PHY 204: Elementary Physics II (2015)   Physics Open Educational Resources

11-19-2015

01. Introduction and Electric Field I

Gerhard Müller
University of Rhode Island, gmuller@uri.edu

Follow this and additional works at: https://digitalcommons.uri.edu/elementary_physics_2

Abstract
Lecture slides 1 for Elementary Physics II (PHY 204), taught by Gerhard Müller at the University of Rhode Island.

Some of the slides contain figures from the textbook, Paul A. Tipler and Gene Mosca. *Physics for Scientists and Engineers*, 5th/6th editions. The copyright to these figures is owned by W.H. Freeman. We acknowledge permission from W.H. Freeman to use them on this course web page. The textbook figures are not to be used or copied for any purpose outside this class without direct permission from W.H. Freeman.

Recommended Citation
Müller, Gerhard, "01. Introduction and Electric Field I" (2015). *PHY 204: Elementary Physics II (2015).* Paper 25.
https://digitalcommons.uri.edu/elementary_physics_2/25

Welcome to PHY204.

- Instructor: Gerhard Muller, 320D East Hall.

- Syllabus is posted online. Check for online updates.

- Course webpage: **http://web.uri.edu/physics/**

- Register (separately) for lecture, lab, and recitation.

- Lecture slides are available online. Come to class regularly and be on time. Earn extra credit by participating in daily quiz. Bring your textbook and your calculator.

- Exams: 3 unit exams (in class) and final exam. Closed book, calculator needed, one sheet of notes permitted. Exam topics will be reviewed in class.

- Homework: Online submission via *WebAssign*. Check due dates online.

- PHY274 Laboratory: Semester schedule on syllabus. Purchase lab notebook and lab manual.

- PHY274 Recitation: Semester schedule on syllabus. Bring textbook and calculator.

Kinematics:

- **position:** $\vec{r}(t) = \int \vec{v}(t)\, dt$

- **velocity:** $\vec{v}(t) = \dfrac{d\vec{r}}{dt} = \int \vec{a}(t)\, dt$

- **acceleration:** $\vec{a}(t) = \dfrac{d\vec{v}}{dt} = \dfrac{d^2\vec{r}}{dt^2}$

Dynamics: cause and effect: $\vec{F} = m\vec{a}$

Modes of motion: translation, rotation

Conservation laws: energy, momentum, angular momentum

Effective forces: elastic, contact, friction, ...

Fundamental forces: gravitational, electric, magnetic, . . .

Particles generate fields:

- Massive particle generates gravitational field.
- Charged particle generates electric field.
- Moving charged particle generates magnetic field.

Fields exert force on particles:

- Gravitational field exerts force on massive particle.
- Electric field exerts force on charged particle.
- Magnetic field exerts force on moving charged particle.

Dynamics:

- Cause and effect between particles and fields and among fields.

Energy and momentum:

- Particles carry energy (kinetic, potential) and momentum.
- Fields carry energy (electric, magnetic) and momentum.

Periodic table: $\sim$100 elements.
Building blocks of atoms: fundamental particles.

particle	charge	mass
electron	$q_e = -e$	$m_e = 9.109 \times 10^{-31}$ kg
proton	$q_p = +e$	$m_p = 1.673 \times 10^{-27}$ kg
neutron	$q_n = 0$	$m_n = 1.675 \times 10^{-27}$ kg

- SI unit of charge: 1C (Coulomb).

- Elementary charge: $e = 1.602 \times 10^{-19}$ C.

- Atomic nuclei (protons, neutron) have a radius of ~ 1fm $= 10^{-15}$ m.

- Atomic electron shells have a radius of ~ 1Å $= 10^{-10}$ m.

- Atoms are electrically neutral (equal numbers of electrons and protons).

- Ions: atoms with one or several electrons added or removed.

- Isotopes: atoms differing in the number of neutrons.

- Positively (negatively) charged objects have a deficiency (surplus) of electrons.

1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57–71 Rare Earths	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89–103 Actinides	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							

Rare Earths (Lanthanides)	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

*The 1–18 group designation has been recommended by the International Union of Pure and Applied Chemistry (IUPAC).
Elements with atomic numbers 112, 114, and 116 have been reported but not fully authenticated as of September 2003.
From http://www.iupac.org/reports/periodic_table/IUPAC_Periodic_Table-3Oct05.pdf

(a)

(b)

(c)

hard rubber

hard rubber

(a)

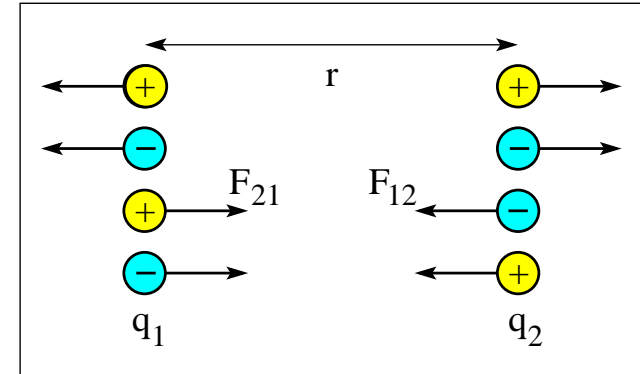glass

glass

(b)

glass

hard rubber

(c)

(a)

(b)

(c)

Electrostatic force between two charged particles:

$$F = \frac{1}{4\pi\epsilon_0}\frac{|q_1 q_2|}{r^2} = k\frac{|q_1 q_2|}{r^2}$$

Permittivity constant: $\epsilon_0 = 8.854 \times 10^{-12}\mathrm{C^2 N^{-1} m^{-2}}$

Coulomb constant: $k = 8.99 \times 10^9\mathrm{Nm^2 C^{-2}}$

Action-reaction pair of forces: $\vec{F}_{21} = -\vec{F}_{12}$.

Electrostatic force between two charged particles:

$$F = \frac{1}{4\pi\epsilon_0} \frac{|q_1 q_2|}{r^2} = k \frac{|q_1 q_2|}{r^2}$$

Permittivity constant: $\epsilon_0 = 8.854 \times 10^{-12} \mathrm{C^2 N^{-1} m^{-2}}$

Coulomb constant: $k = 8.99 \times 10^9 \mathrm{Nm^2 C^{-2}}$

Action-reaction pair of forces: $\vec{F}_{21} = -\vec{F}_{12}$.

