The Four Forces

Gravity

Electromagnetic force

- electrostatics
- magnetism
- light

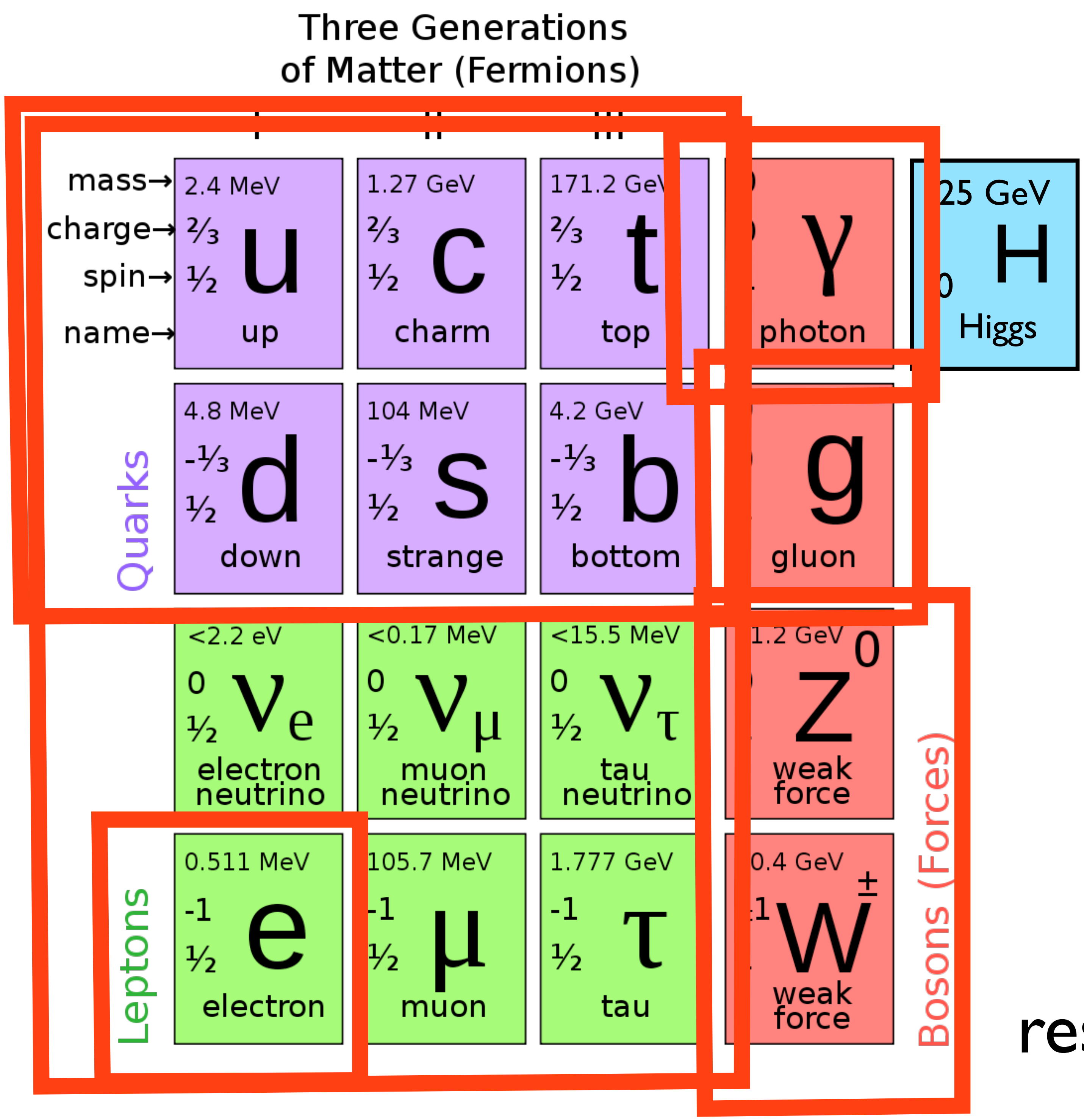
Strong force

- binding energy
- nuclear structure

Weak force

- Nuclear decay (radioactivity)

The Standard Model



This is the electromagnetic force

This is the strong force, responsible for structure (quarks make protons, neutrons, etc,)

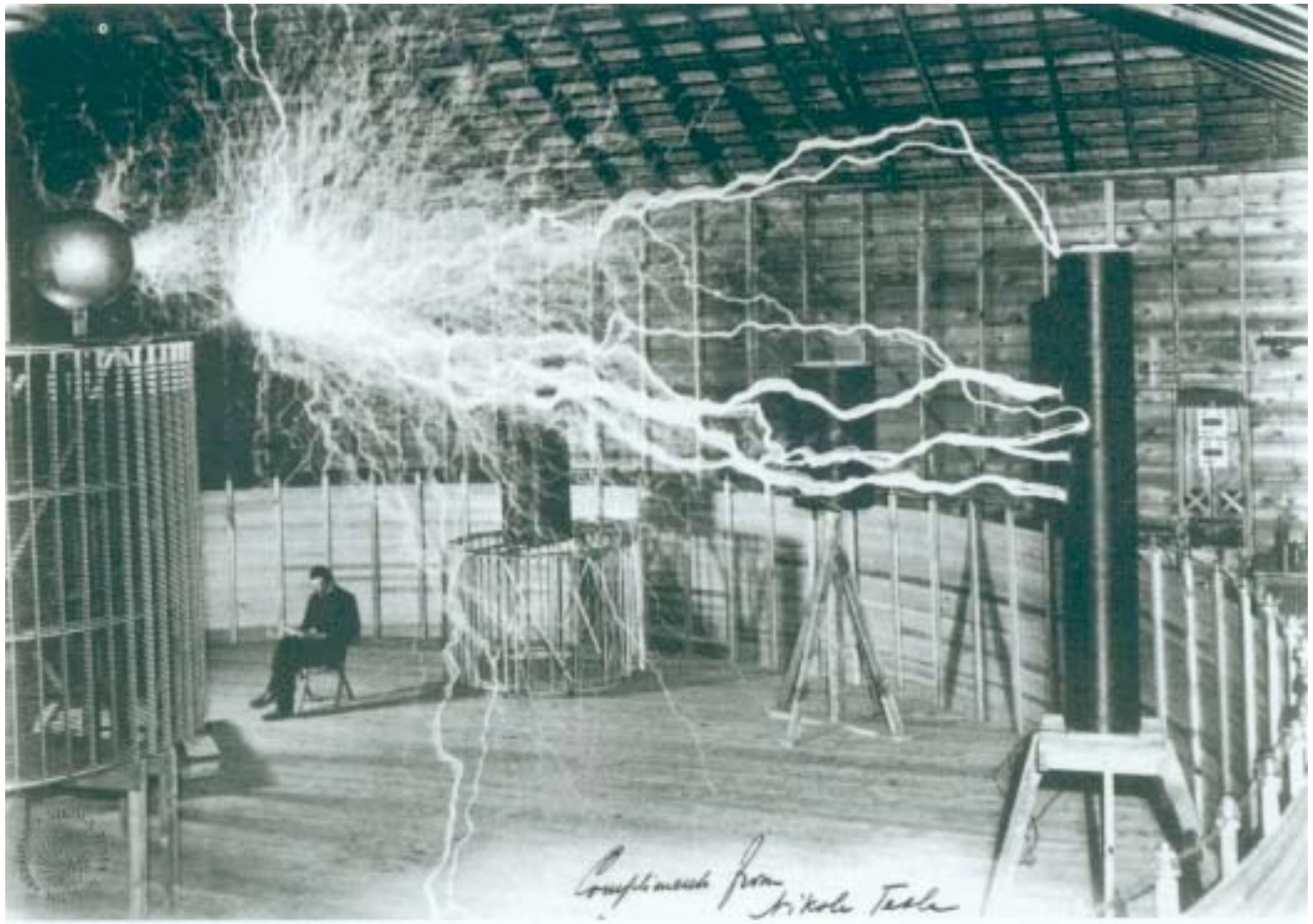
This is the weak force, responsible for nuclear decay

Mathematically, the theory looks like this:

This is the cumulation of the unification of three of the forces

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2} i g^2_s (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2} m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c^2_w} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
&\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
&g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
&W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
&\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
&i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1 - 2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
&i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
&\tfrac{1}{4} g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
&g^1 s^2_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + \\
&m^\lambda_d) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
&\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s^2_w - 1 - \gamma^5) u^\lambda_j) + \\
&(\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s^2_w - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
&\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u^\lambda_j)] + \\
&\tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + \\
&i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \\
&\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j] - \\
&\tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
&\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c^2_w}) X^0 + \bar{Y} \partial^2 Y + \\
&i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
&i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
&i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
&\tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w} \bar{X}^0 X^0 H] + \tfrac{1 - 2c^2_w}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
&\bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \\
&\bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

Electromagnetism



Electromagnetism

We are starting on a journey that will unify electricity and magnetism.
(and unify optics and electromagnetism)

If you **are not** taking more physics: Electromagnetism is likely the richest, most complete, physical theory you will encounter.

