Computing with Magnetic Dots and Spintronic Dynamical Systems

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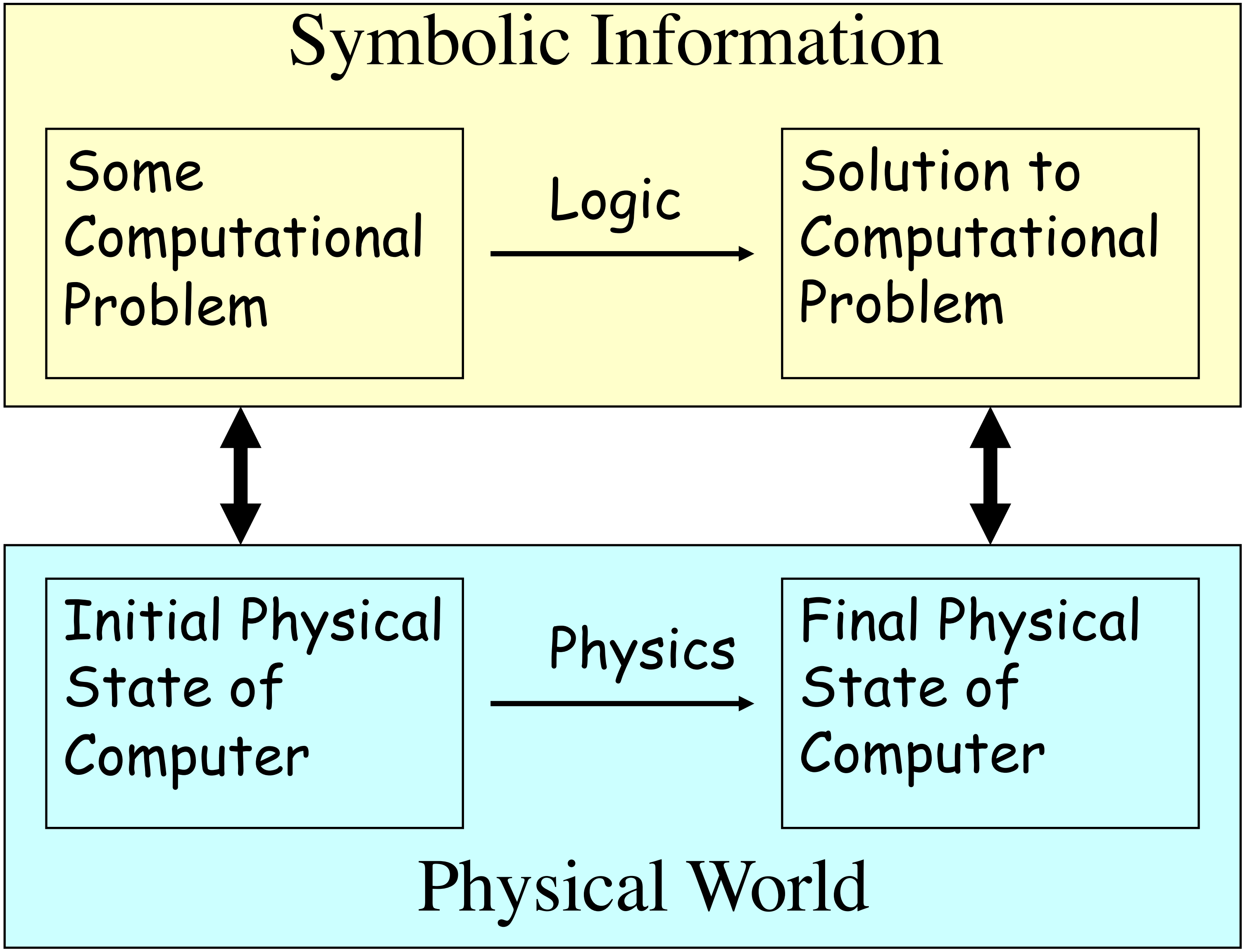
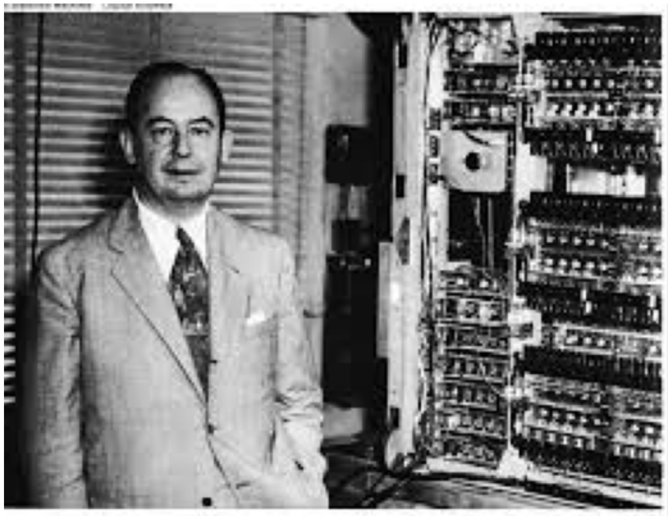
Outline

- Introduction and Overview
- Non-CMOS Computation
  - Coupled Nanostructures
- Non-Boolean Computation
  - Coupled Oscillators
  - Neuromorphic Ring Oscillators
  - Spin Waves
- Quantum Computation

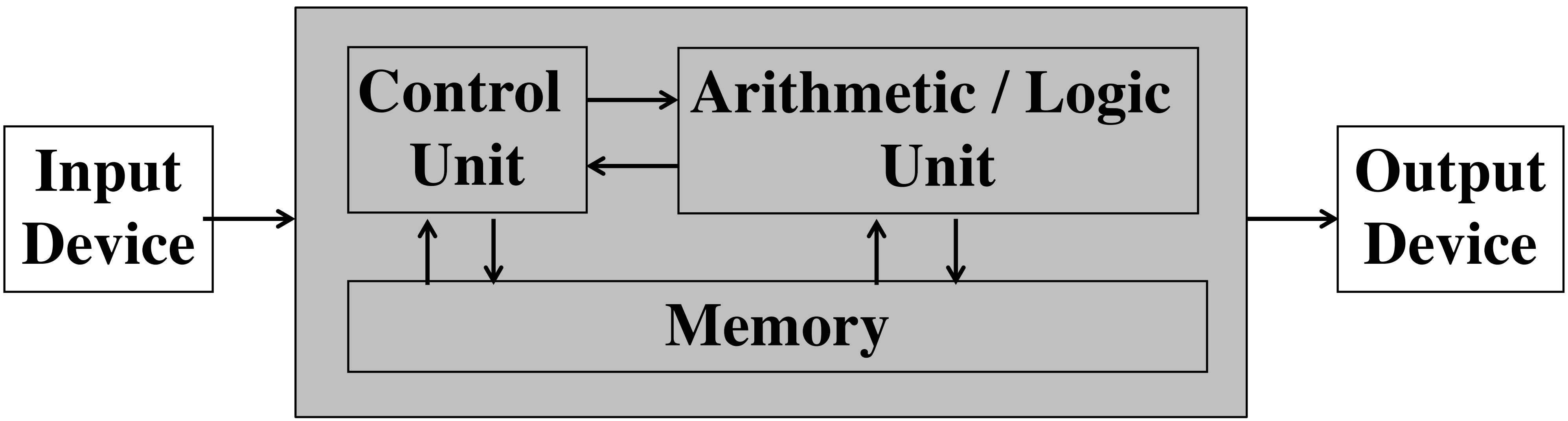
Symbolic Information – Physical World



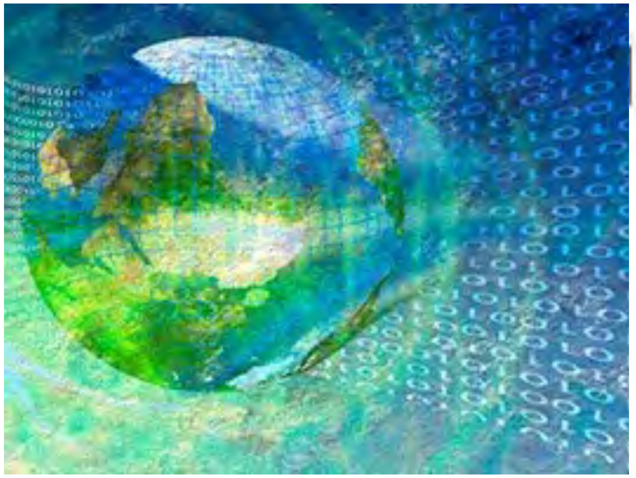


von Neumann Architecture

1945 – *First draft of a report on the EDVAC*

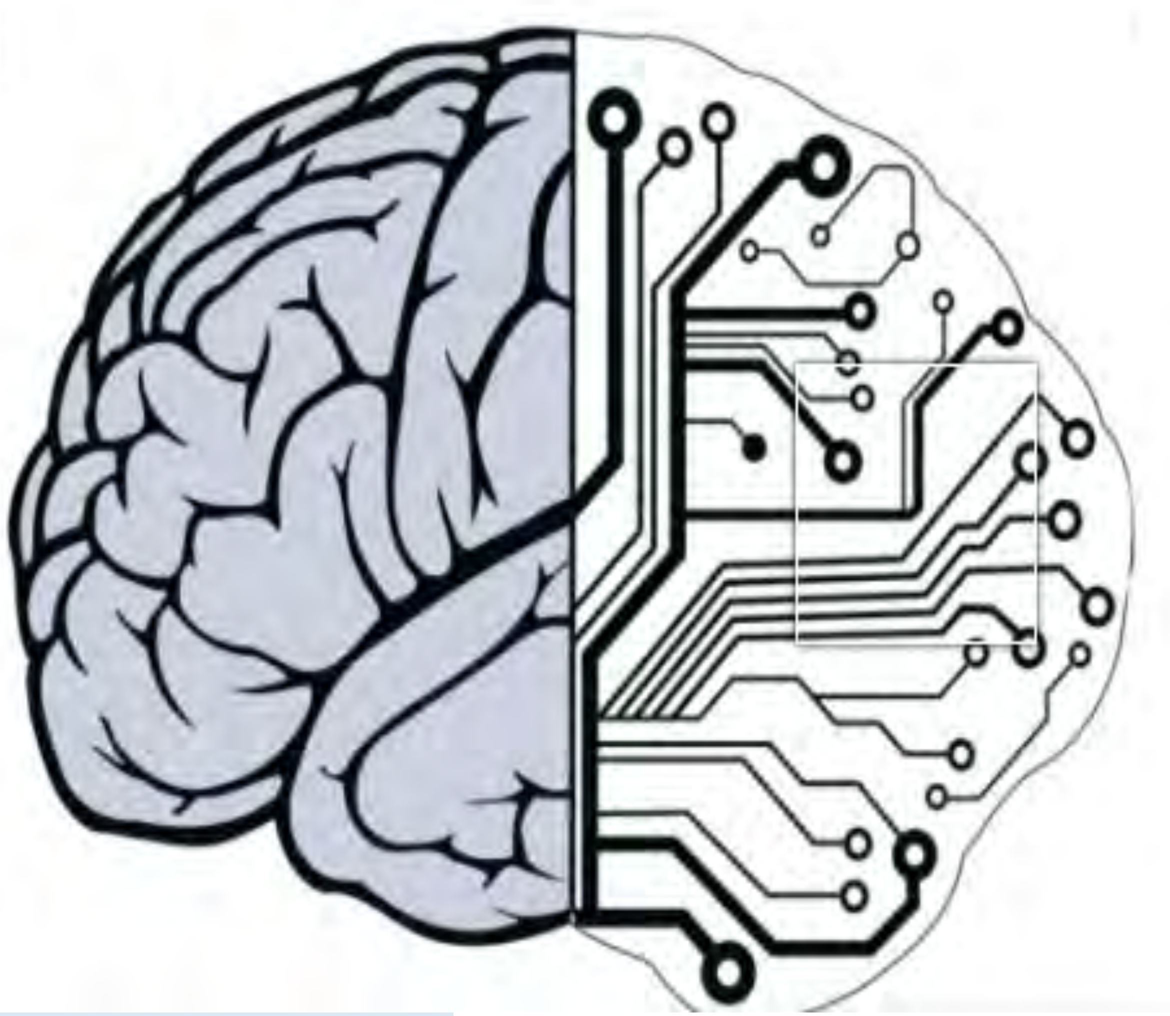


The Boolean Bottleneck



Cyber universe of
Analog sensors

Human understanding



Data
visualization

Data analysis

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G. Bourianoff, Intel

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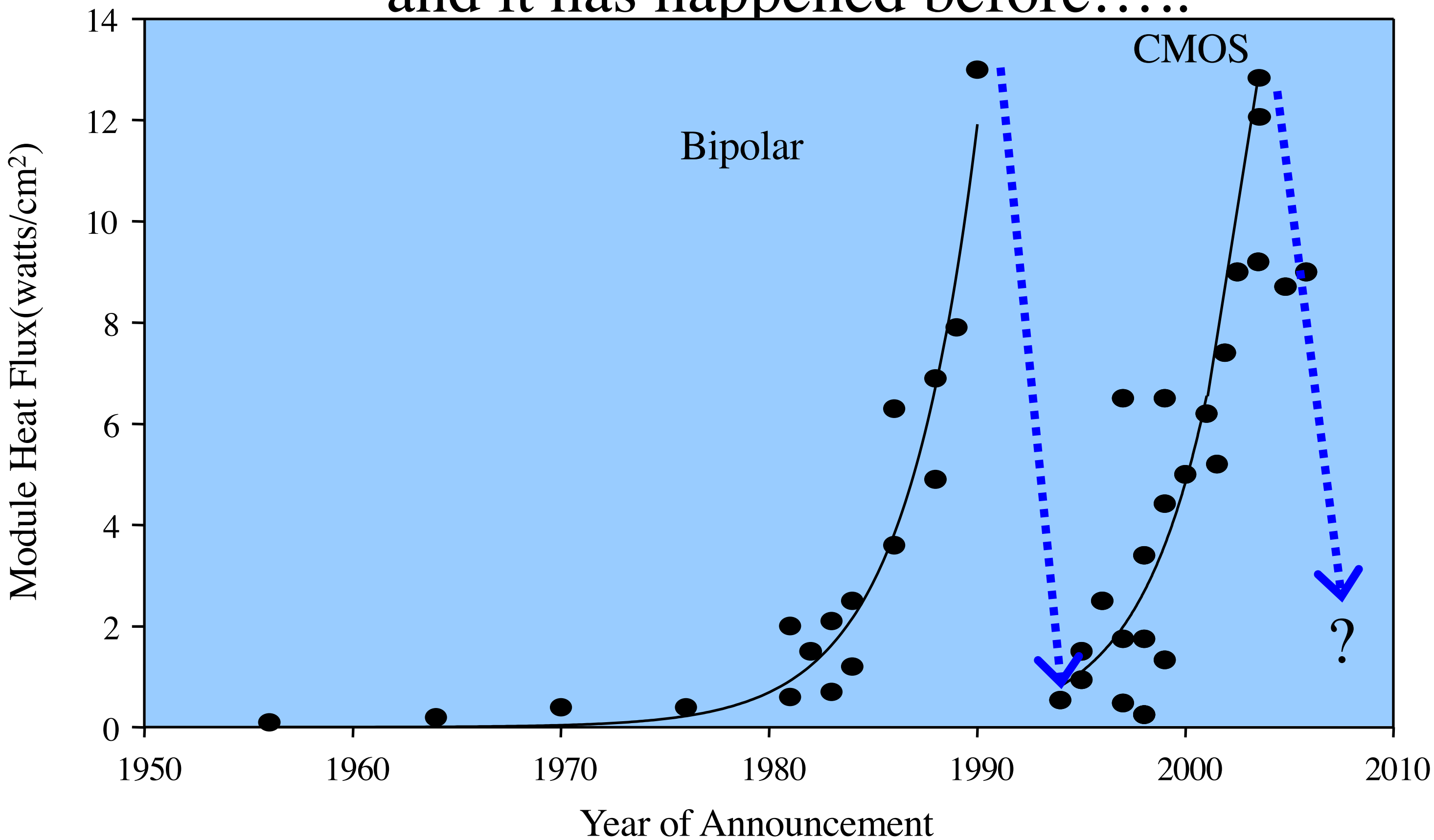
Heat Dissipation is the Problem

and it has happened before…..



SRC-NRI goal: develop next device/paradigm to enable continued growth of electronics

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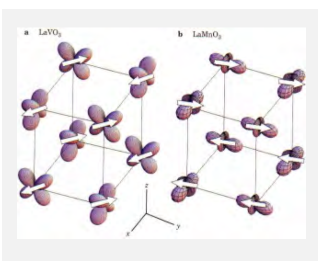
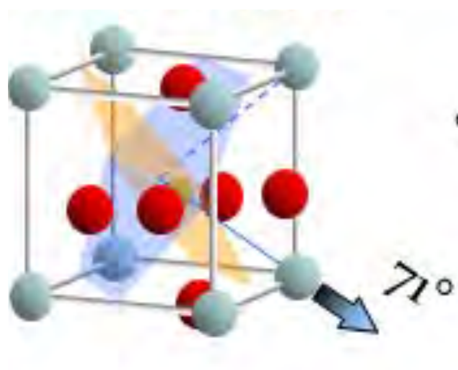
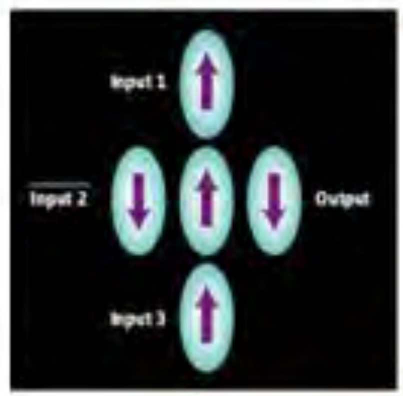
Beyond CMOS Computational State Variable

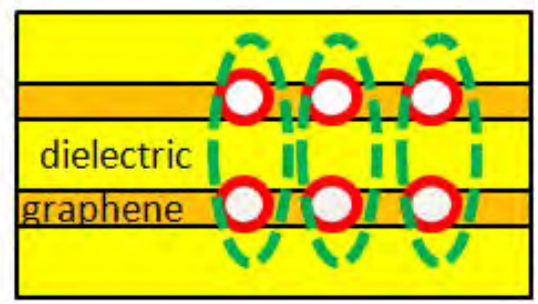
Class	Variables	Example
Charge	Q, I, V	CMOS, TFET
Electric Dipole	P	(FeFET)
Magnetic Dipole	M, I_{spin}	All-Spin Logic (ASL), SpinWave Device (SWD), NanoMagnetic Logic (NML)
Quantum State	Metal-insulator	Mott FET, BisFET, excitonic FETs
Ferroic order	Magneto-electric st.	Magnetoelectric transducers



Tokura, Phys. Today







Ferroic order

E-Dipole

Magnetic -Dipole

Quantum State

G. Bourianoff, Intel

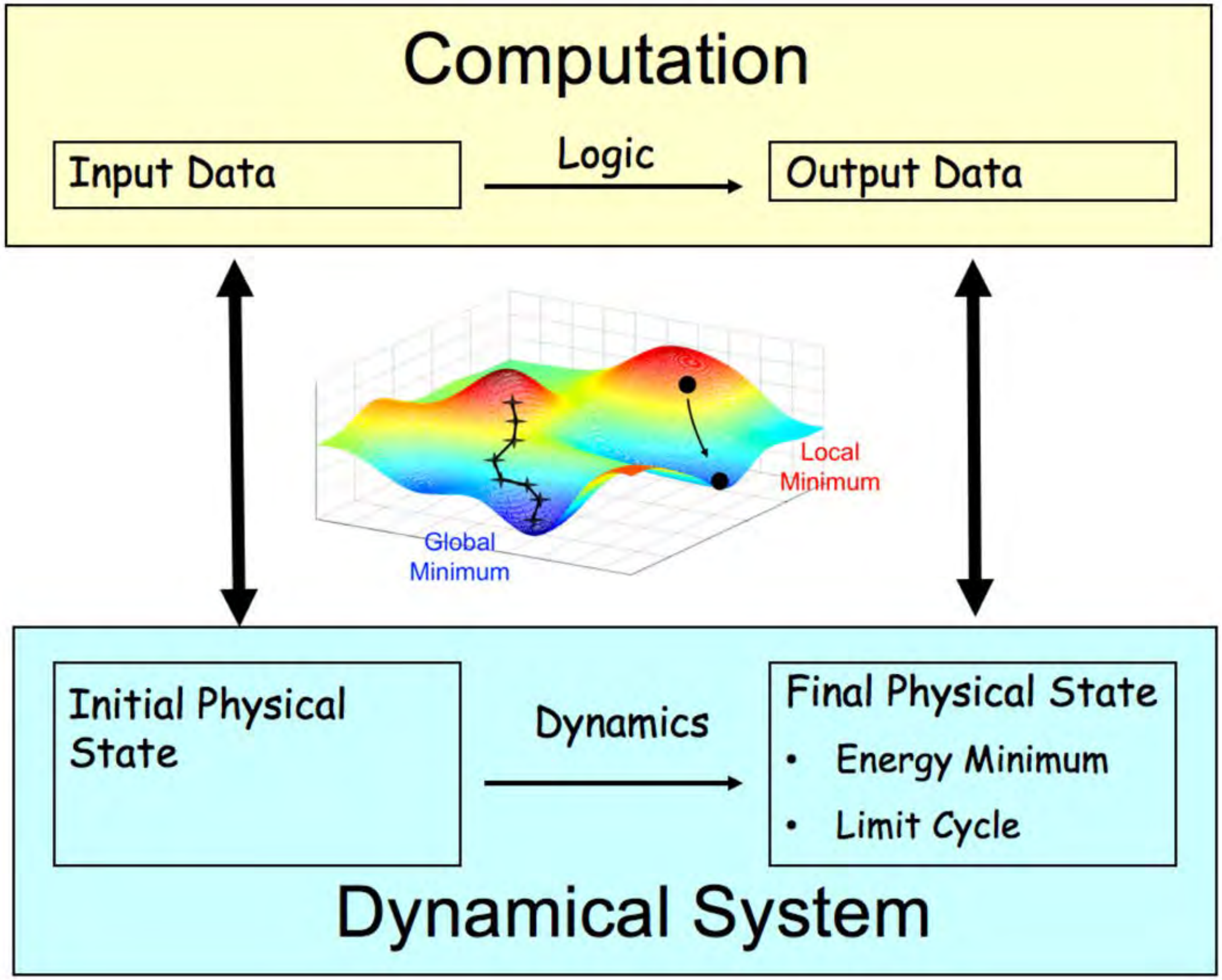
Device and Architecture Outlook for Beyond CMOS Switches

Many new devices that are being studied as replacements for CMOS are discussed in this paper; early results for benchmarking and performance comparison are presented for some of the devices.

By Kerry Bernstein, *Fellow IEEE*, Ralph K. Cavin, III, *Life Fellow IEEE*, Wolfgang Porod, *Fellow IEEE*, Alan Seabaugh, *Fellow IEEE*, and Jeff Welser, *Senior Member IEEE*

Vol. 98, No. 12, December 2010 | Proceedings of the IEEE **2169**

Computing with a Dynamical System



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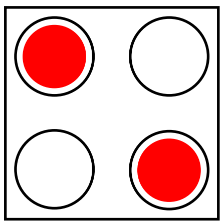
Quantum-Dot Cellular Automata

A Quantum-Dot Cell

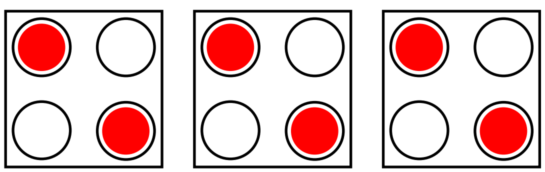


A cell with 4 dots

2 extra electrons

Represent binary information by charge configuration

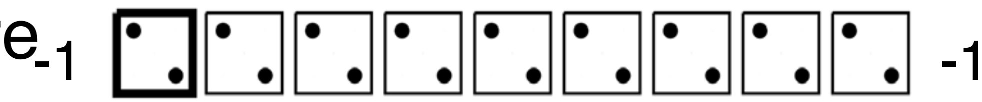
An Array of Cells



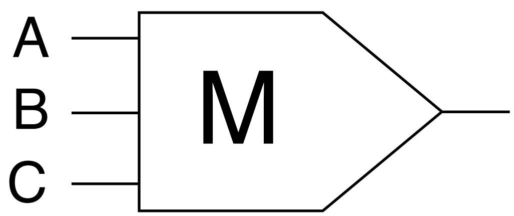
Neighboring cells tend to align due to direct Coulombic coupling

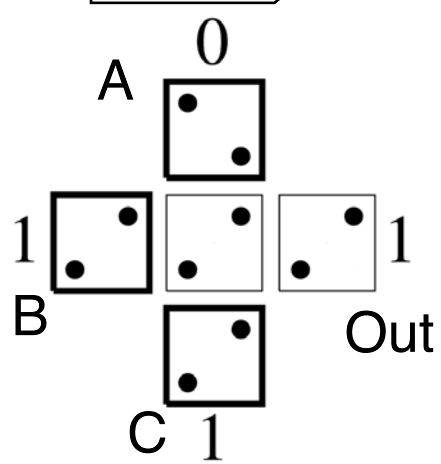
QCA Devices

Binary wire

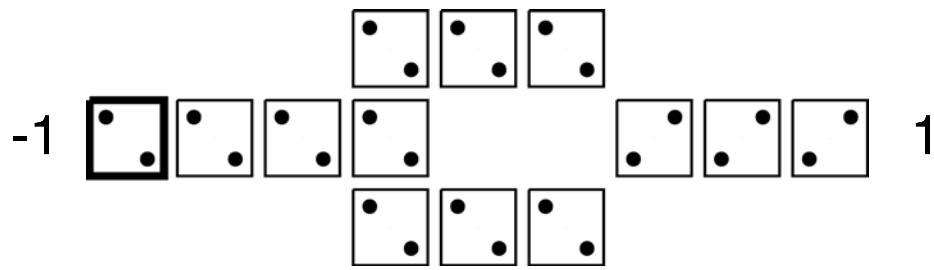


Majority gate

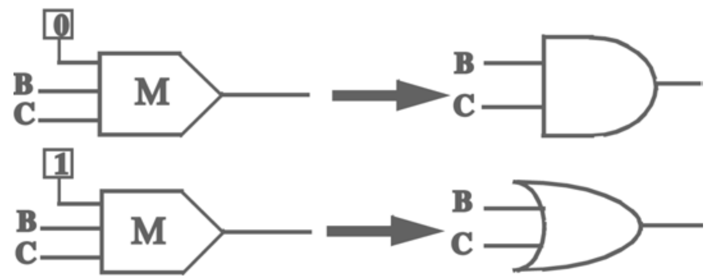




Inverter



	A	B	C	Output
AND gate	0	0	0	0
	0	0	1	0
	0	1	1	1
	0	1	0	0
OR gate	1	1	0	1
	1	1	1	1
	1	0	1	1
	1	0	0	0



Programmable 2-input AND or OR gate.

Nanomagnet Logic

Digital logic based on field coupling of single-domain nanomagnets.

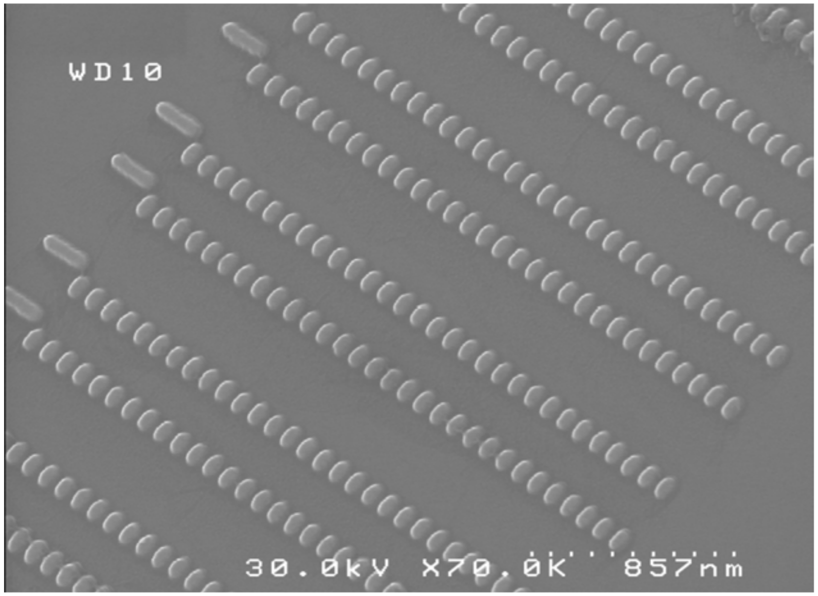
Goal: To investigate its viability as a beyond-Moore technology.

