Week 5

AP Physics 2

Homework bundle for this week

本周作业合集

exercises.lol

Contents 目录

10. Electric Force, Field, and Potential

Starter Quiz · 课前小测

AP Physics 2 Name: ______________________ Score: ______

1. Two negative charges are placed near each other. They will:

   ☐ attract

   ☐ repel

   ☐ do nothing

   ☐ combine into a positive charge

2. In ordinary charging, which particles actually move between objects?

   ☐ protons

   ☐ electrons

   ☐ neutrons

   ☐ whole atoms

3. A 2 C charge sits in a field of 5 $\frac{\text{N}}{\text{C}}$. What force does it feel, in N?

   ________________ N

4. Two +1 C charges are 2 m apart ($k = 9 \times 10^9$). What is their potential energy, in J? (Give the coefficient of 10^9.)

   ________________ $\times 10^9$ J

5. How much energy is needed to move a 2 C charge through a potential difference of 6 V? Answer in J.

   ________________ J

6. A 2 F capacitor is charged to 3 V. How much charge does it store, in C?

   ________________ C

7. A 2 C charge accelerates from rest through 9 V. How much kinetic energy does it gain, in J?

   ________________ J

8. A positively charged object has:

   ☐ gained protons

   ☐ lost electrons

   ☐ gained neutrons

   ☐ lost protons

9. The electric field at a point is defined as:

- ☐ force times charge
- ☐ force per unit charge
- ☐ charge per unit force
- ☐ charge times distance

10. Electric potential energy between two point charges depends on distance as:

- ☐ $1/r^2$
- ☐ $1/r$
- ☐ r
- ☐ r^2

AP Physics 2

1. **repel**

   Like charges repel — two negatives push apart.

2. **electrons**

   Electrons transfer; protons stay locked in the nuclei.

3. **10 N**

   $F = qE = 2 \times 5 = 10$ N.

4. **4.5 $\times 10^9$ J**

   $U = kq_1q_2/r = 9 \times 10^9/2 = 4.5 \times 10^9$ J.

5. **12 J**

   $W = q\Delta V = 2 \times 6 = 12$ J.

6. **6 C**

   $Q = CV = 2 \times 3 = 6$ C.

7. **18 J**

   $\mathrm{KE} = q\Delta V = 2 \times 9 = 18$ J.

8. **lost electrons**

   A positive object has lost electrons, leaving more protons than electrons.

9. **force per unit charge**

   $E = F/q$ — the force a unit positive charge would feel.

10. $1/r$

    $U = kq_1q_2/r$ falls as $1/r$ — one power, unlike the $1/r^2$ force.

10.1 Electric Charge and Electric Force

Name: ______________ Class: __________ Date: ____________ **Total: 10 marks**

KEY WORDS coulomb's law 库仑定律 • electric charge 电荷 • charge quantization 电荷量子化

Objective

Build the skills to answer exam questions on **electric charge and electric force**.

You must be able to:

- describe **electric charge 电荷** as a conserved property in positive and negative types
- state that like charges repel and unlike charges attract
- apply **Coulomb's law 库仑定律** $F = k\frac{q_1 q_2}{r^2}$
- explain **charge quantization 电荷量子化** — charge in whole multiples of e

1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ Charge and force

Charge comes in two types; **like repel, unlike attract**, and total charge is conserved.

■ Coulomb's law

$F = k\frac{q_1 q_2}{r^2}$ with $k = 8.99 \times 10^9$ N m^2 C^{-2} — an inverse-square law like gravity.

■ Quantization

Charge is always a whole multiple of $e = 1.6 \times 10^{-19}$ C.

■ Example

Two $+2.0\ \mu$C charges 0.10 m apart: $F = 8.99 \times 10^9 \times \frac{(2.0 \times 10^{-6})^2}{(0.10)^2} = 3.6$ N (repulsive).

2 Practice

2.1 State whether two negative charges attract or repel. [1]

2.2 Two point charges are moved twice as far apart. State the factor by which the force between them changes. [1]

2.3 Find the force between a $+3.0\ \mu$C and a $-3.0\ \mu$C charge 0.20 m apart ($k = 8.99 \times 10^9$). [2]

3 Exam-style questions

3.1 The Coulomb force between two point charges varies with their separation as [1]

- **A** $1/r$
- **B** $1/r^2$
- **C** r
- **D** r^2

3.2 An object carries a charge of -4.8×10^{-19} C. The number of excess electrons is [1]

- **A** 1
- **B** 2
- **C** 3
- **D** 4

3.3 Two point charges, $+5.0\ \mu$C and $+2.0\ \mu$C, are 0.30 m apart.

(a) Find the force between them. [3]

(b) State whether the force is attractive or repulsive. [1]

Solutions

2.1 repel.

