# PHY 117 HS2024

Week 8, Lecture 1
Nov. 5th, 2024
Prof. Ben Kilminster

Previously, we found that the best possible efficiency for a perfect reversible engine is related to the temp. difference:

$$\varepsilon_c = 1 - \frac{T_c}{T_H} \Rightarrow \frac{T_c}{T_H} = \frac{|Q_c|}{|Q_H|}$$

Switzerland' electricity generation:

~60% hydropower → eff = $\tilde{9}0\%$, not based on temp. difference

~30% nuclear power → $\epsilon \sim 35\%$, ($\epsilon_c \sim 50\%$, $\epsilon_{SL} \sim 70\%$)

5% solar power → $\epsilon \sim 20\%$, not based on temp. difference

⇒ Average Efficiency: ~70%

Heating home

Electrical house heater efficiency =

Swiss power plant efficiency * transmission efficiency * electrical heater efficiency

= (70%) * (95%) * (100%) = 66%

or oil ~~/~~ Modern high-efficiency oil heater : ~90%

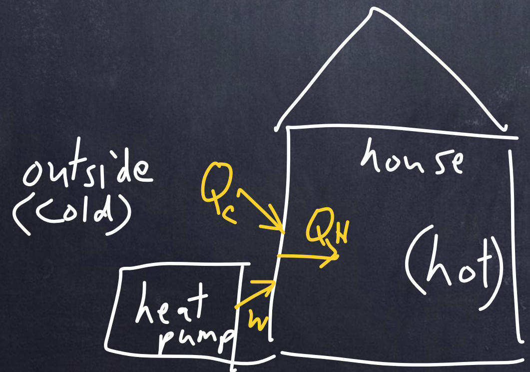
(90% of chemical energy converted to heat)

(but produces $CO_2$)

But, if the goal is to heat a house, we can do much better.

A heat pump is a refrigerator that removes $Q_c$ of heat from a cold reservoir and puts $Q_H$ of heat into a hot reservoir, using $W$ amount of work.

$$|Q_c| + W = |Q_H|$$




What is the efficiency of a heat pump?

$$C.O.P. = \frac{|Q_c|}{W} = \frac{Q_c}{|Q_H| - |Q_c|}$$

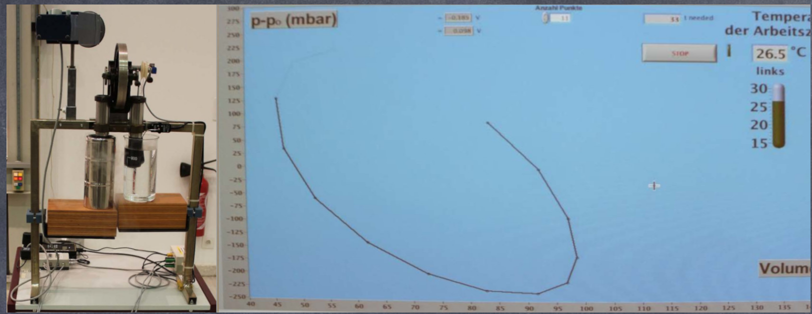
divide the top + bottom by $|Q_H|$ $\Rightarrow C.O.P. = \dfrac{\frac{|Q_c|}{|Q_H|}}{1 - \frac{|Q_c|}{|Q_H|}}$

Using our Carnot conditions, we can replace $Q_c \rightarrow T_c$, $Q_H \rightarrow T_H$

$$C.O.P. = \frac{\frac{T_c}{T_H}}{1 - \frac{T_c}{T_H}} = \frac{T_c}{T_H - T_c} = \boxed{\frac{T_c}{\Delta T} = COP_{max}}$$

$\rightarrow$ the smaller the $\Delta T$, the better the performance.

