The story so far:

- Devices based on ferromagnetism have found tremendous utility in technology.
- Ferromagnetism at the nm scale is increasingly important, and physical effects (*e.g.* superparamagnetism) not usually seen in large devices will become relevant imminently.
- Physics of carriers in ferromagnets is an active area of research - the interplay between magnetization and current is still being explored.

Today:

- Extraordinary magnetoresistance
  - Learning a lesson from a nanostructured material, and applying it to an engineered device.
- Magnetic Random Access Memory (MRAM)
  - Using GMR and TMR in a 21st century form of core memory.
- Other applications of nanoscale magnetic particles
  - Magnetorheological fluids
  - Chemical or immunoassay
  - Medical applications
Extraordinary Magnetoresistance

In 1998, Thio and Solin at NEC were studying an extremely narrow band gap semiconductor, Hg$_{x}$Cd$_{1-x}$Te.

They discovered, much to their surprise, that this material exhibited an extremely large magnetoresistance at room temperature:

EMR

What is going on in this material?

Electrons dominate transport in this material because $\mu_e \sim 10^5$ cm$^2$/Vs even at room temperature (!) (very small electron effective mass), and $\mu_e/\mu_h \sim 200$.

Compositional fluctuations on length scales < 1 micron can result in small inclusions of metallic material with much higher conductivity than the nominal semiconductor:
EMR - mechanism

What do these high conductivity inclusions do?

- In substantial magnetic fields, $B$ is perpendicular to $E$ because the Hall field is very large.
- For very metallic inclusions, $E$ is perpendicular to the surface of the inclusion.

Result:

- In low magnetic fields, current flows mostly through inclusions - conductance is high.
- In high enough fields, current flows mostly \textit{around} inclusions - conductance much lower.

EMR - application

Once the mechanism was understood, Solin \textit{et al.} started engineering structures to magnify this effect.

Now use \textit{n}-type InSb film (again, high mobilities, largely because $m_e \sim 0.014 m_0$).

Instead of accidental inhomogeneous pockets, deliberately introduce Au regions (Ohmic contact to \textit{n}-InSb).
EMR - application

Nonmagnetic read head (!) with very narrow active region and large MR effects. Should be immune to magnetization noise, since contains no FM material.

Magnetic Random Access Memory

The same spin-dependent scattering that has been used to produce GMR and TMR materials for HDD read heads can be used for nonvolatile computer memory.

Remember ferrite cores?
MRAM

Two possible architectures:

- GMR-based
- TMR-based

IBM betting on TMR design.

Refining tunnel junctions - 1 nm Al$_2$O$_3$ tunnel barriers, FeCo alloy for ferromagnet layers.

Imagine:

- As fast as DRAM.
- As nonvolatile as flashRAM.
- Instant-boot computers.

Motorola, IBM trying to move this technology into production by 2004.

Motorola has already demonstrated 1Mb MRAM chip (June ‘02).
Other applications of nanoscale magnetism

- Magnetoassay
- Magnetorheological fluids
- Medical applications

Magnetoassay

There is a big market for biocompatible FM nanoparticles.

The basic idea:
- Functionalize outside of biocompatible FM particle with particular compound that binds to some analyte.
- Expose to bio system and see whether things bind to the magnetic particle.
Magnetoassay

Problems:

- Most magnetic materials aren’t very biocompatible.
- Often researchers try to win by mixing materials with high $M$ values into relatively inert polymer beads.
- Downside: beads end up being large.
- Tricky to handle FM particles without them sticking together.

Magnetoassay

Advantages:

Cheap, fast, reliable, easy to detect w/o fancy optics.

Image from Naval Industrial Partners website
Magnetorheological fluids

Ferrofluids are colloidal suspensions of sub-micron FM particles (often Fe$_3$O$_4$).

Without an applied magnetic field, just act like a viscous fluid.

With an applied magnetic field, effective viscosity can change by several orders of magnitude (!):

Magnetorheological fluids

Highly useful in things like magnetic clutches.

Suggested for applications like body armor.

Suggested for magnetic actuation in medical applications

Image from Technorama.ch website
Medical applications

Similar to magnetooassay, only this time for treatment.

Coat nanoscale FM particles with compound that binds to desired analyte (e.g. prostate specific antigen).

Allow biocompatible FM particles into body.

• Locate analyte by FM resonance.
• Cook tumors by FM resonance heating.
• MRI contrast agents