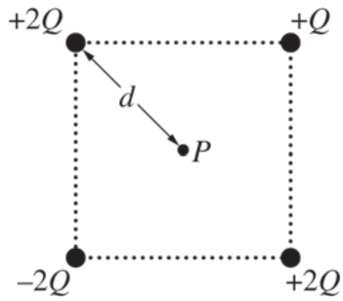
2.2 it becomes one quarter as large ($1/2^2$).

2.3 $F = 8.99 \times 10^9 \times \dfrac{(3.0 \times 10^{-6})^2}{(0.20)^2} = 2.0$ N, attractive.

3.1 B.

3.2 C — $4.8 \times 10^{-19}/1.6 \times 10^{-19} = 3$.

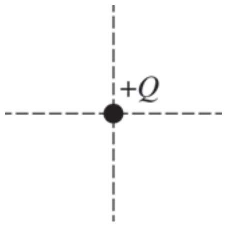
3.3 (a) $F = 8.99 \times 10^9 \times \dfrac{(5.0 \times 10^{-6})(2.0 \times 10^{-6})}{(0.30)^2} = 1.0$ N. (b) repulsive (both charges positive).



4. (10 points, suggested time 20 minutes)

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

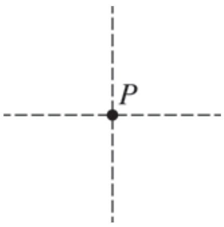
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.



(b)

i. Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P.

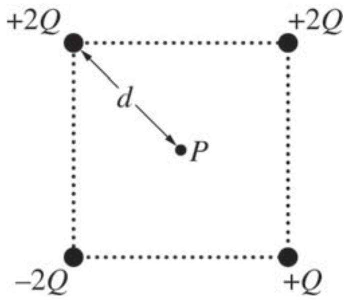
Draw Arrow



Calculate Electric Field

ii. Calculate the electric potential at point P due to all four objects.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.



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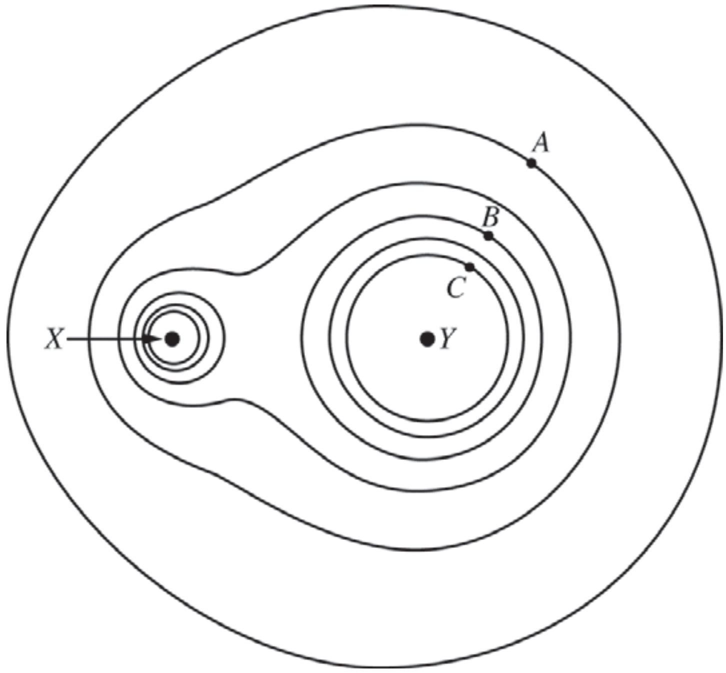

3. (12 points, suggested time 25 minutes)

The dots in the figure above represent two identical spheres, *X* and *Y,* that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere *Y* is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points *A* and *B*.

Potential at point *A* _______ Potential at point *B* _______

(b)

i. How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

ii. The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Let the potentials at the three labeled points be V_A, V_B, and V_C. A proton with charge $+q$ and mass *m* is released from rest at point *B*.

(c) Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

(d) At some time after being released from rest at point B, the proton has moved through a potential difference of magnitude 20 V.

i. Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.

ii. As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.

iii. Two students are discussing how and why the kinetic energy of the proton would change after it is released.

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.

AP PHYSICS 2 • EXERCISE SHEET

10.2 The Process of Charging

Name: ______________ Class: __________ Date: ____________ **Total: 10 marks**

KEY WORDS conductor 导体 • insulator 绝缘体 • friction 摩擦 • induction 感应 • conduction 接触

Objective

Build the skills to answer exam questions on **the process of charging**.

You must be able to:

- distinguish **conductors** 导体 from **insulators** 绝缘体 by how freely charge moves
- explain charging by **friction** 摩擦, **conduction** 接触, and **induction** 感应
- describe how a charged object attracts a neutral one by **polarization** 极化
- apply **conservation of charge** 电荷守恒

1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ Conductors and insulators

In a **conductor** (metal) charge moves freely; in an **insulator** (plastic, glass) it stays put.

