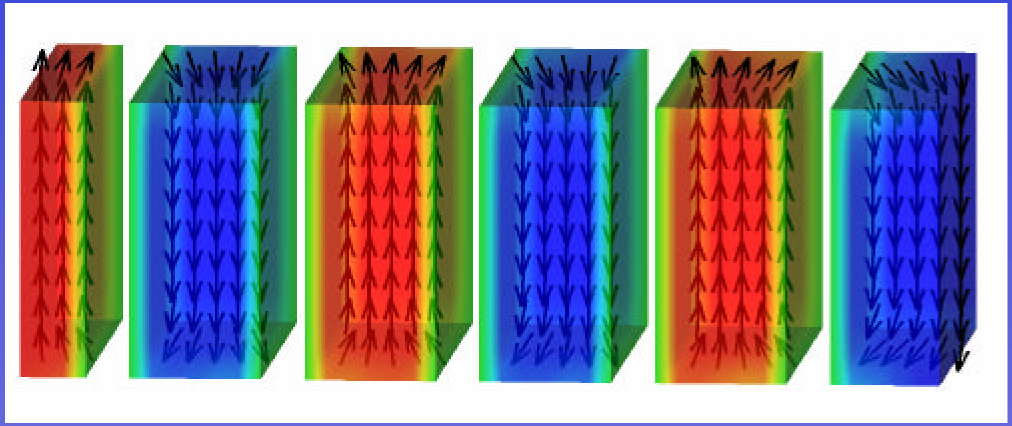
Simulation of Power Gain and Dissipation in Field-Coupled Nanomagnets



G. Csaba, A. Csurgay, P. Lugli and W. Porod

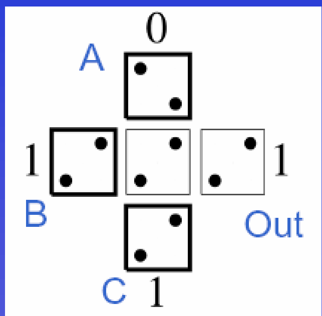
University of Notre Dame

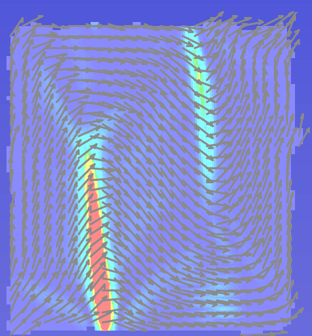
Center for Nano Science and Technology

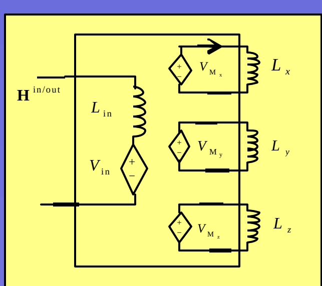
Technische Universität München

Lehrstühl für Nanoelektronik

Outline

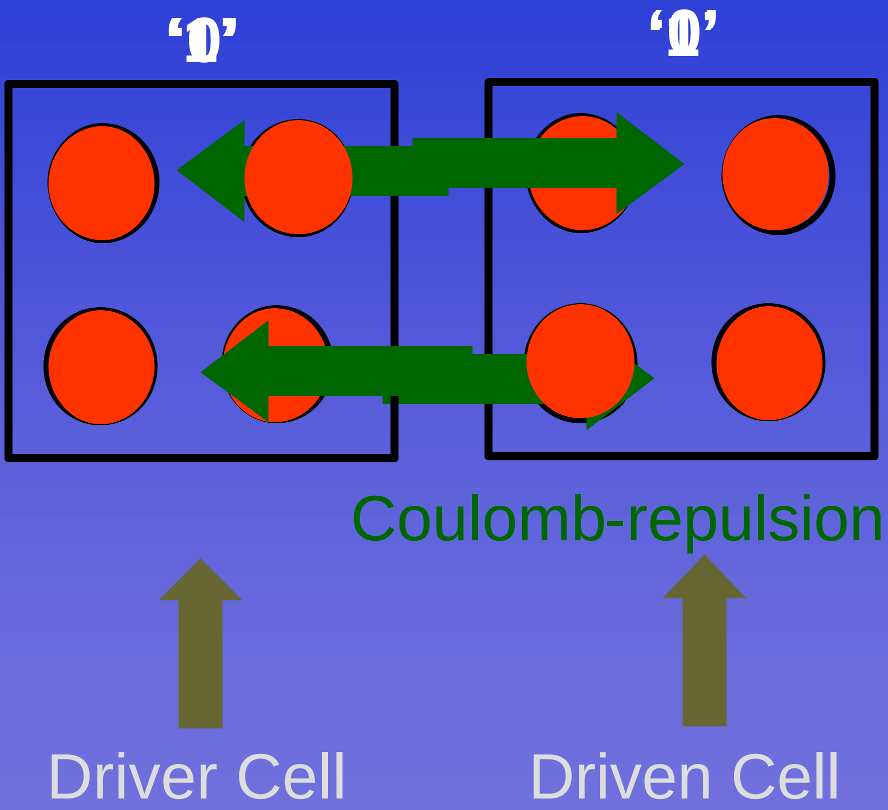






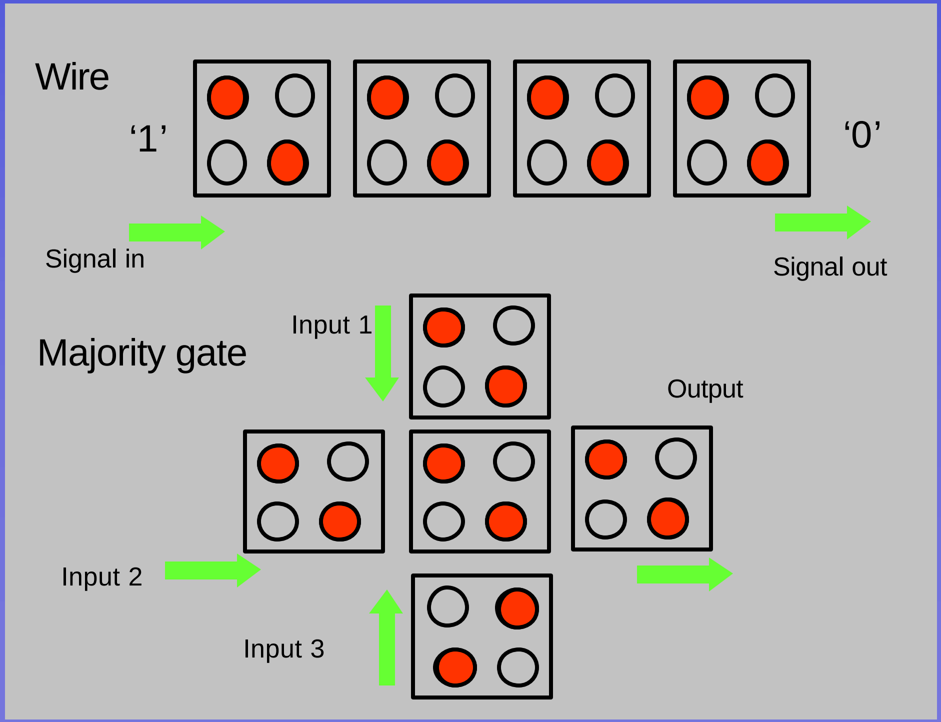
- The Magnetic Quantum Cellular Automata Concept
- Power Dissipation in Nanoscale Magnets
- Power Gain in Nanoscale Magnets

The Quantum Cellular Automata



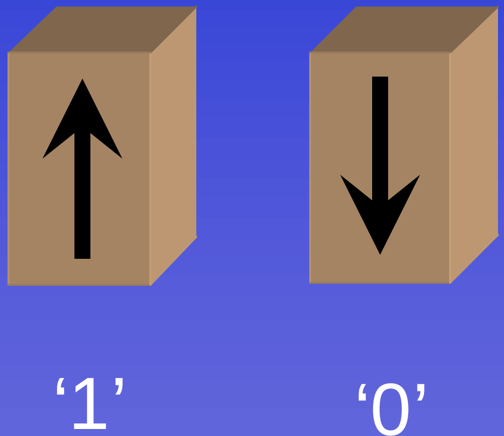
Main idea: Interconnection by stray fields

By changing the geometry one can perform logic functions as well

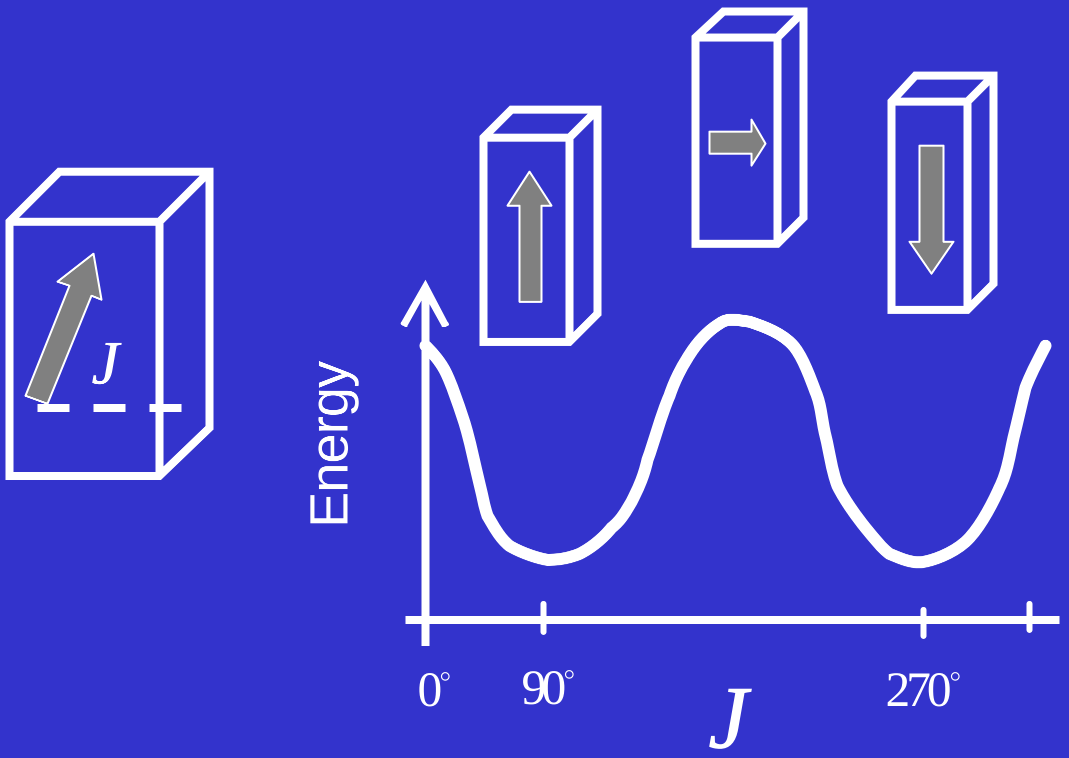


Magnetic Nanopillars

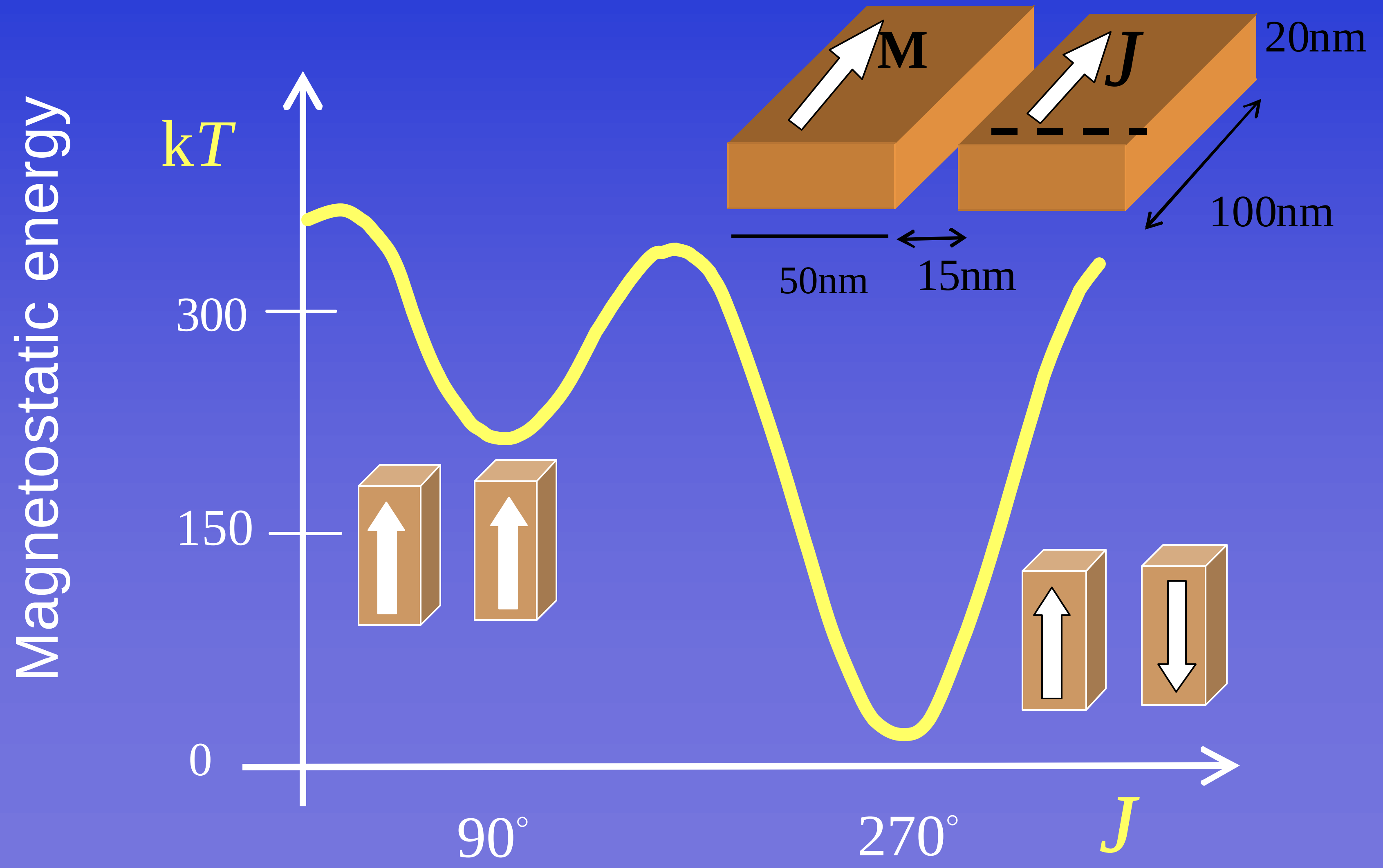
Bistable switch:



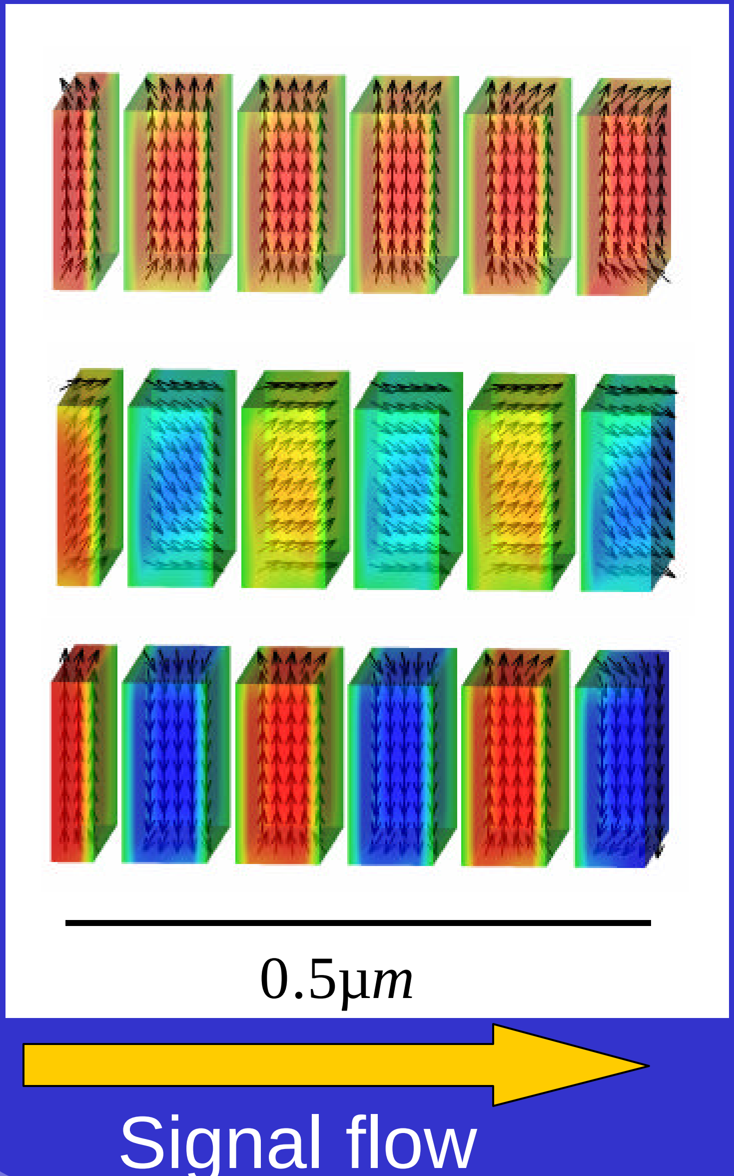
Due to shape anisotropy there is a typically few hundred room-temperature kT energy barrier between the two stationary states.