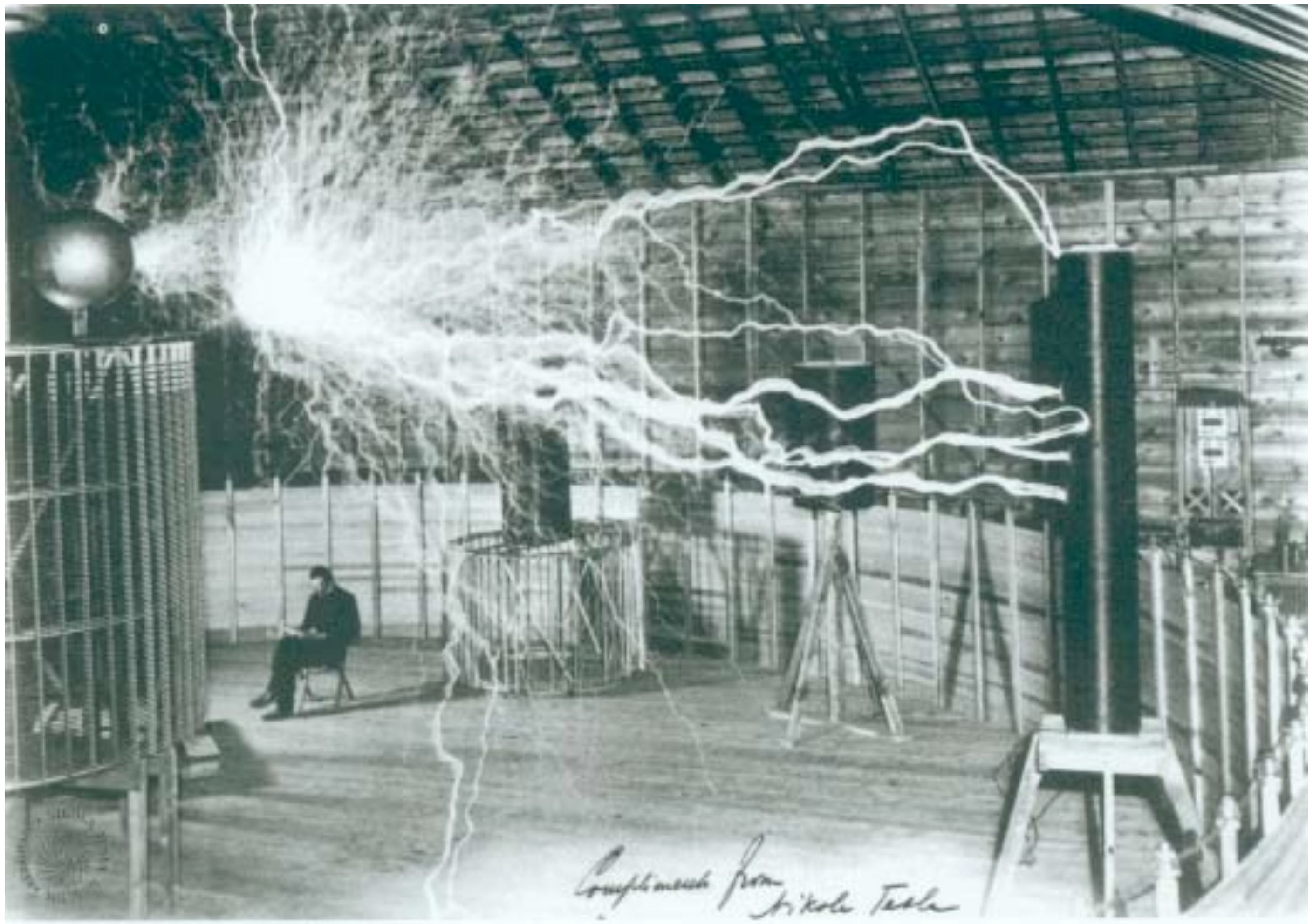
If you **are** taking more physics: Electromagnetism is the foundation of **field theory**, which is the richest, most complete, physical theory you will encounter.

Electromagnetism

Big Picture

1. **Understand the fundamentals** of electrostatics and magnetism.
2. **Use these fundamentals** to "build" circuit components. Learn to analyze these circuits
3. **Express these fundamentals** in the form of ***Maxwell's equations. Unification!*** See how Maxwell's equations predict something new.

Charge



Socks in the Dryer

Two socks are observed to attract each other. Which, if any of the first 3 statements **MUST** be true? (Ignore gravitational force). *Discuss with someone!*

A) The socks both have a non-zero net charge of the same sign.
B) The socks both have a non-zero net charge of the opposite sign.
C) Only one sock is charged: the other is neutral
D) None of the preceding statements MUST be true.

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Properties of Charge

1. **Two types of charge (+ and -):** net charge is the difference in positive and negative charges.

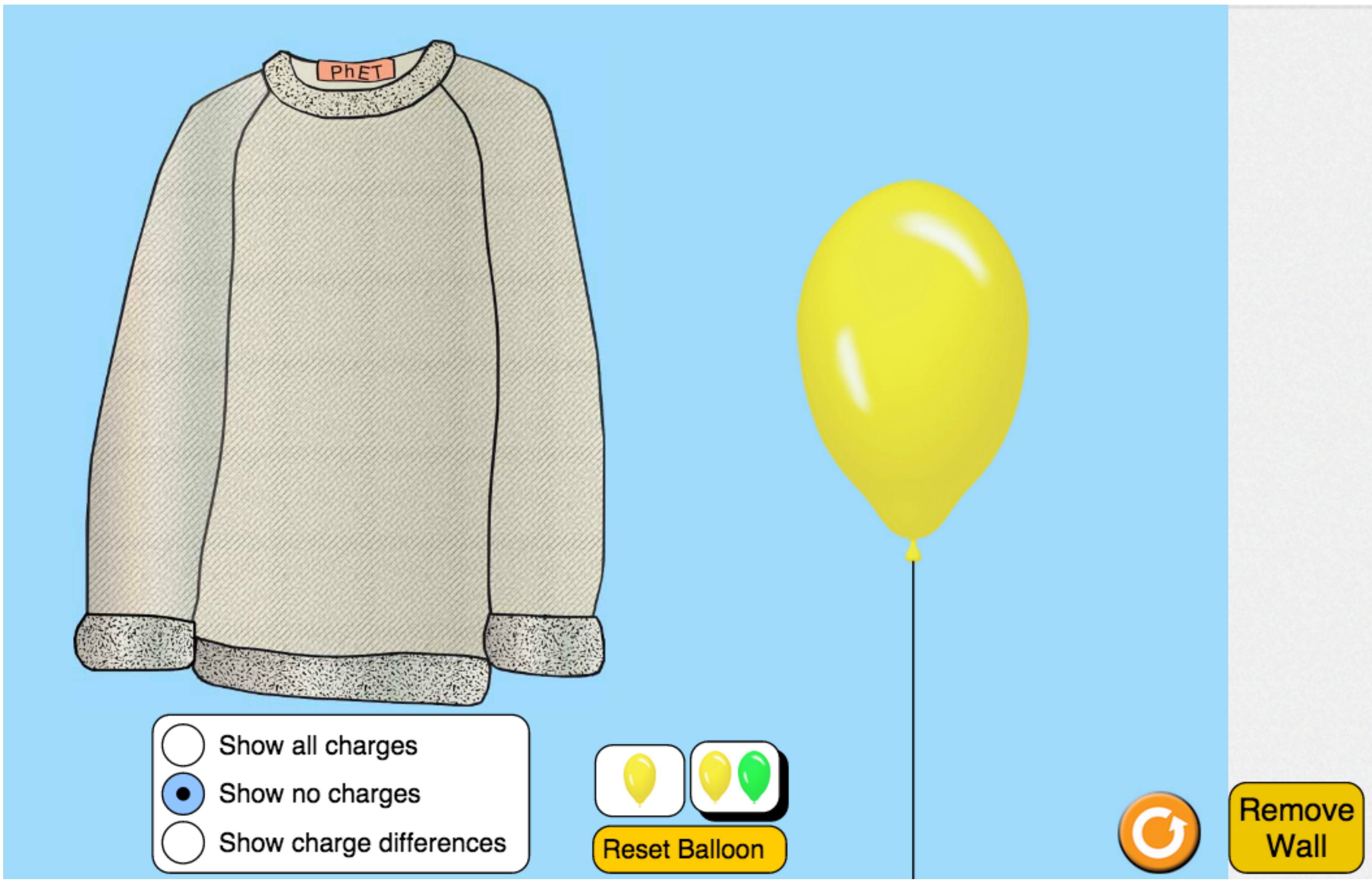
2. **Charge is quantized:** It appears in integer values of e = 1.602 x 10^{-19} C. (except for quarks, which have fractional charge.)

