Now for something totally (?) different…

- OUR FIRST REAL FORCE LAW: $\mathbf{F} = -G\, m\, M\, /\, r^2$
  - Universal gravitational force (Newton); Force constant = $G = 6.7 \cdot 10^{-11}$ N m^2/kg^2
  - Acting between any two masses along a line connecting them
  - Proportional to both of these masses
  - Inversely proportional to the square of their distance
  - Always attractive: $m, M > 0$ => $\mathbf{F}$ is negative - tends to <u>reduce</u> r

- NOW: Electrostatic force (Coulomb):
  - Acting between any two charges Q, q along a line connecting them
  - Proportional to both of these charges; Force constant = $k = 9 \cdot 10^9$ Nm^2/C^2
  - Inversely proportional to the square of their distance
  - Sign of force depends on relative sign of charges; can be both attractive (opposite sign) or <u>repulsive</u> (equal sign)

$$F = +k \frac{Qq}{r^2}$$

What are charges?

- Charge is a fundamental property of matter
  - Measured in units of Coulomb (C) - 1 C = 1 A x 1 s
- Most elementary particles are charged
  - Charge is **quantized**: all charges are multiples of $e = 1.61 \cdot 10^{-19}$ C *)
- Comes in TWO kinds: + or -
  - Equal sign charges repel each other, opposite sign charges attract
- Total charge (sum of all "+" minus all "-") never changes - charges cannot be created or destroyed, only moved around or "neutralized" (*Charge conservation*)

*) Except quarks which have charges of +/- 1/3 *e* or +/- 2/3 *e* **)

**) But in any elementary particle reaction charges change only by integer multiples of *e*

Coulomb's Law

$$F = +k\frac{Qq}{r^2}$$

- Measure each charge in Coulomb
- Measure *r* in m
- Measure force in N
- => $k = 9 \cdot 10^9$! [Nm^2/C^2]
- NOTE: 1kg of protons = $6 \cdot 10^{26}$ protons = 100,000,000 C! => Force between to 1kg-bags of protons 1 m apart = $9 \cdot 10^{25}$ N !!
- GRAVITATIONAL force between those same two bags is $6.7 \cdot 10^{-11}$ N - 36 orders of magnitude less!!!

Huh?

- Because Coulomb forces are so tremendous, and…
- Because there are both positive and negative charges,
- and because like charges repel and opposite charges attract
- -> charges are nearly always nearly perfectly balanced.
  - Example: Atom, matter in the Universe
- Coulomb forces simply add (*Principle of Superposition*), so positive and negative charges cancel each other out
- Small amounts of charges can be transferred fairly easily from one object to another (typically μC or less)
  - Example: Shuffling over a carpet, combing a cat,…
  - Photocopier, laser printer, plastic wrap,…

