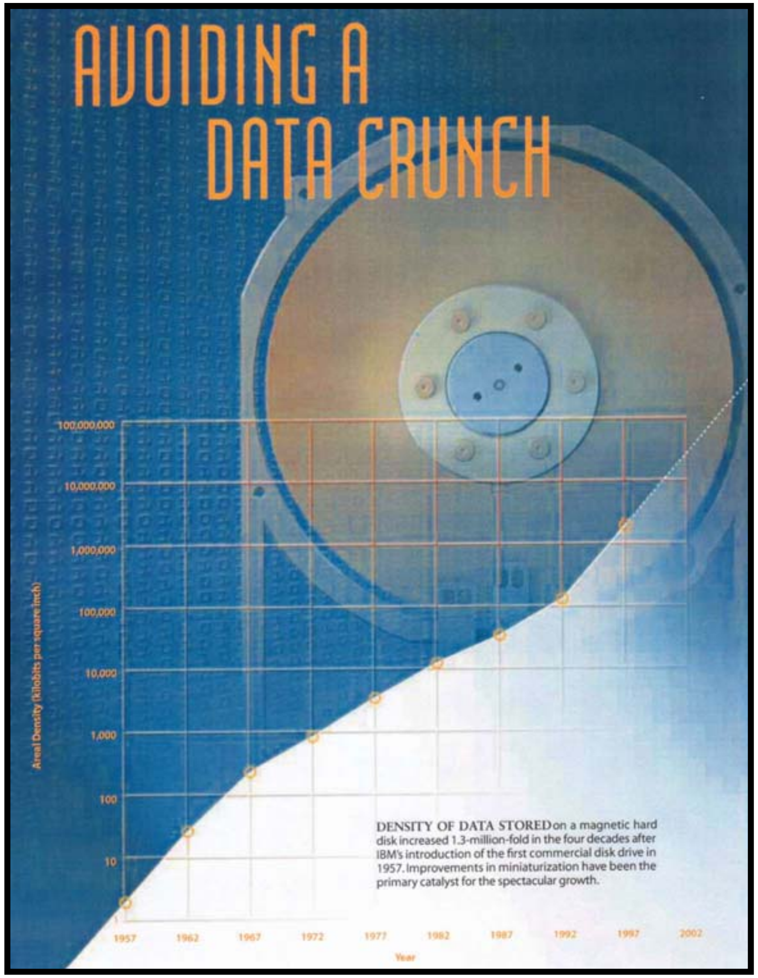
Nanomaterials

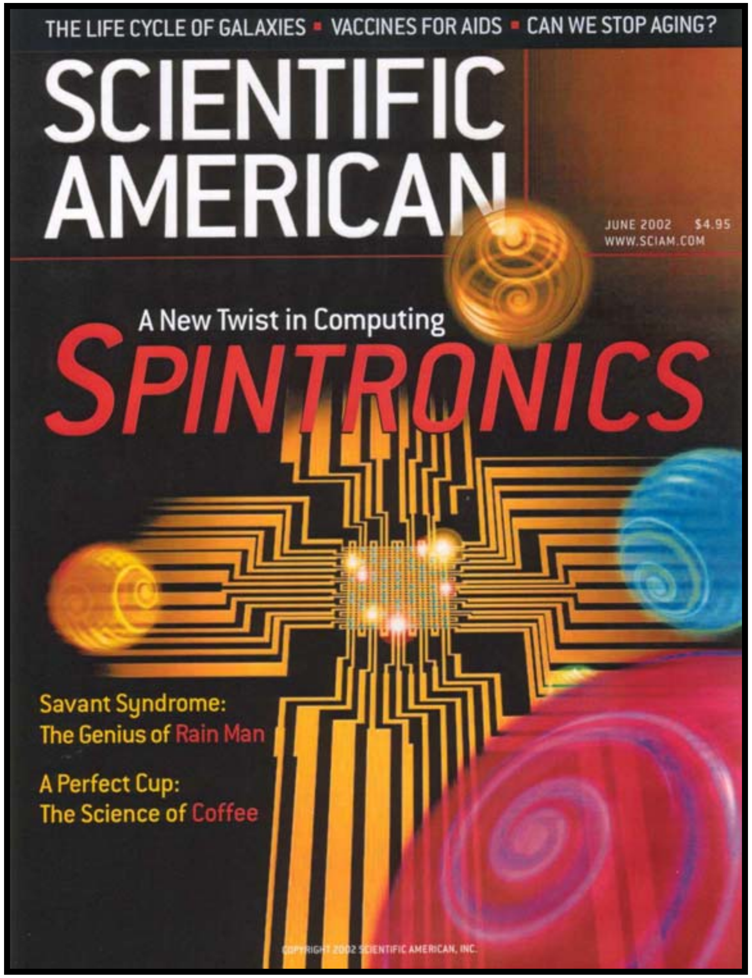
Lecture 15: Nanomagnetism

Nanomagnetism



AVOIDING A DATA CRUNCH

DENSITY OF DATA STORED on a magnetic hard disk increased 1.3-million-fold in the four decades after IBM's introduction of the first commercial disk drive in 1957. Improvements in miniaturization have been the primary catalyst for the spectacular growth.



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Review "Macro" Magnetism

At thermal equilibrium, define:

(1) Magnetization density: $M = -\frac{1}{V}\frac{\partial F}{\partial H}$

V = volume, H = magnetic field,
F = magnetic Helmholtz free energy

(2) Susceptibility: $\chi = \frac{\partial M}{\partial H} = -\frac{1}{V}\frac{\partial^2 F}{\partial H^2}$

Review "Macro" Magnetism

NOTE: Force per unit volume (*f*) exerted on a specimen by an inhomogeneous magnetic field is:

$$f = -\frac{1}{V}\frac{\partial F}{\partial x} = -\frac{1}{V}\frac{\partial F}{\partial H}\frac{\partial H}{\partial x} = M\,\frac{\partial H}{\partial x}$$

To determine M and χ, quantum mechanics is required; in particular, we need to consider the modification to the Hamiltonian by spin.

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Review “Macro” Magnetism

(1) Diamagnetism: negative susceptibility

→ induced moment opposes applied field (similar to Lenz’s Law)

→ common for noble gas atoms and alkali halide ions (e.g., He, Ne, F^-, Cl^-, Li^+, Na^+, ….)

(2) Paramagnetism: positive susceptibility

→ induced moment is favored by applied field (but is opposed by thermal disorder)

→ magnetization is immediately lost upon removal of field

→ common for isolated rare earth ions, iron (group 3d) ions (e.g., Sm^+, Er^+, Fe^{3+}, Co^{2+}, Ni^{2+}, ….)

Magnetic Ordering

In solids, electron-electron interactions lead to magnetic ordering (one of the less well-developed theories in solid state physics)

Types of interactions:

(1) Exchange interaction (electrostatic)

(2) Dipolar interaction (spin-spin coupling)

(3) Anisotropy interaction (spin-orbit coupling)

