Lecture 8

Lightning and Lodestone

Outline of Lecture 8

- Empirical Laws of Electricity and Magnetism:
  - There are no magnetic monopoles.
  - Total electric charge is conserved.
  - Electric fields accelerate electric charges; moving electric charges give currents.
  - Electric currents yield magnetic fields, which in turn deflect moving charges.
  - A time-varying magnetic field will induce a (time-varying) electric field.
- Maxwell’s unification of electricity, magnetism, & light:
  - Need to add time-rate of change of electric field to Ampere’s law for current as source of magnetic field.
  - Possibility in vacuum (absence of charges and currents) for time-varying magnetic fields and time-varying electric fields to sustain each other – light as an electromagnetic wave.
- Generation of light via the acceleration or deceleration of electric charges (next lecture).

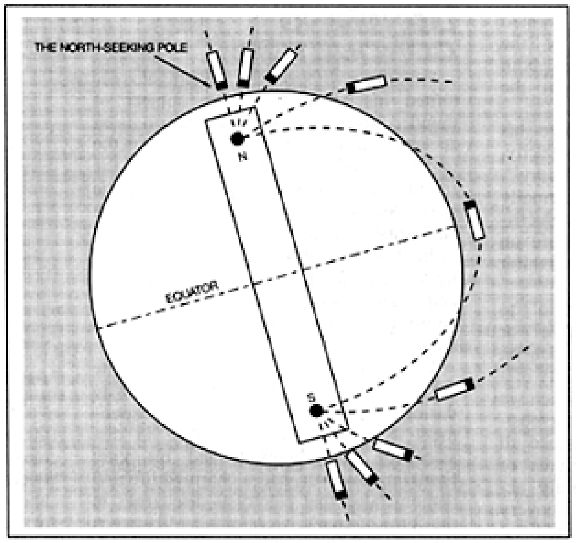
Lightning and Lodestone

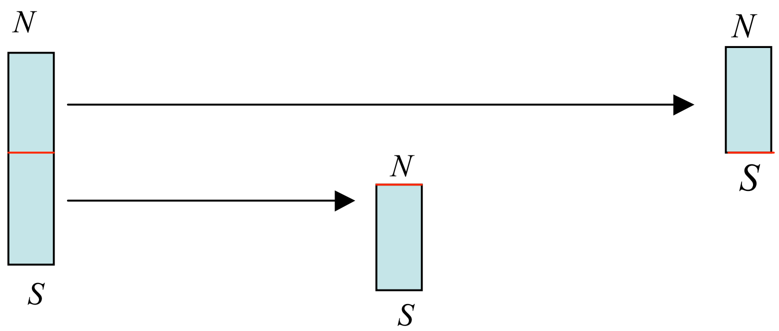
- *Fire* from *lightning* and striking *sparks.*
- Sparks from walking on carpets in dry weather and touching a *metallic* object (*conductor*).
- Rubbing amber with wool → pick up pieces of straw or bits of paper (ability to exert *force*).
- Greek word for amber = *elektron* (ca. 600 BC).
- Iron ore from Thessaly attracts ordinary iron → natural *magnet* (from Greek city *Magnesia*).
- AD 121: Chinese find that an iron needle stored in contact with a natural magnet becomes itself magnetized.
- Such a needle suspended by surface tension in a bowl of water (or threaded through a cork) will point (approximately) *north*.
- Today, we call such a device a *compass*; ancient mariners, a lodestone (a “ treasured rock”), which is a natural magnet.

Chinese float compass

Electricity & Magnetism (1)

- William Gilbert (1540-1603), physician to Elizabeth I (only rival to Newton as greatest person in English history):
  - Scale model of Earth from lodestone.
  - Magnetic needle placed on surface points to pole → Earth is a big magnet!
  - Cut bar magnets in half; always get pieces with *two poles*, never one pole → magnetic monopoles do not exist.



