Check your grade book !!

Make sure all scores are entered correctly.

Errors do occur, occasionally.

Second Exam: Wednesday, November 6, in class

- Open notes (your handwriting), closed book. I will supply essential formulas.
- The exam will cover from Griffiths, section 3.4.4 (dipole field) through section 6.3 (magnetic problems with boundary conditions)
- This was completed at the beginning of Monday's (Oct. 28) lecture.
- Homework 10 (due today) covers this material as well.
  The solution will be posted on Tuesday.
- Monday will be a review lecture. Monday's discussion will also be a review.

Suggested practice homework problems from Griffiths: (You've already seen some of them):

- Chapter 3: 31, 32, 33
- Chapter 4: 4, 5, 6, 9, 10, 11, 15, 18, 19, 20, 22, 31, 32, 33
  More difficult: 24, 25, 29, 36
- Chapter 5: 4, 5, 6, 8, 9, 10, 13, 14, 15, 16, 22, 23, 24, 25, 26, 35, 47, 58,
- Chapter 6: 1, 3, 5, 7, 8, 9, 12, 18, 23

These problems cover the concepts, but remember that homework problems are usually too long to be good exam questions.

Ferromagnetism (6.4.2)

I will do a bit more detail than G. Ferromagnetism is interesting not only because those materials have large μ:

$\mu_{iron} \sim 10^3$; μ(superferrics) $\sim 10^6$

but also because it illustrates:

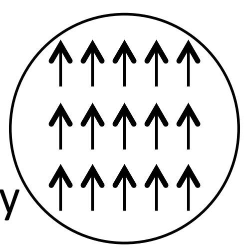
- Phase transitions (Curie temperature)
- Spontaneous symmetry breaking (like the Higgs boson!)
- Hysteresis and saturation (I might not have time for this.)

The important microscopic features of ferromagnets:

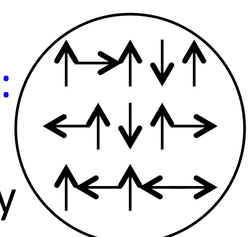
- Each atom (or molecule) has an intrinsic dipole moment.
- The interactions are such that energy is minimized when all the dipoles line up.

The state of the bulk material is determined by statistical mechanics.
Remember P213 ??

Polarized:
Low energy
Low entropy



Unpolarized:
High energy
High entropy



Which configuration is favored?

Equilibrium is determined by minimizing the free energy:

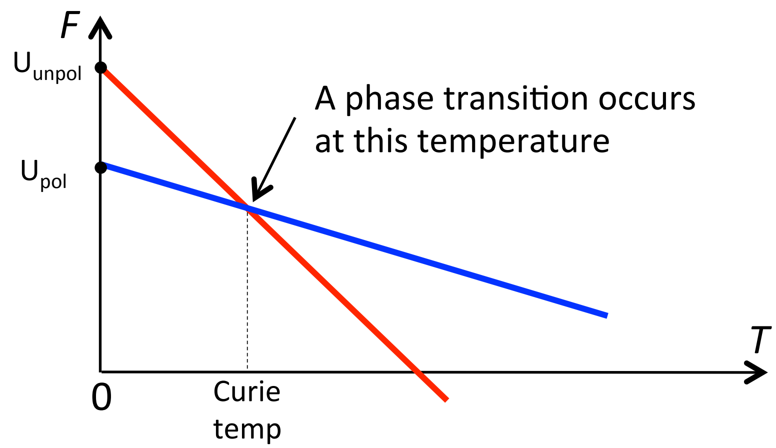
$$F = U - TS$$

- S: Entropy
- T: Temperature
- U: Internal energy

Choose the state with the smallest free energy. This minimizes the total entropy, including that of the thermal reservoir (the object's environment).

Plot F *vs* T:

Above the Curie temperature (1043 K for iron) the material is unpolarized. Below that, it prefers to be polarized.

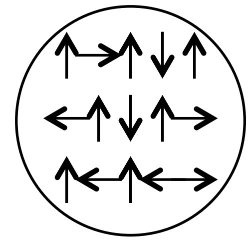


Question: Why isn't every piece of iron magnetized at room temperature?

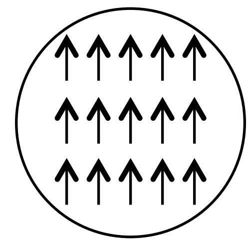
Answer: It is!

We don't see macroscopic magnetization because of spontaneous symmetry breaking.

Consider an unmagnetized piece of iron (*i.e.*, at $T > T_c$). The magnetic moments point in random directions, so, on large scales (that contain many atoms), the material is isotropic (rotationally invariant).



Now, lower the temperature (to $T < T_c$). The magnetic moments all point the same direction. The material is no longer isotropic. Rotational symmetry has been broken.



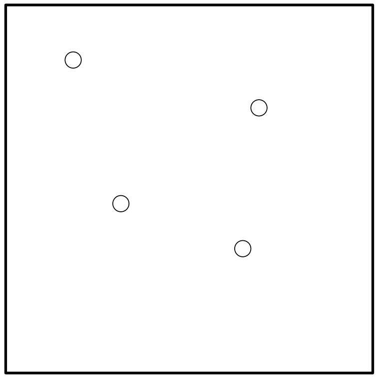
How was the direction determined?

