors within his nonlinear circuit theory.

2005
Leon Chua receives IEEE Gustav Robert Kirchhoff Award, which recognizes him as the father of both nonlinear circuit theory and cellular neural networks.

...et pour breveter des applications technologiques

- Exemple : le memristor

54 TECHNOLOG

La résistance élect

LE MEMRISTOR POURRAIT RAFLER LA MISE

Toutes ces technologies promettent miniaturisation, non-volatilité et vitesse élevée de lecture-écriture. Mais l'expérience suggère la prudence... Le memristor ne sera-t-il qu'un énième candidat au rôle envié de mémoire du futur? Ce qui est sûr, c'est qu'il lui faudra faire des compromis : par exemple, la taille du matériau actif est infinitésimale, mais la connectique associée est soumise aux limites de la lithographie. La création de HP bénéficie toutefois de deux atouts qui pourraient faire mouche. D'une part, sa double capacité à créer des circuits logiques et des mémoires. D'autre part, une structure minimaliste qui augure bien de son potentiel d'industrialisation.

20 MAI 2010 | N° 3193 | L'USINE NOUVELLE

DES ÉTATS SUPPLÉMENTAIR POUR UNE CAPACITÉ ACCRU

# U.S. Patents Claiming Memristor Application	Non-volatile Memory	Logic/ Computation	Neuromorphics
AMD	14	0	0
Axon Tech.	20	1	0
Energy Conversion Devices	28	5	2
Hewlett Packard	49	10	1
Micron Tech.	241	0	0
Samsung	18	0	0
Sharp	41	0	0
Unity Semi.	54	0	0

From : Blaise Mouttet,
USA PATENT Office
"The Business Landscape for Memristor Electronics,"
June 1, 2009
http://knol.google.com/k/anonymous/the-business-landscape-for-memristor/23zgknsxnlchu/6#

http://knol.google.com/k/the-business-landscape-for-memristor-electronics#

L'Usine Nouvelle (Mai 2010)

http://www.industrie.com/it/electronique/memristor-une-memoire-deux-fois-plus-dense-des-2013.9657

Le memristor en projets d'étudiants à l'INSA

Memristor

Le chaînon manquant de l'informatique grand public

Les suites de 0 et de 1, bientôt un lointain souvenir ? Avec le memristor, **Hugo Leroux** prédit l'avènement d'une nouvelle génération de transistors aux possibilités de calcul décuplées.

C'est le composant qui pourrait révolutionner l'informatique. IBM, Intel, Hewlett Packard, mais aussi le CNRS, le CEA… tous les laboratoires de recherche en électronique se sont lancés dans la course pour concevoir, fabriquer et assembler une puce d'un nouveau genre – qui pourrait réinventer l'informatique, donnant accès à des capacités de calcul sans comparaison avec celles de nos ordinateurs actuels.

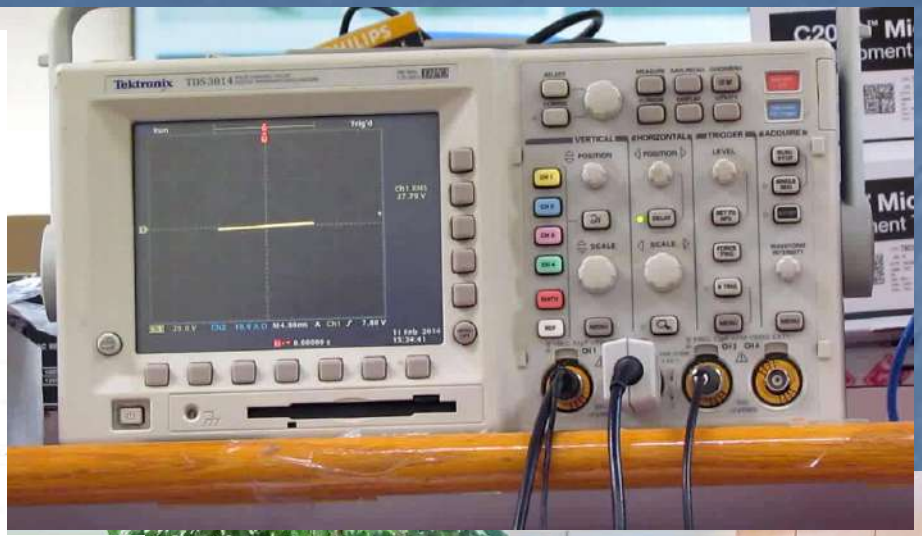
Le premier prototype a été mis au point il y a dix ans, un peu par hasard, par les chercheurs de Hewlett-Packard. Alors qu'ils planchent sur de nouvelles technologies de mémoire à base d'oxydes de titane, ils remarquent que la migration progressive de l'oxygène au sein du matériau, causée par les impulsions électriques, modifie sa résistivité… et que cette valeur persiste lorsque l'on interrompt le courant. Ils font alors le rapprochement entre ce comportement original et un vieux concept, imaginé en 1971 par le mathématicien Léon Chua, de l'université de Berkeley. Pour le théoricien, il manquait un composant fondamental de l'électronique, un composant qui aurait la faculté d'ajuster sa résistance aux impulsions électriques : le memristor. *"L'idée est de parvenir, en jouant sur les propriétés de matériaux exotiques, à un composant analogique qui n'adopte plus une résistance de 1 ou 0 – comme les transistors traditionnels qui ne sont que des interrupteurs* on/off *miniatures – mais toute une série de valeurs intermédiaires laissant passer plus ou moins le courant. Par exemple, un memristor pourrait passer d'une résistance de 0,12 à 0,63 en fonction du signal d'entrée"*, explique Vincent Derycke, qui travaille sur le sujet au CEA.

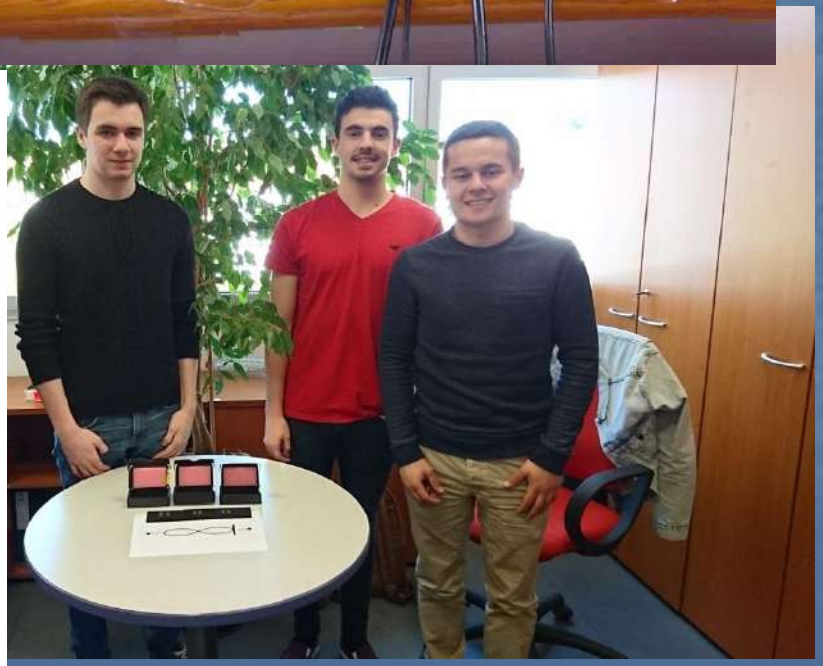
Le memristor se présente comme un hybride, à mi-chemin entre un transistor – ce composant de base qui effectue tous les calculs dans

