Bio-inspired Information Processing: The Future of Artificial Intelligence?

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Chair of Nanoelectronics

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January 2020

Outline

- Information Technology
  Current Status and Perspectives
- Information Processing in Nervous Systems
  A few Amazing Examples
- Bio-Inspired Electronics
  Looking for Novel Computing Architectures

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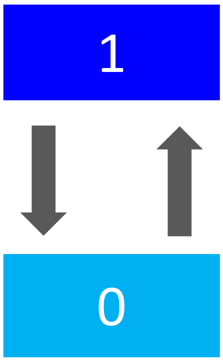
Bits and Energy: The Landauer Limit

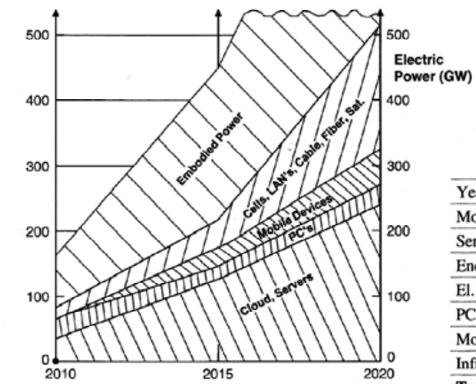


3×10^{-21} Joule/bit
@ T = 300K

R. Landauer, "Irreversibility and heat generation in the computing process"
IBM J. Res. Dev. 5, 183 (1961).
Minimum Energy of Computing, Fundamental Considerations
V. Zhirnov et al., ICT DOI: 10.5772/57346 (2013).

3

Energy Consumption and Information Technology



0.1 Electric wall-plug power and embodied power for the mobile Internet

Year	2010	2015	2020
Mobile traffic (TB/s)	0.11	1.5	13.2
Server performance (rel.)	1	20	200
Energy eff. (rel.)	1	7	25
El. power (GW)	40	120	240
PC's power (GW)	30	30	30
Mobile devices (GW)	0.4	28	56
Infrastructure (GW)	10	50	200
Total Operative El. (GW)	**80.4**	**228**	**526**
Embodied El. power (GW)	80	228	526
Total El. power (GW)	**160.4**	**456**	**1052**
Global El. power (GW) generation	**2300**	**2800**	**3300**

B. Hoefflinger, CHIPS 2020 Vol. 2, Springer, p. 191

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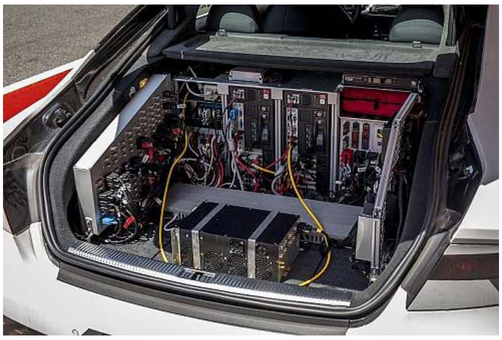
Energy Efficiency:
Human versus Artificial Intelligence

Jeopardy! Supercomputer IBM Watson vs. Human´s

Microsoft Launches Submersible Datacenter:
June 7th, 2018

https://www.enterprisetech.com/2018/06/07/microsoft-launches-a-submersible-datacenter/ 6

Autonomous Vehicles

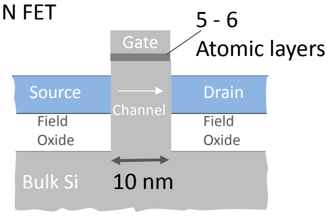


Nivida graphic processor: 600 Tera-OPS

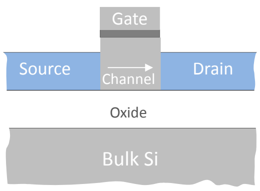
System dissipation power 1.5 kW

The Dead End on Moore´s Roadmap

FIN FET



FD-SOI-FET



Feature size:
10 nm → 100 Atoms

Doping variance:
Si volume-cube: $V = (10\ \text{nm})^3$
Doping level: $N_{A,D} = 10^{18}\ /\ \text{cm}^3$

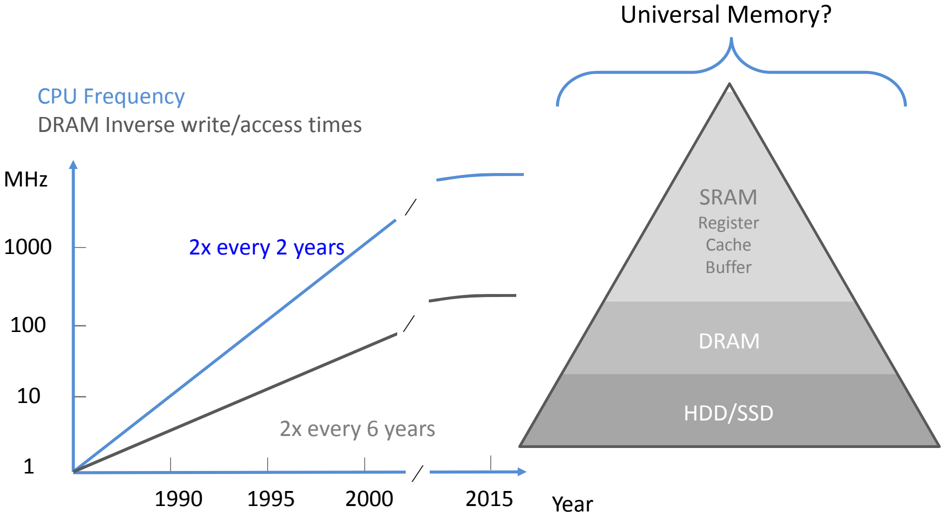
Results in 1 active acceptor or donator atom in average.
Standard deviation $(N_{A,D})^{1/2}$
$N_{A,D} < 50$ Strong conflict with threshold voltage

