Magnetism

Chapter 21

Magnetic Materials

- Natural magnets known since ancient times, called *lodestones*, made of *magnetite*, an iron ore
- All magnetic effects caused by moving electrical charges
- *Ferromagnetic* materials highly attracted to magnets: Fe, steel, Co, Ni, Nd, Pa

Ferromagnetism

- Due to spinning electrons in atoms
- In most materials, magnetic effects cancel -- paired electrons with opposite spin
- Fe, Ni, Co, Gd, Dy, Nd have unpaired electrons in outer valence shells with same spin causing atoms to become small magnets (Fe has 4)

Domain Theory

- *Domains* are microscopic groups of atoms with same magnetic orientation
- When placed in strong external mag. field, domains aligned with ext. field grow in size
- Other domains turn towards external field
- If domains remain aligned after external field removed, permanent magnet results

Loss of Magnetism

- Domain alignment can be destroyed by heat or excessive vibration
 Curie Point:
- Temperature at which magnetic domains disappear and material becomes paramagnetic

Weak Magnetic Effects: Paramagnetism

- *Paramagnetism*: some materials have slight natural magnetic moment and are weakly attracted by strong external magnetic field (Al, Pt, O_2)
- Effects of orbiting and spinning electrons don’t cancel out and atoms are slightly magnetic

Weak Magnetic Effects: Diamagnetism

- *Diamagnetism:* In a strong external magnetic field, some materials experience induced magnetic moment (become slightly magnetic) and are weakly repelled (Zn, Bi, Au, Hg, NaCl)
- Strong ext. field opposes motion of electrons causing slight repulsive force

Magnetic Poles

- Most magnets have 2 poles: North (north seeking) and South (south seeking)
- Named because of effect due to earth’s magnetic field
- Opposite poles attract; like poles repel

Magnetic Poles

- Since magnetic N poles point north, earth's magnetic pole in the north is actually a S pole
- Some magnets have more than one N or S pole
- Some circular magnets have no exposed poles

Magnetic Poles

- If magnet is cut, each piece has N and S pole
- Magnetic unit pole (single N or S pole) never been found but is used in theory

Magnetic Forces

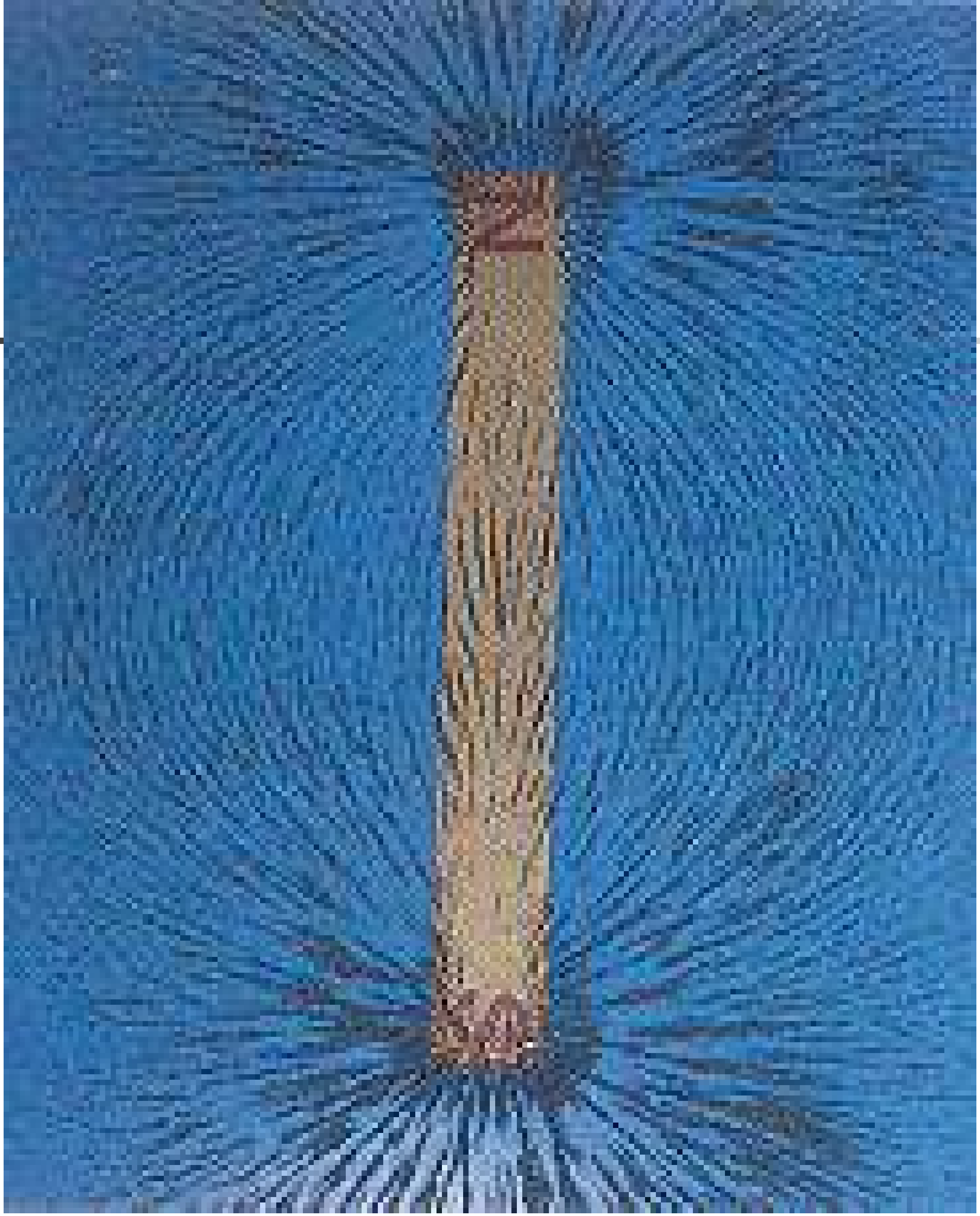
- Magnetic forces of attraction and repulsion obey inverse square law similar to those of gravitation and electrostatics
- Force is directly proportional to product of strength of poles & inversely prop. to square of distance between them