Newton's law of gravitation

Gravitational force between two massive particles:

$$F = G \frac{m_1 m_2}{r^2}$$

Gravitational constant: $G = 6.673 \times 10^{-11} \mathrm{Nm^2 kg^{-2}}$
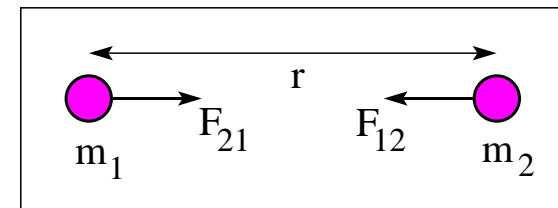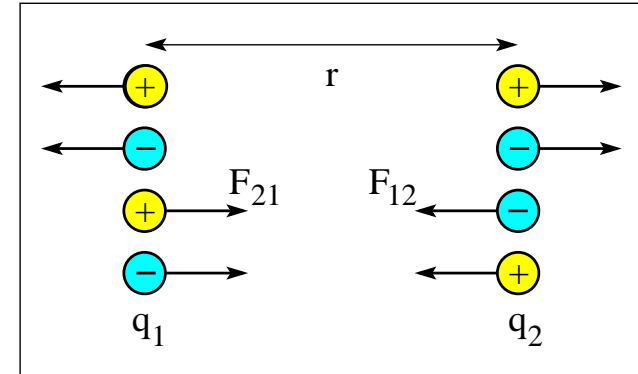
Coulomb's law for electrostatic force in vector form:
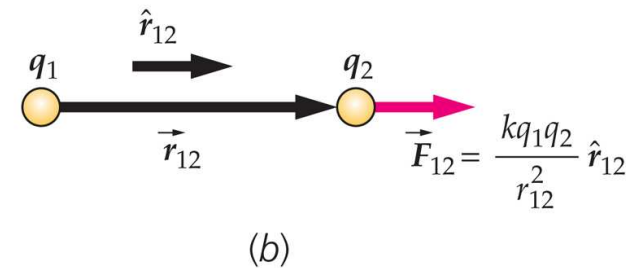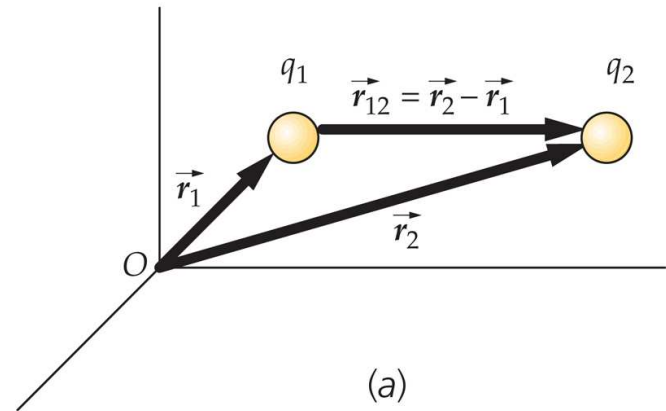
$$\vec{F}_{12} = k\,\frac{q_1 q_2}{r_{12}^2}\,\hat{r}_{12},$$

$$\vec{r}_{12} \doteq \vec{r}_2 - \vec{r}_1, \quad \hat{r}_{12} \doteq \frac{\vec{r}_{12}}{r_{12}}.$$

(a)

(b)

Coulomb's law for electrostatic force in vector form:

$$\vec{F}_{12} = k\,\frac{q_1 q_2}{r_{12}^2}\,\hat{r}_{12},$$

$$\vec{r}_{12} \doteq \vec{r}_2 - \vec{r}_1, \quad \hat{r}_{12} \doteq \frac{\vec{r}_{12}}{r_{12}}.$$
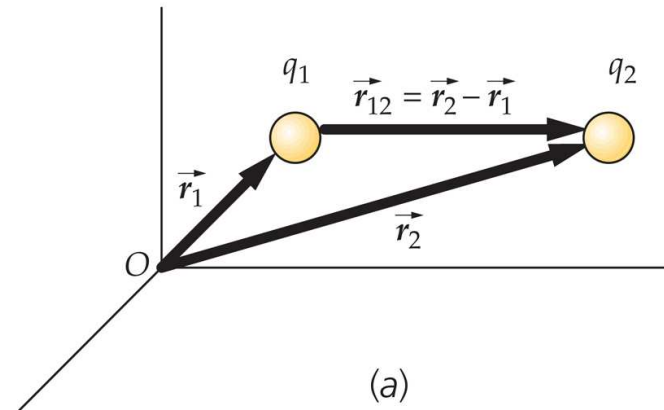
Electric force in hydrogen atom:

Average distance: $r = 5.3 \times 10^{-11}\,\text{m}$.

Elementary charge: $e = 1.60 \times 10^{-19}\,\text{C}$.

$$F = k\,\frac{|q_1 q_2|}{r^2}$$

$$= \frac{(8.99 \times 10^9\,\text{Nm}^2/\text{C}^2)(1.60 \times 10^{-19}\,\text{C})^2}{(5.3 \times 10^{-11}\,\text{m})^2}$$

$$= 8.2 \times 10^{-8}\,\text{N}.$$

(a)

$$\vec{F}_{12} = \frac{kq_1 q_2}{r_{12}^2}\,\hat{r}_{12}$$

Proton

q_1

$q_1 = +e$

Electron

q_2

F

$q_2 = -e$

r
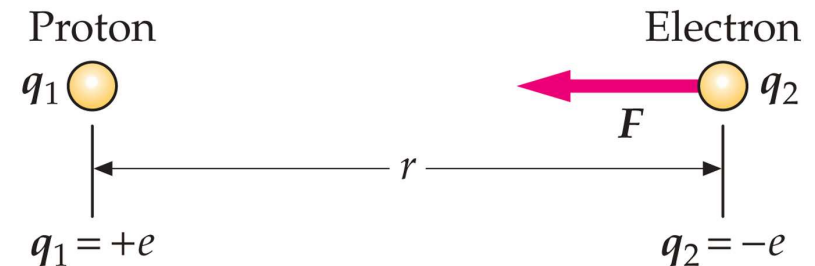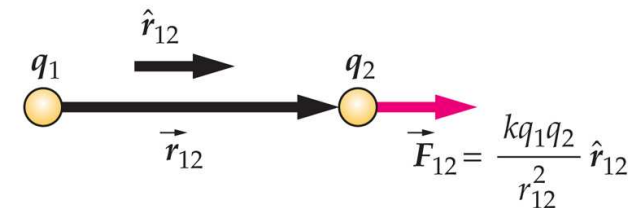
Find net force on charge q_0 due to charges q_1 and q_2.
Consider x-component of force.

$$F_0 = +k\frac{|q_1 q_0|}{(3.5\text{m})^2} - k\frac{|q_2 q_0|}{(1.5\text{m})^2} = +3.67 \times 10^{-7}\text{N} - 7.99 \times 10^{-7}\text{N} = -4.32 \times 10^{-7}\text{N}.$$

Find net force on charge q_2 due to charges q_1 and q_0.