3. **Like Charges repel, unlike charges attract.**

4. **Like energy, momentum, etc., charge is conserved.** The symmetry associated with it is not obvious. It has to do with the phase of the electron wave function.

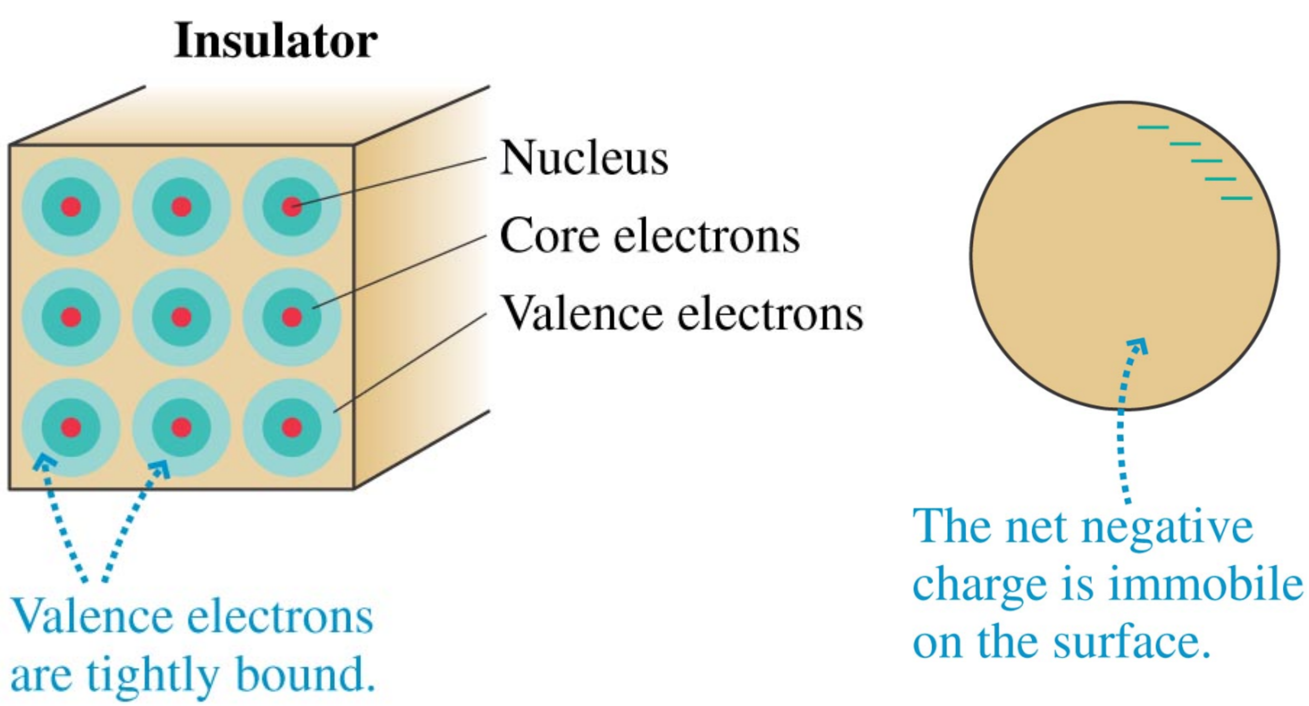
Pieces of paper with balloon

Why does the balloon stick to the wall?

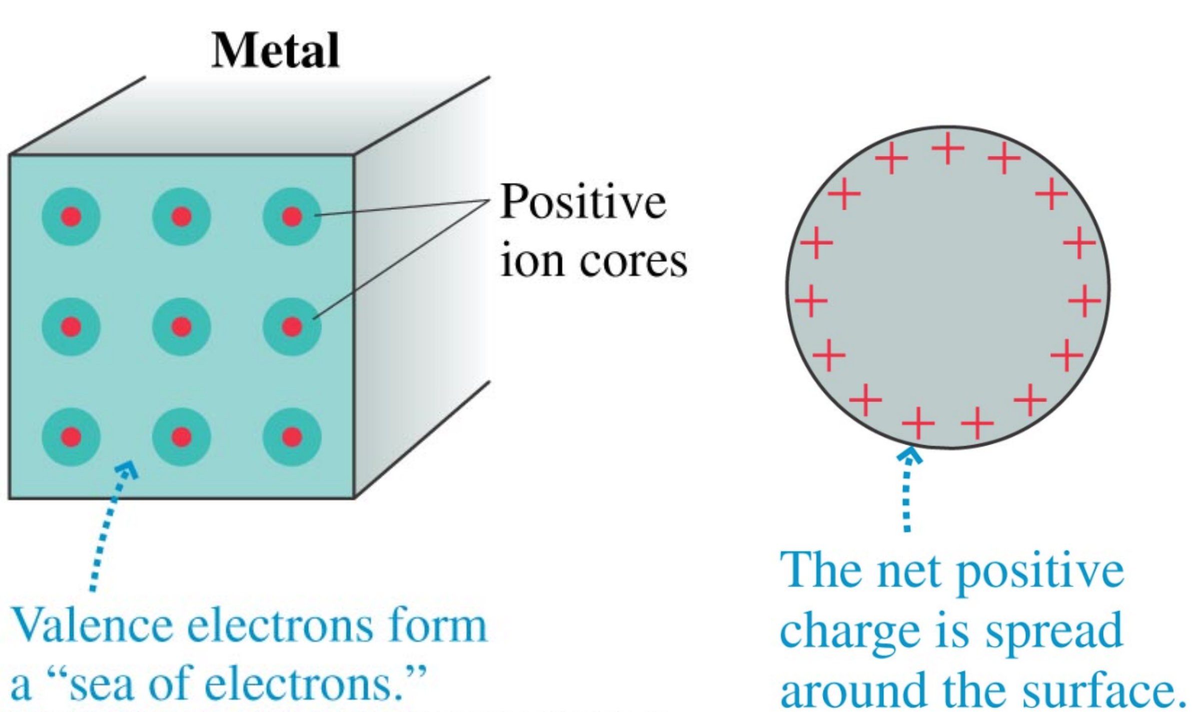


Balloon PhET

Conductors and Insulators



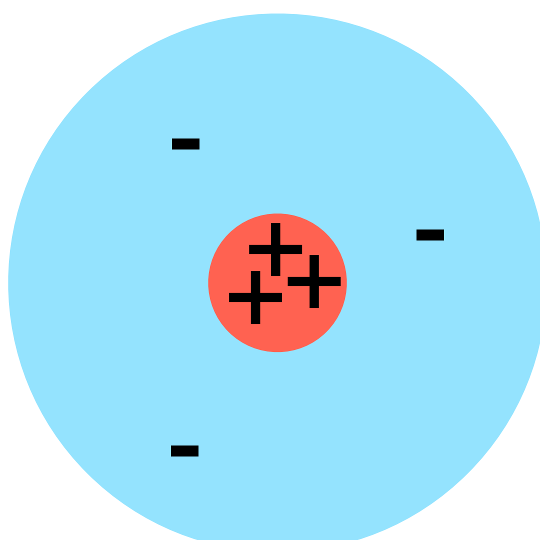
- No freely mobile charges
- plastics, rubber, glass, paper



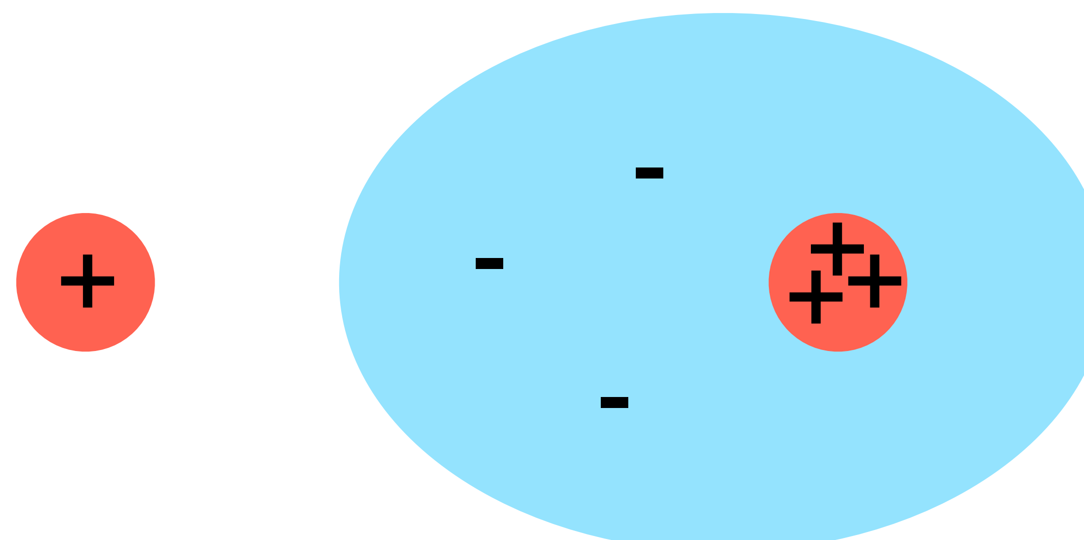
- Freely mobile charges
- metals, ionic solutions (salt water)

Polarization of Atoms

Atoms get **polarized** in the presence of charge. One side of the atom is more negative than the other.



