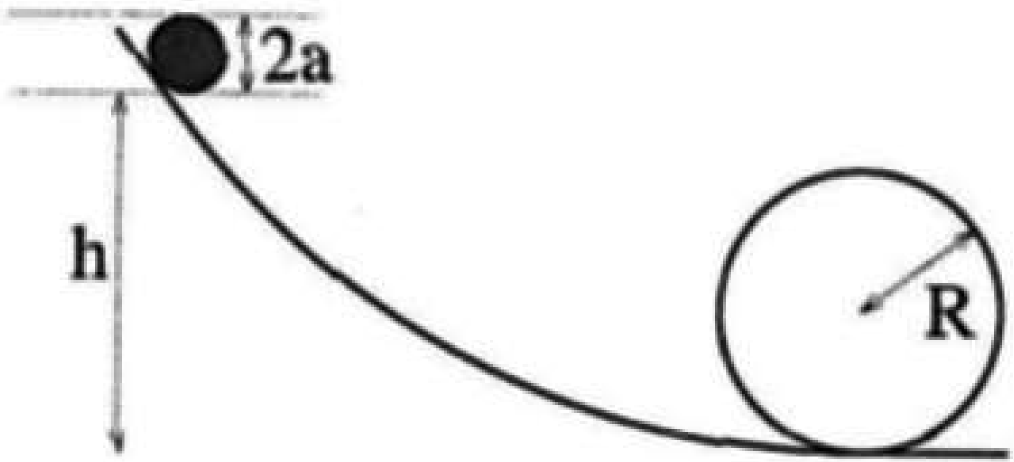
Electrons in a spin

Gareth Conduit

University of Cambridge

Pt IA: Single-body physics

This cylinder is placed on a track as shown in the figure below. The track contains a downhill section which joins smoothly to a vertical circular loop of radius R, finishing with a horizontal section.



The cylinder is released from rest from a point at which its centre is at a height $h + a$ above the lowest point of the track. It rolls along the track without sliding, and

Question B8, Part IA Physics, 2010

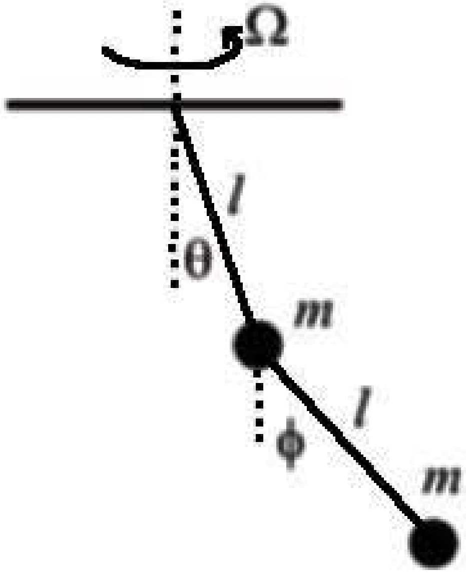
Pt IB: Two-body physics

The double pendulum, as shown below, rotates at a fixed angular velocity Ω. Write down the Lagrangian and hence the dynamical equations for this system.

Use this Lagrangian to show, for small θ and ϕ, that the angular frequencies, ω_1 and ω_2, of the normal modes are given by:

$$\omega_{1,2}^2 = (2 \pm \sqrt{2})\,\omega_0^2 - \Omega^2,$$

where $\omega_0 = \sqrt{g/l}$.



Find and sketch the normal modes. How will the double pendulum behave if Ω lies between ω_1 and ω_2?

Question D14, Part IB Physics, 2007

Pt III physics

Study many-body phenomena driven by firmly established equations of motion

Advanced Quantum Condensed Matter Physics
Atmospheric Chemistry and Global Change
Atmospheric Physics
Atomic and Optical Physics
Biological Physics
Climate Change
Frontiers of Experimental Condensed Matter Physics
Materials, Electronics & Renewable Energy
Medical Physics
Non-linear Optics and Quantum States of Light
Nuclear Materials
Origin and Evolution of Galaxies
Phase Transitions and Collective Phenomena
Physics of Nanoelectronic Systems
Quantum Condensed Matter Field Theory
Quantum Field Theory
Superconductivity and Quantum Coherence

Search for new fundamental equations of motion

Advanced Quantum Field Theory
Formation of Structure in the Universe
Frontiers of Observational Astrophysics
Gauge Field Theory
Particle Astrophysics
Particle Physics
Physics of Nanoelectronic Systems
Quantum Field Theory
Quantum Information
Relativistic Astrophysics and Cosmology

10^{11}-body physics

Stars **all interact** and obey classical laws of motion

10^{11}-body physics

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16 September 2011 Last updated at 18:47

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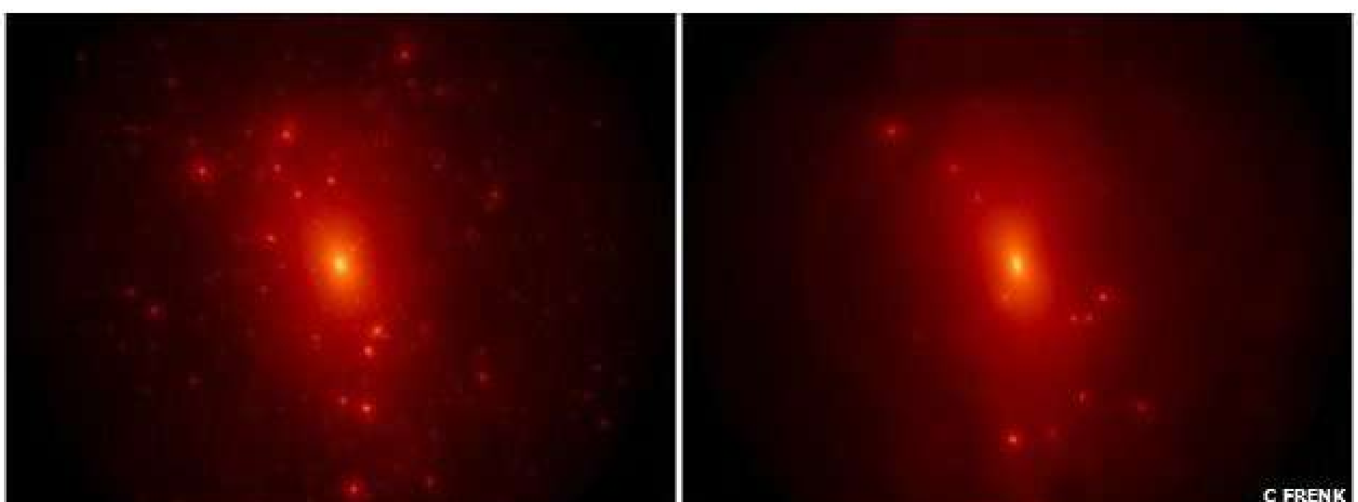
Dwarf galaxies suggest dark matter theory may be wrong

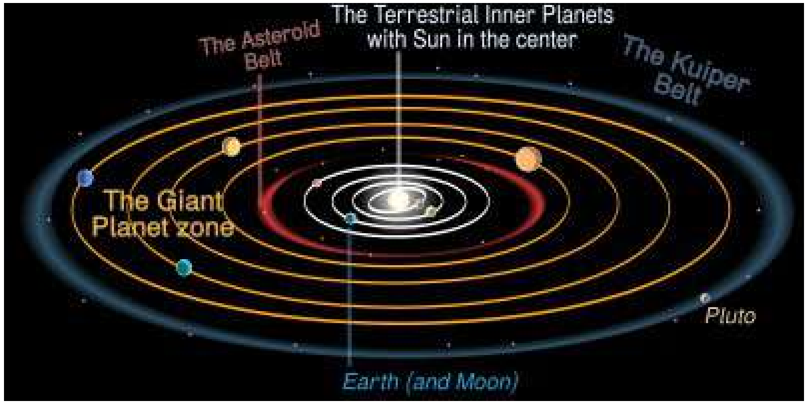
By Leila Battison
Science reporter, Bradford



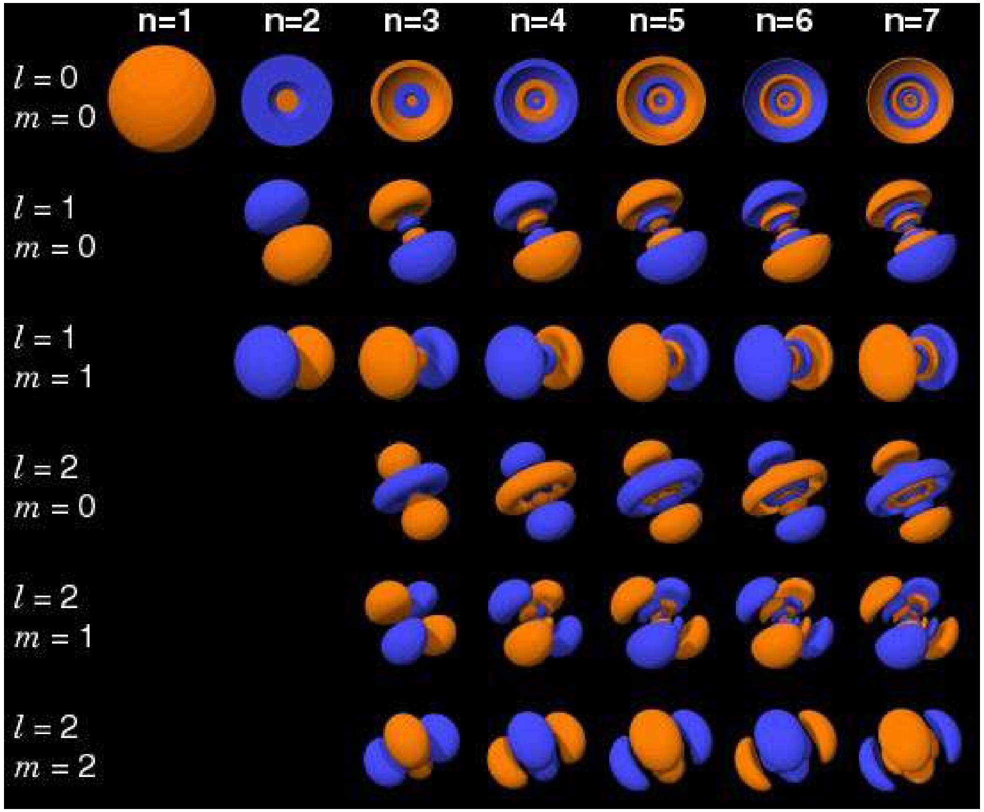
Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

Classical vs. quantum orbitals

- 10^{11} bodies **all interact**
- Follow circular orbits



- 10^{24} electrons in solids **all interact** and are **quantum degenerate**
- Follow complicated orbits



10^{24}-body physics

- Why is gold shiny, does not tarnish, gold-colored, a good conductor, and so malleable?