Contexte

L'industrie de l'électronique arrive à la croisée des chemins. **Les big data** imposent des puissances de calcul toujours plus grandes, et les ordinateurs classiques sont à la peine : **la loi de Moore,** qui prédit empiriquement le doublement de la miniaturisation des circuits tous les 18 mois, se heurte à des limites physiques.

IBM

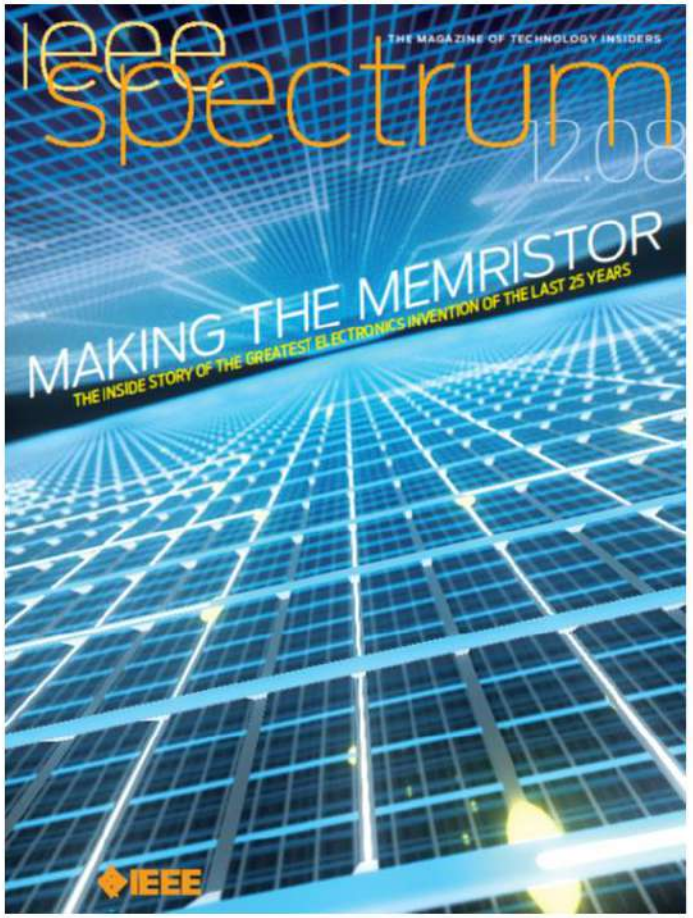




Projet INSA 1A (19 avril 2016)

Pourquoi les memristors ?

- Annonce de HP en 2008
  - Mais pas que HP
- Qu'est-ce qu'un memristor ?
  - Un nanocomposant ~50nm x 50nm
  - « Une résistance qui apprend » : Plus le courant traverse la résistance, plus la résistance est faible: U=R(i).i
  - Rôle de facilitateur : fonctionnement semblable à une synapse…



Informatique bio-inspirée

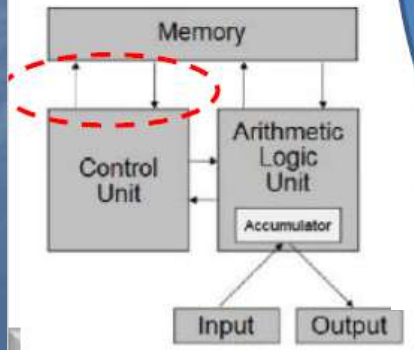
Increase of Fault (nanoscale engineering)

Saturation of clock frequency + Energy consumption

New needs for computing Recognition, Mining, Synthesis (Intel)

SEMICONDUCTOR TECHNOLOGY CHALLENGES

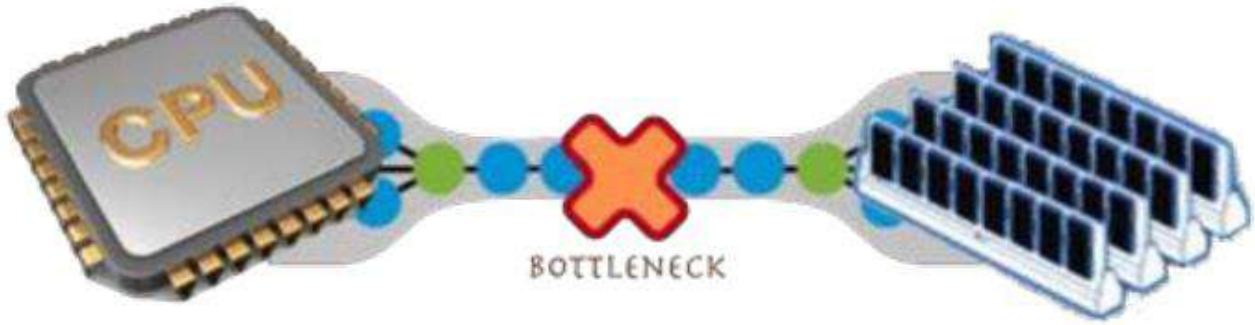
Von Neumann bottleneck



Shift toward a new paradigm for computation

BIO-INSPIRED COMPUTING to match the brain performances (low power consumption, fault tolerant, performances for RMS)

Informatique bio-inspirée



Von Neumann is not enough any more!

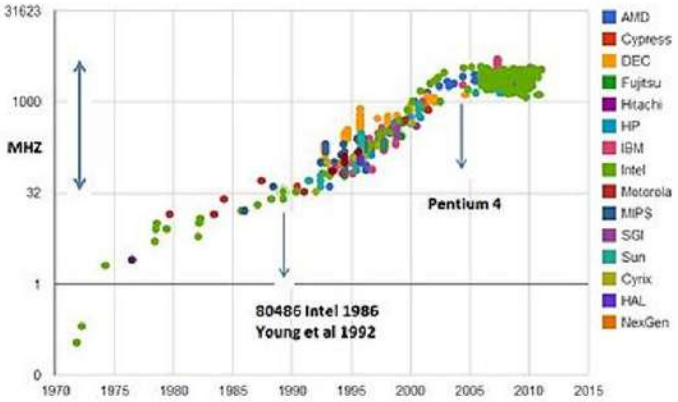
Big Data, big deal!