Magnetic Fields

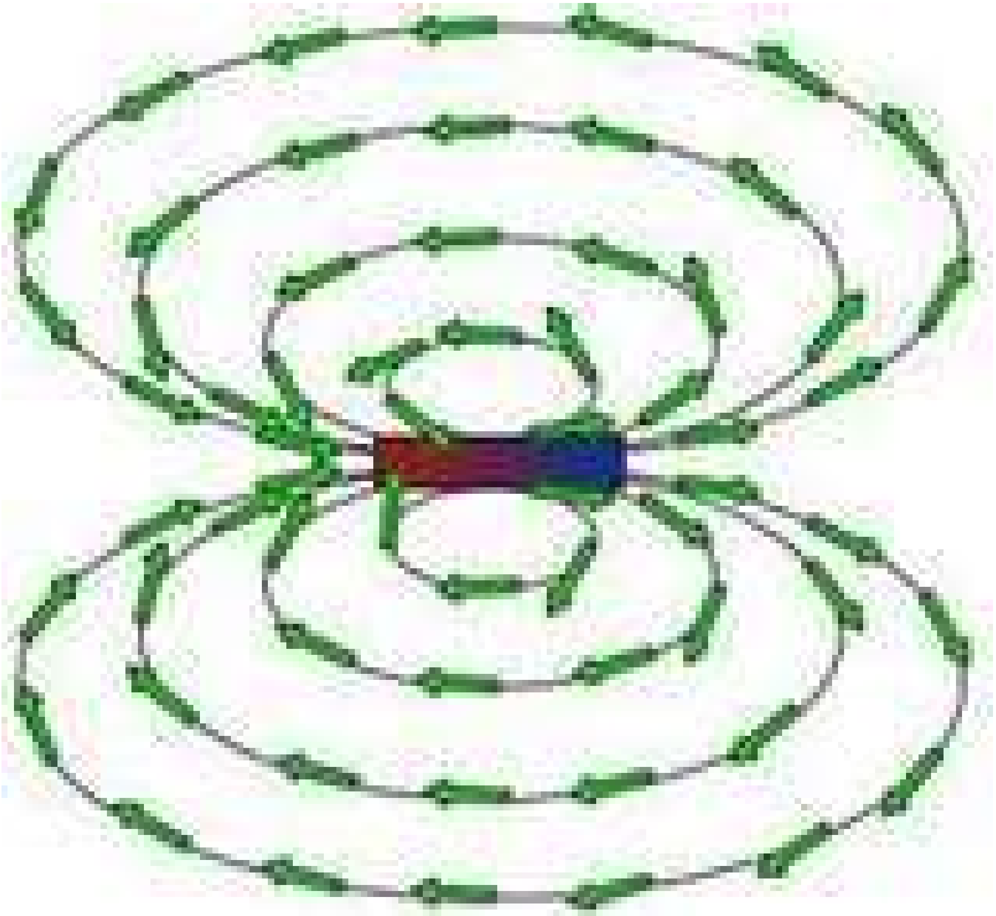
- Represented like electrical field: lines of flux showing magnitude and direction of force on N unit pole
- Arrows point from N to S, lines continue through magnet
- Magnetic flux (Φ_B): number of lines passing through a surface; unit is weber (Wb)

Magnetic Field

- *Flux Density*: number of lines of flux per unit area, often called magnetic field strength; symbol ***B*,** a vector; unit: tesla (T)
- $\boldsymbol{B} = \Phi/\boldsymbol{A}$; $1T = 1Wb/m^2$
- Magnetic field can be mapped by using tiny magnets (compasses) or iron filings



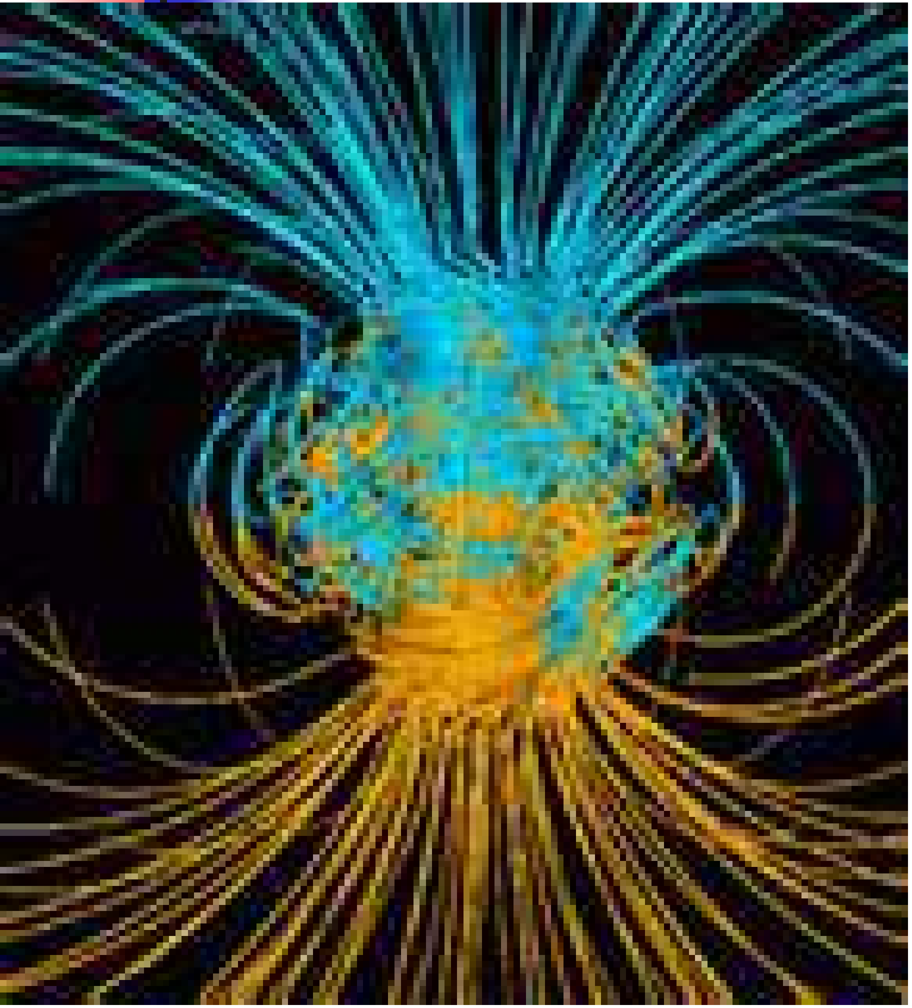
Bar Magnet Magnetic Field



Earth’s Magnetic Field

- Cause is convection currents of ions in molten core
- Magnetic axis is not in line with rotational axis
- Difference between true north and magnetic north is called *declination*

