2nd Midterm

- The midterm is scheduled for November 15.
- It will cover Chapters 30, 31, and 32.
- Some review material is already on the web site:
  - Practice exam (from last year).
  - Additional end-of-chapter problems, with solutions.
- I’m working on more review material to post.
- Access to the material requires the same user name and password as before.
Magnetic Force on a Conductor

\[ F = N_{\text{moving charges}} \cdot (qv_d B) \]

\[ F = (nA\ell) \cdot (qv_d B) = (nqv_d)A \times \ell B = jA \cdot \ell B = I\ell B \]
For non-perpendicular field...

\[ F = I\ell B \sin \phi \quad \text{Direction out of the page} \]
**Torque on a Current Loop**

\[
F = IaB
\]

\[
\tau = 2 \cdot \left( F \cdot \frac{b}{2} \sin \phi \right) = IaB \cdot b \sin \phi = I \cdot (ab) \cdot B \sin \phi = \mu B \sin \phi
\]
Example

A circular coil of wire 8.6 cm in diameter has 15 turns and carries a current of 2.7 A. The coil is in a region where the magnetic field is 0.56 T.

a) What orientation of the coil gives the maximum torque and what is the maximum torque?

b) For what orientation of the coil is the magnitude of the torque 71% of that found in part (a)?
B field from wire 2 at the location of wire 1.

\[
\vec{B}_2 = \frac{\mu_0}{2\pi} \frac{I_2}{r_{1,2}} \hat{j}
\]

\[
\vec{F} = I_1 \vec{\ell} \times \vec{B}_2
\]

\[
\vec{F} = \frac{\mu_0 I_1 I_2}{2\pi} \frac{\ell}{r_{1,2}} \hat{i}
\]
Force Between Parallel Conductors

The result respects Newton’s 3rd law!
Force Between Antiparallel Conductors

B field from wire 2 at the location of wire 1.

\[ \vec{B}_2 = \frac{\mu_0}{2\pi} \cdot \frac{I_2}{r_{1,2}} \hat{j} \]

\[ \vec{F} = I_1 \ell \times \vec{B}_2 \]

\[ \vec{F} = -\frac{\mu_0}{2\pi} \cdot \frac{I_1 I_2}{r_{1,2}} \ell \hat{i} \]

Parallel currents attract.
Antiparallel currents repel.
Force Between Parallel Conductors

Force per unit length: \[ F = \frac{\mu_0}{\ell} \cdot \frac{I_1 I_2}{2\pi r_{1,2}} \]

Example: 2 wires 1 meter apart, each carrying 1 Ampere of current.
\[ \rightarrow \text{force/length} = 2 \times 10^{-7} \text{ N/m} \]

This is the definition of the SI unit of current, Ampere, and therefore also determines the unit of charge, since Ampere=Coulomb/second.

This definition of Ampere also explains why \( \mu_0 \) is an exact number.
Internal Forces on Current Loops

Magnet windings always want to explode and must be held in place with strong structures.
Force Between Magnetic Dipoles

- North Pole
- S
- N
- B
- F
- $F_{\text{net}}$
- North Pole
Force Between Magnetic Dipoles

[Diagram showing the force between two magnetic dipoles, with vectors and labels indicating the direction of force and magnetic field.]
Force Between Magnetic Dipoles

Repulsion. Also, this is an unstable equilibrium. Any slight misalignment will result in a torque. One or the other will try to turn around, until the dipole moments align.

Attraction.
Example: Torque Between 2 Dipoles

\[ B_1 \approx \frac{\mu_0}{2\pi} \cdot \frac{\mu_1}{d^3} \]

Because \( d \gg \) radius of loop #1

Also, since \( d \gg \) radius of loop #2, then \( B_1 \) is approximately constant over the dimensions of loop #2. In that case,

\[ \vec{\tau}_2 = \vec{\mu}_2 \times \vec{B}_1 \]

\[ \vec{\tau}_2 = \frac{\mu_0}{2\pi d^3} \vec{\mu}_2 \times \vec{\mu}_1 \]

Dipoles try to align with each other.
Magnetic Properties of Materials

- Paramagnetism
- Diamagnetism
- Ferromagnetism

Weak effects, not familiar to most people, but all materials exhibit one or the other.

Strong effect:
- Responsible for all permanent magnets.
- Responsible for the strong magnetic properties of iron.
- Only special materials (ferromagnetic).
- Very familiar to everybody.
Paramagnetism

In some materials the atoms (or ions) have zero magnetic moment (e.g. NaCl). Such materials are not paramagnetic.

Each atom has a magnetic moment, but they are randomly oriented, giving zero net magnetic field.

The external field causes the dipoles to align slightly (depending on temperature).

$B = 0$

$B_{\text{external}}$

$B = \text{external field plus the field from the magnetization}$
Paramagnetism is “Linear”

\[ \vec{M} \propto \vec{B} \]

The magnetization always goes back to zero when the external field is removed.
Diamagnetism

- An external magnetic field alters the internal electronic currents of atoms.
- This produces a magnetization in the opposite direction (but still proportional to $B$).
- Linear effect (as with paramagnetism).
- This occurs in all materials, but in paramagnetic materials the paramagnetism is stronger and is dominant.

- Paramagnetism: parallel to applied field; slightly strengthens the field.
- Diamagnetism: opposite to the applied field; slightly weakens the field.
Ferromagnetism

Magnetic domains. Each domain is 100% polarized, with all atomic magnetic moments in the domain pointing in one direction.

An external field moves the domain boundaries.
Hysteresis & Permanent Magnets

- Start with an unmagnetized sample.
- Turn up the $B$ field until the magnetization is the maximum possible.
- Turn off the field, and part of the magnetization remains!
- Very non-linear!
- Partially reverse the field to demagnetize the sample again.
- $B_{\text{external}}$
- Turn up the $B$ field until the magnetization is the maximum possible.

Magnetization vs. Ferromagnetic material
Curie Temperature

- If a ferromagnetic material is raised to high enough temperature (Curie temperature, $T_C$), then the atomic magnetic moments will no longer align within domains, and the material becomes paramagnetic.

- This change from ferromagnetism to paramagnetism happens suddenly at $T_C$ and is an example of a phase transition (boiling water is another example of a phase transition).  

  Iron: $T_C = 770^\circ C$

- When any material is *paramagnetic*, the magnetization will decrease with rising temperature.

  $$\vec{M} \propto \frac{\vec{B}}{T}$$  

Curie’s law