Supply voltage V has to be large enough to assure the transistor`s on/off (digital 0 / 1)

$$P = n\left(CV^2 f\right) + V\,I)$$

Currently: From nano-meter electronics to femto-joule electronics

The von Neumann Bottleneck: Memory Latency



CMOS Processors and Memories, Ed. K. Inewski, Springer 2010
Embedded Memories for Nano-Scale VLSIs, Springer 2010

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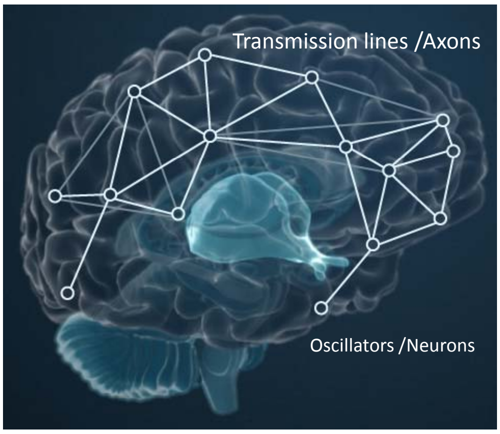
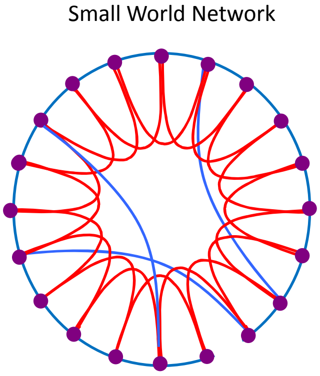
Brain Networks – Graph Theory – Time varying Circuits





- Topology shows Small World characteristics
- Short paths and high clustering
- Transmission delays between nodes (spiking oscillators)

In addition needed:
Delay $\Delta\tau$
Variable Coupling $\Delta\kappa$
Noise, Stoachstic
External stimuli

Adapted from Watts and Strogatz Nature 1998
Olaf Sporns, Networks of the Brain, The MIT press, 2011
Fornito/Zalesky/Bullmore, Brain Network Analysis, AP 2016

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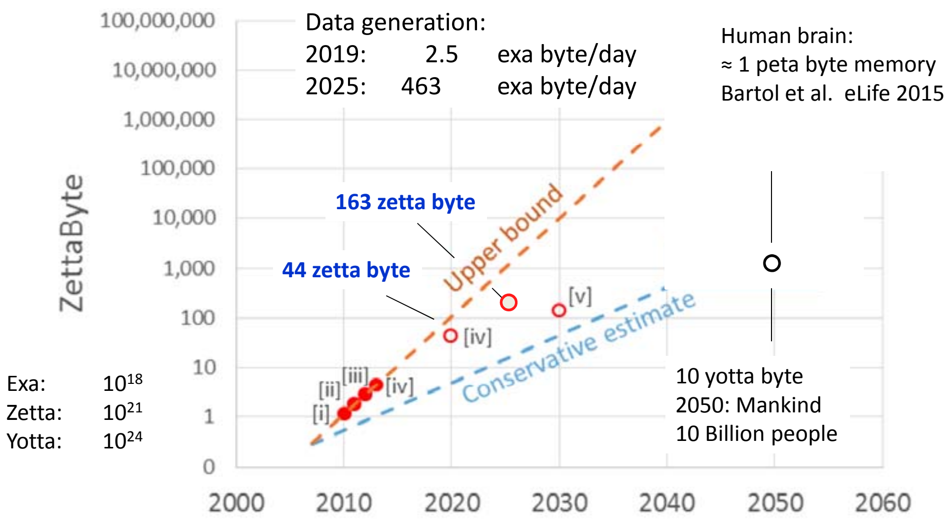
Global Memory Demand



https://www.semiconductors.org/resources/rebooting-the-it-revolution-a-call-to-action-2/
M. Hilbert and P. Lopez, "The world's technological capacity to store, communicate, and compute information," *Science 332 (2011) 60-65.*

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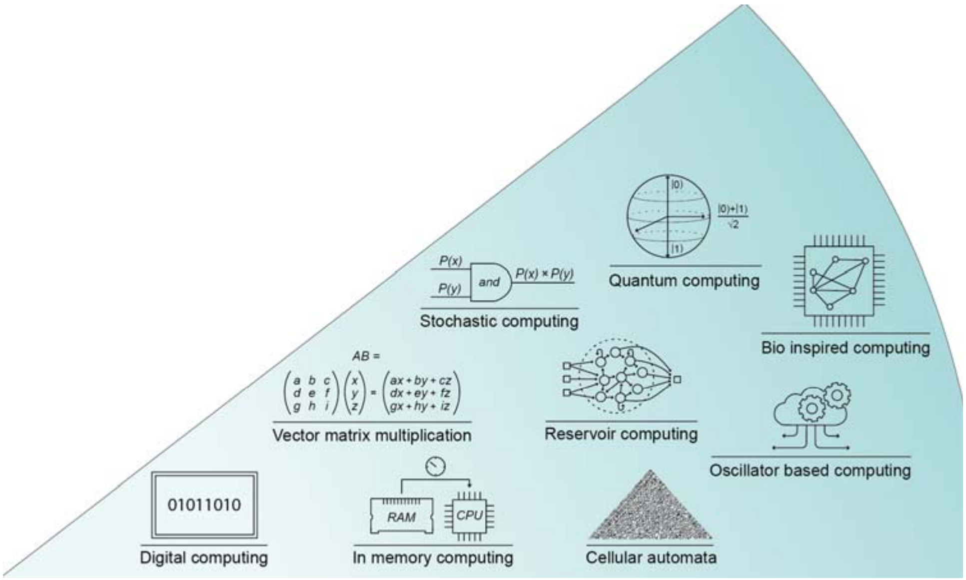
Information Technology: Current Status and Perspectives