Why Nanomagnets for Beyond Moore?

ITRS ERD 2007: …nanodevices, that implement **both logic and memory in the same device** would revolutionize circuit and nanoarchitecture implementation.

Magnets work better on the nano-scale:

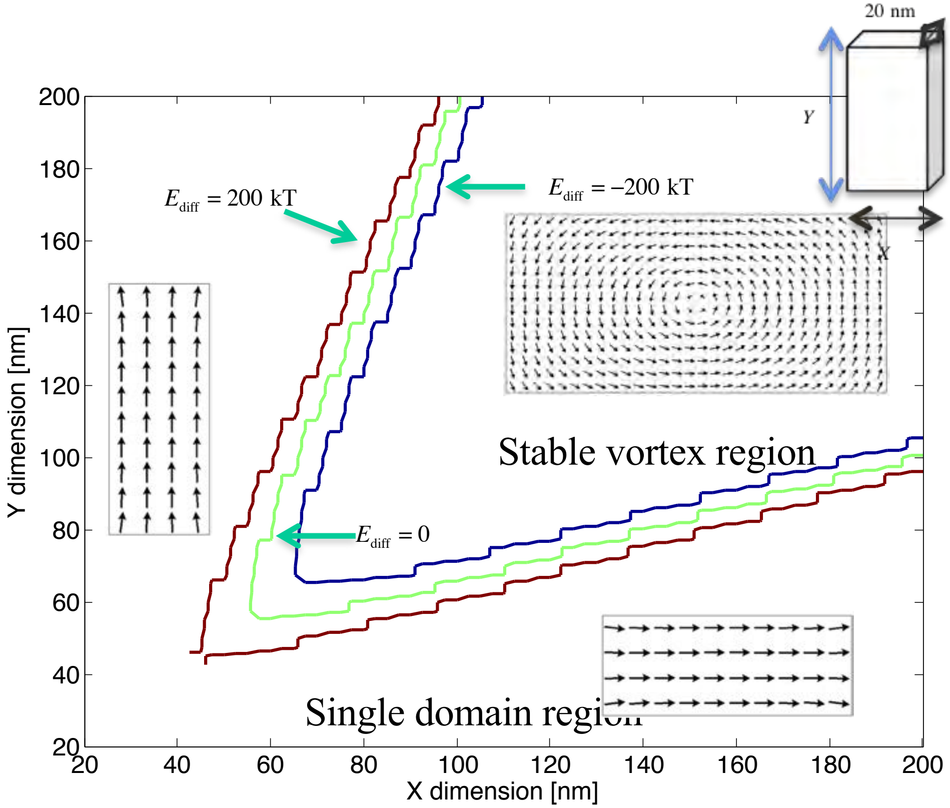
- Low power-delay-area product
- Wide temperature operating range
- Radiation hard
- Nonvolatile logic and memory
- Generally many fewer process steps
  ⇒ overall cheaper to manufacture
- Array-like architecture allows specialized lithographic tools and techniques
  ⇒ smaller minimum feature size
- Relative lack of contacts
  ⇒ higher packing density

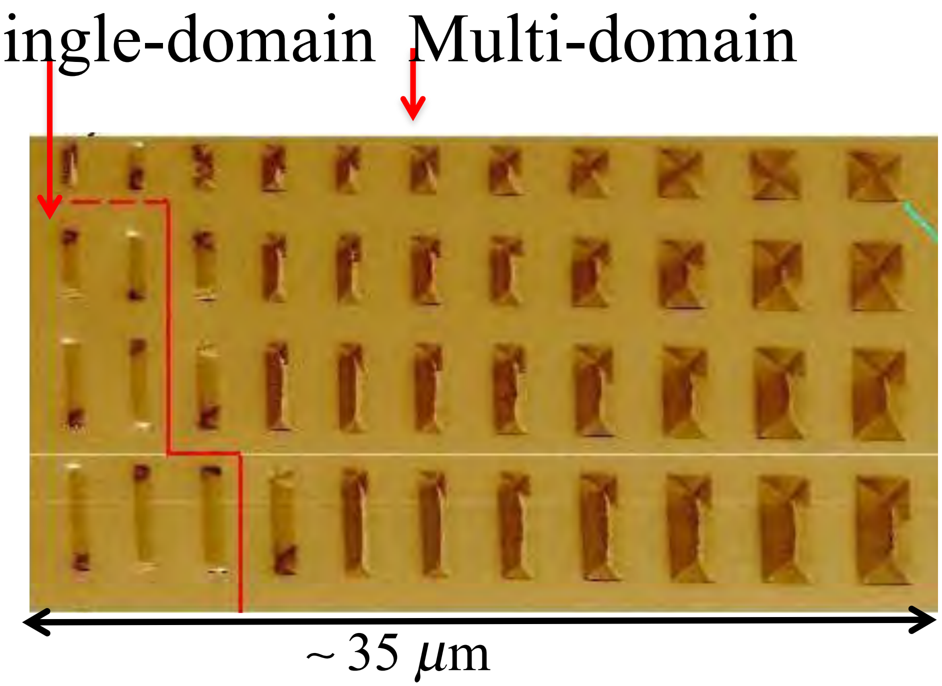


Nanomagnet Logic Elements

Image: Edit Varga

Elementary Building Block of NML: *Single-Domain Magnets*





A. Imre, PhD thesis, 2006

If magnets are sufficiently small, they do behave as ideal bistable switches.
Sufficiently small is < 60 nm for Permalloy nanomagnets

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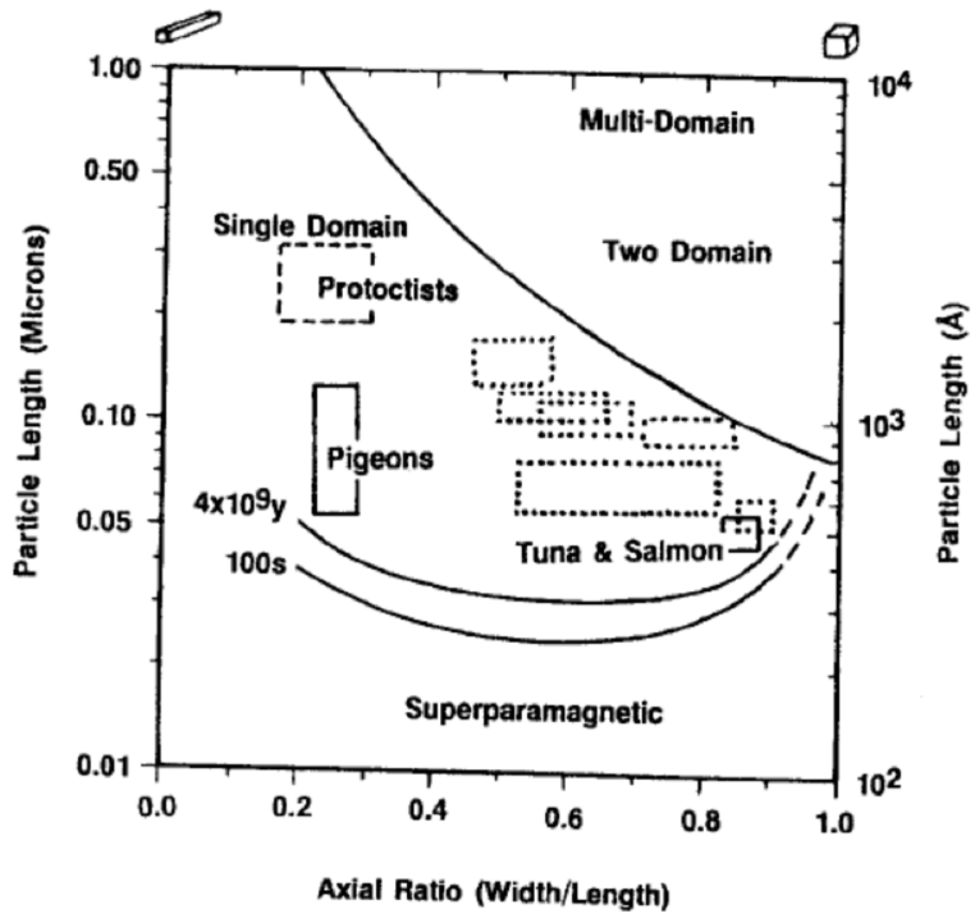
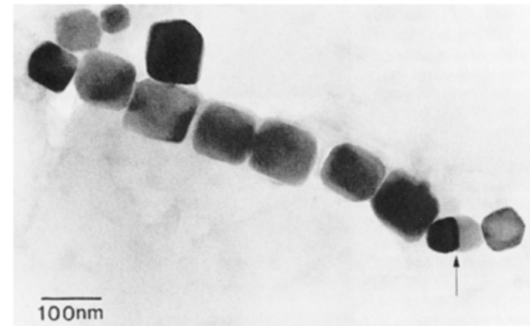
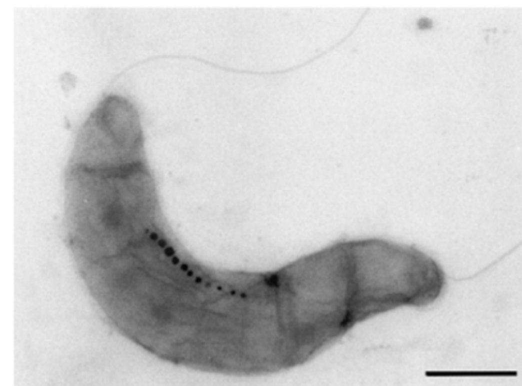
Magnetite Biomineralization



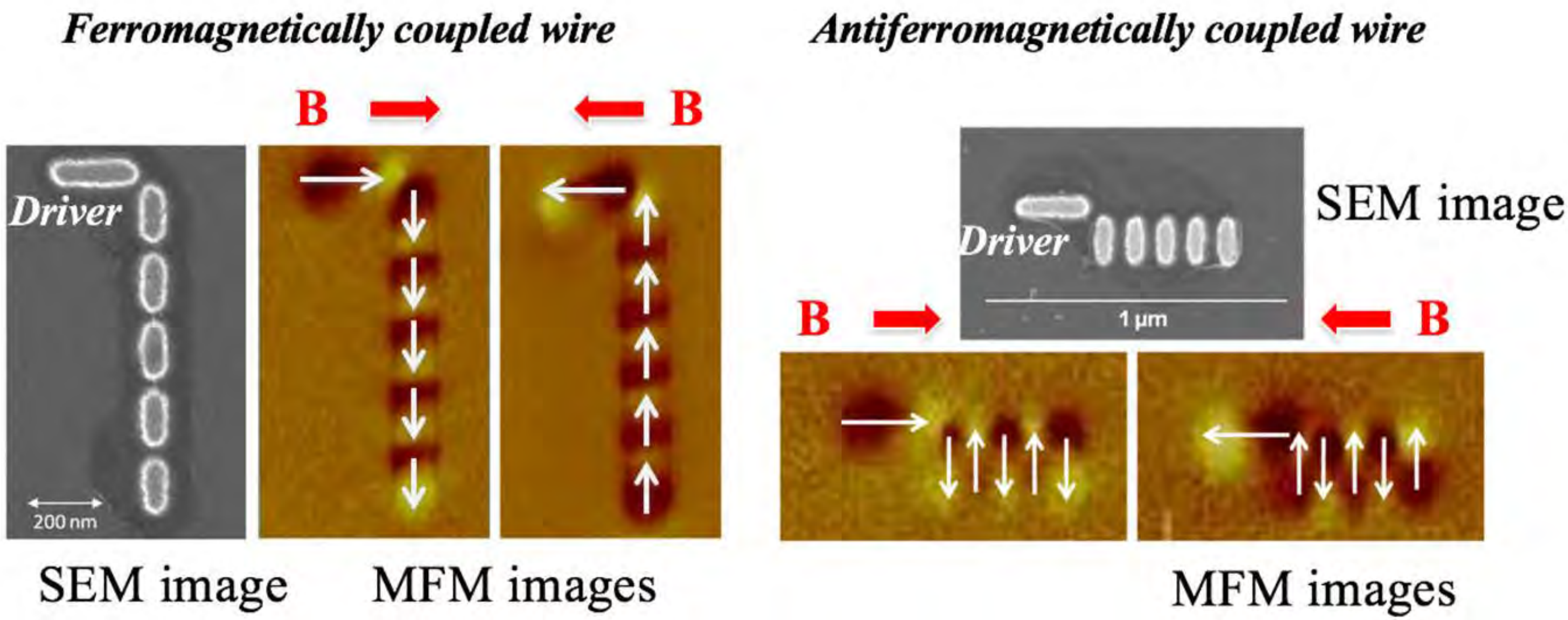
Joseph L Kirschvink et al.





Biomineralization in Magnetotactic Bacteria
Bob Kopp, 2001

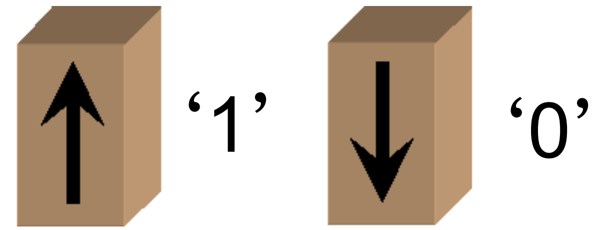
Elementary Coupled Structures

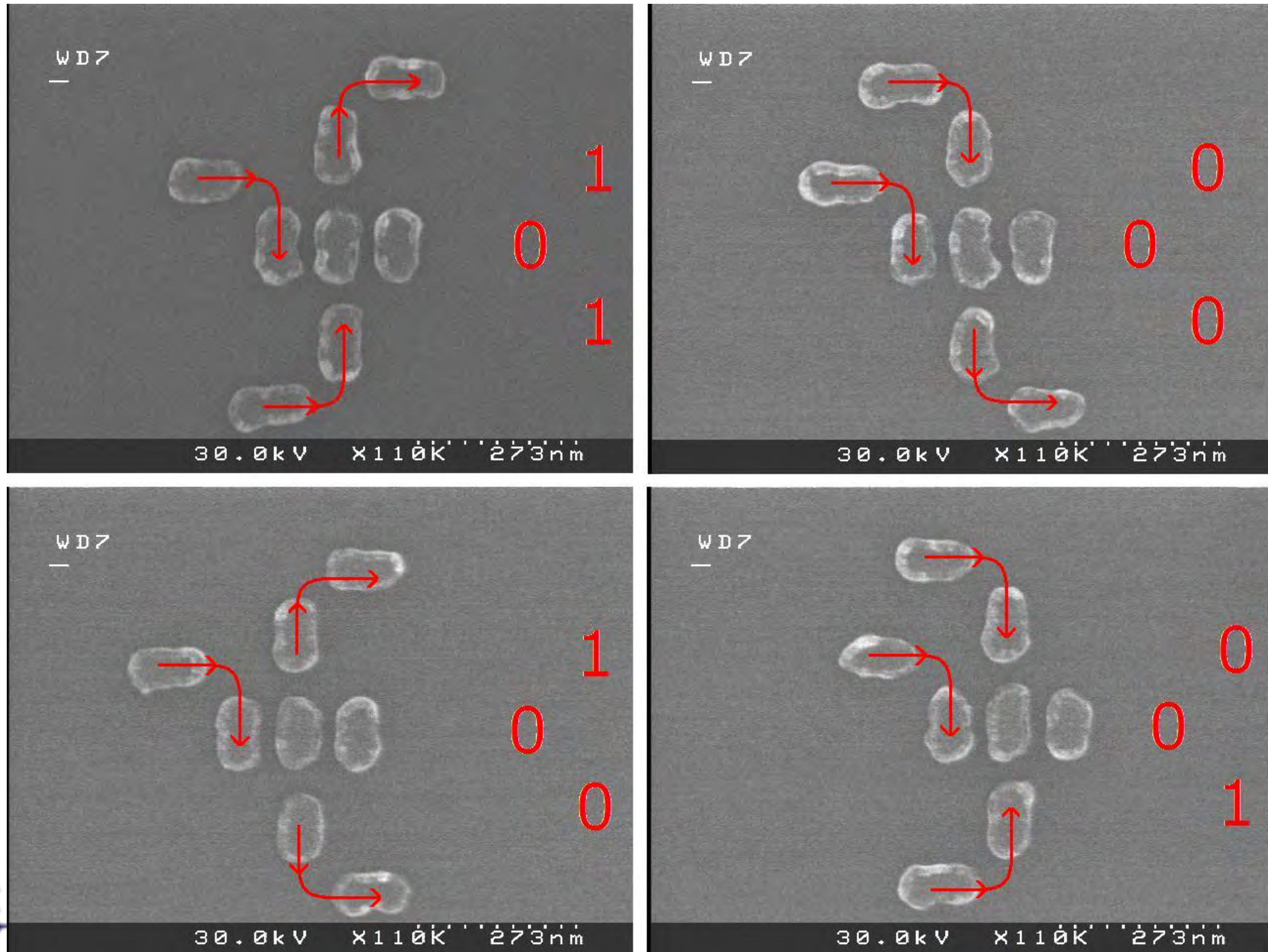


- Driver magnet is set to right or left direction using a horizontal field
- Ferromagnetically or antiferromagnetically coupled wires follow the driver

Images courtesy of E. Varga

Majority-Gate Structures





A. Imre

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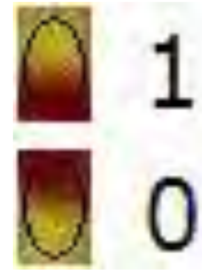
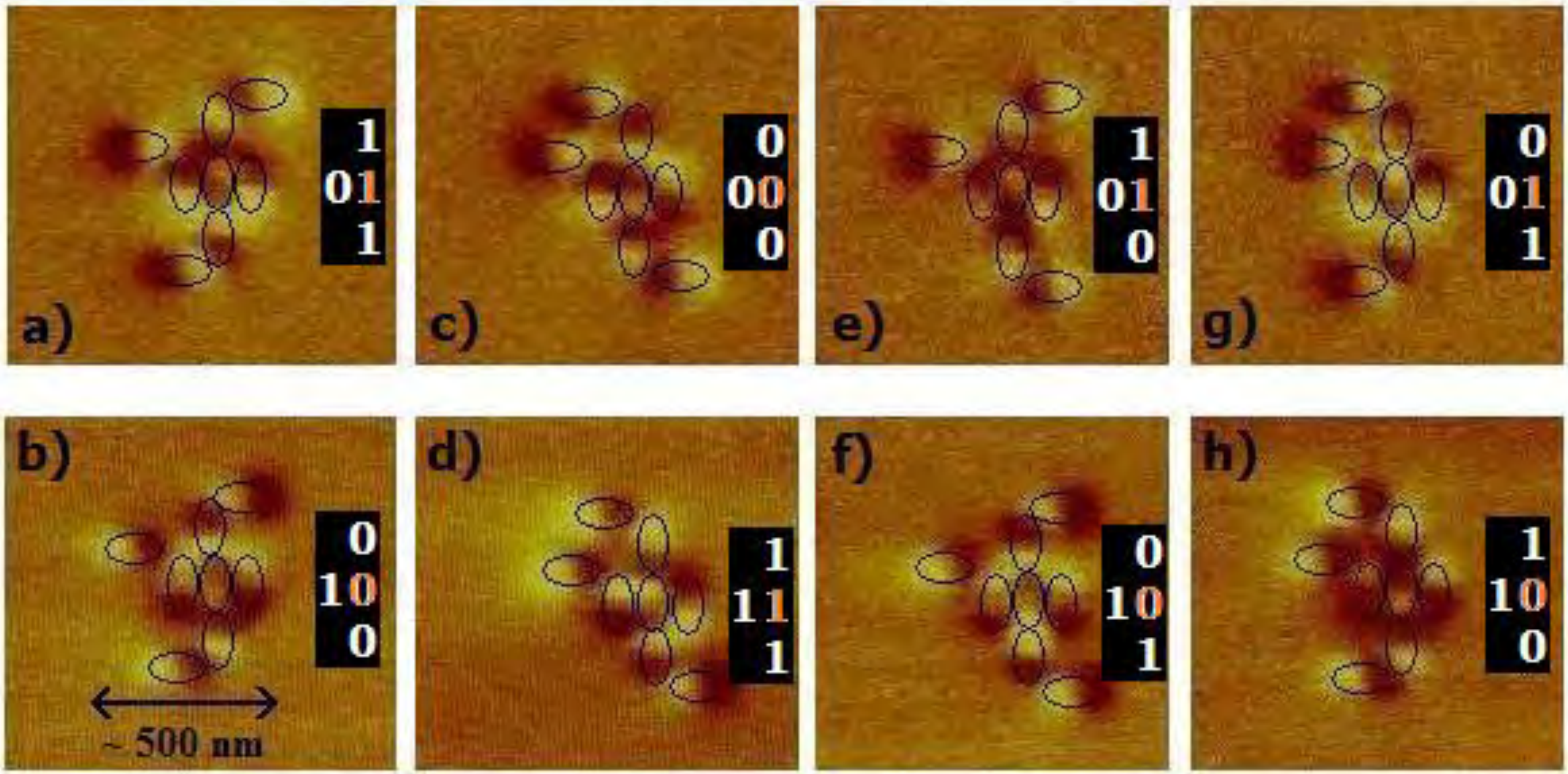
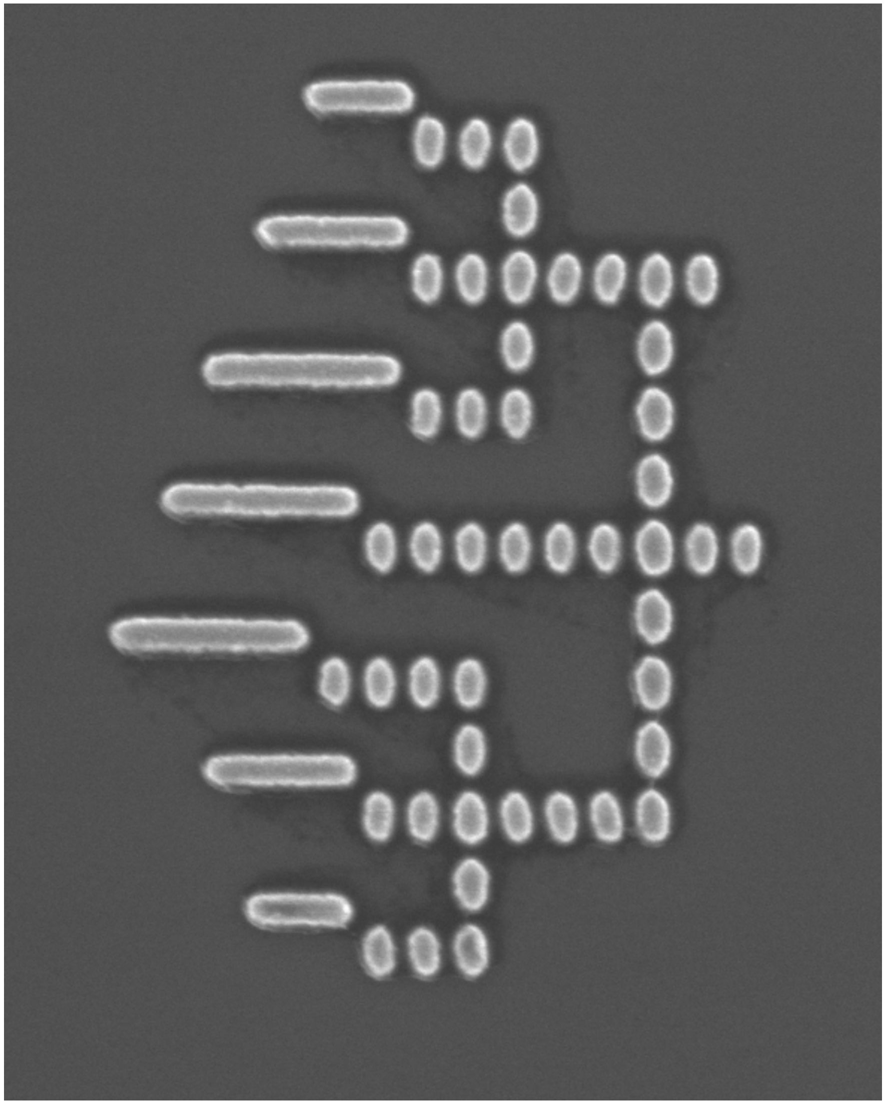
Demonstration of Majority-Gate Operation