- A "flood of data" is moving attention to data-centric approaches
- Von Neumann's paradigm lead to a bandwidth limit due to data transfer time

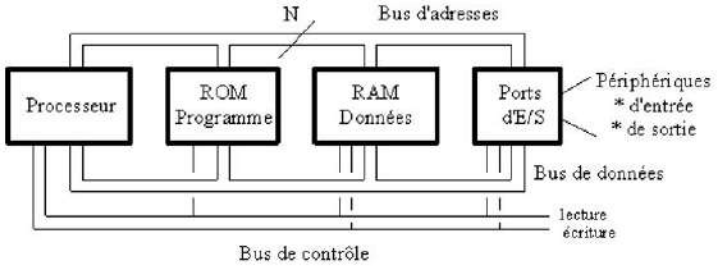
Informatique bio-inspirée

Limitation des processeurs

- Dissipation thermique



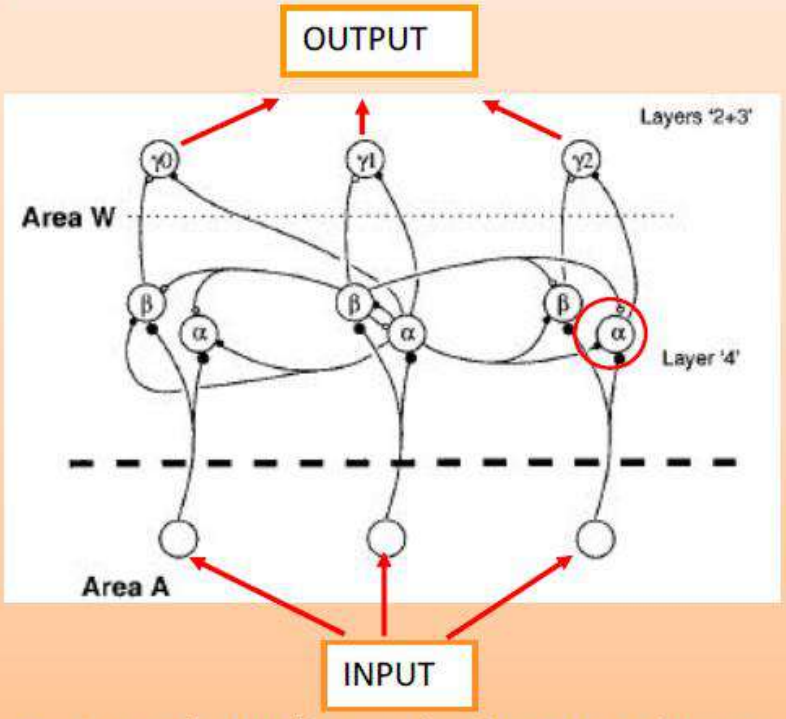
- Accès mémoire



Architectures originales de calcul à explorer !

Réseaux de Neurones bio-inspirés ou artificiels

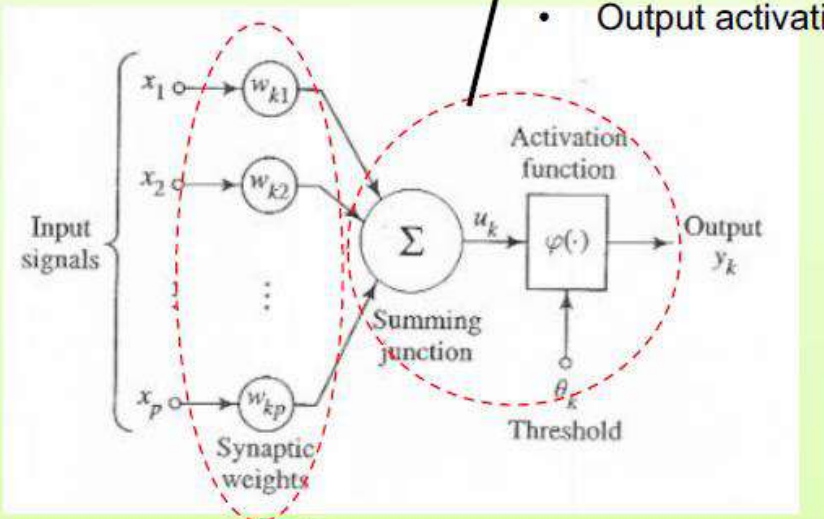
Biological neural network



- Lots of new discoveries in neurosciences (characterization tools, non invasive probing,…)

Artificial neural network

NEURON:
- Summation
- Thresholding
- Output activation



SYNAPSES:
- Input weighting
- Weight adaptation

- Performances of GPU increase the complexity of ANNs implmentation

Brain

- Brain demonstrates
  - massive parallelism (10^{11} neurons)
  - massive connectivity (10^{15} synapses)
  - excellent power-efficiency
    - much better than today's microchips
  - low-performance components (~ 100 Hz)
  - low-speed communication (~ metres/sec)
  - adaptivity – tolerant of component failure

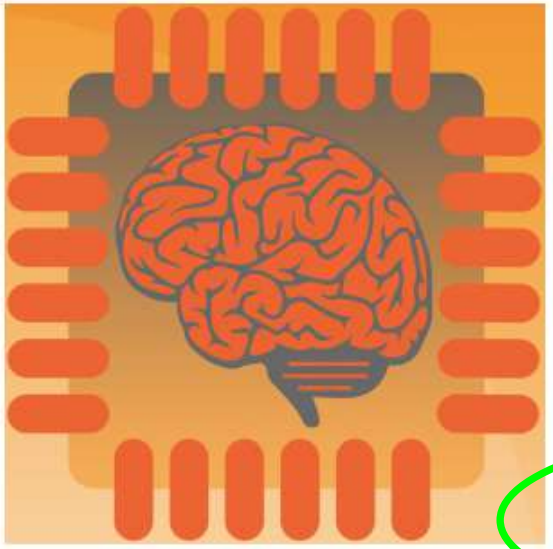
Top 10 emerging technologies of 2015

The 2015 list is:

1. Fuel cell vehicles
2. Next-generation robotics
3. Recyclable thermoset plastics
4. Precise genetic engineering techniques
5. Additive manufacturing
6. Emergent artificial intelligence
7. Distributed manufacturing
8. 'Sense and avoid' drones
9. Neuromorphic technology
10. Digital genome

9. Neuromorphic technology

Computer chips that mimic the human brain



Even today's best supercomputers cannot rival the sophistication of the human brain. Computers are linear, moving data back and forth between memory chips and a central processor over a high-speed backbone. The brain, on the other hand, is fully interconnected, with logic and memory intimately cross-linked at billions of times the density and diversity of that found in a modern computer. Neuromorphic chips aim to process information in a fundamentally different way from traditional hardware, mimicking the brain's architecture to deliver a huge increase in a computer's thinking and responding power.