- Why does a superconductor expel magnetic fields and conduct electricity perfectly?

10^{24}-body physics

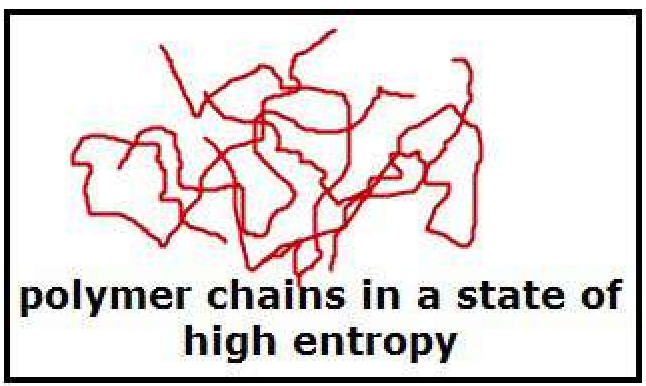
- How is the magnetic field generated?

- How does a hard disk drive store so much data?

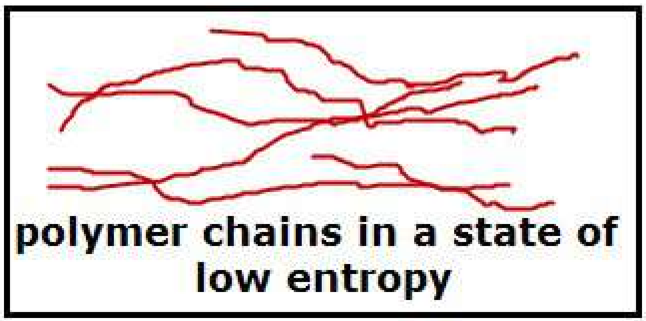
Elastic bands

Elastic bands consist of long polymer chains that interact strongly, but obey classical laws of motion

Natural state



Stretched



Energy stored

- Potential energy stored in elastic band

$$E = \frac{1}{2}kx^2 = \frac{1}{2}Fx = \frac{1}{2}10 \times 0.1 = 0.5\ \mathrm{J}$$

Energy stored

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$$E = \frac{1}{2}kx^2 = \frac{1}{2}Fx = \frac{1}{2}10 \times 0.1 = 0.5\ \mathrm{J}$$

- Kinetic energy in handgun bullet

$$E = \frac{1}{2}mv^2 = \frac{1}{2}0.005 \times 400^2 = 400\ \mathrm{J}$$

Energy stored

- Potential energy stored in elastic band

$$E = \frac{1}{2} kx^2 = \frac{1}{2} Fx = \frac{1}{2} 10 \times 0.1 = 0.5\ \mathrm{J}$$

- Kinetic energy in handgun bullet

$$E = \frac{1}{2} mv^2 = \frac{1}{2} 0.005 \times 400^2 = 400\ \mathrm{J}$$

- Potential energy in enormous elastic band

$$E = \frac{1}{2} kx^2 = \frac{1}{2} Fx = \frac{1}{2} 100 \times 10 = 500\ \mathrm{J}$$

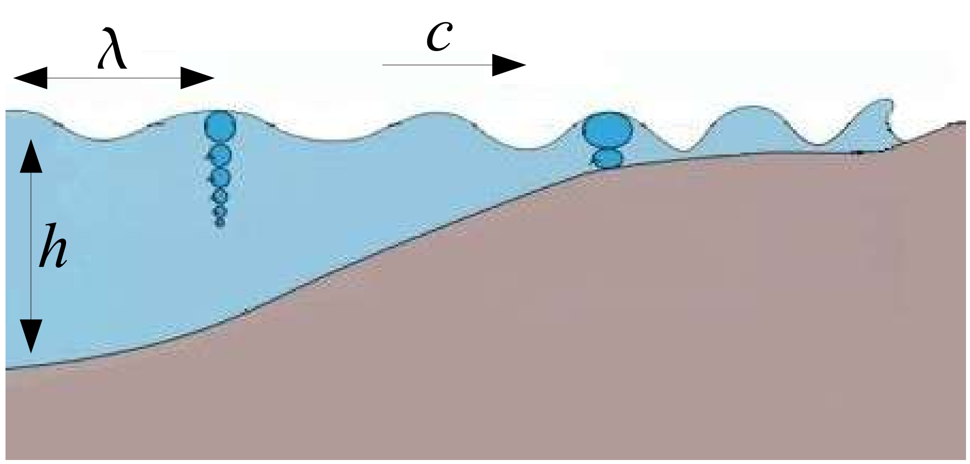
Effect of material thickness

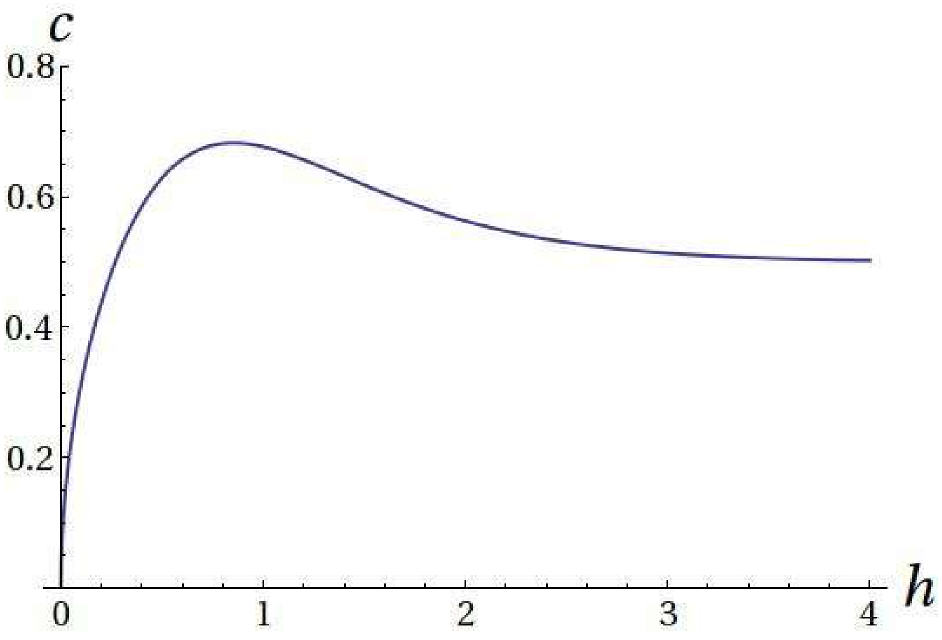
Thin band: <10ms^{-1}

Cylindrical: >100ms^{-1}

Wave velocity

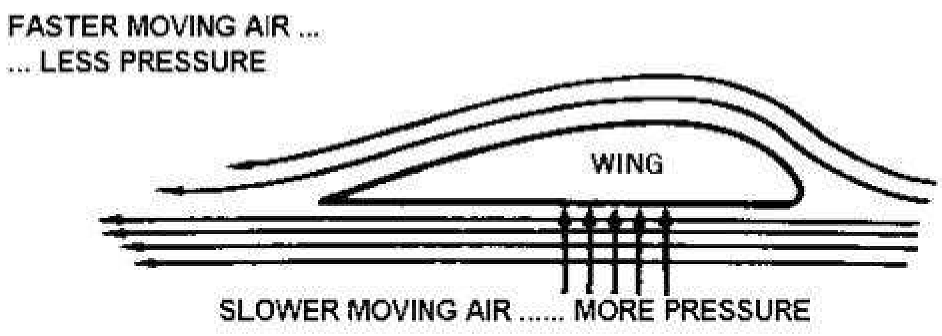
$$c = \frac{\sqrt{gh}}{2}\left(\sqrt{\frac{\tanh kh}{kh}} + \sqrt{\frac{kh}{\tanh kh}}\right) \qquad k = \frac{2\pi}{\lambda}$$





How does an aircraft generate lift?