■ Three ways to charge

- **Friction** — rubbing transfers electrons between materials.
- **Conduction** — touching a charged object shares charge.
- **Induction** — a nearby charge rearranges charge, then grounding removes some.

■ Polarization

A charged rod attracts a neutral object by pulling its opposite charges slightly closer — the near side becomes oppositely charged.

2 Practice

2.1 State the difference between a conductor and an insulator. [2]

2.2 Name the charging method in which two objects are rubbed together. [1]

2.3 Explain how a charged balloon sticks to a neutral wall. [2]

3 Exam-style questions

3.1 Charge moves freely through a [1]

- **A** insulator
- **B** conductor
- **C** vacuum only
- **D** neutral object

3.2 Charging by induction involves [1]

- **A** rubbing two materials
- **B** direct contact only
- **C** bringing a charge near, then grounding
- **D** heating the object

3.3 A negatively charged rod is brought near (but not touching) a neutral metal sphere on an insulating stand.

(a) Describe the arrangement of charge on the sphere. [2]

(b) State the net charge on the sphere. [1]

Solutions

2.1 in a conductor charge moves freely; in an insulator charge stays fixed in place.

2.2 friction (rubbing).

2.3 the balloon's charge polarizes the wall, pulling opposite charge to the near surface, so the balloon is attracted and held.

3.1 **B**.

3.2 **C**.

3.3 (a) the near side becomes positive and the far side negative (charges separate). (b) zero — the sphere is still neutral overall.

AP PHYSICS 2 • EXERCISE SHEET

10.3 Electric Fields

Name: ______________ Class: __________ Date: ____________ **Total: 11 marks**

KEY WORDS electric field 电场 • field lines 电场线

Objective

Build the skills to answer exam questions on **electric fields**.

You must be able to:

- define the **electric field** 电场 as force per unit positive charge, $\vec{E} = \vec{F}/q$
- draw and interpret **field lines** 电场线 (direction and density)
- calculate the field of a **point charge**, $E = k\dfrac{q}{r^2}$, and add fields as vectors
- describe the uniform field between parallel plates

1 Worked examples

Study these first. Each one shows the method for a question type used later.

The electric field

$\vec{E} = \dfrac{\vec{F}}{q}$, measured in N C^{-1} — the force a small positive test charge would feel per unit charge.

Field lines

Lines point **away** from positive and **toward** negative charge; where the lines are **denser**, the field is stronger.

Point charge and parallel plates

$E = k\dfrac{q}{r^2}$ for a point charge. Between parallel plates the field is **uniform**, running from the + plate to the − plate.

2 Practice

2.1 A charge of 2.0×10^{-6} C feels a force of 0.10 N. Find the electric field there. [2]

2.2 State the direction of the field around a positive point charge. [1]

2.3 Find the field 0.20 m from a +4.0 μC charge ($k = 8.99 \times 10^9$). [2]

3 Exam-style questions

3.1 The electric field is defined as [1]

- **A** force $\times$ charge
- **B** force per unit charge
- **C** charge per unit force
- **D** charge $\times$ distance

3.2 Field lines around a negative point charge point [1]

- **A** away from it
- **B** toward it
- **C** in circles around it
- **D** there are none

3.3 A +6.0 μC charge sits at the origin.

(a) Find the electric field 0.30 m from it. [3]

(b) State the direction of the field. [1]

Solutions

2.1 $E = \frac{F}{q} = \frac{0.10}{2.0 \times 10^{-6}} = 5.0 \times 10^4 \text{ N C}^{-1}$.

2.2 radially outward, away from the charge.

2.3 $E = k\frac{q}{r^2} = 8.99 \times 10^9 \times \frac{4.0 \times 10^{-6}}{(0.20)^2} = 9.0 \times 10^5 \text{ N C}^{-1}$.

3.1 **B**.

3.2 **B**.

3.3 (a) $E = 8.99 \times 10^9 \times \frac{6.0 \times 10^{-6}}{(0.30)^2} = 6.0 \times 10^5 \text{ N C}^{-1}$. (b) away from the charge (radially outward).

Begin your response to **QUESTION 4** on this page.

4. (10 points, suggested time 20 minutes)

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$.
- Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(a) **Calculate** the ratio $\frac{K_2}{K_1}$.

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Continue your response to **QUESTION 4** on this page.