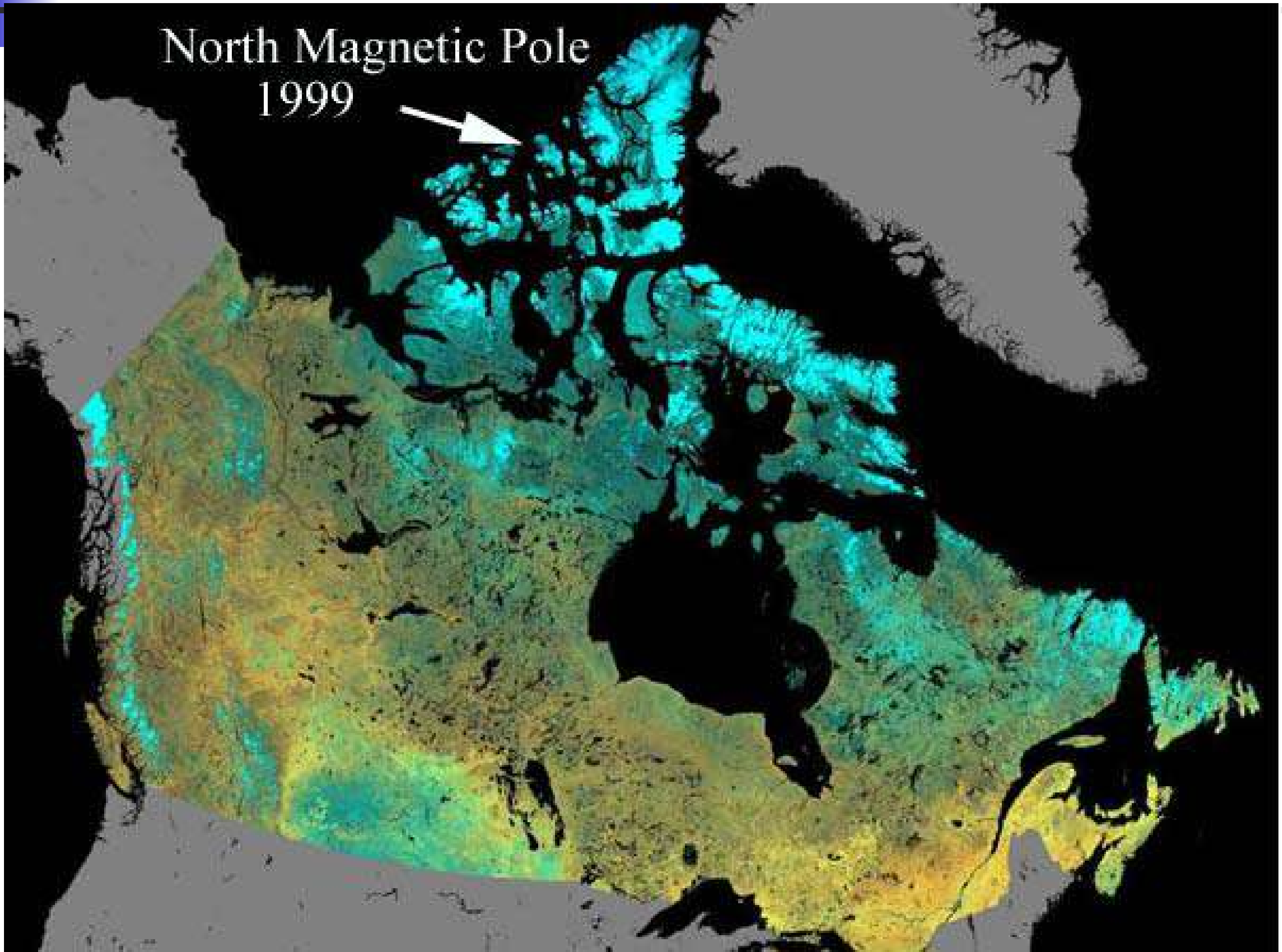
Earth’s Magnetic field



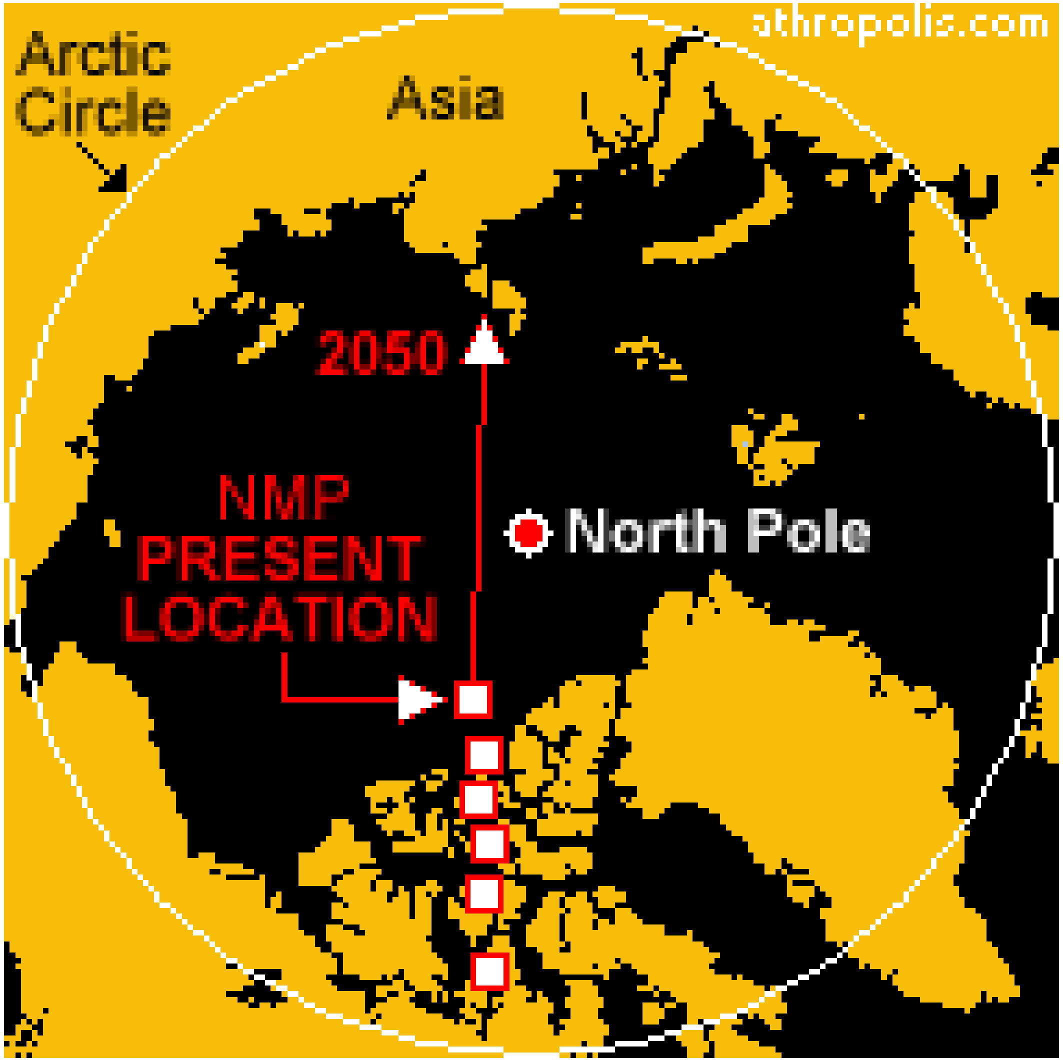
Earth's Magnetic Field

- Magnetic field has shifted over historical time
- Geologic record shows field has reversed polarity many times, even disappeared for long periods