Miniaturization has delivered massive increases in conventional computing power over

https://agenda.weforum.org/2015/03/top-10-emerging-technologies-of-2015-2/

Informatique bio-inspirée

REPORT TO THE PRESIDENT

Ensuring Long-Term U.S. Leadership in Semiconductors

Executive Office of the President

President's Council of Advisors on Science and Technology

January 2017

Ensuring Long-Term U.S. Leadership in Semiconductors

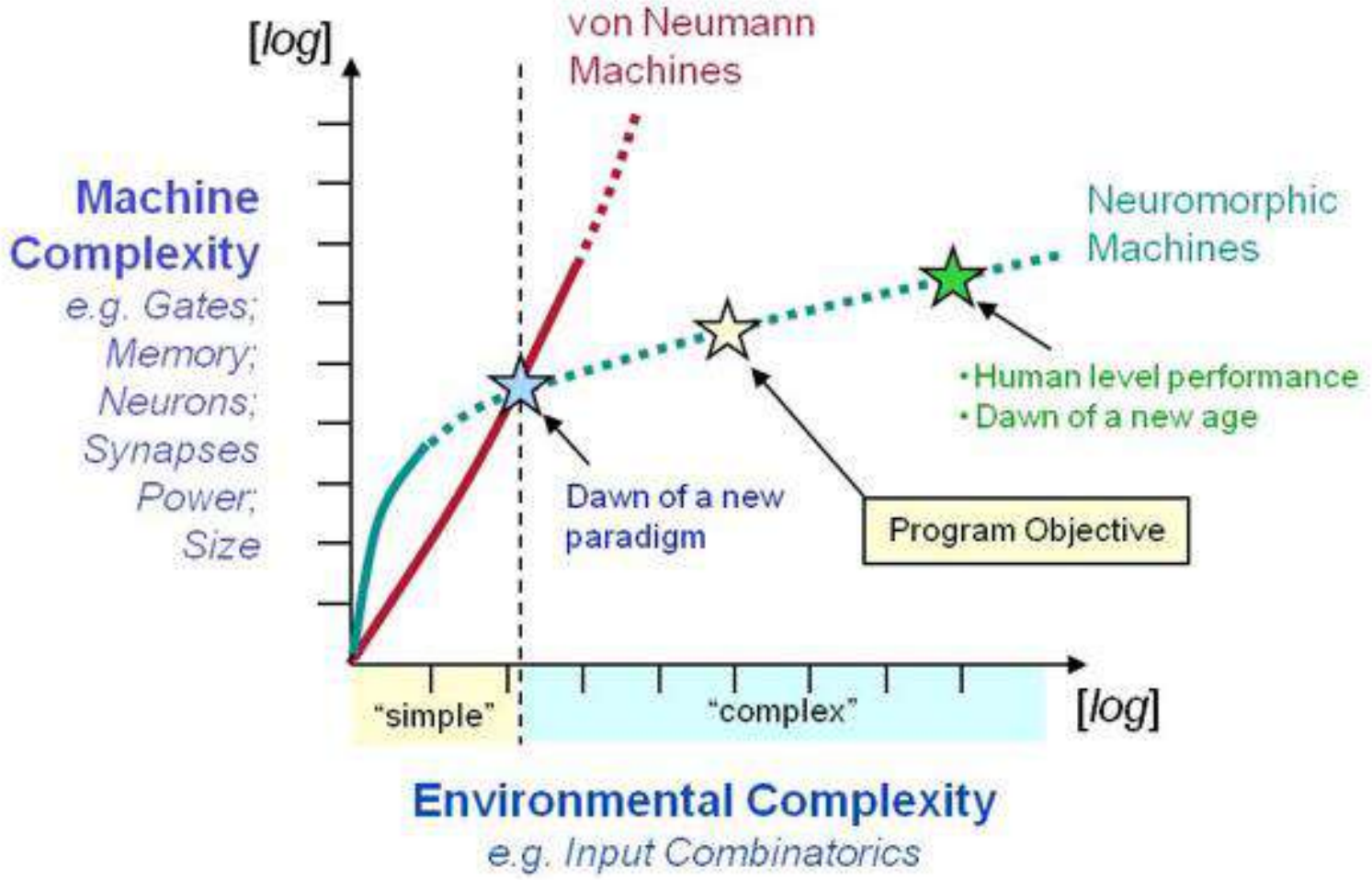
Table A1. Selected component technology vectors that have a high probability of deployment in ten years

(* denotes more speculative deployment within this timeframe)

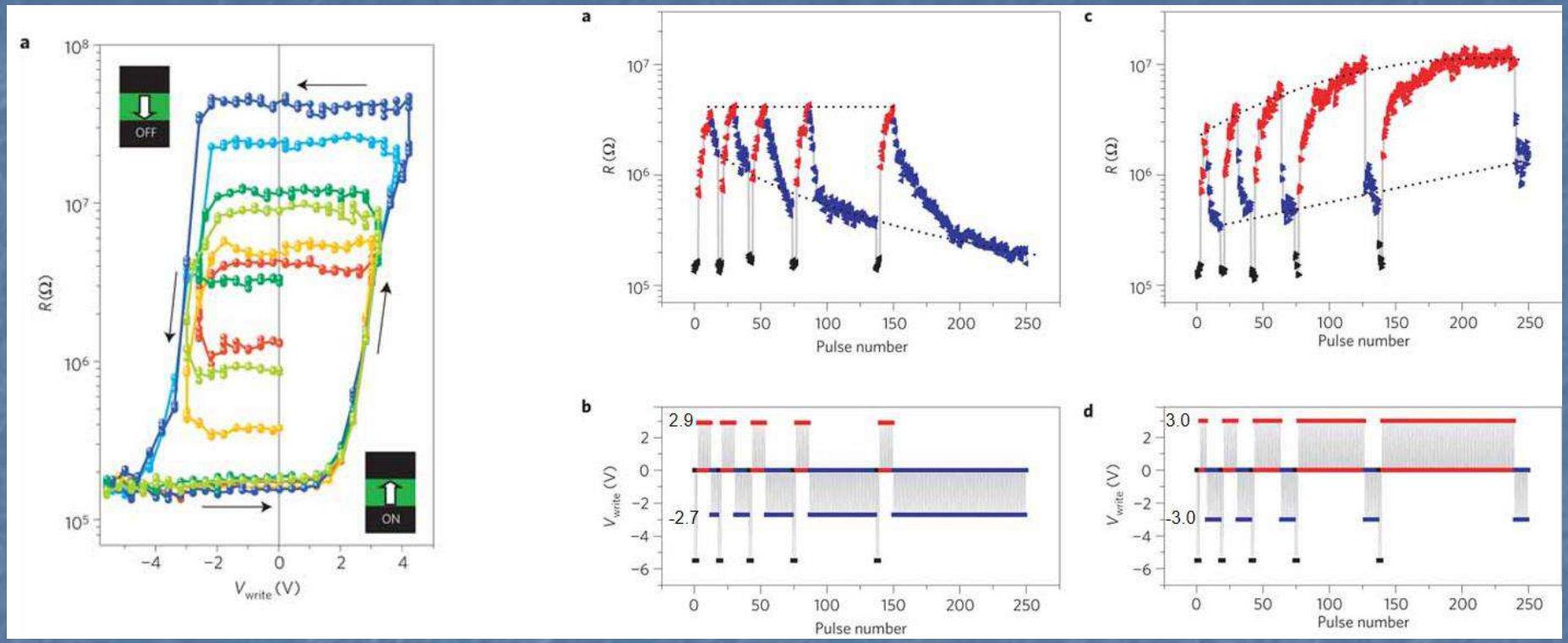
Component technology vector	Time-frame to first commercial products	Approach to achieving and retaining competitive advantage
Neuromorphic Computing	Available now	Continued R&D into new architectures coupled with 3D technologies and new materials, Deep Learning accelerators (for mobile and data center applications), and applications for true brain-inspired computing
Photonics	Available now	Foundries for tools and materials R&D; integrate photonics with CMOS and other materials
Sensors	Available now	Foundries for tools and materials R&D; integrate new types/classes of sensors with CMOS and other materials
CMOS (sub 7nm node size or new 3D structures)*	Advances in thermal management available with new process nodes	Deep understanding of transistor physics and chipset architecture and related design know-how; foundries and labs for transistor and materials R&D
Magnetics	1-2 years (MRAM as eFlash), 3 years (as DRAM), 5-7 years (as SRAM)	Foundries for tools and materials R&D; integrate magnetics with CMOS and other materials
3D	2-3 years (wafer-to-wafer	Deep understanding of applications space and benefits associated