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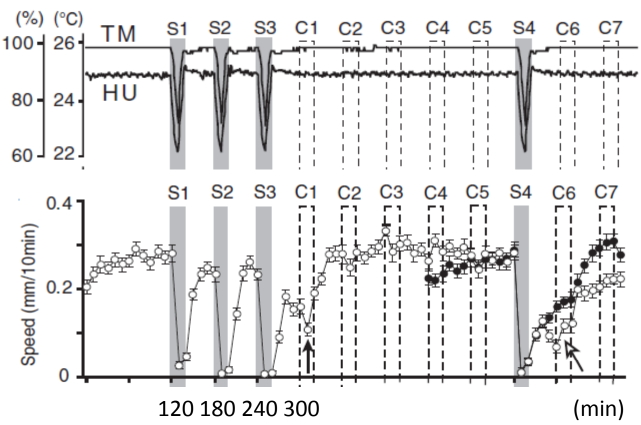
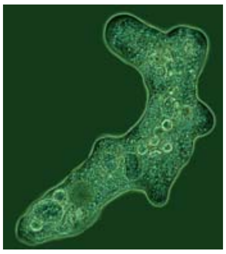
Learning and Memory in an Amoeba (unicellular)



Anticipation of an unicellular system!

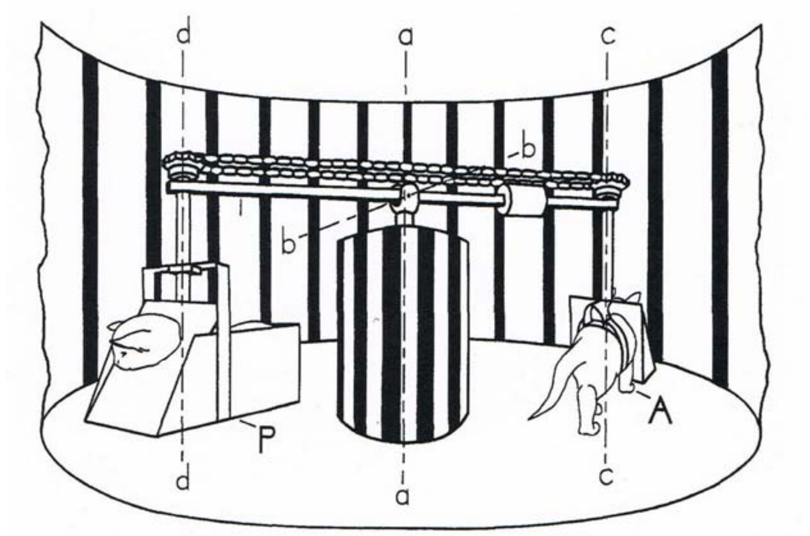
ca. 0,1 mm bis 0,8 mm



Kiel University
Center for Molecular Biosciences

Amoebae Anticipate Periodic Events, Tetsu Saigusa et al., Phys. Rev. Lett. (2008)

Experiment from Held and Hein 1963



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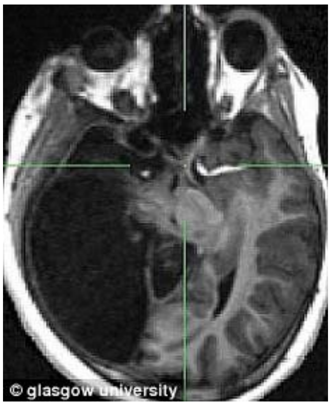
What means Failure Tolerant? Network Plasticity

Child with half a brain life's a normal live!
She is witty, charming and intelligent.



Glasgow University, MPI Frankfurt

The girl's brain rewired itself after the right side failed to develop properly in the womb

see: http://www.dailymail.co.uk/health/article-1200958/Girl-born-half-brain-person-world-fields-vision-eye.html
Proceedings of the National Academy of Science USA, 2009

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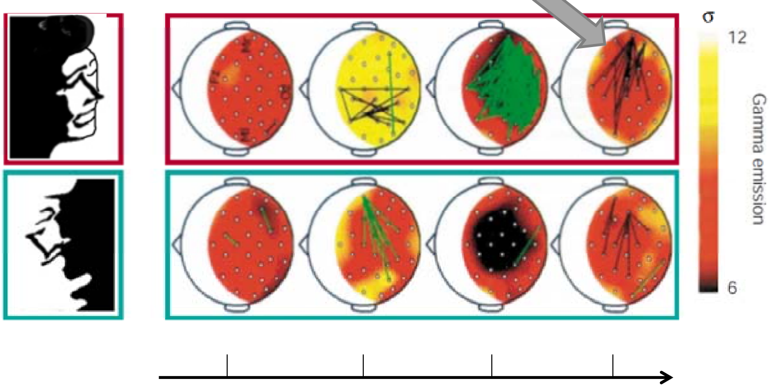
Perception und Synchronization

EEG: Elektroenzephalography

Correlated firing during recogniton process
tendency to synchrony – „binding problem“