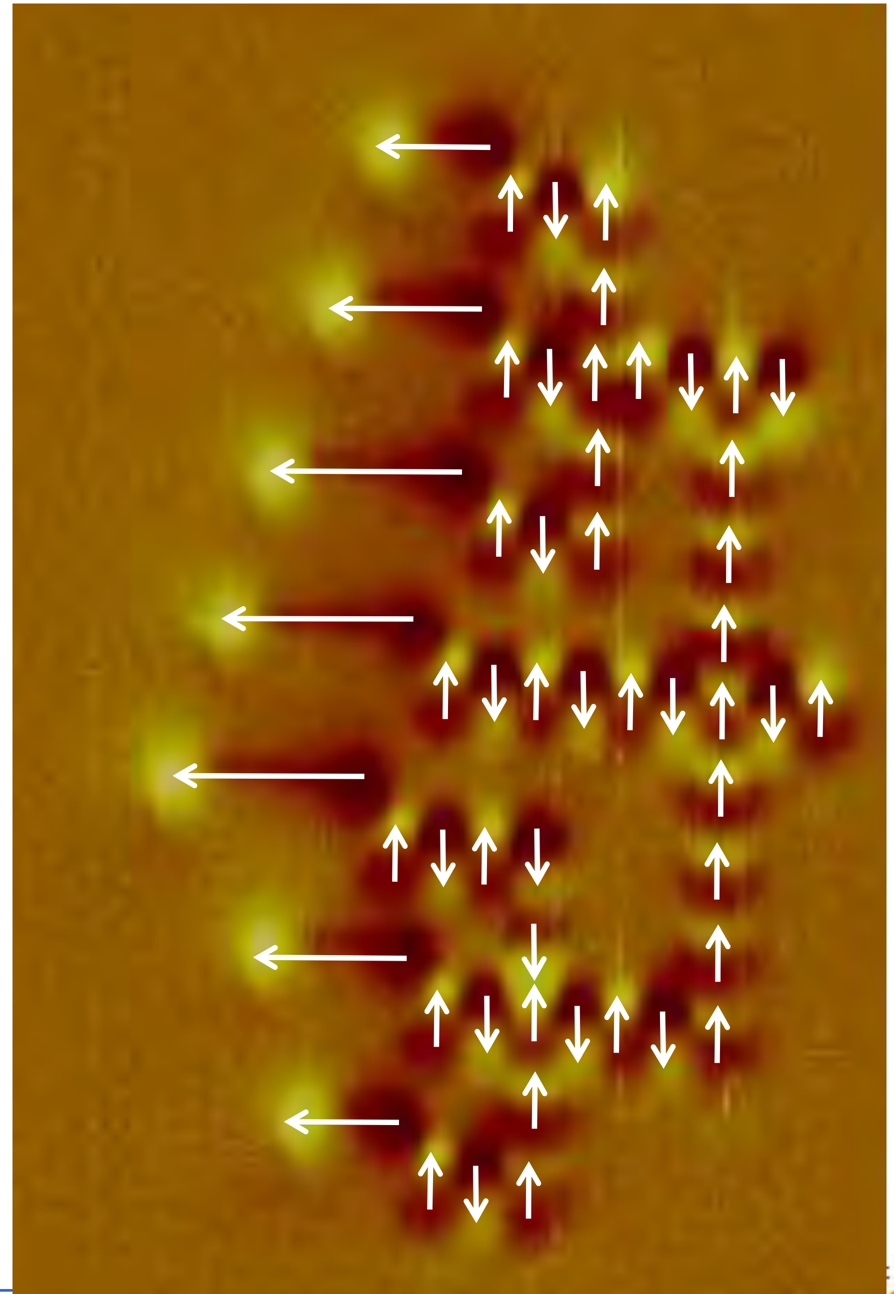




A. Imre *et al*, SCIENCE, VOL. 311, 205 (2006)

1 Bit Adder





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Edit Varga

Set#53 array5

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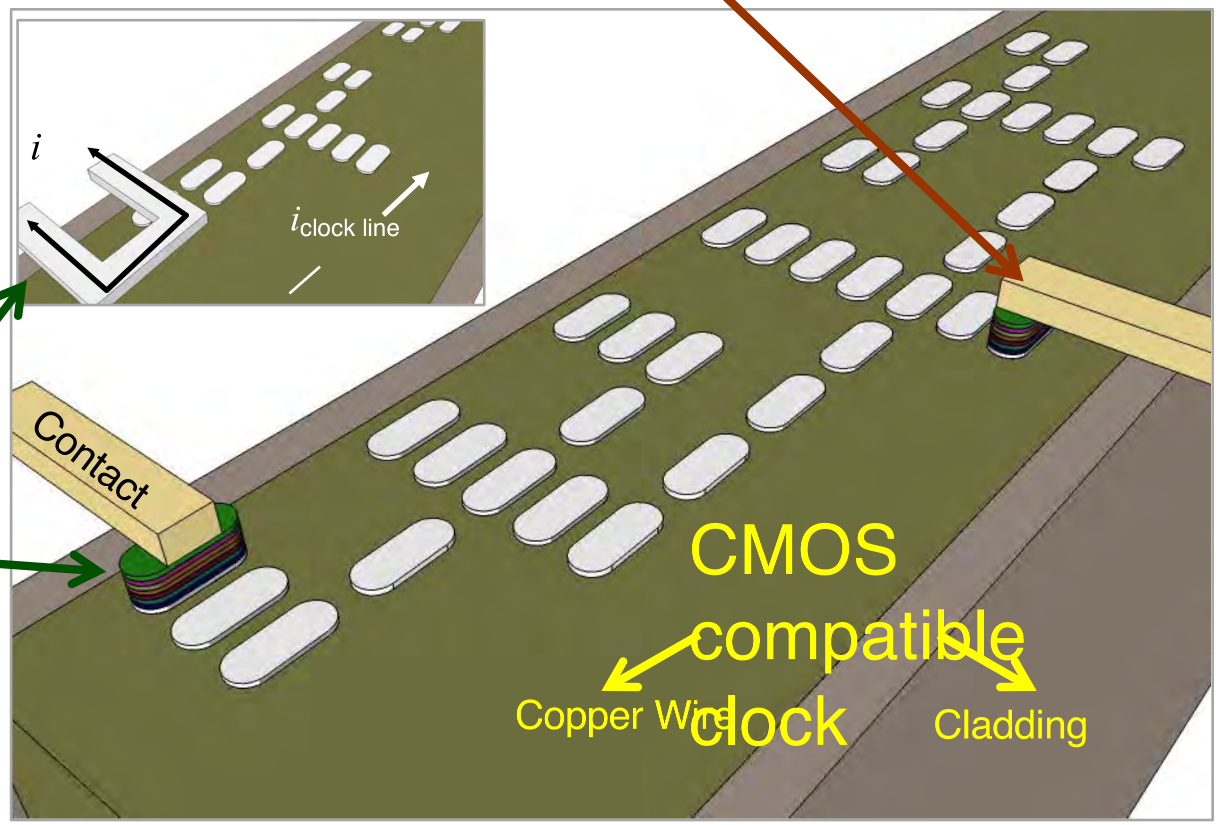
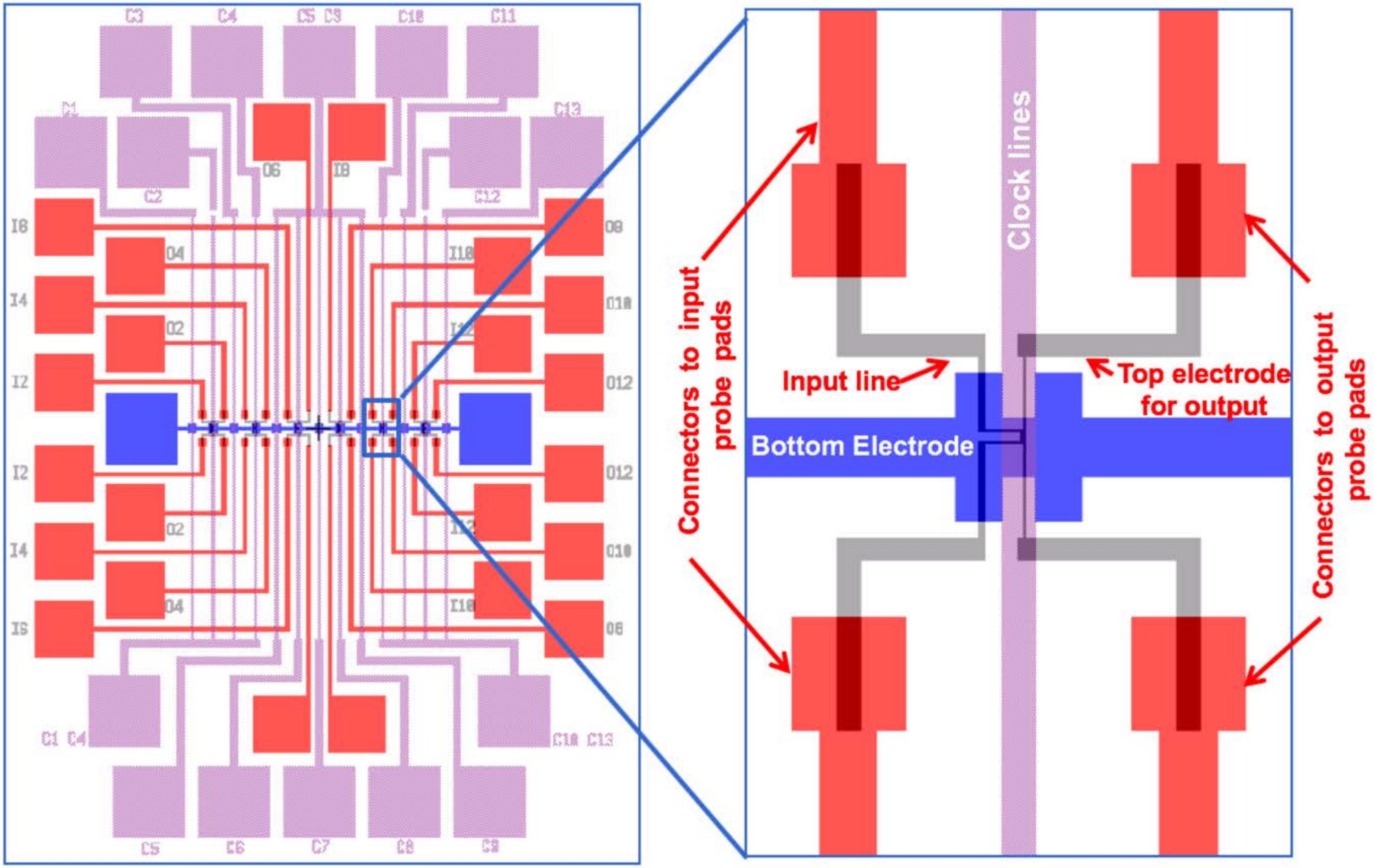
Input and Output Stack Development
MEI: "Magnetic-Electric Interface"

Output MEI: MTJ, Spin Valve…

Input: Biasing line or STT



Full System Integration with Clock Lines



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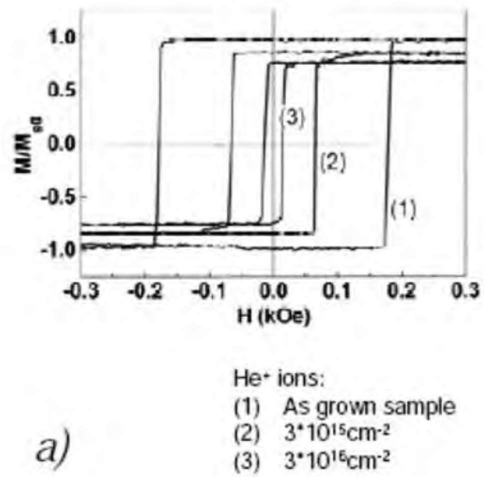
Perpendicular Magnetization

Tailoring Magnetic Properties by FIB Irradiation

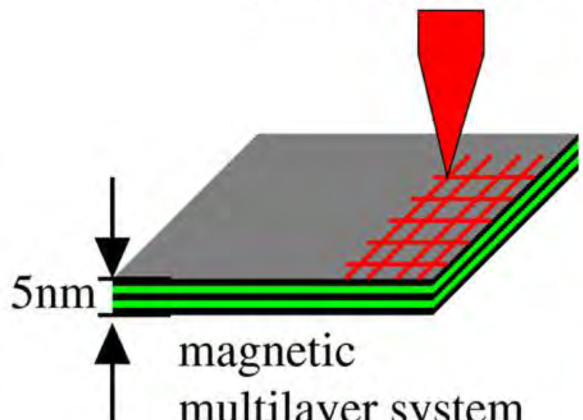
'Low' FIB dose:
Tailoring coercivity

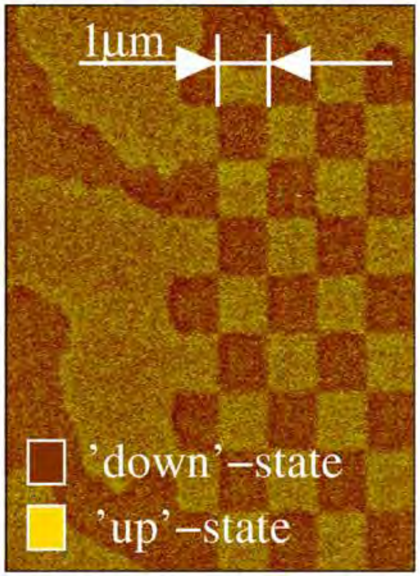
'High' FIB dose:
'Artificial' domains



a)

* C. Chappert et. al., Science, 1998.





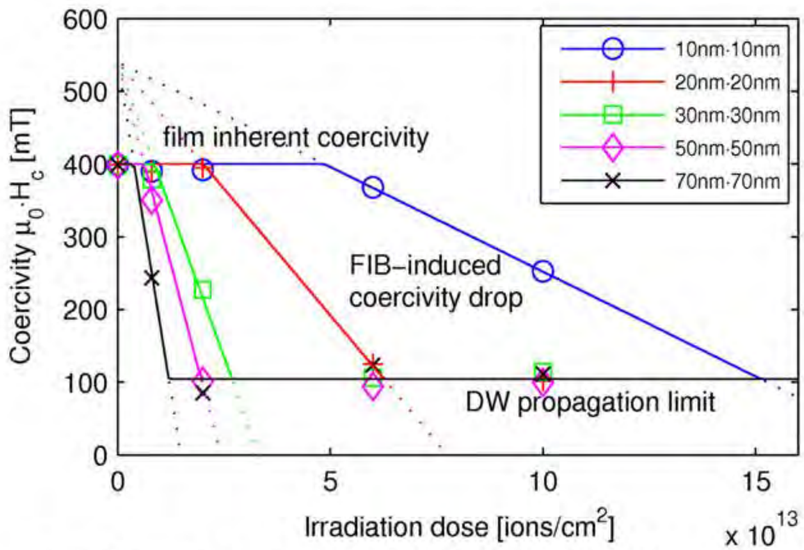
Logic Operation in Perpendicular NML

Partial irradiation:

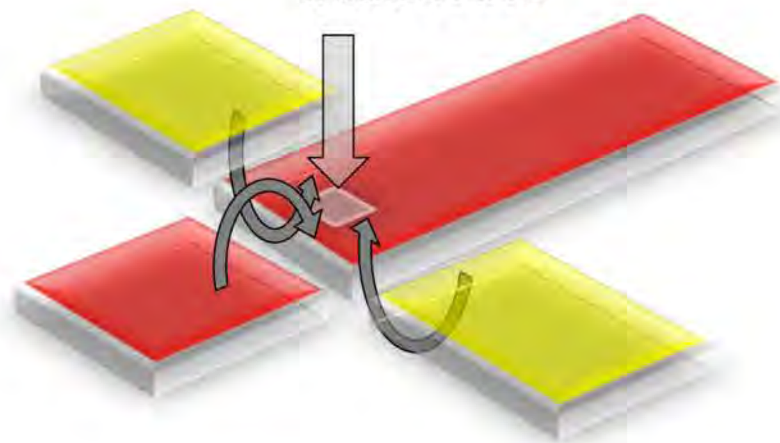
⇨ Locally reduced anisotropy
→ Artificial nucleation center (ANC)

⇨ Nucleation at user-defined position

⇨ Coercivity is controlled by size and dose of the partial irradiation



Breitkreutz et al, J. Appl. Phys., 111, 07A715 (2012).



Logic operation:

DW nucleation at ANC is supported or prevented by input coupling fields

Logic Operation in Perpendicular NML

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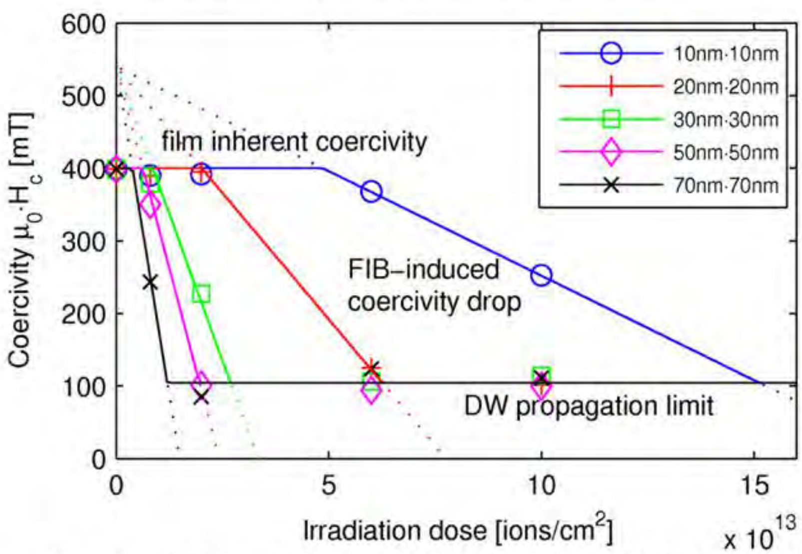
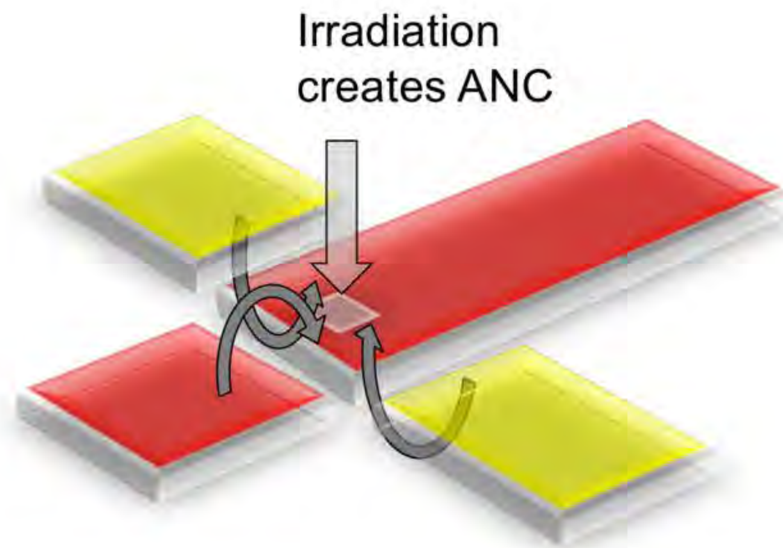


Breitkreutz et al, J. Appl. Phys., 111, 07A715 (2012).



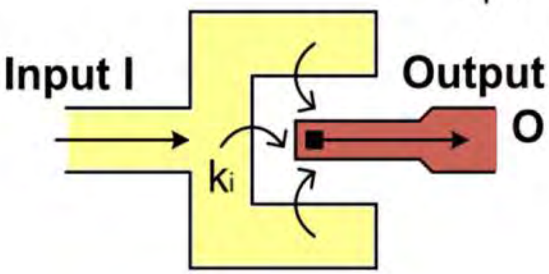
Logic operation:

DW nucleation at ANC is supported or prevented by input coupling fields

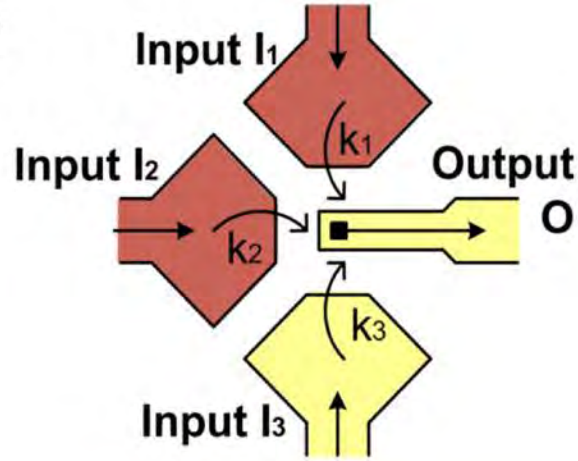
Basic Building Blocks

a) Inverter

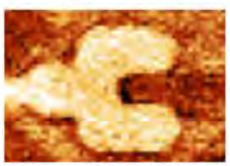
I	O
0	1
1	0

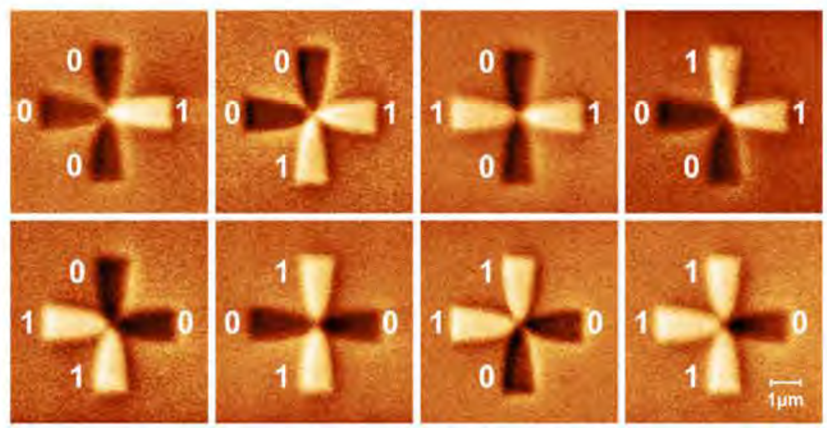


b) Majority gate



I1	I2	I3	O	
0	0	0	1	NAND
0	1	0	1	
1	0	0	1	
1	1	0	0	
0	0	1	1	NOR
0	1	1	0	
1	0	1	0	
1	1	1	0	



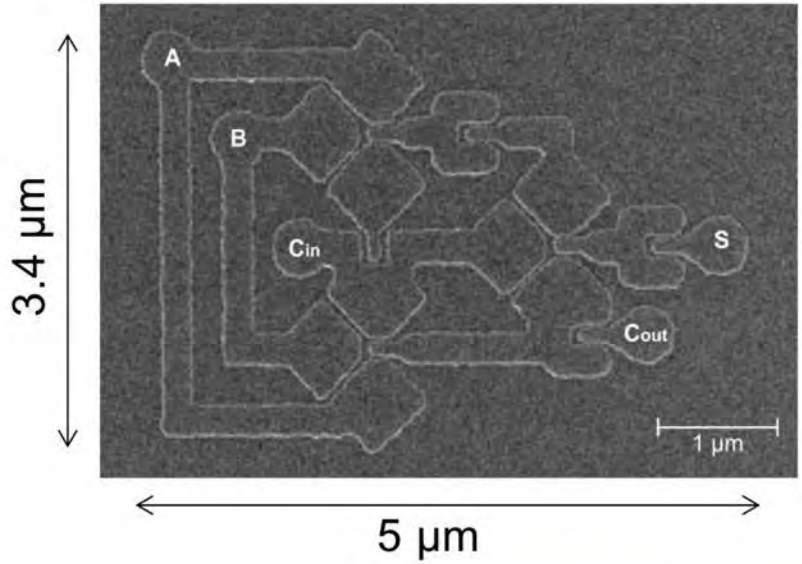


Breitkreutz et al, IEEE Trans. Mag. 48(11), 2012.

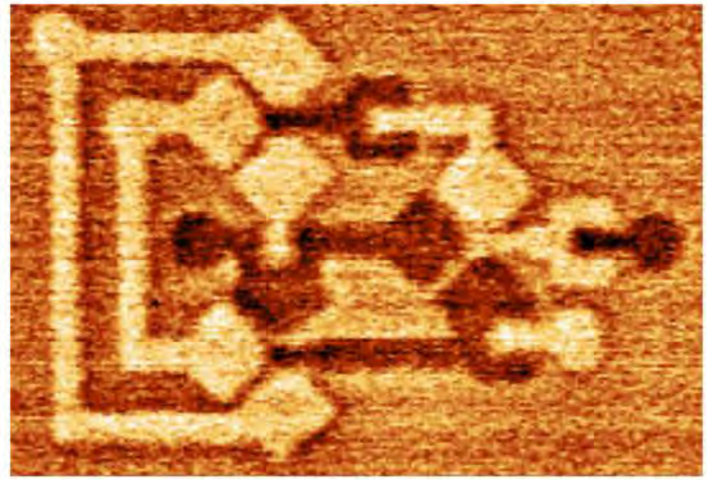
Majority Gate:

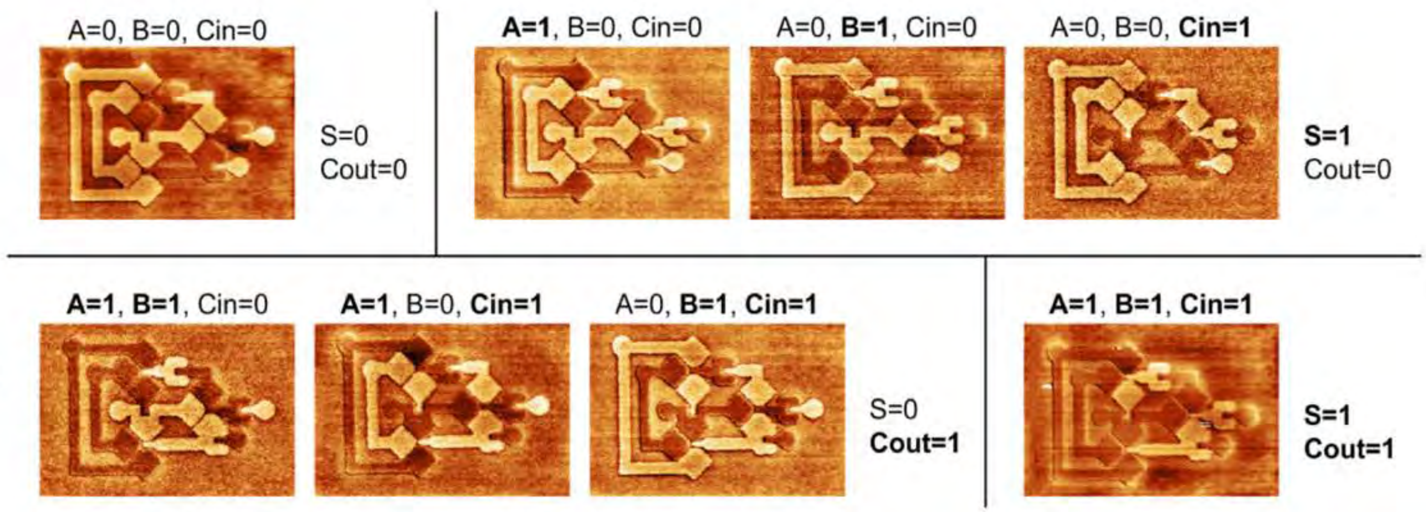
⇨ **Programmable NAND/NOR**

Full Adder Circuit



Breitkreutz et al, IEEE Trans. Magn. 49, 4464 (2013)





Structure:

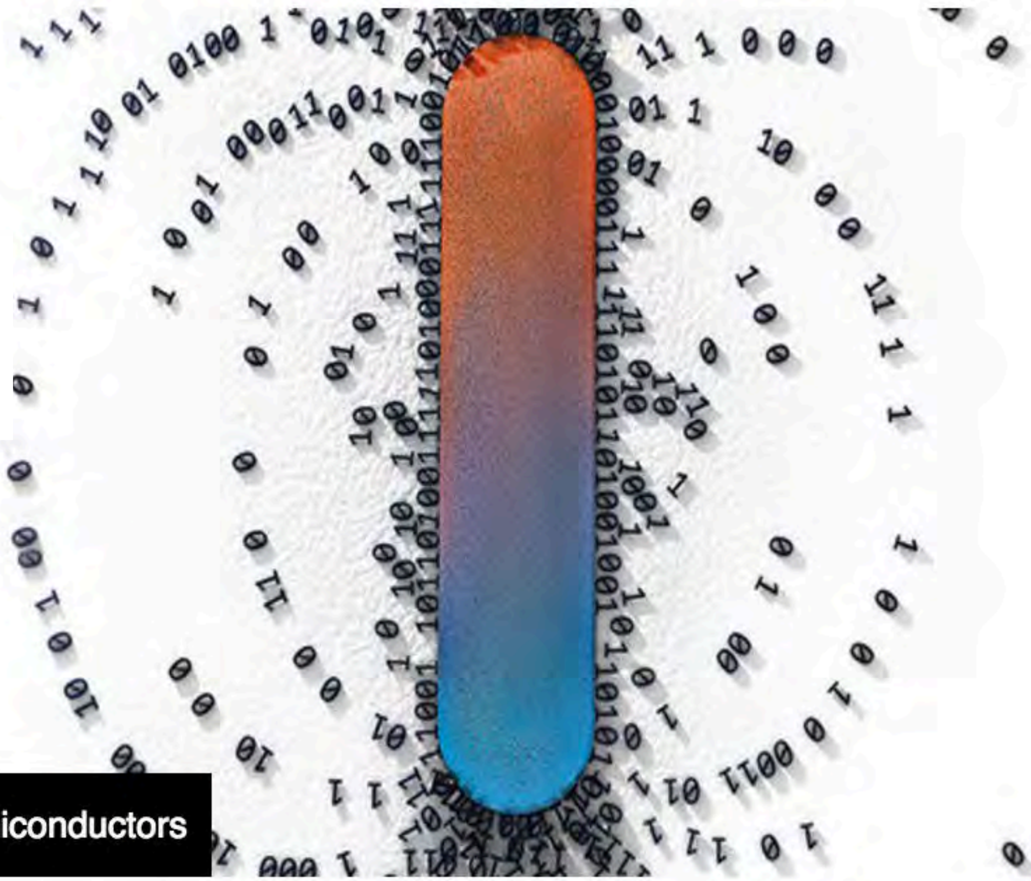
- •17 µm²
- •3 Majority Gates
- •4 Inverters
- •3 clocking cycles per operation

IEEE SPECTRUM

Follow on:

September 2015

Features



Semiconductors

Building Ultra-Energy-Efficient Computers Out of Tiny Bar Magnets

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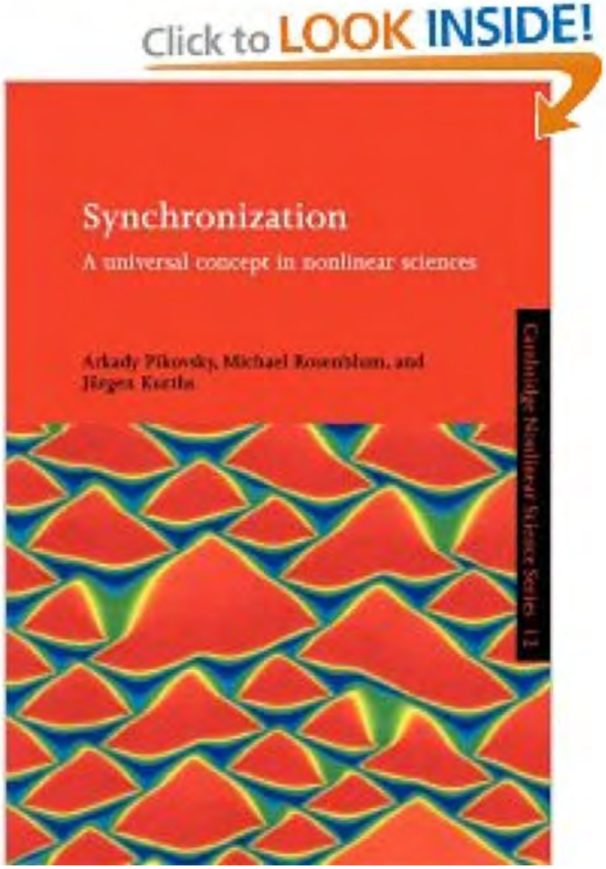
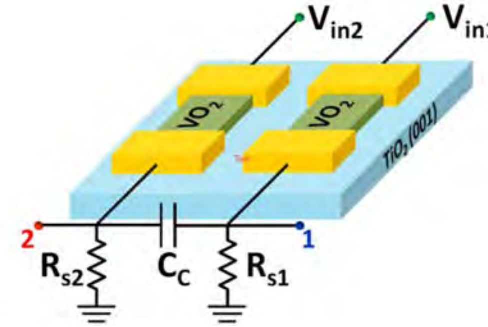
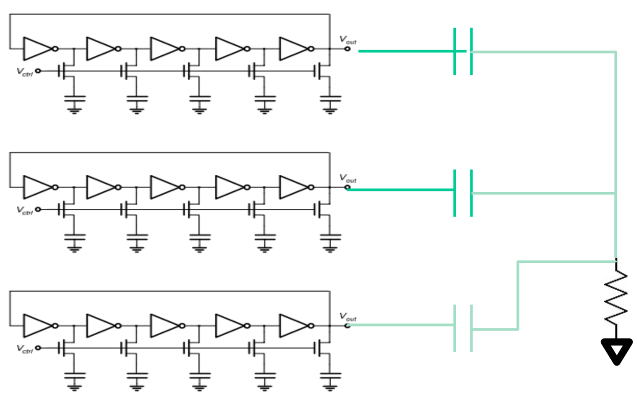
Synchronization of Coupled Oscillators



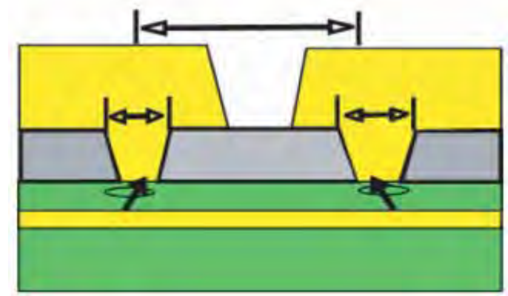
Coupled metronomes



Coupled VO_2 oscillators



Coupled ring oscillators



Coupled spin torque oscillators

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非線形問題解決軍団
池口研究室
NONLINEAR DYNAMICAL SYSTEM

メトロノーム同期 (32個)

Synchronization of thirty two metronomes

2012年09月14日，池口研究室前廊下にて撮影

Filmed at Ikeguchi Laboratory, on September 14, 2012.