Exchange Interactions

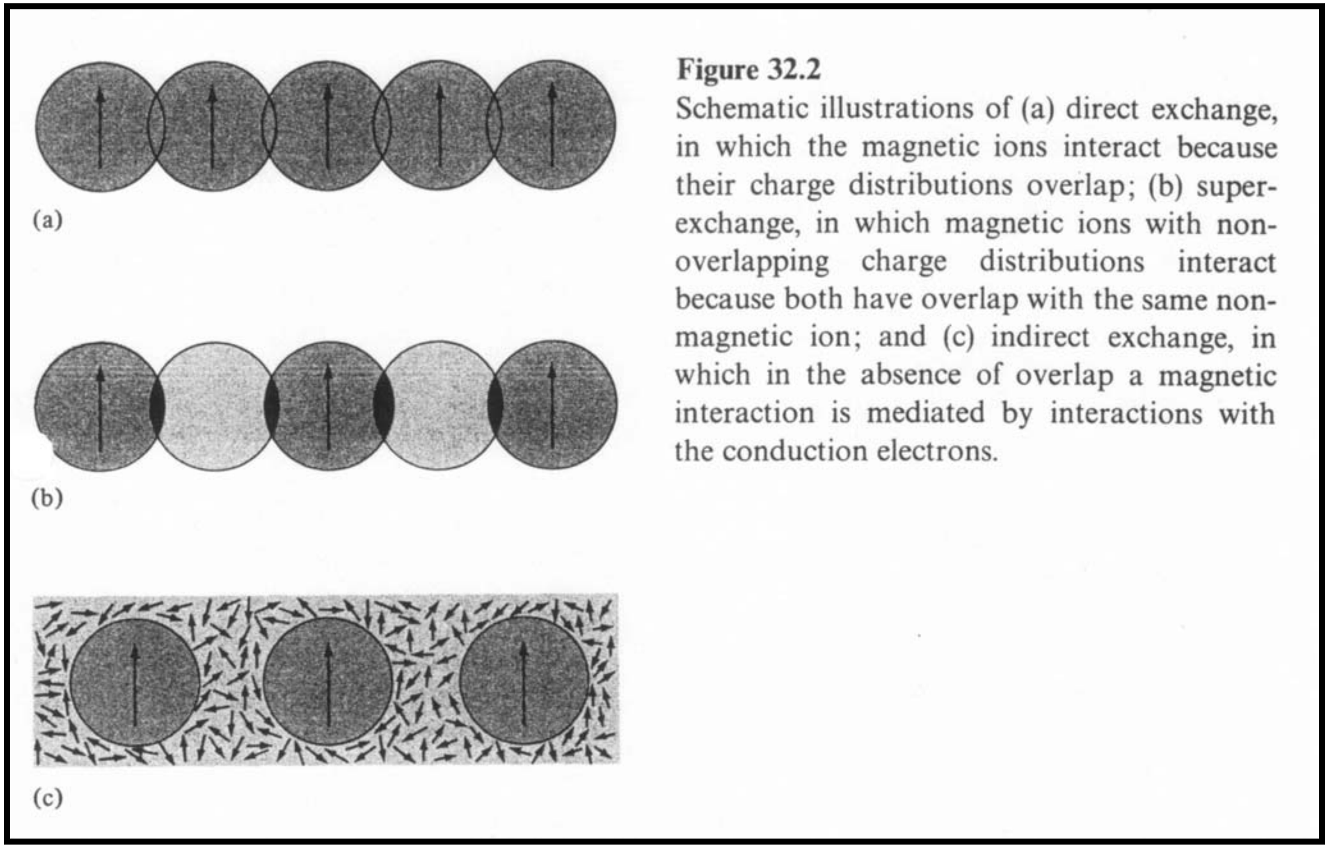


Figure 32.2
Schematic illustrations of (a) direct exchange, in which the magnetic ions interact because their charge distributions overlap; (b) superexchange, in which magnetic ions with nonoverlapping charge distributions interact because both have overlap with the same nonmagnetic ion; and (c) indirect exchange, in which in the absence of overlap a magnetic interaction is mediated by interactions with the conduction electrons.

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

Types of Magnetic Ordering

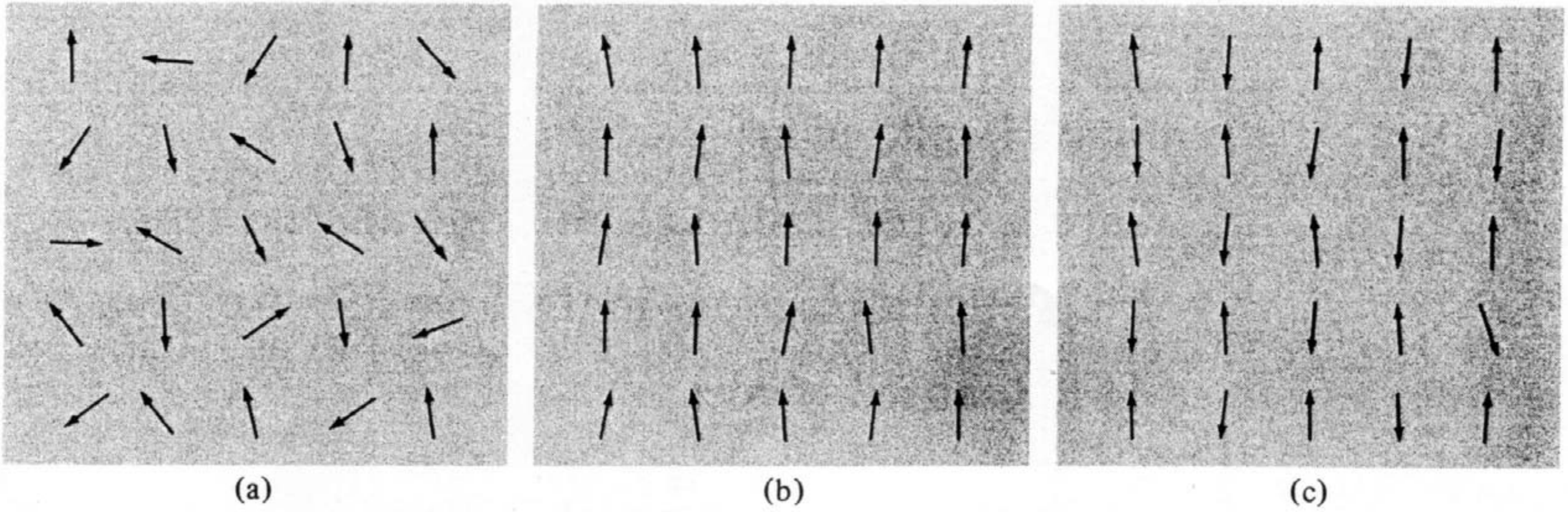
If magnetic interactions are consequential and the temperature is below T_c, a solid can exist in the following magnetically ordered states even with no applied field:

(1) Ferromagnetic: all local moments have a positive component along the direction of the spontaneous magnetization

(2) Antiferromagnetic: individual local moments sum to zero total moment (no spontaneous magnetization)

(3) Ferrimagnetic: local moments are not all oriented in the same direction, but there is a non-zero spontaneous magnetization

Types of Magnetic Ordering



(a) (b) (c)

Figure 32.1

Typical distribution of directions for the local magnetic moments when no magnetic field is present (a) in a solid with inconsequential magnetic interactions, (b) in a ferromagnetic solid below its critical temperature, and (c) in an antiferromagnetic solid below its critical temperature. Cases (b) and (c) illustrate *magnetically ordered* states.

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

Types of Magnetic Ordering

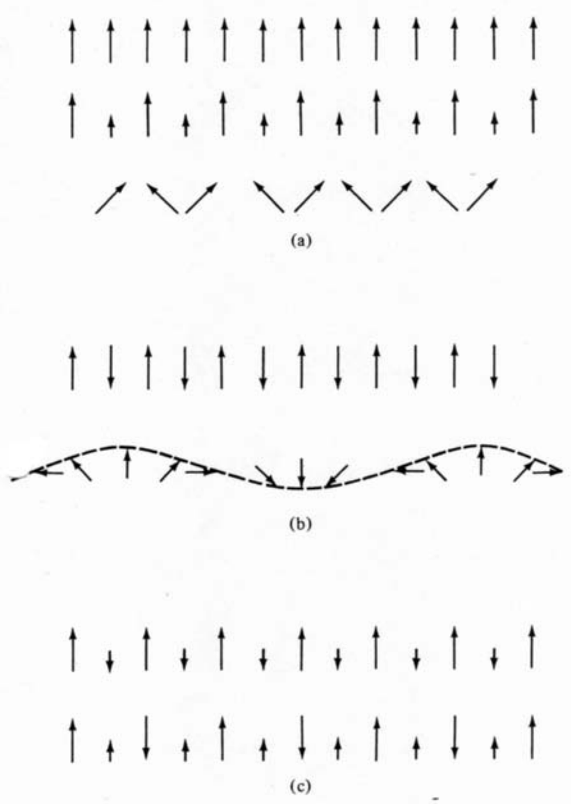


Figure 33.2
Linear arrays of spins illustrating possible (a) ferromagnetic, (b) antiferromagnetic, and (c) ferrimagnetic orderings.

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

"Unusual" Behavior of Iron

Even though T_c for iron is >1000 K, iron is normally "unmagnetized" at room temperature

However,

(1) Iron is more strongly attracted by magnetic field than a paramagnetic material

(2) Iron can be "magnetized" by stroking it with a permanent magnet

Why? We need to consider "weak" interactions besides electrostatic exchange coupling