- Bernoulli's principle:



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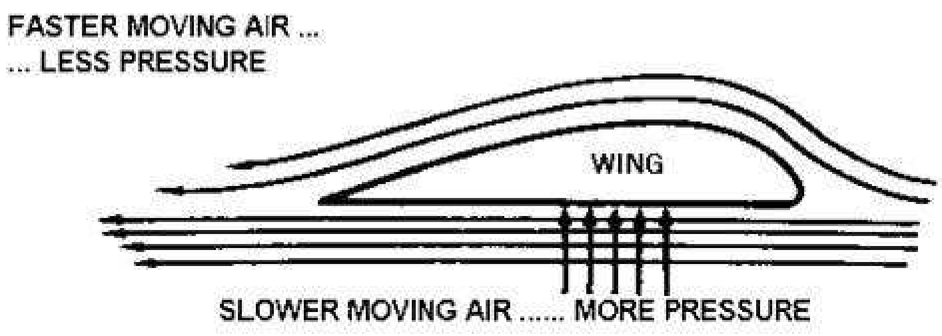
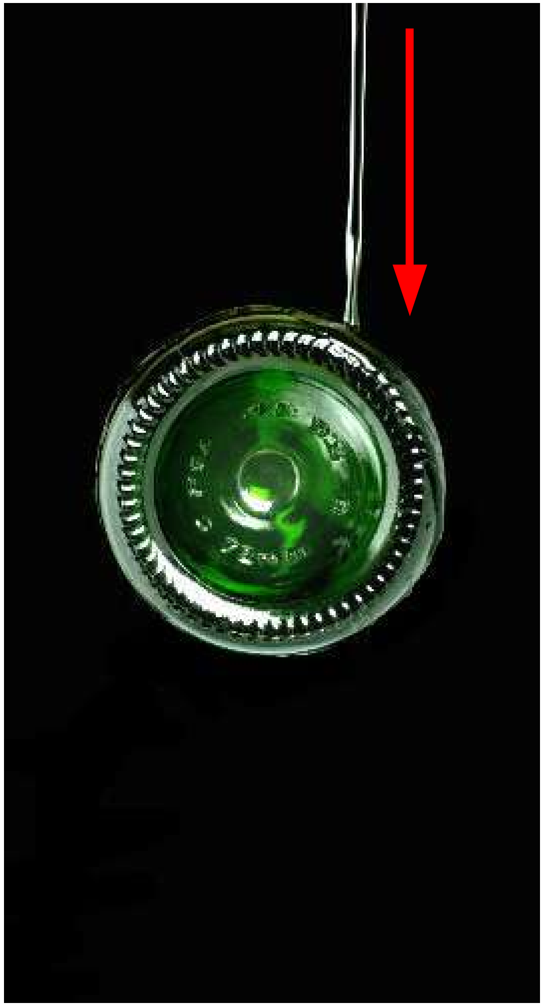


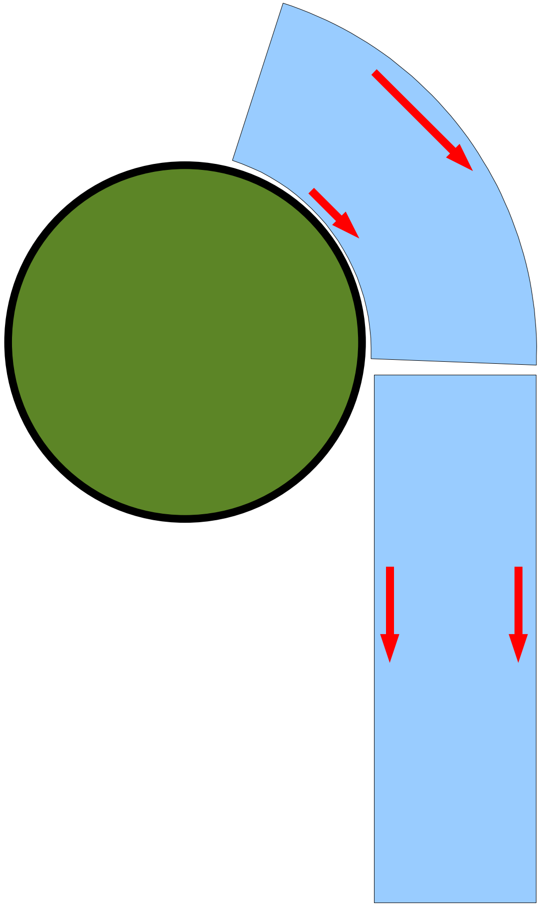
- Air is not incompressible
- Violation of Newton's 3rd law

Coandă effect

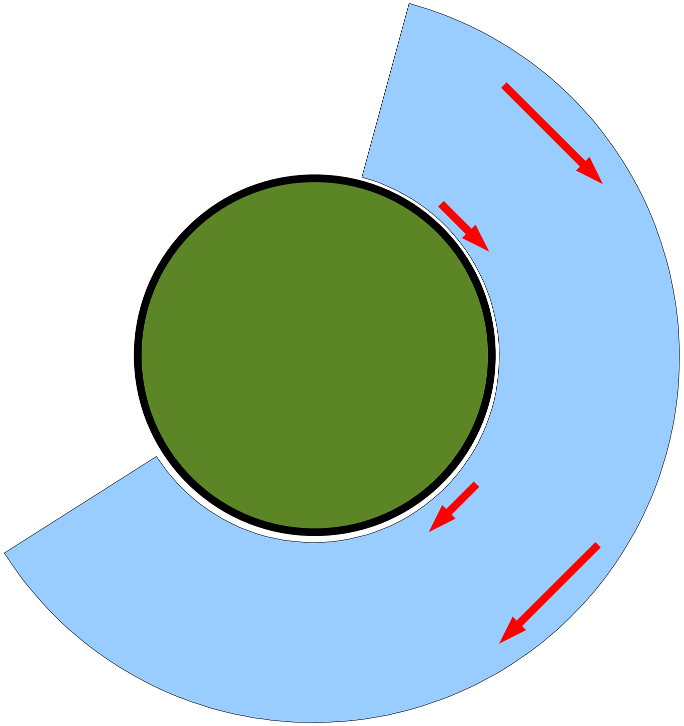


Coandă effect

Coandă effect

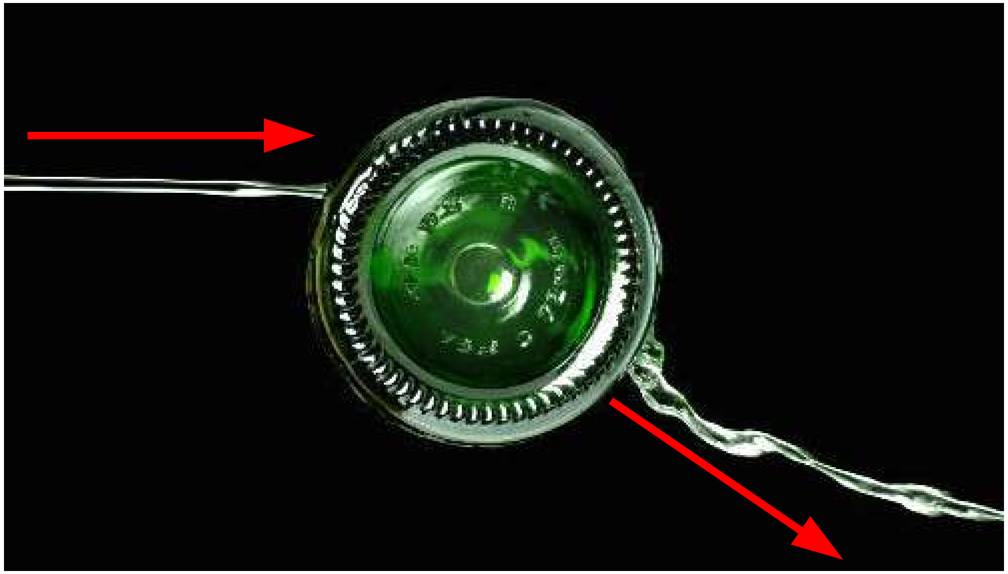


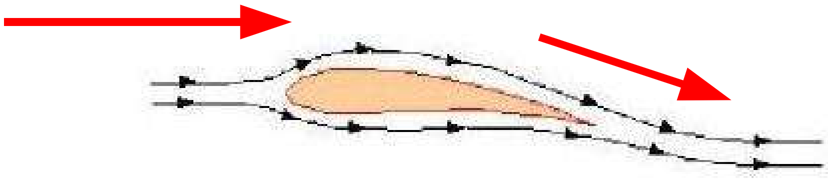
Coandă effect



How does an aircraft generate lift?

Expels mass downwards so Newton's Law pushed plane upwards

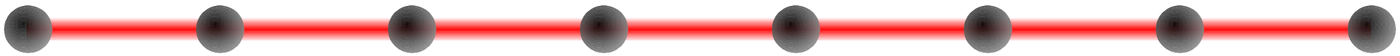




Upper surface of a wing generates lift

Quantum mechanics: electrons in solids

Atoms:



Quantum mechanics: electrons in solids

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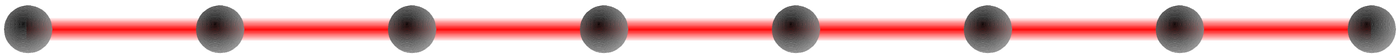
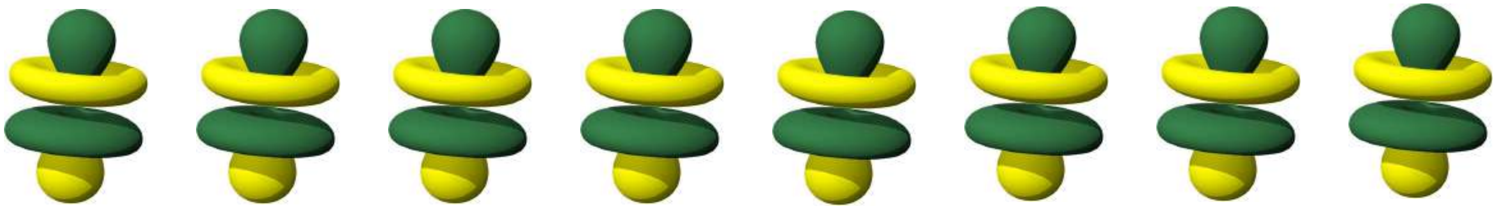


Orbitals:



Quantum mechanics: electrons in solids

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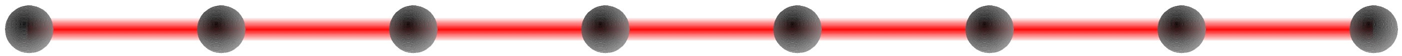