North Magnetic Pole



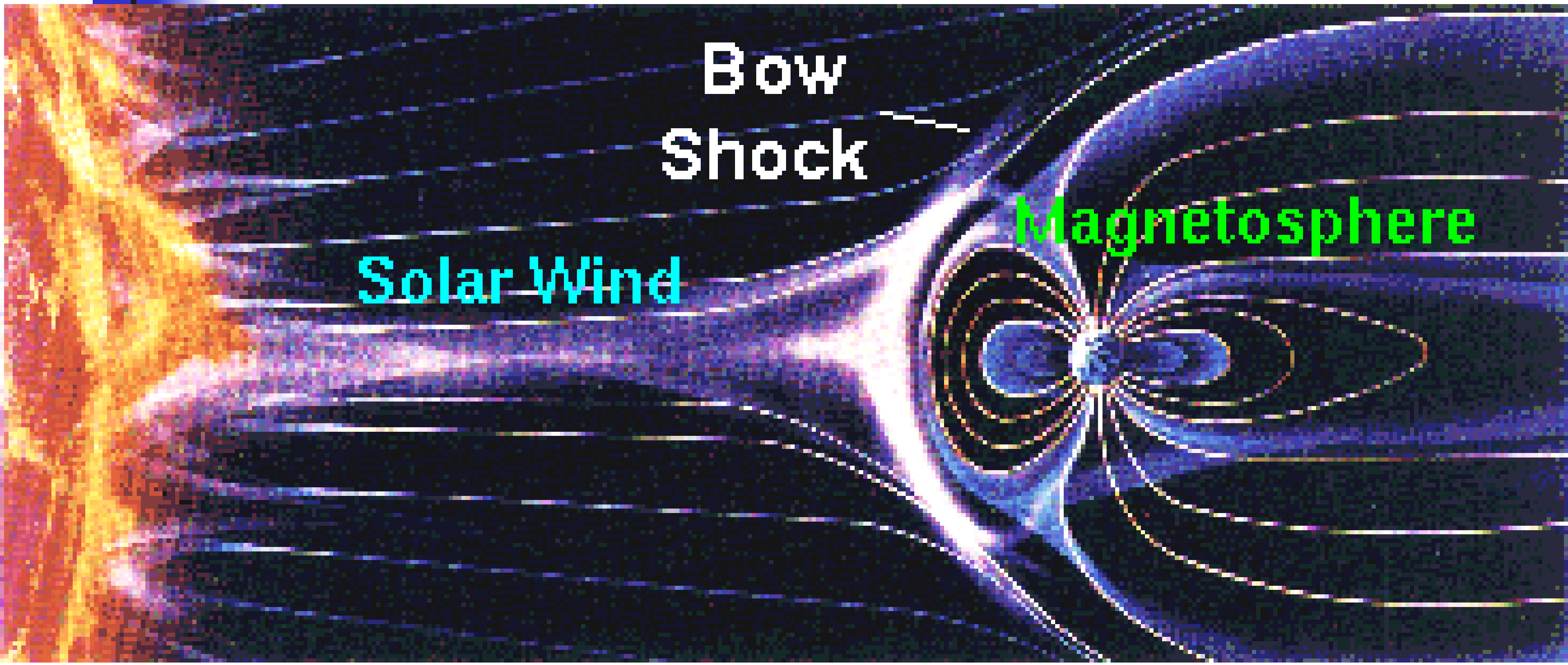
North Magnetic Pole



The Magnetosphere

- Sun emits many charged particles in solar wind, most are deflected by earth's magnetic field
- Magnetosphere: area where charged particles are affected - about 57,000 km up on side facing sun; greatly elongated away from sun
- Many particles are concentrated in 2 regions called Van Allen radiation belts

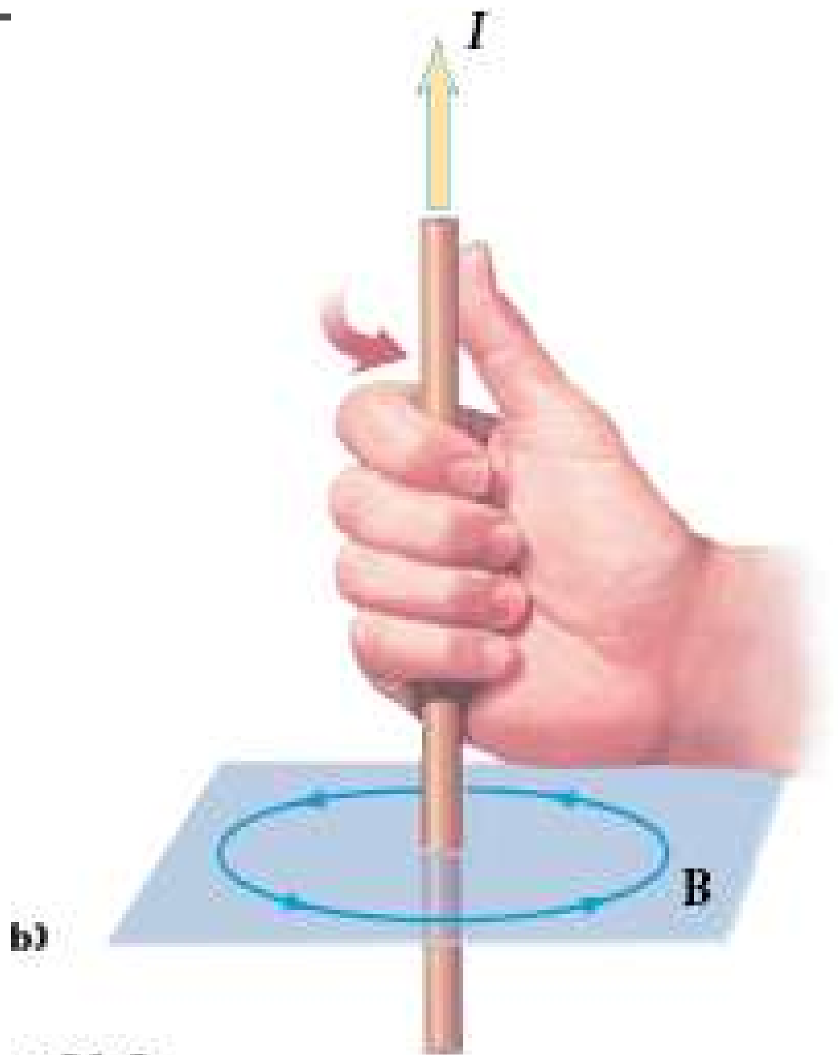
The Magnetosphere



Electric Current and Magnetism

- 1820: Oersted showed current in wire will deflect compass needle
- Magnetic field around current carrying wire is in concentric circles
- Direction of ***B*** found using right hand rule: point right thumb in direction of current; curled fingers point in direction of field
- $\boldsymbol{B} = 2kI/r\ ;\ k = 10^{-7}\mathrm{N/A^2}$