Face

Nonsense



F. Varela et al., Nat. Rev. Neurosciences, 2001
György Buzsáki: Rhythms of the Brain, Oxford University Press, 2006

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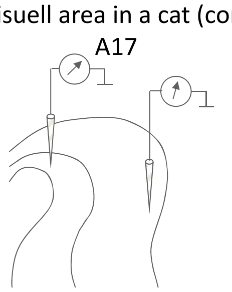
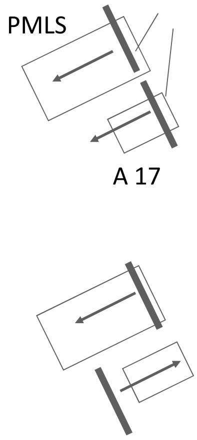
Interareal Synchronization: Orchestra of Neuronal Ensembles

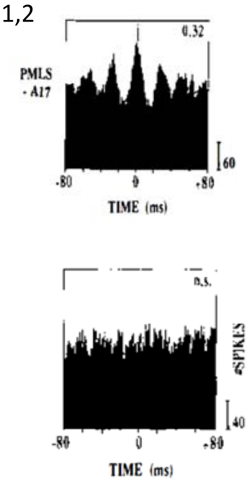
Visuell area in a cat (cortex, in-vivo experiment)



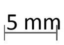
Cross-correlation histograms

receptive fields 1,2





PMLS: posteromedial lateral suprasylvian area



in accordance to:
W. Singer and C. M. Gray, Ann. Rev. Neurosci. 1995
P. J. Uhlhass et al. Front. Int. Neurosci. 2011
E. M. Izhikevich, Dynamical Systems in Neuroscience, Springer 2004

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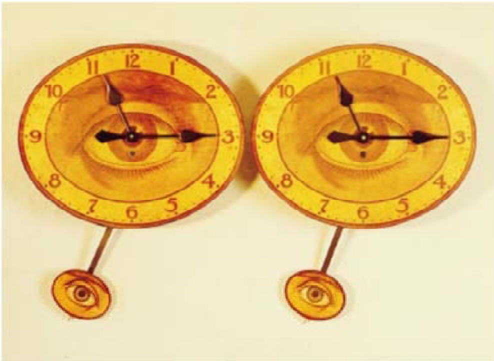
Pulse-coupled Oscillators

Christiaan Huygens
1629 – 1695
Non-linear dynamics



Steven H. Strogatz:
Sync: The Emerging Science of Spontaneous Order
Hachette Books, 2003

Steven H. Strogatz:
Scientific American 1993

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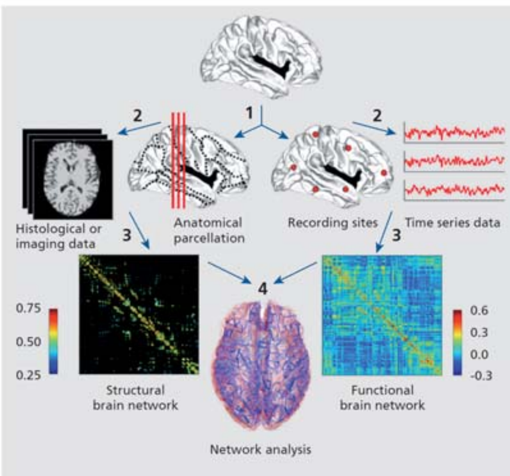
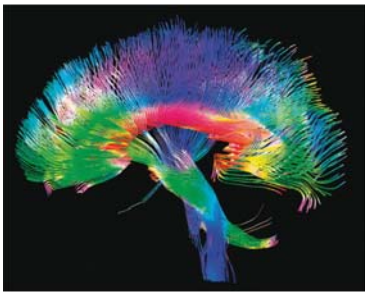
Structural and Functional Brain Networks: The Connectome





O. Sporns, Complex brain networks,
Dialogues in Clinical Neuroscience (2013)

Human Brain Project
Jonathan Webb | BBC | July 22, 2016

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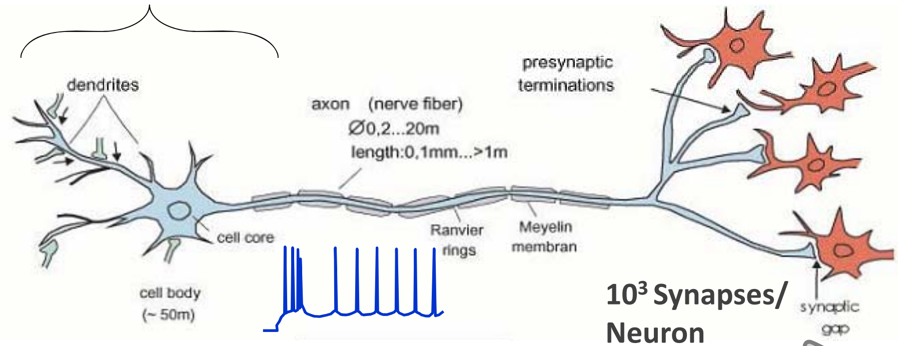
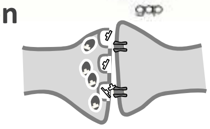
Information Processing by Neurons: The Human Brain

10^{11} Neurons



10^3 Synapses/ Neuron



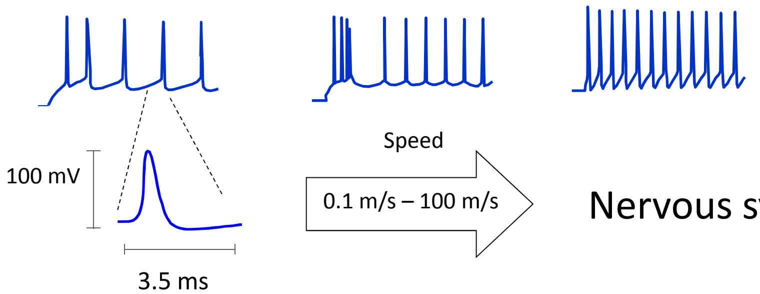
Action potentials: Spikes

500.000 km total axon length

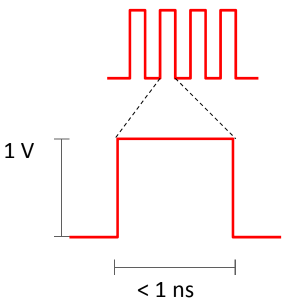
3 D time varying network with 10^{14} interconnects!