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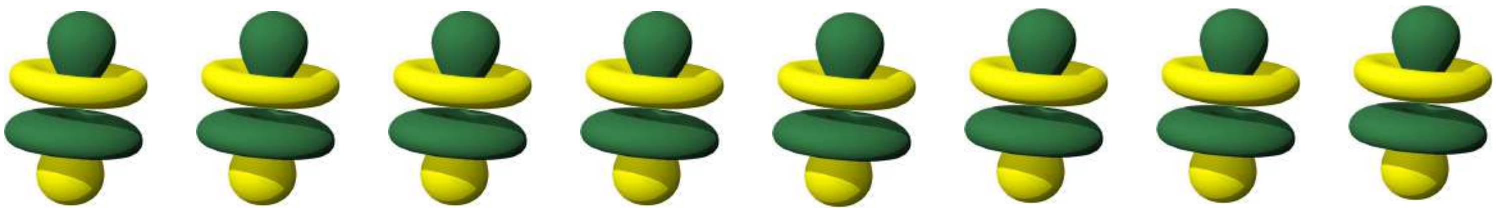

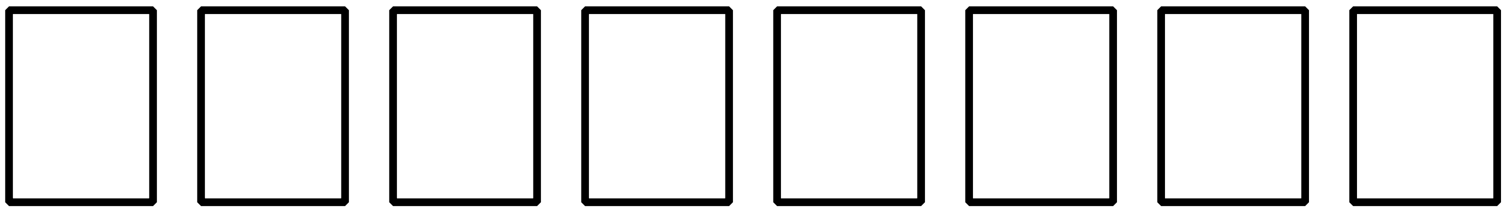

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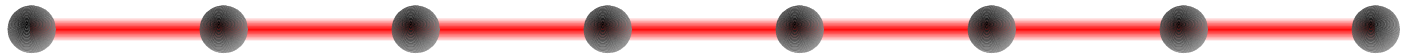

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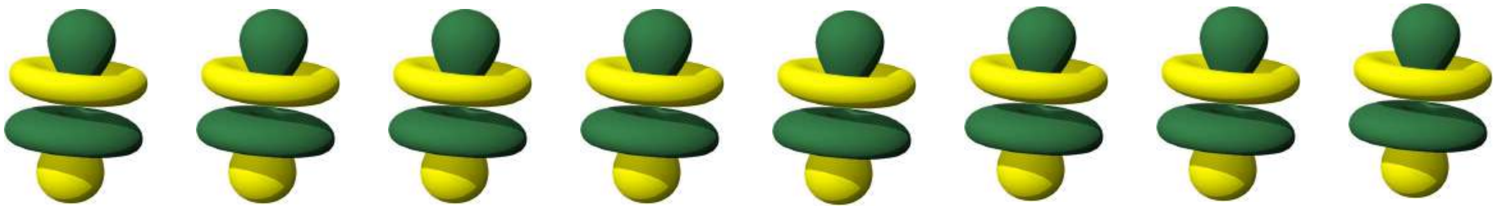
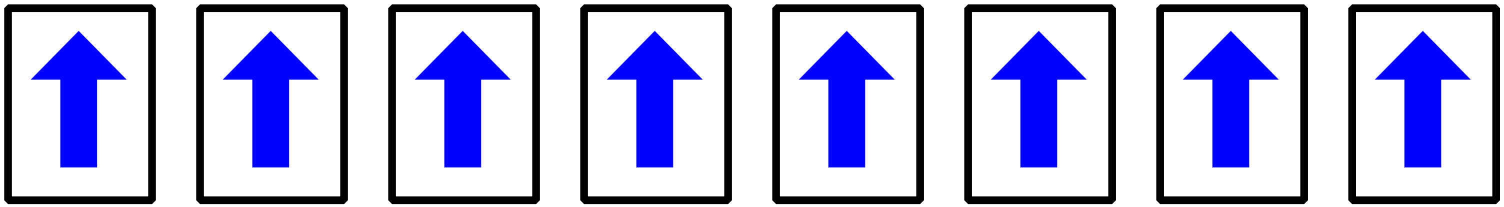


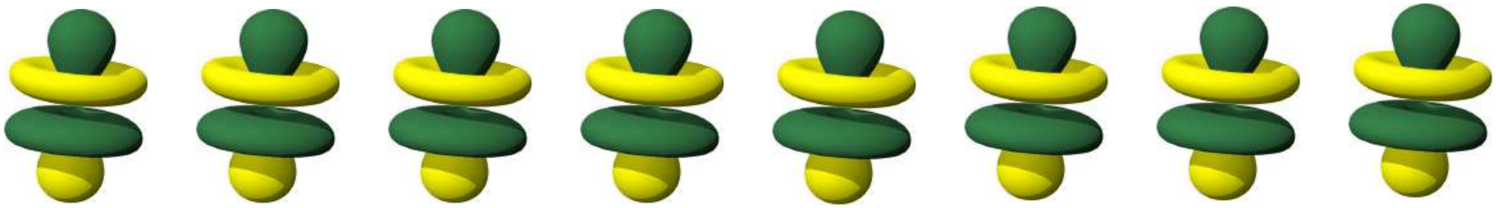
Ferro:



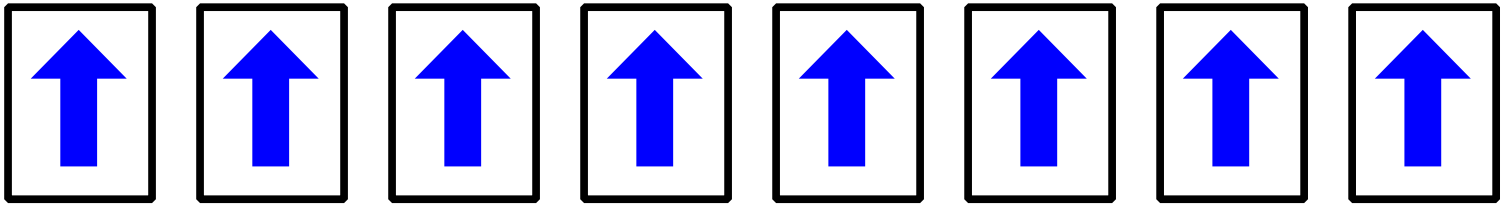
Quantum mechanics: electrons in solids

Atoms:

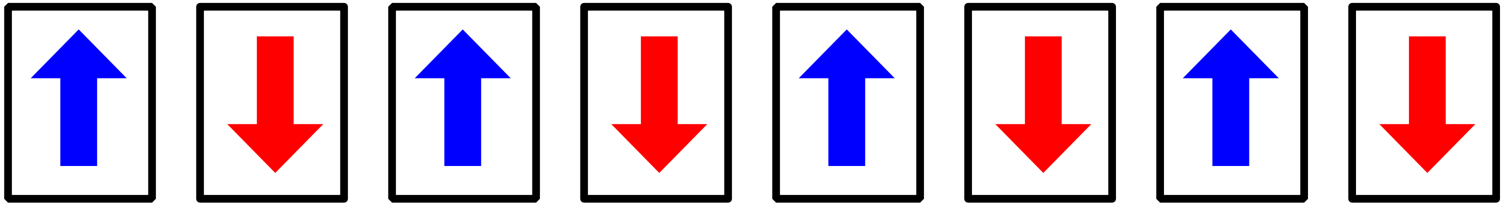
Orbitals:



Ferro:

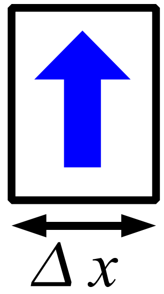


Antiferro:



Antiferromagnetic mechanism

Heisenberg uncertainty principle

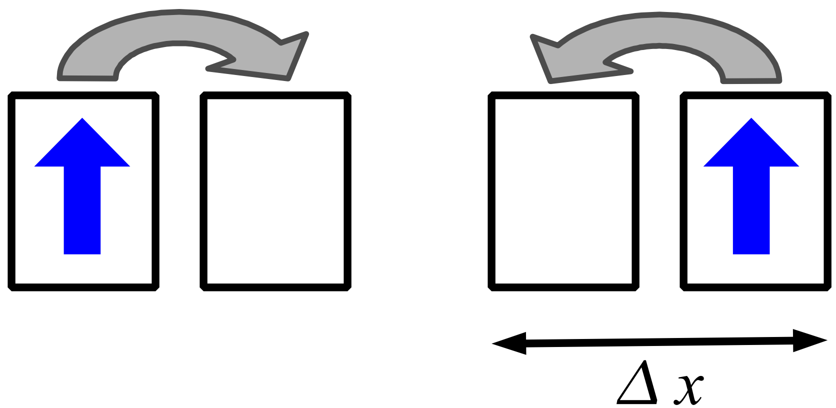


$$\Delta p \Delta x = \hbar$$

$$\Delta p = \hbar / \Delta x$$

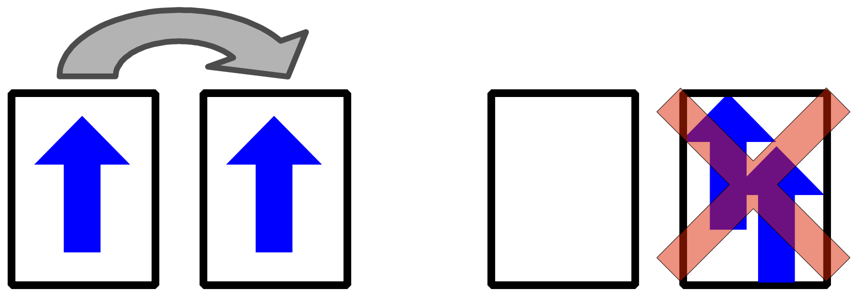
$$KE = \frac{\Delta p^2}{2m} = \frac{\hbar^2}{2m \Delta x^2}$$