Furber, Steve (2022). 2022 roadmap on neuromorphic computing and engineering. Neuromorphic Computing and Engineering, 2(2). https://doi.org/10.1088/2634-4386/ac4a83

Informatique neuro-morphique



Memristors pour la conception neuromorphique



- La valeur dépend de :
  - Amplitude
  - Nombre d'événements
  - Durée des événements
- Hystérésis à effet mémoire

A. Chanthbouala, *et al* (2012)

Nouveauté 2021 en Cours de Traitement du Signal à l'INSA

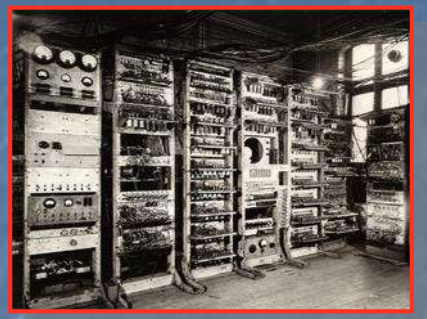
https://www.label-ddrs.org/

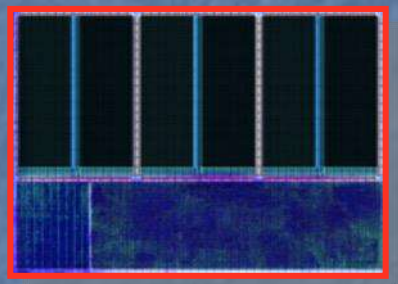
Le Ministère de la transition écologique et sociétale prépare et met en œuvre la politique du Gouvernement dans les domaines du développement durable, **de l'environnement**, notamment de la protection et de la valorisation de la nature et de **la biodiversité**, des technologies vertes, de la transition énergétique **et de l'énergie**, notamment en matière tarifaire, du climat, de la prévention des risques naturels et technologiques, du **contrôle de la sécurité industrielle**, des transports et de leurs infrastructures, de l'équipement et de la mer. Il élabore et met en œuvre la politique de lutte contre le réchauffement climatique **et la pollution** atmosphérique.
Il promeut une gestion durable des **ressources rares**.

- Pollution
- Contrôle
- **Énergie**

65 ans de progrès

- *Manchester Baby (1948):*
  - used 3.5 kW of electrical power
  - executed 700 instructions per second
  - 5 Joules per instruction
- *SpiNNaker ARM968 CPU node:*
  - uses 40 mW of electrical power
  - executes 200,000,000 instructions per second
  - 0.000 000 000 2 Joules per instruction





25,000,000,000 times better than Baby!

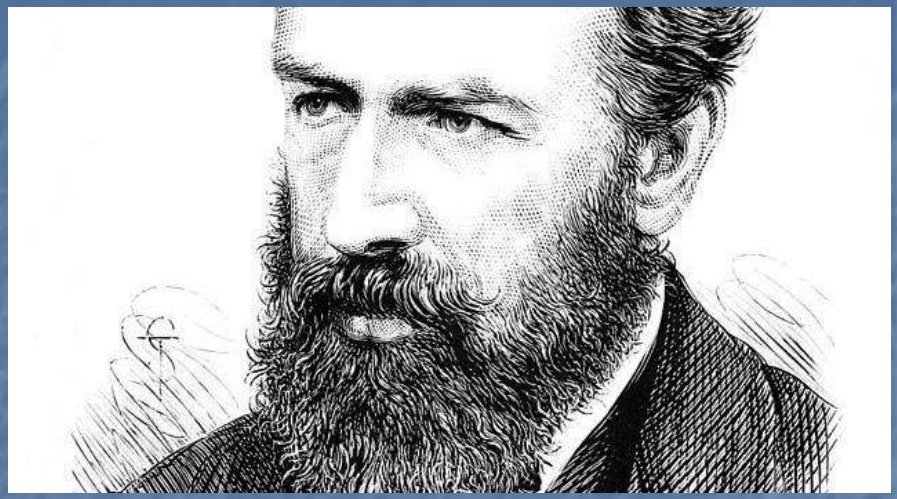
(James Prescott Joule born Salford, 1818)

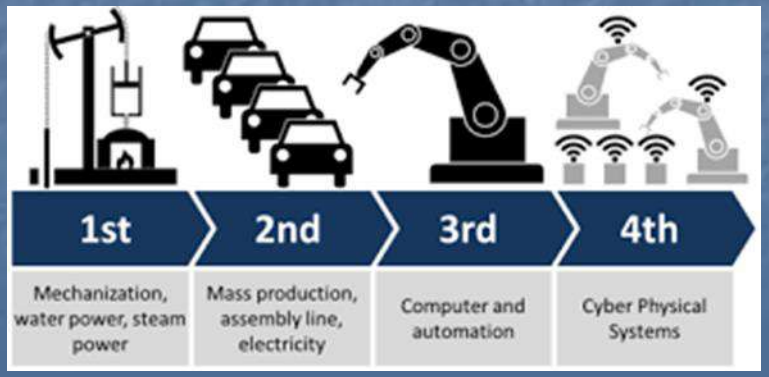
51

Le paradoxe de Jevons

1865 "The Coal Question"