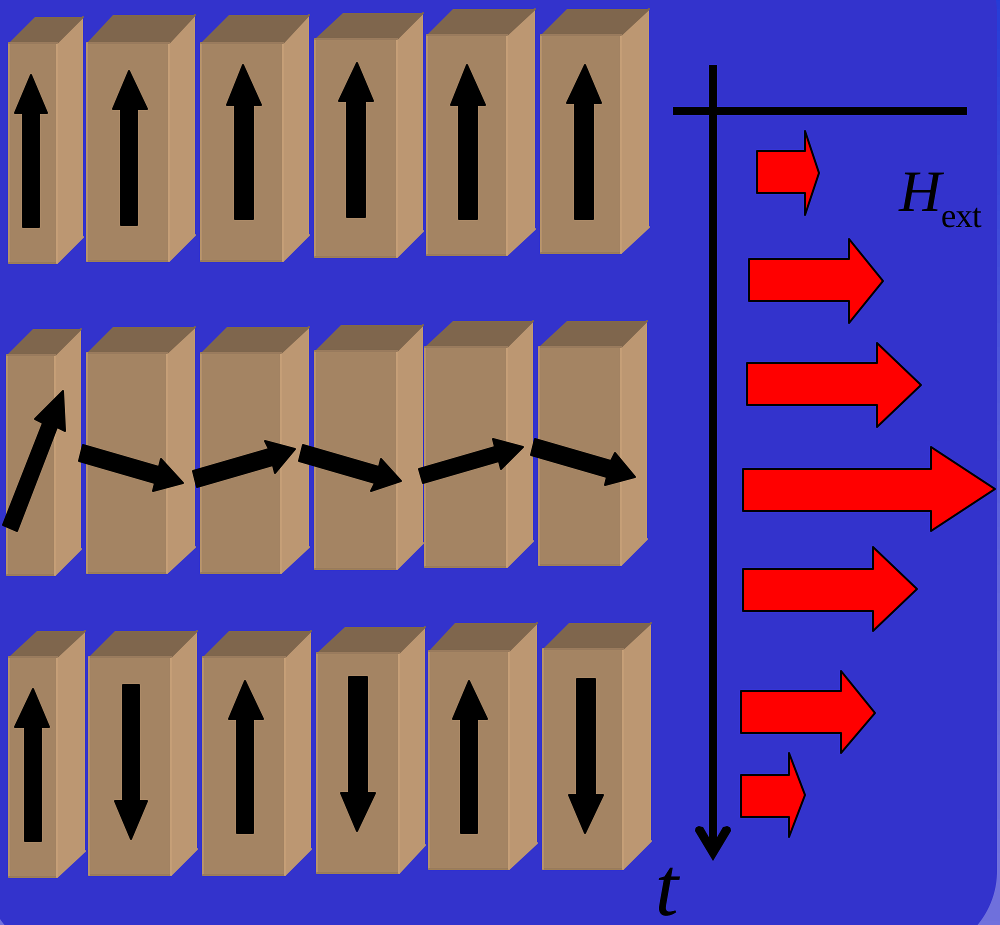


Interaction Between Two Nanoscale Magnets



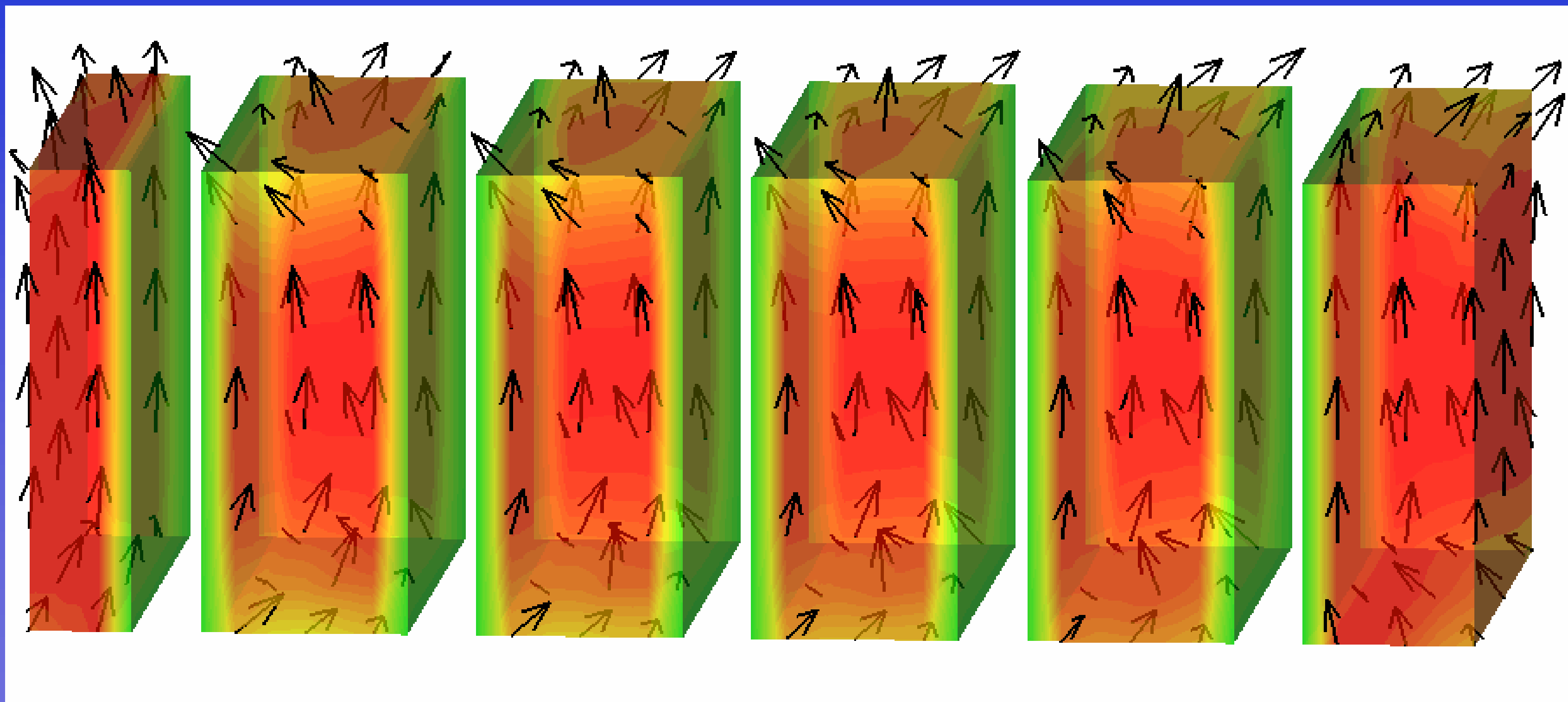
The Nanomagnet Wire





Clocking results in predictable switching dynamics

Micromagnetic Simulation of the Nanomagnet Wire

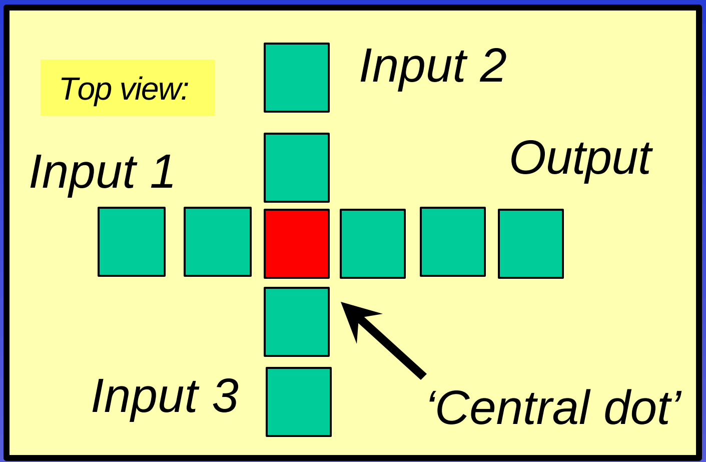


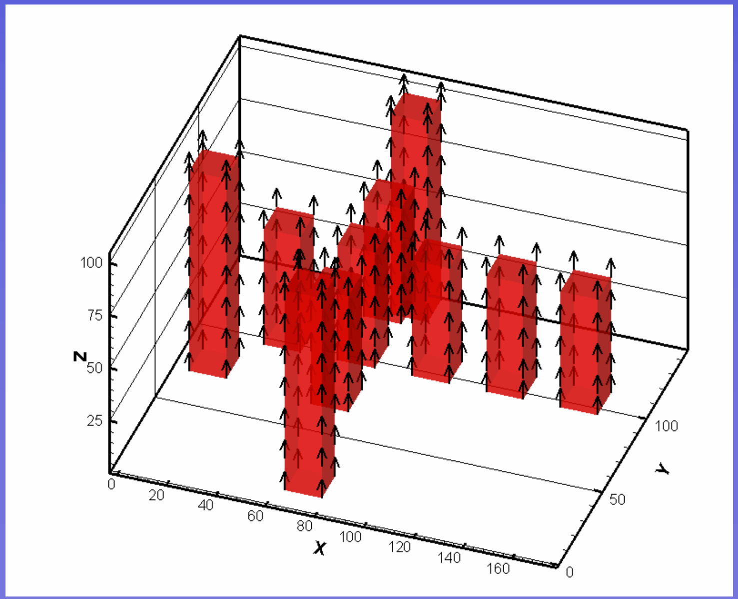
0.5μm

H_{pump}

Input dot: retains its magnetization

The Magnetic Majority Gate



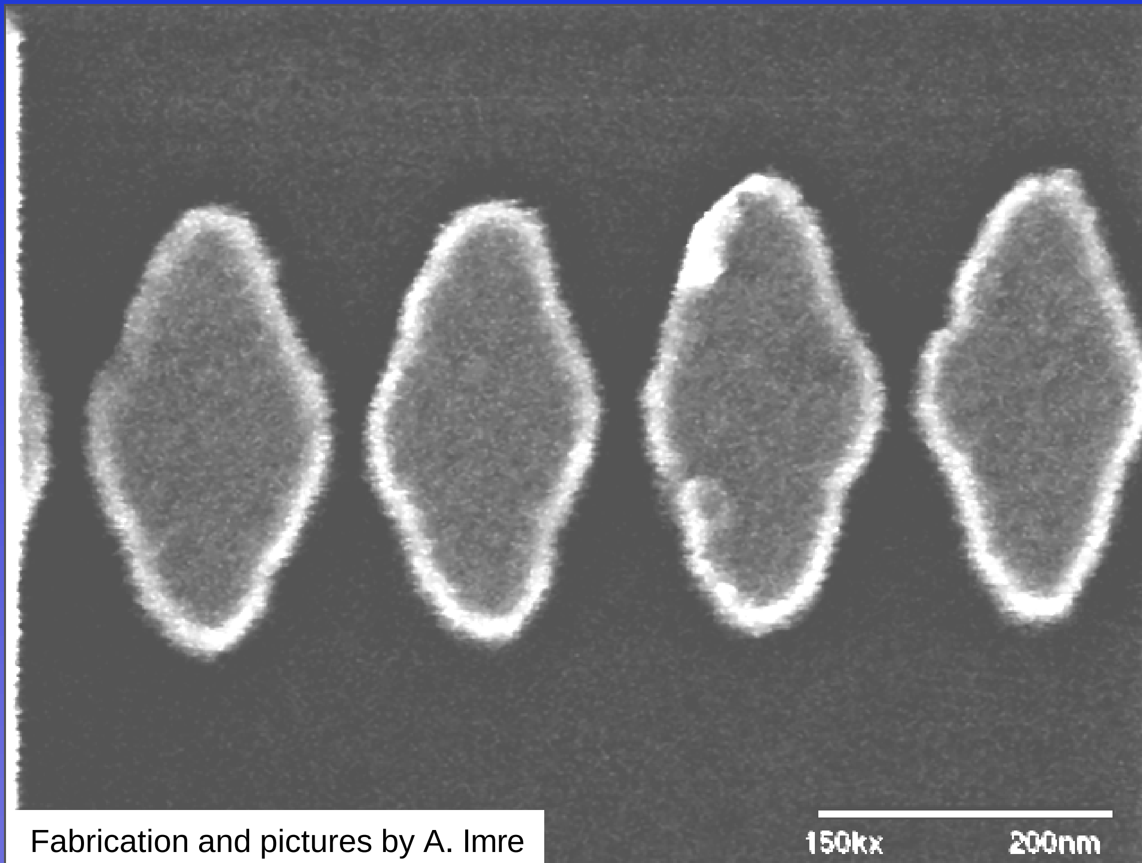


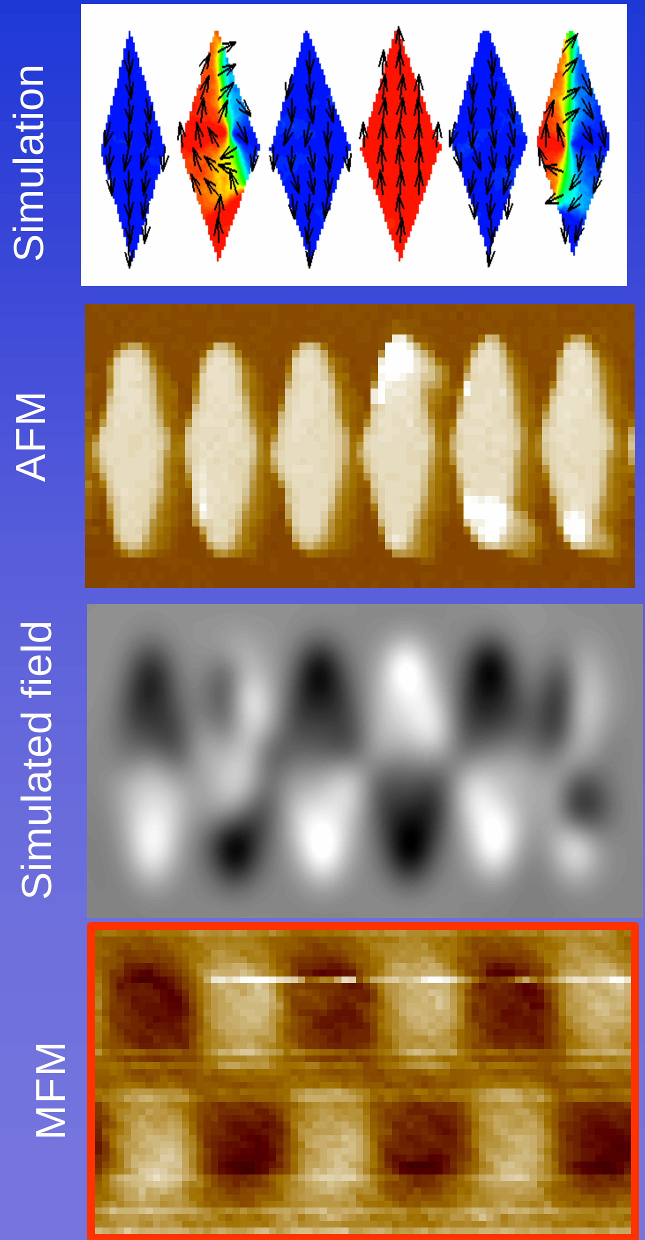
Input 1	Input 2	Input 3	Output
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1

Input 2 **OR** Input 3

Input 2 **AND** Input 3

Experimental Progress



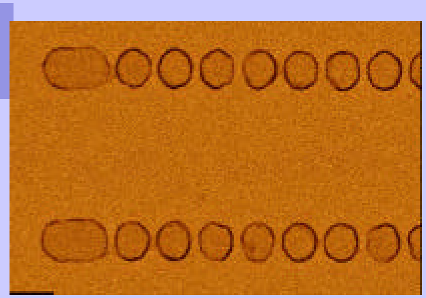


Investigations of permalloy nanomagnets (thermally evaporated and patterned by electron beam lithography) confirm the simulation results

Approaches to Magnetic Logic Devices

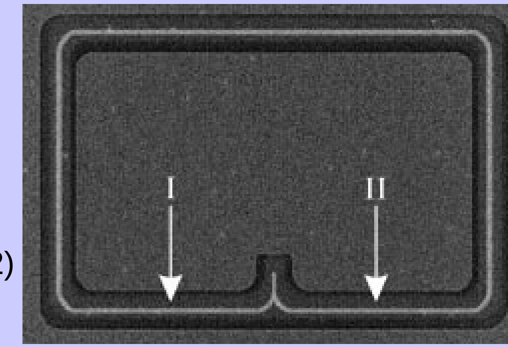
Soliton – propagation in coupled dots

(Cowburn, *Science*, 2000)



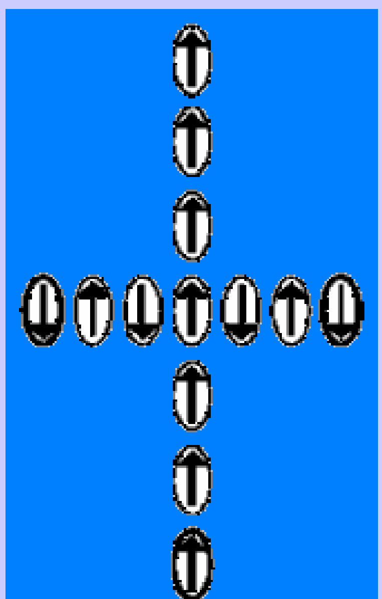
Manipulation of domain wall propagation

(Cowburn, *Science*, 2002)



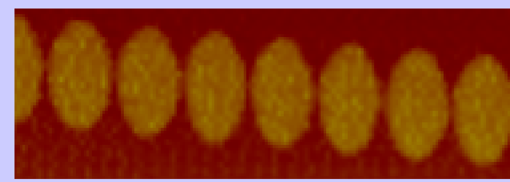
Joint ferro- and antiferromagnetic coupling

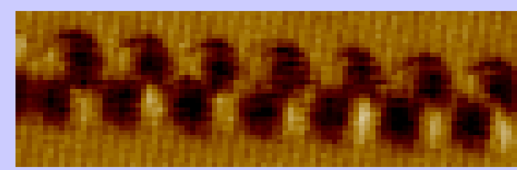
(Parish and Forshaw, 2003)

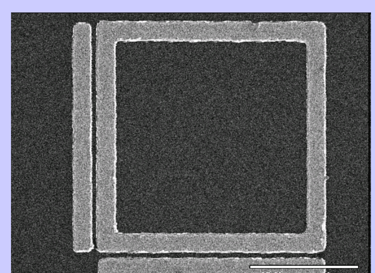


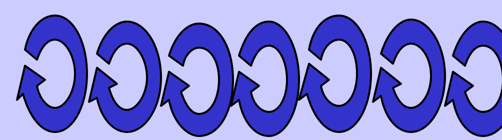
Coupling between magnetic vortices, domain walls

(Our group)









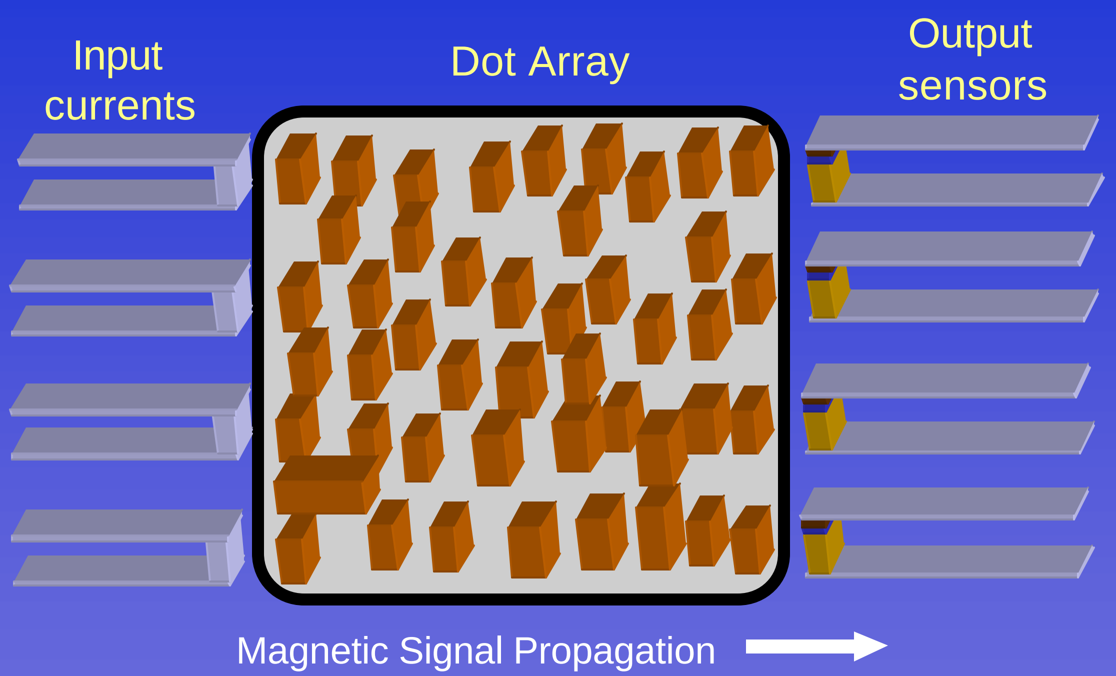
Pictures and fabrication by A. Imre

Larger-Scale Systems

Small building blocks

↓ ?

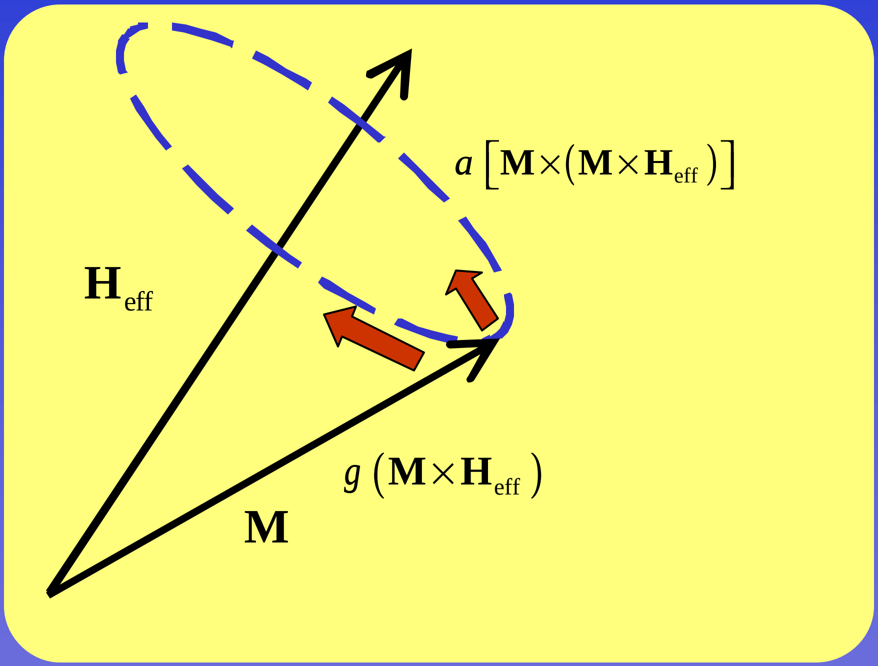
Complex systems



Fundamental questions from the system perspective:

- ***What is the amount of dissipated power?***
- ***Do nanomagnets show power gain?***

Model of Dissipation in Magnets



Magnetic moments (spins) of the ferromagnetic material perform a damped precession motion around the effective field.