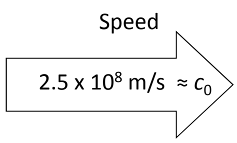
Eric R. Kandel et a., Principles of Neural Science, McGraw-Hill, 2000

Action Potentials - "Spikes"

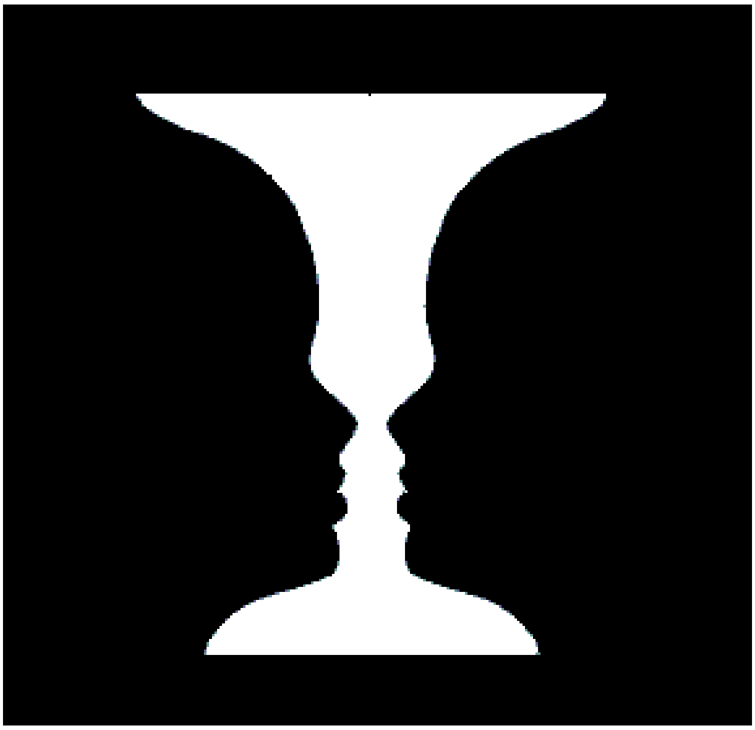


Nervous system

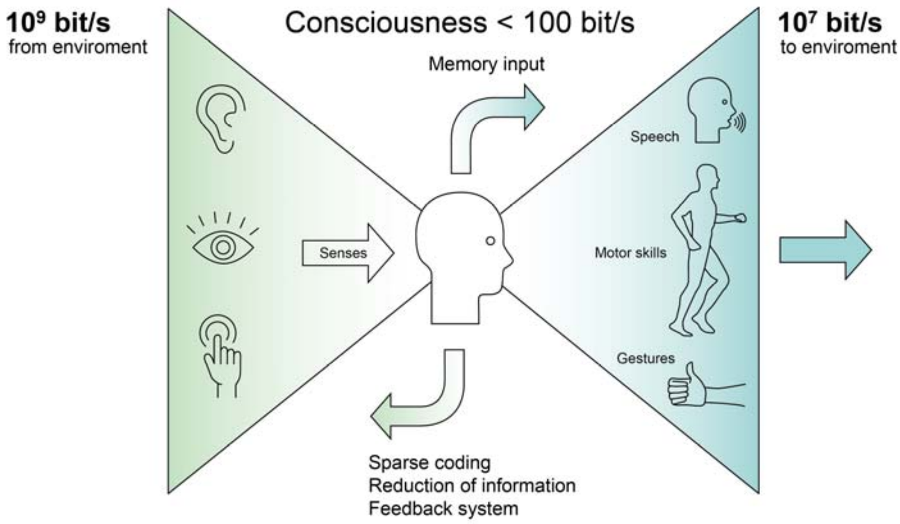




Computer



Information Processing: Humans



Adapted from: W. D. Keidel: Biokybernetik des Menschen,
Wissenschaftl. Buchgesellschaft, S. 161, 1989.

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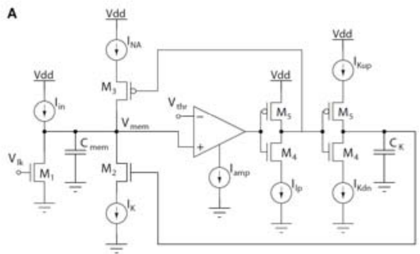
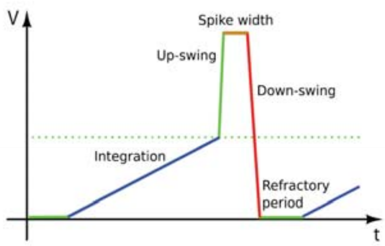
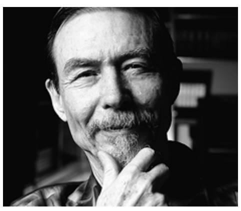
Neuromorphic Engineering: A short Survey