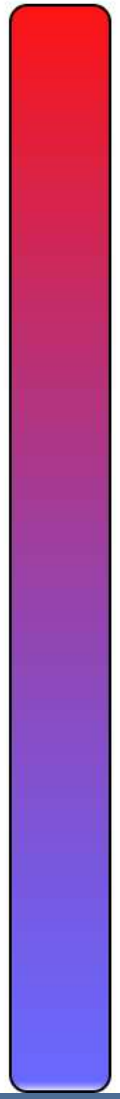
- James Watt's coal-fired steam engine was much more efficient than Thomas Newcomen's…
- …and coal consumption ***rose*** as a result





Puissance et #data

10^9 W	Barrage Hoover dam (CO, USA)
745 W	1 cheval vapeur
170 W	Intel Titanium Quad-core
100 W	Métabolisme corps humain
80 W	Intel Pentium 4
30 W	**Cerveau humain (~ 10^{11} neuron)**
10^{-2} W	Laser dans un lecteur DVD
10^{-5} W	Montre à quartz
10^{-9} W	Courant d'air à 5m/s/mm^2
10^{-12} W	1 cellule humaine (moyenne)
10^{-18} W	Bruit thermique
10^{-21} W	Signal Galiléo reçu



Traitement du signal à l'INSA

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES CENTRE VAL DE LOIRE

Énergie !

Article | Published: 19 December 2022

A memristor-based Bayesian machine

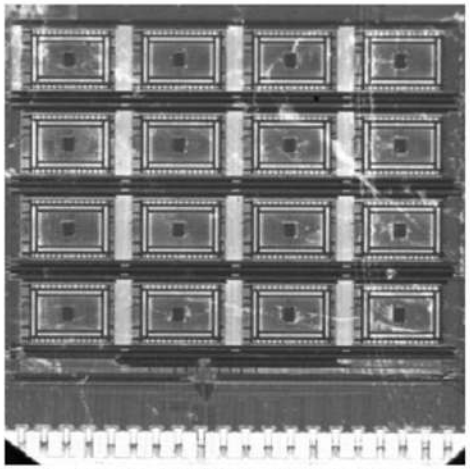
Kamel-Eddine Harabi, Tifenn Hirtzlin, Clement Turck, Elisa Vianello, Raphaël Laurent, Jacques Droulez, Pierre Bessière, Jean-Michel Portal, Marc Bocquet & Damien Querlioz

Nature Electronics 6, 52–63 (2023) | Cite this article

3418 Accesses | 1 Citations | 105 Altmetric | Metrics

Abstract

Memristors, and other emerging memory technologies, can be used to create energy-efficient implementations of neural networks. However, for certain edge applications (in which there is access to limited amounts of data and where explainable decisions are



Photographie de la machine Bayésienne (dimension 2mmx2mm). Les seize blocs de memristors (apparaissant comme des carrés noirs) sont entourés de circuits à base de transistors. © Damien Querlioz (CNRS/Univ. Paris-Saclay)

https://www.isir.upmc.fr/actualites/une-intelligence-artificielle-a-faible-consommation-denergie/

Traitement du signal à l'INSA

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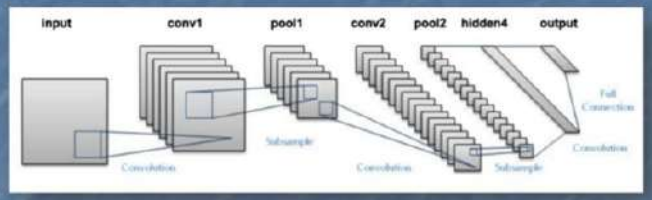
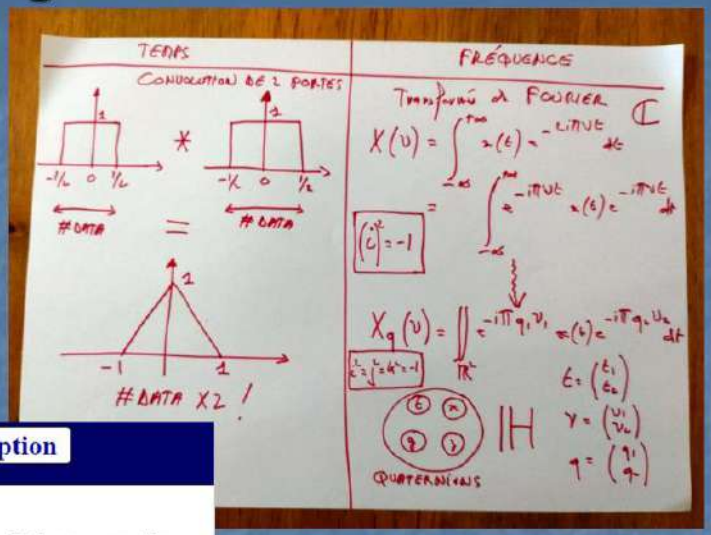
Énergie et #data !



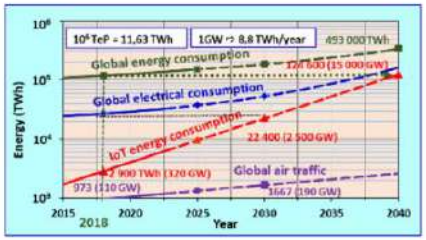
https://www.datasciencetoday.net/index.php/en-us/deep-learning/173-les-reseaux-de-neurones-convolutifs



Evolution: flow of data, energy consumption

Parallel energy consumption evolution

The energy consumption related to the Internet which takes into account all the consumption items induced between the providers and the users, including maintenance/storage of duplicated data, represented in 2020 about 4 times the energy consumption of air traffic worldwide.



After O. Bonnaud, Proc. LASCAS'2022, pp. 41-44, 2022

In 2030, the equivalent of all the electrical energy produced worldwide in 2018, should be used by the digital sector.