Right-hand rule



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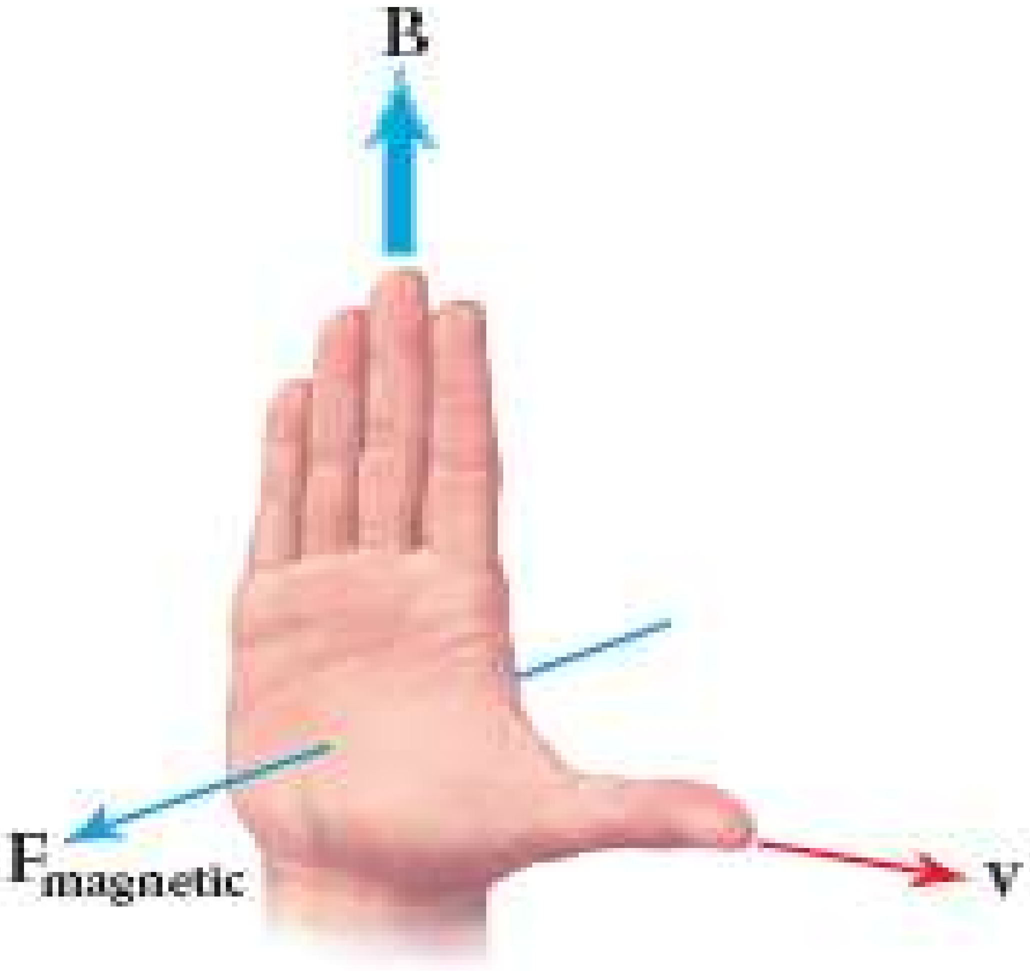
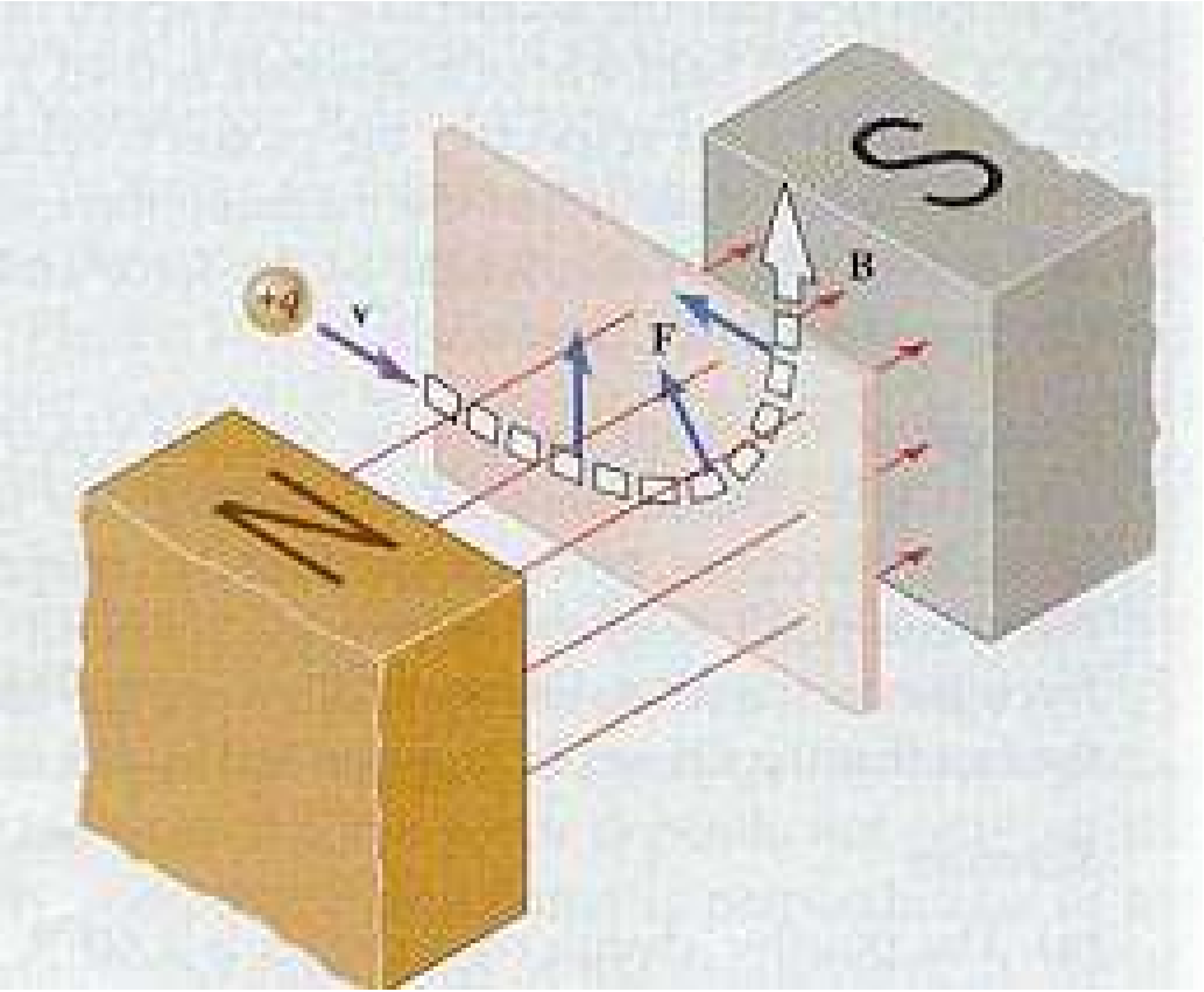
Magnetic Field of a Wire

Force on Moving Charges

- Force on a charge Q, moving at speed v, in magnetic field of flux density B; $F = QvB$
- Force is always perpendicular to velocity
- Can’t change speed, only direction of velocity - creates centripetal acceleration and circular motion