Computing with Coupled Oscillators

- **Associative Computing**
  - **Phase dynamics computes distance metrics efficiently**
- **Combinatorial Optimization**
  - **Phase dynamics computes color sorting algorithm efficiently**

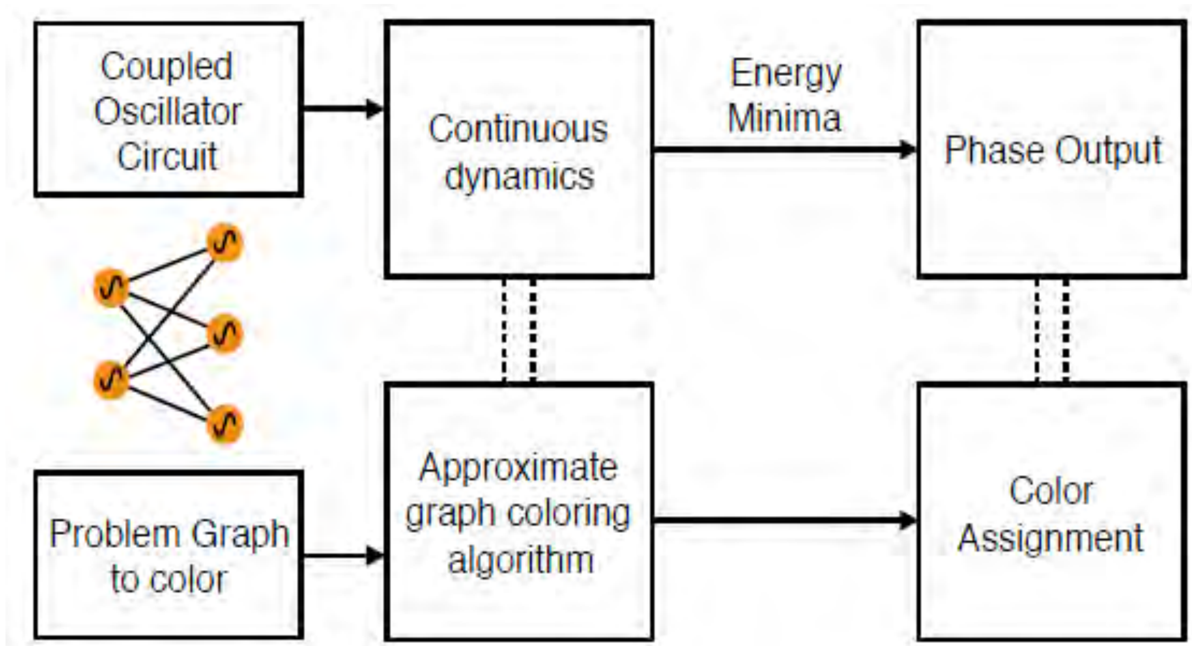
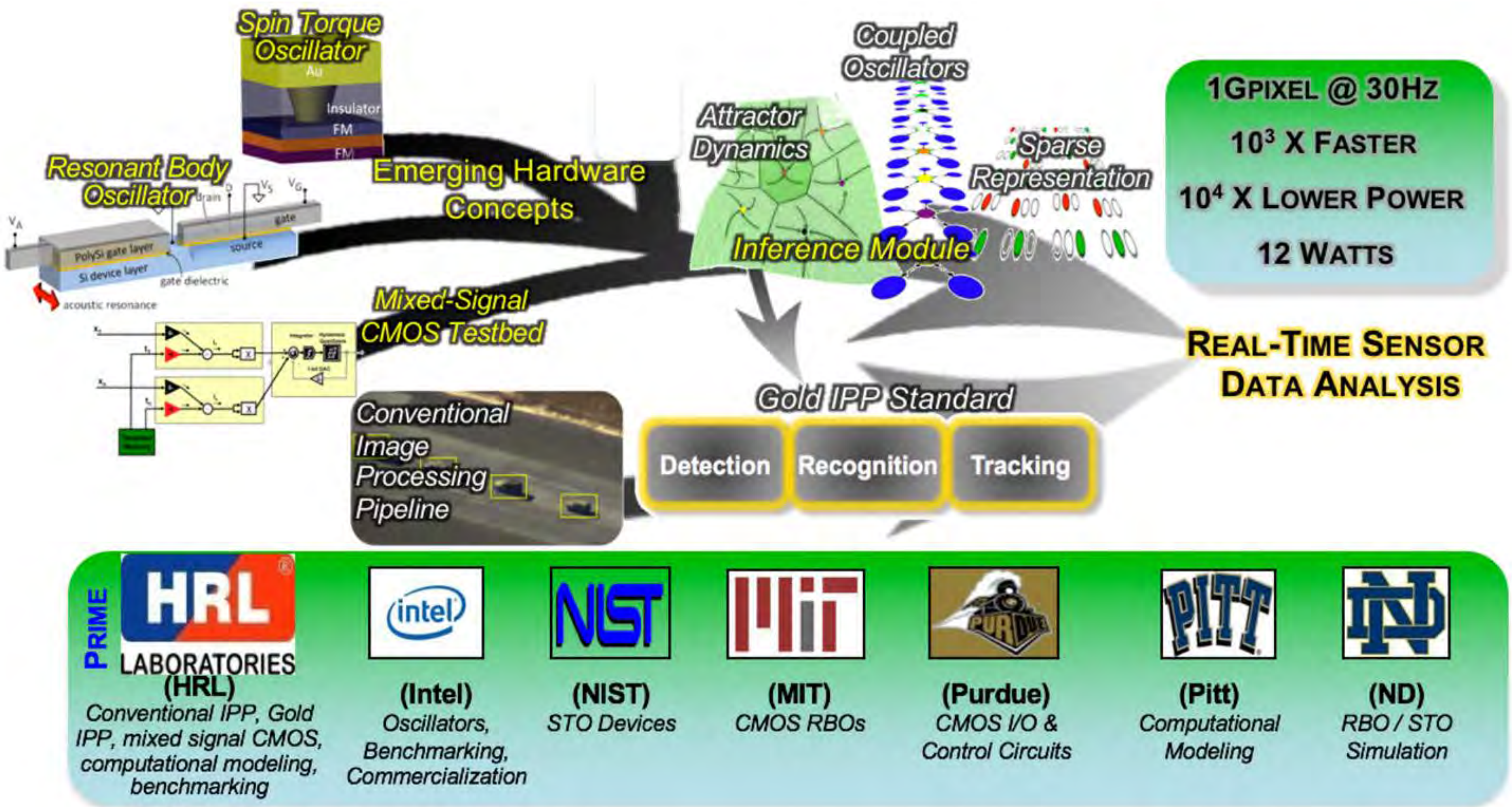


Image processing pipeline using spin-torque oscillators



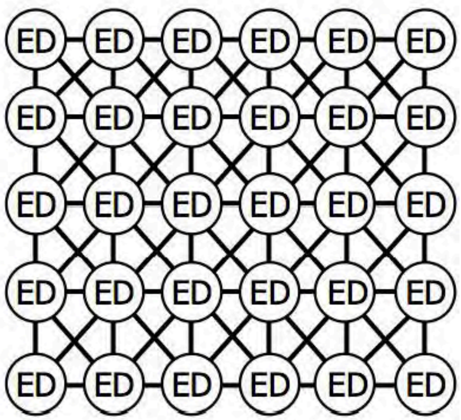
- ***DARPA-UPSIDE: A project to address energy efficient processing of massive video streams***
- ***We study the emerging device-based filtering block (pre-processor)***

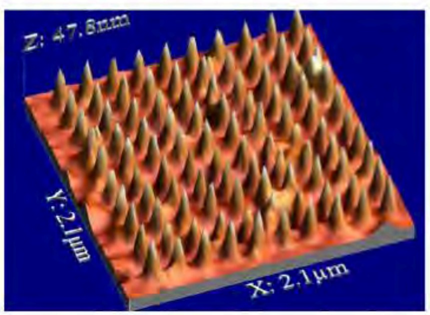
Picture courtesy of Narayan Srinivasa, HRL laboratories

Key Concept: Association Via Emerging Devices:
The Hardware is the Algorithm

Device Physics

- Coupled devices operating at very low power levels

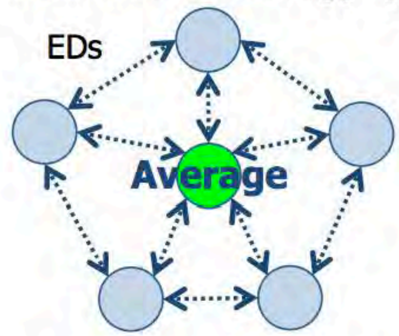




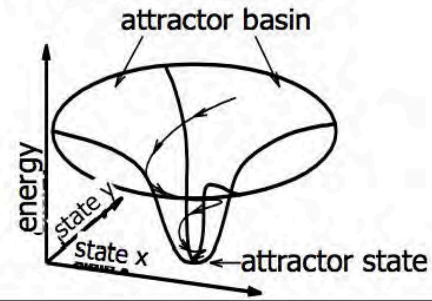
Nano-device Array

Interacting Nonlinear Systems

- Spontaneous synchronization corresponds to a stable minimum in an energy space

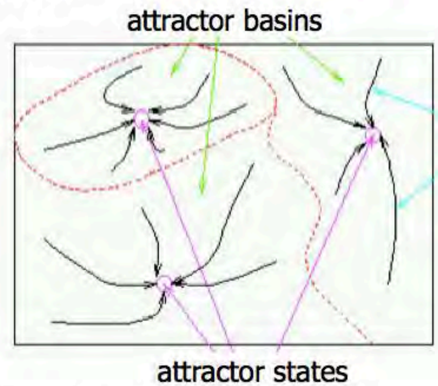


- The coupling coefficients create a controlled energy surface with specific local minima that models a probability distribution

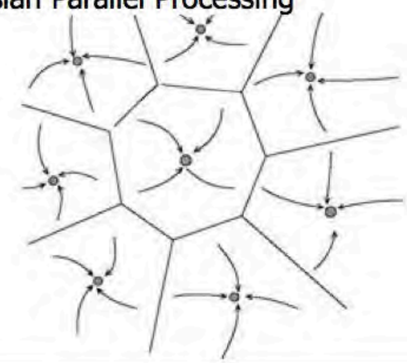


Bayesian Inference

- The system converges to the "closest" energy minimum, which is generally the most likely vector in a Bayesian sense



Bayesian Parallel Processing

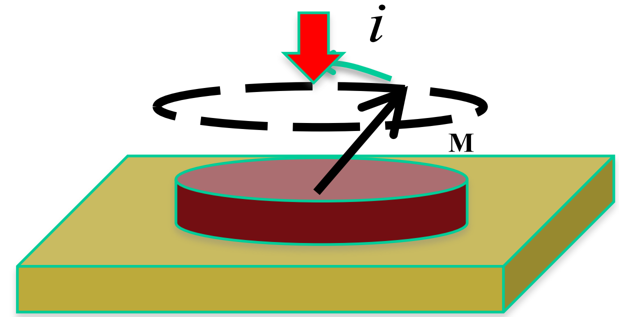


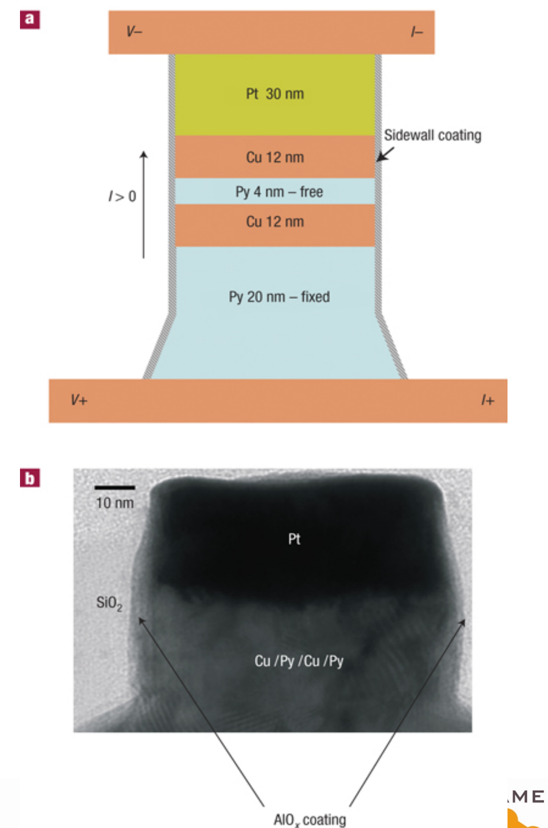
Associative memories approximate probabilistic inference, Giga-ops Performance and micro-watts of power

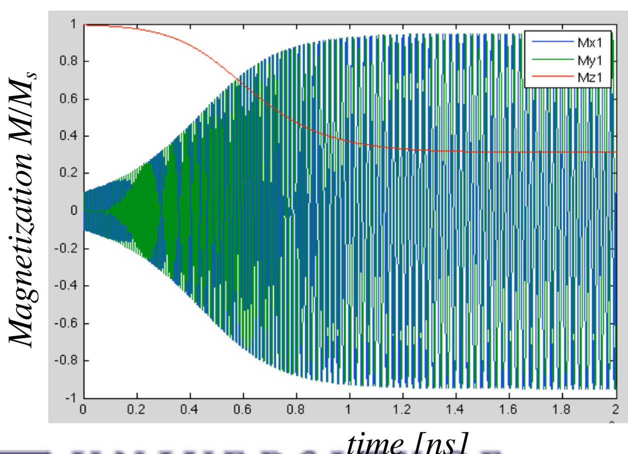
Dr. Dan Hammerstrom
Program Manager, MTO

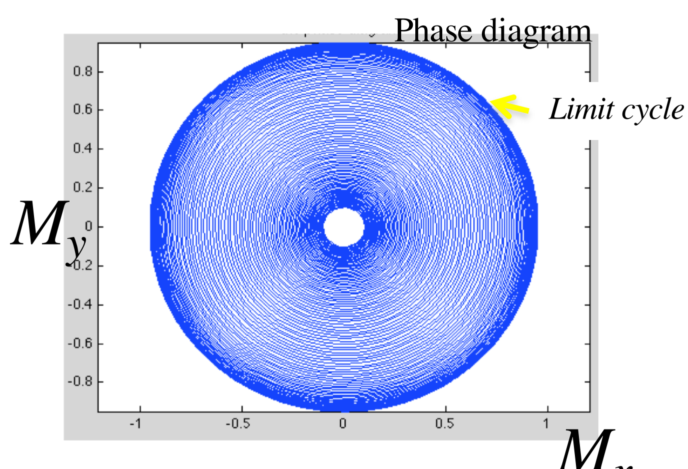
Magnetic Spin-Torque Oscillator (STO)

- Spin polarized current induces torque on magnetization vector
- For steady state oscillations, dissipation must balance torque
- Straightforward fabrication
- Potential low power (~10 µA @ 10 mV = 100nW) operation









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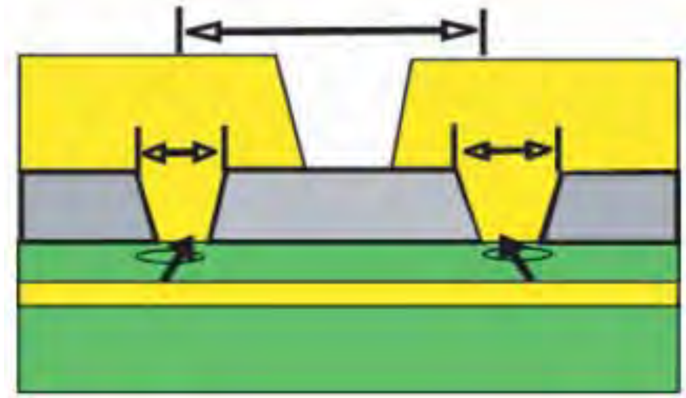
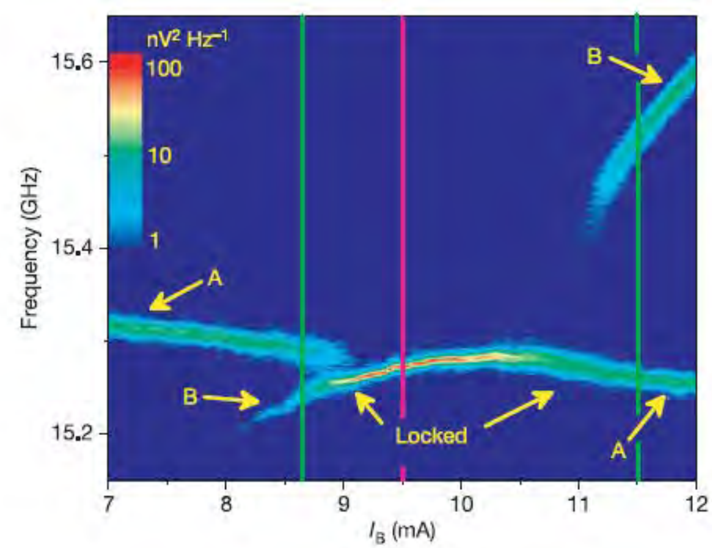
Coupled STOs

- Phase locking demonstrated over 500 nm distance and reasonable current range
- Phase synchronization mediated by spin waves
- Robust, room temperature effect in conventional magnetic materials



40 nm Spin torque point contacts with 500nm separation



Combined spectrum from both contacts as current through contact B is ramped from 7mA to 12 mA. Current through contact A is fixed at 8 mA.

Vol. 437|15 September 2005|doi:10.1038/nature04035

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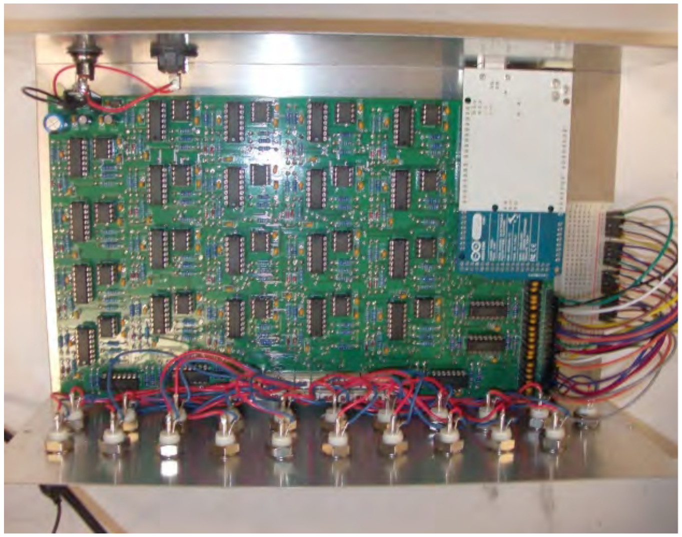
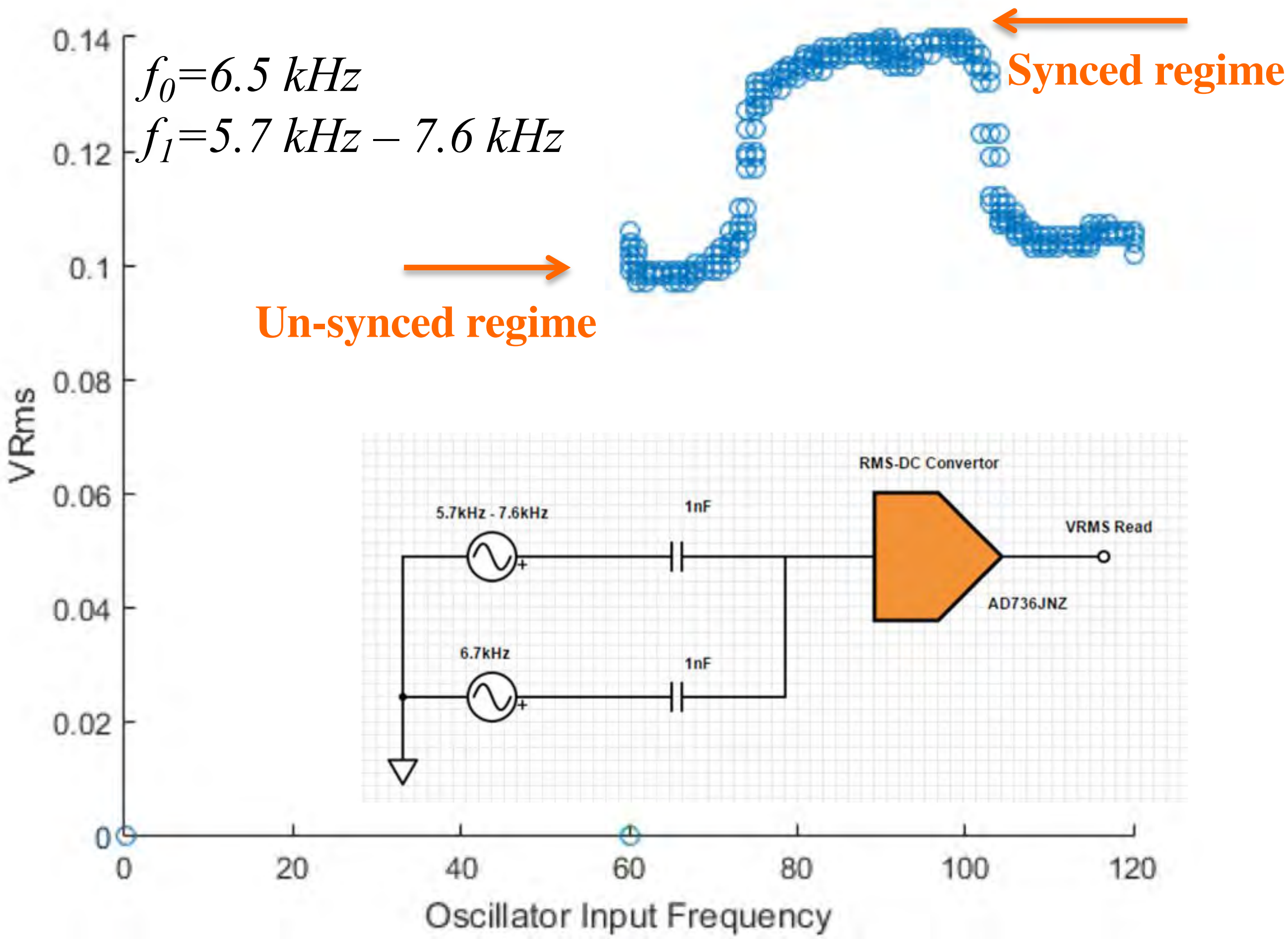
A DIY oscillator board





Circuit built by Bob Frame, REU / NURF student

We added an RMS-measuring chip to the common (coupling) node of the oscillators. This graph shows one of the oscillators being swept continuously, while the other kept at a fix value.

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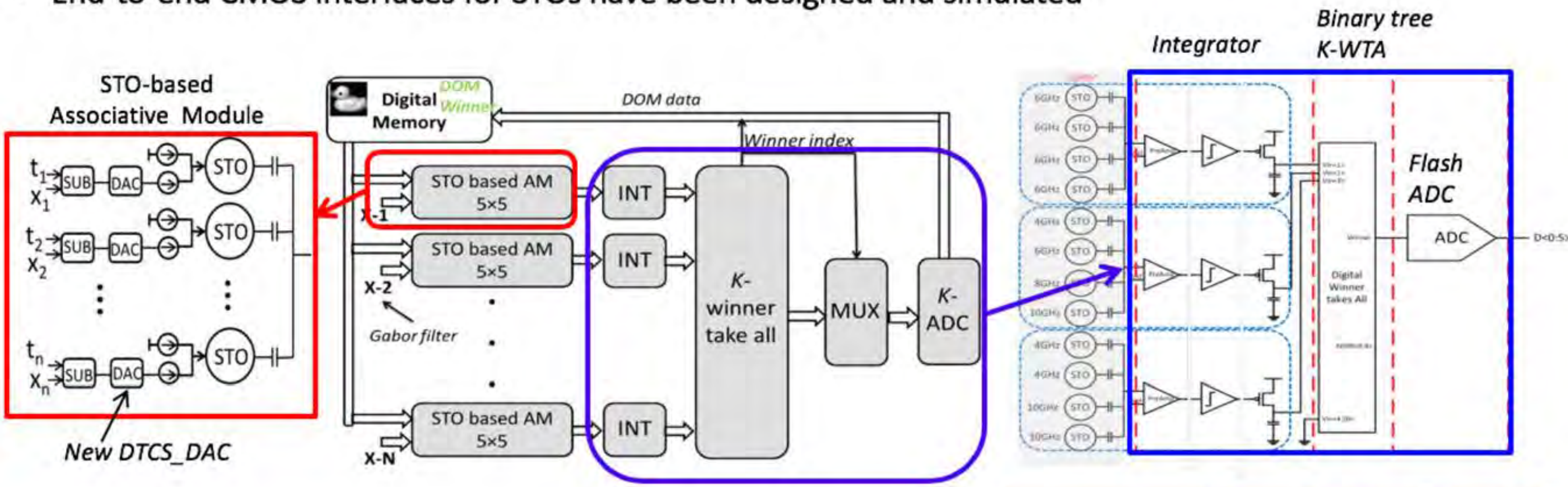
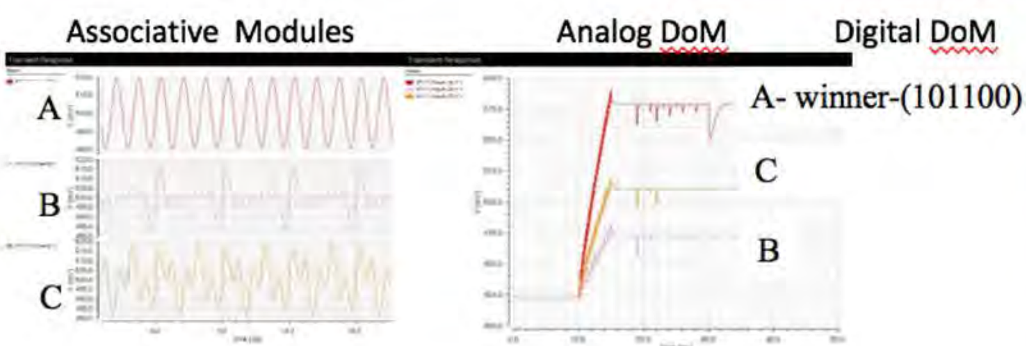
CMOS Interface Progress (STO)

- End-to-end CMOS interfaces for STOs have been designed and simulated





Element	Energy for one	Number of units	Energy per IM
Subtractor	33.1 fJ	500	16.55pJ
New DTCS_DAC	98fJ	500	49pJ
SHE-STO (0.2mA*0.1V*5ns)	100fJ	500	50pJ
Integrator (5ns)	2pJ	20	40pJ
Digital k-WTA	4pJ	1	4pJ
ADC	23pJ	2	46pJ
total			**206pJ**