O. Bonnaud, RTSI 2022, Paris (France), 24-26 August 2022 16/32

$i^2=j^2=k^2=ijk=-1$ $ij = -ji = k$

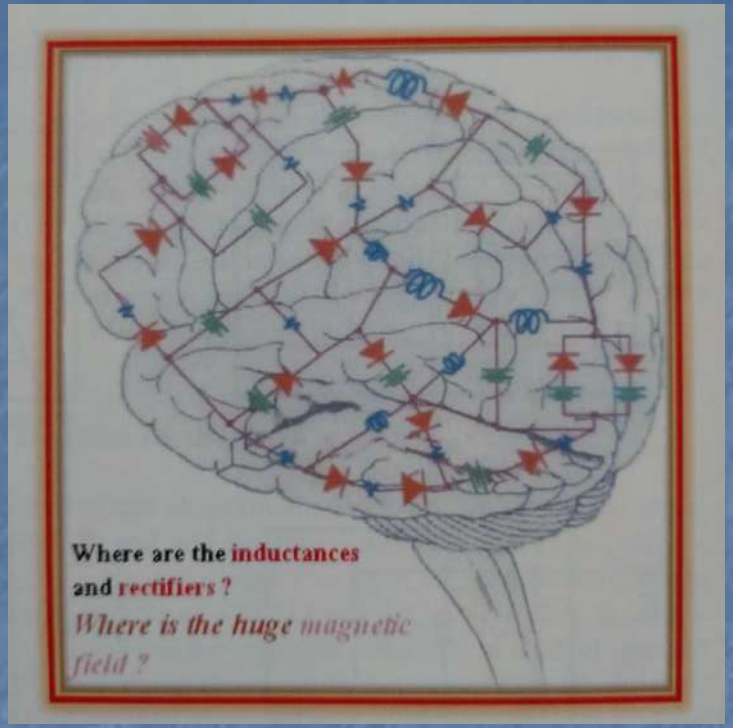
$[j,k]=jk-kj=2i$

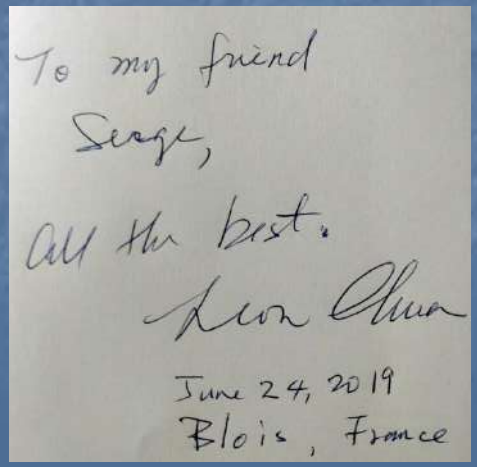
digital footprint !

Serge Dos Santos Traitement du Signal, INSA Centre Val de Loire, Département Génie des Systèmes Industriels, Année 2022-2023 43

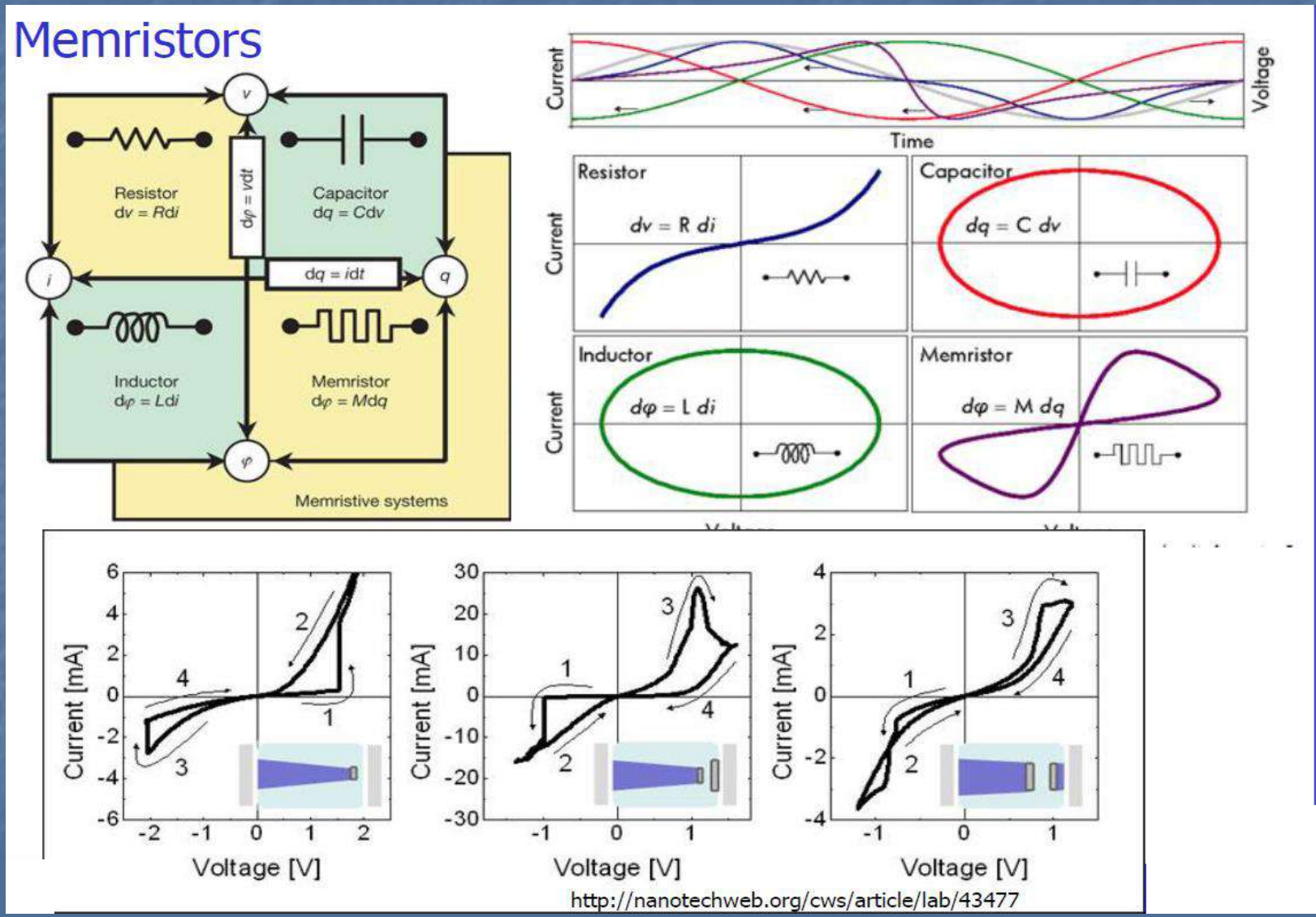
Conclusion

- La vision de Turing des machines avec une intelligence humaine est sur le point d'être réalisée !
- Ada Lovelace avait des espoirs d'obtenir un jour des phénomènes cérébraux tels que je puisse les mettre en équations mathématiques… J'espère léguer aux générations un calcul du système nerveux