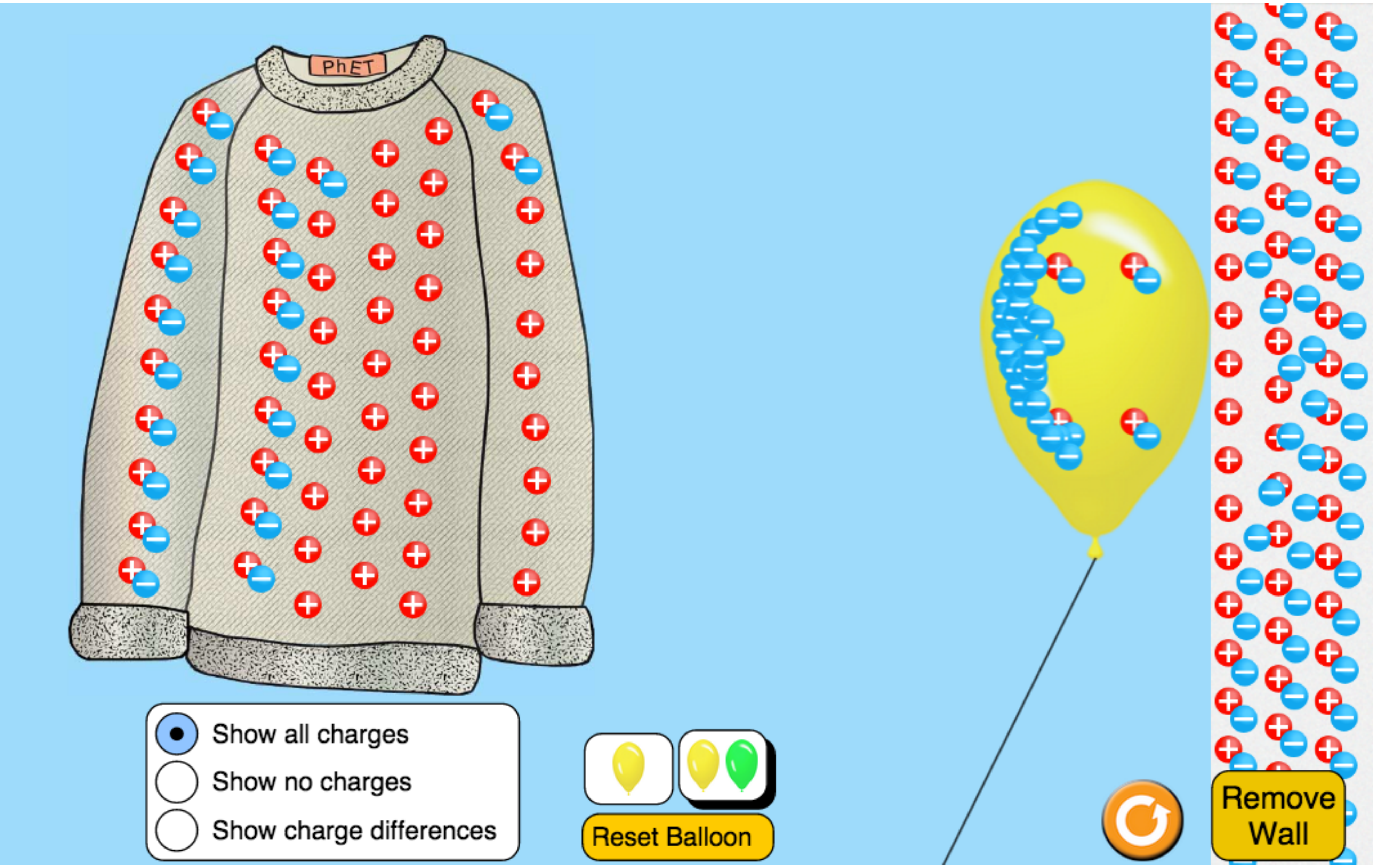
no external charge



with external charge present

This is how the bits of paper get attracted by the balloon.
The polarized atom now attracts the positive charge.
An induced dipole!

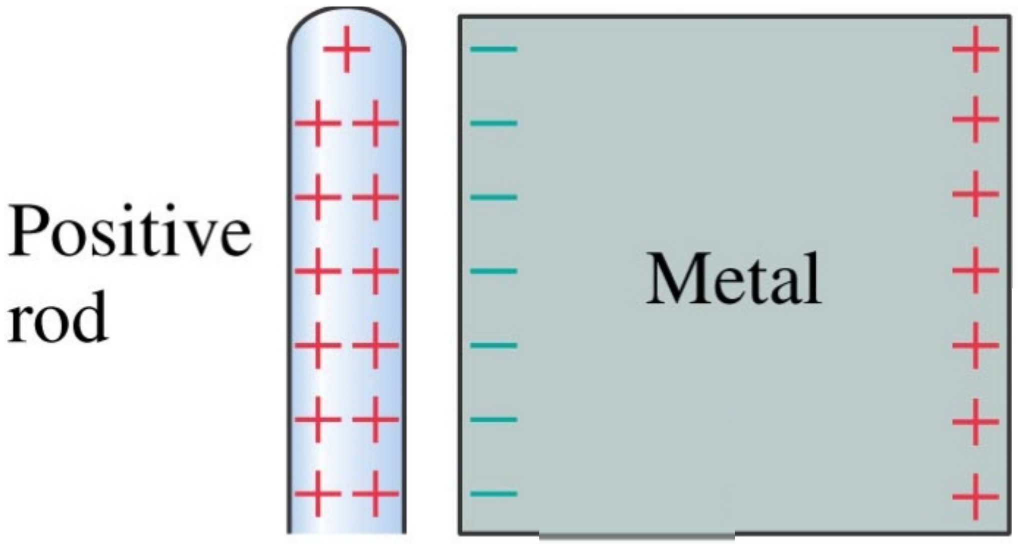
Why does the balloon stick to the wall?