Ferromagnetic Domains

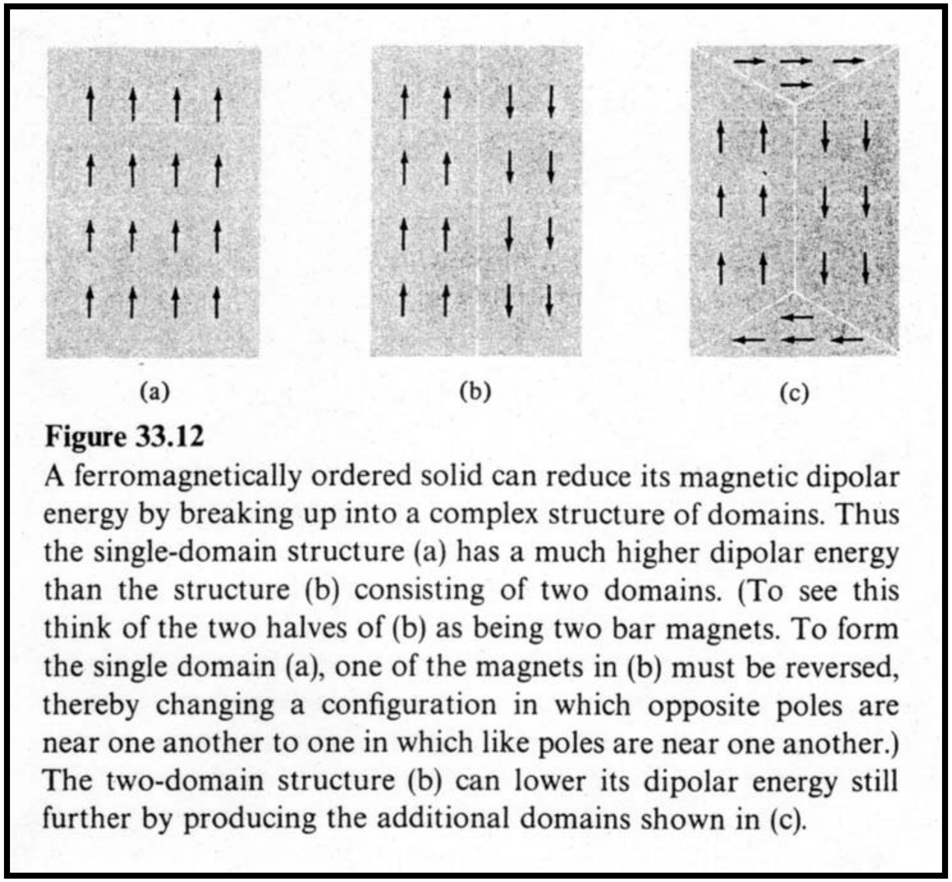
Note: (1) Exchange coupling is 1000X greater than dipolar coupling for nearest neighbors

(2) But, exchange coupling is short ranged (falls off exponentially) compared to dipolar coupling ($1/r^3$)

→ In large samples, dipolar coupling can alter spin configurations favored by short range exchange coupling

→ Overall magnetic energy is minimized by formation of domains

Ferromagnetic Domains



(a) (b) (c)

Figure 33.12

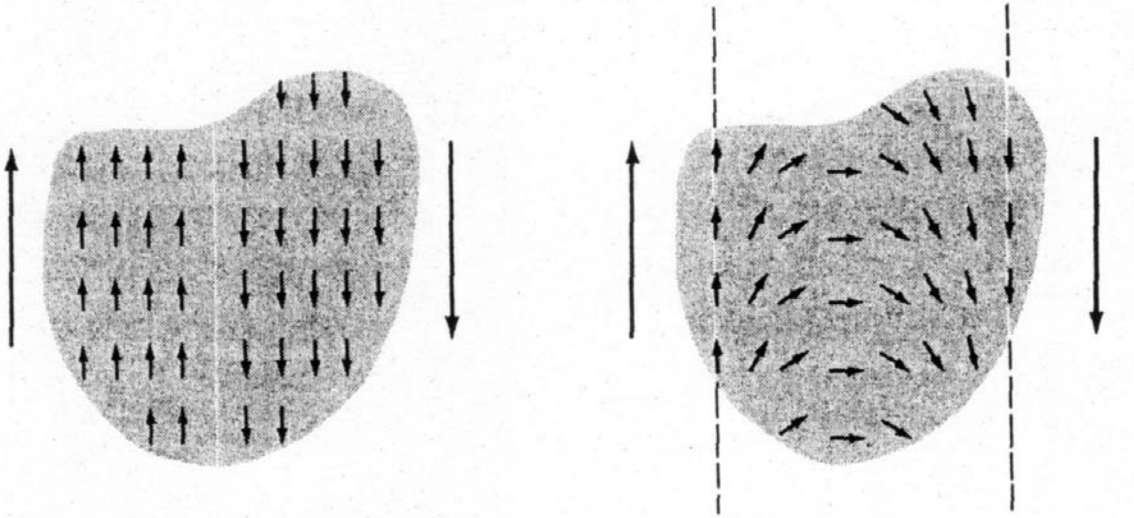
A ferromagnetically ordered solid can reduce its magnetic dipolar energy by breaking up into a complex structure of domains. Thus the single-domain structure (a) has a much higher dipolar energy than the structure (b) consisting of two domains. (To see this think of the two halves of (b) as being two bar magnets. To form the single domain (a), one of the magnets in (b) must be reversed, thereby changing a configuration in which opposite poles are near one another to one in which like poles are near one another.) The two-domain structure (b) can lower its dipolar energy still further by producing the additional domains shown in (c).