The Landau-Lifschitz Equation (fundamental equation of domain theory) gives quantitative description of this motion:

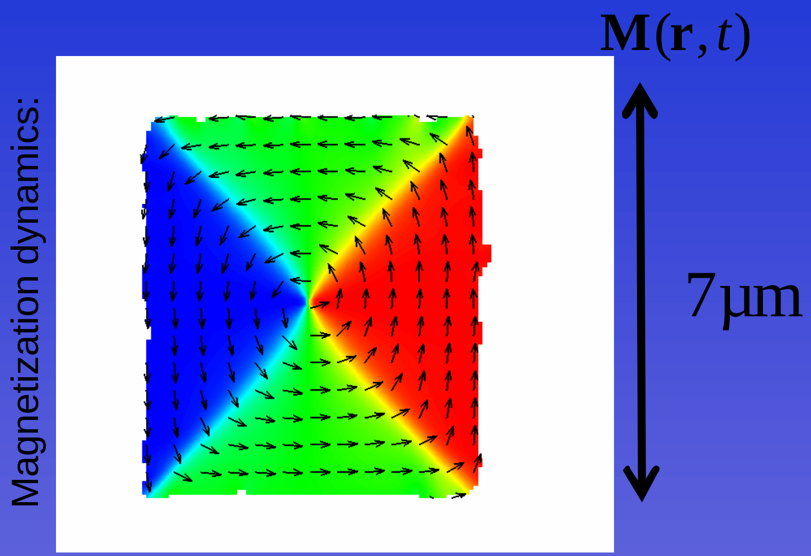
$$\frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t} = -g\,\mathbf{M}(\mathbf{r},t)\times\mathbf{H}_{\text{eff}}(\mathbf{r},t) - \frac{ag}{M_s}\left[\mathbf{M}(\mathbf{r},t)\times\left(\mathbf{M}(\mathbf{r},t)\times\mathbf{H}_{\text{eff}}(\mathbf{r},t)\right)\right]$$

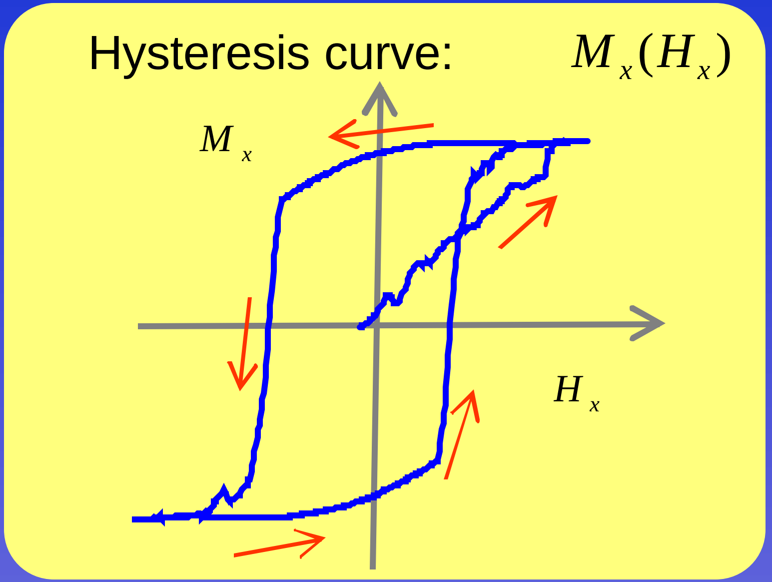
Dissipative term

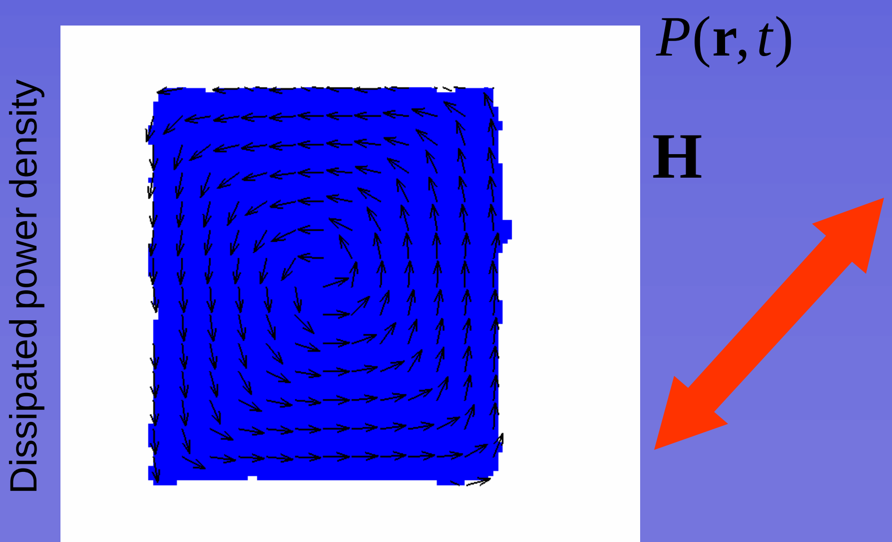
<u>Power density:</u>

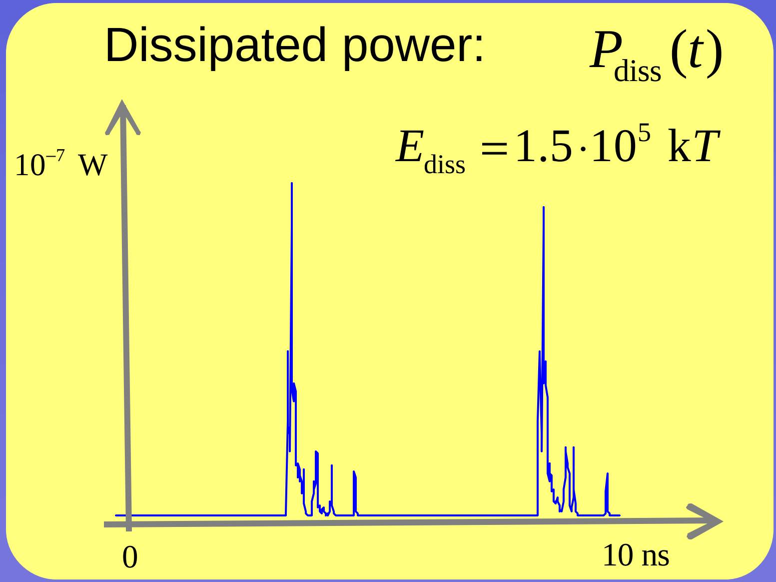
$$P_{\text{diss}}(\mathbf{r},t) = mH_{eff}\left.\frac{\partial M}{\partial t}\right|_{\text{diss}} = mH_{\text{eff}}\left(\frac{ag}{M_s}\left[\mathbf{M}^{(\text{i})}(\mathbf{r},t)\times\left(\mathbf{M}^{(\text{i})}(\mathbf{r},t)\times\mathbf{H}_{\text{eff}}^{(\text{i})}(\mathbf{r},t)\right)\right]\right)$$

Switching of a Large Magnet



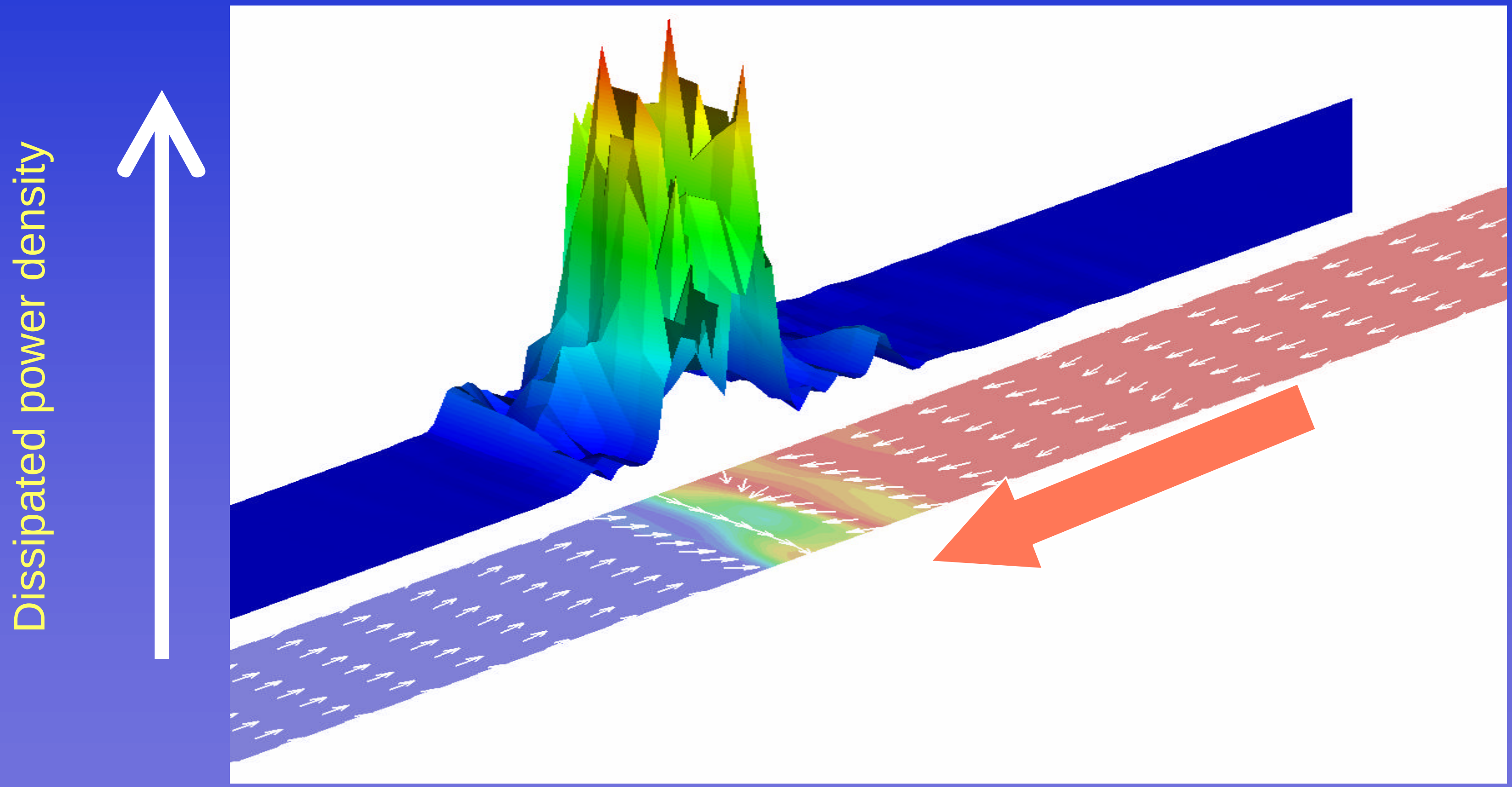


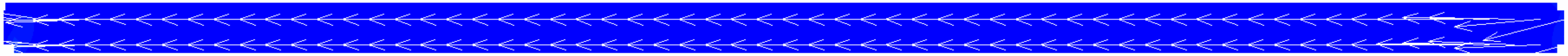




Dissipation in a Domain-wall Conductor

$$P_{\text{diss}} \approx 10^{-7}\ \text{W}$$



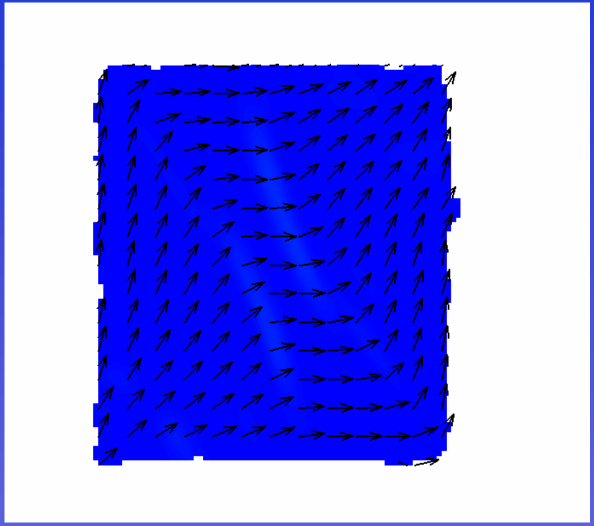


Simulation of a 50 nm by 20 nm permalloy strip

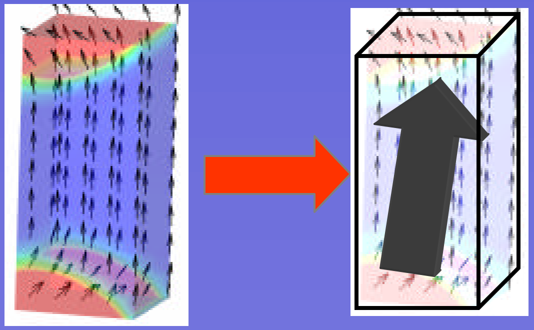
Minimizing the Dissipation

Rapidly moving domain walls are the main source of dissipation in magnetic materials

- ➢Make the magnets sufficiently small (submicron size magnets has no internal domain walls)
- ➢Switch them slowly (use adiabatic pumping)