Balloon PhET

Polarization of Metals

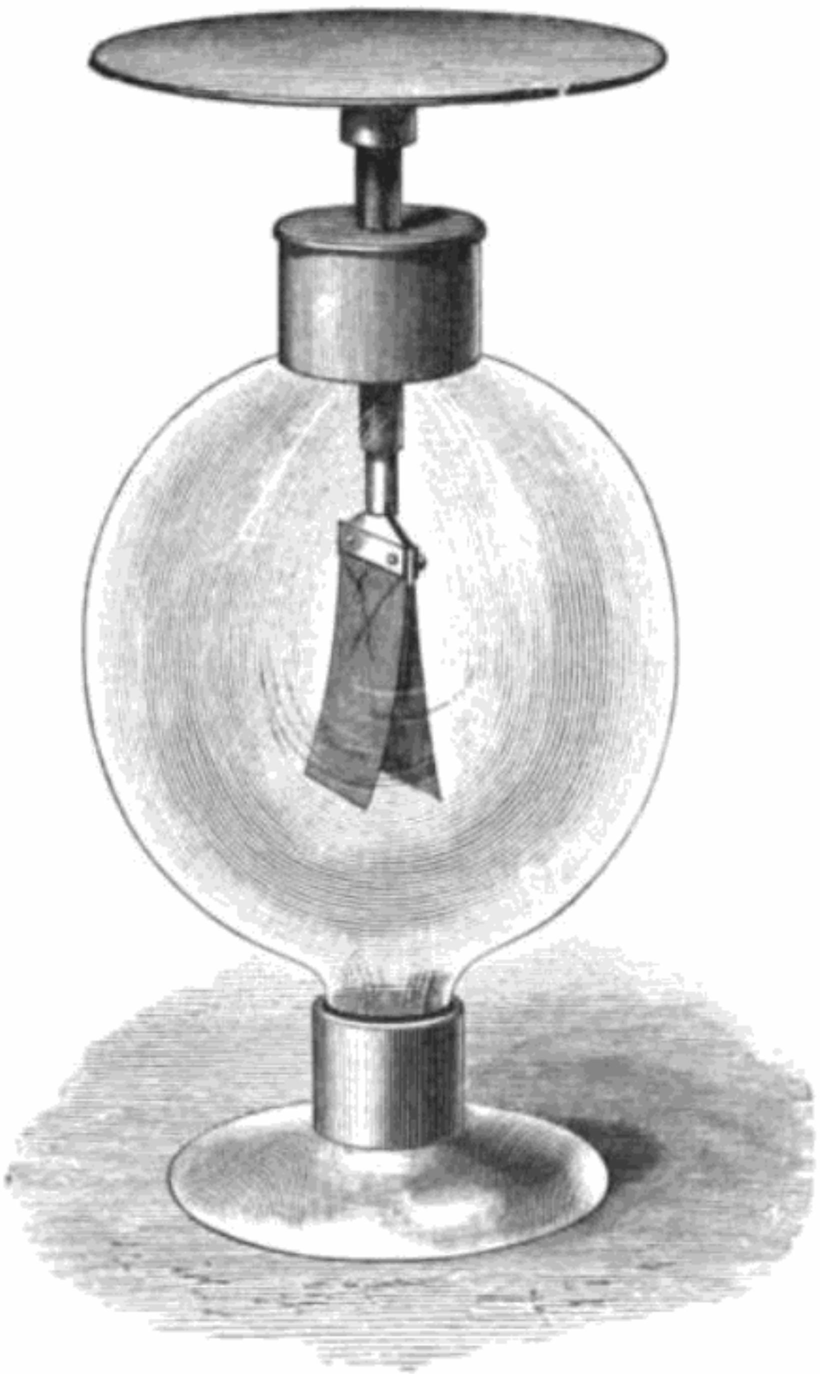
Metals also get polarized.



In this case the charge is free to move right to the boundaries of the material.

Franklin Bells

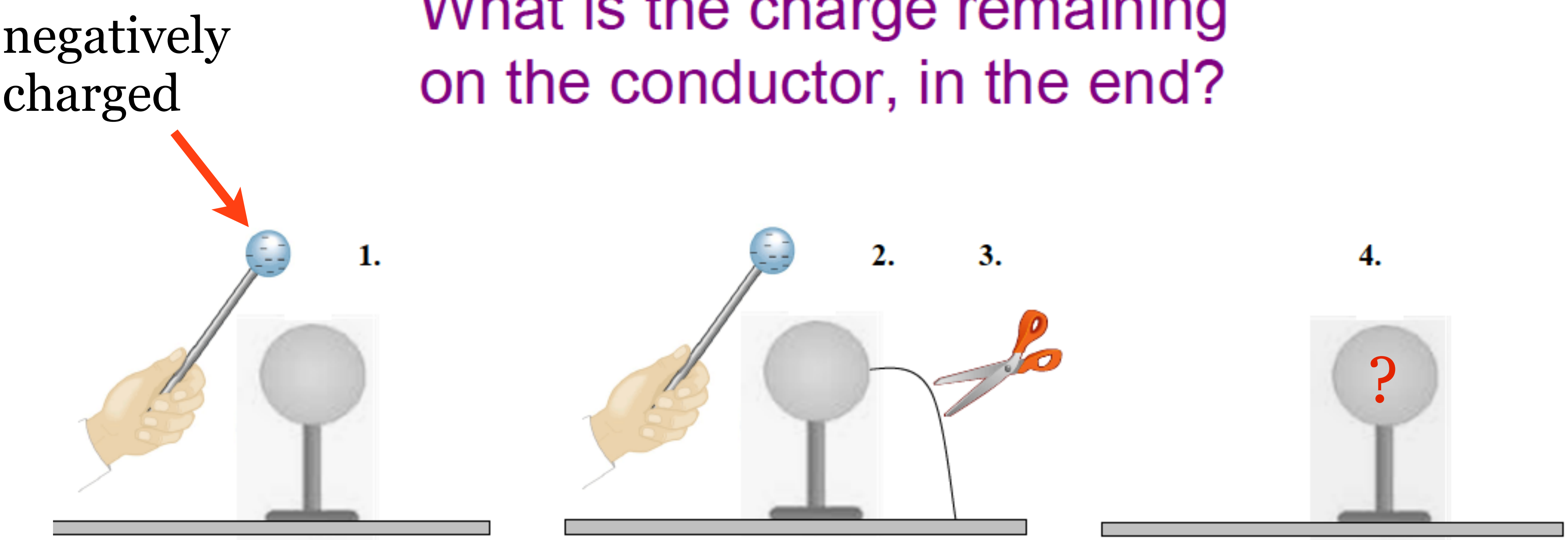
The Electroscope



Electroscope demo

Charge Transfer

What is the charge remaining on the conductor, in the end?

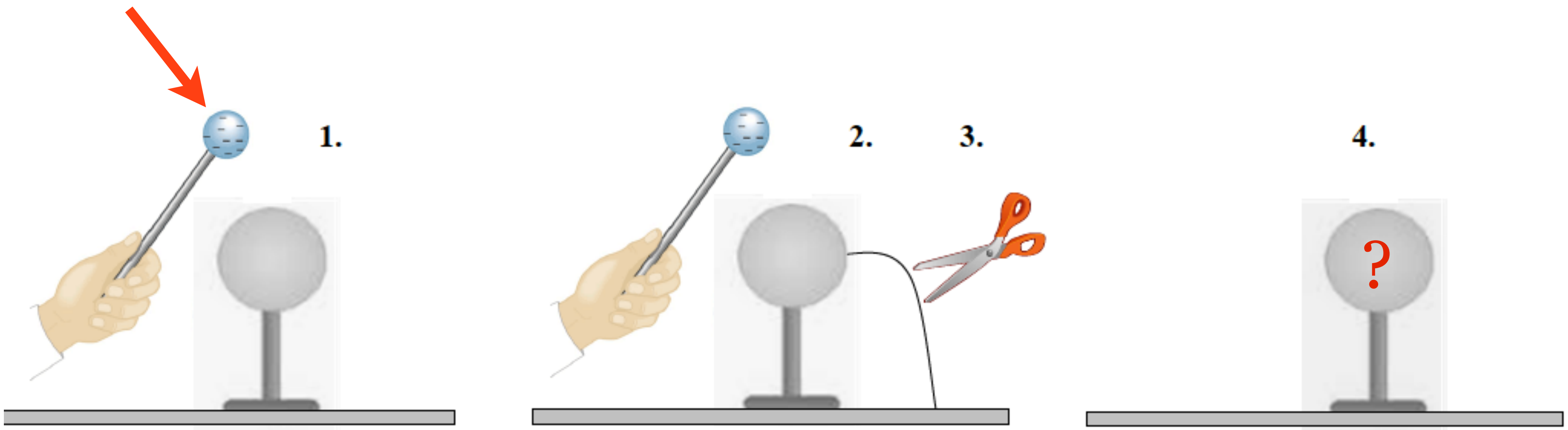


A: + (positive)
B: - (negative)
C: 0 (Neutral)
D: Not sure/can't decide.