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

Domain Boundaries

- Upon domain formation, dipolar energy (bulk effect) is minimized and exchange energy is only raised for a small number of sites at the domain boundary → domain boundaries are gradual
- Domain boundaries are not infinitely large due to spin-orbit coupling
- Overall spin energy depends on angle of spin with respect to crystal axes → anisotropy energy
- Domain wall thickness is dictated by a competition between exchange and anisotropy energies

Domain Boundaries



(a)

(b)

Figure 33.13
Detailed view of a portion of domain wall showing (a) an abrupt boundary and (b) a gradual boundary. The latter type is less costly in exchange energy.

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

Magnetization of “Unmagnetized” Iron

(1) In small fields, domains reversibly align with fields by smooth motion of domain walls

(2) At high fields, domains irreversibly align with fields → defect mediated process → defects can prevent domain walls from returning to original zero bulk magnetization

→ Magnetization of iron (non-zero bulk magnetization at zero field)

→ A reverse field is required to return to zero bulk magnetization (coercive force)

→ Hysteresis in $B = H + 4\pi M$ vs. H curves

Magnetic Hysteresis

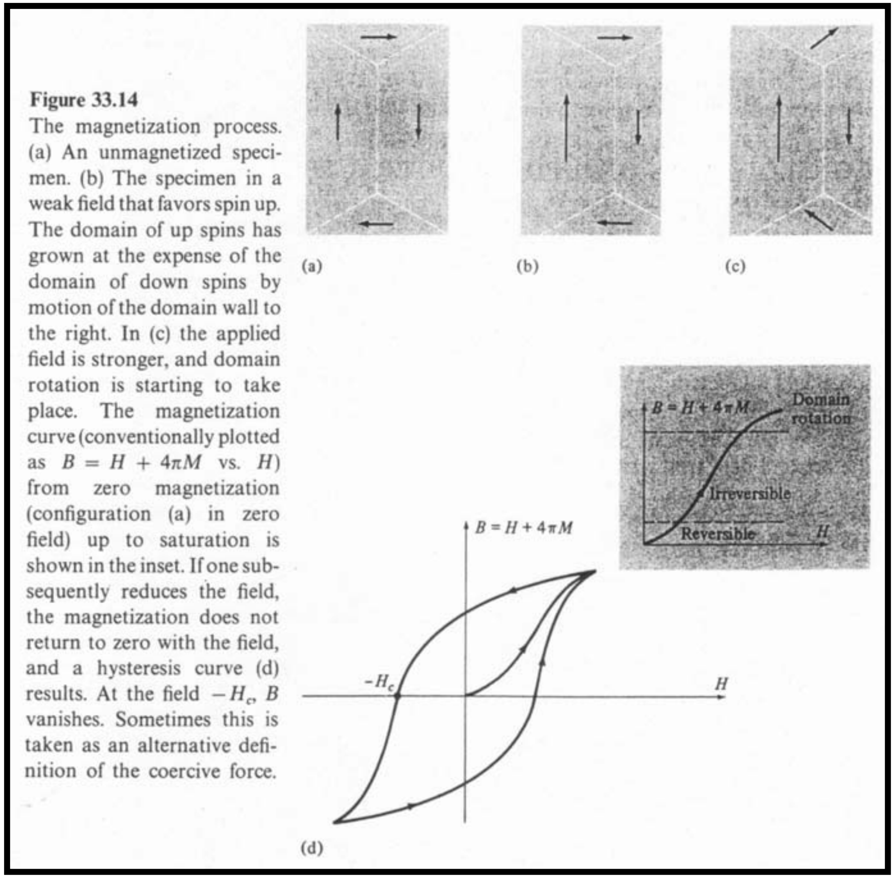
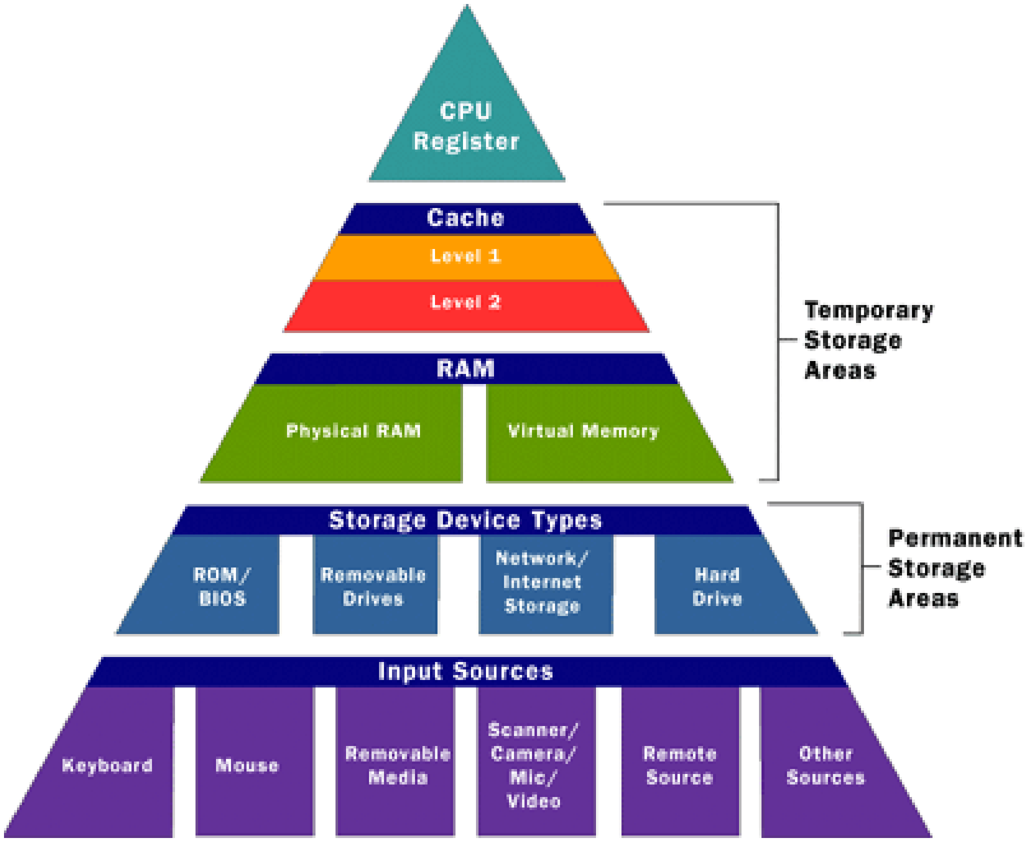


Figure 33.14
The magnetization process. (a) An unmagnetized specimen. (b) The specimen in a weak field that favors spin up. The domain of up spins has grown at the expense of the domain of down spins by motion of the domain wall to the right. In (c) the applied field is stronger, and domain rotation is starting to take place. The magnetization curve (conventionally plotted as $B = H + 4\pi M$ vs. H) from zero magnetization (configuration (a) in zero field) up to saturation is shown in the inset. If one subsequently reduces the field, the magnetization does not return to zero with the field, and a hysteresis curve (d) results. At the field $-H_c$, B vanishes. Sometimes this is taken as an alternative definition of the coercive force.

N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Harcourt, 1976.