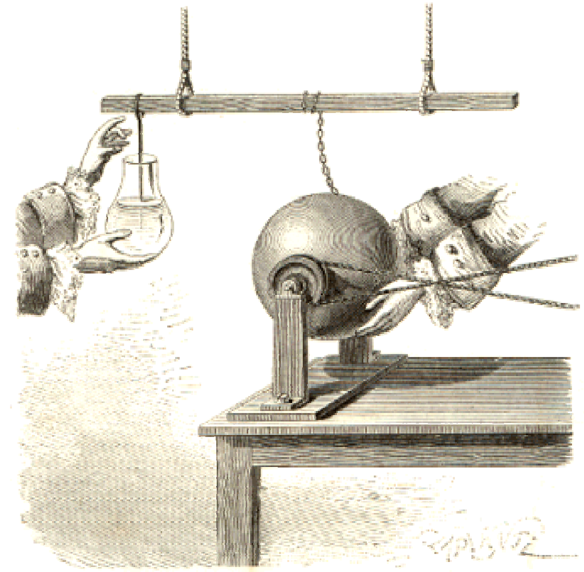


(1) No magnetic monopoles.

Electricity & Magnetism (2)

- Stephen Gray (1666-1736), an astronomer, showed that *electric charge* can be transferred, like a fluid, from one body to another.
- Charles Dufay (1698-1739) discovered charge obtained from rubbing glass differs from rubbing rosin → *two kinds of electric charges*.
- Benjamin Franklin (1706-1790), the American statesman and scientist:
  - Labeled two kinds of electric charges positive and negative.
  - Discovered that appearance/disappearance of negative charge always compensated by appearance/disappearance of equal positive charge → algebraic sum of charges = constant.

(2) Conservation of total electric charge.



Electricity & Magnetism (3)

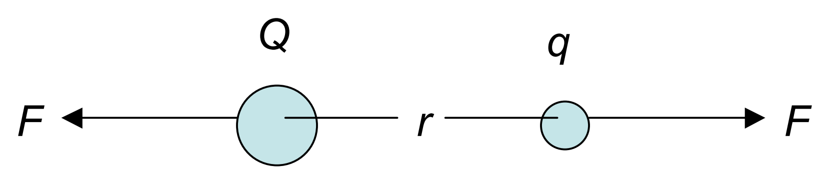
- Charles Coulomb (1736-1806) showed force $\boldsymbol{F}$ exerted between two point charges, q and Q, has magnitude (in rationalized cgs units):

(3) $F = Qq/r^2$,

and is directed along the radius vector $\boldsymbol{r}$ joining their centers. The electric force is attractive between unlike charges, repulsive for like charges. (cgs units for electric charge need no analog for G.)

Unit of charge = esu = $\text{gm}^{1/2}\ \text{cm}^{3/2}\ \text{s}^{-1}$

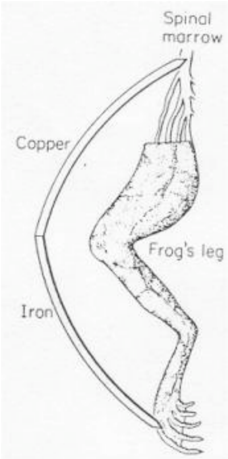
Repulsive case when Q and q have same sign:



Because matter in bulk usually comes with equal positive and negative charges, electric forces generally cancel in large scale bodies as a whole, such as the Earth and the Sun. Thus, the left-over long-range $1/r^2$ force between the Earth and the Sun is associated with gravity, not electricity.

Discovery of Electricity in Neurological Function and Invention of the Battery

- Luigi Galvani (1737-1798) is startled by twitching of a dead frog when a steel scalpel made contact with the frog's leg and a brass hook that held the leg in place (origin of phrase "galvanize into action").
  - Note that this experiment suggests that some biological functions are associated with electricity (& magnetism).
  - Last time, we said biology equals chemistry. In a future lecture, we shall show that chemistry is electricity (& magnetism) applied to atoms and molecules.
- Allesandro Volta (1745-1827): electricity must have flowed when steel connected to brass through salty medium of frog's blood (an electrolyte).
- Volta creates "voltaic pile" (a battery) from a stack of disks alternating between copper and zinc sandwiching brine.