Charge Transfer

What is the charge remaining on the conductor, in the end?

negatively charged



A: + (positive)

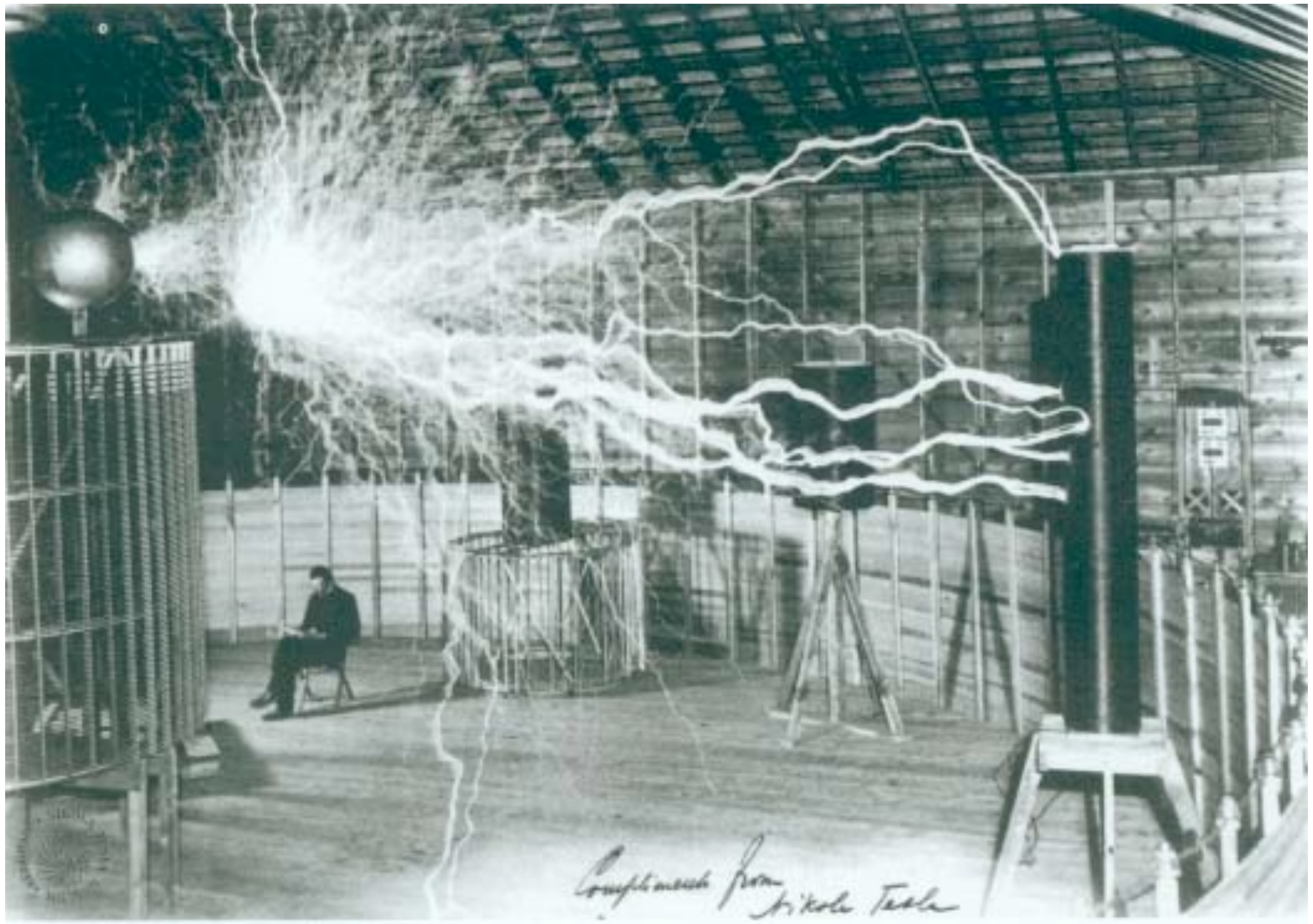
B: - (negative)

C: 0 (Neutral)

D: Not sure/can't decide.

This process is how you charge an object by induction.

Coulomb's Law



Coulomb Force

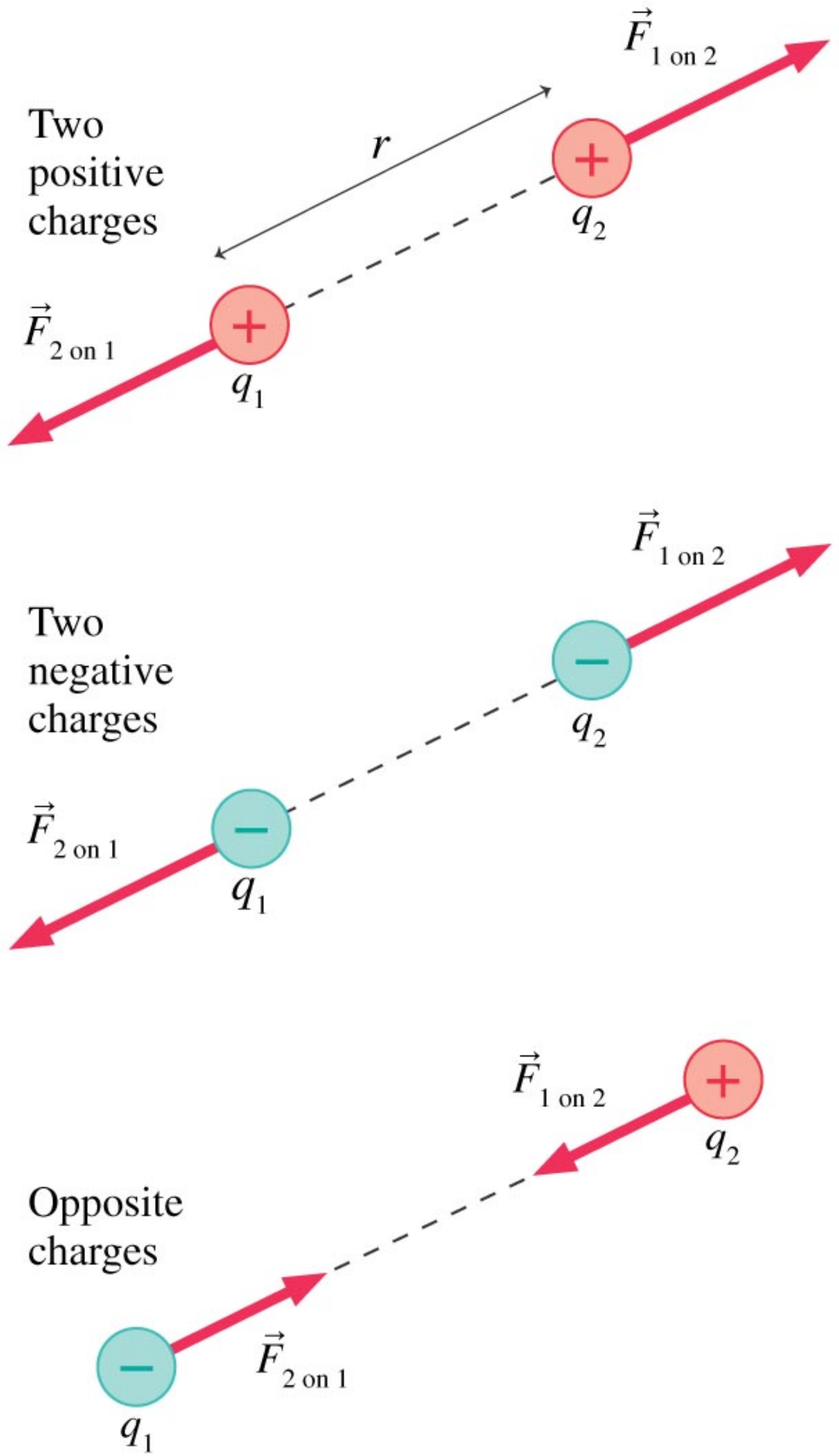
The Coulomb force **from charge 2 on charge 1** is given by:

$$\vec{F}_{2 \text{ on } 1} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$$

