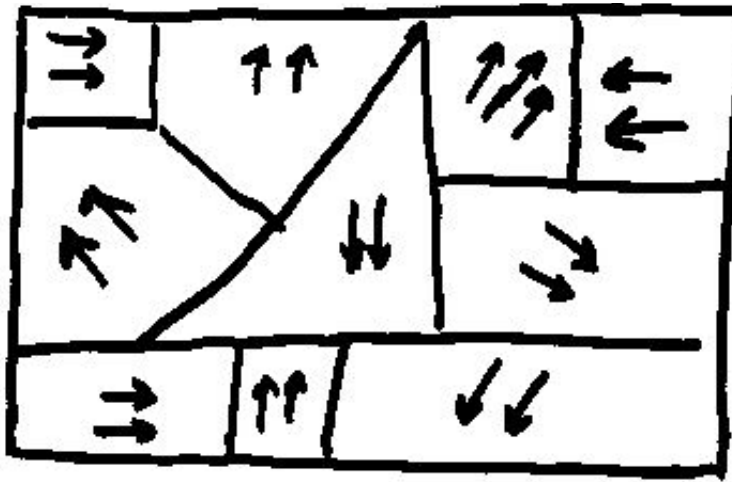
Static Magnetism

- At first blush: some similarity with electrostatic forces:
  - Can be attractive and repulsive
  - Falls off with distance
  - Different magnets have different strength
- Maybe the same thing? NO, because
  - Charged objects aren't necessarily attracted to magnets
  - Permanent magnets seem all to be made of iron and a few other metals
  - Biggest difference: Magnets never come alone - every positive (North) pole always is attached to a negative (South) pole. Even cutting a magnet in pieces doesn't change this
- New phenomenon
  - Due to "magnetic charges" (monopoles)? NO! (we haven't found one yet)
  - Actually due to MOVING electric charges (see later)
- Has its own field!

Dipole Magnets

- North and South pole
- Equal poles repel, opposite poles attract
- Force "transmitted" by magnetic field **B** (similar to **E**)
  - exit from North Pole and enter through South pole of magnet, but continue throughout the interior
- In a homogeneous external magnetic field, dipoles experience no net force but they DO experience TORQUE!
- Example: Compass in Earth's magnetic field
  - Earth itself is a magnet
  - South pole somewhere in Canada (NOT at typo)
  - North pole somewhere south of Australia
  - Compass aligns itself with field so **its** North pole points north