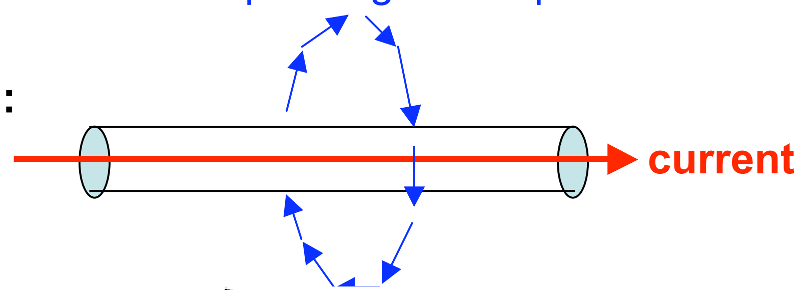
Electricity & Magnetism (4)

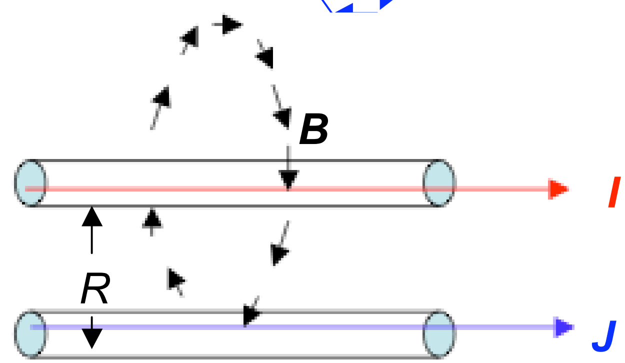
- Flowing electric charges, say, in a wire connected to a battery, give rise to *electric currents.* Hans Oersted (1777-1851) discovered that a wire carrying a current can deflect the needle of a nearby compass:

  (4) Currents yield magnetic forces.
- Quantified by Andre Ampere (1775-1836).
- Michael Faraday (1791-1867), the best experimental physicist of all time, introduced the idea of *fields,* in particular, electric and magnetic fields, ***E*** and ***B***.

Direction of pointing of compass needle

Oersted:





Ampere : Force $\propto \frac{IJ}{R}$

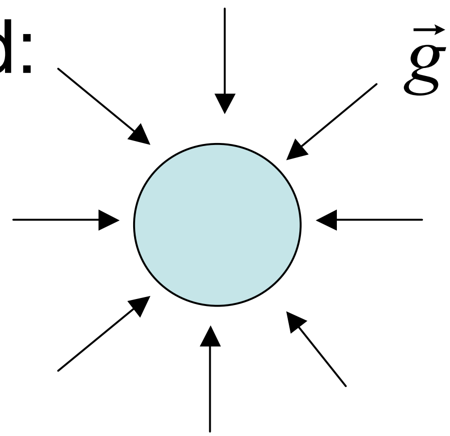
Attractive if ***I*** and ***J*** parallel; repulsive if anti-parallel

Faraday: Flowing current ***I*** produces magnetic field ***B*** $\propto I/R$; flowing current ***J*** in field ***B*** feels force ***F*** $\propto$ ***J*** x ***B*** $\propto IJ/R$

Electric Field

- Gravitational field:

positive M

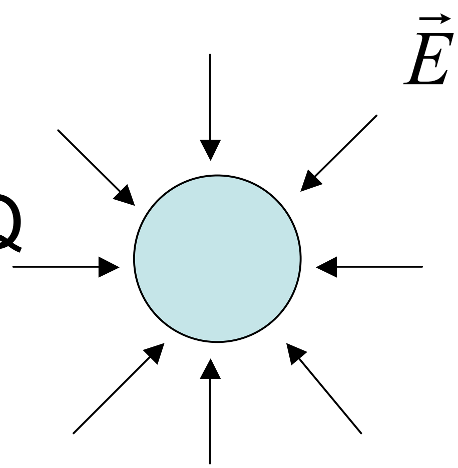


$$g = \frac{GM}{r^2}$$

$$\vec{F} = m\vec{g}$$

- Electric field:

negative Q

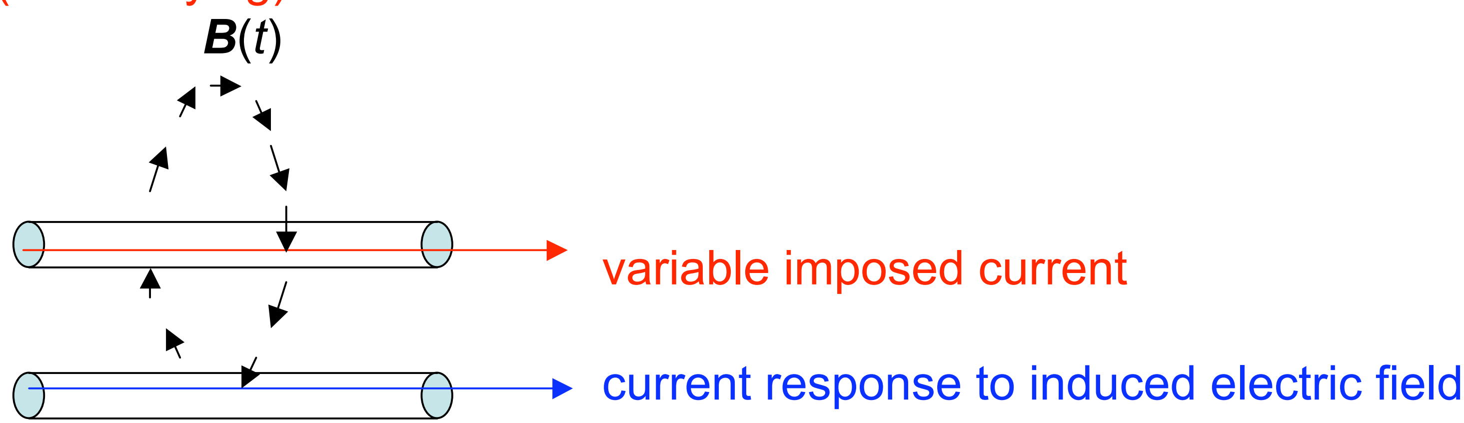


$$E = \frac{Q}{r^2}$$

$$\vec{F} = q\vec{E}$$

Electricity & Magnetism (5)

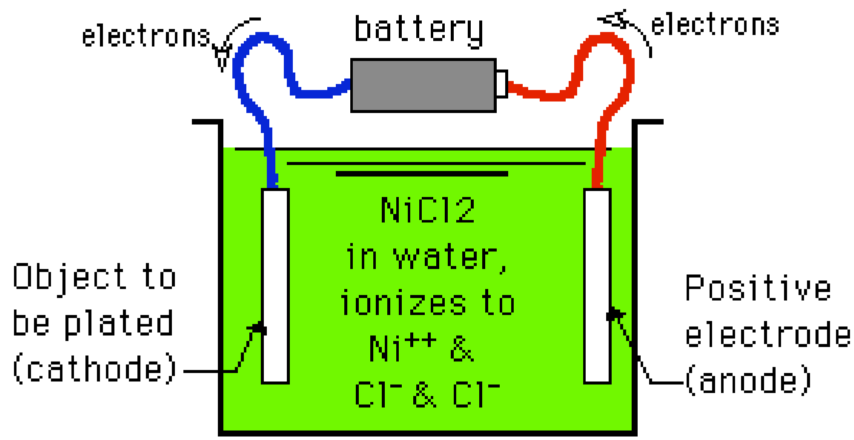
- Faraday reasons:
  - Electric fields can cause currents to flow.
  - Flowing currents generate magnetic fields (according to Ampere).
  - Therefore, in a sense, electric fields generate magnetic fields (via currents).
  - Can magnetic fields generate electric fields?
  - In experiments, no effect for steady state, see effect only when turning on or turning off apparatus.
- Faraday's law of induction: (5) A time-varying magnetic field will generate a (time-varying) electric field.