Courtesy of Kaushik Roy (Purdue) and HRL labs

All the physics / circuit knowledge goes into a circuit model

Micromagnetic model of STOs

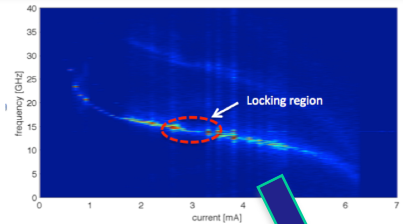
- Magnetic Material parameters
- Fit between full micromagnetic and simple model

SPICE model for electrical components

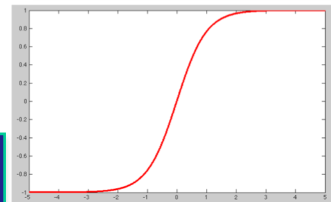
- Transmission line
- Filters, biasing circuits
- Feedback amplifiers

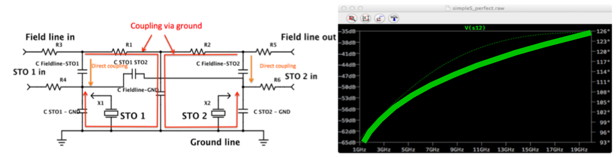
Parasitics / interconnect modeling

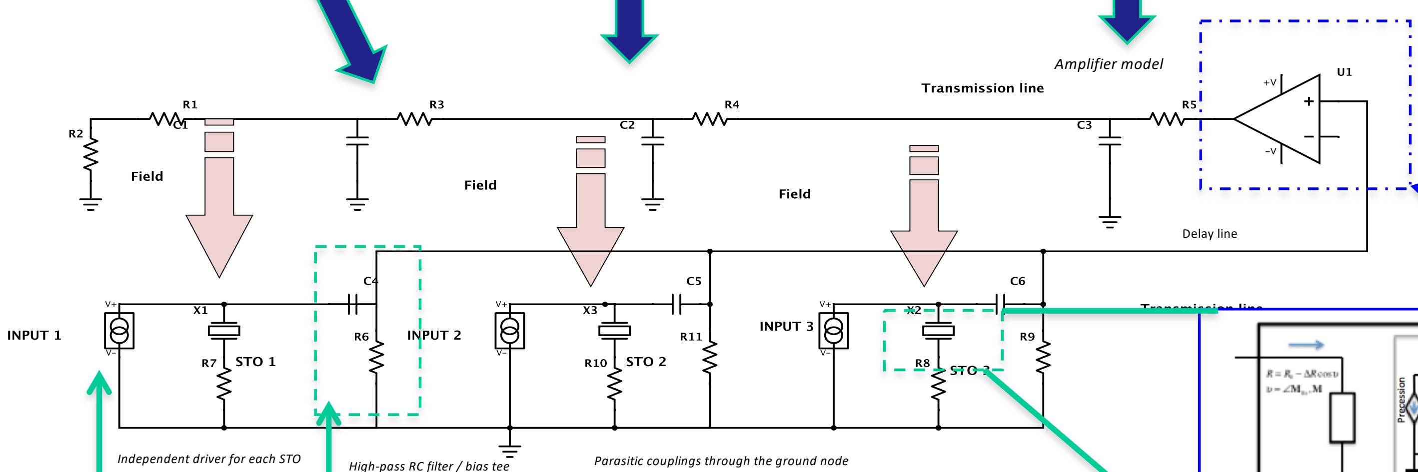
- Parasitic capacitances, resistances
- Long cable delays
- Crosstalk, self-oscillations



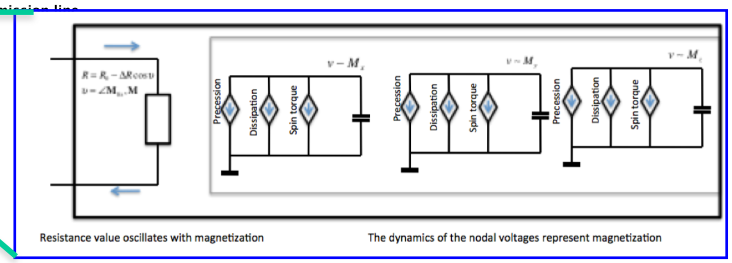
Micromagnetic simulation of STO spectrum


Saturating amplifier characteristics





Feedback amplifier



STO circuit model

The entire coupled-STO system is modeled via an equivalent circuit

➢ ***Allows to model STO behavior in arbitrary environment***

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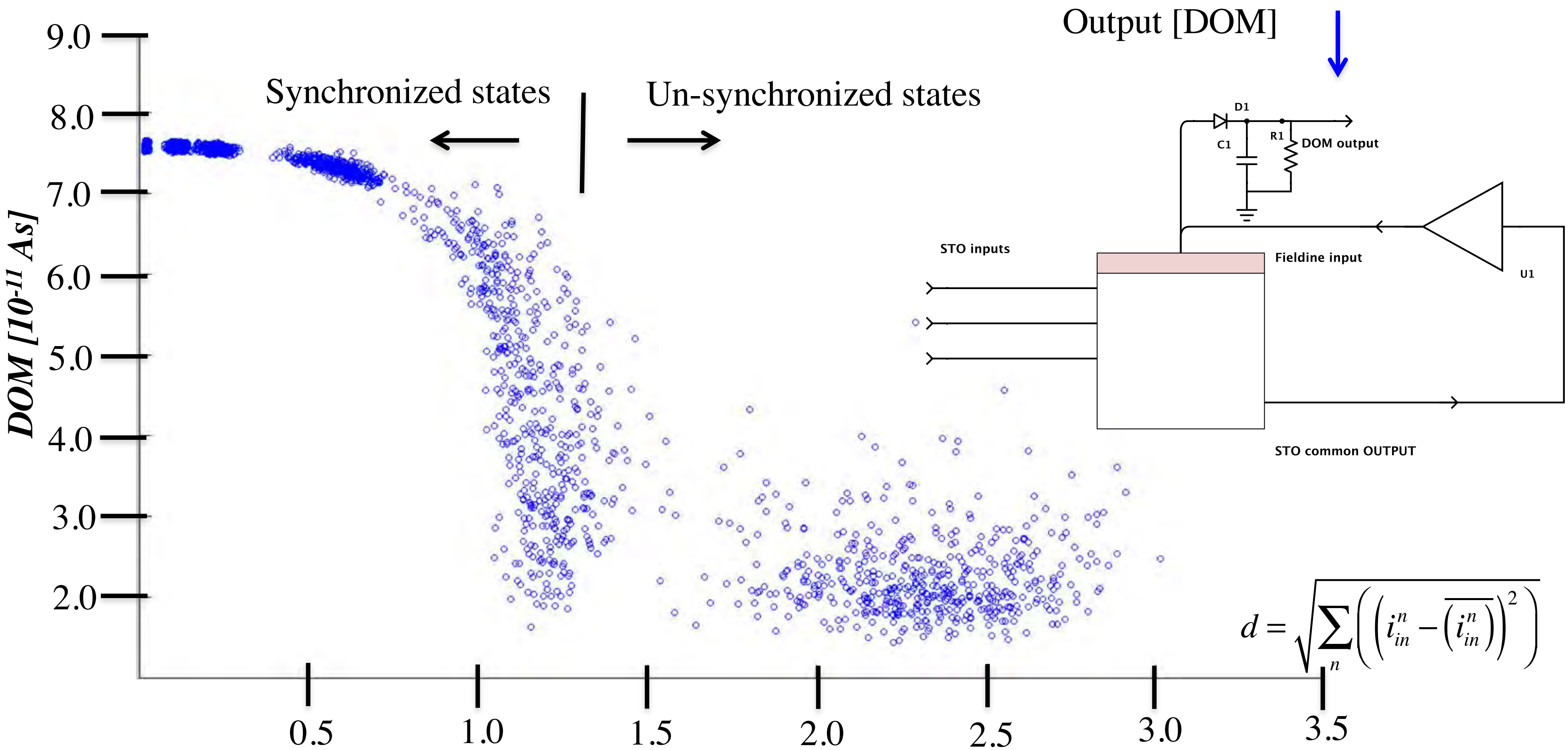
The degree of synchronization in an STO cluster

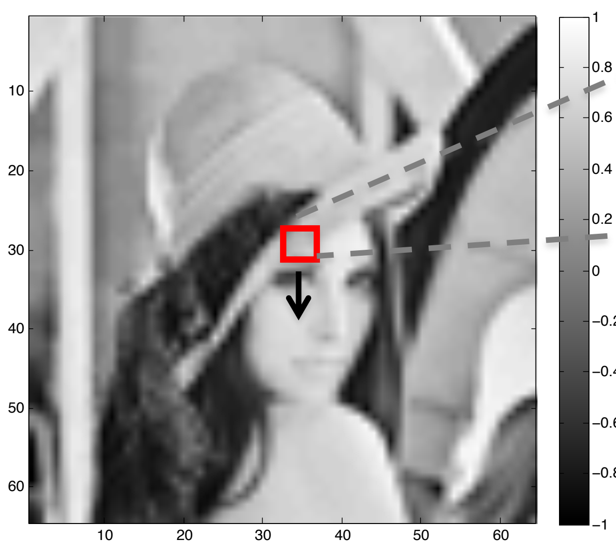


$$d = \sqrt{\sum_n \left(\left(i_{in}^n - \overline{\left(i_{in}^n \right)} \right)^2 \right)}$$

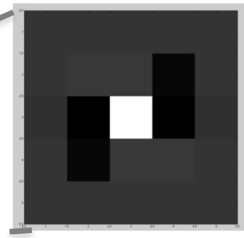
Circuit output measures the length of analog input current vector or Euclidean distance between vectors

Nikonov, Dmitri E., Ian A. Young, and George I. Bourianoff. "Convolutional Networks for Image Processing by Coupled Oscillator Arrays." *arXiv preprint arXiv:1409.4469* (2014).

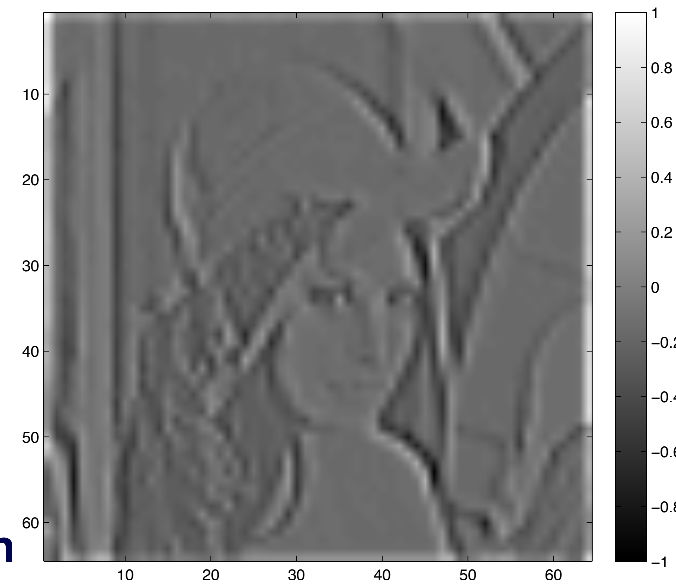
Simulation of patch-based Gabor filtering



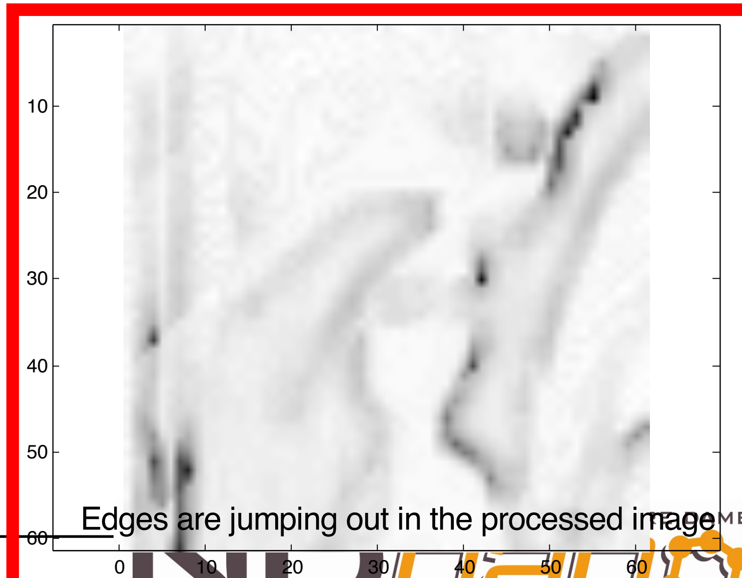
5 x 5 Gabor filter for 45° lines



Convolution using Matlab

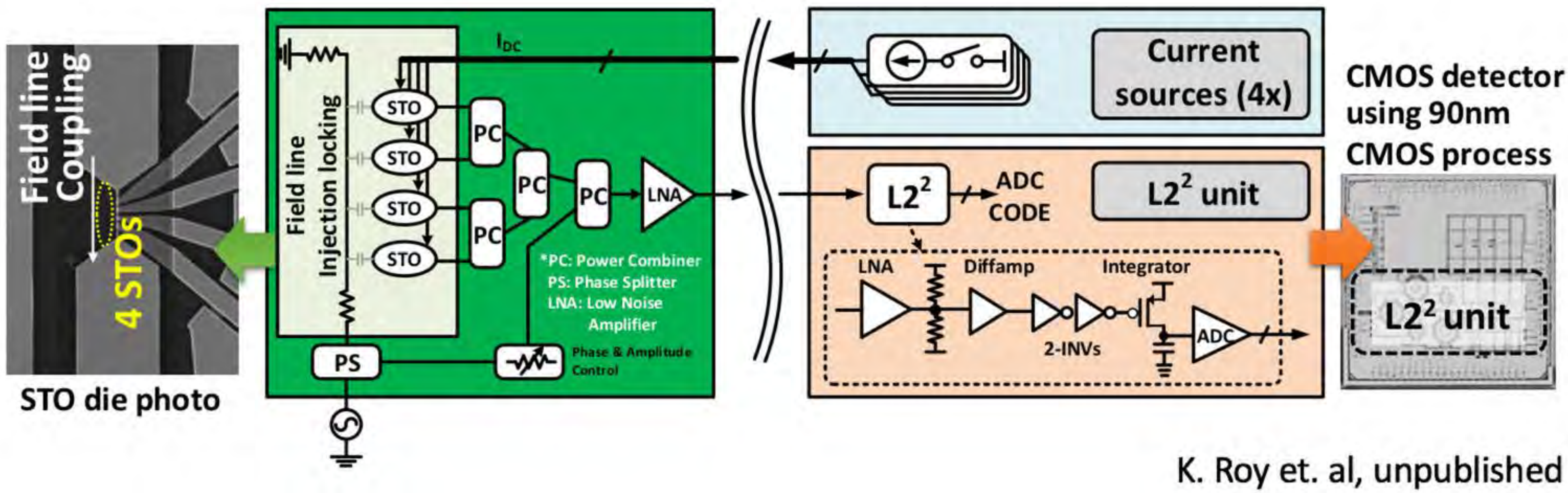


Oscillator-based convolution



- **Pixel intensities in image segments are represented by analog current values**
- **An image is convolved patch-by-patch with a Gabor filter**
- **The processed analog image is formed by the oscillator array outputs**
- **Oscillators synchronization does the analog Gabor filtering**

The entire system… and what we learned

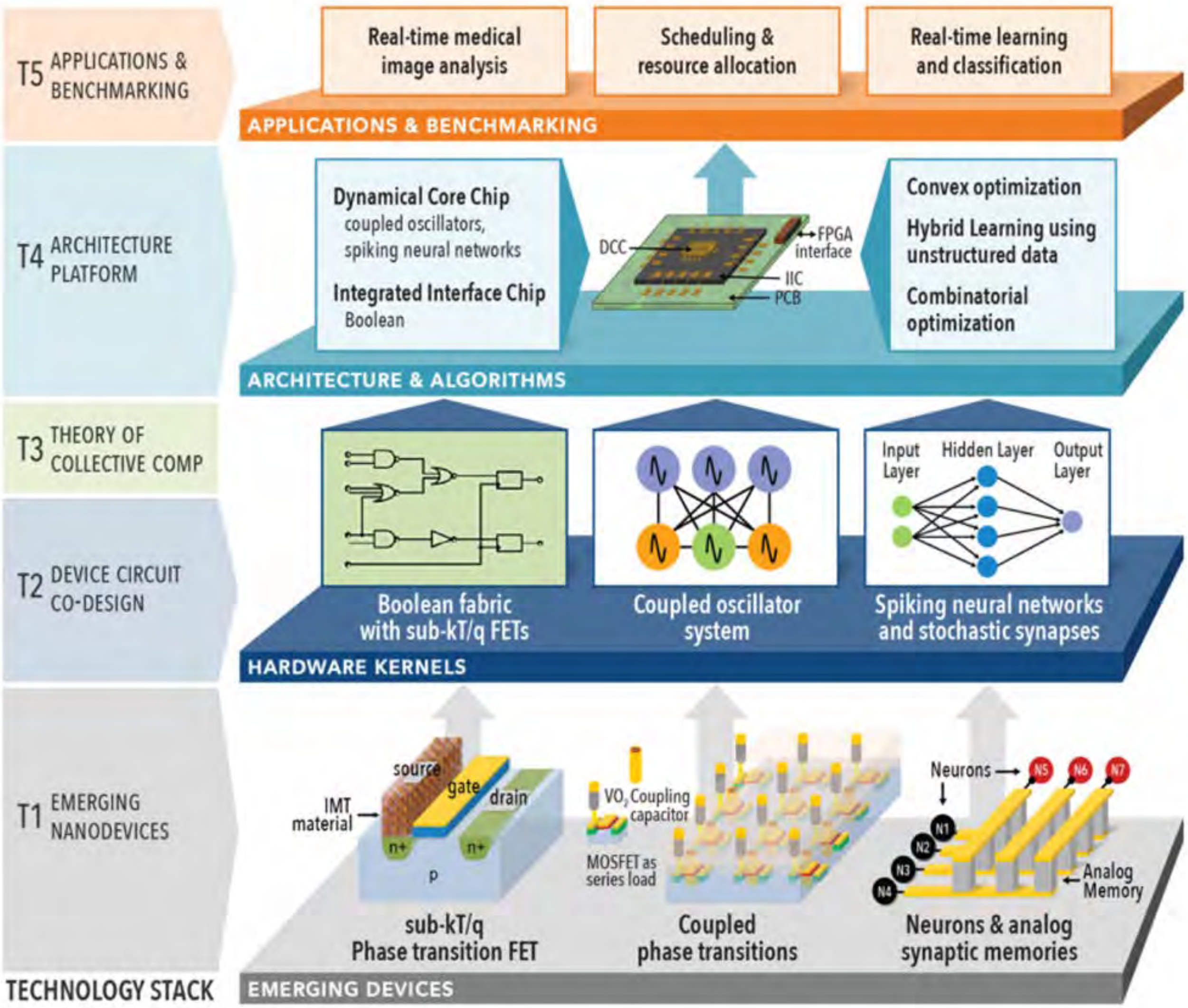


STO module is actually dwarfed by all the required CMOS circuitry….

Spiking neural networks have done better in the benchmarking

Highly optimized, low-accuracy digital circuits have also done better

EXtremely Energy Efficient Collective ELectronics (EXCEL) – Lead PI: Suman Datta



EXCEL is organized into a vertically integrated structure of computer scientists, mathematicians, architects, integrated circuit designers, device physicists and material scientists

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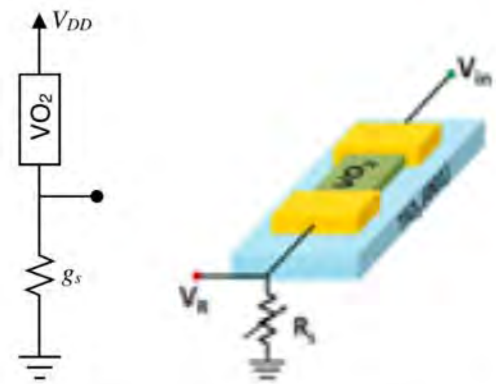
Phase transition in VO_2 and relaxation oscillators

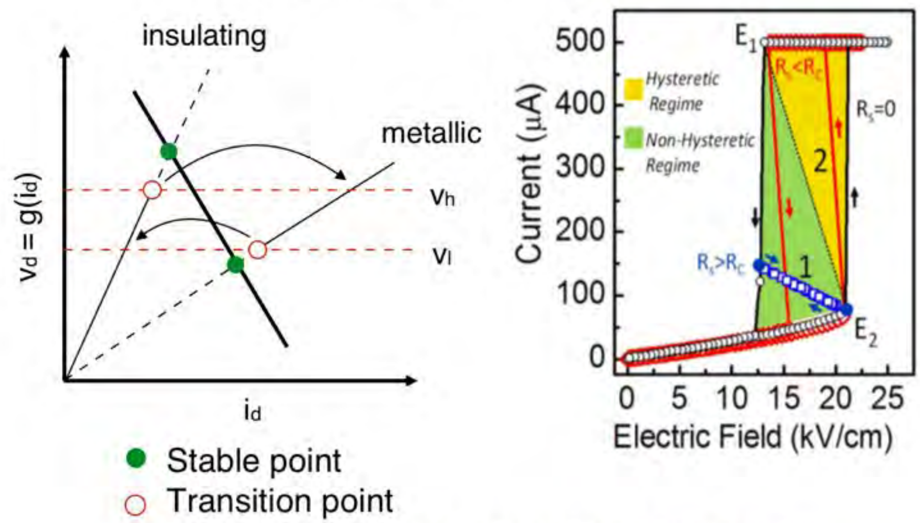
VO_2 shows MIT (metal-insulator transition), i.e. it switches to a metallic state at a higher *E*-field, and to a insulating state at lower *E*-field.

VO_2 oscillators can be created using a series combination of VO_2 device and a resistance. The resistance can be a MOSFET.

When the load line does not intersect the V-I curve within the regions of operation, the circuit never reaches the stable points, and oscillates.



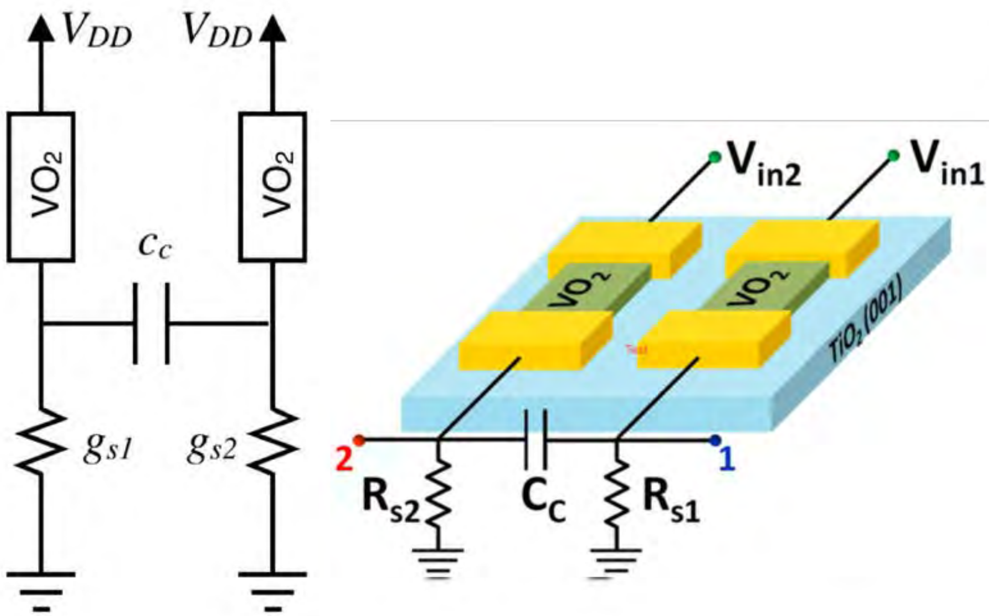
VO_2 oscillator with series resistance



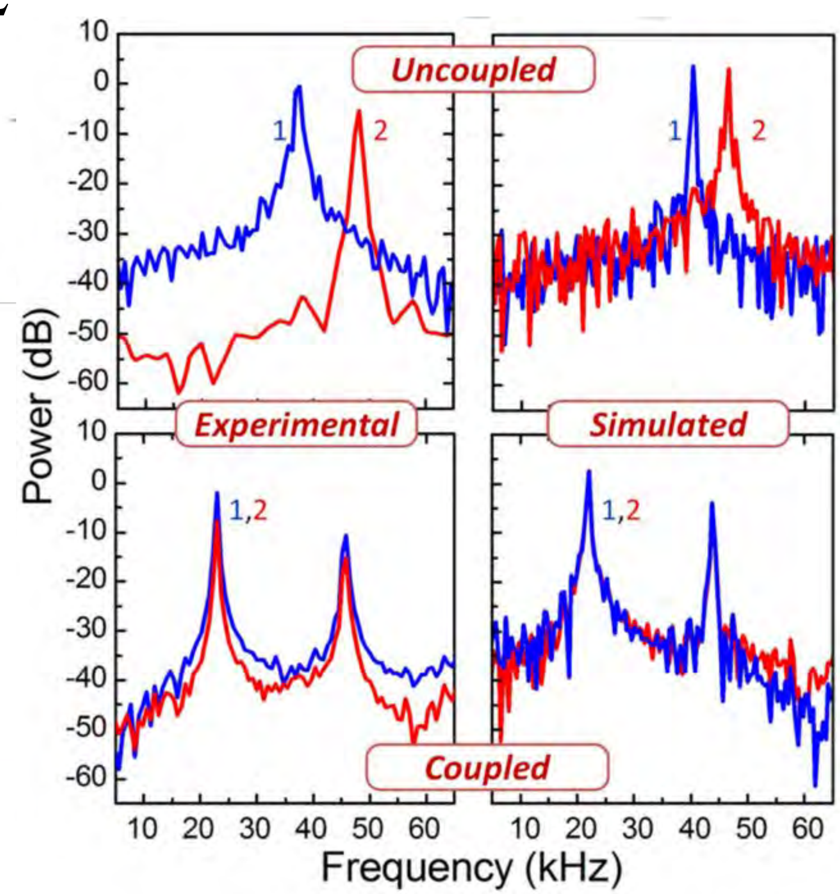
Mechanism of oscillation : Load line graph

Shukla et. al. *Scientific Reports*, 2014

Coupled VO_2 oscillators



Coupled VO_2 oscillators with series resistance



Coupled VO_2 oscillators synchronize in frequency

Shukla et. al. *Scientific Reports*, 2014

When coupled using a capacitor, the VO_2 oscillators show synchronization in frequency and they lock anti-phase

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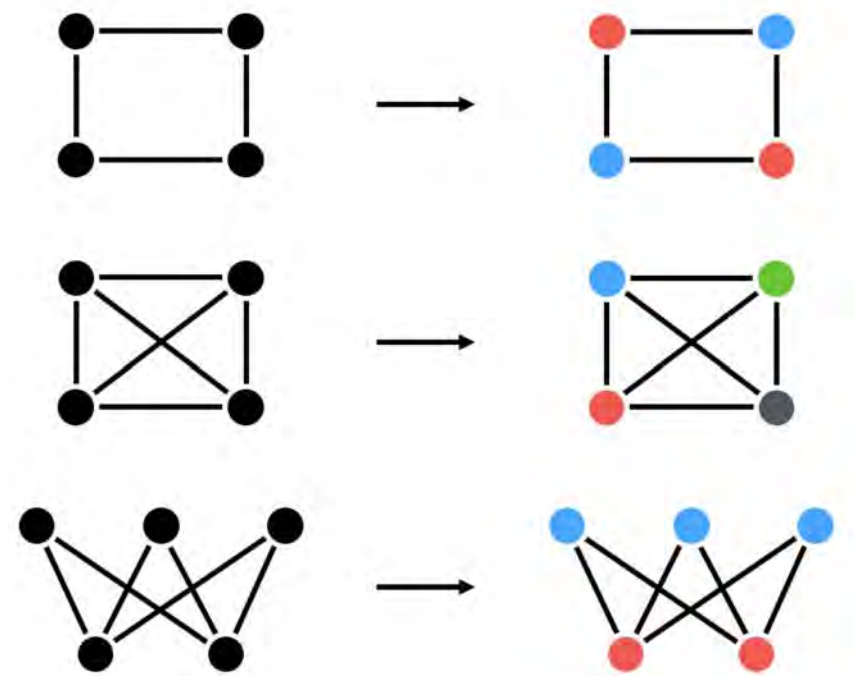
Graph coloring problem

Also known as vertex coloring, the aim of GCP (graph coloring problem) is to assign a color to each vertex of a graph such that no 2 vertices connected by an edge receive the same color



Graph coloring with minimum possible number of colors is called minimum graph coloring

Graph coloring is a critical problem in combinatorial optimization with applications in pattern matching, scheduling, resource allocations, timetabling, analysis of networks properties.