$$F_2 = -k\frac{|q_1 q_2|}{(2.0\text{m})^2} + k\frac{|q_2 q_0|}{(1.5\text{m})^2} = -5.62 \times 10^{-7}\text{N} + 7.99 \times 10^{-7}\text{N} = +2.37 \times 10^{-7}\text{N}.$$
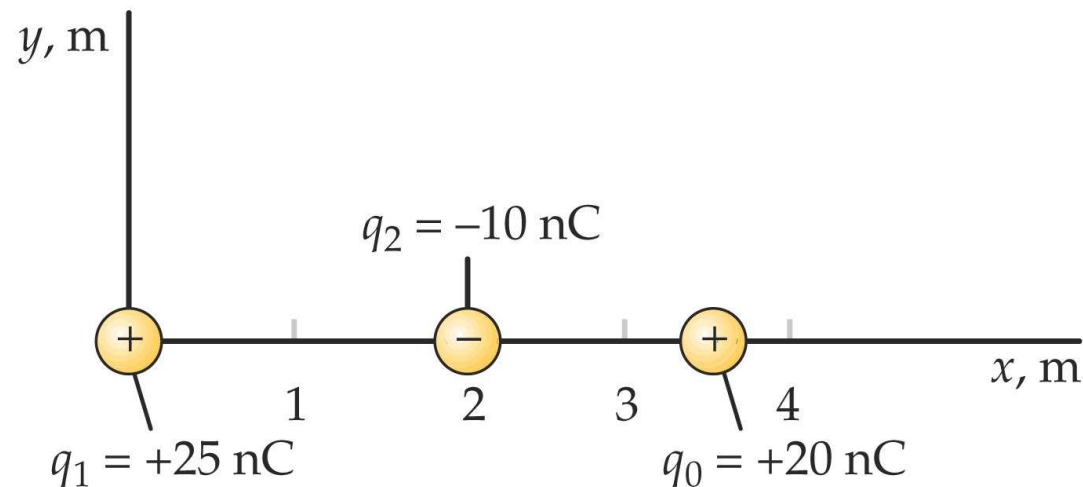
Three particles with charges of magnitude 1C are positioned on a straight line with two equal spacings.
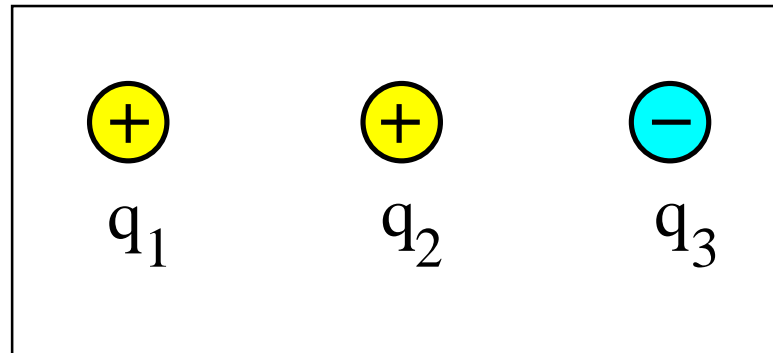
(a) Find the direction (left/right) of the net forces $\vec{F}_1, \vec{F}_2, \vec{F}_3$ on each particle.

(b) Which force is the strongest and which force is the weakest?

Four point charges equal magnitude are lined up in three different configurations. The Coulomb force between nearest neighbors is 4N.

(a) $\oplus$ $\ominus$ $\oplus$ $\ominus$

(b) $\ominus$ $\ominus$ $\oplus$ $\oplus$

(c) $\oplus$ $\ominus$ $\ominus$ $\oplus$
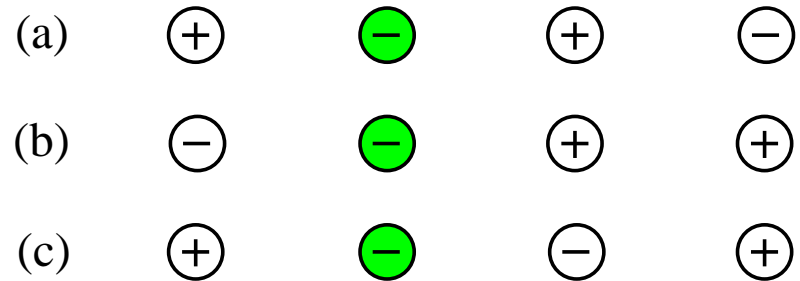
Find direction and magnitude of the net force experienced by the green particle in each configuration.

Three charged particles are positioned along a straight line with two equal spacings .
The net Coulomb force on charge q_3 happens to vanish.

$$F_3 = 0$$

$$q_1 = ? \qquad q_2 = 1\mu C \qquad q_3 = 2\mu C$$
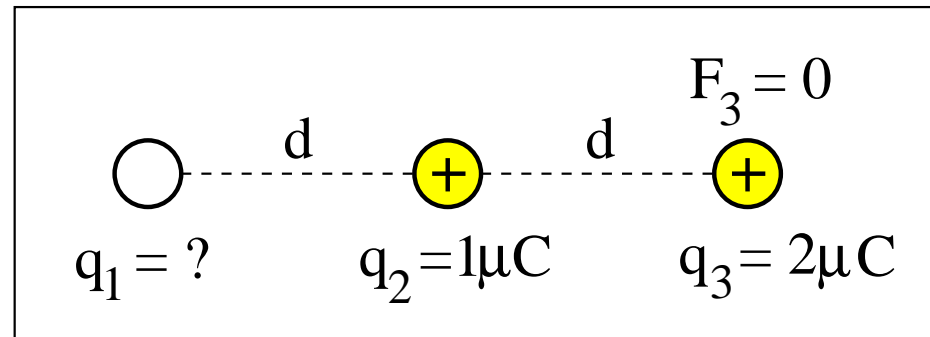
What is the value of q_1?