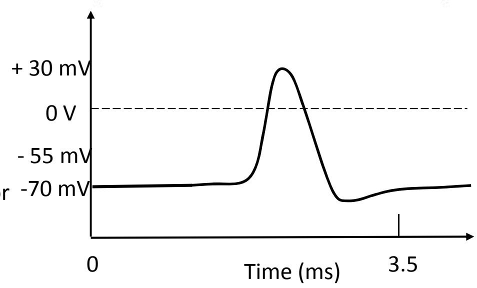
Simple Leaky & Integrated Firing (LIF) Neuron





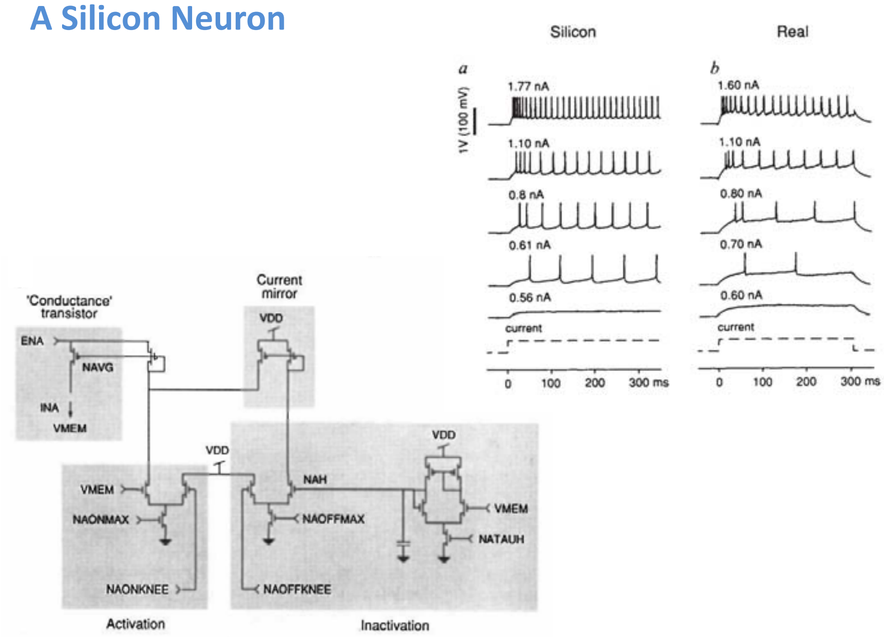


<u>1989</u>
Silicon Retina
Electronic Cochlea
Optical Motion Sensor



Carver Mead, Analog VLSI and Neural Systems, Addison-Wesley Pub., 1989
G. Indiverie et. Al., Frontiers in Neurosci. 2011
Shih-Chii Liu et al., Event-Based Neuromorphic Systems, Wiley, 2015

A Silicon Neuron



M. Mahowald & R. Douglas, Nature 1991

Comparison to the state-of-the-art

Giacomo Indiveri, ETH Zürich & U Zürich, Swiss

	[2]	[3]	[4]	[1]	[5]	**This work**
Implementation	Mixed-signal	Mixed-signal	Digital	Digital	Digital	Mixed-signal
Technology	180 nm	180 nm	28 nm	28 nm	14 nm	28 nm
Supply voltage	1.8V	1.8V	0.55V-1V	0.7V-1.05V	0.5V-1.25V	0.73V-1V
Neuron type	Analog	Analog	Digital	Digital	Digital	Analog
Core area $[mm^2]$	51.4	7.5	0.086	0.095	0.4	0.36 (Core<x>) 1.01 (Core<L>)
Neurons per core	256	256	256	256	max 1k	256 (Core<x>) 64 (Core<L>)
Synapses per core	128k	16k	64k	64k	1M-114k	16k (Core<x>) 20k (Core<L>)
Fan-in/Fan-out	256/256	64/4k	256/256	256/256	16/4k	2^{11}/8k (Core<x>) 1k/8k (Core<L>)
Reconfigurable dendritic tree	Yes	No	No	No	No	Yes
Synaptic weight	Capacitor	(1+1)-bit	(3+1)-bit	1-bit	1- to 9-bit	(4+1)-bit
On-line learning	STDP	No	STDP	No	Programmable	STDP
Operation mode	Parallel processing	Parallel processing	Time multiplexing	Time multiplexing	Time multiplexing	Parallel processing
Energy per SOP	77fJ@1.8V	17pJ@1.3V@1.8V	9.8pJ@0.55V	26pJ@0.775V	23.6pJ@0.75V	2pJ@0.73V

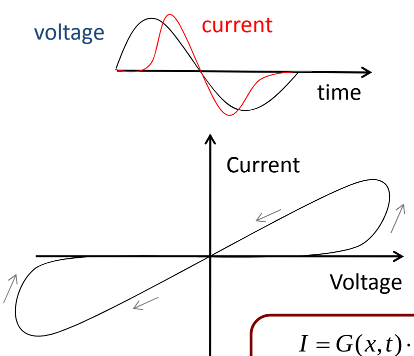
[1] P. A. Merolla et al. Science. 2014.
[2] N. Qiao et al. Frontiers in Neuroscience, 2015.
[3] S. Moradi et al. Biomedical Circuits and Systems, IEEE Trans. 2017
[4] C. Frenkel et al., arXiv:1804.07858. 2018.
[5] M. Davies et al. IEEE Micro, 2018.