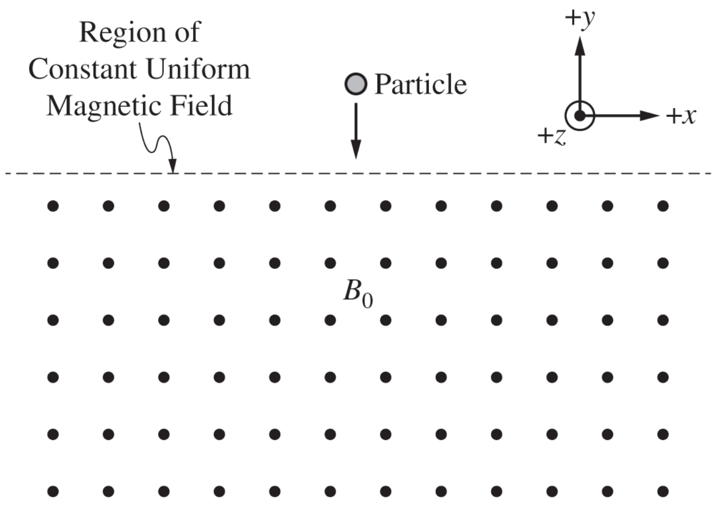


Figure 1

After exiting the device, the particles enter a large region of constant uniform magnetic field of magnitude B_0 that is directed in the $+z$-direction (out of the page), as shown in Figure 1. Each particle is moving in the $-y$-direction when entering the region, and each particle is moving in the $+y$-direction when exiting the region.

(b)

i. **Determine** an expression for the speed of Particle 2 in the region. Express your answer in terms of M, K_2, and physical constants, as appropriate.

ii. **Derive** an expression for the horizontal distance Δx between the locations where Particle 2 enters and leaves the region. Express your answer in terms of M, Q, K_2, B_0, and physical constants, as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 4** on this page.

(c) On the following diagram in Figure 2, **sketch** and clearly **label** the paths of both particles 1 and 2 in the region.

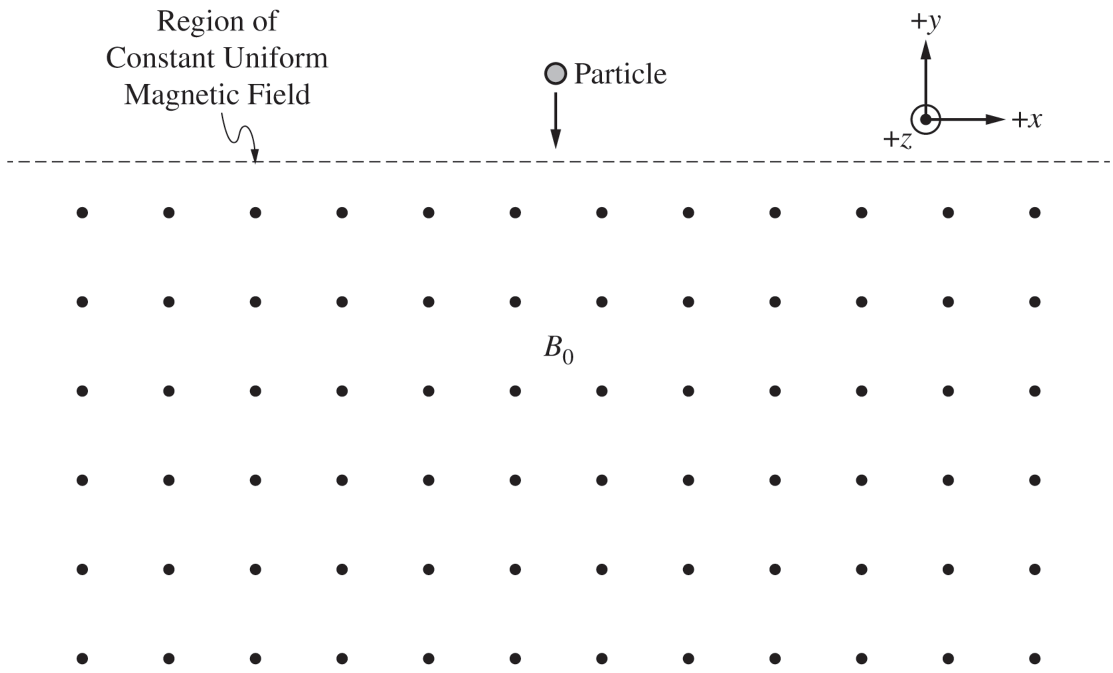


Figure 2

(d) A uniform electric field is added to the region such that Particle 1 of negative charge $-Q$ travels with constant speed in a straight line through the region. **Determine** the direction of the electric field.

GO ON TO THE NEXT PAGE.

STOP

END OF EXAM

Begin your response to **QUESTION 1** on this page.

(10 points, suggested time 20 minutes)

Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side length d, as shown. Point P is located equidistant from each vertex of the triangle.

Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed at the bottom-right vertex. The students make the following statements.

Student Y: “If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P.”

Student Z: “To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex.”

(a) In a coherent, paragraph-length response, evaluate the accuracy of each student’s statement. If any aspect of either student’s statement is inaccurate, explain how to correct the student’s statement. Support your evaluations using appropriate physics principles.

GO ON TO THE NEXT PAGE.