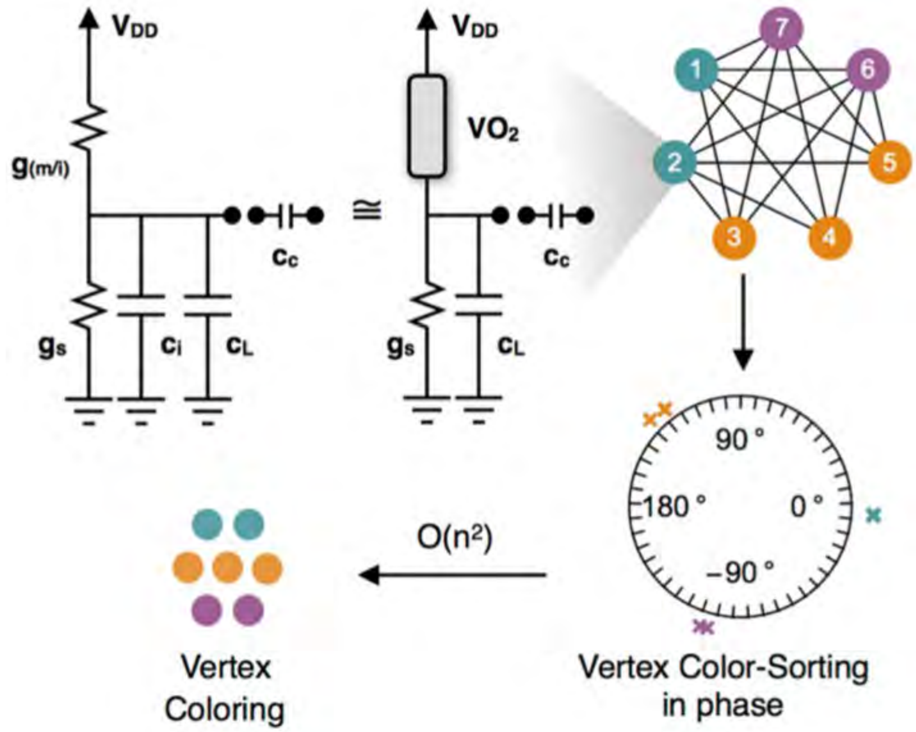
NP-complete problem; even approximate coloring is NP.

Graph coloring circuit

Coupled relaxation oscillators based on VO_2, when coupled in a graph, result in output phases that approximately solve vertex coloring problem.

Phases align in an order such that same colored vertices appear together.

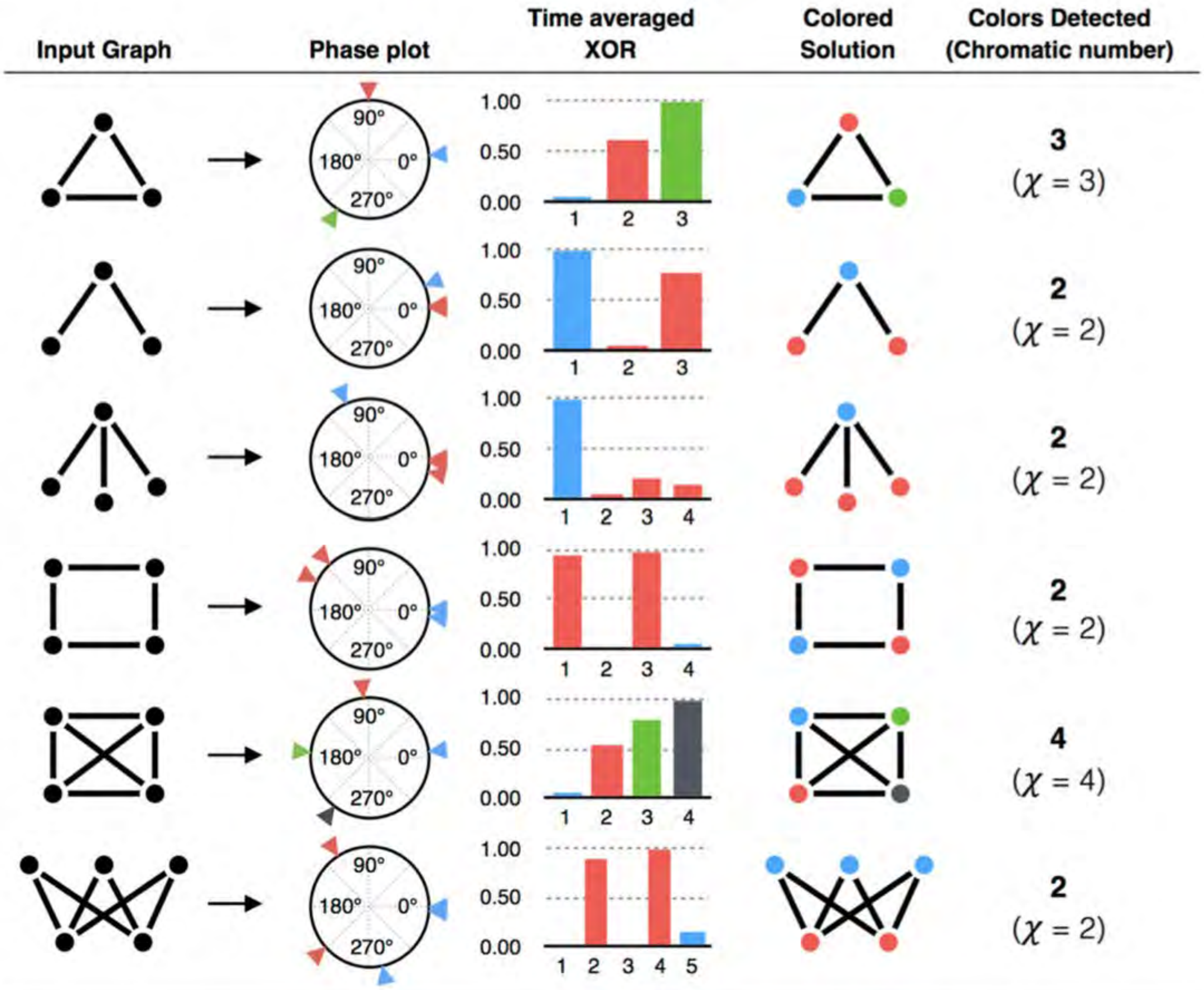
Calculating the coloring from such an ordering of phases is $O(n^2)$.



Parihar et. al., *Nature Scientific Reports*, 2017

Earlier Work:
Chai-Wah Wu, *IEEE Trans. Circ. Syst.*, 1998
J. Wu et al., *Physica D*, 2011

Experimental results



Parihar et. al., *Nature Scientific Reports*, 2017

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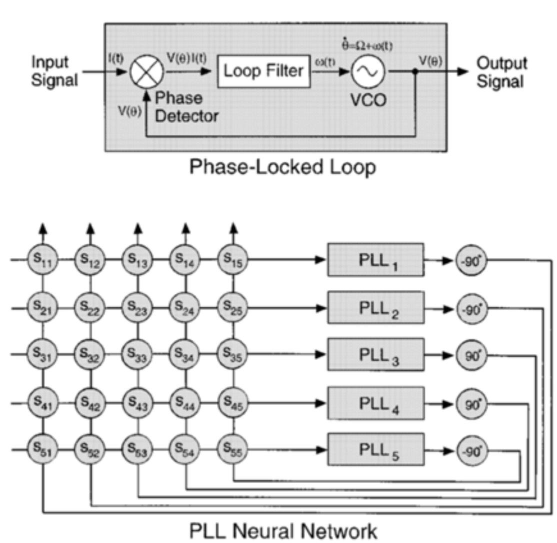
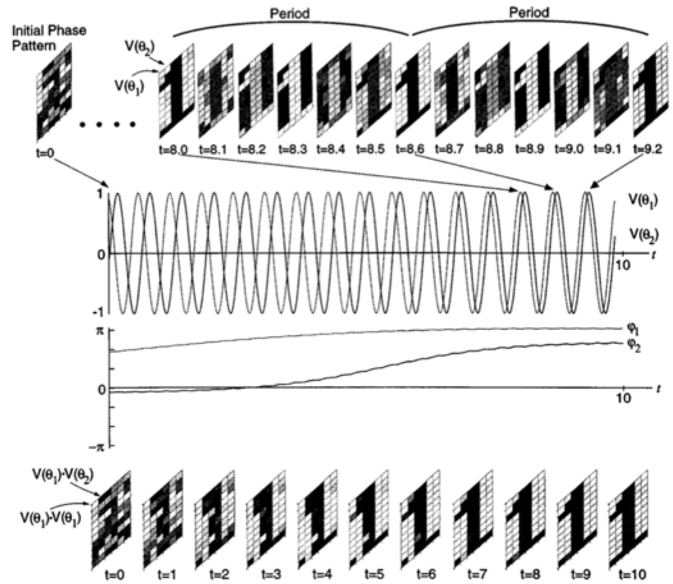
Outline

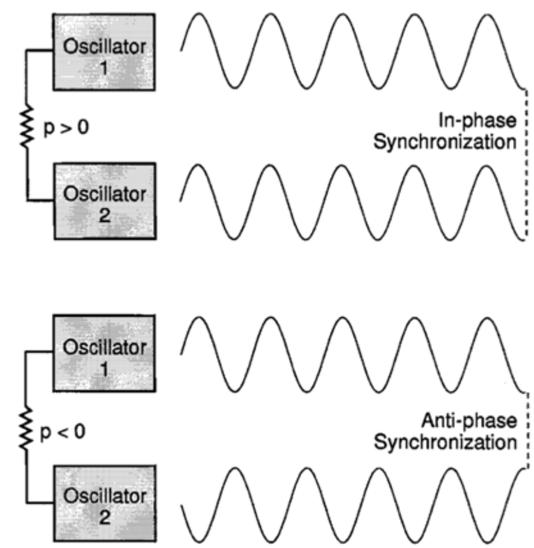
- Introduction and Overview
- Non-CMOS Computation
  - Coupled Nanostructures
- Non-Boolean Computation
  - Coupled Oscillators
  - Neuromorphic Ring Oscillators
  - Spin Waves
- Quantum Computation

Neuromorphic circuits from electrical oscillators

It is well established that oscillators can realize Hopfield-like networks



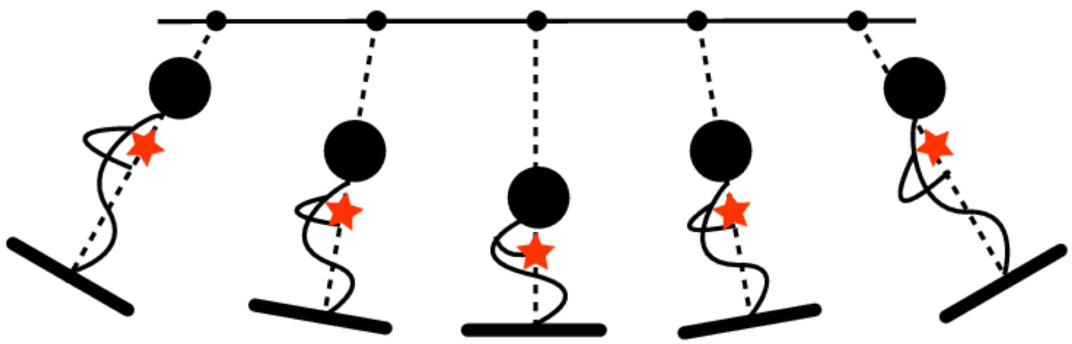




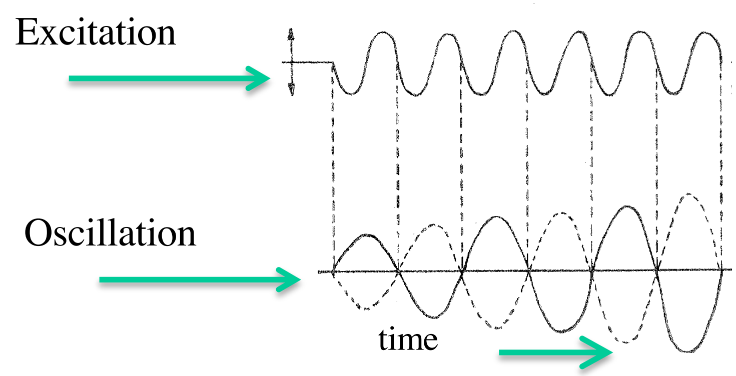
F.C. Hoppensteadt, E.M. Izhikevich, Pattern recognition via synchronization in phase-locked loop neural networks, IEEE Trans. Neural Networks 11 (3) (2000) 734–738.
F.C. Hoppensteadt, E.M. Izhikevich, Synchronization of laser oscillators, associative memory, and optical neurocomputing, Phys. Rev. E 62 (3) (2000) 4010–4013.
F.C. Hoppensteadt, E.M. Izhikevich, Synchronization of MEMS resonators and mechanical neurocomputing, IEEE Trans. Circuits Syst. I Fund. Theory Appl. 48 (2) (2001) 133–138.

This schemes does not well for real oscillators (frequencies are all different, phase noise) – would be better to have a scheme for stabilizing the oscillators.

Parametric oscillators as two-state systems

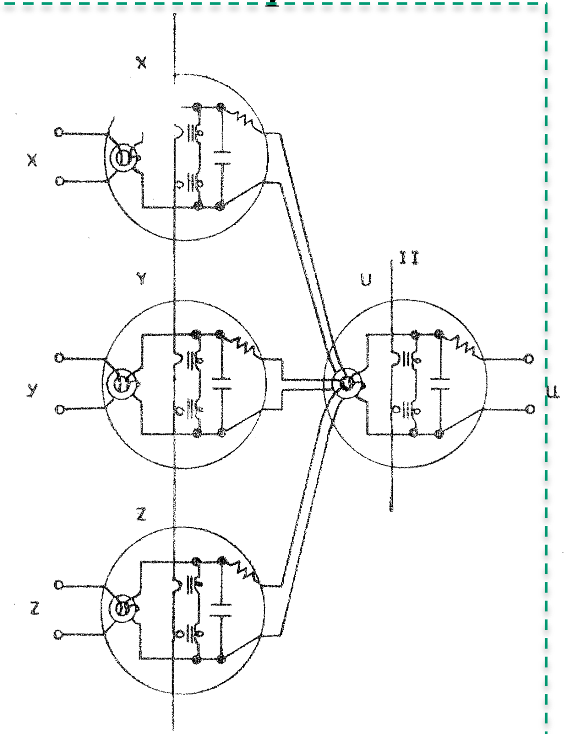


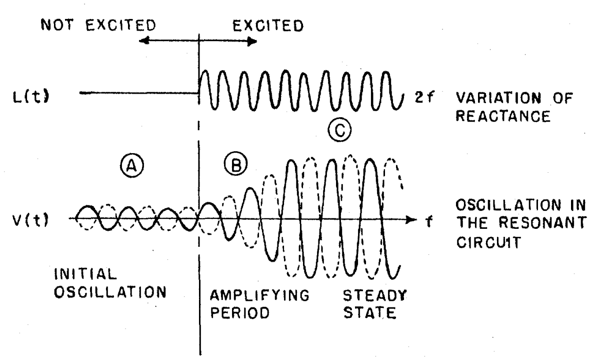
Nation et. al.: arXiv:1103.0835v3 [quant-ph] 12 Jan 2012



Locking may occur in one of two possible phases

Entire computers have been built based on parametric oscillators:

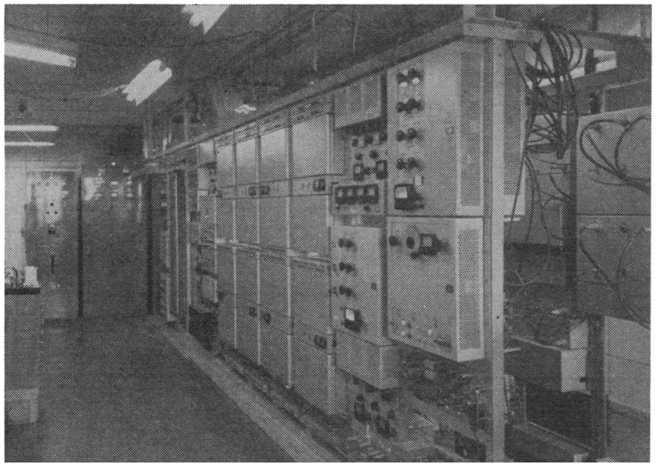




1304 *PROCEEDINGS OF THE IRE*

The Parametron, a Digital Computing Element which Utilizes Parametric Oscillation*

EIICHI GOTO†

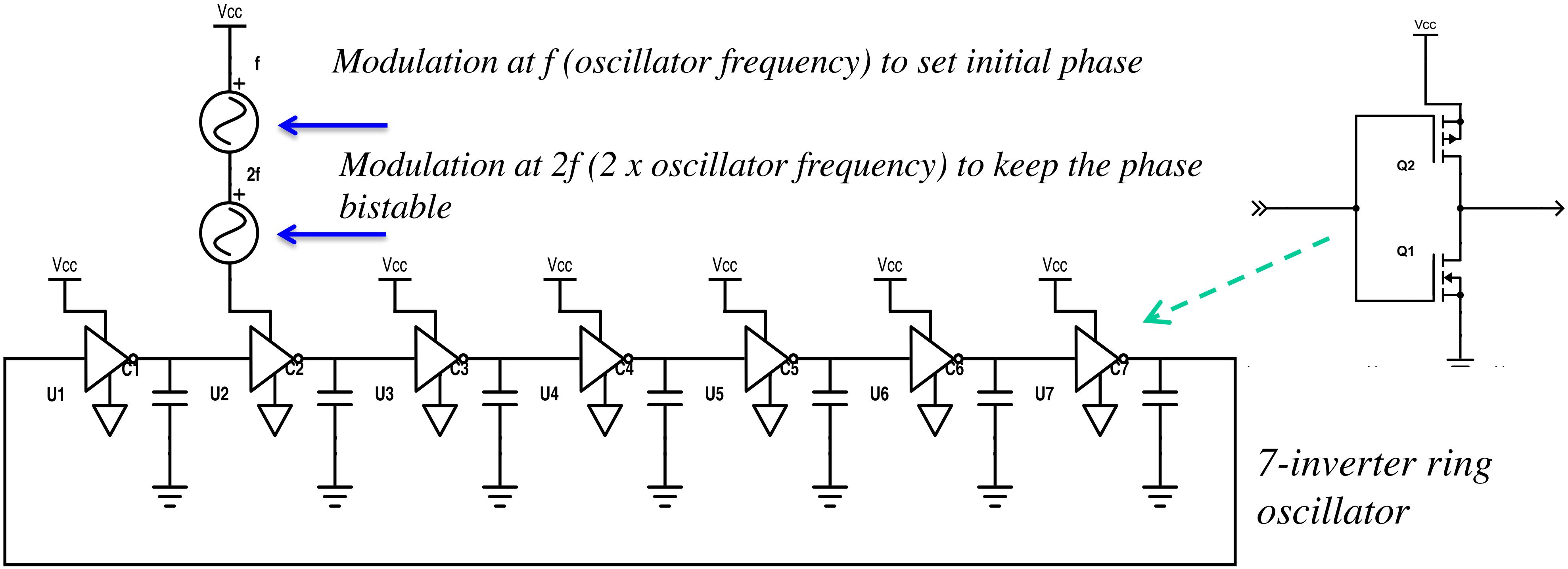


A historical computer based on parametrons

Wigington, R. "A new concept in computing." Proceedings of the IRE 4, no. 47 (1959): 516-523.

Muroga S, Takashima K. The parametron digital computer Musasino-1. Electronic Computers, IRE Transactions on. 1959 Sep(3):308-16.

Subharmonic locking of ring oscillators

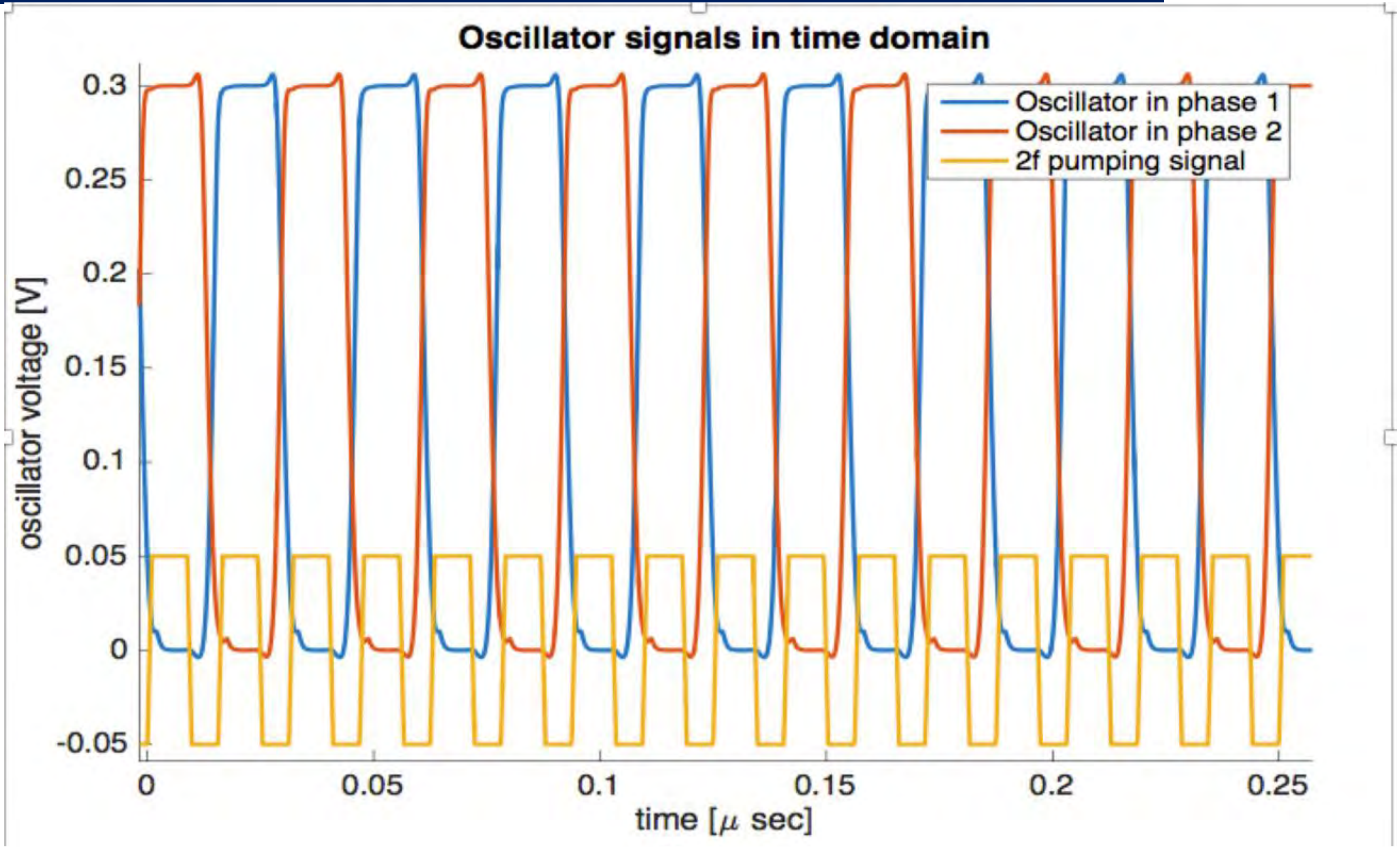


Ring oscillators may work as parametric oscillators, if the power supply of one inverter is modulated. This is lot more practical in a integrated realization than *LC* oscillators.

Trond Ytterdal, *Dept Electron and Telecom, Norwegian University of Science and Technology, Trondheim, Norway*

For a related concept, but with Boolean devices, see: Roychowdhury J. Boolean Computation Using Self-Sustaining Nonlinear Oscillators. Proceedings of the IEEE. 2015 Nov;103(11):1958-69.

Simulation of a single oscillator



- ***Depending on the initial conditions / initial f pumping, the oscillator may oscillate in one or the other phase.***
- ***Oscillators with somewhat different frequencies still remain perfectly in phase***

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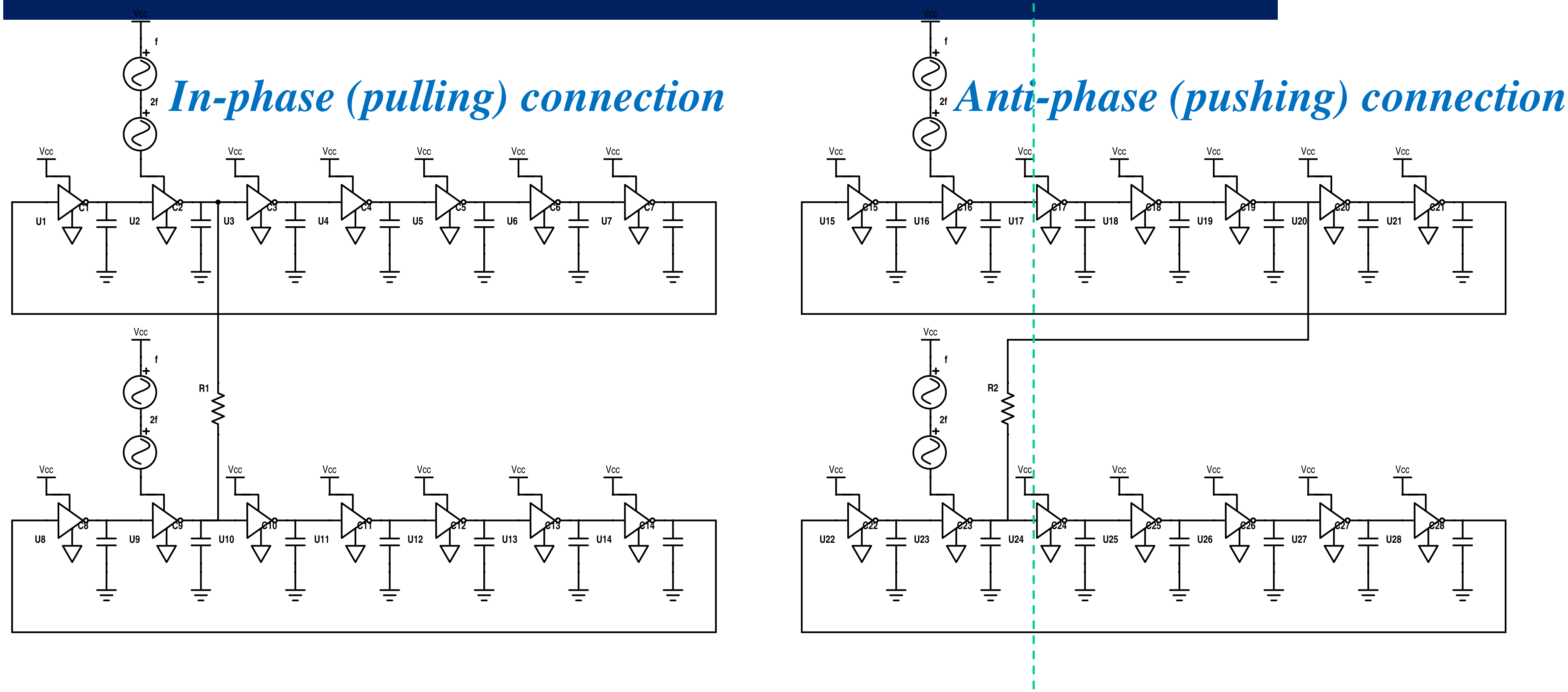
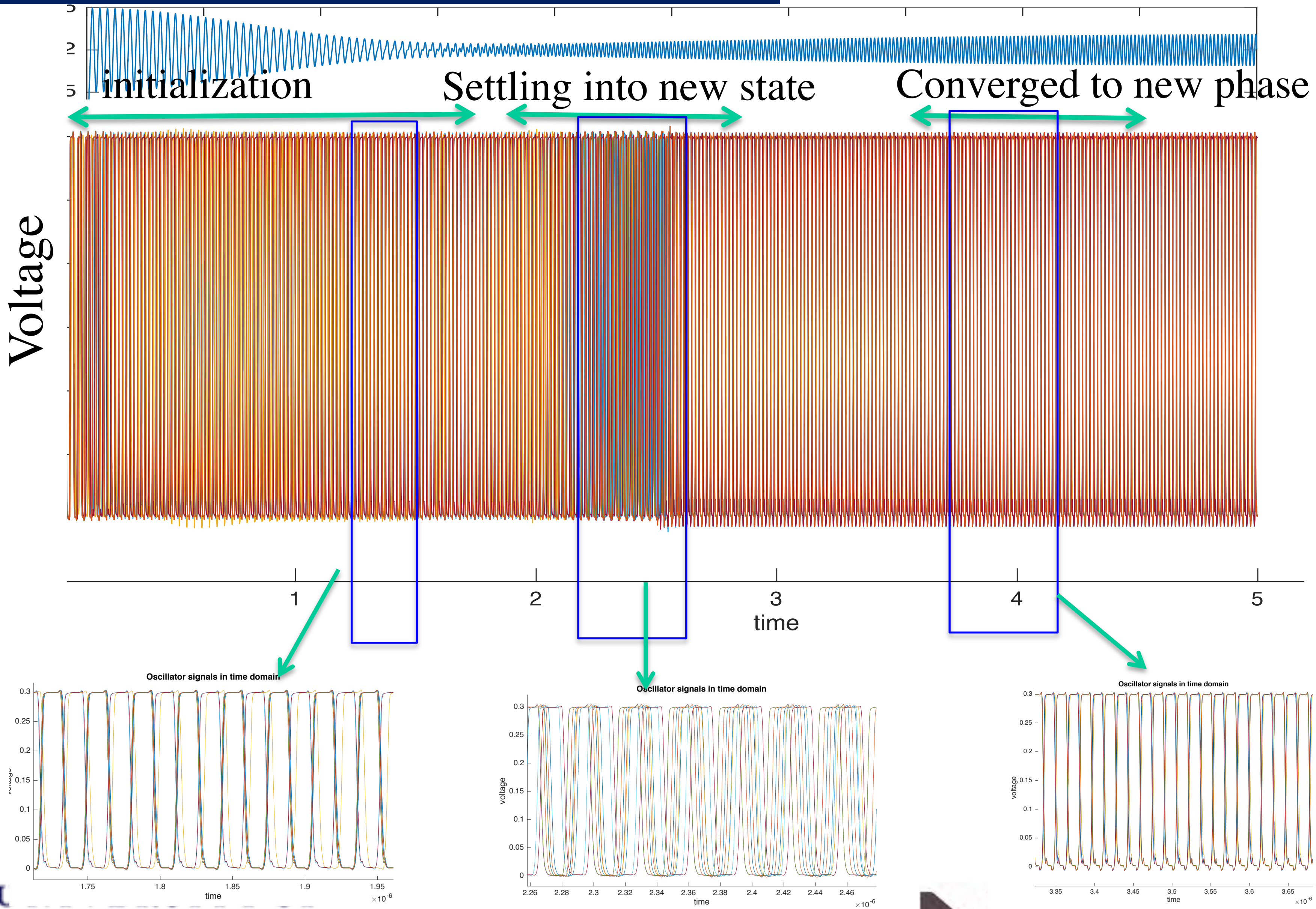
Interconnecting two oscillators