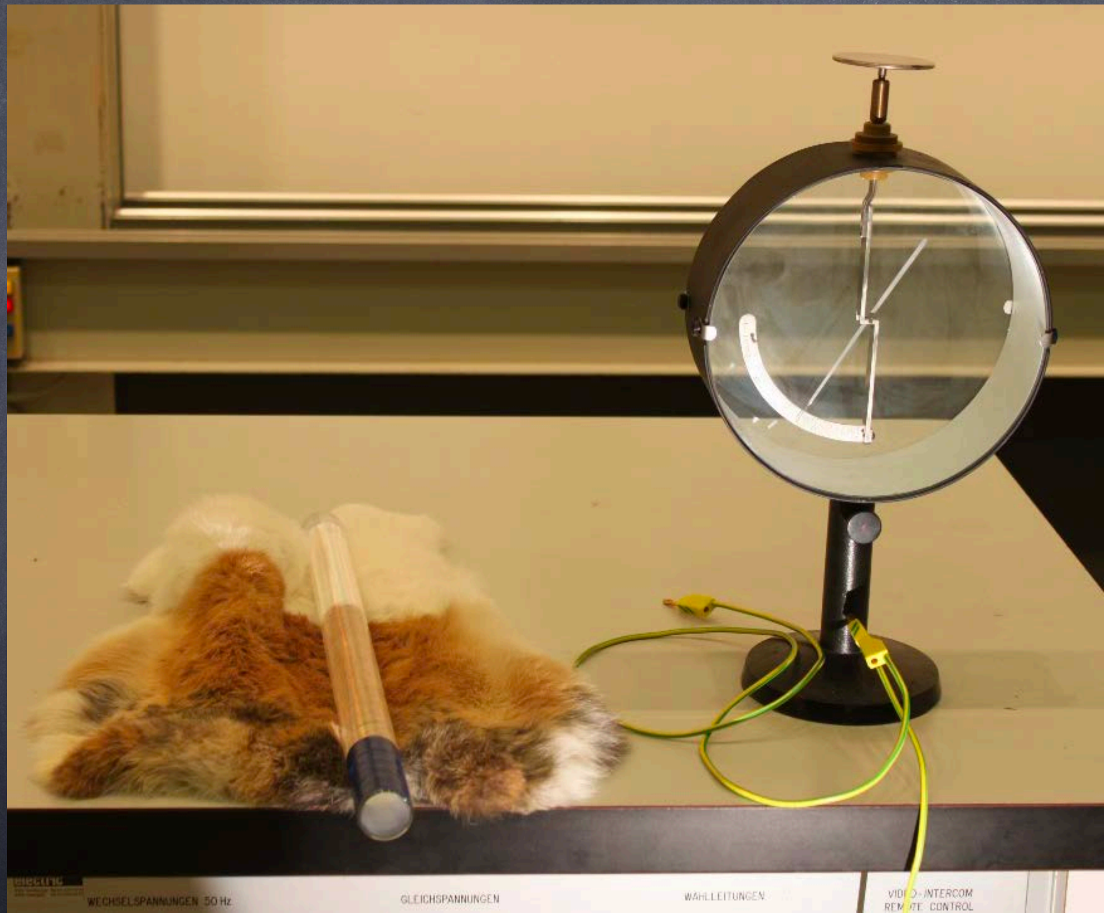
As an efficiency, $\varepsilon = \dfrac{Q_H}{W} = \dfrac{\cancel{W}(1 + C.O.P.)}{\cancel{W}}$



p-p$_0$ (mbar)
Tempera
der Arbeitsz
26.5 °C
links
30
25
20
15
Volum

End of thermodynamics

Switching to electromagnetism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Electrostatics:

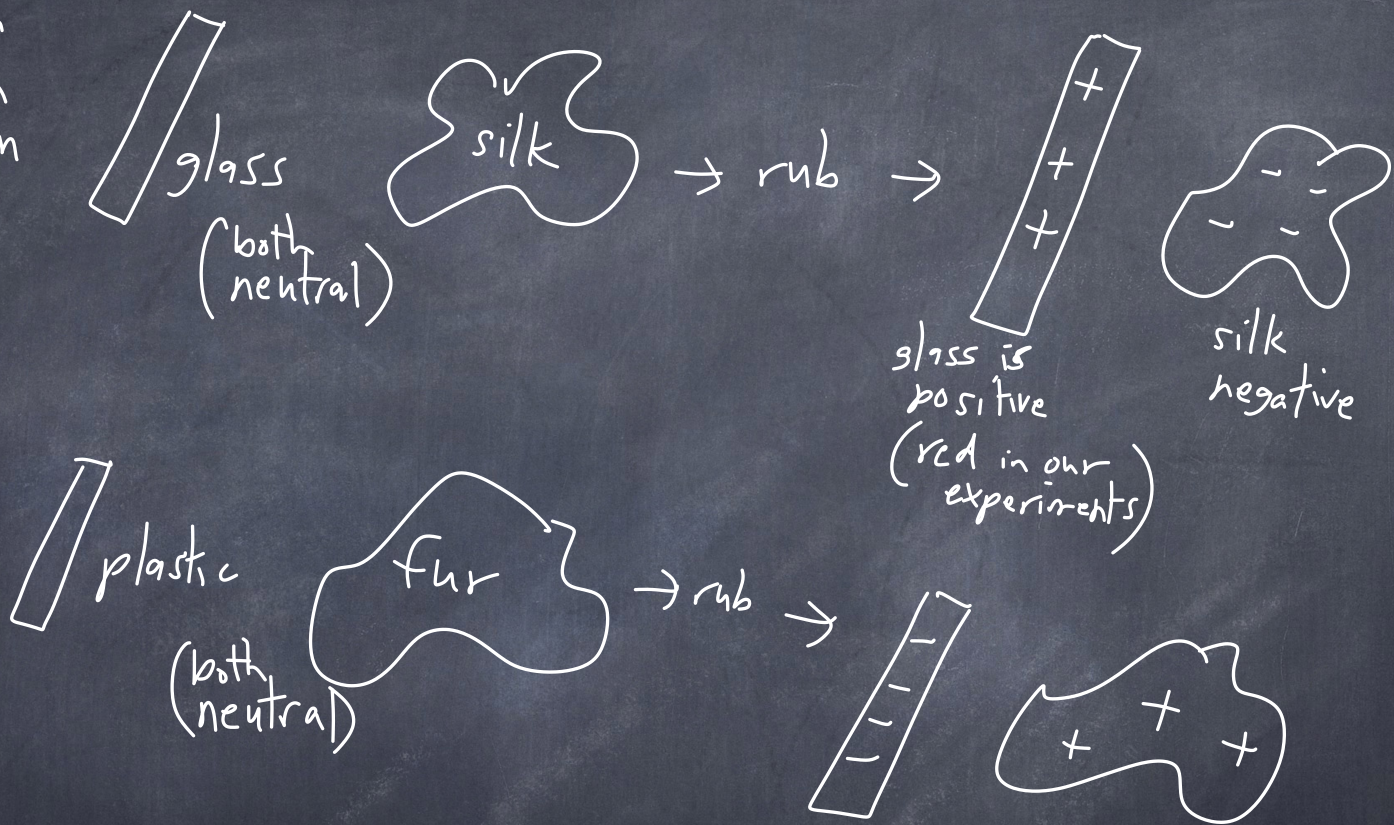
Observations: 3 groups of charged objects:

1) pairs attract
2) pairs repel
3) pairs that do nothing

Ideas:

1) something called charge exists
2) we can move charge
3) attraction or repulsion between charged objects.

Benjamin Franklin convention

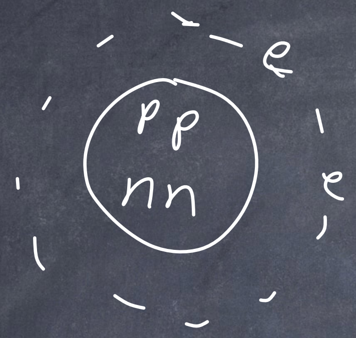



Now, we know that:

- negative charges are electrons (the moving charges in solids)
- charge $\equiv Q$ ; $+, -, 0$

Matter consists of atoms

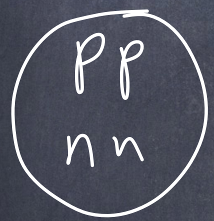
neutral




| | | Q (charge) |
|---|---|---|
| proton | = p | $+e$ |
| neutron | = n | $0$ |
| electron | = e | $-e$ |

e: fundamental unit of charge

charge $+Ze$




ion: charged atom

we have observed that charge is quantized.

$$Q = \pm Ne \qquad N: \text{integer} \quad \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots$$

The unit of charge is the Coulomb, [C]

A single electron has a charge of $-e$

$$e = 1.6 \times 10^{-19}\ C$$

Rubbing materials together (static electricity) typically produces charges $\sim 10^{-8}\ C = 0.01\ \mu C$

$$\#\text{electrons} = 10^{-8}\ C \cdot \frac{1e}{1.6E{-19}\ C} = 6E10 \text{ electrons}$$

Note: It is unknown why a proton has the opposite charge as an electron. A proton is actually a composite particle, and has a mass 2000 times greater than an electron.

(Electron is a fundamental particle)

Experiments have shown that a proton is really made of 3 quarks, each with a fractional charge.

u: up quark $Q(u) = +\frac{2}{3}e$

d: down quark $Q(d) = -\frac{1}{3}e$

$$p = \begin{matrix} u & u \\ d & \end{matrix}$$

$$Q(p) = +1\,e$$

$$n = \begin{matrix} d\,d \\ u \end{matrix}$$

$$Q(n) = -\frac{1}{3}e + -\frac{1}{3}e + \frac{2}{3}e = 0$$

Quarks are observed only as combinations with integer electric charge. We can study quarks individually in a particle collider, like at CERN LHC

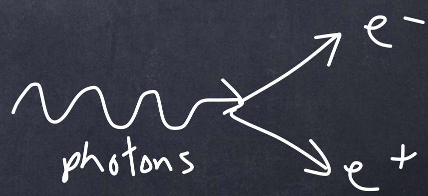
Charge conservation is a law of Nature.
(like energy + momentum conservation)

Electric charges move, but don't disappear.