Basis of modern power industry – generation of alternating current via spinning magnets surrounded by electrically conducting coils of wire.

Faraday's Anticipation of Atomism of Electricity (extra material)

- Faraday's earlier work on electroplating of metals had demonstrated that electric charges were a basic component of matter, and that such charges came in fixed units.
- This evidence suggested the existence of units of matter (atoms?) that contained units of electric charge.
- Faraday resisted drawing this conclusion (the atomism of electricity) because his law of electroplating could just as well arise if matter and electricity came in continuous rather than discrete amounts.



Amount of Ni electroplated = current x time = charge transferred form one electrode to other. Deposition of 1 mole of doubly charged ion requires flow of 193,000 Coulombs of charge Q:

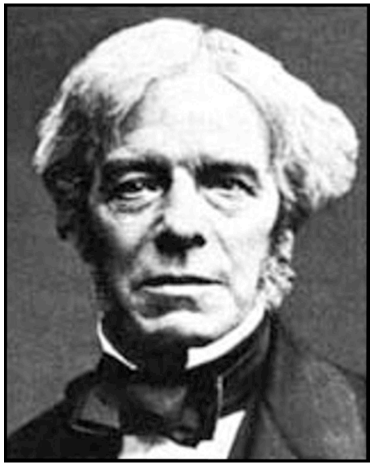
$$N_A(2e) = Q \Rightarrow e = \frac{Q/2}{N_A} = 1.60 \times 10^{-19} \text{ Coulomb}$$

$$= 4.80 \times 10^{-10} \text{ esu (charge of electron)}$$

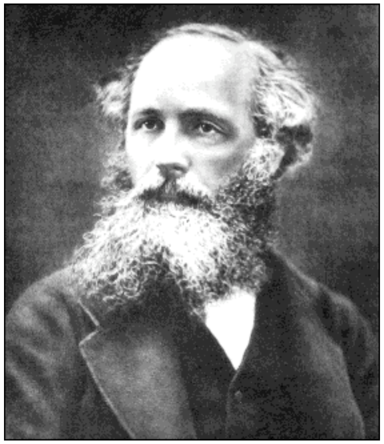
where $\text{esu} = \text{gm}^{1/2}\ \text{cm}^{3/2}\ \text{s}^{-1}$.

Faraday & Maxwell: Plebian & Patrician

- Faraday's question: Can a time-varying electric field give rise to a magnetic field, even in the absence of an electric current?
- Maxwell found a way to give precise mathematical expression to:
  - Gilbert's discovery of no magnetic monopoles (magnetic field lines neither begin nor end on "magnetic charges").
  - Coulomb's law for the electric field associated with any collection of electric charges.
  - Ampere's law for the magnetic field associated with any distribution of electric currents.
  - Faraday's law of induction that time-varying magnetic fields can generate time-varying electric fields.
- Discovered four equations given above are inconsistent with Franklin's law of the conservation of electric charge unless one adds a term in Ampere's law that allows time-varying electric fields to generate time-varying magnetic fields, *even in the absence of electric currents.*



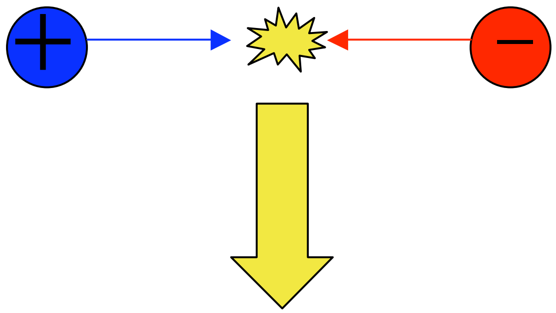
Michael Faraday (1791-1867)



James Clerk Maxwell (1831-1879)

A Thought Experiment (extra material)