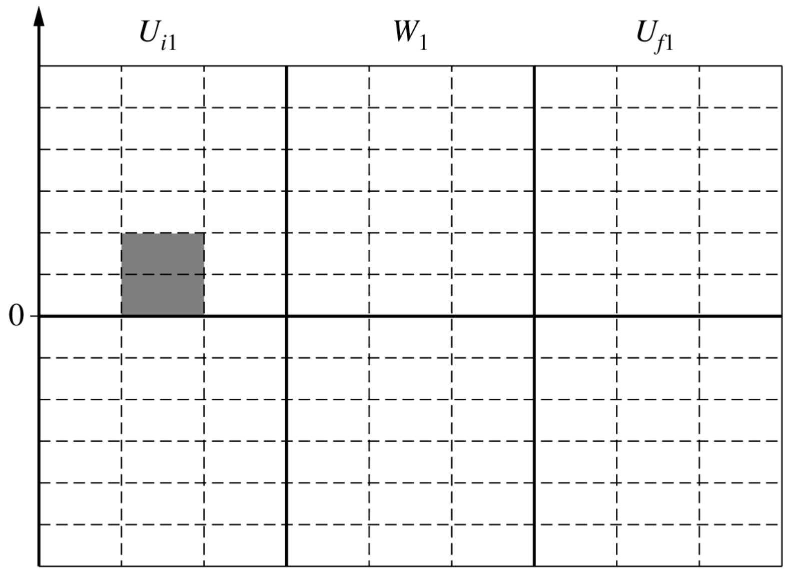
(b) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles when a third charged particle is brought from very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

i. In Scenario 1, a third particle with positive charge $+Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i1} of the system consisting of all three particles when the third particle with positive charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_1 required to move the third particle with positive charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f1} of the system consisting of all three particles when the third particle with positive charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a “0” in that column.



Scenario 1

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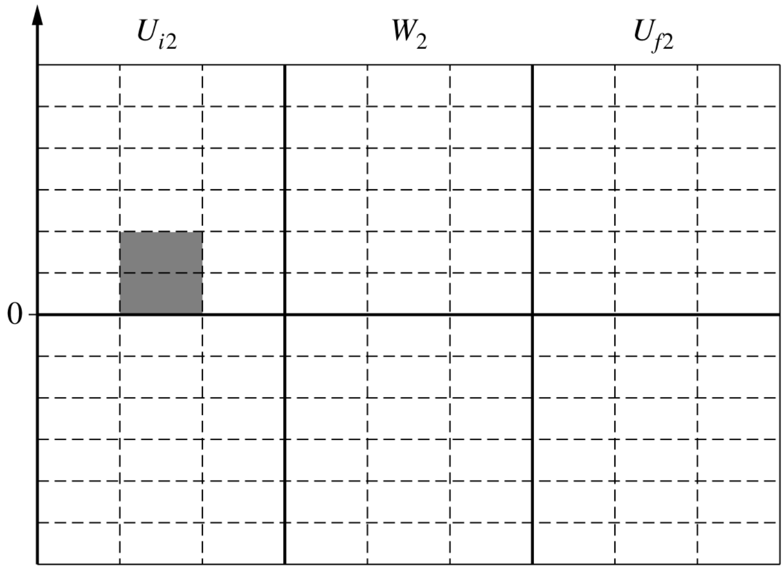
ii. In Scenario 2, a particle with negative charge $-Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i2} of the system consisting of all three particles when the particle with negative charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 2

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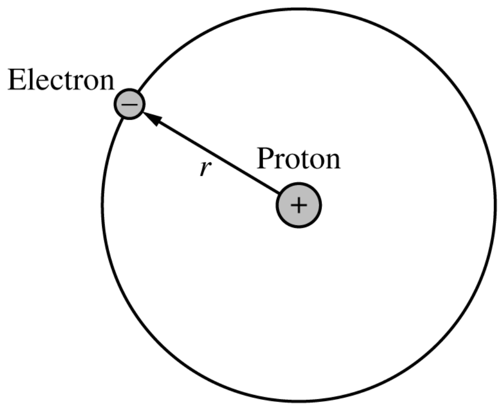

Note: Figure not drawn to scale.

. (12 points, suggested time 25 minutes)

A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(a) Derive an equation for the speed v of the electron in terms of r and physical constants, as appropriate.

(b) Derive an equation for the total energy of the atom in terms of r and physical constants, as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(c) When the hydrogen atom absorbs a photon, the electron moves to an orbit with a larger radius and the total energy of the atom increases. Is your equation for the energy derived in part (b) consistent with this description of the model of a hydrogen atom absorbing a photon? Explain why the equation is or is not consistent.

(d) Experiments show that a hydrogen atom can absorb a photon of frequency 3.2×10^{15} Hz.

i. Calculate the energy of a photon with this frequency.

ii. A student claims that when a hydrogen atom absorbs a photon at this frequency, the energy could be converted into mass, adding an electron to the atom. Calculate the amount of energy needed to create a particle with the mass of an electron and determine whether or not there is sufficient energy gained by the atom to add another electron.