How are the forces $\vec{F}_1$ and $\vec{F}_2$ in (a) affected by the changes made in (b) and (c)?
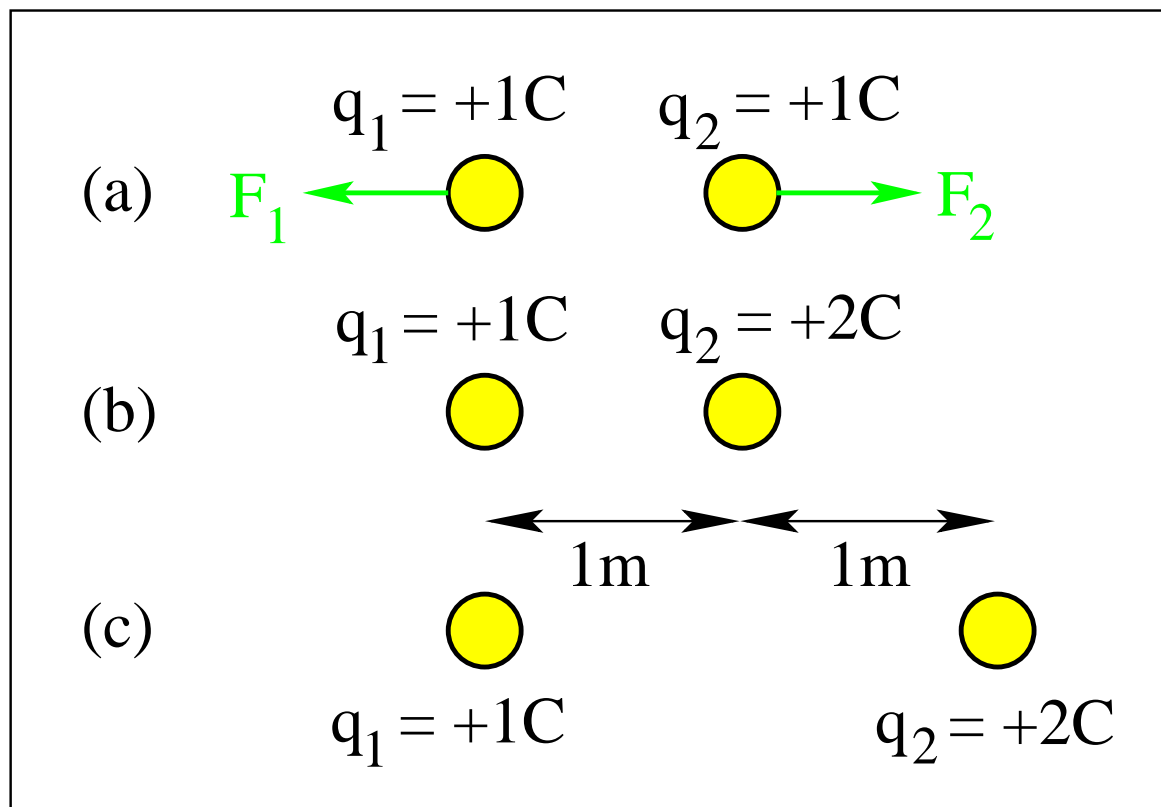
What changes if the charge q_2 is made negative?
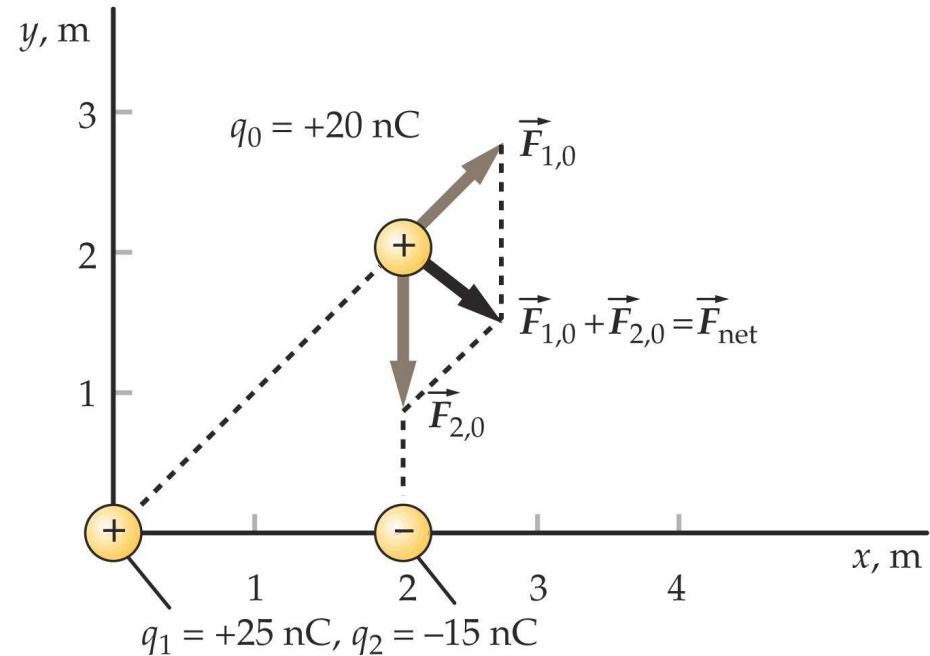
Find the magnitude and direction of the resultant force on charge q_0.

- Magnitude of individual forces:

$$F_{1,0} = k\frac{|q_1 q_0|}{r_{1,0}^2} = 5.62 \times 10^{-7}\text{N}, \quad F_{2,0} = k\frac{|q_2 q_0|}{r_{2,0}^2} = 6.74 \times 10^{-7}\text{N}.$$

- Components of individual forces:

$$F_{1,0}^x = F_{1,0}\cos 45°, \quad F_{1,0}^y = F_{1,0}\sin 45°, \quad F_{2,0}^x = 0, \quad F_{2,0}^y = -F_{2,0}.$$

- Components of resultant force:

$$F_x = F_{1,0}^x + F_{2,0}^x = 3.97 \times 10^{-7} \text{N}, \quad F_y = F_{1,0}^y + F_{2,0}^y = -2.77 \times 10^{-7} \text{N}.$$

- Magnitude of resultant force: $F = \sqrt{F_x^2 + F_y^2} = 4.84 \times 10^{-7} \text{N}.$

- Direction of resultant force: $\theta = \arctan(F_y/F_x) = -34.9°.$

The unknwon point charges q_1, q_2 exert a force $F_0 = 2$N on the known point charge $q_0 = 1$nC. This force is directed in the positive y-direction as shown.

Determine first whether q_1, q_2 are positive or negative. Then determine the values of the two point charges.

The unknwon point charges q_1, q_2 exert a force $F_0 = 2$N on the known point charge $q_0 = 1$nC. This force is directed in the positive y-direction as shown.

Determine first whether q_1, q_2 are positive or negative. Then determine the values of the two point charges.

Point charges of equal magnitude are positioned at the corners of an equilateral triangle.
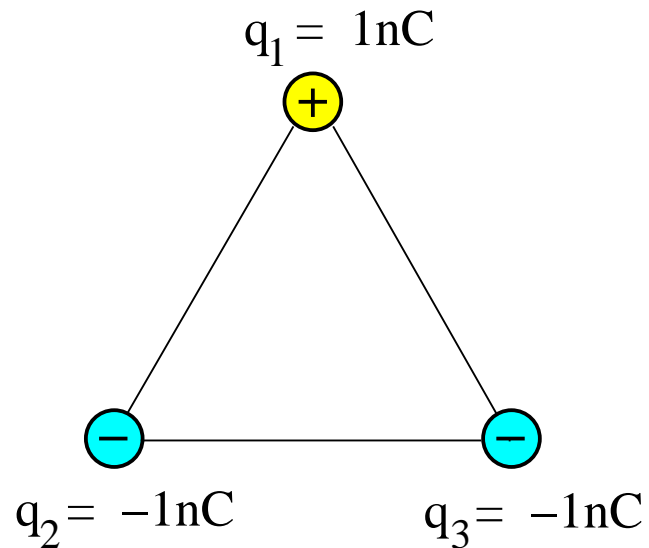
$q_1 = 1nC$

$+$

$q_2 = -1nC$ $q_3 = -1nC$

- Copy this configuration and indicate by arrows the direction of the resultant force on each point charge.

- Which point charge experiences the strongest force?

Point charges of equal magnitude are positioned at the corners of a square.
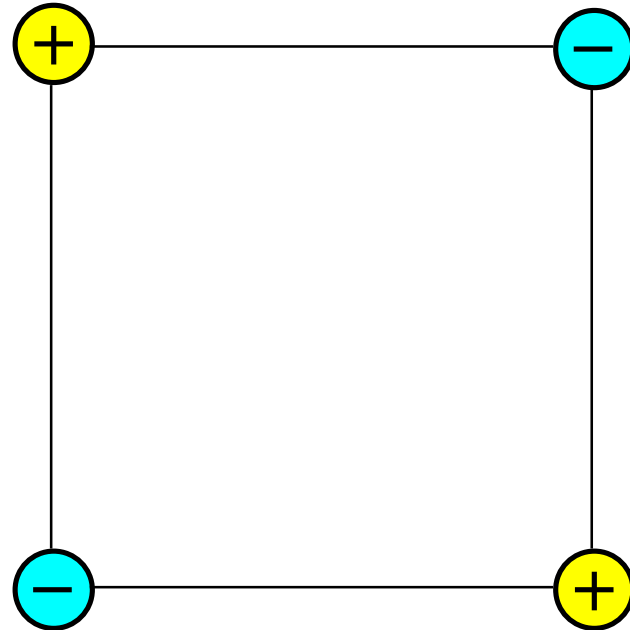
- Copy this configuration and indicate by arrows the direction of the resultant force on each point charge.

- If the force between nearest-neighbor charges is 1N, what is the strength of the resultant force on each charge?