Caveat: In particle physics, you can destroy + create particles, but conservation laws still apply:

photon: $\gamma$

$$\gamma \to \underset{\text{electron}}{e^-}\,\underset{\substack{\text{positron}\\ \text{(antimatter)}}}{e^+}$$




$$Q(\gamma)=0 \to (-1)+(+1)=0$$

**Conductors** – in some materials, electrons are free to move around.

**insulators** – materials where electrons are bound to atoms tightly, + do not move freely.

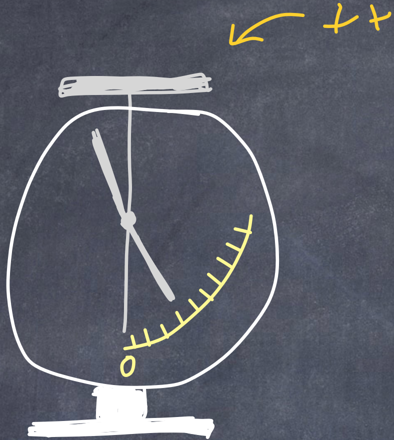
For instance, copper is a good conductor. When you combine a large number of copper atoms together, the binding energy of the electrons changes. One or more electrons per atom becomes free to move around the material.

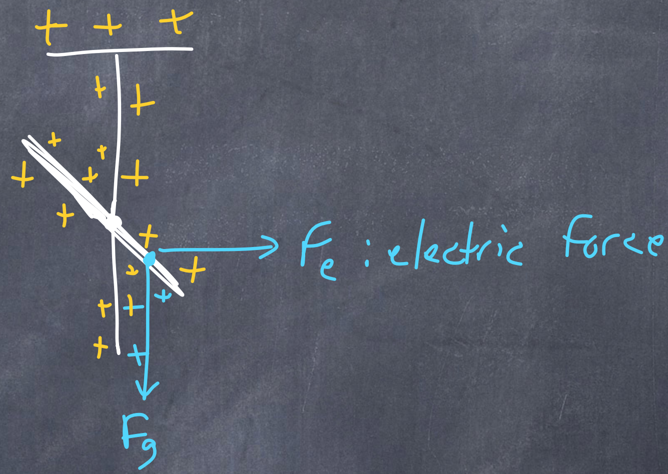
Normally neutral, but can have + or – charge.

In solids, electrons may move

In liquids + gases, electrons + negative ions (or positive) may move.

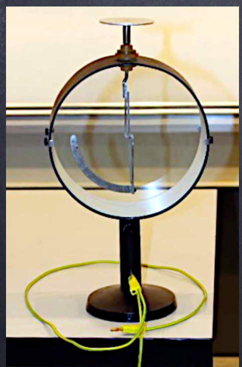
# How to measure electric charge:




$F_g$: $\tau_{cw}$ clockwise torque

$F_e$: $\tau_{ccw}$ counter-clockwise torque



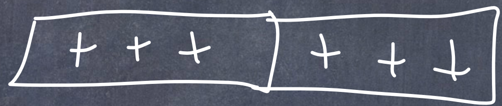
## charging by conduction

1)

charged metal rod

neutral metal rod

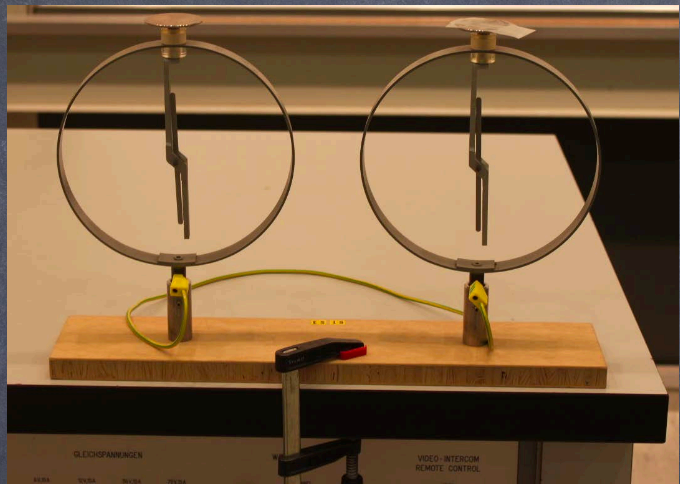
2)



charge transferred by contact

3)

both rods have a charge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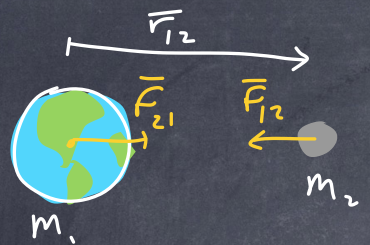
REMOTE CONTROL

Remember! what is the gravitational force between two masses:



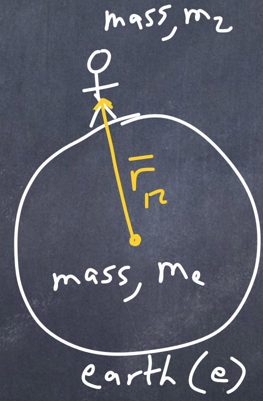

$F_{12}$ = force of $m_1$ on $m_2$, points toward $m_1$ $(-\bar{r}_{12})$

$$\bar{F}_{12} = \frac{-G m_1 m_2}{r_{12}^2} \hat{r}_{12}$$

(−) means always attractive

G: gravitational constant, applies to all massive objects

$$G = 6.672 E{-11} \frac{Nm^2}{kg^2}$$




$$\bar{F} = m_2 \bar{g}$$

$$\bar{F} = \frac{-m_2 m_1}{r_{12}^2} G (\hat{r}_{12})$$

$$\bar{g} = \frac{-m_1}{r_{12}^2} G \hat{r}_{12}$$

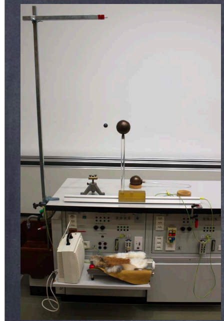
$r_{12}$ = radius of the earth

$r_{12} = r_e = 6370$ km

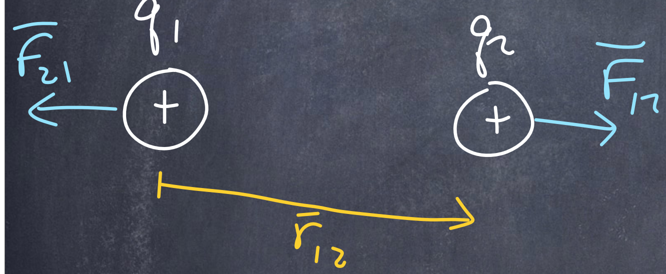
$m_e = 5.98 E24$ kg

$$g = \frac{\left(6.672 E{-11} \frac{Nm^2}{kg^2}\right)(5.98 E24 \text{ kg})}{(6370 E3 \text{ m})^2} = 9.8 \text{ m/s}^2$$

what is the electric force between 2 charges.



$$\text{Coulomb's Law:} \quad \boxed{\bar{F}_{12} = \frac{k q_1 q_2}{r_{12}^2} \hat{r}_{12}}$$




$\bar{F}_{12}$: "the force of $q_1$ on $q_2$"

$\bar{r}_{12}$: distance vector from $q_1$ to $q_2$

$\hat{r}_{12}$: unit vector of $\bar{r}_{12}$

$|\hat{r}_{12}| = 1$

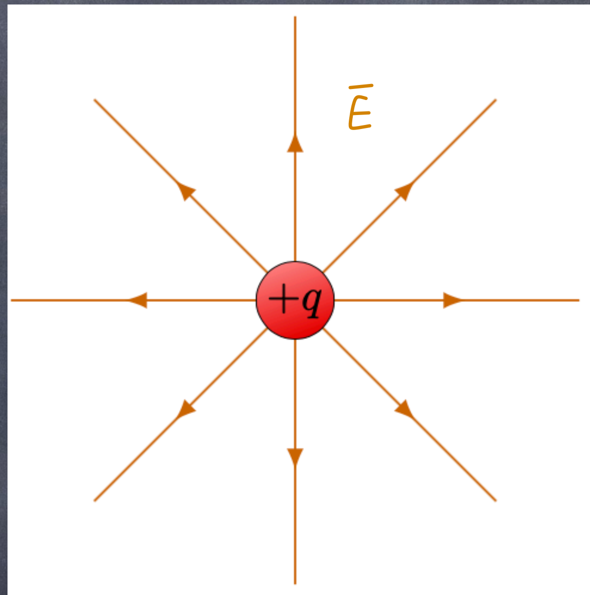
$q_1, q_2$: amounts of charges in coulombs (+) or (−)

$$K = 8.99\text{E}9 \ \frac{Nm^2}{C^2} \simeq \frac{1}{4\pi\varepsilon_0}$$

$\varepsilon_0$ = permittivity constant = $8.85\text{E-}12 \ C^2/Nm^2$

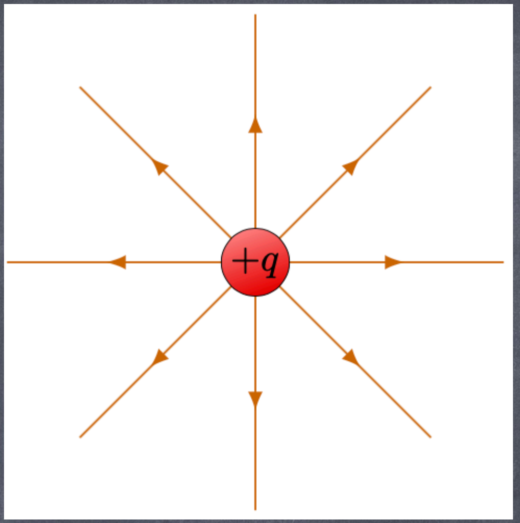
$$\underbrace{\bar{F}_{12} = -\bar{F}_{21}}_{\text{Newton's third law}}$$

The force comes from the electric field surrounding a charge distribution. $\bar{F} = q\bar{E}$