Right-Hand Rule for Force



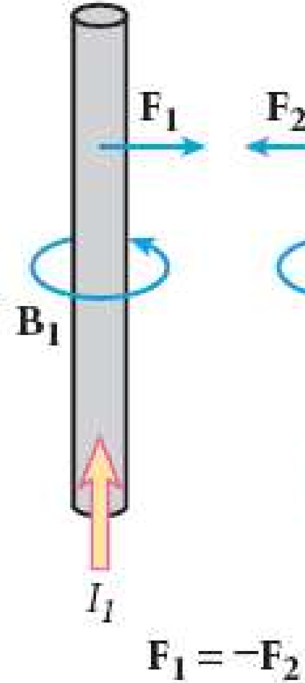


S
N
B
F
v
+q

Parallel Conductors

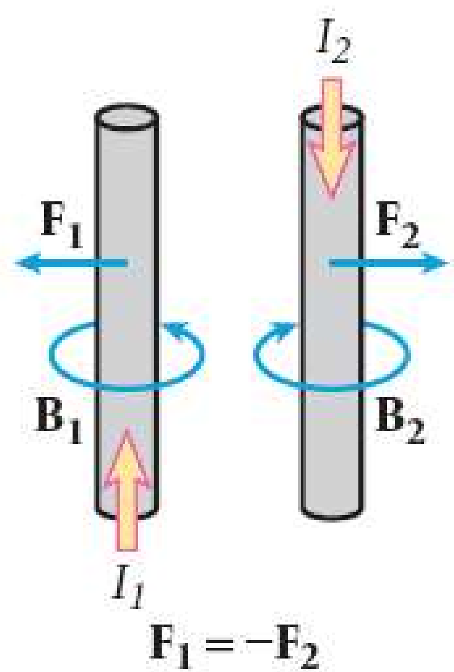
- Current in parallel wires create forces on wires
- Currents in same direction - attractive force; opposite direction – repel
- $F = (2klI_1I_2)/d$: $k = 10^{-7}$N/A^2; l = length of wires; I_1I_2=currents in wires; d = distance between wires

Parallel Currents



Attracting Force

Anti-parallel Currents

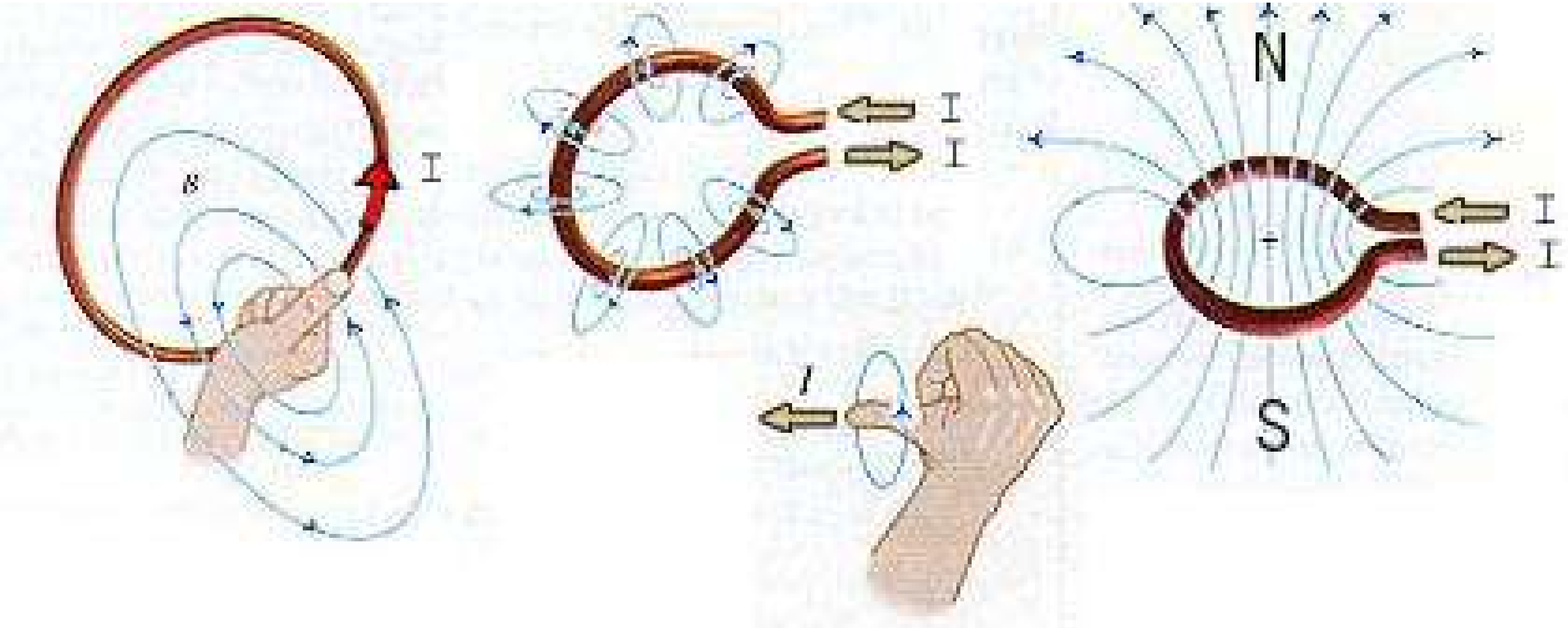


Repelling Force

Loops and Solenoids

- If straight conductor is bent into loop, magnetic field is concentrated inside loop creating *magnetic dipole* (with exposed N and S pole)
- Use right hand rule to find direction of B through loop: fingers point in direction of current, thumb points in direction of magnetic field through loop
- To increase mag. strength, add more loops