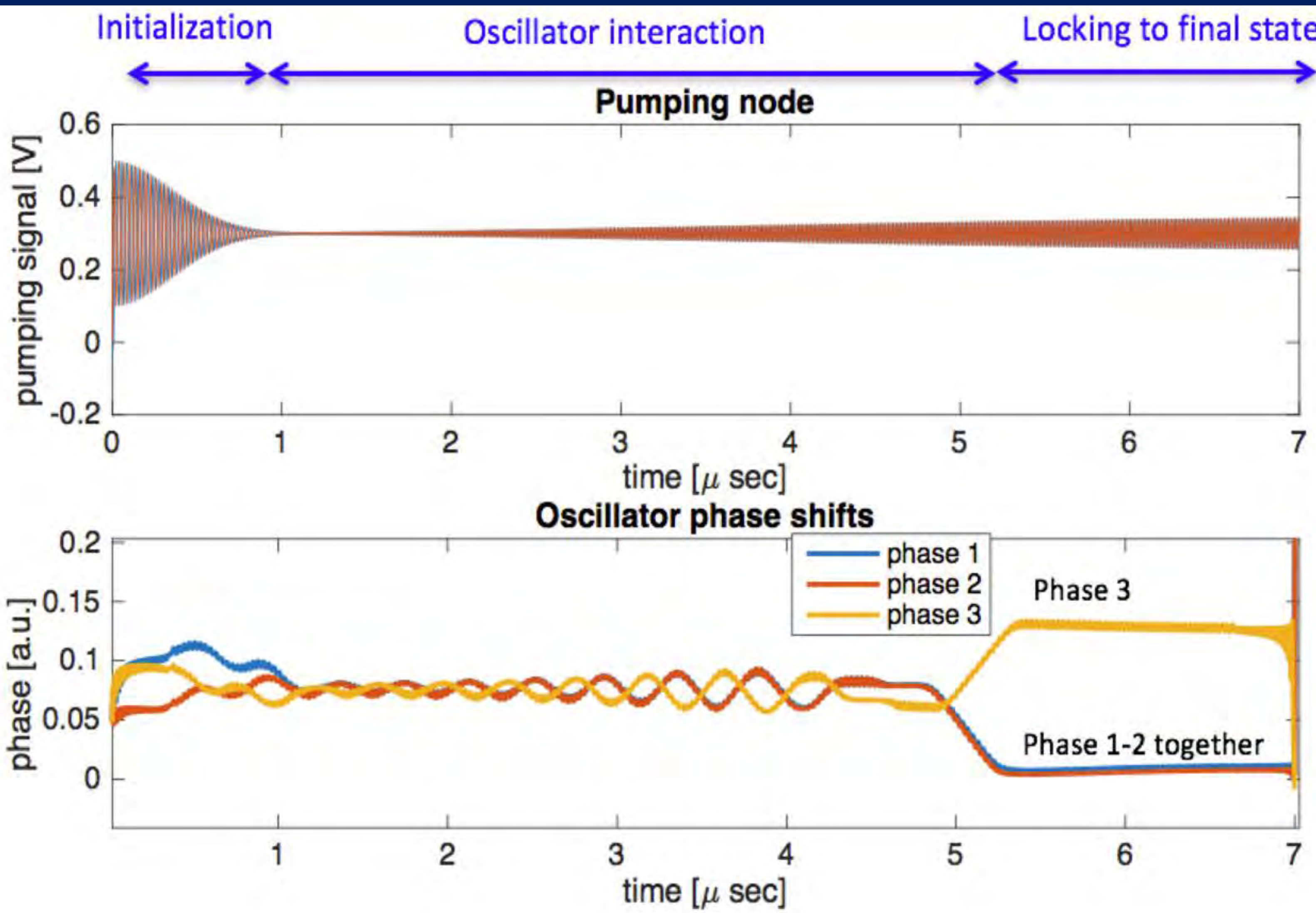
We use a three-stage pumping scheme to put coupled oscillators into ground state:

- **Initialize** the oscillators into a given phase by *f*-pumping
- Let them **push and pull** each others phase and settle
- Use a *2f* scheme to **lock** their phases into one of two possible states

A simulation snapshot



Phase evolution of three coupled oscillators



- Oscillators **1 and 2 pull toward** each other due to in-phase coupling
- Oscillator **3 pushes away from 1 and 2** due to anti-phase coupling

A Hopfield-network-like interconnection scheme

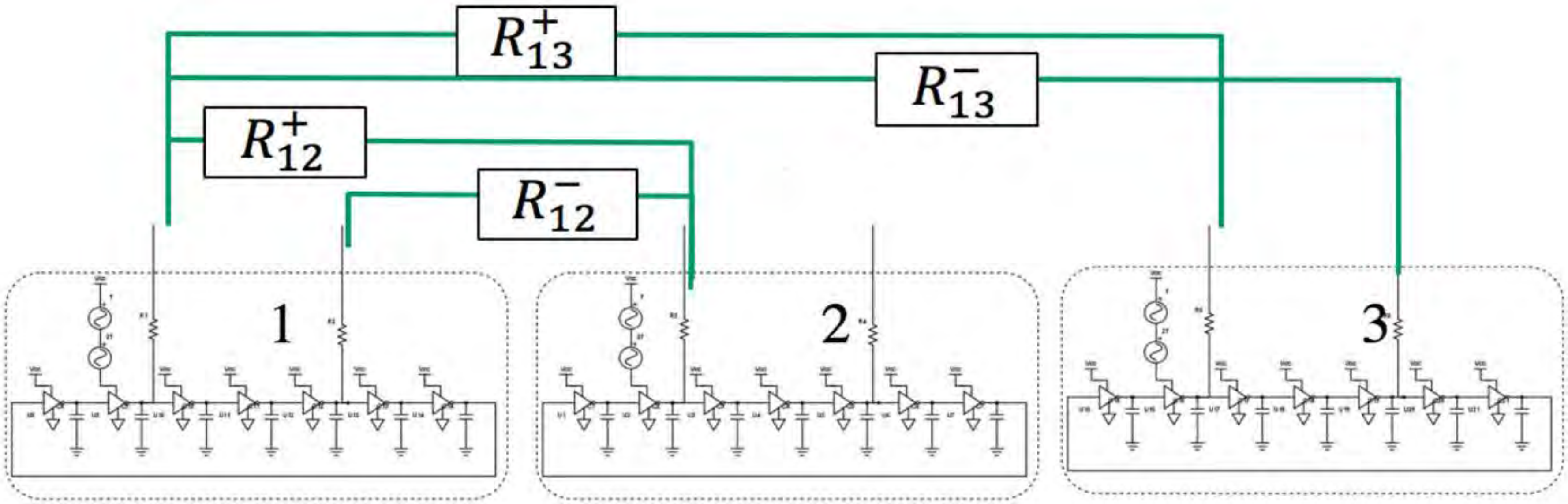


Illustration of connections starting from oscillator 1 to oscillator 2 and 3

According to Hebbian rule, the P_k pattern vectors can be encoded into C_{ij} coupling weights between the oscillators:

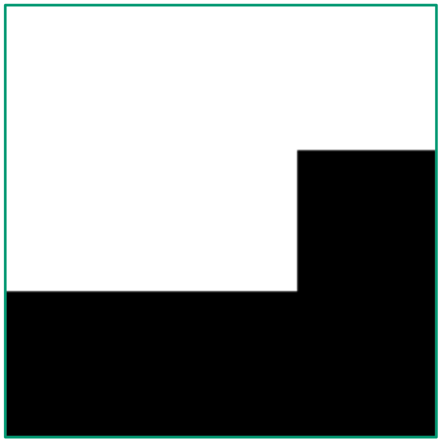
$$C_{ij} = \sum_k P_{k,i} P_{k,j}$$

…and implemented as resistors:

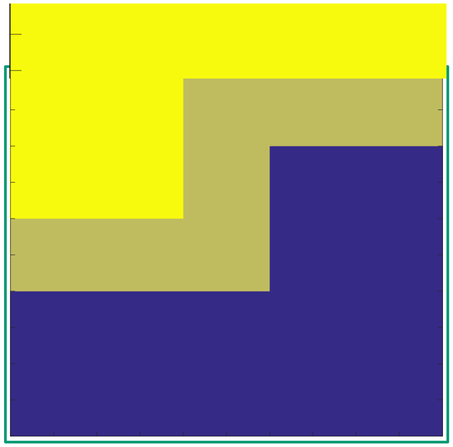
Negative couplings are positive resistors between **pushing** nodes.
Positive couplings are positive resistors between **pulling** nodes.

$$R_{ij} = \left|\frac{1}{C_{ij}}\right| R_{scale}$$

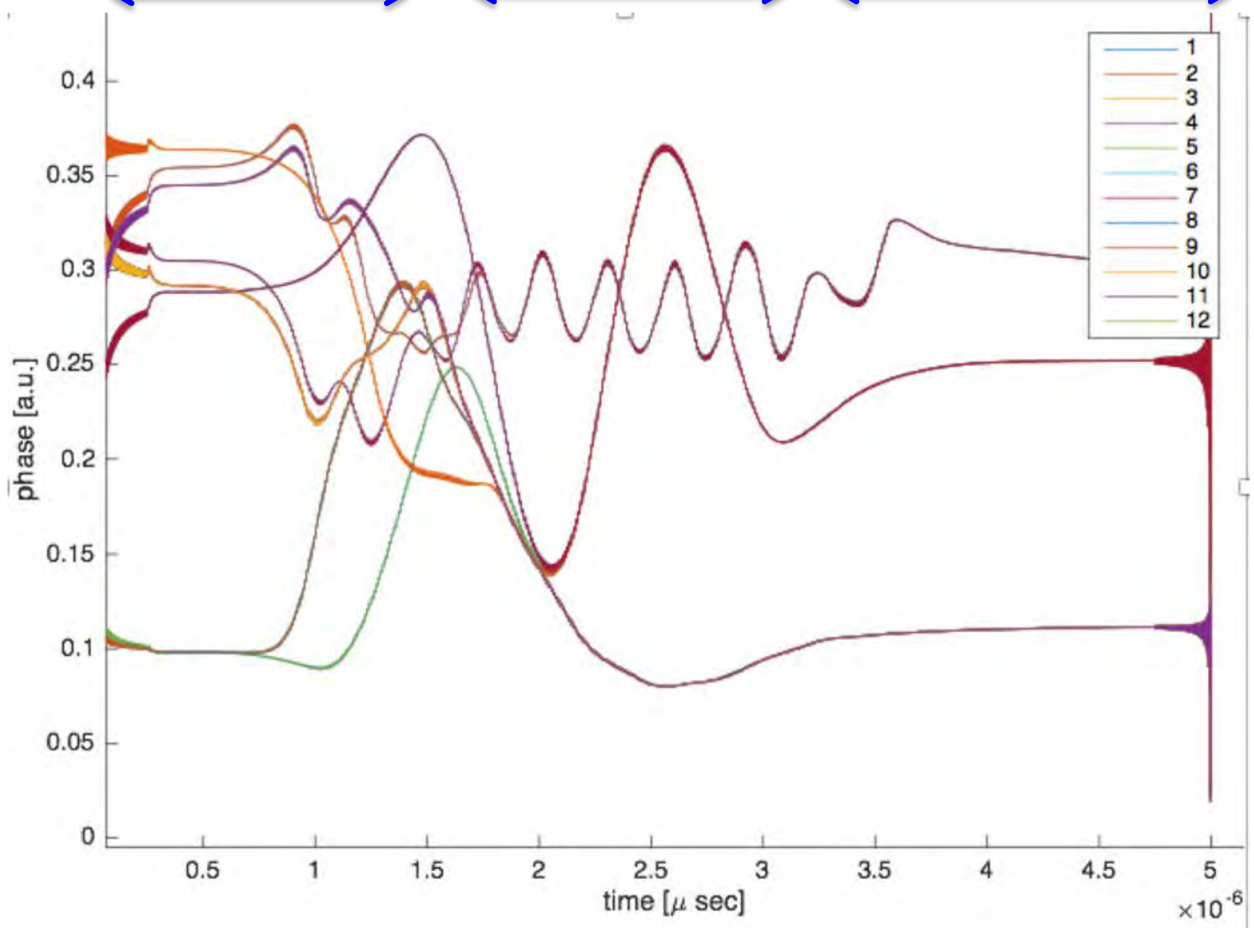
Convergence to a 4x4 image



Programmed phase pattern



Converged phase pattern



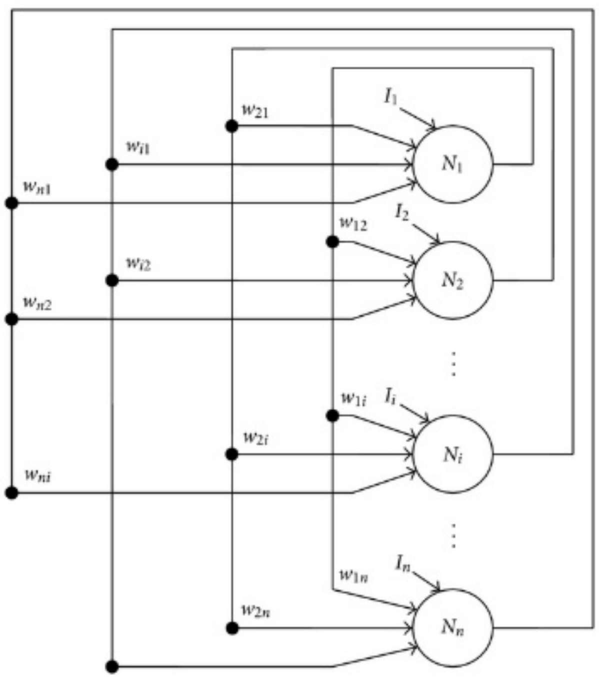
Csaba, György, Trond Ytterdal, and Wolfgang Porod. "Neural network based on parametrically-pumped oscillators." In Electronics, Circuits and Systems (ICECS), 2016 IEEE International Conference on, pp. 45-48. IEEE, 2016.

Physical limits of neuromorphic computation

For conventional, binary computation, it is widely accepted that computation requires at least kT energy per operation

For neuromorphic / non-Boolean computation, it is not clear what operation means

- **So we look at dynamic computing devices and adding noise models**
- **Johnson-Nyquist noise in the interconnection network**
- **Basic Hopfield model for case study**



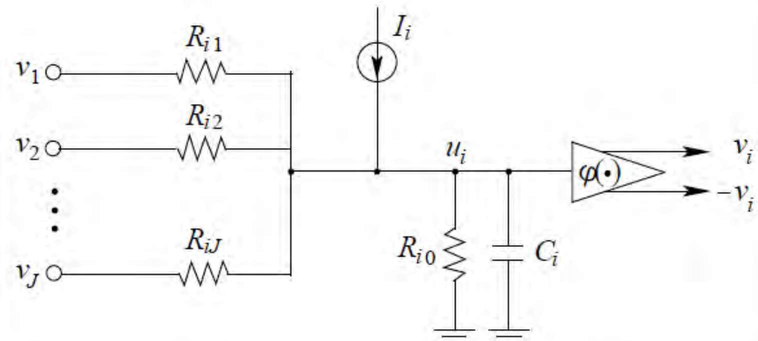


Figure 2: A circuit for neuron i in the Hopfield model. $w_{ji} = 0$ is the output voltage of neuron $\vec{\phi}(.)$ is the external bias current source for neuron $\vec{\theta}$ is the voltage at the interconnection point, C_i is a capacitor, and $R_{ik}, k = 0,1,...,J$ are resistors. The sigmoidal function $\phi(.)$ is used as the transfer function of the amplifiers.

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Journal of Information Technology & Software Engineering

Wang et al. J Inform Tech Soft Engg 2011, 1:2
DOI: 10.4172/2165-7866.1000104

Review Article Open Access

Recurrent Neural Networks: Associative Memory and Optimization

Hui Wang[1], Yue Wu[1], Biaobiao Zhang[1] and K. -L. Du[1,2*]

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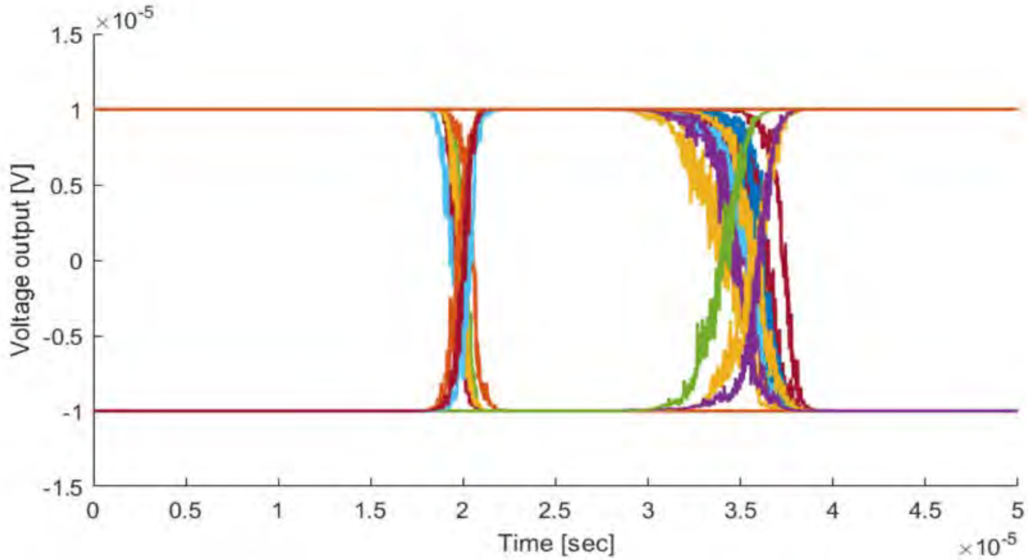
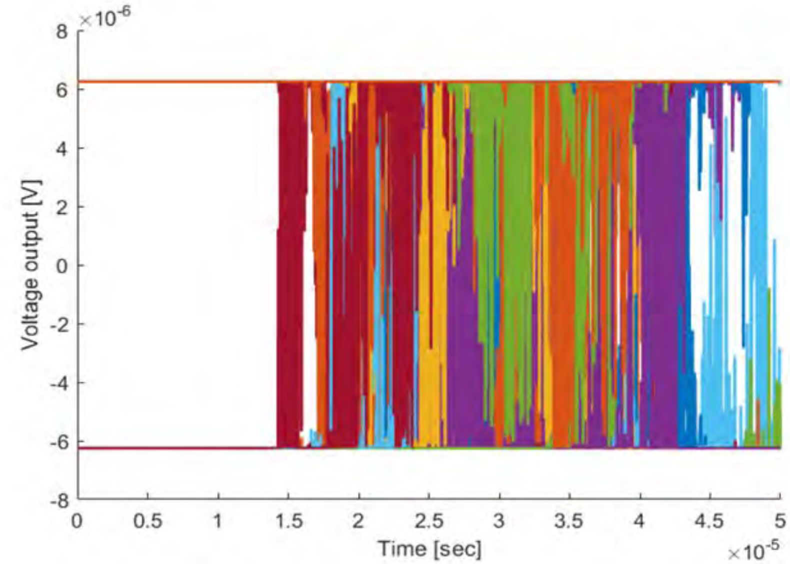
Behavior of Hopfield networks in the presence of noise

Network dynamics at $T = 10\ \mathrm{K}, V_{dd} = 10\ \mu\mathrm{V}$



Network dynamics at $T = 300\ \mathrm{K}, V_{dd} = 6.\ \mu\mathrm{V}$



a back of envelope calculation for the just working case:

$$V = 6\ \mu V, R = 250\ k\Omega, \qquad \Delta t = 50\ \mu s \ \rightarrow\ P = \frac{V^2}{R} \ \rightarrow W = P\times t = 7\times 10^{-21} J = 1.7\ k_{Boltzmann}T$$

The numbers seem reasonable – each resistor dissipates roughly 1.7 $k_B T$ energy during the operation.

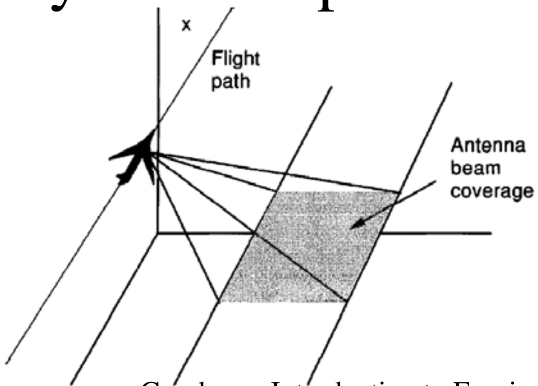
Lesson: Highly interconnected networks are not that great at very low powers…
each interconnection has to dissipate at least kT over the course of the computation…
that adds up to a lot in the case of a fully-interconnected static Hopfield network.

Outline

- Introduction and Overview
- Non-CMOS Computation
  - Coupled Nanostructures
- Non-Boolean Computation
  - Coupled Oscillators
  - Neuromorphic Ring Oscillators
  - Spin Waves
- Quantum Computation

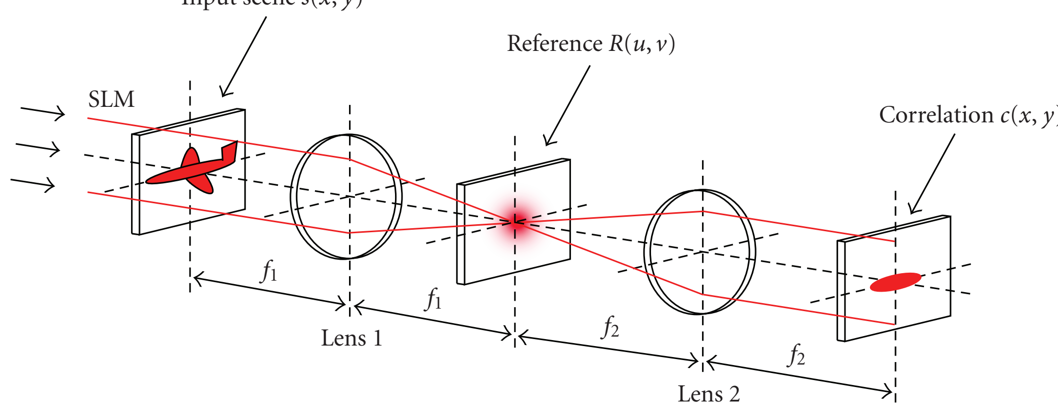
Optical computing

Synthetic-aperture radar



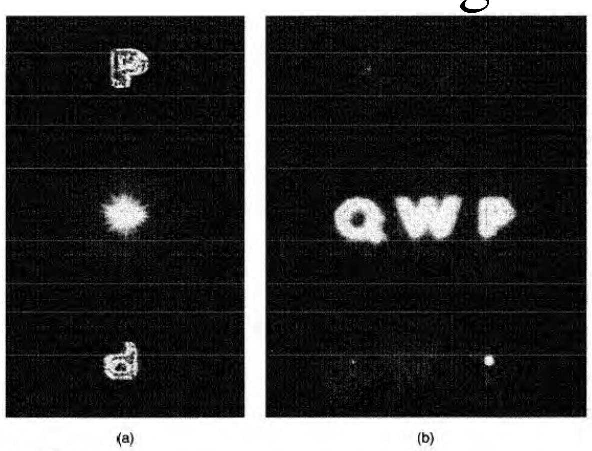
Goodman, Introduction to Fourier optics

4-f correlator



Pierre Ambs, "Optical Computing: A 60-Year Adventure," Advances in Optical Technologies, vol. 2010, Article ID 372652, 15 pages, 2010.

Character recognition

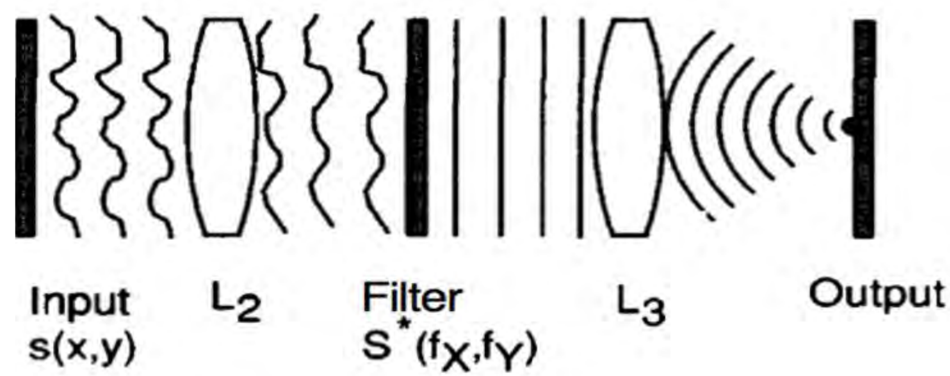


(a) (b)

FIGURE 8.19
Photographs of (a) the impulse response of a VanderLugt filter, and (b) the response of the matched filter portion of the output to the letters Q, W, and P.

Goodman, Introduction to Fourier optics

Matched filter



Goodman, Introduction to Fourier optics

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Why Spin Waves?