Rules for drawing $\vec{E}$-field lines

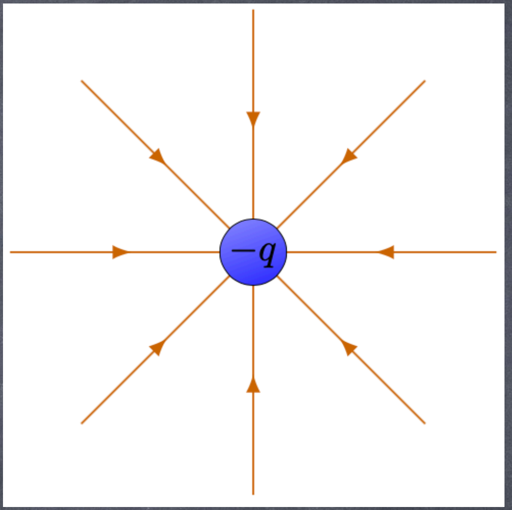
1) start on positive charges



Rules for drawing E-Field lines:

1) Start on positive charges

2) End on negative charges

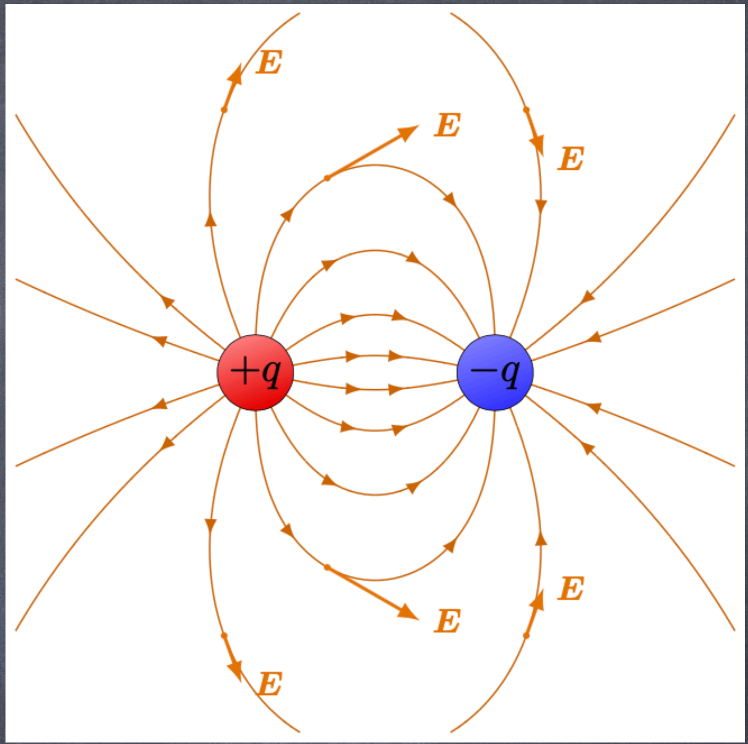


Rules for drawing E-field lines:

1) Start on positive charges

2) End on negative charges

3) Lines are symmetric as they enter or leave a charge



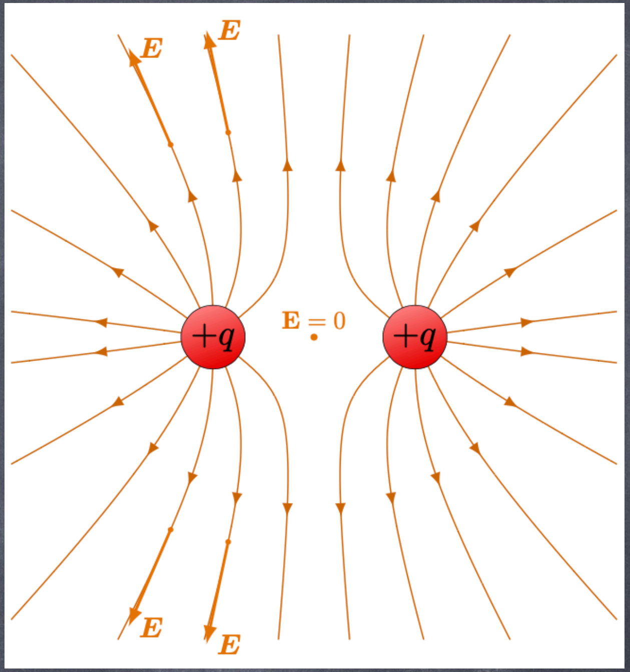
Rules for drawing E-field lines:

1) Start on positive charges

2) End on negative charges

3) Lines are symmetric as they enter or leave charge

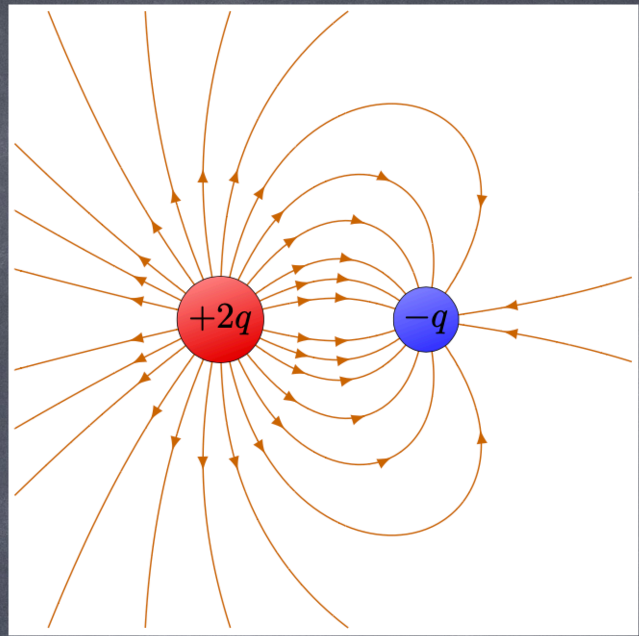
4) Lines do not cross




This causes regions of $\bar{E} = 0$

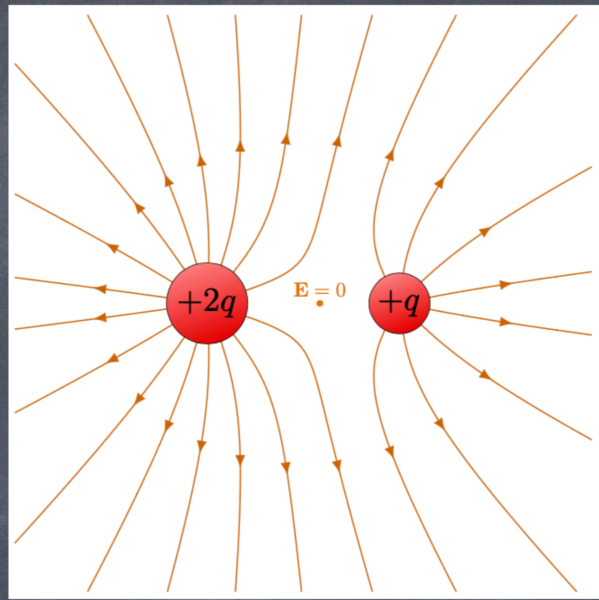
Rules for drawing E-field lines:

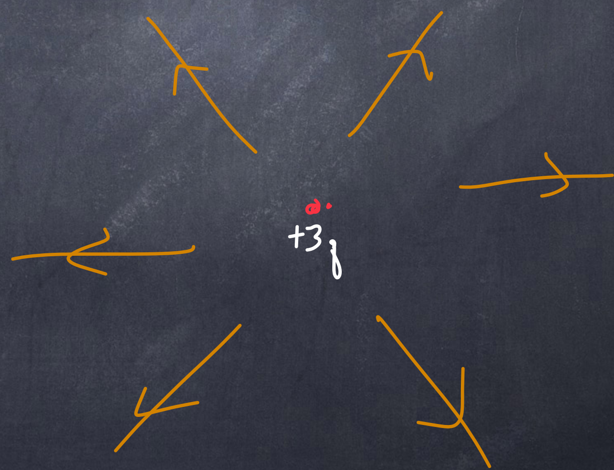
1) Start on positive charges
2) End on negative charges
3) Lines are symmetric as they enter or leave charge
4) Lines do not cross
5) The number of lines is proportional to the charge.
6) the density of lines is proportional to the magnitude of $\vec{E}$



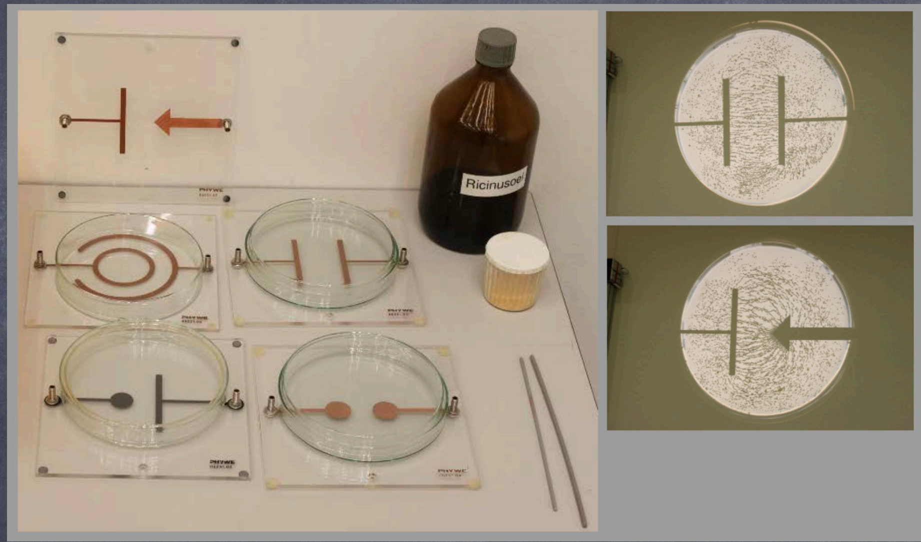
Rules for drawing E-field lines:

1) Start on positive charges
2) End on negative charges
3) Lines are symmetric as they enter or leave charge
4) Lines do not cross
5) The number of lines is proportional to the charge.
6) The density of lines is proportional to the magnitude of E
7) At large distances, the E-field lines are equally spaced as if from a single point of charge equal to the sum of charges.