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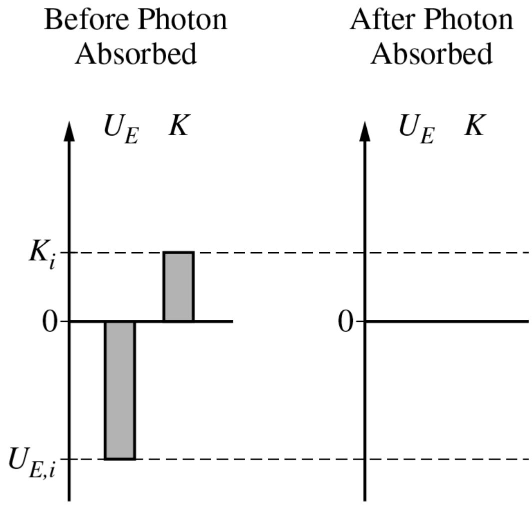
Continue your response to **QUESTION 3** on this page.



iii. The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,\,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

GO ON TO THE NEXT PAGE.

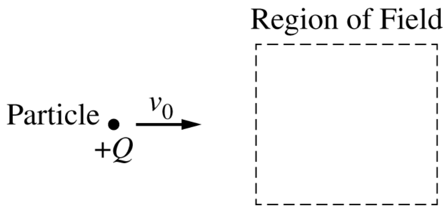
PHYSICS 2

Section II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

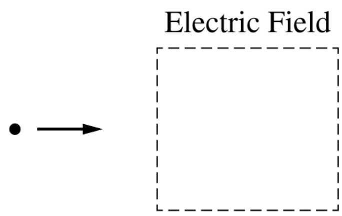


1. (10 points, suggested time 20 minutes)

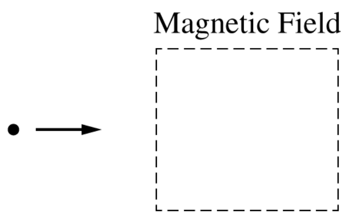
The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.

(a)

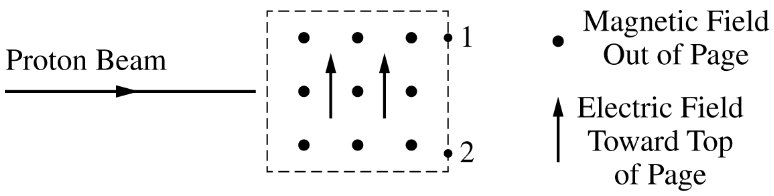
i. On the figure below, draw a possible path of the particle in the region if the region contains only an electric field directed toward the bottom of the page.



ii. On the figure below, draw a possible path of the particle in the region if the region contains only a magnetic field directed out of the page.



iii. For which of the previous situations is the motion more similar to that of a projectile in only a gravitational field near Earth's surface, and why?



(b) Another region of space contains an electric field directed toward the top of the page and a magnetic field directed out of the page. Both fields are constant and uniform. A horizontal beam of protons with a variety of speeds enters the region, as shown above. Protons exit the region at a variety of locations, including points 1 and 2 shown on the figure. In a coherent, paragraph-length response, explain why some protons exit the region at point 1 and others exit at point 2. Use physics principles to explain your reasoning.

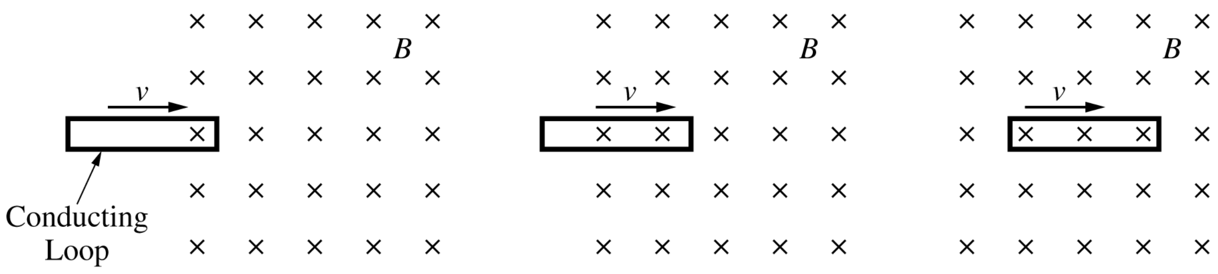
PHYSICS 2

Section II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.