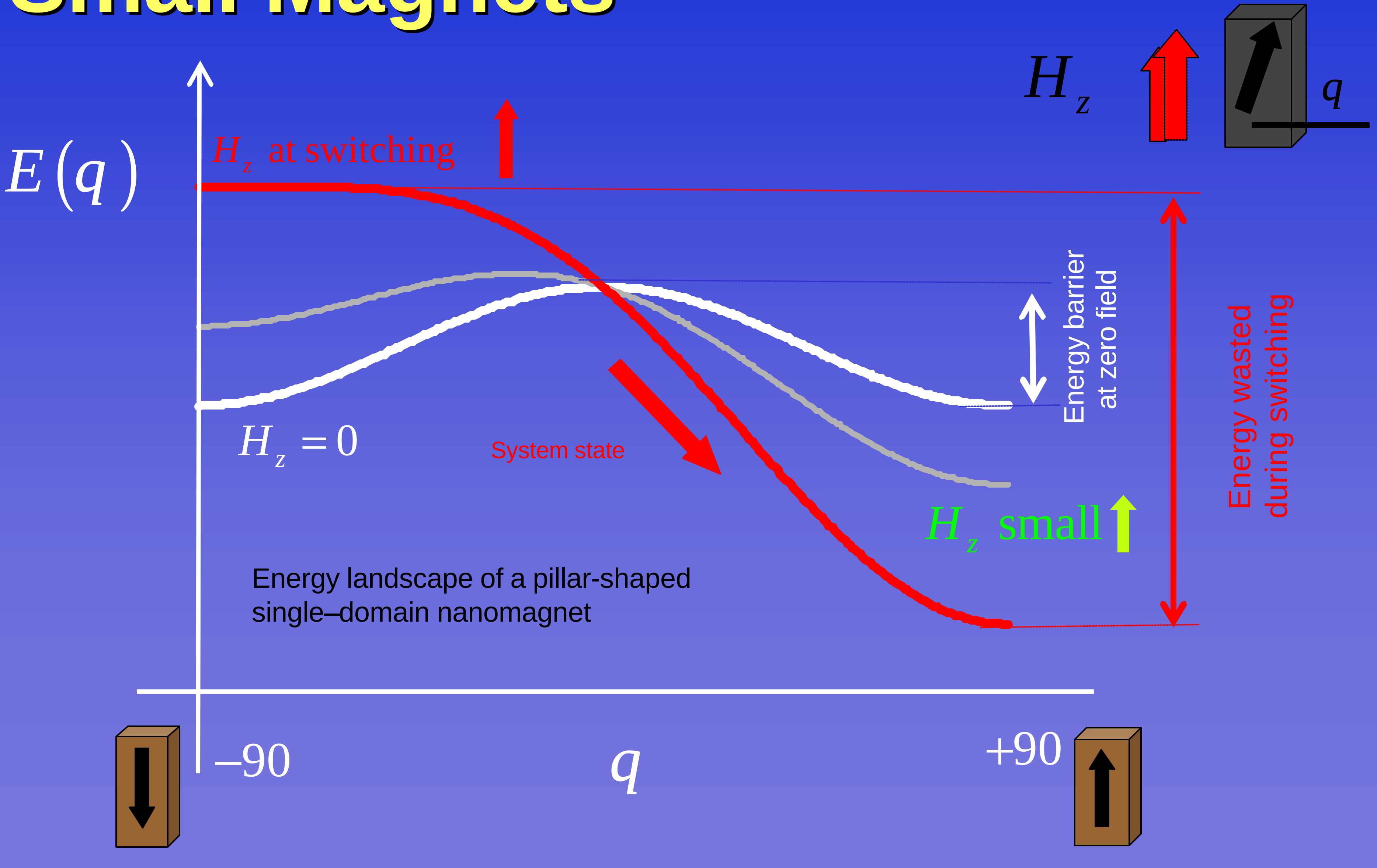


Dissipation is strongest around domain walls

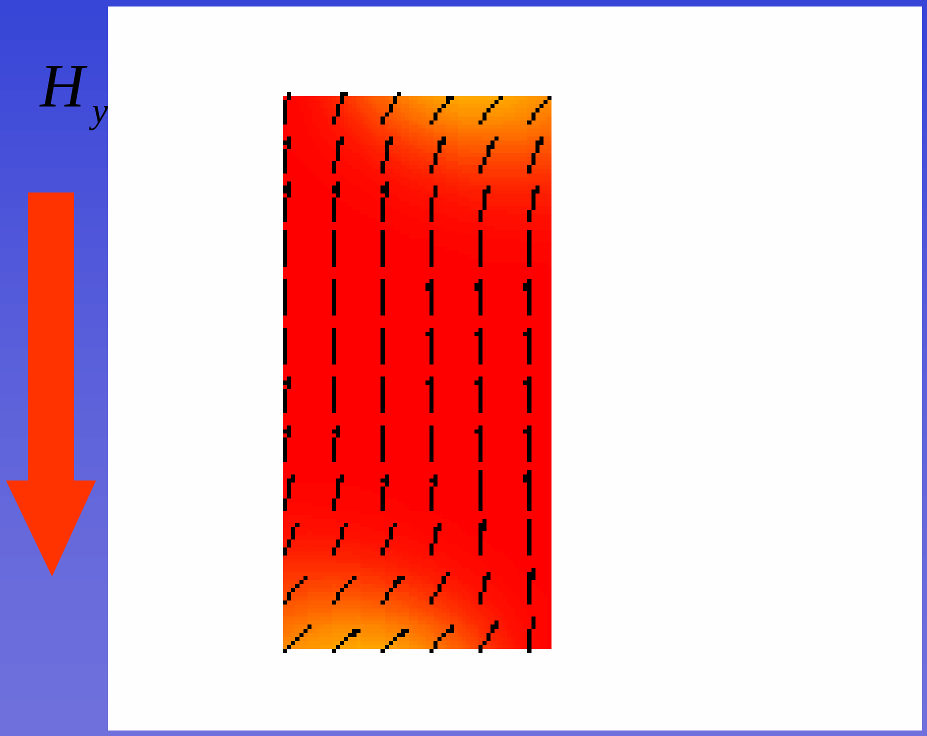


Small magnets have no internal domain walls

Non – Adiabatic Switching of Small Magnets

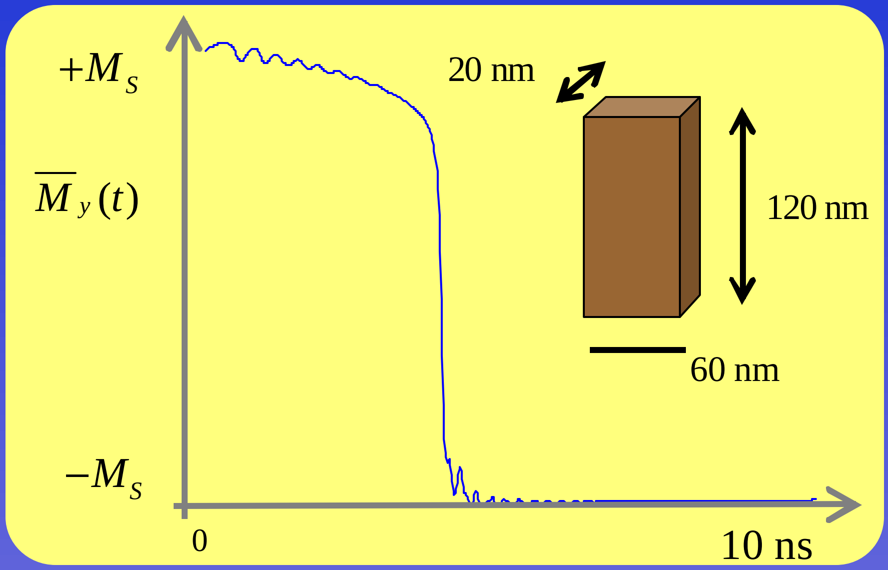


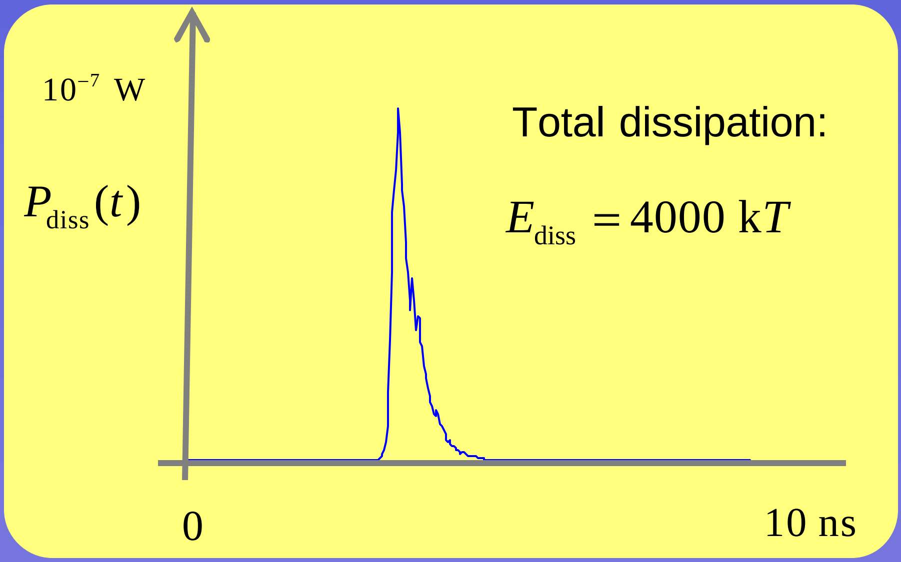
Micromagnetic Simulation of the Non-Adiabatic Switching Process



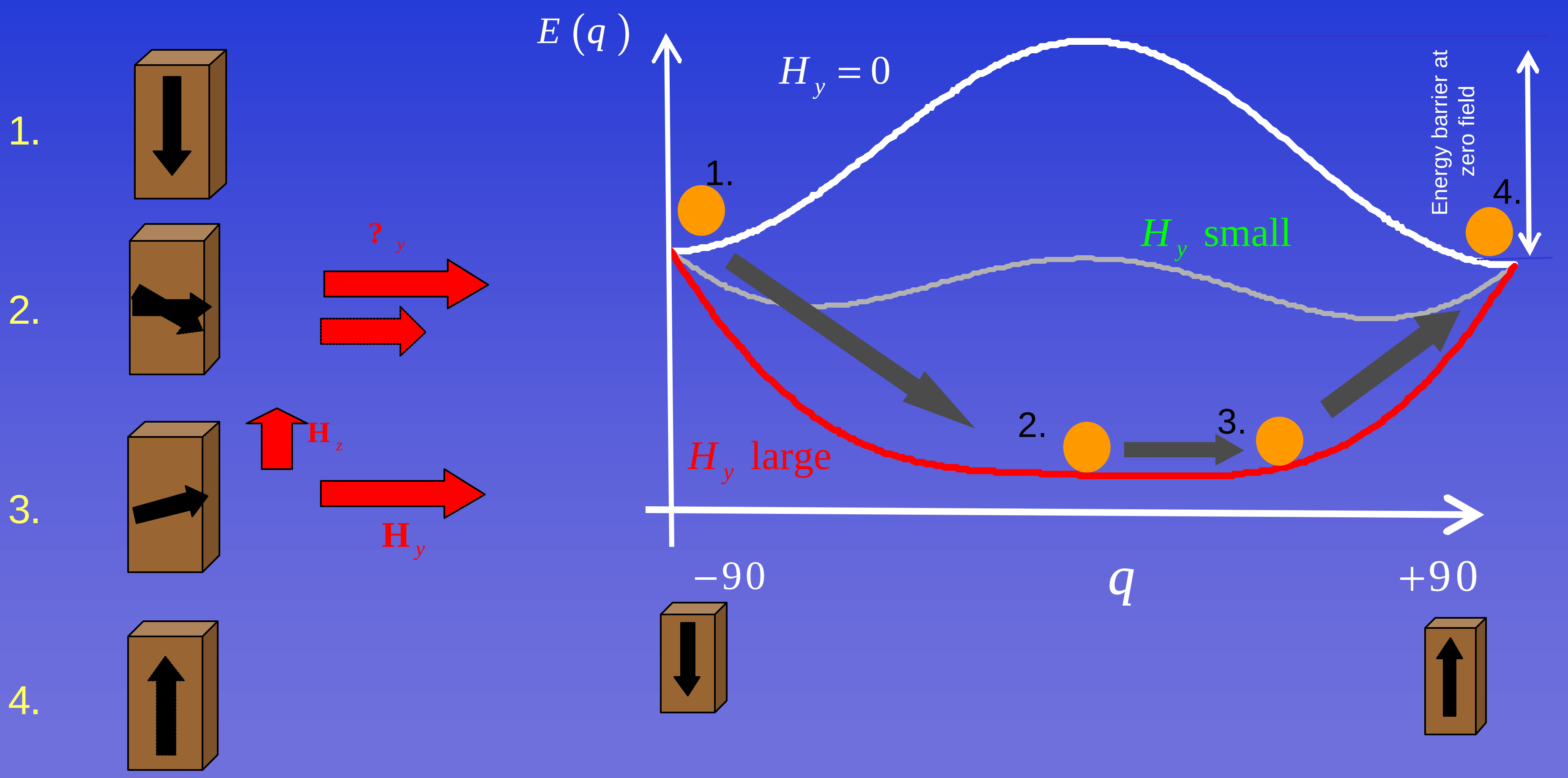
Micromagnetic simulation

$$\mathbf{M}(\mathbf{r},t)$$



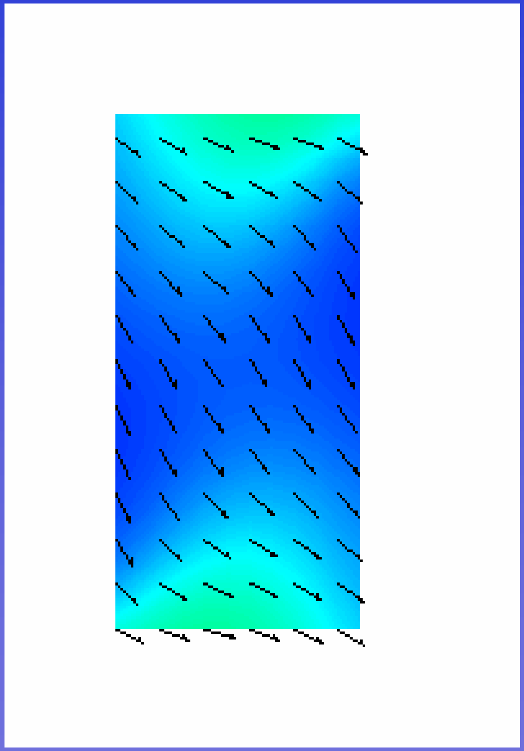


Adiabatic Switching



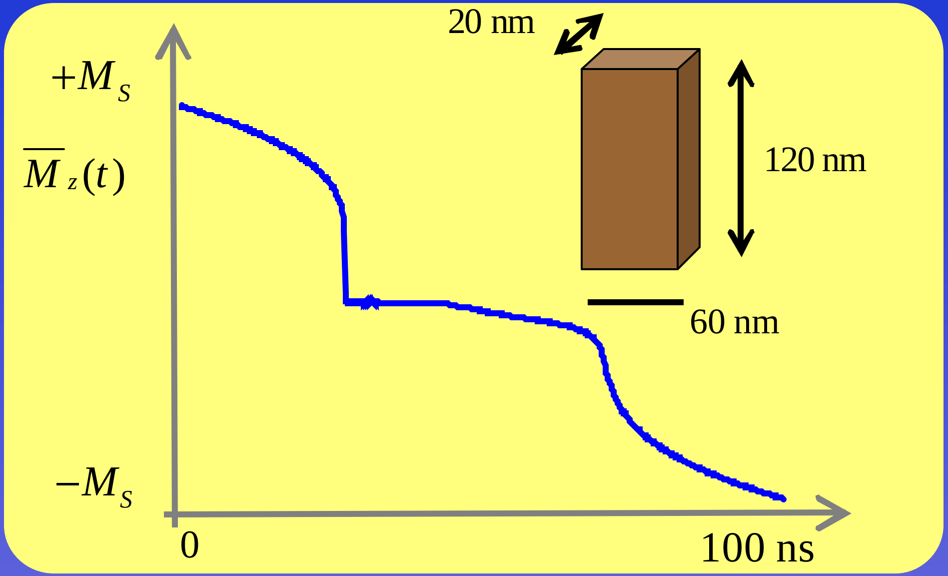
By adiabatic clocking, the system can be switched with almost no dissipation, but at the expense of slower operation.