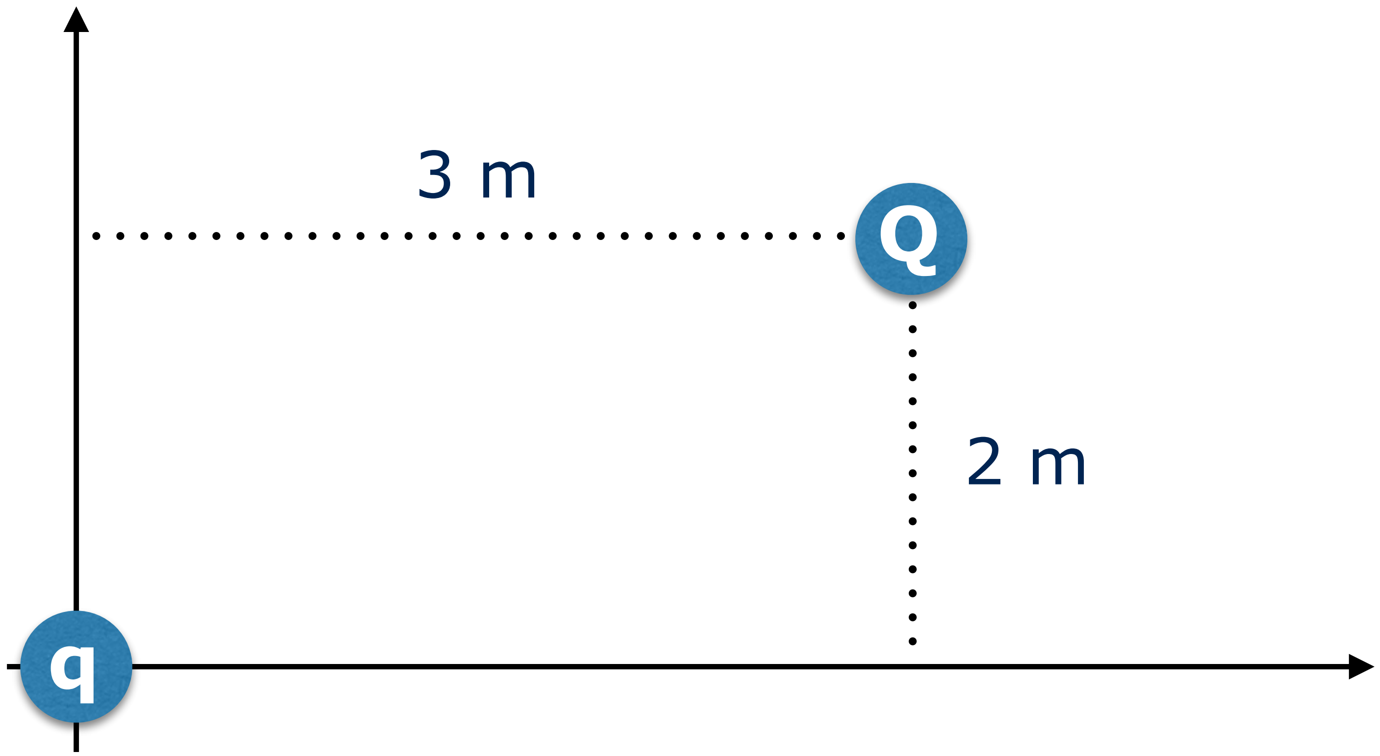
where $\hat{r} = \frac{\vec{r}}{|\vec{r}|}$ is a **unit vector**.

Also: $\frac{1}{4\pi\epsilon_0} = K = 9.0 \times 10^9 \text{ Nm}^2/\text{C}^2$

$$\epsilon_0 = \text{permittivity of free space}$$
$$\approx 8.85 \times 10^{-12} \text{ F/m}$$

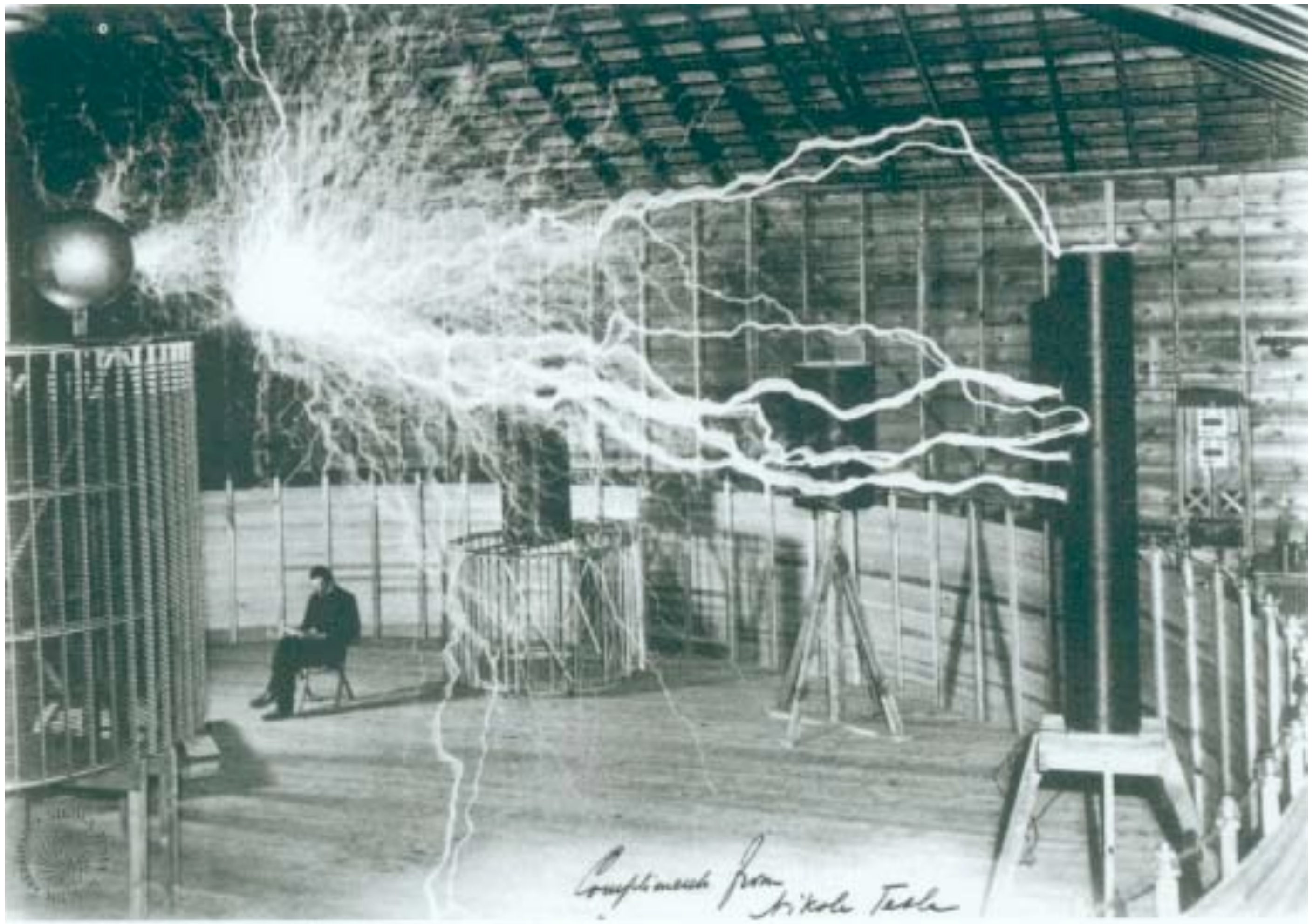


An Example

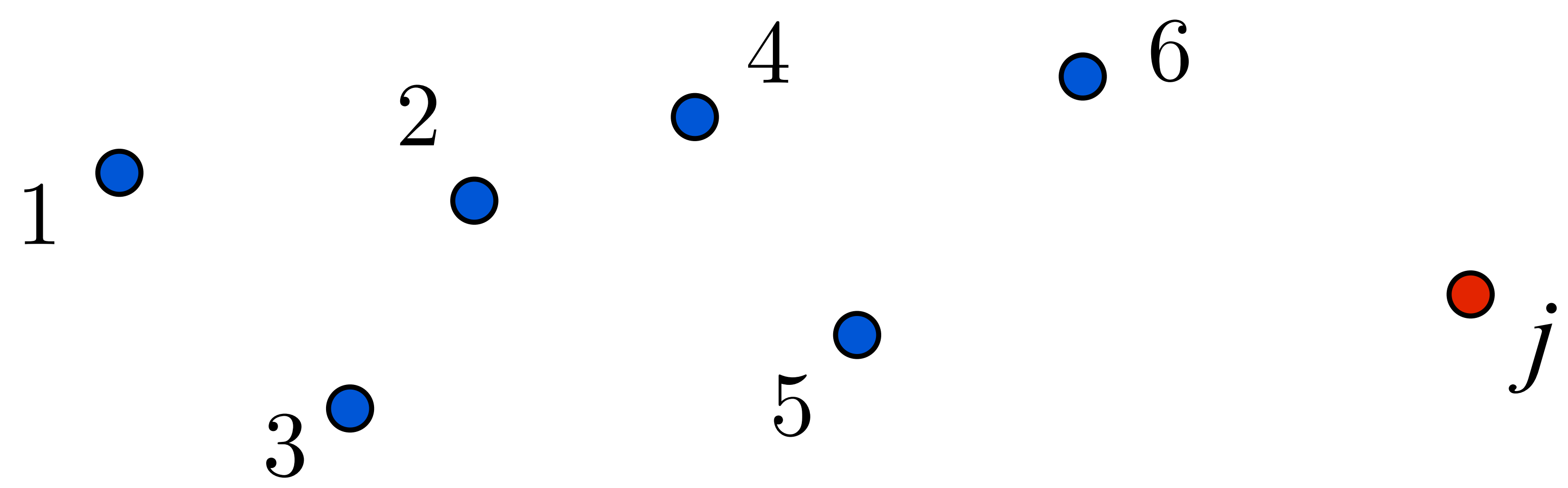


Find the force that q acts on Q where q = 2 nC and Q = 1 nC.
Write it in terms of the unit vectors *i* and *j*.