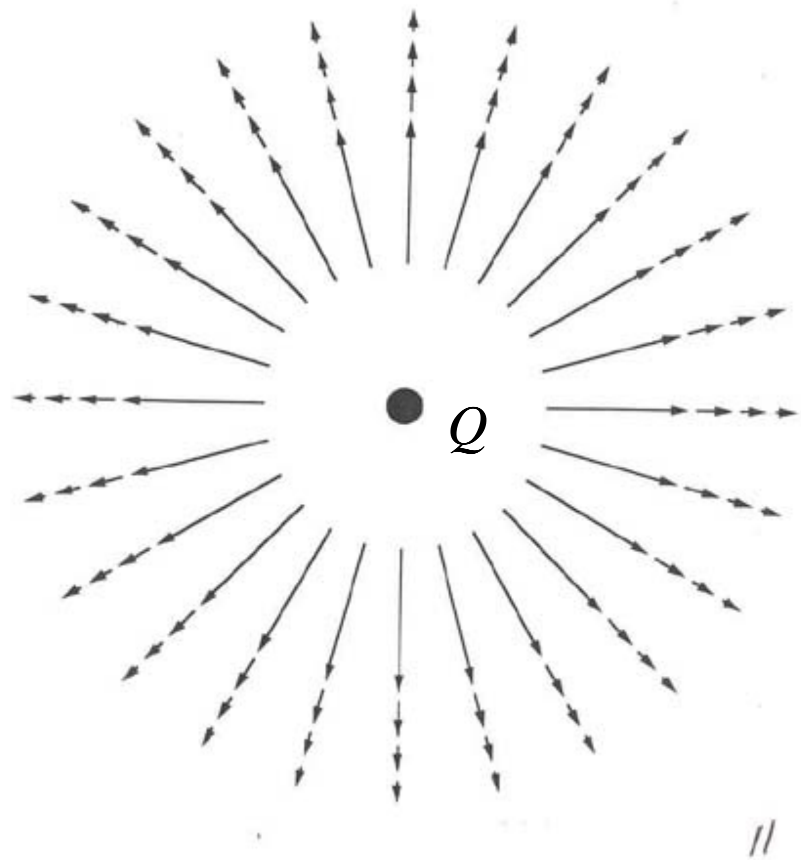
Moving charges around

- Two (or more) different types of materials in everyday life:
- Conductors
  - Huge amounts of charges (usually electrons) can move around easily:
    - Can shield other charges; charges tend to even out quickly
    - Can induce charges
    - Can transfer charges
  - Examples: All metals, plasma, sea water,…
  - Most perfect example: Superconductors
- Insulators
  - Charges are "stuck" - can keep charges in place (except for small transfers from surface to surface – shuffling, rubbing,…)
  - BUT: can induce "polarization" (e.g. balloons stuck to ceiling)
- …and semiconductors (in transistors, computer chips etc.)

$$F = +k\frac{Qq}{r^2}$$

Electric Field

- Coulomb's Law tells us what force a charge Q would exert on charge q if charge q sits at **r** - see Fig.
- But the electric properties of Q don't depend on whether we measure the force on q or not
- => Concept of a FIELD: An intrinsic property of ALL OF SPACE due to some agent
- Make electrostatic force a two-step process: First charge Q generates a field $E = kQ/r^2$, second charge q interacts with that field: $F = qE$



Is it "real"?

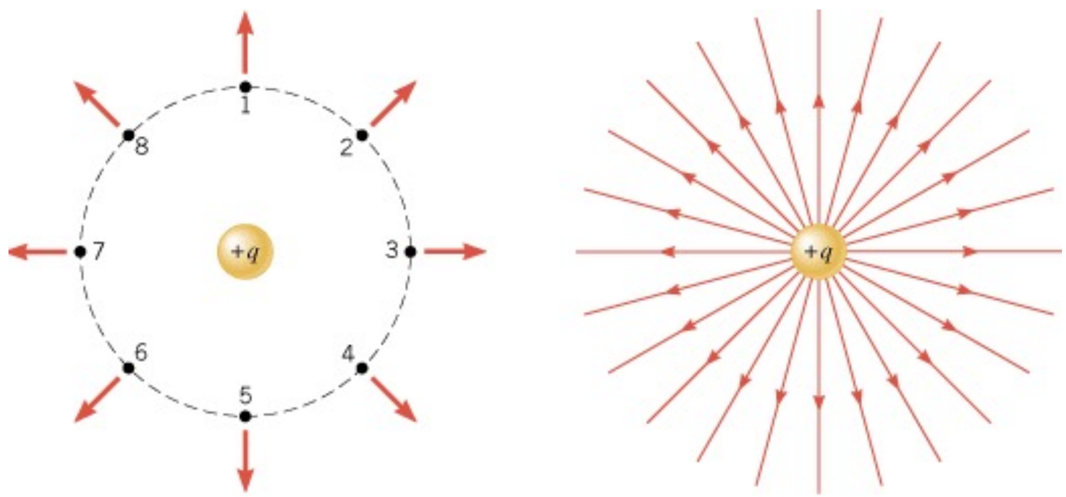
- Can be used to calculate the behavior of a complicated arrangement of charges: First calculate the field **E** it produces, then you'll know what force it will exert on any "test" charge q that you put somewhere into this field: $\mathbf{F} = q\mathbf{E}$
  (Note: force is proportional to q and points in the SAME direction as **E** if q is positive; else in the opposite direction!)
- Can be used to describe how CHANGES in the distribution of charges propagate (at most with speed of light -> Einstein)
- Can carry energy (charged up capacitor, electromagnetic wave)
- Can even carry "mass" (via Einstein's $m = E/c^2$)
- On fundamental (quantum mechanical) level, is associated with a "real" particle: the photon.

How to visualize?