Two identical small charged spheres, each having a mass $m = 30$g, hang in equilibrium at an anlge of $\theta = 5°$ from the vertical. The length of the strings is $L = 15$cm.
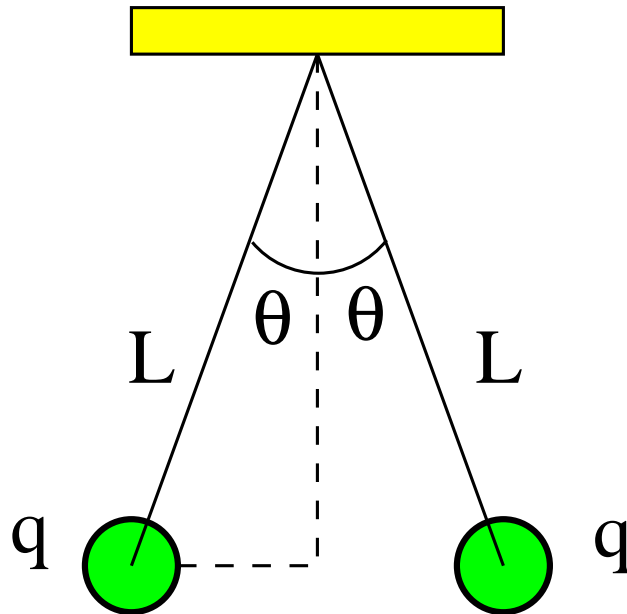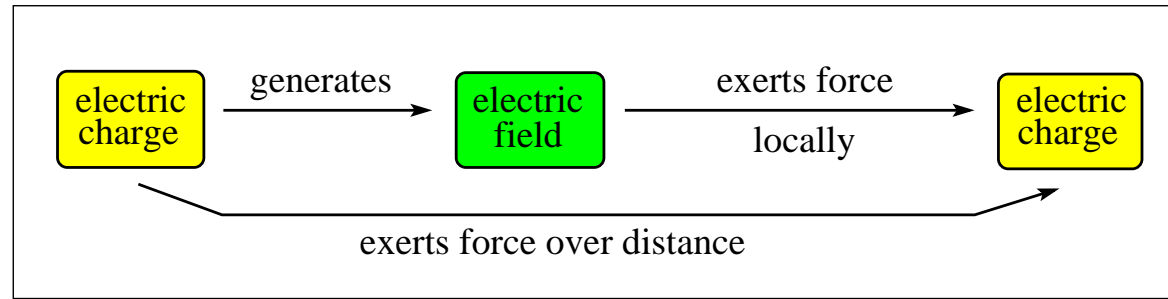

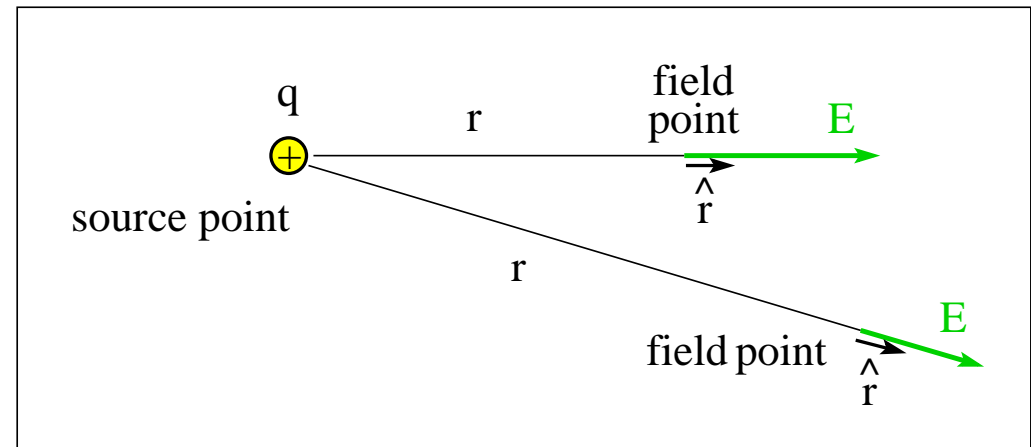- Identify all forces acting on each sphere.
- Find the magnitude of the charge q on each sphere.

Two identical small charged spheres, each having a mass $m = 30$g, hang in equilibrium at an anlge of $\theta = 5°$ from the vertical. The length of the strings is $L = 15$cm.
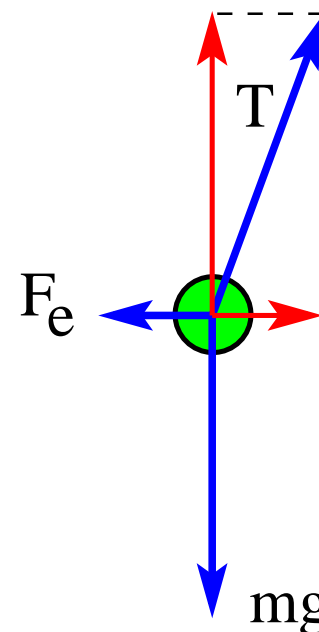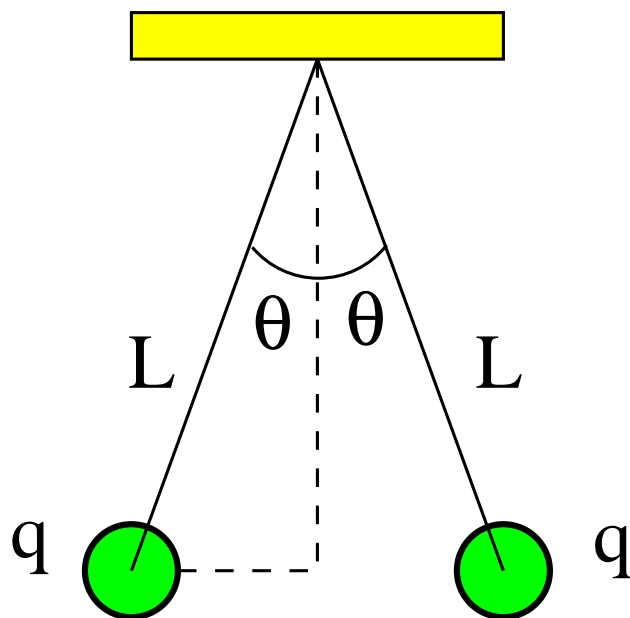
- Identify all forces acting on each sphere.
- Find the magnitude of the charge q on each sphere.