# Some electric field shapes



Electric field: produced by electric charges

The E-field exerts a force on other charges that are nearby:

$$\bar{F} = q\bar{E} \qquad \bar{E} = \frac{\bar{F}}{q}$$

$q_1$ $\qquad$ O

What is the E-field here?

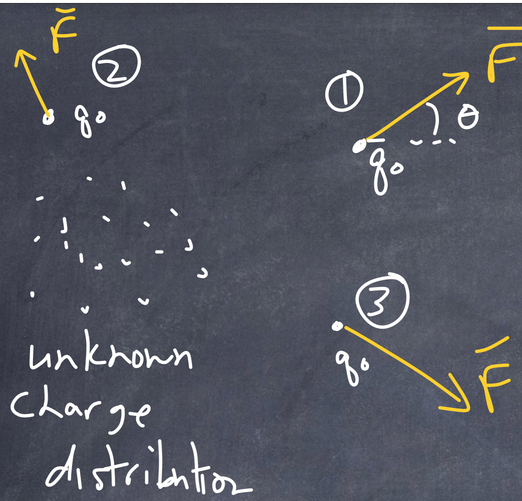
To do this, we put a test charge, $q_0$, here and measure the force.

$$q_1 \xrightarrow{\bar{r}_{10}} q_0$$

$$\bar{F}_{10} = \frac{k q_1 q_0}{r_{10}^2}\hat{r}_{10}$$

To get $\bar{E}$, we divide by $q_0$: $\bar{E} = \dfrac{\bar{F}}{q_0} = \dfrac{k q_1}{r_{10}^2}\hat{r}_{10}$

This is the E-field generated by $q_1$ at the point O




What is $\bar{E}$ of an unknown charge distribution?

To do this we measure $\bar{F}$ at different locations.

Example, at ① we use a test charge of $q_0 = 10\,nC$

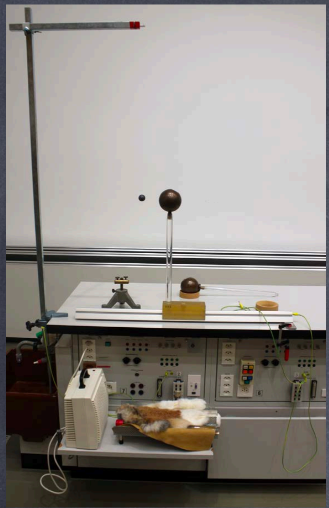
we measure $\bar{F} = 10^{-5}\,N$ at $\theta = 60^\circ$

$$\bar{E} = \frac{10^{-5}\,N}{10\,nC} = \frac{10^{-5}\,N}{10\mathrm{e}{-9}\,C} = 1000\,\frac{N}{C} \text{ at } \theta = 60^\circ$$

Important note: $q_0$ should be small so as not to change $\bar{E}$-field too much

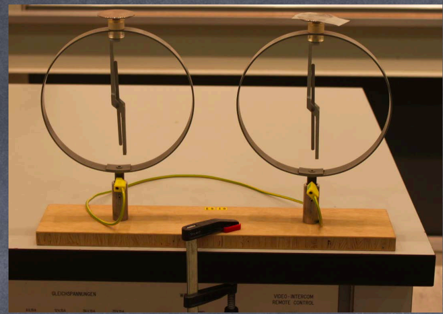
At ② + ③ different $\bar{F}$ + $\bar{E}$

So we can map out the $\bar{E}$-field strength experimentally.

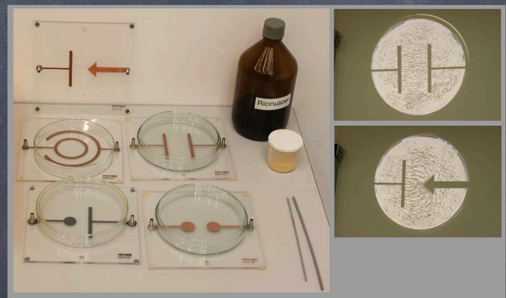


ES2

ES8



ES19



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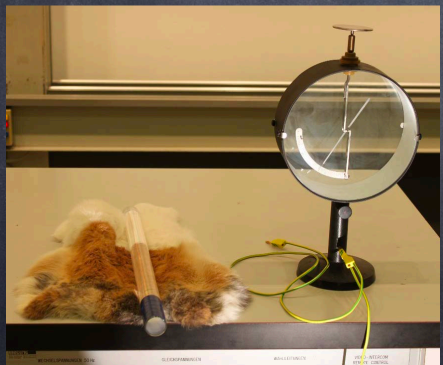

ES24