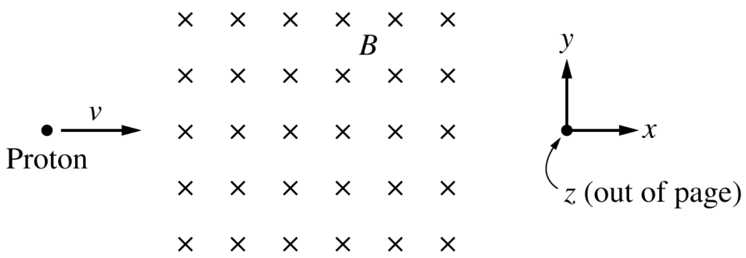
Time t_1 Time t_2 Time t_3

1. (10 points, suggested time 20 minutes)

The figures above show a rectangular conducting loop at three instants in time. The loop moves at a constant speed v into and through a region of constant, uniform magnetic field B directed into the page. The magnetic field is zero outside the region.

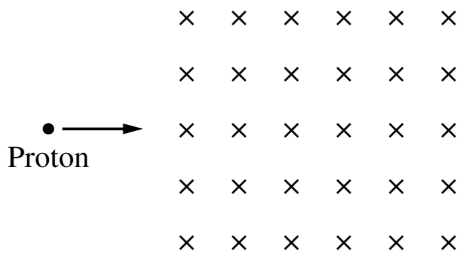
(a) In a coherent paragraph-length response, compare the magnitude and direction of the current at times t_1, t_2, and t_3. Include an explanation of why there is or is not a current and the direction of the current if one is present. Use fundamental physics concepts and principles in your explanation.

(b) The loop is removed. A proton traveling to the right in the plane of the page, as shown below, then enters the region of magnetic field with a speed $v = 3.0 \times 10^5$ m/s. The magnitude of the field is 0.030 T. The effects of gravity are negligible.



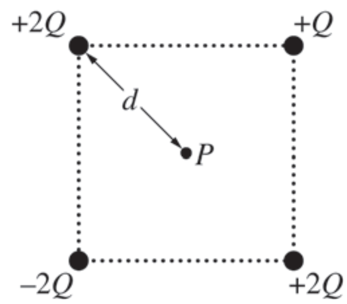
i. Calculate the magnitude of the force on the proton as it enters the field.

ii. On the figure below, sketch a possible path of the proton as it travels through the magnetic field. Clearly label the path P1.



iii. A second proton now enters the magnetic field at the same point and from the same direction but at a greater speed than the first proton. On the figure above, draw the path of the second proton as it travels through the field. Clearly label the path P2.

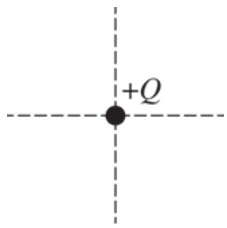
iv. Next an electric field is applied in the same region as the magnetic field, such that there is no net force on the first proton as it enters the region. Calculate the magnitude and indicate the direction of the electric field relative to the coordinate system shown in part (b).



4. (10 points, suggested time 20 minutes)

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.

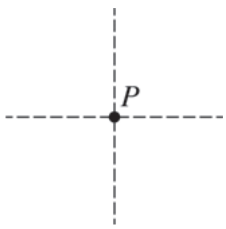


(b)

i. Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P.

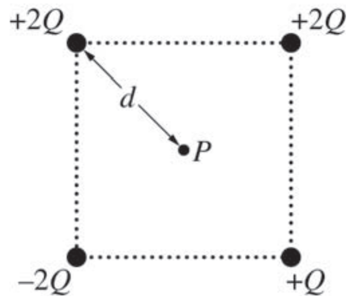
Draw Arrow

Calculate Electric Field



ii. Calculate the electric potential at point P due to all four objects.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.



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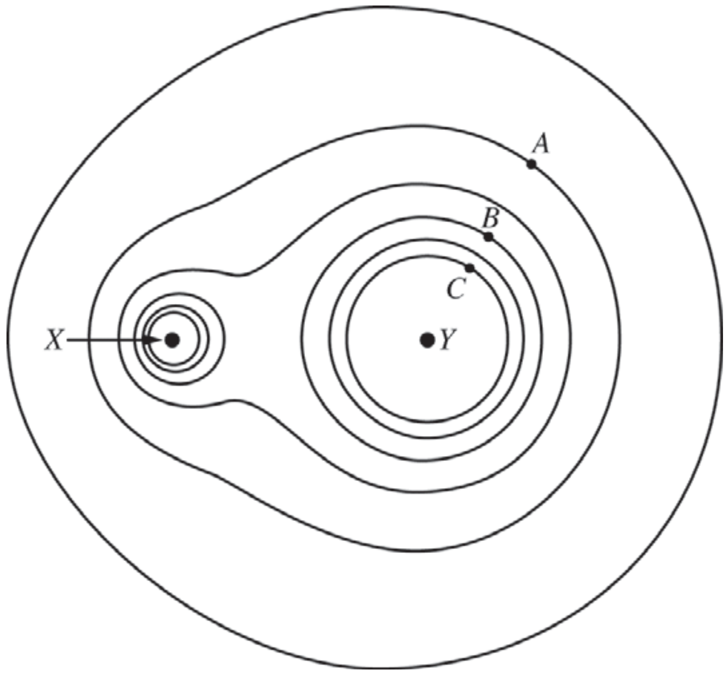
END OF EXAM



3. (12 points, suggested time 25 minutes)

The dots in the figure above represent two identical spheres, *X* and *Y,* that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere *Y* is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points *A* and *B*.