Superposition



Superposition of Forces



Electric forces are additive! The force of charge *j* is

$$\vec{F}_{\text{net on } j} = \vec{F}_{1 \text{ on } j} + \vec{F}_{2 \text{ on } j} + \vec{F}_{3 \text{ on } j} + \ldots$$
$$= \sum_{i \neq j} \vec{F}_{i \text{ on } j}$$

This gets hard when there are many charges. We can use Gauss's Law to simplify things.

Clicker question

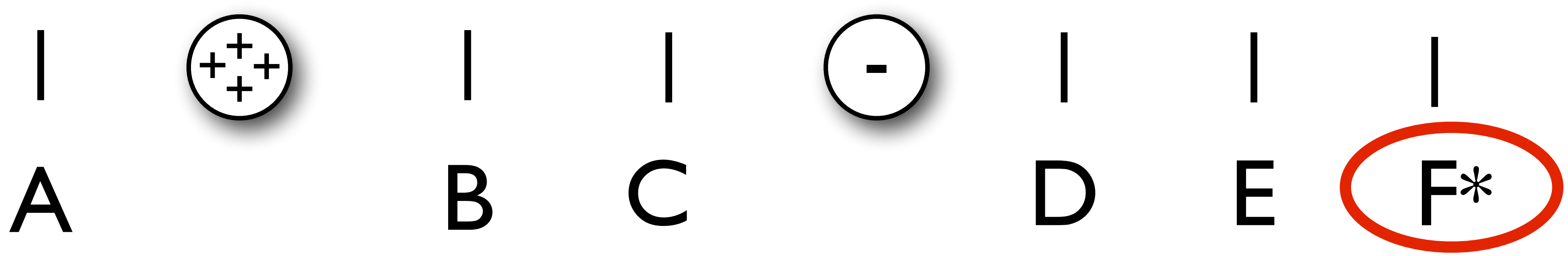
At what position could you place an electron such that it experiences no net force?

extra: does the answer change if you're placing a proton?

*raise your hand to answer F

Clicker question

At what position could you place an electron such that it experiences no net force?



To cancel it must be one of A, D, E, or F. Point A is too close to the 4q charge, so it can't be that. The forces cancel when their magnitudes are equal.

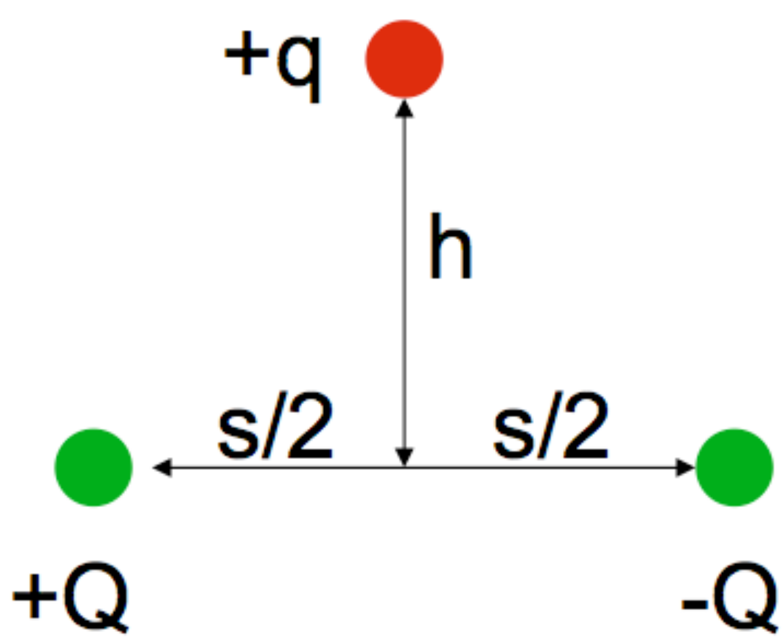
$$\frac{4q^2}{r_1^2} = \frac{q^2}{r_2^2} \Rightarrow \frac{r_1^2}{r_2^2} = \frac{4q^2}{q^2} \Rightarrow \frac{r_1}{r_2} = 2$$

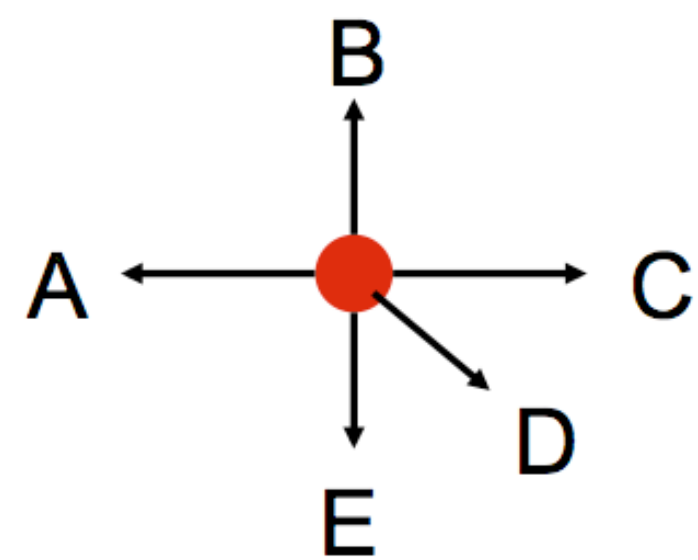
The point where 4q is twice as far away as q is F.

*raise your hand to answer F

Clicker question

Principle of Superposition:
3 charges arranged at the corners of an equilateral triangle.

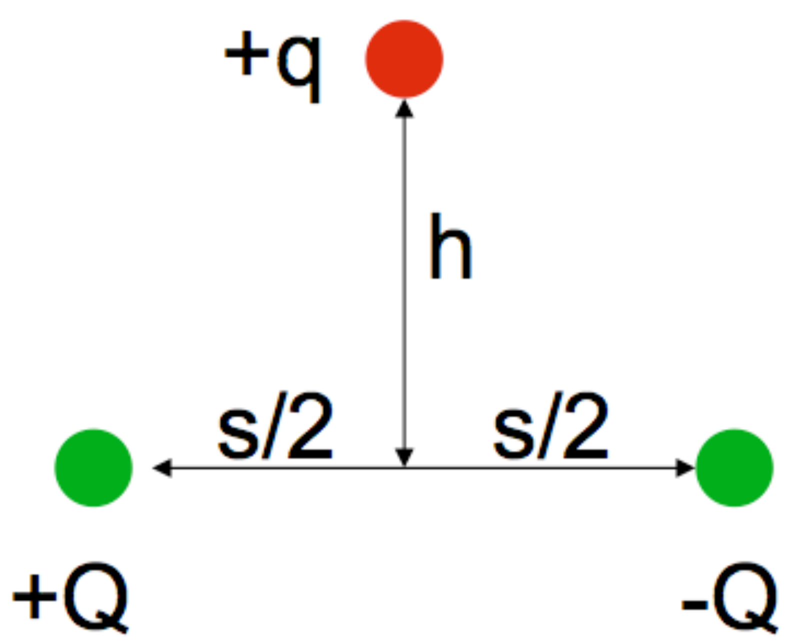


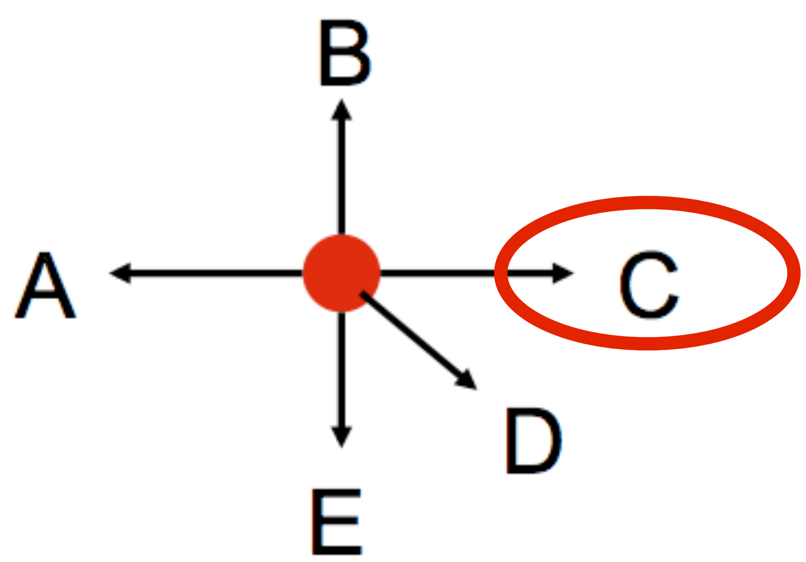


What is the direction of the force on $+q$, the red charge?

Clicker question

Principle of Superposition:
3 charges arranged at the corners of an equilateral triangle.





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