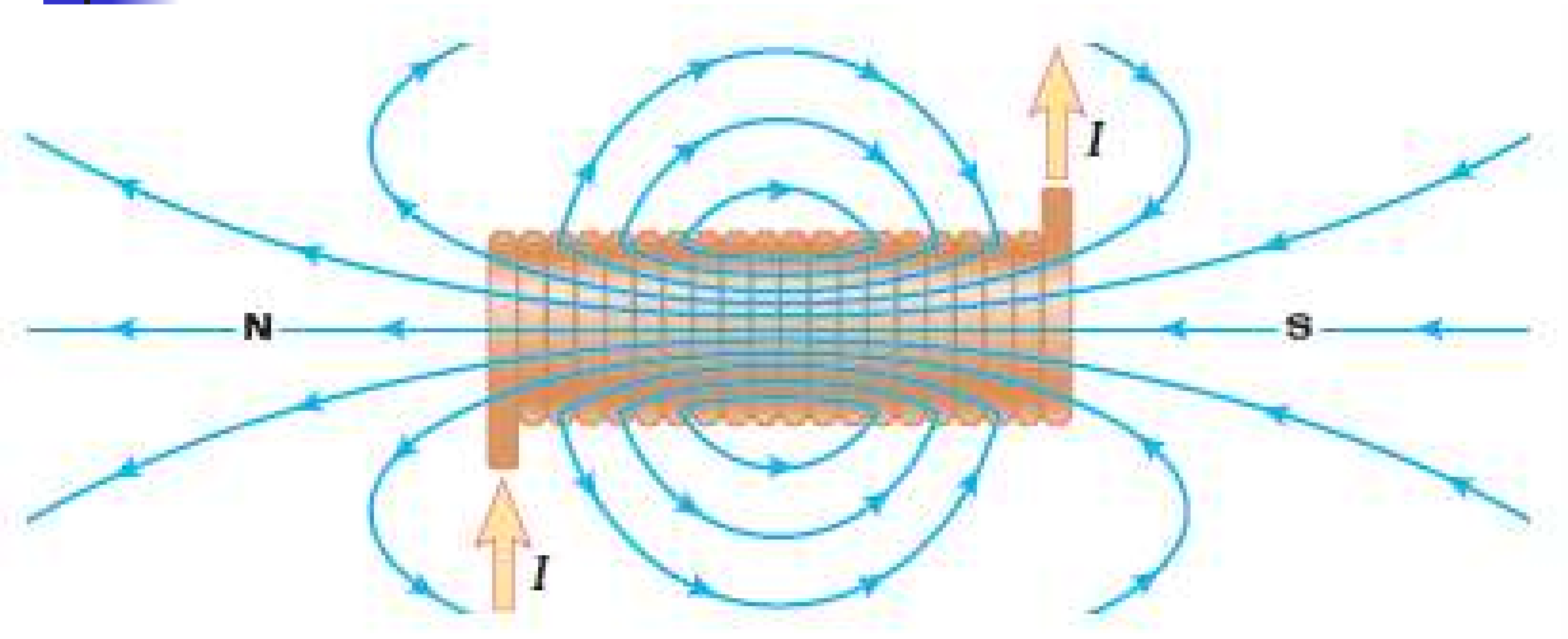
Magnetic Field of Loop



Loops and Solenoids

- A long coil makes *solenoid* with strong magnetic field inside coils
- If iron core is added to solenoid, electromagnet results whose strength depends on number of ampere-turns
- If long solenoid is bent into circle (donut shape) result is called *toroid*

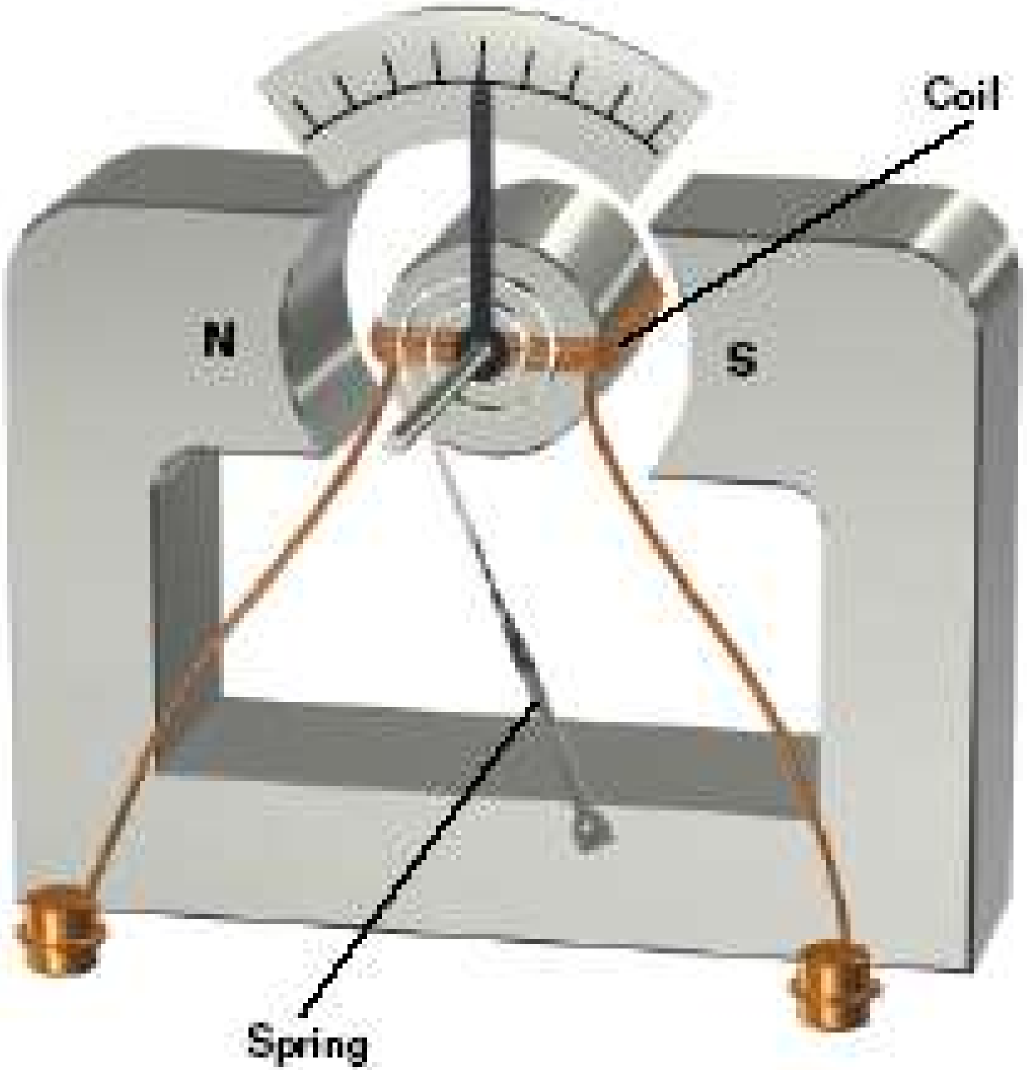
Magnetic Field of a Solenoid



Analog Meters

- Use a pointer to show readings, not digital readout
- Simplest meter is a galvanometer, which detects current with coil of wire on soft iron core between poles of permanent magnets
- Current in coil creates electromagnet whose polarity depends on direction of current
- Electromagnet tries to align itself with permanent magnets, held back by springs

Galvanometer



Analog Meters

- Needle attached to coil shows deflection along the scale
- Very sensitive to small currents, but not calibrated to give actual reading
- Voltmeter is galvanometer adapted with high resistance in series with coil
- Can be calibrated to measure voltage

Analog Meters

- Ammeter is a galvanometer adapted for higher currents by placing low resistance shunt in parallel with meter coil
- Calibrate meter for desired current range

Electromagnetic Induction

Chapter 22

Induced EMF and Current

- 1831 Faraday (England) & Henry (US) found that if a conductor is located in a changing magnetic flux, an emf will be induced in the conductor
- If conductor makes complete circuit, induced current will result
- Changing flux can be result of motion between conductor and magnetic field or changing magnetic field strength

Induced EMF and Current

- Only motion perpendicular to lines of flux will induce emf
- Magnitude of emf depends on rate of change of flux
- $\mathcal{E} = -\Delta\Phi/\Delta t$ (rate of change of flux)
- For straight conductor of length *l*, moving at speed *v*, $\mathcal{E} = Blv$
- For a coil of N number of turns, $\mathcal{E} = -N\Delta\Phi/\Delta t$

Lenz's Law

- Negative sign means induced emf is in a direction opposite to the change that created it
- If flux is decreasing, induced emf will be in a direction to produce a supporting magnetic field
- If flux is increasing, induced emf will produce an opposing magnetic field