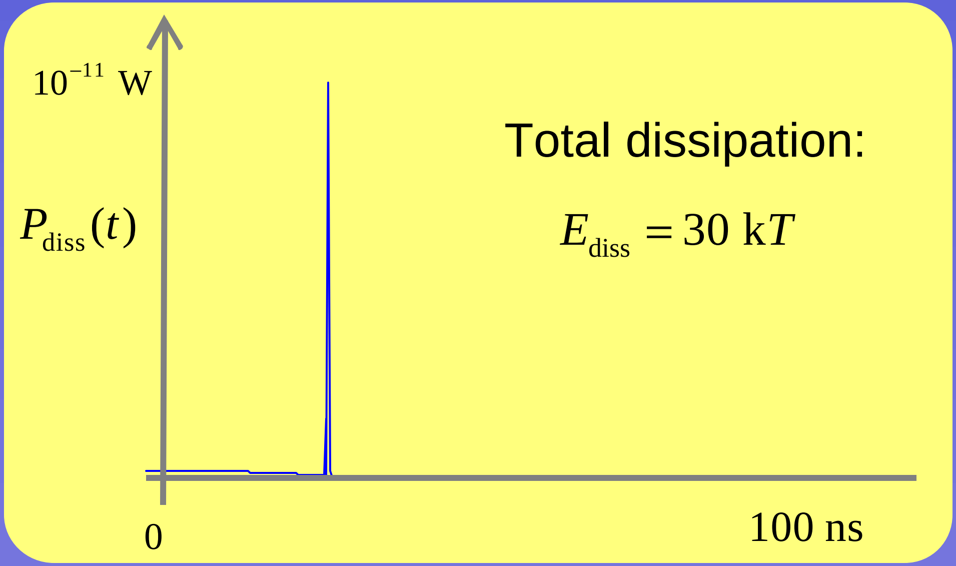
Simulation of Adiabatic Switching



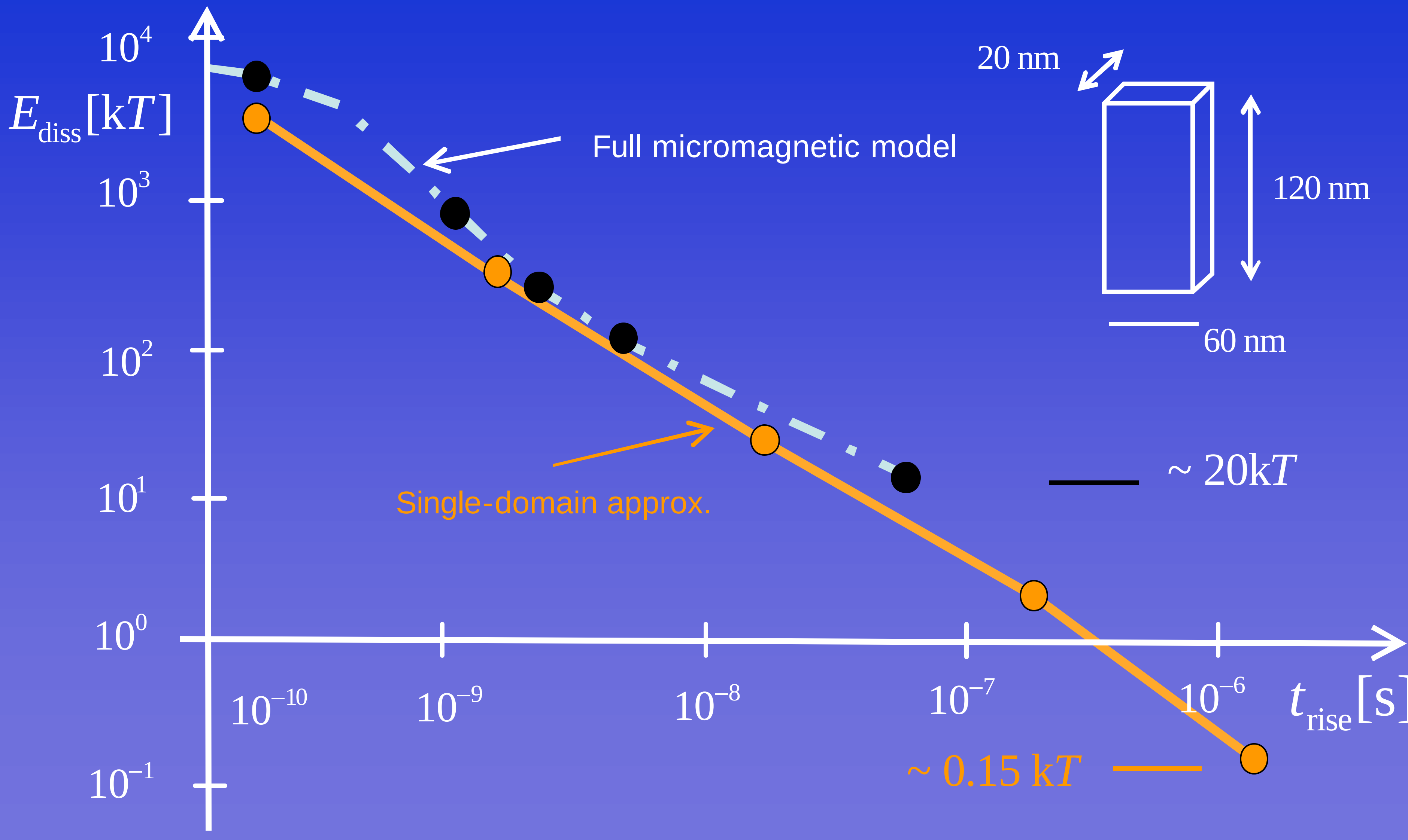
Dynamic simulation

$$\mathbf{M}(\mathbf{r},t)$$



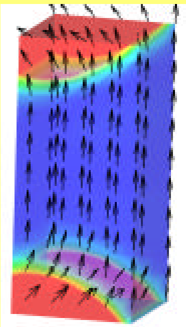


Switching Speed vs. Dissipated Power

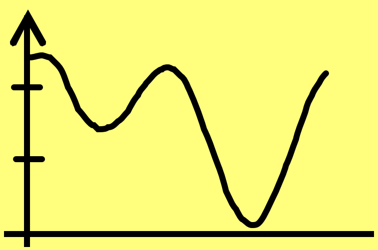


Adiabatically switched nanomagnets can dissipate at least two orders of magnitude less energy than the height of the potential barrier separating their steady-states

The Lowest Limit of Dissipation in Magnetic QCA



Deviations from the ideal single-domain behavior -→ abrupt domain wall switches will always cause dissipation (few $\mathrm{k}T$)

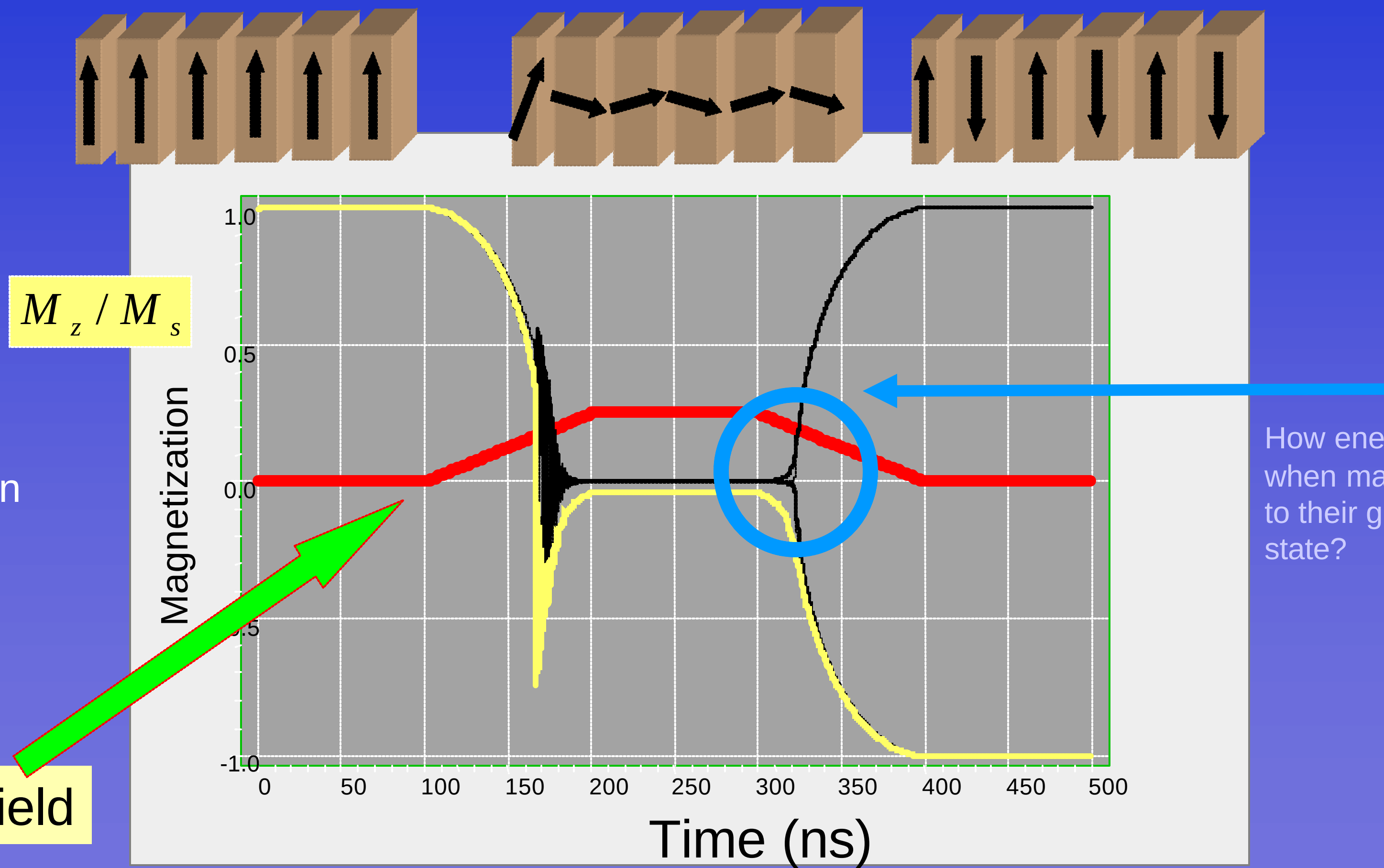


Coupling between dots should be stronger than few $\mathrm{k}T$ → dot switching cannot be arbitrarily slow → few $\mathrm{k}T$ dissipation unavoidable

The minimal dissipation of nanomagnetic logic devices is around a few $\mathrm{k}T$ per switching.

Power Gain of Adiabatically Pumped Nanomagnets

Schematic:

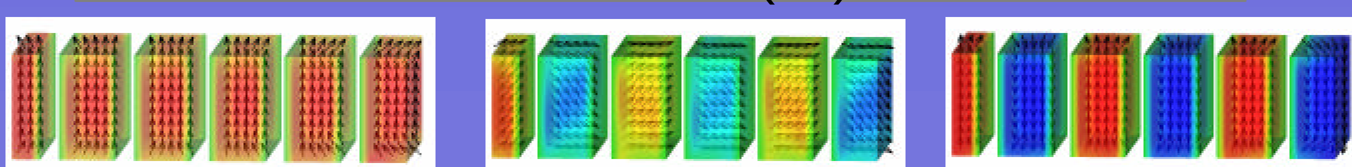


How energy flows, when magnets flip to their ground state?