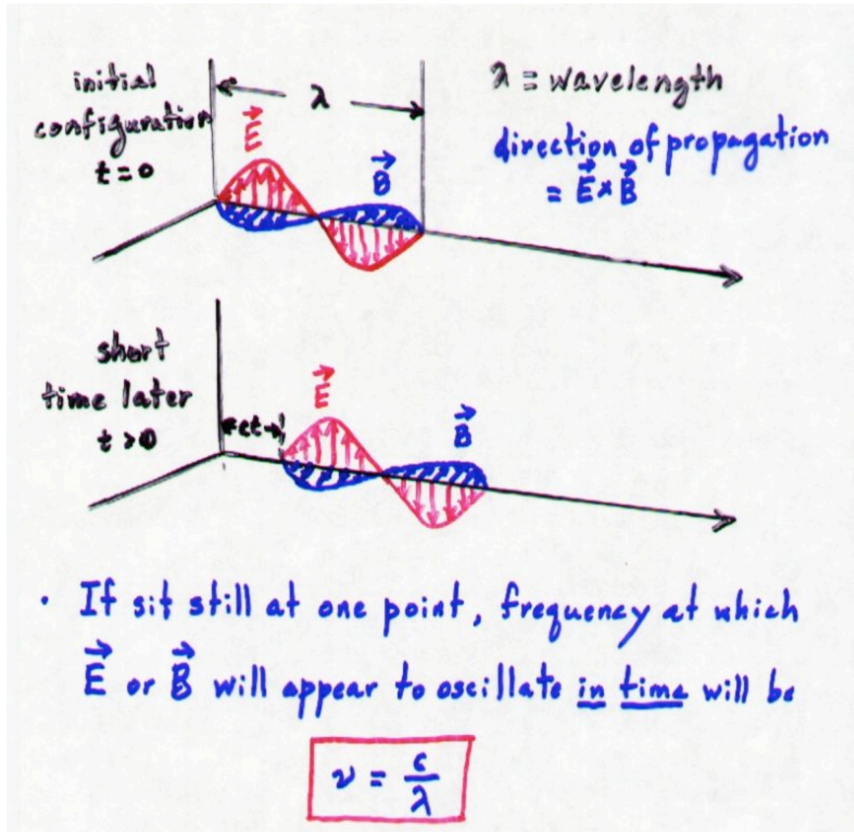
- Positive charge moving to right and negative charge moving to left give a net current, which must have an associated magnetic field that pervades all space. When the two charges meet and neutralize one another, magnetic and electric fields must begin to decay, but they cannot disappear from all space immediately. The time-varying magnetic field can sustain the time-varying electric field according to Faraday's law of induction, but what sustains the time-varying magnetic field?
- Answer: the time-varying electric field!
- Moreover, the original energy of the moving charges cannot have disappeared. Something permanent must have appeared to replace this energy. What?
- Answer: radiation. The time-varying electric and magnetic fields are equivalent to some kind of radiation!



Radiation!

Maxwell's Picture of Light as an Electromagnetic Wave

- Time-varying ***B*** gives rise to time-varying ***E***, even in the absence of charge; whereas time-varying ***E*** gives rise to time-varying ***B***, even in the absence of current.
- Can time-varying ***E*** and ***B*** sustain each other in a vacuum absent of any charges or currents? If so, what are the properties of the resulting electromagnetic fields?
- Maxwell's answer: Disturbances that propagate at the speed of light, *c* = 300,000 km/s. In other words, light is an electromagnetic wave!



More next lecture.

Summary: Unification of Electricity, Magnetism, & Light

- For millennia, electricity, magnetism, & light were studied as separate curiosities, devoid of many practical applications (apart from the magnetic compass).
- Then, in the space of a few centuries, the efforts of many scientists began to reveal quantitative relationships.
- The effort culminates in the great synthesis by Faraday and Maxwell, which results in a comprehensive theory of the related phenomena, as well as many practical applications (power generation by alternating currents, artificial sources of light, radio and television, telephone, telegraph, wireless communication, etc.).
- Einstein later tried to unify theory of electromagnetism and the theory of gravitation. Today, scientists are trying to unify all the forces of nature under the banner of a single super-force. Will these attempts to understand everything in terms of a single thing ever stop? Is fundamental physics finite or infinite?