Hierarchy of Computer Memory



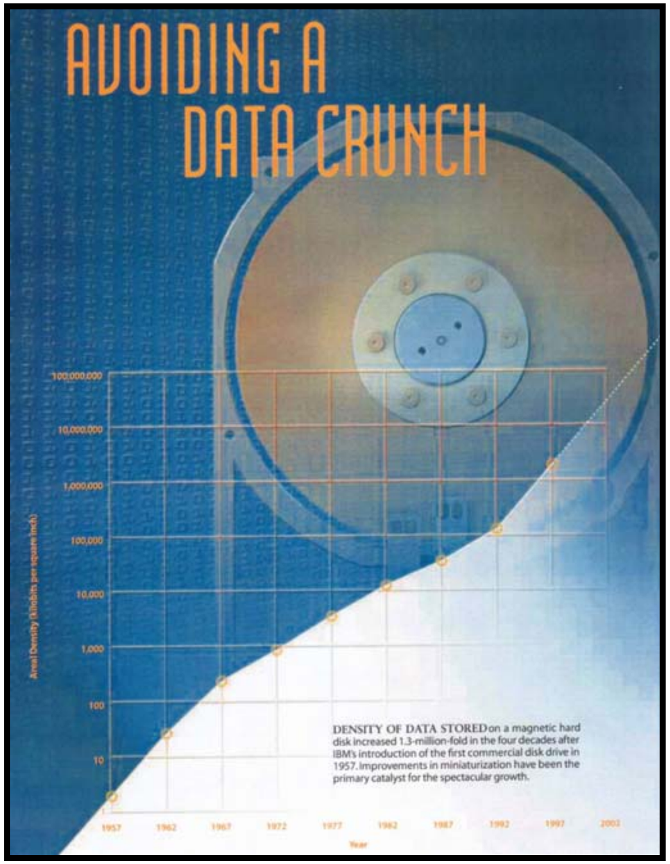
<u>Issues</u>:

(1) Cost
(2) Data Storage Density
(3) Access Time
(4) Power Dissipation
(5) Volatility

- What is the role of nanomagnetism?
- What are the alternatives?

http://computer.howstuffworks.com/computer-memory1.htm

Magnetic Miniaturization



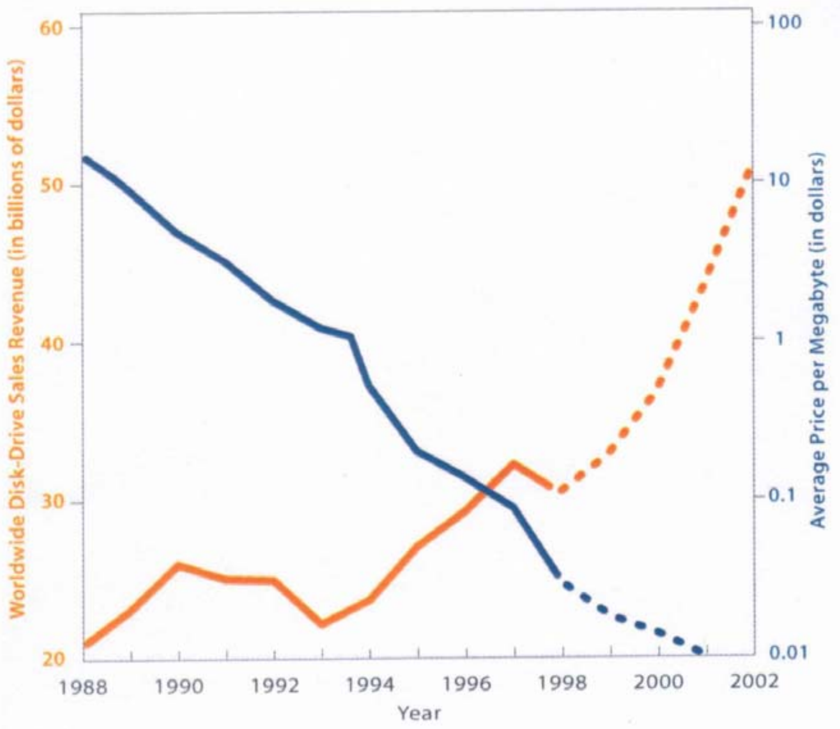
DENSITY OF DATA STORED on a magnetic hard disk increased 1.3-million-fold in the four decades after IBM's introduction of the first commercial disk drive in 1957. Improvements in miniaturization have been the primary catalyst for the spectacular growth.

<u>Capacity of magnetic hard disks</u>:

- 1980's: 30% growth per year
- early 1990's: 60% growth per year
- late 1990's: 130% growth per year
- disk capacity doubling every 9 months (twice the pace of Moore's Law)

J. W. Toigo, *Scientific American*, **282**, 58 (2000).

Economics of Magnetic Storage



SALES OF HARD-DISK DRIVES have soared as costs per megabyte have plummeted. Sales revenues are expected to grow to $50 billion in 2002.

J. W. Toigo, *Scientific American*, **282**, 58 (2000).