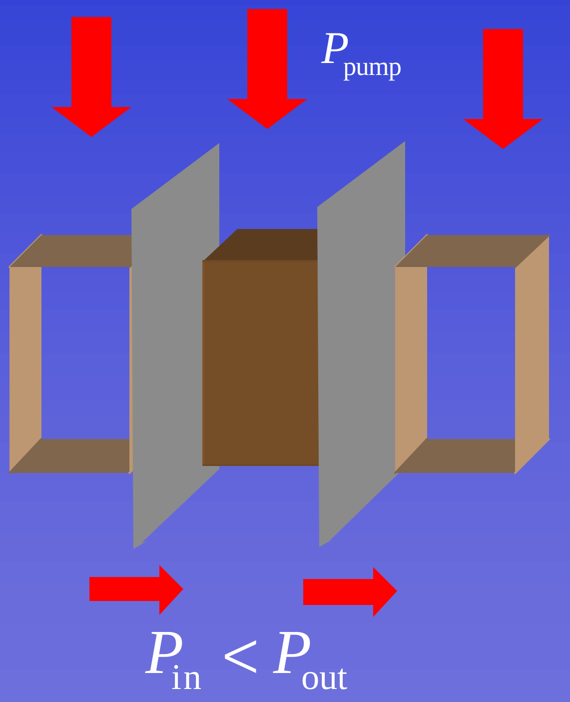
Single-domain model

External field

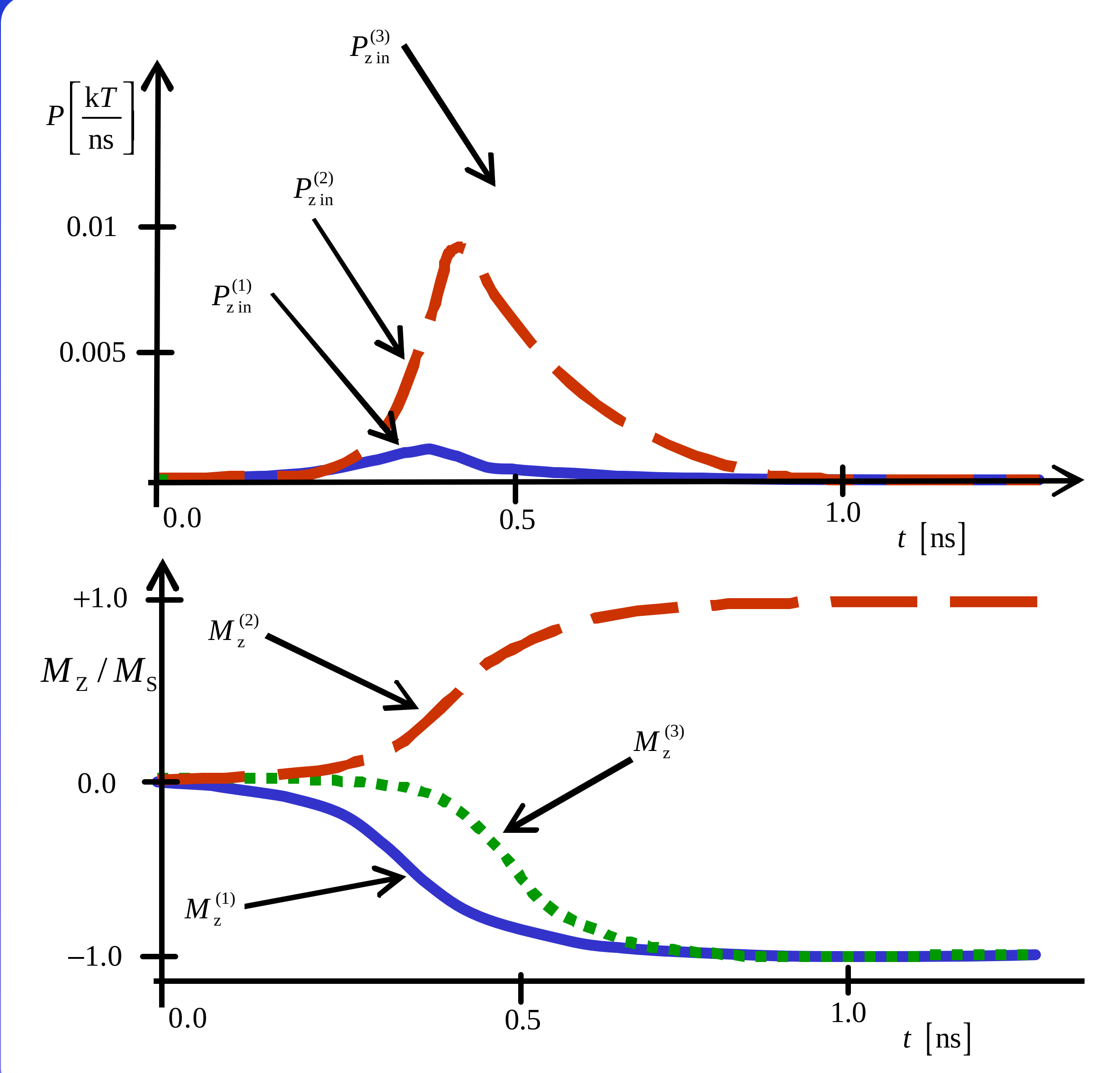
Micromagnetic simulation:



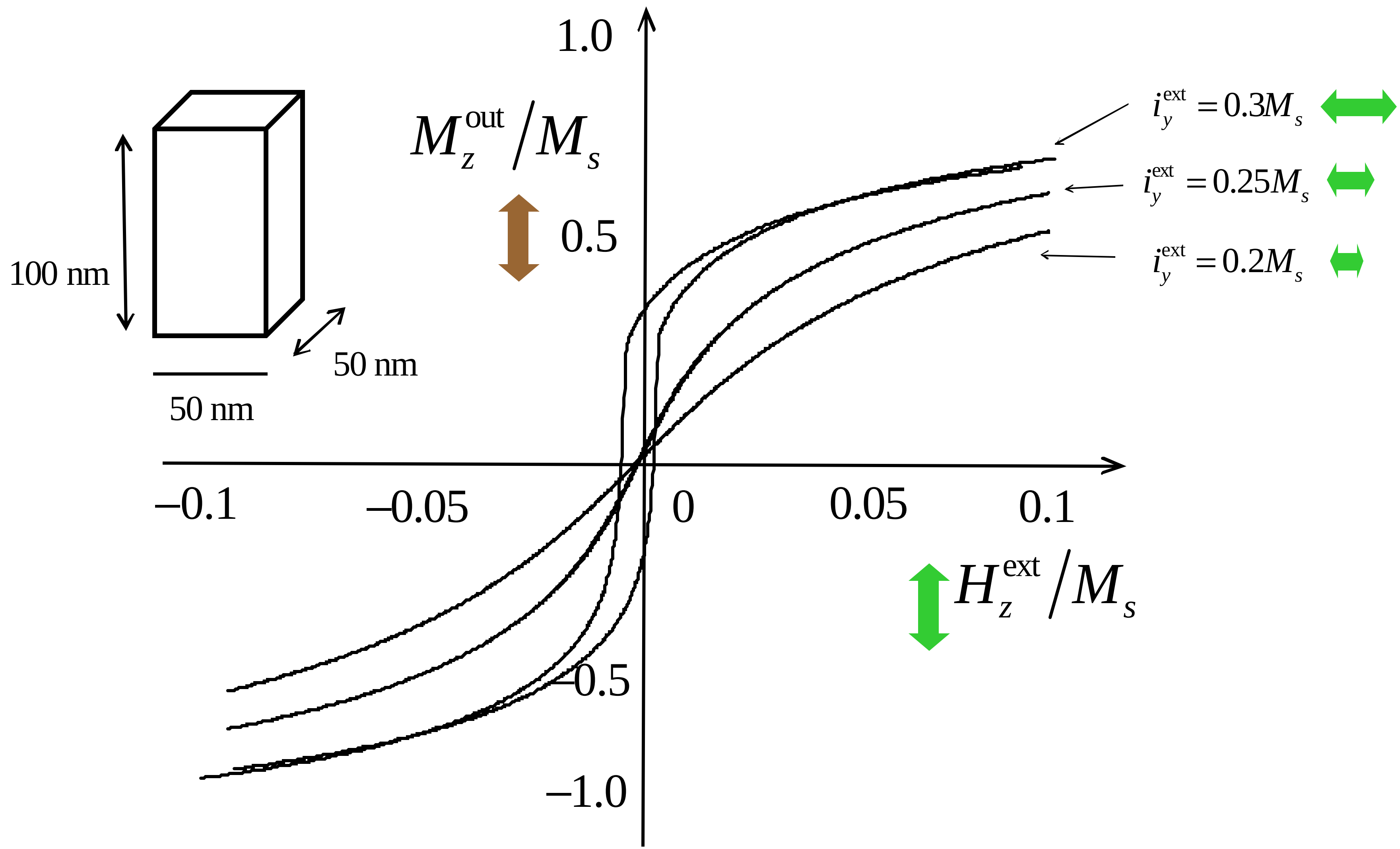
Detailed View of the Switching Process



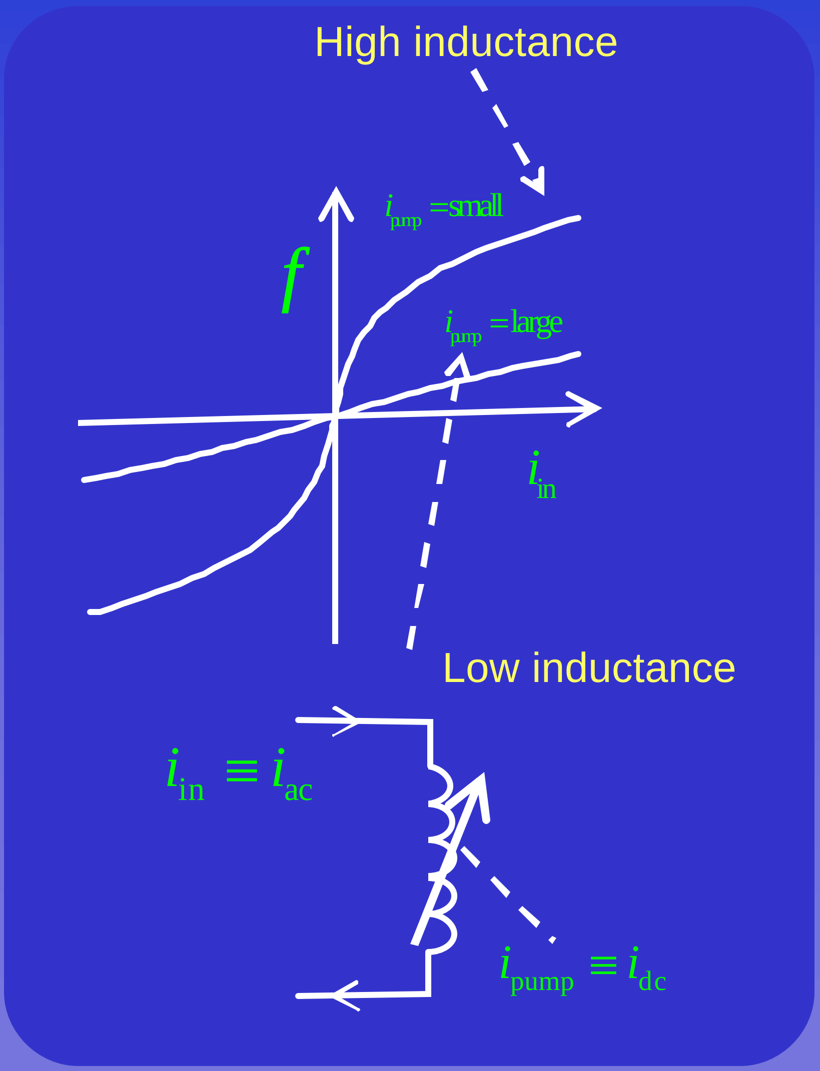
Energy of the magnetic signal increases as the soliton propagates along the wire

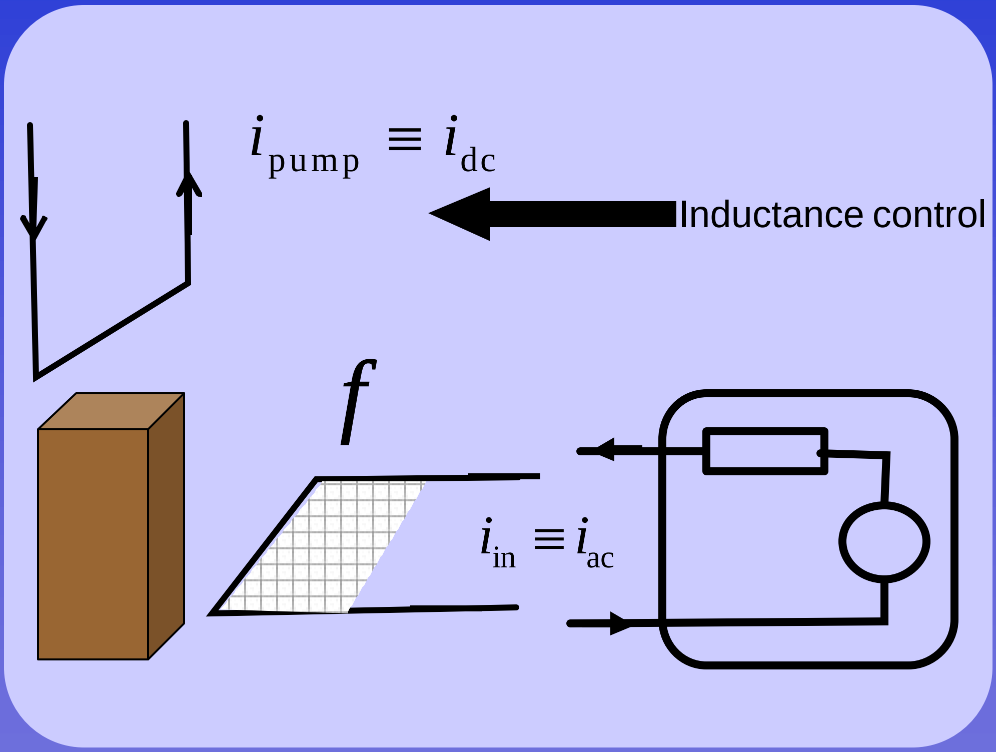


Hysteresis Curves of Single-Domain Nanomagnets



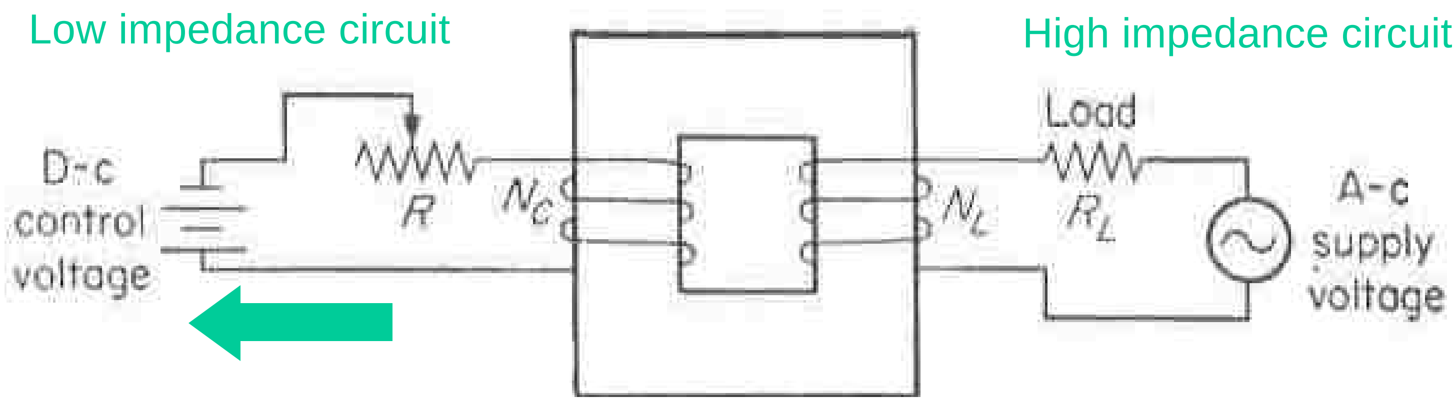
A Nanomagnet Driven by Current Loops





This is a circuit with a variable inductance.
Does it have applications?