Spreading lowers energy

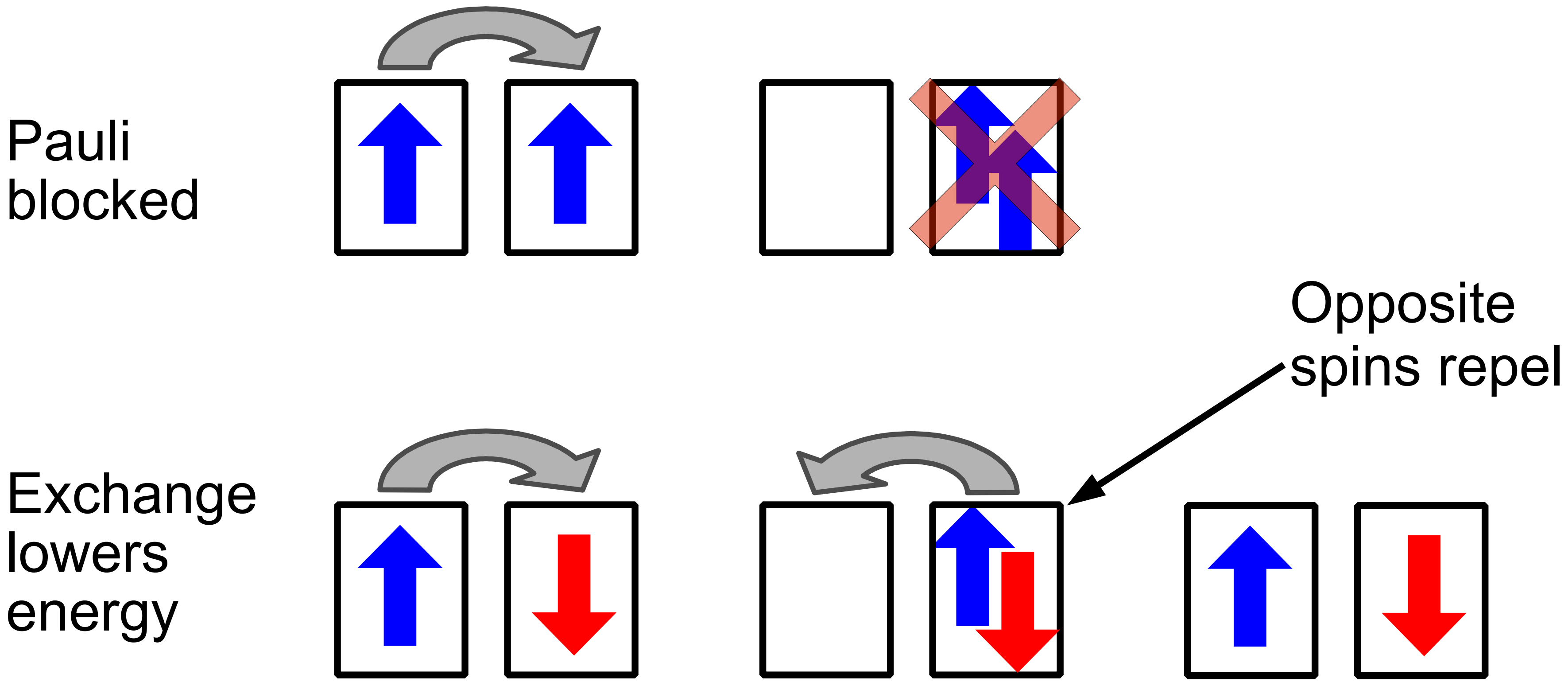


Antiferromagnetic mechanism

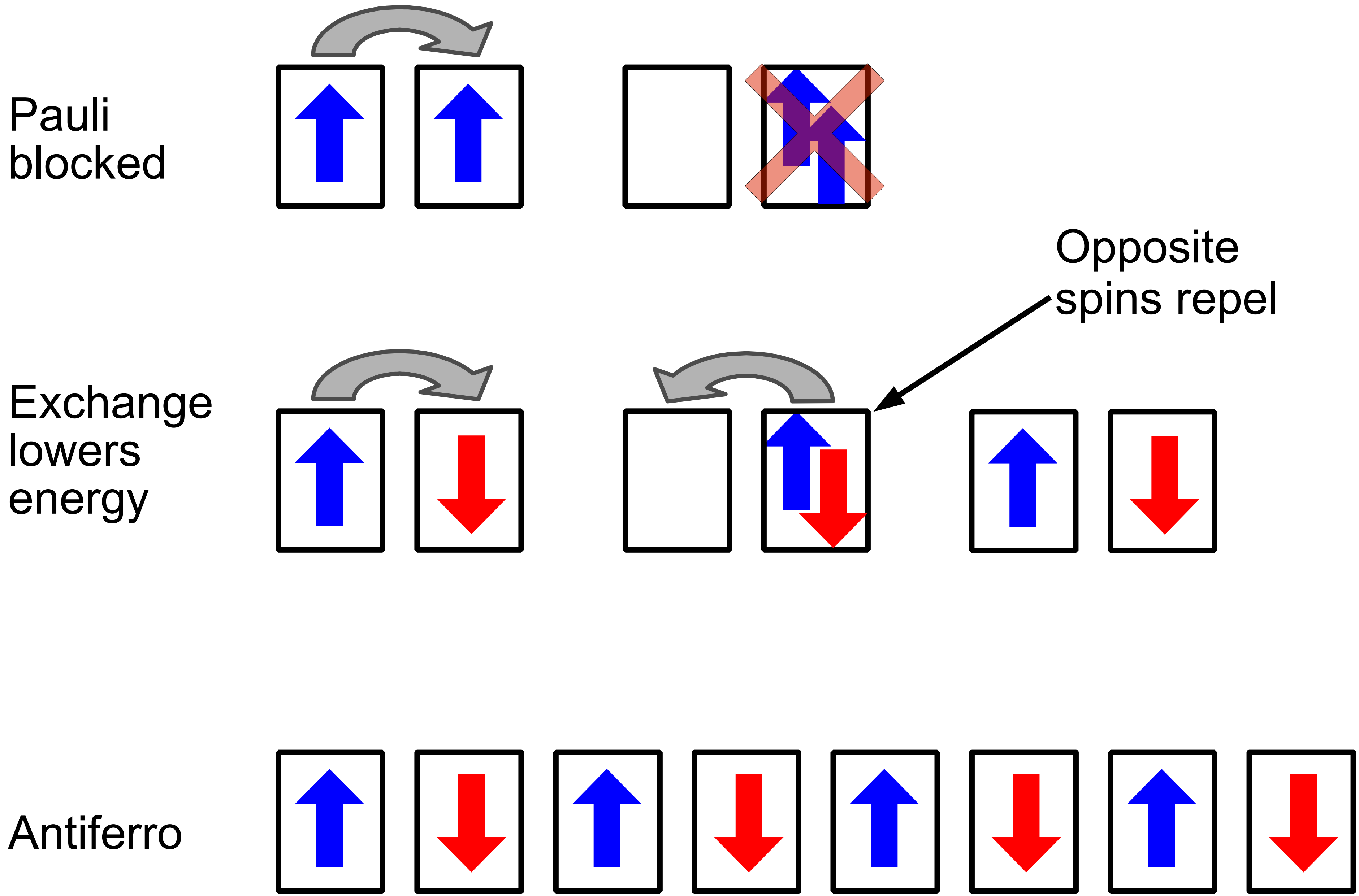
Pauli blocked



Antiferromagnetic mechanism

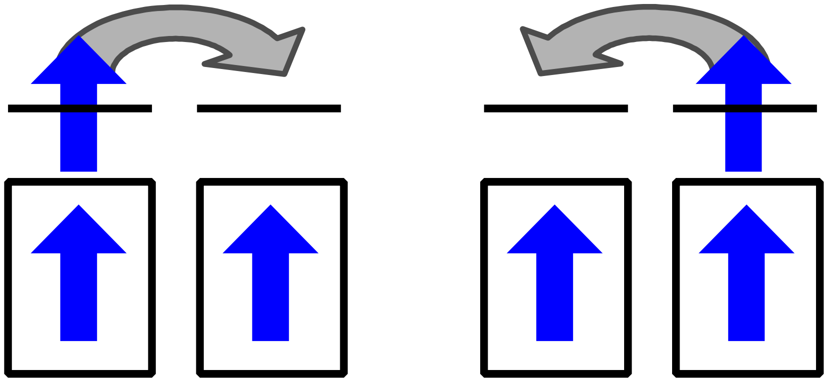


Antiferromagnetic mechanism

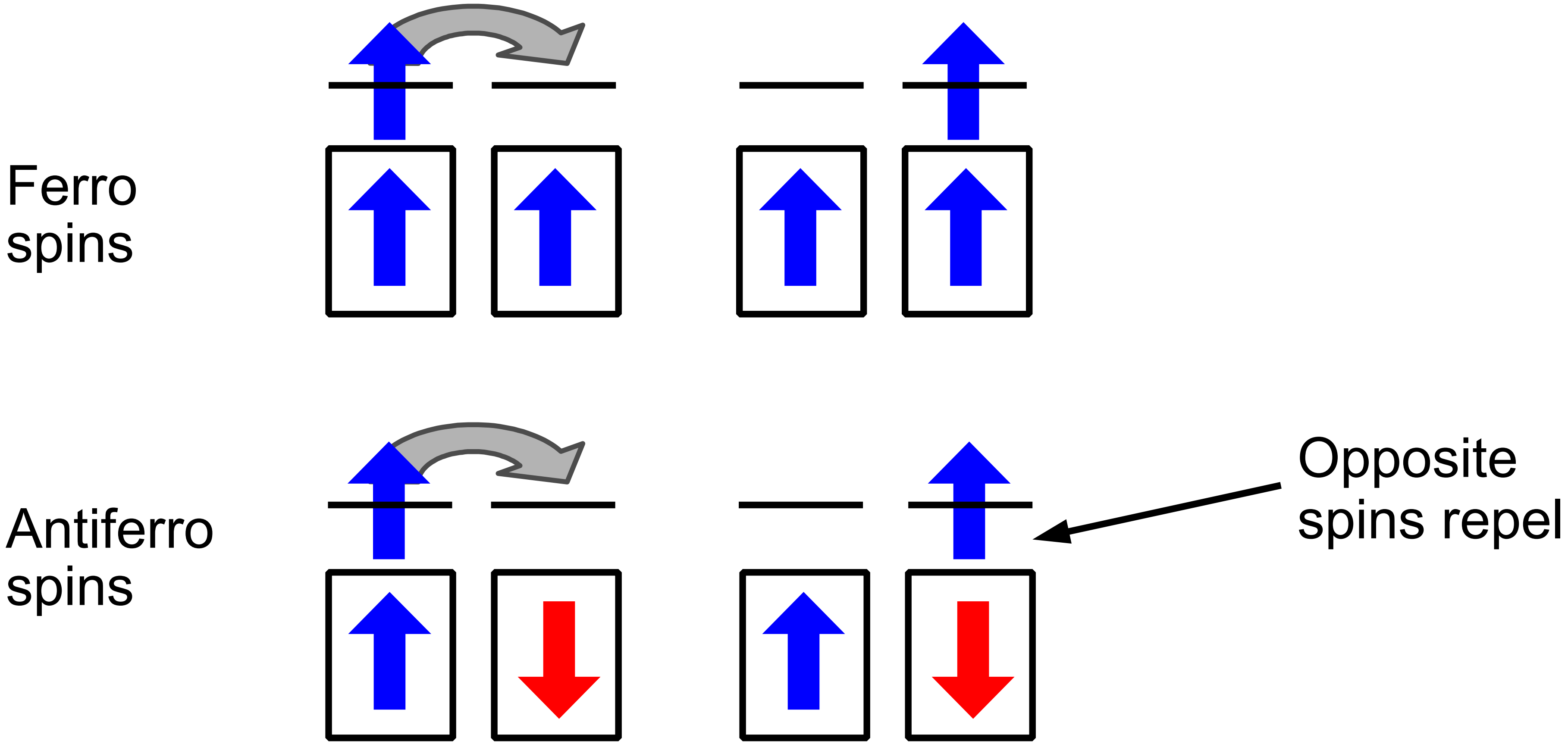