Electric Field of a Point Charge

(1) Electric field $\vec{E}$ generated by point charge q: $\vec{E} = k\,\dfrac{q}{r^2}\hat{r}$

(2) Force $\vec{F}_1$ exerted by field $\vec{E}$ on point charge q_1: $\vec{F}_1 = q_1\vec{E}$

(1+2) Force $\vec{F}_1$ exerted by charge q on charge q_1: $\vec{F}_1 = k\,\dfrac{qq_1}{r^2}\hat{r}$ (static conditions)
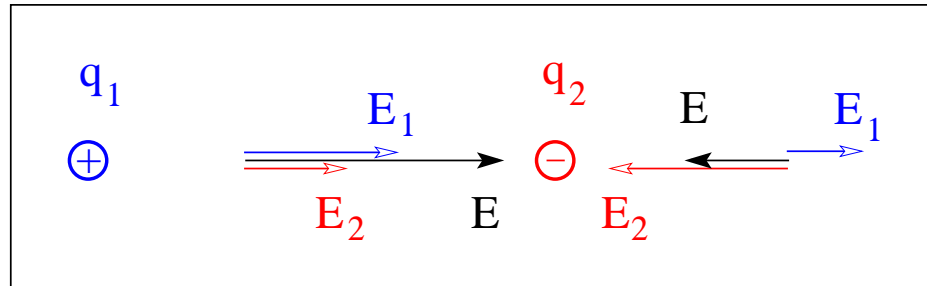
- $\epsilon_0 = 8.854 \times 10^{-12}\mathsf{C^2N^{-1}m^{-2}}$

- $k = \dfrac{1}{4\pi\epsilon_0} = 8.99 \times 10^9\mathrm{Nm^2C^{-2}}$

Electric field on line connecting two point charges:

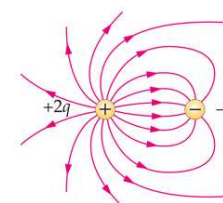Electric field of point charges in plane:

- The electric field is a vector field:

$$\vec{E}(\vec{r}) = \vec{E}(x, y, z) = E_x(x, y, z)\hat{i} + E_y(x, y, z)\hat{j} + E_z(x, y, z)\hat{k}$$
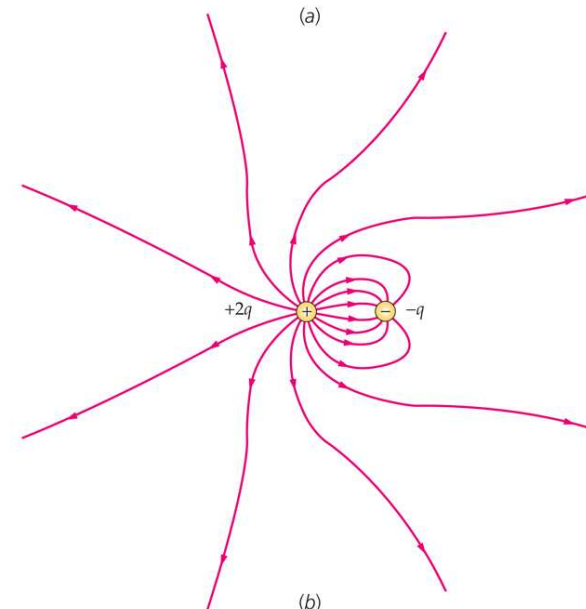
- Electric field lines: graphical representation of vector field.

- Properties of electric field lines (electrostatics):

  ○ Electric field lines begin at
    positive charges or at infinity.
  ○ Electric field lines end at
    negative charges or at infinity.
  ○ The direction of $\vec{E}$ is tangential to
    the field line going through the field point.
  ○ Electric field lines bunched together
    indicate a strong field.
  ○ Electric field lines far apart
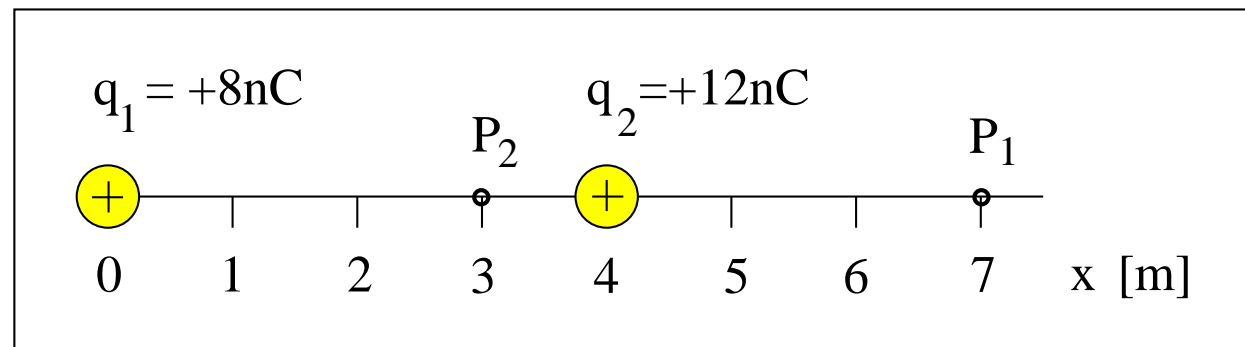   indicate a weak field.
  ○ Field lines do not intersect.

Consider the x-component of the electric field.

- Electric field at point P_1:

$$E = E_1 + E_2 = \frac{kq_1}{(7\text{m})^2} + \frac{kq_2}{(3\text{m})^2} = 1.47\text{N/C} + 12.0\text{N/C} = 13.5\text{N/C}.$$
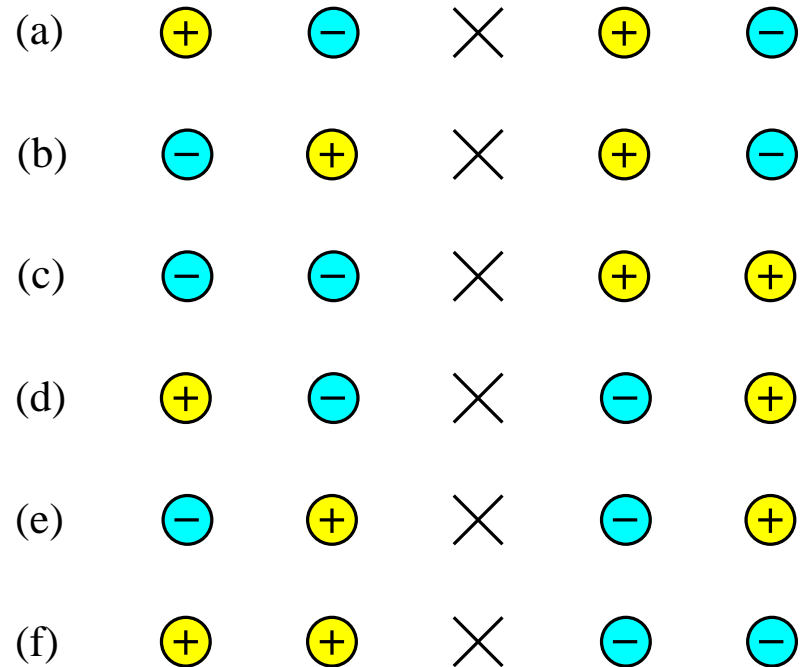
- Electric field at point P_2:

$$E = E_1 + E_2 = \frac{kq_1}{(3\text{m})^2} - \frac{kq_2}{(1\text{m})^2} = 7.99\text{N/C} - 108\text{N/C} = -100\text{N/C}.$$

Four particles with charges of equal magnitude are positioned on a horizontal line in six different configurations.