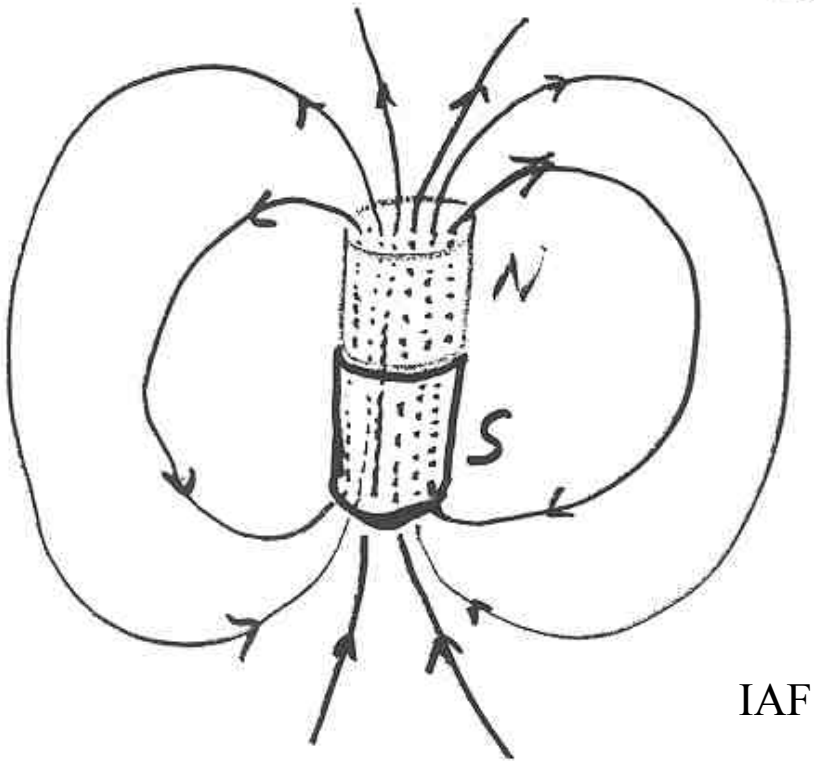
Magnetic materials



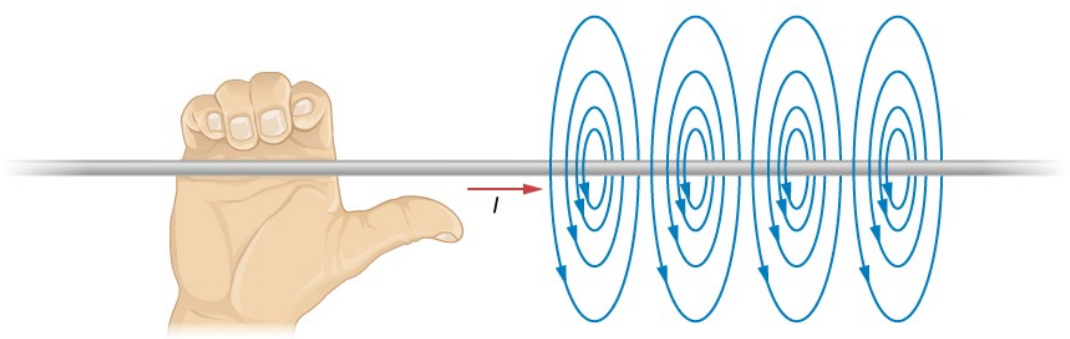
- Permanent magnets (*Ferromagnetism*)
  - Domains
  - Examples: Iron, Nickel, Cobalt, …
- Induced magnets (*Paramagnetism*)
  - Polarization along external field
  - Attracted towards magnets; e.g. liquid oxygen)
- Non-magnetic material (doesn't really exist)
- Anti-magnetic material (*Diamagnetism*)
  - Practically ALL materials; most extreme: superconductor
  - repelled away from magnets (levitation)
- Quiz: How to distinguish a bar magnet from a piece of non-magnetic iron if you have no other materials around?
  Answer: Saw it in half, making 2 dipoles - the two opposite ends attract and the same poles repel; or hang it up on a thin thread and see whether it keeps orienting itself in the same direction again and again (presumably along Earth's magnetic field).

Rules for field lines

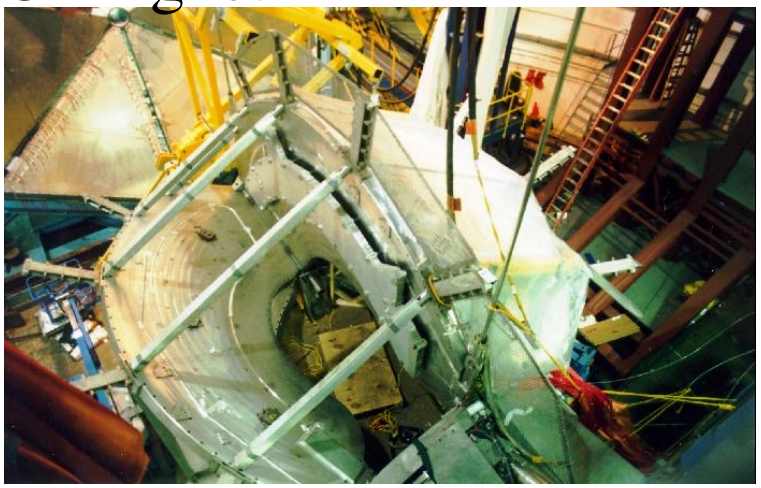
- In some aspects, just like electric field lines:
  - Direction shows direction of field
  - Density shows strength of field
- However, in other aspects very different:
  - Field lines can NEVER begin or end
  - They can go on forever, or
  - They can form closed loops!
- Example: dipole magnet



Magnetic fields due to currents



- Any moving charge produces a magnetic field!
- Simple straight wire: Magnetic field lines circle the wire; field falls of like 1/distance from the wire
- Simple loop of wire: Field similar to a very short dipole *)
- Solenoid: Field similar to a very long dipole *)
- Electromagnet: Field can be enhanced and shaped by magnetic materials, like iron. Example: C-magnet
- Superconducting electromagnet
  Example: CLAS at Jefferson Lab



*) This similarity is NOT accidental - in permanent magnets, all the spinning electrons combine to create a circumferential current