Ferromagnetism

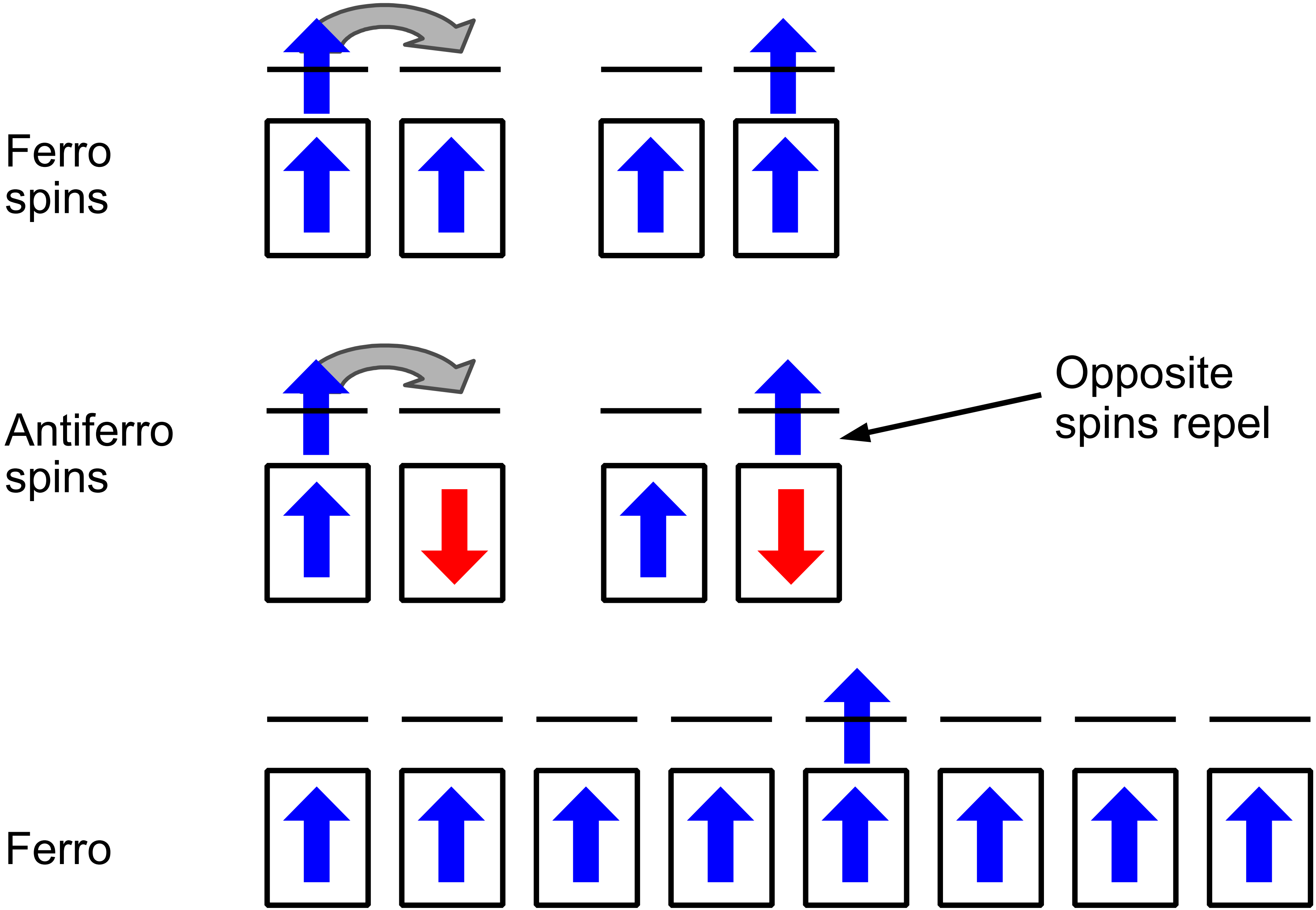
Ferro
spins



Ferromagnetism

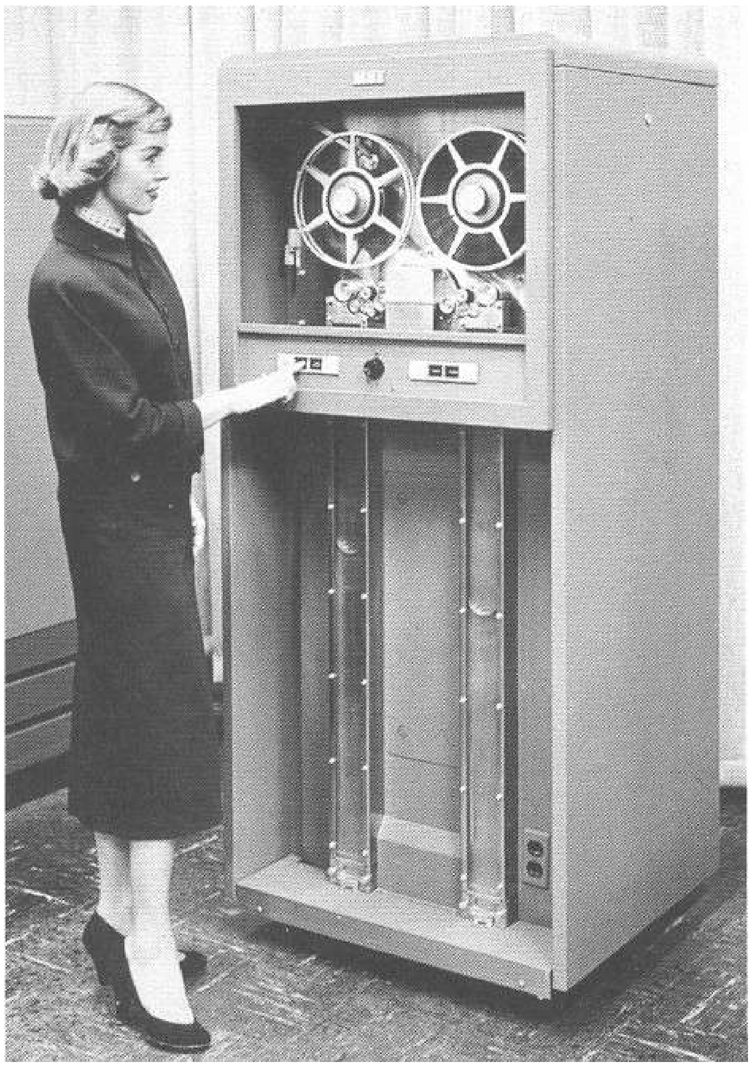


Ferromagnetism



Magnetic data storage

10½-inch tape (1953) **5 MB**



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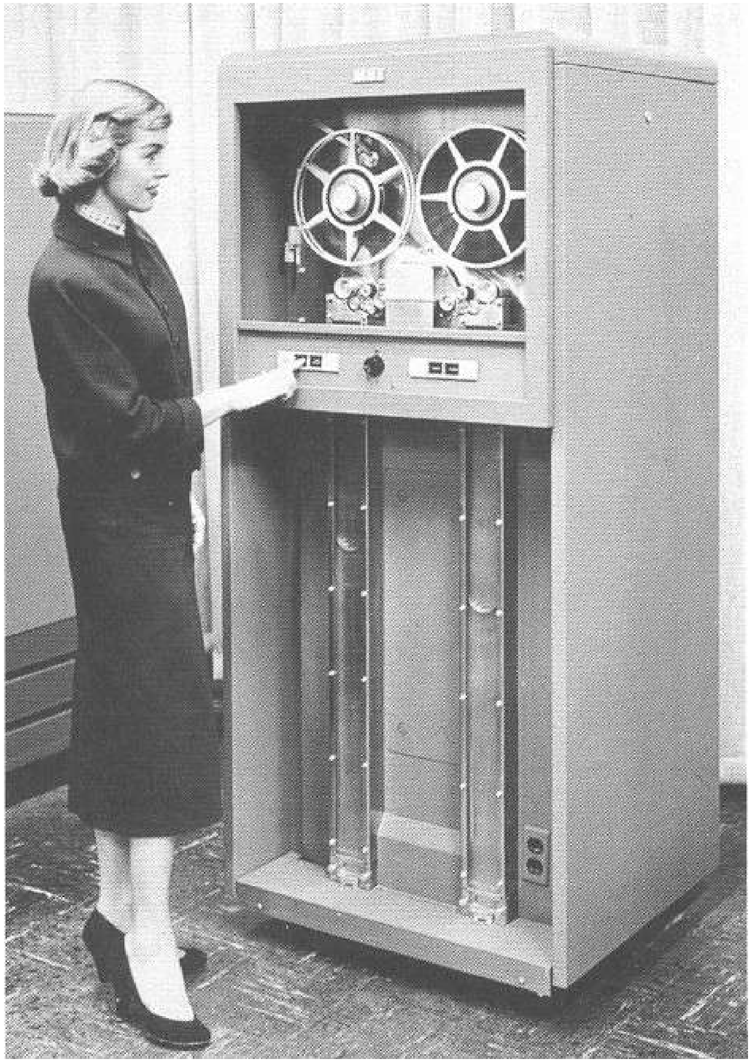