(a)   ⊕   ⊖   ✕   ⊕   ⊖

(b)   ⊖   ⊕   ✕   ⊕   ⊖

(c)   ⊖   ⊖   ✕   ⊕   ⊕

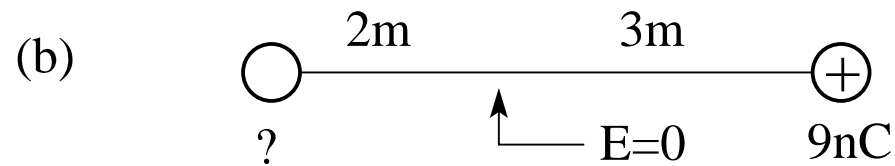(d)   ⊕   ⊖   ✕   ⊖   ⊕

(e)   ⊖   ⊕   ✕   ⊖   ⊕

(f)   ⊕   ⊕   ✕   ⊖   ⊖
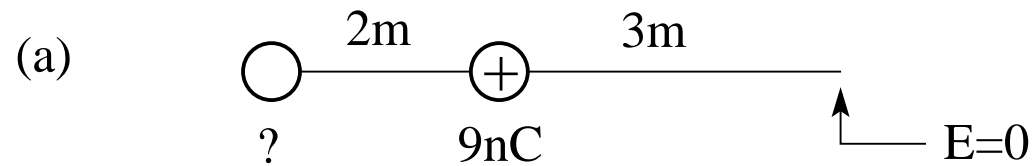
Determine for each configuration the direction of the resultant electric field (left/right/zero) at the location indicated by ✕.

- Is the unknown charge positive or negative?
- What is the value of the unknown charge?

(a)

2m   3m

?   9nC   E=0

(b)

2m   3m

?   E=0   9nC

Determine magnitude of $\vec{E}_1$ and $\vec{E}_2$
and identify directions in plane:

$$E_1 = \frac{k|q_1|}{(3\text{m})^2} = 7.99\text{N/C}, \quad E_2 = \frac{k|q_2|}{(5\text{m})^2} = 4.32\text{N/C}.$$

Determine x- and y-components of $\vec{E}_1$ and $\vec{E}_2$
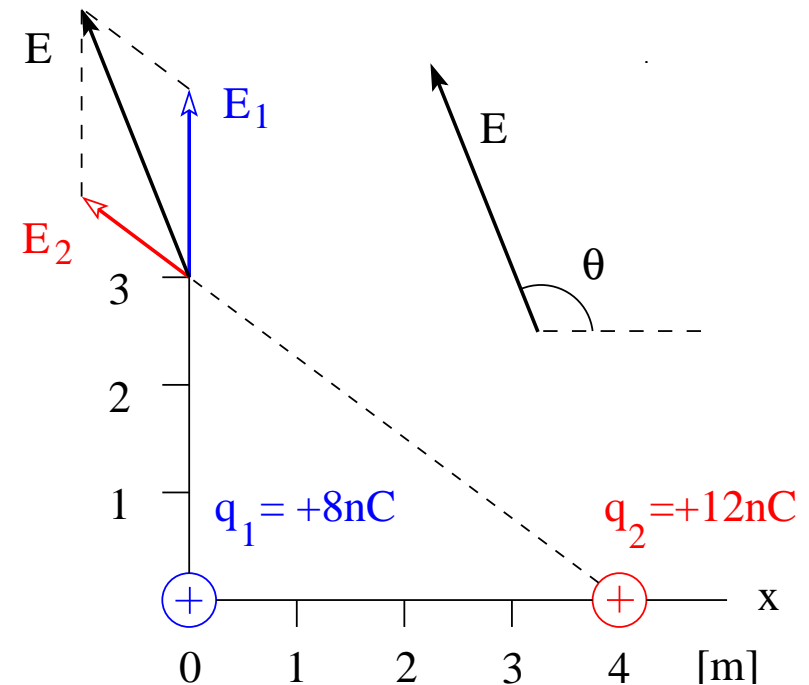and of the resultant field $\vec{E}$:

$$E_1^x = 0, \quad E_1^y = 7.99\text{N/C};$$
$$E_2^x = -3.46\text{N/C}, \quad E_2^y = 2.59\text{N/C};$$
$$E_x = -3.46\text{N/C}, \quad E_y = 10.6\text{N/C}.$$
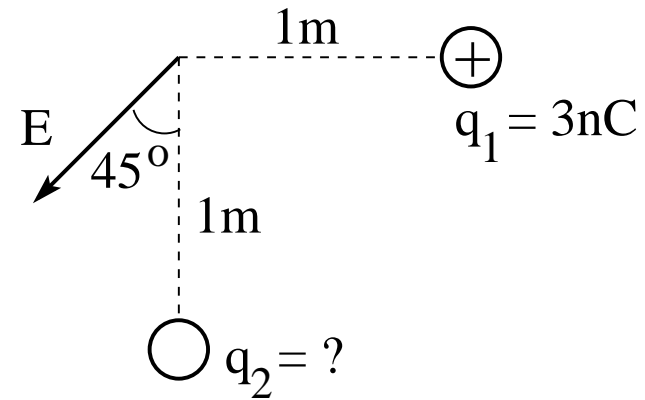
Determine magnitude and direction of $\vec{E}$:

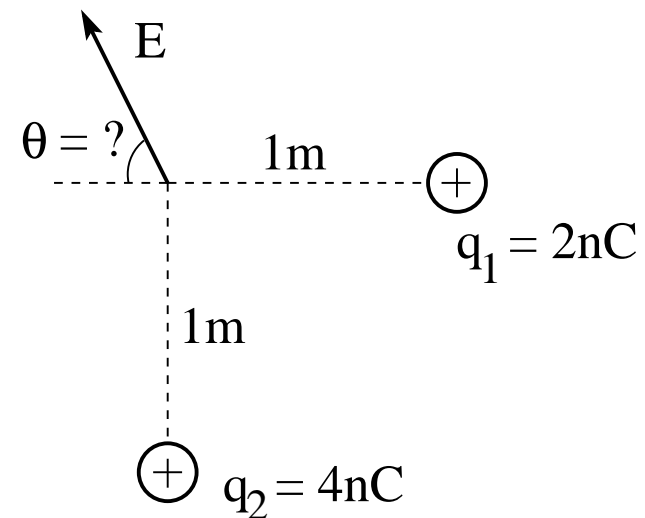$$E = \sqrt{E_x^2 + E_y^2} = 11.2\text{N/C}, \quad \theta = \arctan\left(\frac{E_y}{E_x}\right) = 108°.$$

(a) Find the electric charge q_2.

E

45°

1m

$q_1 = 3nC$

1m

$q_2 = ?$

(b) Find the angle θ.