PRO

- Wavelength and frequencies compatible will nanoelectronics: 30-100nm, 10-25 GHz
- Spin waves can be generated, detected and manipulated electrically
- Material set compatible with modern nanoelectronics
- Low voltage and current ~10-20 mV, 10-100 μA
- Nonlinear collective effects useful for convolution integrals

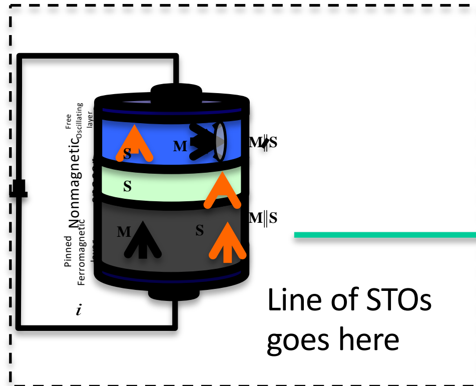
CON

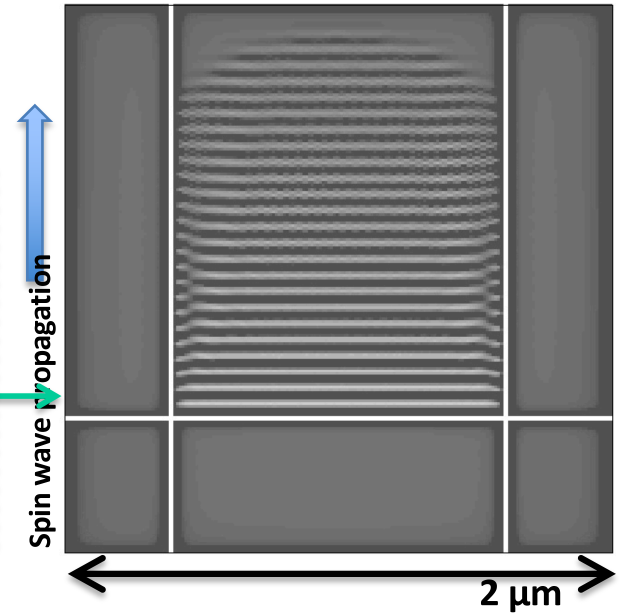
- Spin wave damping lengths ~1 μm
- Scattering and device variation
- Nonlinear effects poorly understood
- An immature but rapidly developing technology

Components for 'Spin-Wave Optics'

1: Coherent sources

Spin-torque oscillators are a well-established technology and has been used to create spin-waves in many experiments. In our studies we used a ~20 GHz AC current to drive the STOs – this keeps the wavefront coherent.

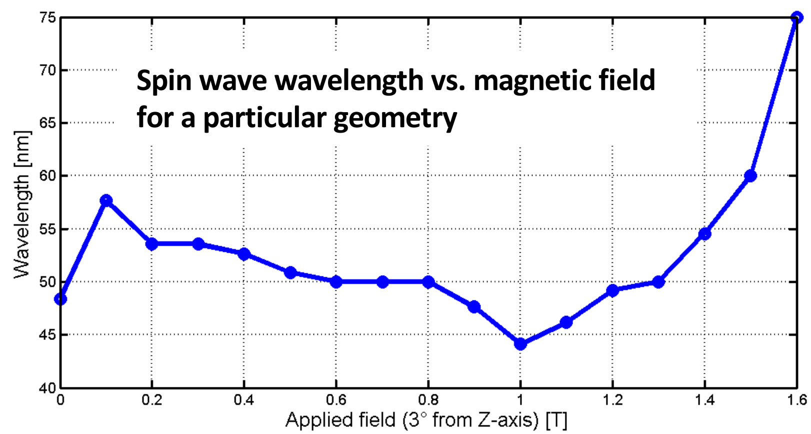




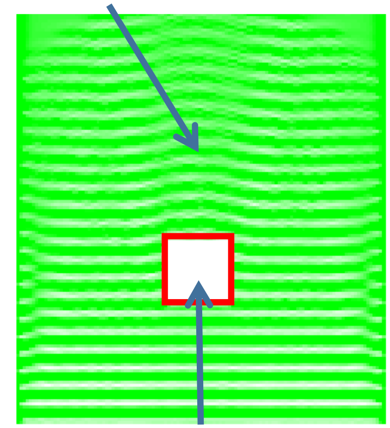
The device can be given a vector input by a series of STOs

2: Phase shifters

A localized magnetic field changes the wavelength of the spin wave – we characterized this by micromagnetic simulations. A certain magnetic field corresponds to a certain n refractive index over a region and one can use this analogy to design 'spin wave optic' devices.



Phase shifted spin waves



Localized magnetic field

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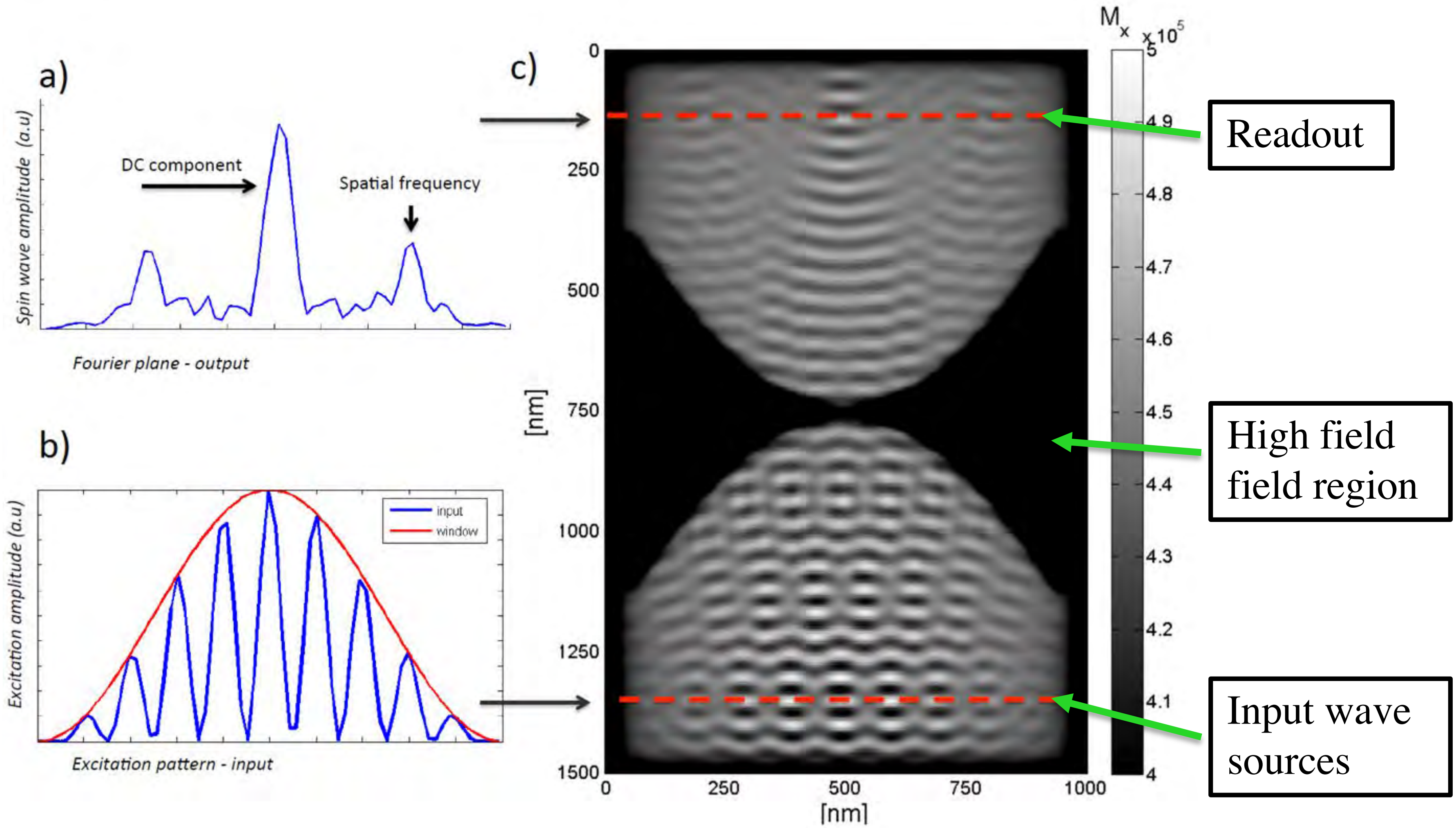
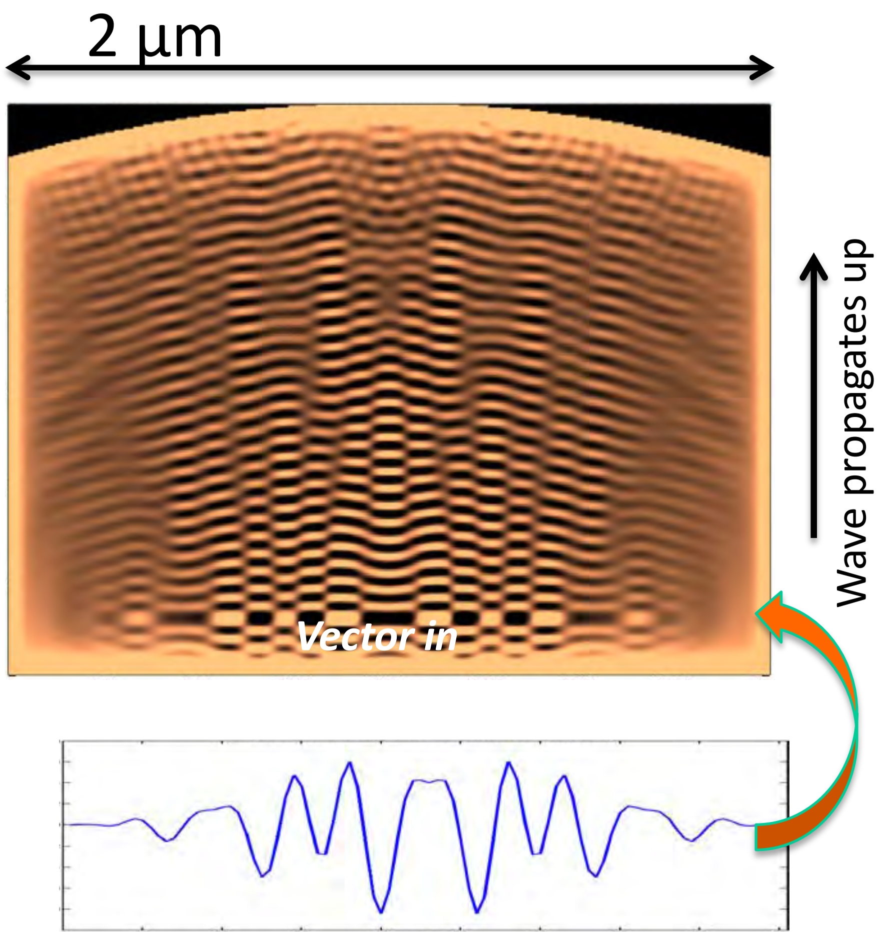
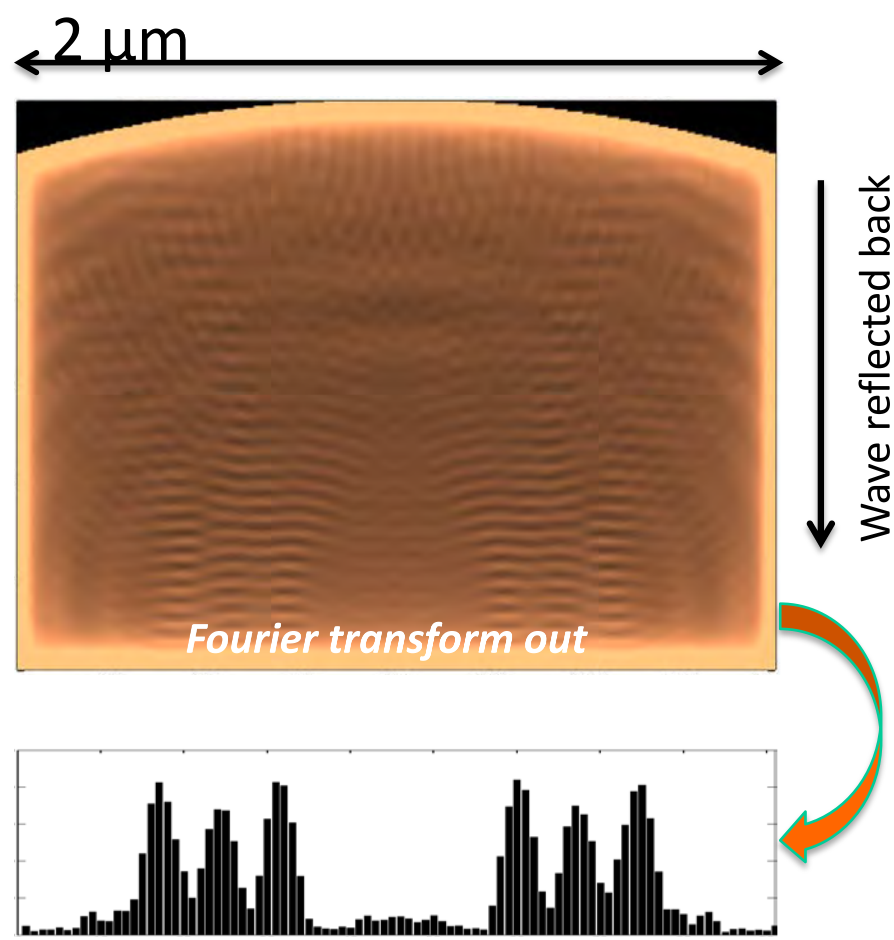
Spin-Wave Lens and Fourier Transform



G. Csaba, A. Papp, and W. Porod, "Spin-wave based realization of optical computing primitives," *Journal of Applied Physics*, vol. 115, no. 17, p. 17C741, May 2014.

Spin-Wave Mirror and Fourier Transform





- Input vector is is used as a boundary condition (to excite the STOs).
- The amplitude of 64 oscillators represents the input vector

- The pulse train that arrives back represents the Fourier transform (both amplitude and phase)

SCIENTIFIC REPORTS

OPEN

Nanoscale spectrum analyzer based on spin-wave interference

Ádám Papp[1,2], Wolfgang Porod[1], Árpád I. Csurgay[2] & György Csaba[1,2]

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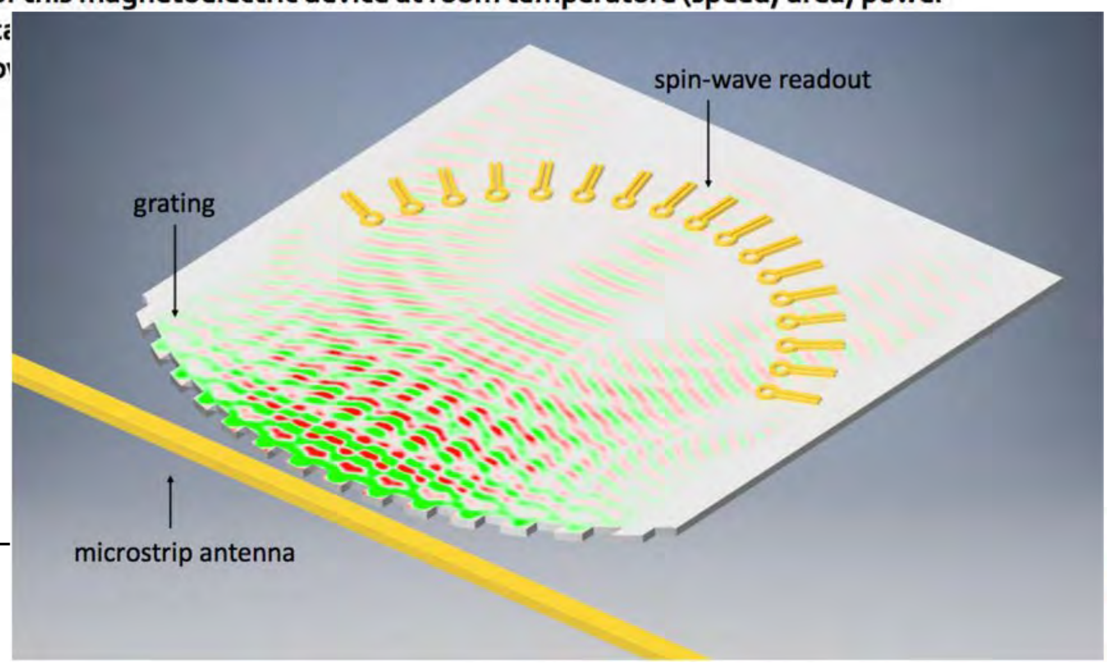
We present the design of a spin-wave-based microwave signal processing device. The microwave signal is first converted into spin-wave excitations, which propagate in a patterned magnetic thin-film. An interference pattern is formed in the film and its intensity distribution at appropriate read-out locations gives the spectral decomposition of the signal. We use analytic calculations and micromagnetic simulations to verify and to analyze the operation of the device. The results suggest that all performance figures of this magnetoelectric device at room temperature (speed, area, power consumption) may be significa
envision that a new class of lo
spin-waves.



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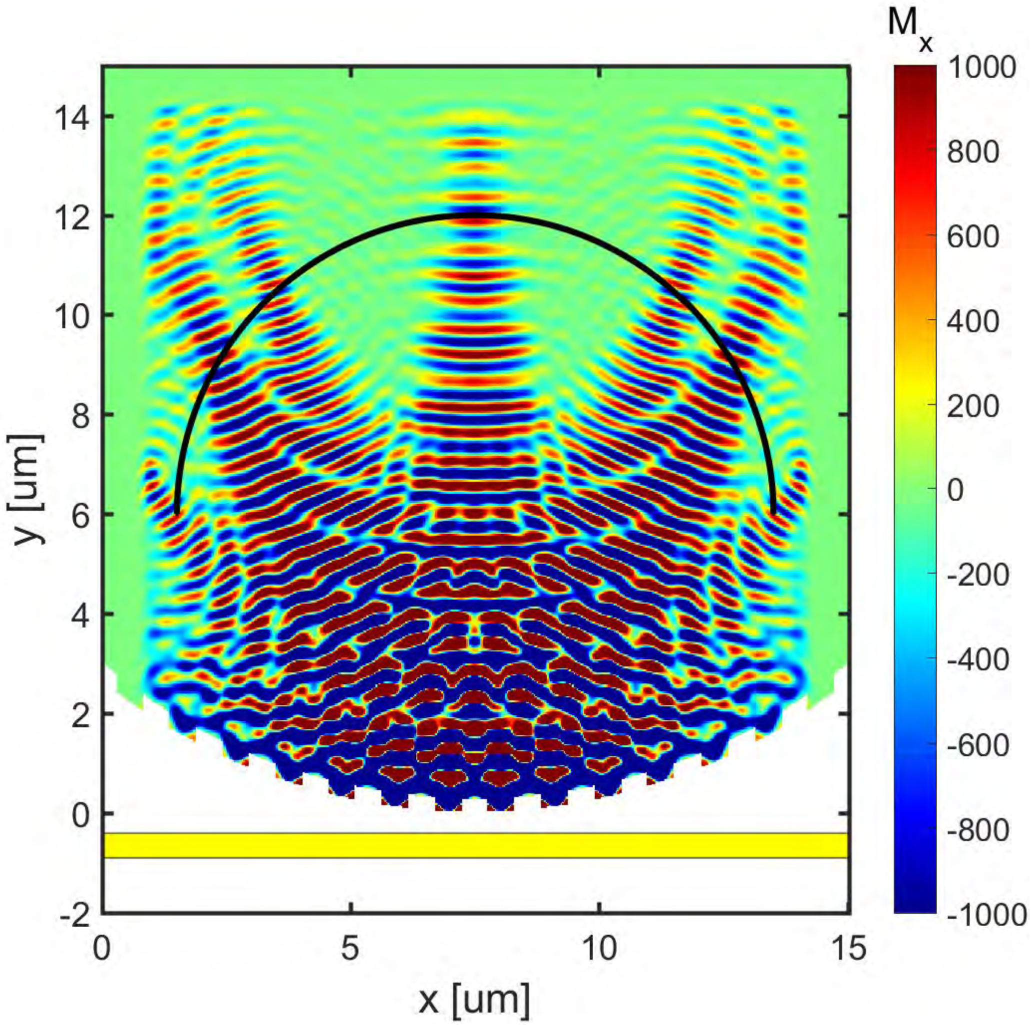
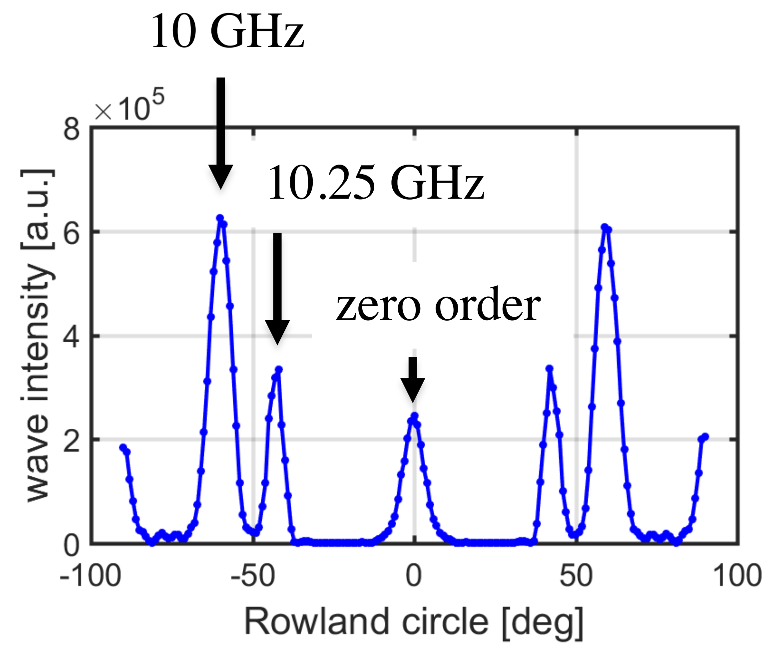
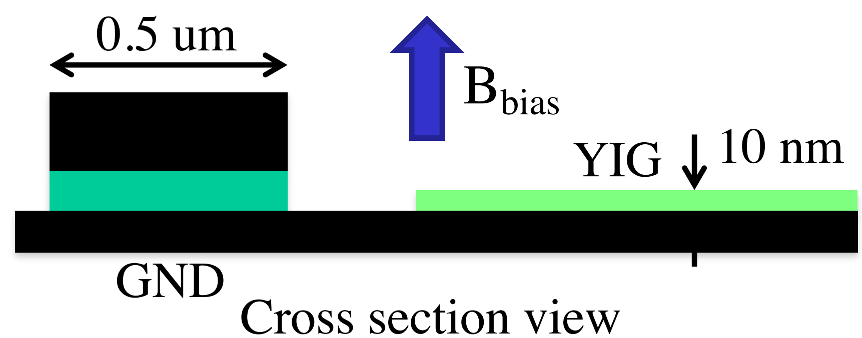
Spin-wave diffraction (simulation)







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Design of a 40-nm CMOS integrated on-chip oscilloscope for 5-50 GHz spin wave characterization

Eugen Egel,[1, a)] György Csaba,[2] Andreas Dietz,[1] Stephan Breitkreutz-von Gamm,[1] Johannes Russer,[3] Peter Russer,[3] Franz Kreupl,[1] and Markus Becherer[3]

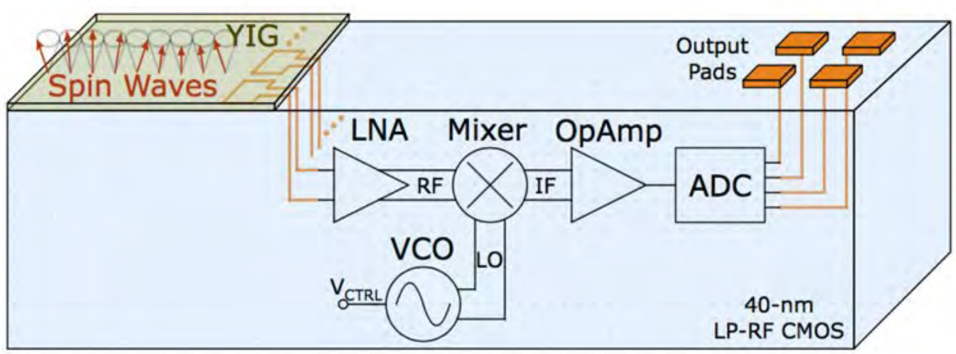
[1)] *Chair of Technical Electronics, Technical University of Munich, Munich, Germany*

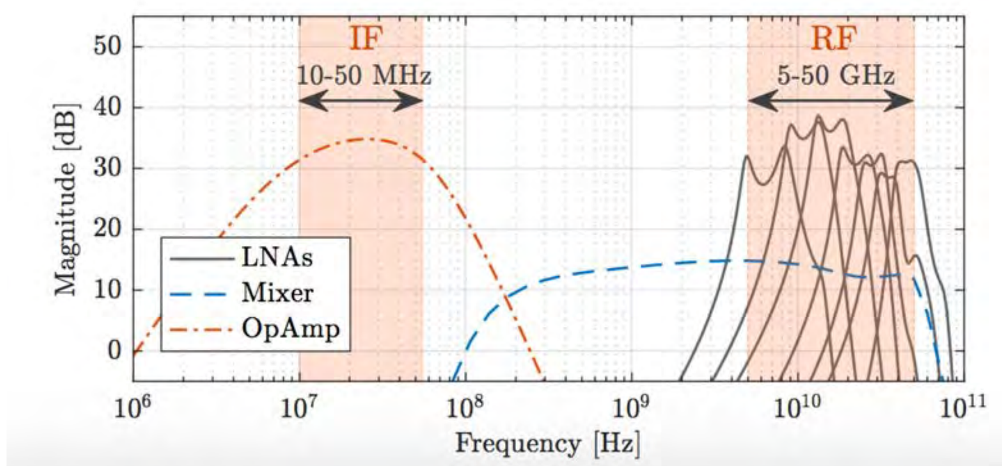
[2)] *Faculty of Information Technology and Bionics, Pázmány Péter Catholic University, Budapest, Hungary*

[3)] *Chair of Nanoelectronics, Technical University of Munich, Munich, Germany*

(Dated: 1 October 2017)

Spin wave (SW) devices are receiving growing attention in research as a strong candidate for low power applications in the beyond-CMOS era. All SW applications would require an efficient, low power, on-chip read-out circuitry. Thus, we provide a concept for an on-chip oscilloscope (OCO) allowing parallel detection of the SWs at different frequencies. The readout system is designed in 40-nm CMOS technology and is capable of SW device characterization. First, the SWs are picked up by near field loop antennas, placed below yttrium iron garnet (YIG) film, and amplified by a low noise amplifier (LNA). Second, a mixer down-converts the radio frequency (RF) signal of $5-50\,\text{GHz}$ to lower intermediate frequencies (IF) around $10-50\,\text{MHz}$. Finally, the IF signal can be digitized and analyzed regarding the frequency, amplitude and phase variation of the SWs. The power consumption and chip area of the whole OCO are estimated to $166.4\,\text{mW}$ and $1.31\,\text{mm}^2$, respectively.





Outline

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  - Spin Waves
- Quantum Computation

Classical Computer

Representation of Information by classical 2-State System

- Switch, magnetization direction, presence/absence of charge

Single Bit: $(\uparrow), (\downarrow)$

- 2^1 possible states

Two Bits: $(\uparrow\uparrow), (\uparrow\downarrow), (\downarrow\uparrow), (\downarrow\downarrow)$

- 2^2 possible states

N Bits: String of N $(\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\ldots)$

- 2^N possible states

Quantum Computer

Representation of Information by quantum 2-State System

- Electronic spin, quantum dot, impurity atom

Single Qubit: 2^1 basis states $|\uparrow\rangle$, $|\downarrow\rangle$

- Superposition states $\psi = a\,|\uparrow\rangle + b\,|\downarrow\rangle$
- Complex amplitudes a, b with $|a|^2 + |b|^2 = 1$
- Continuum of states

Two Qubits: 2^2 basis states $|\uparrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\downarrow\downarrow\rangle$

- Superposition $\psi = a\,|\uparrow\uparrow\rangle + b\,|\uparrow\downarrow\rangle + c\,|\downarrow\uparrow\rangle + d\,|\downarrow\downarrow\rangle$
- Amplitudes a, b, c, d with $|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$

N Qubits : String of N $|\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\ldots\rangle$

- 2^N basis states and complex amplitudes

Classical vs Quantum

In a classical computer with N bits:

- Its state at any given time is one of 2^N discrete states
- State is described by N integers
- Information is processed by controlled transition between states, one bit at a time

In a quantum computer with N qubits:

- Its state at any given time is in a superposition of 2^N basis states
- State is described by 2^N complex amplitudes
- Information is processed by unitary transformations (quantum gates) that change these amplitudes in a controlled manner

How many qubits are needed?

Common estimate is N = 1000 qubits

- Information qubits, without error correction
- With error correction, increases by factor of 100

Quantum state described by $2^{1000} \sim 10^{300}$ complex amplitudes

- This is a VERY large number
- Number of particles in whole universe $\sim 10^{80}$

Quantum computer is an analog machine with a super-astronomical number of degrees of freedom, which are continuous parameters that need to be controlled precisely

So, when will we have a useful quantum computer?

The experts say …

- Optimistic expert: In 10 years
- Moderate expert: In 20 to 30 years
- Cautious expert: Not in my lifetime

Michel Dyakonov: When we learn to control quantum states with 2^{1000} complex analog amplitudes (which means Never)

Günter Mahler: Quantum computers are attractive because they do not suffer from the exponential increase in algorithmic complexity, as classical computers do. However, they likely suffer from an exponential increase in hardware complexity, which classical (digital) computers do not.

Let Physics do the Computing!

Thank You!