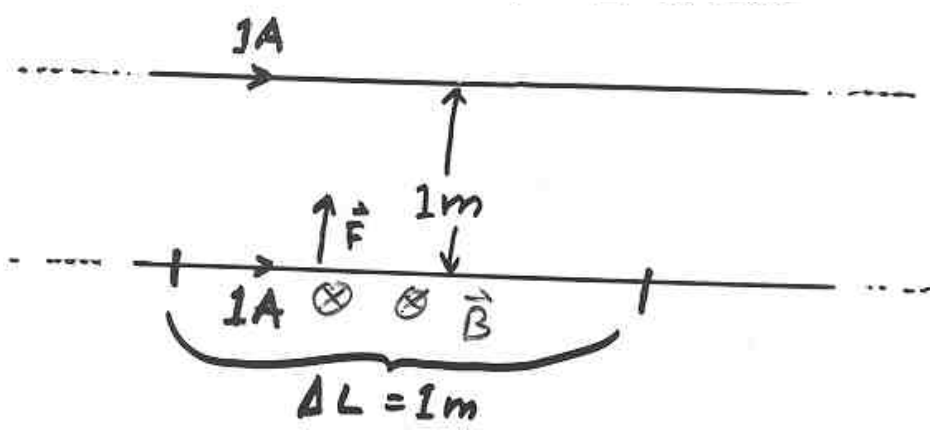
Magnetic force on moving charges

- The weirdest force law yet:
  If a charge q moves to the left and the magnetic field points up, then the charge will be deflected away from you *) (unless q is negative - then the deflection is in the opposite direction)
- This (Lorentz-)Force is proportional to q, **B** and **v**!!!
  - ONLY the part of **B** that is perpendicular to **v** counts!
  - Because force is perpendicular to v, charged particles neither speed up nor slow down in magnetic fields - kinetic energy is conserved!
- Interesting applications: CRT screens, accelerators,…
- Typical motion: Circle (for a homogeneous magnetic field)

*) "right hand rule": thumb in direction of motion, index finger in direction of B, middle finger in the direction of force

Magnetic force on current-carrying wires

- Equally weird:
  If a current flows to the right and the magnetic field points away from you, then the wire will be pushed UP (right hand rule again)
- This (Lorentz-)Force is proportional to *I*, *L* and **B**!
- Interesting applications:
  - Electric Meters
  - Electric Motors, relays,…
- To close the circle: Two parallel wires exert a force on each other! If both carry 1 A
  and are 1 m apart,
  the force will be $2 \cdot 10^{-7}$N
  => Previous definition of
  1 Ampere!



Changing Magnetic Fields

- We learned: Moving charges produce magnetic field…
  - Wires, loops, coils…
  - Even true in permanent magnets
- …and magnetic fields change motion of charges (sideways)…
  - Deflection of electron beams
  - Electric motors
  - Electric generators! (IAF)
- New phenomenon: Changing magnetic fields!
  - Can make charges move!
  - Just like generators - it doesn't matter whether the magnet moves or the wire!
  - It also doesn't matter whether the magnet moves or simply changes strength
- …a new source for ELECTRIC fields!

Faraday's Law

- A changing magnetic field induces an electric field **E** circling around it:
  - Larger if the field fills a larger area
  - Larger if the magnitude of the field changes more rapidly
  - We can "harness" this as a source of electric energy - if we use a coil with many windings, the same **E**-field can be used repeatedly
  - Total voltage induced in the coil is also proportional to the number of windings in the coil
- An infinite source of energy?!?
  Unfortunately not: Lenz' Law says that the effect of a changing magnetic field will oppose the change

Examples for Lenz' Law

- Generator
  - More windings - more voltage -> GOOD
  - But current flowing in coil will repel magnet -> BAD
  - You need as much mechanical energy to keep a generator running as you can extract electrical energy from it -> NO FREE LUNCH
- Fall tube, Induction brake,… (Demos)
- Jumping ring
- Sparking

Applications for Induction

- Generators (AC)
- Magnetic information storage (tape, hard disk,…)
- Electric guitar
- Electric brakes, esp. regenerative ones (hybrid cars!)
- Transformers - closing the loop (mutual induction)
  - Current in primary coil creates magnetic field
  - Changing current -> Changing magnetic field
  - Changing magnetic field induces electric field in secondary coil
  - Electric field pushes current in secondary coil
  - “Step up” and “Step down” transformers, HV power grid,…
- Inductors: Coils with changing current can induce electric field in themselves!
  - Spark plugs powered by coil and distributor