Tianjic Chip
Jing Pei et al., Nature 2019

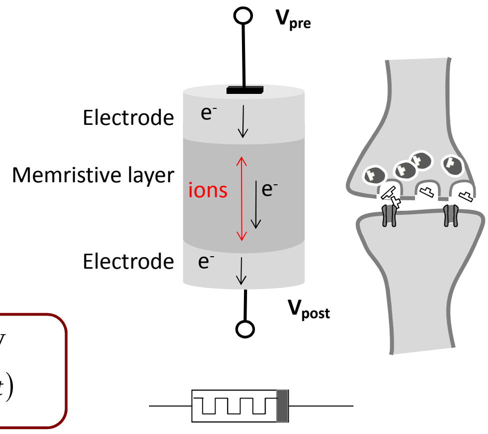
Tianjic Chip, Jing Pei et al., Nature 2019

Memristive Devices

Memristor = Memory + Resistor: non-volatile, passive

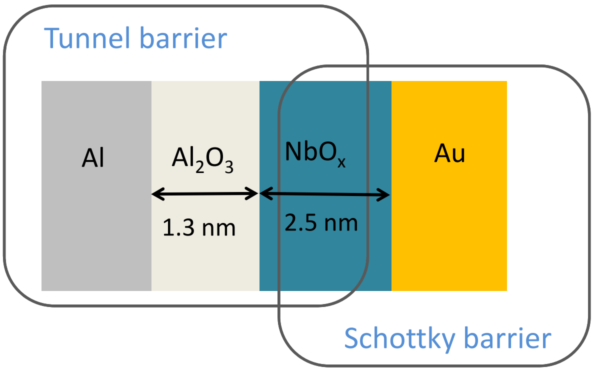


$$I = G(x,t)\cdot V$$
$$\frac{dx}{dt} = f(x, V, t)$$



Leon O. Chua 1970
Dmitri B. Strukov & R. Stanley Williams 2008

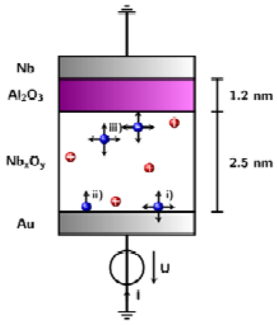
A double-barrier memristive device (DBMD)



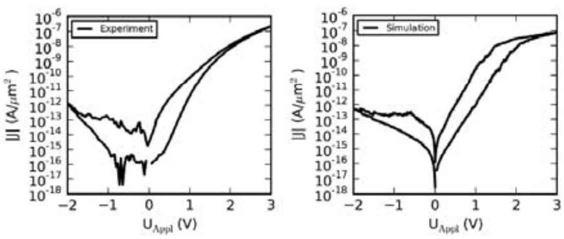
➢ **Coupled mechanisms by ultra-thin solid state electrolyte**

M. Hansen et al., Sci. Rep. 5 (2015)

Kinetic Monte Carlo Simulation



- **Tunnel barrier:** voltage controlled current source (Simmons formula)
- **Au / NbO_x interface:** Schottky model
- **NbO_x layer:** ohmic resistance dependent on inner atomic structure
- **hopping of negatively charged ions within the NbO_x:**
  i. diffusion within the solid state electrolyte
  ii. adsorption
  iii. desorption



Dirkmann et al., Sci. Rep. 6 (2016)

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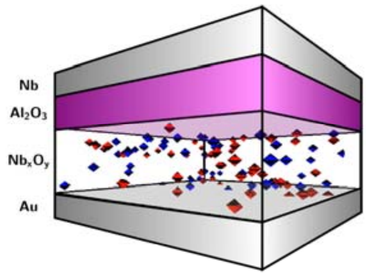
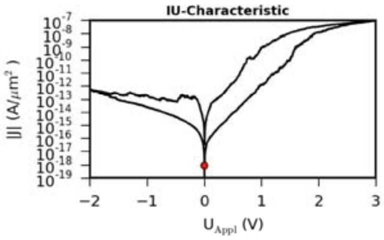
Kinetic Monte Carlo Simulation

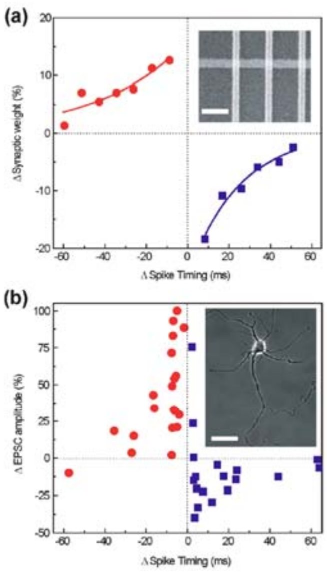


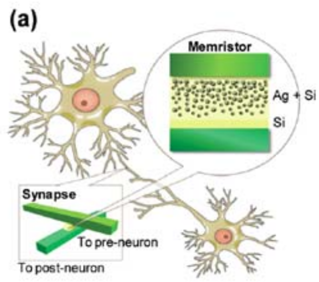


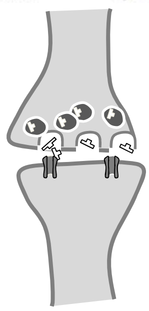
Dirkmann et al., Sci. Rep. 6 (2016)

Spike Time Dependent Plasticity (STDP)

Synaptic Strength







post

pre

Schematic view graph of a synapse

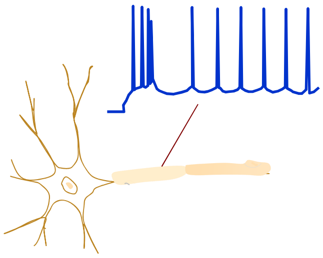
Bi and Poo, The J. of Neuroscience, 1998 (Biology)
Jo et al., Nano Lett. 2010 (Memristor)