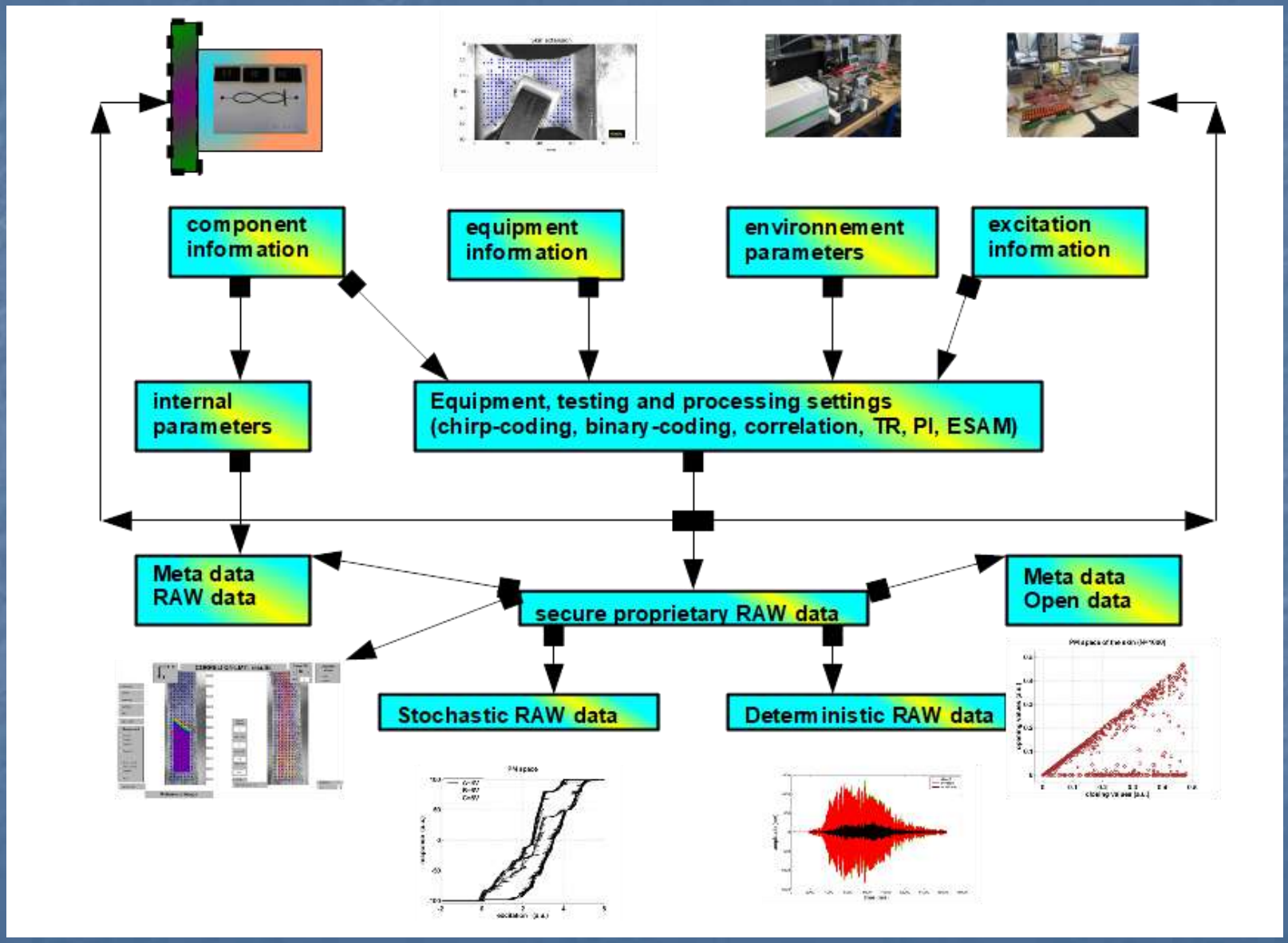




Caractéristiques d'un memristor (courbe I-V)



Memristors pour l'accès aux #data du CND4.0 !



Conclusion et Perspectives

- Grace à la flexibilité du nombre de ses variables d'états internes, ou la nature topologique du réseau connectant ses éléments memristifs élémentaires, l'approche **memristive mutiéchelle, inspirée des espaces PM**, peut permettre de comprendre les mécanismes micro-meso-nanoscopiques responsables du vieillissement des organismes et biomatériaux.

- La modélisation des processus biologiques *via* l'utilisation de mémoires résistives non volatiles doit intégrer des **problématiques transdisciplinaires**, afin de quantifier **le potentiel et les limites** de l'ingénierie memristive.

- C'est une formidable opportunité que de valider le concept **d'électronique bio-inspirée** utilisant des technologies memristives afin de proposer des axes de recherche dans le domaine des **technologies pour la santé et du contrôle non destructif**.

- Le **memristor**, en raison de ses propriétés de stockage d'information non volatile et de basse consommation d'énergie, pourrait permettre la conception de systèmes électroniques **économes en énergie**, réduisant ainsi l'empreinte carbone induite par la **transition numérique**.

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  - USA : A. Sutin and A. Sarvazyan (TR-NEWS experimentation for NDT and bubbles)
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  - Spain : V. Sanchez Morcillo (TR-NEWS optimization of focusing with phononic cavities)
  - France : O. Bou Matar (TR-NEWS simulations), V. Gusev (Nonlinear Acoustics), M. Caliez (TR-NEWS for skin)
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  - UK : T. Stratoudaki (bimodality laser/US for TR-NEWS, invited researcher)
  - Germany : S. Hirsekorn (nonlinear NDT; invited researcher at INSA Centre Val de Loire)
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  - Latvia : V. Kurtenoks (TR system instrumentation; electronics)
  - USA : **Leon O. Chua (memristive effects ; nonlinear systems),** R. Singh (NDE 4.0)
  - Japan : **S. Furui (symmetry analysis of memristor based TR-NEWS systems)**
  - Estonia : A. Salupere, M. Lints (solitonic and delayed TR-NEWS), T. Rang (INSA students)

- U1253 « Imaging and Brain : iBrain », Inserm-Université de Tours (GIP Ultrasons), Greman UMR 7347 CNRS-CEA, Lamé
  - Abellard A.-P., Arruga D., Bouakaz A., Caliez M., Callé S., **Chaline J.**, Domenjoud M., **Farova Z.**, Feuillard G., Fortineau J., Girault JM, Guilloteau D., **Goursolle T.**, Gratton M., Haumesser L., Hemmati P., Kozena C., Lethiecq M., **Lint M.**, Masood A., Novell A., Papouskova J., Patat F., Plag C., Poirot, N., Pourcelot L., Remenieras J.P., Tauber C., Tran P., Vander Meulen F., **Vila M.**

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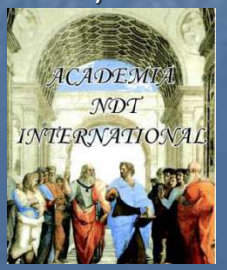
  - Dr. Ing. Rainer Link, Dr. Sotirios J. Vahaviolos



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Instituts thématiques Inserm Institut national de la santé et de la recherche médicale

Merci de votre attention !

serge.dossantos@insa-cvl.fr

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Région Centre-Val de Loire