E

$\theta = ?$

1m

$q_1 = 2nC$

1m

$q_2 = 4nC$

Two point charges, one known and the other unknown, produce a horizontal electric field as shown.
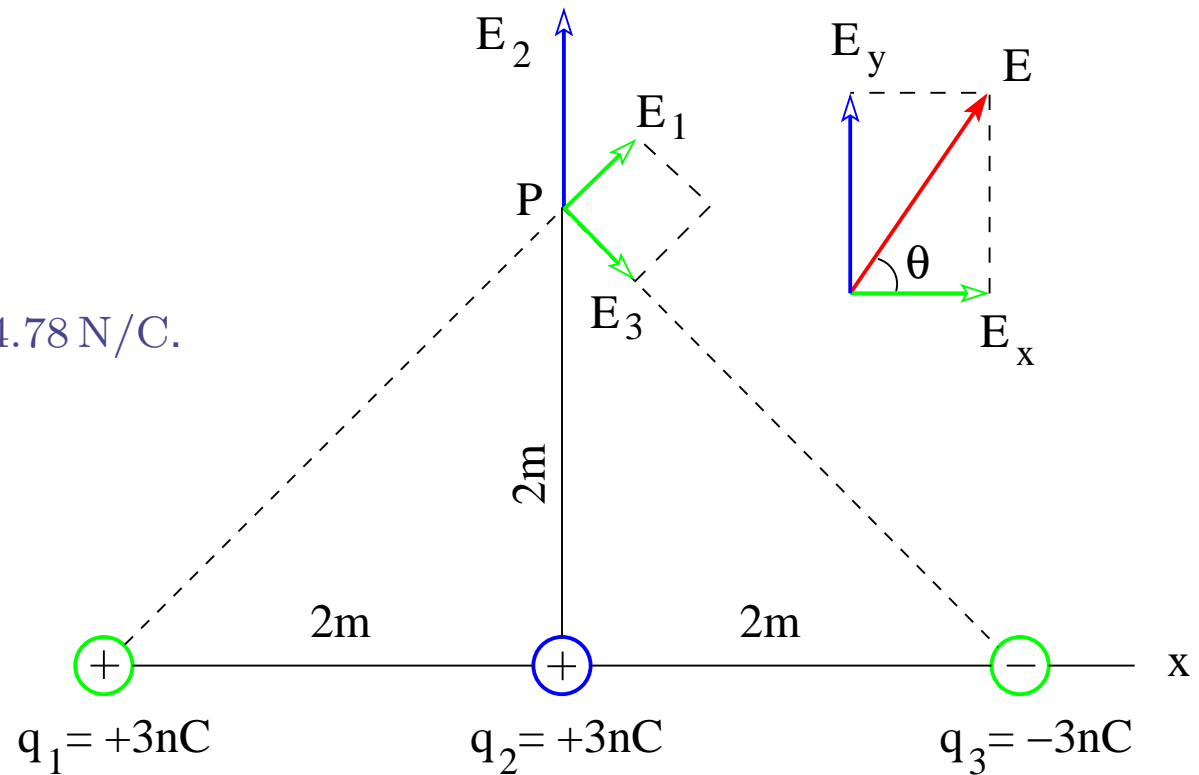
What is the value of the unknown charge?

Find magnitude and direction of the resultant electric field at point P.

- $E_1 = \dfrac{k|q_1|}{8\text{m}^2} = 3.38\,\text{N/C}.$

- $E_2 = \dfrac{k|q_2|}{4\text{m}^2} = 6.75\,\text{N/C}.$

- $E_3 = \dfrac{k|q_3|}{8\text{m}^2} = 3.38\,\text{N/C}.$

- $E_x = E_1 \cos 45^\circ + E_3 \cos 45^\circ = 4.78\,\text{N/C}.$

- $E_y = E_2 = 6.75\,\text{N/C}.$

- $E = \sqrt{E_x^2 + E_y^2} = 8.27\,\text{N/C}.$

- $\tan \theta = \dfrac{E_y}{E_x} = 1.41.$
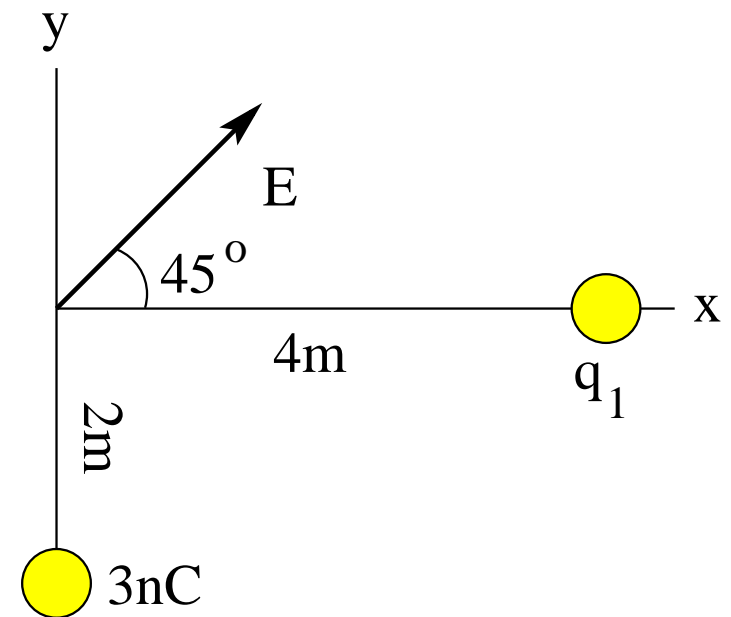
- $\theta = \arctan 1.41 = 54.7^\circ.$

The electric field $\vec{E}$ generated by the two point charges, 3nC and q_1 (unknown), has the direction shown.

(a) Find the magnitude of $\vec{E}$.

(b) Find the value of q_1.
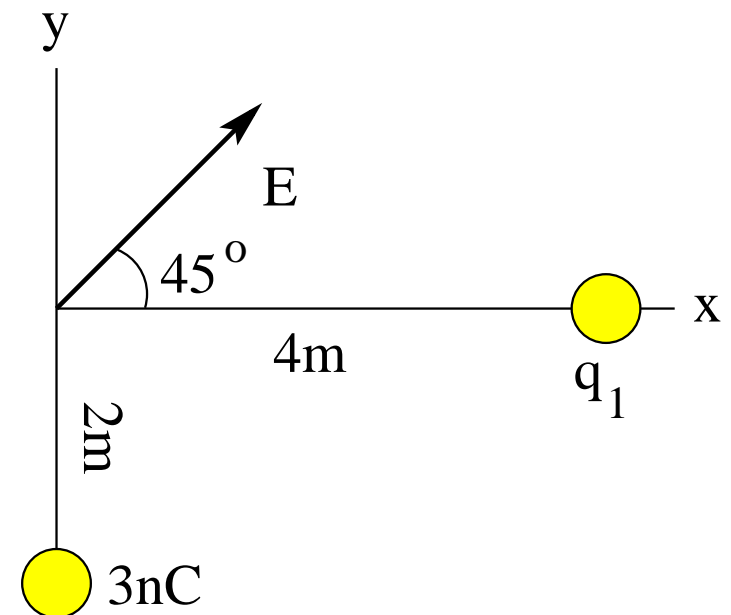
The electric field $\vec{E}$ generated by the two point charges, 3nC and q_1 (unknown), has the direction shown.

(a) Find the magnitude of $\vec{E}$.

(b) Find the value of q_1.

Solution:

(a) $E_y = k\dfrac{3\text{nC}}{(2\text{m})^2} = 6.75\text{N/C}$,

$E_x = E_y$,

$E = \sqrt{E_x^2 + E_y^2} = 9.55\text{N/C}$.

The electric field $\vec{E}$ generated by the two point charges, 3nC and q_1 (unknown), has the direction shown.

(a) Find the magnitude of $\vec{E}$.

(b) Find the value of q_1.

Solution:

(a) $E_y = k\dfrac{3\text{nC}}{(2\text{m})^2} = 6.75\text{N/C},$

$E_x = E_y,$

$E = \sqrt{E_x^2 + E_y^2} = 9.55\text{N/C}.$

(b) $E_x = k\dfrac{(-q_1)}{(4\text{m})^2},$

$q_1 = -\dfrac{(6.75\text{N/C})(16\text{m}^2)}{k} = -12\text{nC}.$