- Draw field lines: Starting at “+” charges, ending at “-” charges (or going on forever)
- The bigger the charge, the more field lines start (end) at it
- Point in the direction of the field at each point
- Spread out evenly
- Never cross
- Example: Hair standing up

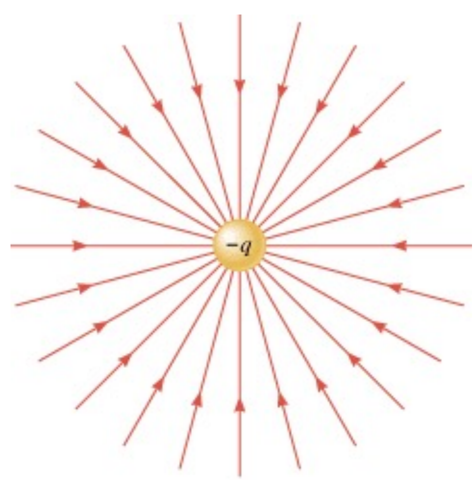
- Surprise: “automatically” give the correct STRENGTH of the field as well: proportional to DENSITY of field lines

Examples of Electric Fields I



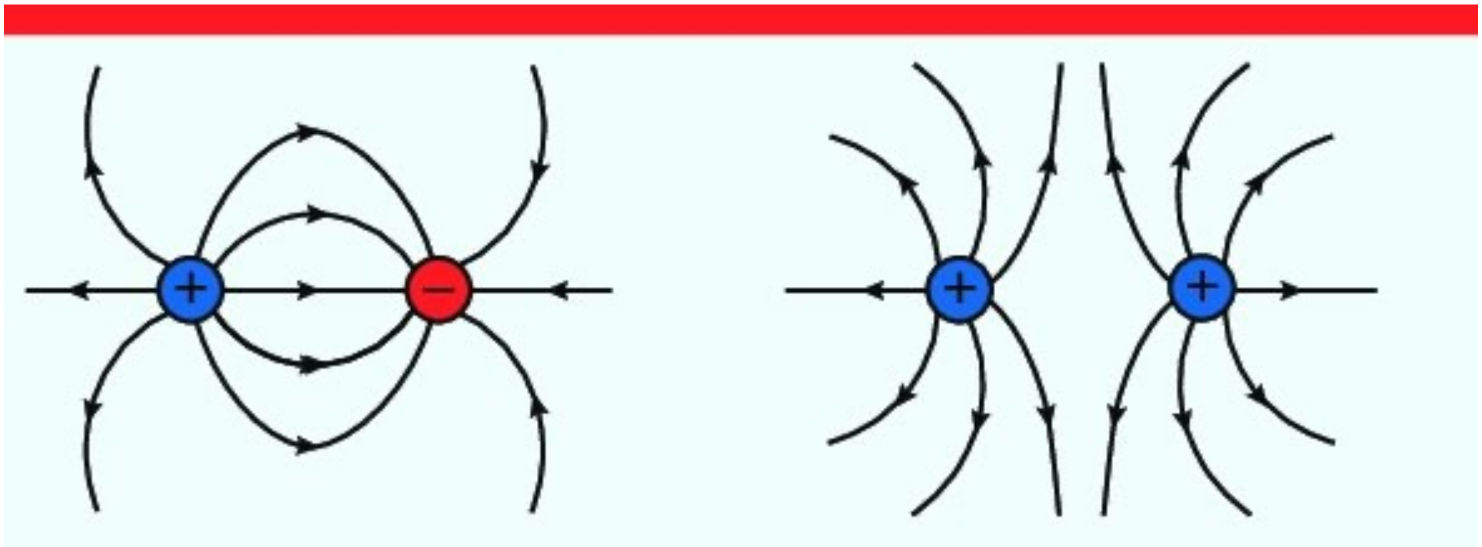
(a) (b)