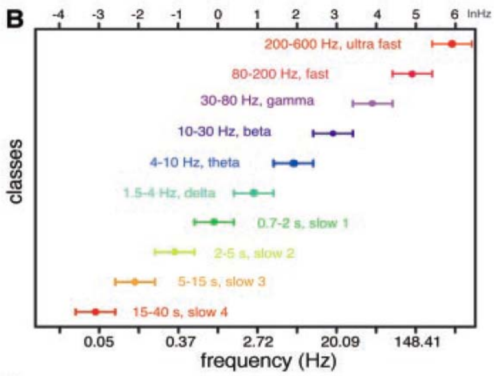
Back to Biology: Brain Activity - Rhythms

At the **local** neuron level:
Stochastic signals

At the **global** brain level:
Rhythms (alpha, beta, gamma)

EEG: Electroencephalography





G. Buzsàki and A. Draguhn Science 2004
G. Buzsàki, Rhythm of the Brain, Oxford, 2006
B. J. He, Cell Press 2014

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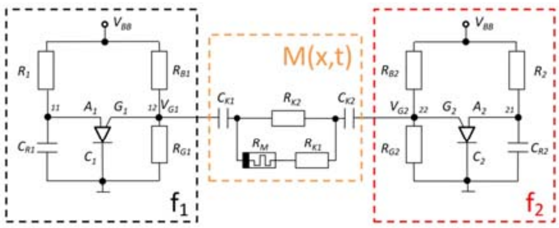
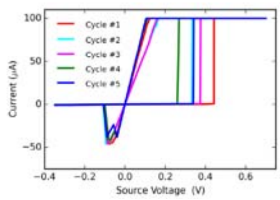
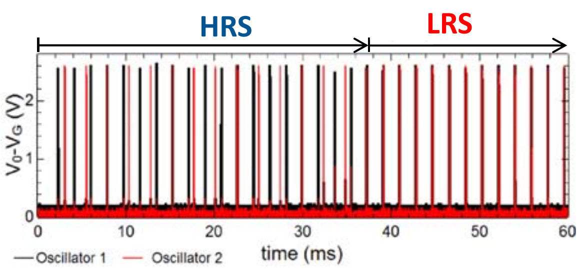
Memristively coupled Van der Pol oscillator







ISIF 2019:
Memory and Data Storage
Stochastic Learning
Tuesday: Martin Ziegler, 10:30 Icon

M. Ignatov, M. Hansen, M. Ziegler, H. Kohlstedt, Appl. Phys. Lett. (2016)
M. Ignatov et al., Sci. Adv. 2017

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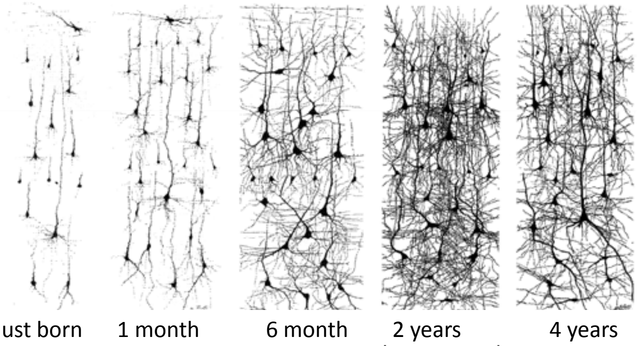
Growth: Blooming & Pruning under external Stimuli



Two year old baby: 1000 days

Average growth rates:

2300 neurons/s

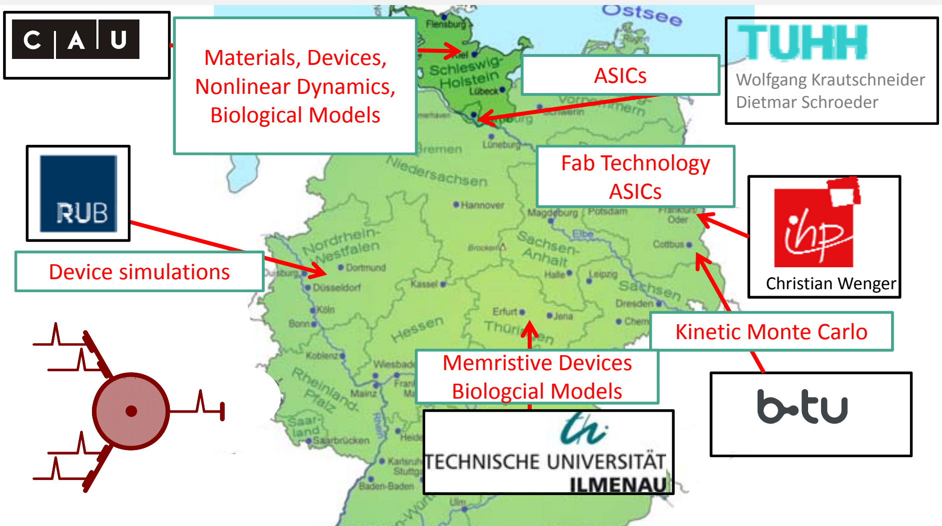
2.3 million synapses/s

6 m/s axon formation

2 x 10^{11} Neurons
2 x 10^{14} Synapses
500 000 km entire axon length

S. Seung: "Connectome: How the brain`s wiring makes us who we are?"
MIT Cambridge, 2012 (German Version: Das Konnektom, S. 99, Springer Spektrum) 37

Acknowledgement: DFG-Research Unit 2093
Memristive Devices for Neuronal Systems



http://www.for2093.uni-kiel.de/en?set_language=en

Group Meeting: Research Unit 2093: Memristive Devices for Neuronal Systems