8-inch Floppy disk (1973) **250¼ kB**

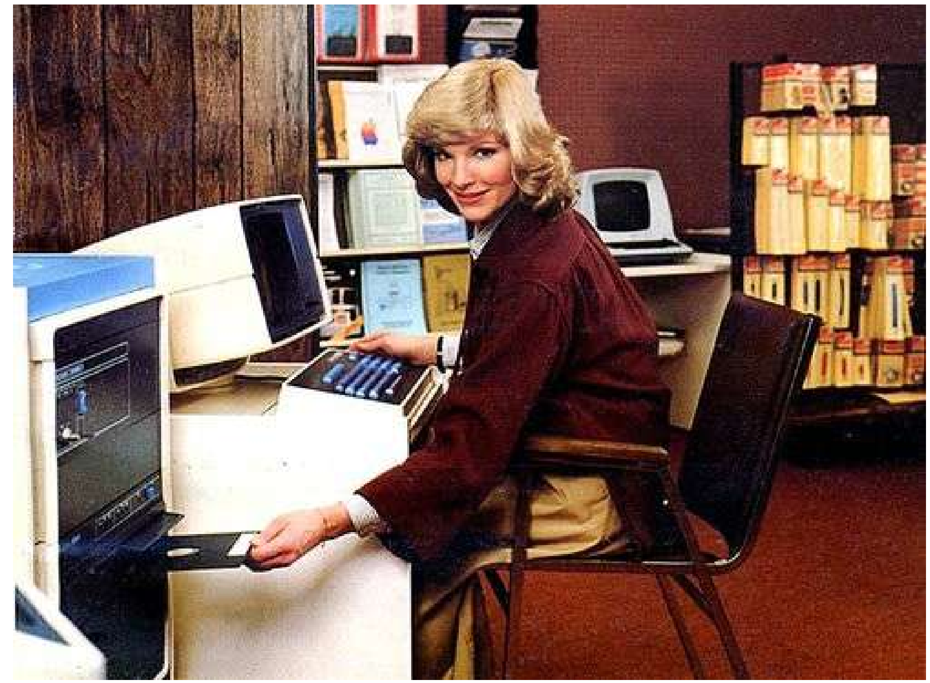
Magnetic data storage

Cassette (1979) **660 KB**

Magnetic data storage

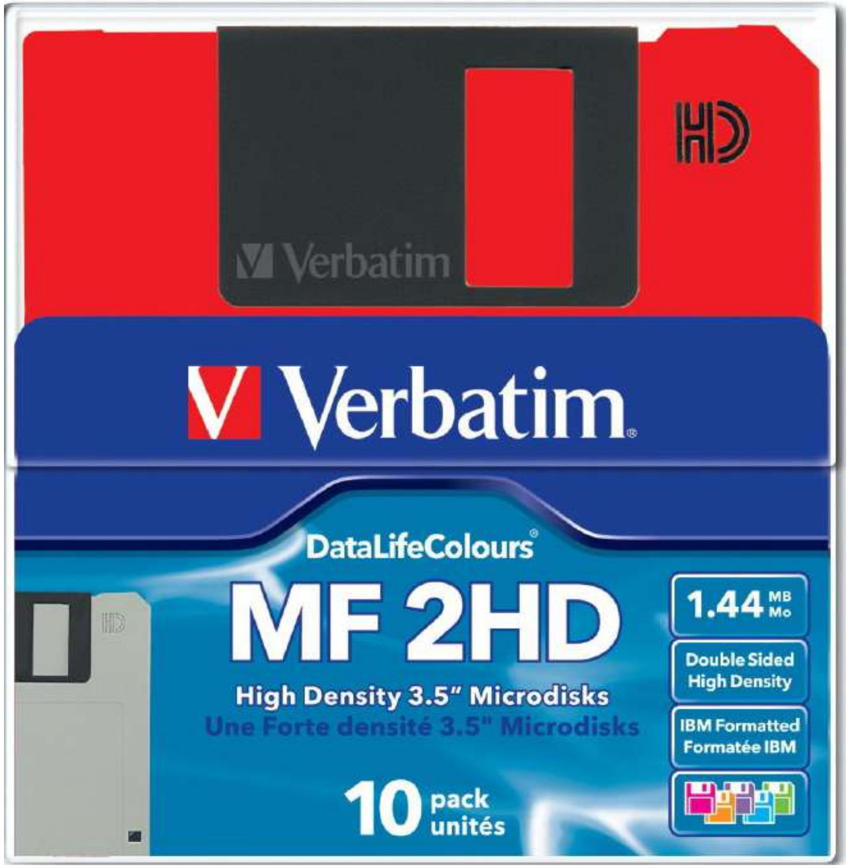
Cassette (1979) **660 KB**

5¼-inch Floppy disk (1983) **1200 KB**



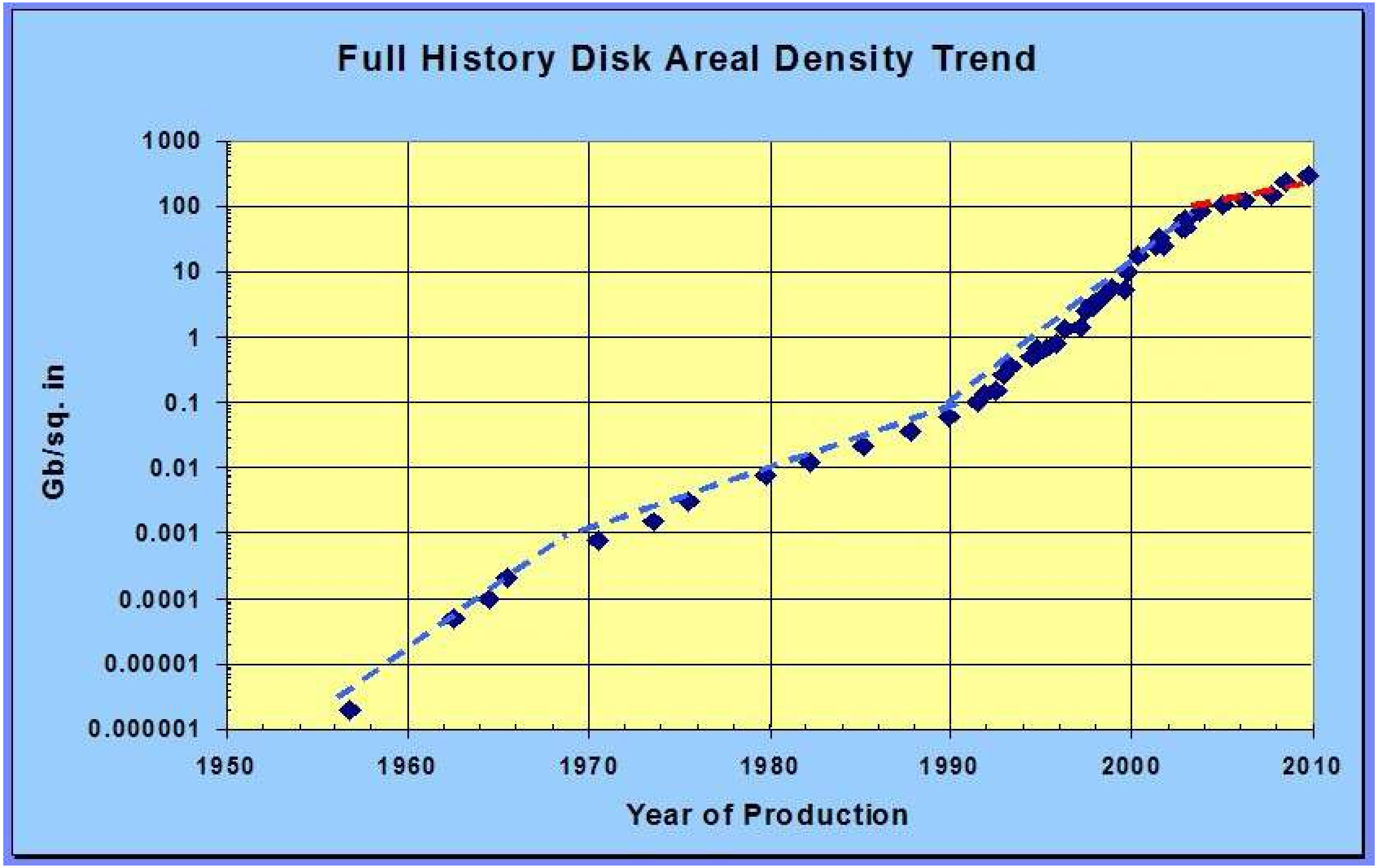
Magnetic data storage

3½-inch Floppy disk (1989) **1.44 MB**

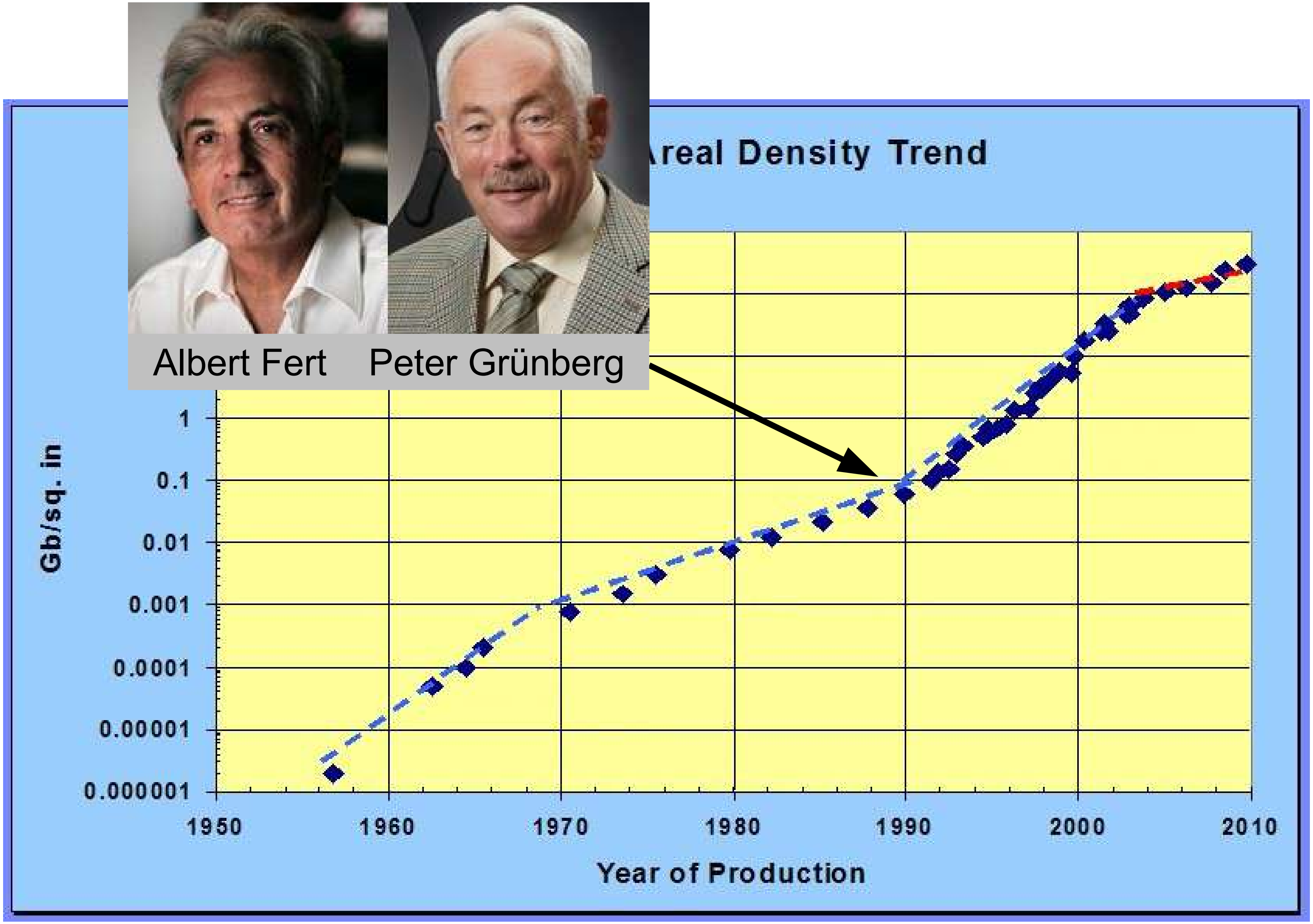


Hard disk drive (2010) **2 TB**

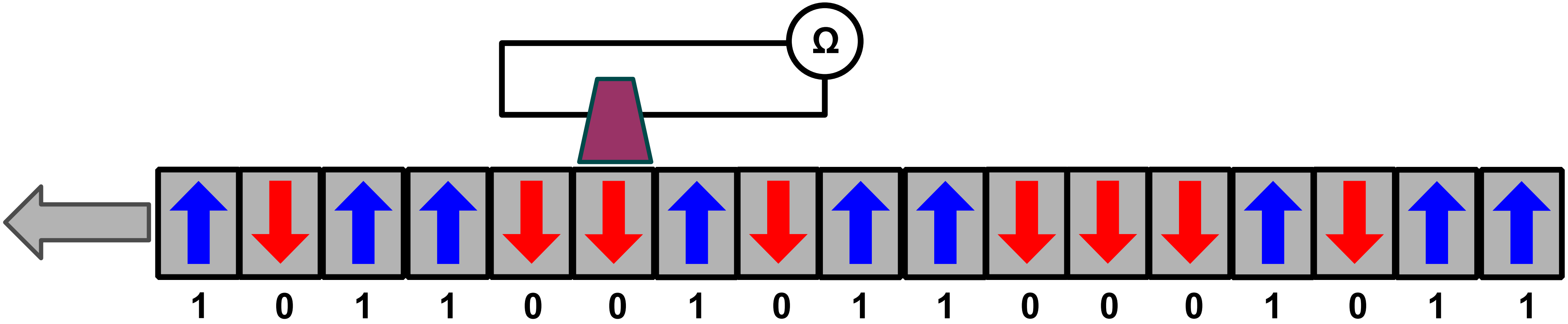
Storage over the years



Giant-magnetoresistance (1988)



Magnetic data storage



Magnetoresistance

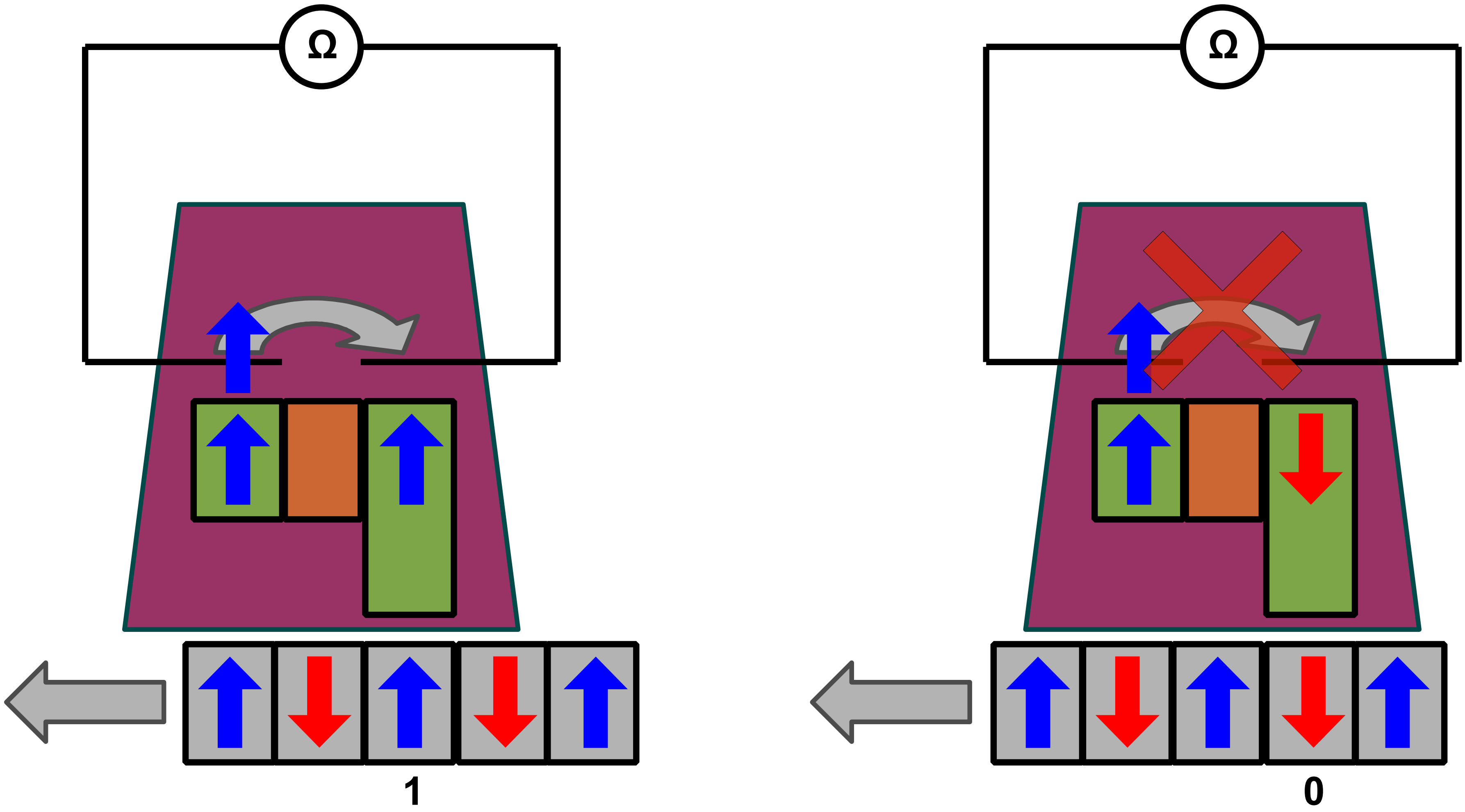
Carrier velocity due to fields

$$\boldsymbol{v} = M(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \qquad \boldsymbol{v} = \frac{M}{1+(M\,B)^2}(\boldsymbol{E} + \boldsymbol{E} \times \boldsymbol{B})$$

which is reduced by 5% in typical metals so need large magnetic domains → low data density

Giant & colossal magnetoresistance

Change in resistance is up to 100000% so can have very small magnetic domains and high data storage density



Summary: *more is different*

- Particles obeying well understood microscopic physics display important collective motion – *more is different*
- Many-body interactions coupled with quantum mechanics leads to new counterintuitive phenomena
- Real-life applications:
  - Electronics
  - Material science
  - Chemistry