Positive Point Charge



Negative Point Charge

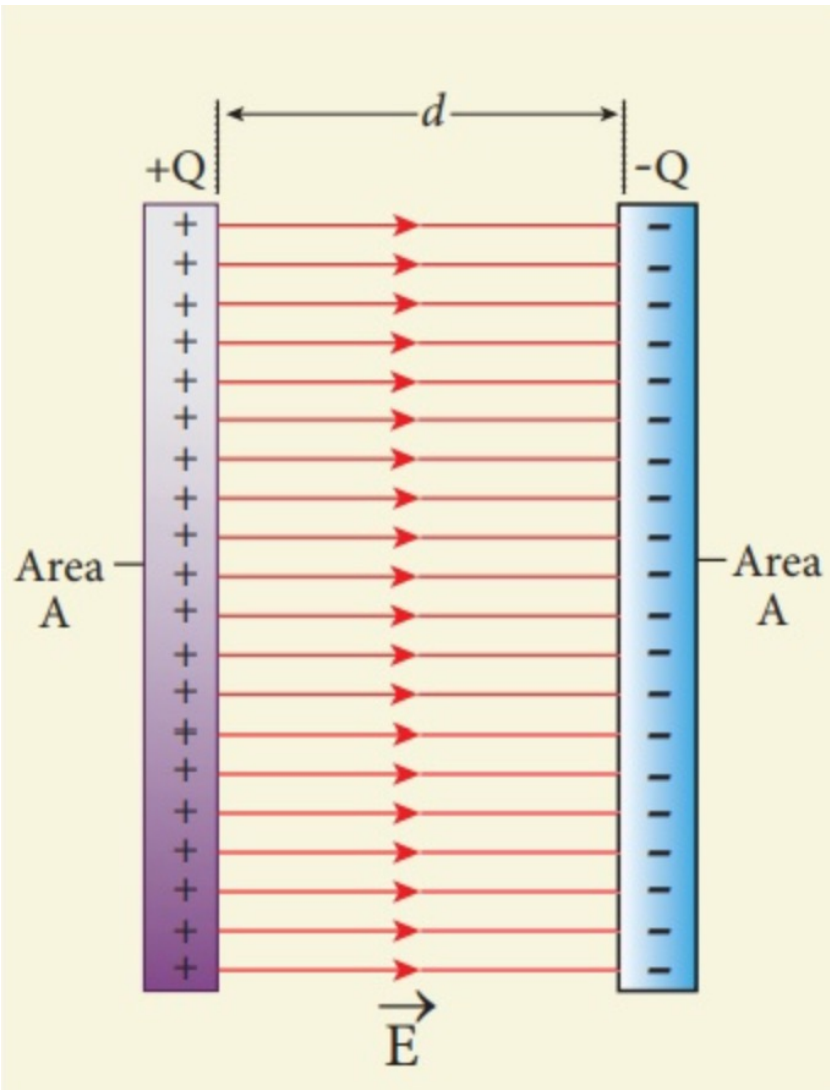
Examples of Electric Fields II



Two opposite Charges

Two identical charges

Examples of Electric Fields III



Electric Field in a Capacitor

Revisit

- Conductors in electric fields
  - Huge amounts of charges can move around easily:
    - Shields outside electric fields completely on the inside *)
    - All charges sit on the outside
    - Keep safe inside cars during thunderstorms
  - => Conductors are attracted to charged objects

- Insulators in electric fields
  - Charges are “stuck” - can’t completely shield outside electric fields
  - BUT: can induce polarization -> outside electric fields will be weakened inside (e.g.: Water or oil will weaken the field to 1/100 or less)
  - Polar molecule align themselves with the electric field so that the negative sides are closer to the source of the field lines
  - => Insulators are attracted to charged objects!

*) as long as no currents are flowing

Potential energy in Electrostatics

- Electric field **E** (e.g., due to a positive charge *Q*) times amount of (test) charge *q*: Force **F**
- Move charge *q* towards charge *Q* (against field direction): Need to do work if *q* is positive, get work out if *q* is negative!
- This work can be retrieved by letting go of *q* - it will accelerate (-> kinetic energy from stored potential energy)
- Work only depends on initial and final position -> CONSERVATIVE FORCE
- Can define electrostatic potential energy U_{pot}^{elec} of charge *q* (in presence of charge *Q*):
  - Larger if |*q*| increases
  - positive if *q* is positive, negative otherwise
- Can store energy in electric devices (like vdGG, capacitor, battery) by storing charges at a high electrostatic potential energy
- Example: Electrostatic potential energy for q in field of point charge *Q*: Similar as for gravitational potential energy…

$$U_{pot}^{elec} = k\frac{qQ}{r}$$

Electric POTENTIAL

- Since potential ENERGY is proportional to q, can define electric POTENTIAL *U (= "voltage")* at every point: equal to potential ENERGY that q would have at that point, divided by q.
- Similar to electric field: electric potential becomes a function of point in space alone (once the charge distribution creating it is known)
- Unit: J/C = V
- Potential due to a single point charge Q: $V_{pot} = k\dfrac{Q}{r}$
- Very important practically: Batteries, household outlets, transmission lines, charged up objects…
- Remember: Energy stored = Voltage x charge

$$
\begin{tikzcd}
\mathbf{E} \arrow[r, "\text{over some distance d}"] \arrow[d, "\text{times}"', "q"] & V = \mathbf{E}d \arrow[d, "\text{times}"', "q"] \\
\mathbf{F} \arrow[r, "\text{over some distance d}"] & U_{pot} = \mathbf{F}d
\end{tikzcd}
$$