Magnetic Amplifiers



1.Ettinger, G. M.: “Magnetic Amplifiers”, Wiley, New York, 1957

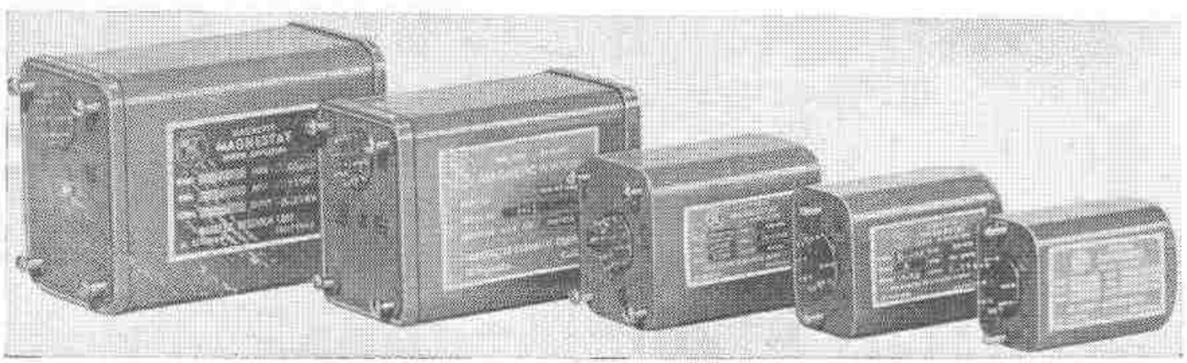
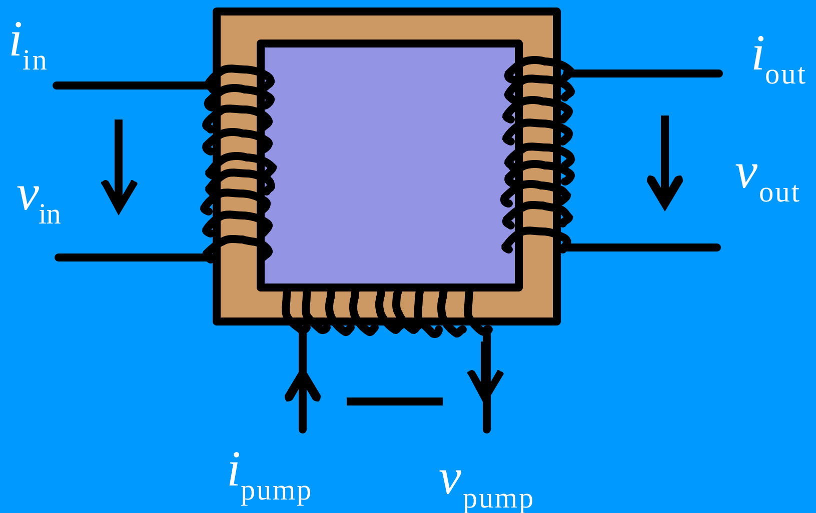
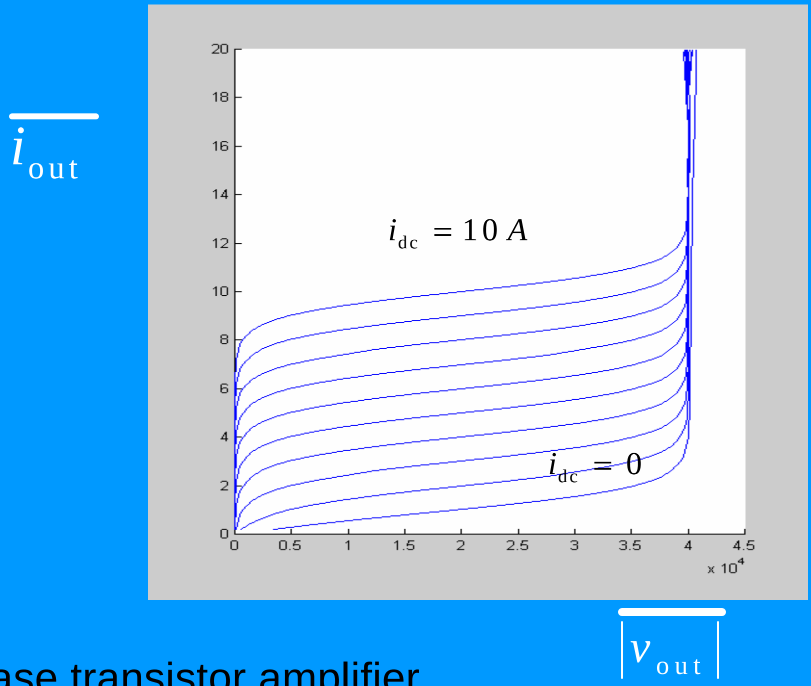


Fig. 1-1. Packaged magnetic amplifiers. (*Courtesy, Magnetic Research Corporation.*)

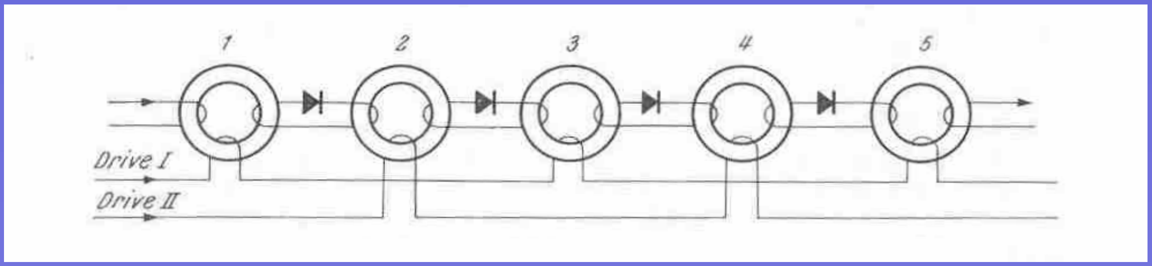
Nonlinearity of the hysteresis curve → Tunable inductances → Power gain

Magnetic Computers





This three-coil device behaves like a common-base transistor amplifier



A magnetic shift register

from Gschwind: Design of Digital Computers, 1967

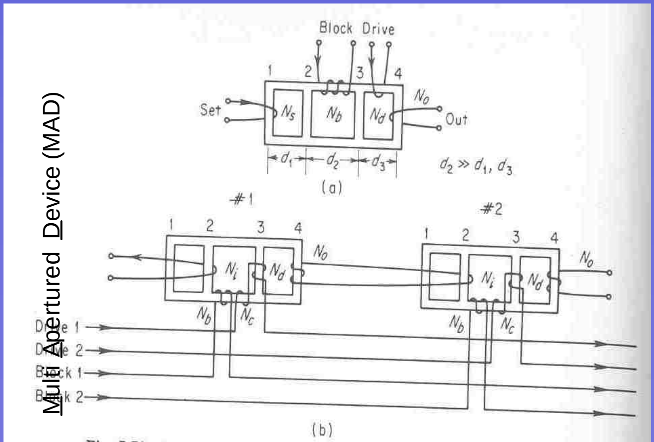
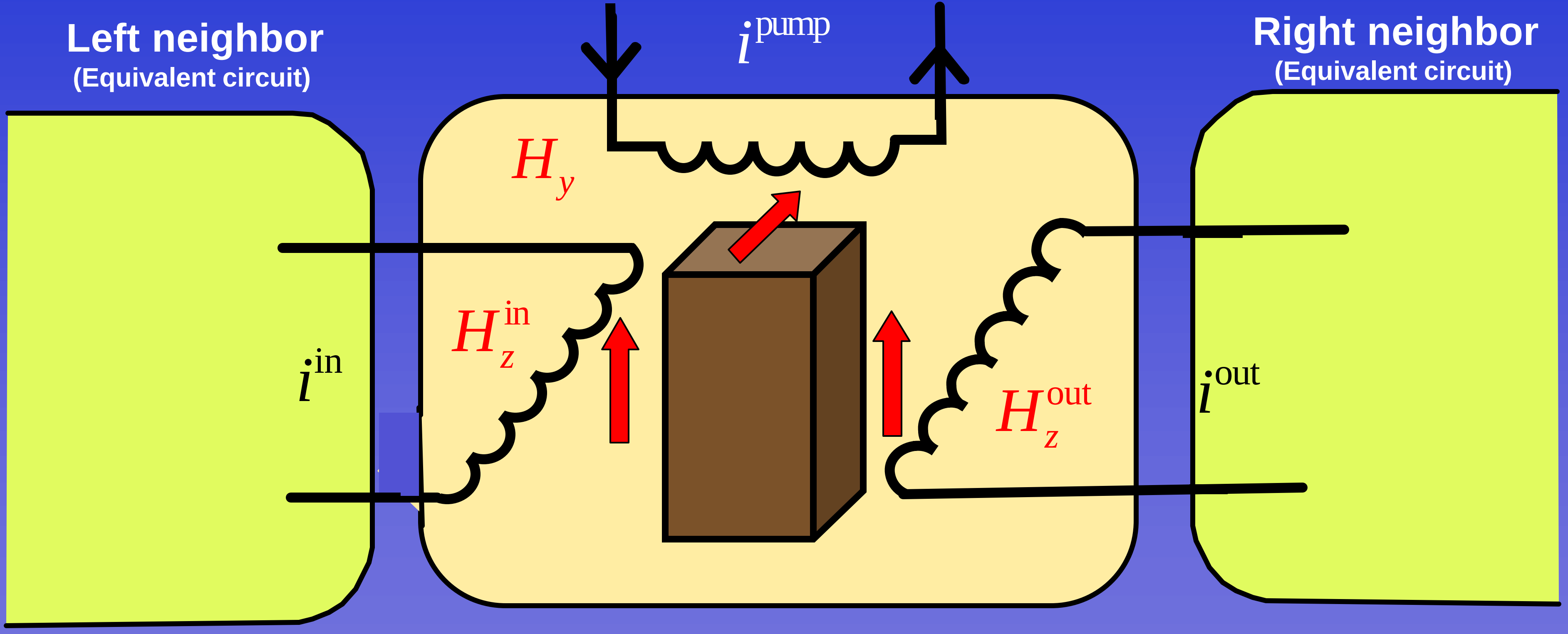


Fig. 5.50. (a) A multi-apertured magnetic device. (b) A MAD register.

Coupled Nanomagnets as Circuits

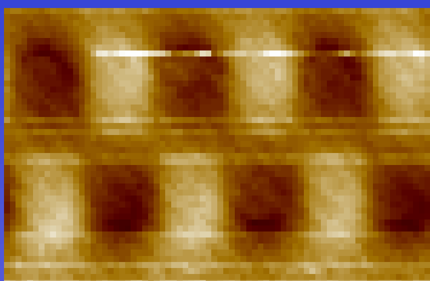


The origin of power gain in field-coupled nanomagnets can be understood on the same basis as the operation of magnetic parametric amplifiers

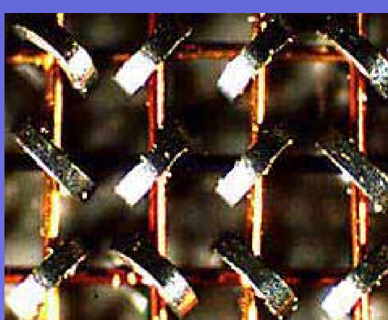
→ **Nanoelectronic circuit design**

Conclusions

1.0µm



1cm



Magnetic field-coupling is an idea worth pursuing…

Low dissipation, robust operation, high integration density and reasonably high speed

As they are active devices, there is no intrinsic limit to their scalability

Field-coupling is functionally equivalent to electrically interconected device architectures

Our Group

Prof. Wolfgang Porod

Prof. Paolo Lugli

Prof. Arpad Csurgay

(Circuit modeling)

Prof. Gary H. Bernstein

(Experiments)

Prof. Vitali Metlushko

(Fabrication)

Prof. Alexei Orlov

(Electrical measurements)

Alexandra Imre

(Fabrication, Characterization)

Ling Zhou

(Electrical measurements)

Our work was supported by the Office of Naval Research, the National Science Foundation and the W. M. Keck Foundation