The answer: It's random (*e.g.*, due to thermal fluctuations). If you repeat the process, you'll get a different result.

This is spontaneous symmetry breaking. It is a very important phenomenon in condensed matter (superconductivity), particle physics (mass generation), and cosmology (inflation, we think).

We still haven't answered the question: Why is cold iron unmagnetized? usually
The answer: Magnetic domains.

When we cool a piece of hot iron, it begins to magnetize itself at various regions (domains) in the material:

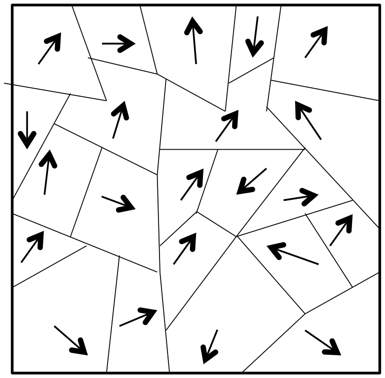


This is similar to the bubbles that form when water begins to boil.

As the material cools, the domains grow and begin to touch. However, because each domain points in a different (random) direction, the domains can't merge. There are "domain walls" where magnetic moments that point different directions are near each other.

See G, figure 6.26 (p. 279).

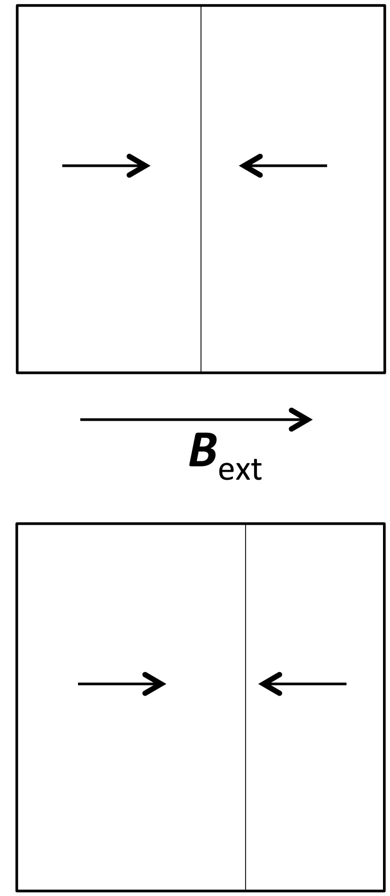
The walls are defects (much like crystal defects). They have high energy than thermal equilibrium predicts, but they can't be removed. They can, however move around.



These domain walls are an example of what are called topological solitons.

Permeability of a ferromagnet.

Let’s apply a B field to a piece of unmagnetized cold iron.
For clarity, there are only two domains.



The left hand domain now has lower energy.
Thus, it is energrtically favorable for the domain wall to move to the right. The iron is now magnetized.

The permeability is determined by how easy it is to move the wall. This depends on:

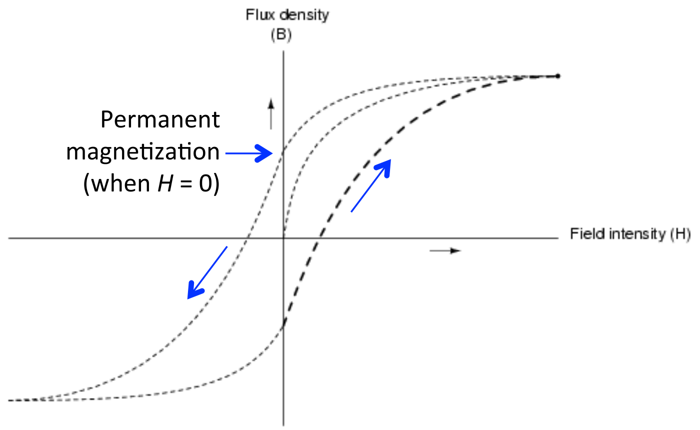
- The size of the domain wall.
- The number of crystal defects (which pin the walls)
- ?? (I’m not an expert.)

Saturation and Hysteresis:

The magnetization of a piece of iron is a result of the alignment or existing magnetic dipoles. This means that the iron has a maximum response (saturation) to an applied external field (***H***, produced by free current), when all of the atoms are aligned. The response curve is nonlinear for strong fields. The maximum B is about 1.6 T. In the linear regime (B << 1.6 T), μ/μ_0 ~ 1000, so the response becomes nonlinear when $\mu_0 H$ ~ 0.01 T.

The shape of the response curve was a worked example in physics 213. The answer is:

$$m(H,T) = m_{max} \tanh\left(\frac{(\mu_0 H) m_{atom}}{kT} \right)$$



Magnetization results from motion of domain walls, which is subject to friction (as the walls slide over crystal defects, *etc.*). So, the response tends to lag behind the driving force. This is called hysteresis. For some purposes (*e.g.*, permanent magnets) this is desirable, but for others (*e.g.*, electromagnets) it is not.

End 11/1/13