Generators

- Conducting loop rotated in magnetic field induces current in loop
- Electrical contact with external circuit through slip rings and brushes
- Converts mechanical energy to electrical
- Many coils combined in *armature*
- Direction of electron flow in armature coil will create force that opposes coil rotation

AC Generators

- AC current pushes electrons back and forth with alternating + and – emf
- As the coil rotates, it cuts lines of flux first in one direction, then in opposite
- EMF varies from + $\mathcal{E}$ to - $\mathcal{E}$ and has instantaneous value that varies sinusoidally depending on angle of armature with magnetic field
- Maximum emf ($\mathcal{E}_{max}$) generated when coil is perpendicular to magnetic field

DC Generators

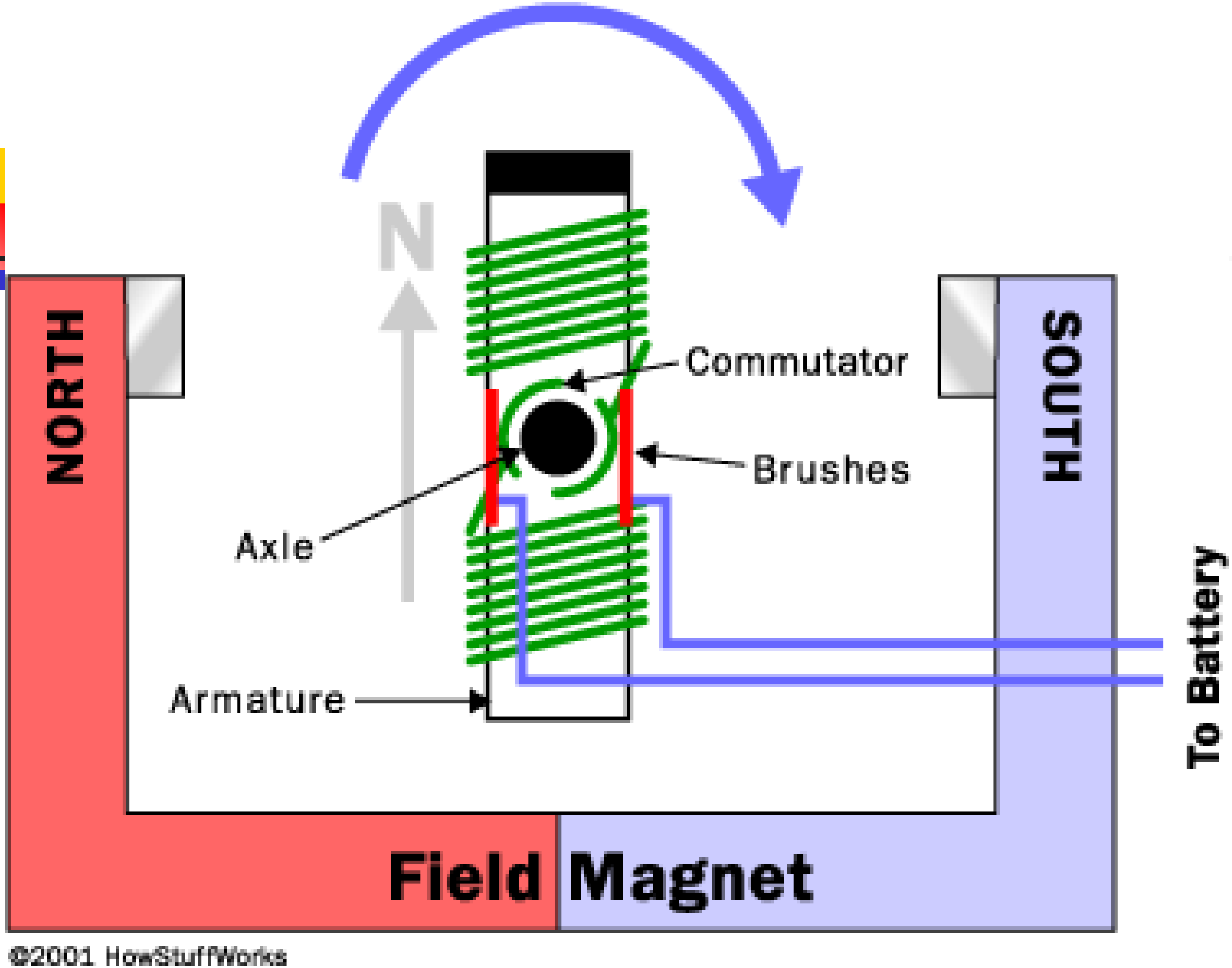
- To supply dc (current in one direction) armature coils are connected to *commutator* that reverses connection to external circuit when induced emf changes direction
- Produces pulsed dc - can be made smoother with many coil windings

Electric Motors

- Reverse operation of generators–converts electrical energy to mechanical
- Current through coil in magnetic field creates force that tries to expel coil from field
- Equal but opposite forces on opposite sides of coil create torque that turns coil

Electric Motors

- Force is maximum when conductor moves perpendicular to magnetic field
- To keep armature from being held in zero torque position, current direction must be reversed using commutator



N
NORTH
SOUTH
Commutator
Brushes
Axle
Armature
To Battery
Field Magnet
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Inductors and Inductance

- Inductance is a property of a coil to produce emf in a changing magnetic field
- Change in magnetic field can be due to relative motion between conductor and magnetic source or from collapsing or strengthening field
- Coil can respond to changes in its own magnetic field–self inductance
- Change in current through a coil creates induced emf that opposes this change

Inductors and Inductance

- Inductance is ratio of induced emf to rate of change of current
- Symbol: L; unit: henry (H)
- Inductors are circuit elements with specific inductance whose function is to store energy in a magnetic field
- Similar to capacitors storing energy in electric fields

Inductors and Inductance

- Equivalent inductance of combinations of inductors are found like resistors
- Change in current through a coil will induce emf in nearby coil–mutual inductance
- Ratio of induced emf in one coil (secondary) to rate of change of current in the other (primary)

Transformers

- Two coils wound on same iron core
- Electric energy is transferred through magnetic flux in the core
- AC current through primary coil induces alternating emf in secondary
- Ratio of voltages = ratio of turns
- $V_S / V_P = N_S / N_P$
- For current: $I_S N_S = I_P N_P$ if ideal, no losses

Transformers

- Actual efficiency is high but not 100%
  Efficiency = P_S/P_P x 100%
- Losses due to resistance of coil wires – *copper losses* – and to *eddy currents* in iron core
- Laminated core reduces eddy current losses

Electric and Magnetic Fields

- Faraday's law holds even if no conductor is present
- A changing magnetic field induces an electrical field
- Maxwell extended Faraday's idea to say a changing electrical field induces a magnetic field

Electrical and Magnetic Fields

- Electrical and magnetic fields are perpendicular to each other
- Magnitude of induced field is proportional to rate of change of the other field
- Explained operation of electromagnetic waves
- Speed of light is only speed where induction will continue without energy gain or loss