Potential at point *A* _______ Potential at point *B* _______

(b)

i. How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

ii. The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Let the potentials at the three labeled points be V_A , V_B , and V_C . A proton with charge $+q$ and mass *m* is released from rest at point *B*.

(c) Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

(d) At some time after being released from rest at point *B*, the proton has moved through a potential difference of magnitude 20 V.

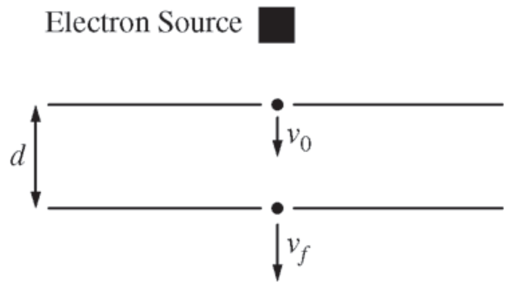
i. Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.

ii. As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.

iii. Two students are discussing how and why the kinetic energy of the proton would change after it is released.

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.



Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

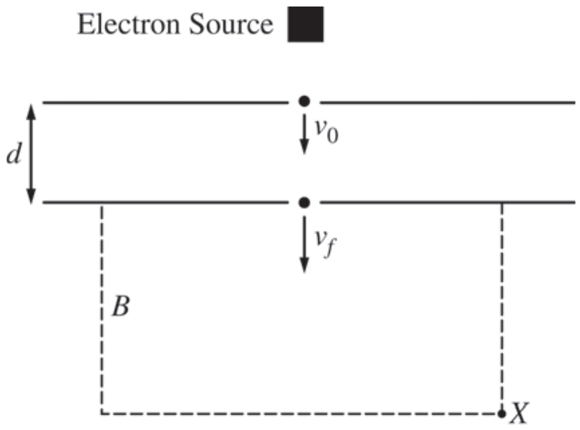
The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010\ \text{m}$. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6\ \text{m/s}$, take $1.49\ \text{ns}$ to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\ \text{m/s}$.

(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

(b) Calculate the magnitude of the electric field between the plates.

(c) Calculate the magnitude of the charge on each plate.

(d) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude B that is perpendicular to the page. The electrons then leave the magnetic field at point X.



Note: Figure not drawn to scale.

i. On the figure above, sketch the path of the electrons from the bottom plate to point X. Explain why the path has the shape that you sketched.

ii. Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

STOP

END OF EXAM

10.4 Electric Potential Energy

Name: ____________ Class: ________ Date: __________ **Total: 10 marks**

KEY WORDS electric potential 电势 • electric potential energy 电势能

Objective

Build the skills to answer exam questions on **electric potential energy**.

You must be able to:

- define **electric potential energy 电势能** as the work done to assemble a charge configuration
- calculate the potential energy of two point charges, $U = k\dfrac{q_1 q_2}{r}$
- relate changes in potential energy to **work** done by the electric force
- apply **conservation of energy** to charges moving in a field

1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ Potential energy of two charges

$U = k\dfrac{q_1 q_2}{r}$ — **positive** for like charges (they store energy as they are pushed together) and **negative** for unlike charges.

■ Work and energy

Work done by the field $= -\Delta U$. A charge released from rest gains kinetic energy equal to the drop in U.

■ Example

A $+1.0$ μC and a $+2.0$ μC charge 0.10 m apart: $U = 8.99 \times 10^9 \times \dfrac{(1.0 \times 10^{-6})(2.0 \times 10^{-6})}{0.10} = 0.18$ J.

2 Practice

2.1 Find the electric potential energy of a +2.0 μC and a +3.0 μC charge 0.50 m apart ($k = 8.99 \times 10^9$). [2]

2.2 State the sign of the potential energy for two opposite charges. [1]

2.3 A charge is released and its potential energy falls by 5.0 J. State the kinetic energy it gains. [1]

3 Exam-style questions

3.1 The electric potential energy of two point charges is [1]

- **A** $k\frac{q_1 q_2}{r^2}$
- **B** $k\frac{q_1 q_2}{r}$
- **C** qE
- **D** $\frac{1}{2}CV^2$

3.2 The electric potential energy of two unlike charges is [1]

- **A** positive
- **B** negative
- **C** zero
- **D** infinite

3.3 Two +4.0 μC charges are held 0.20 m apart.

(a) Find the electric potential energy of the pair. [3]

(b) State what happens to this energy if the charges are released. [1]

Solutions

2.1 $U = 8.99 \times 10^9 \times \dfrac{(2.0 \times 10^{-6})(3.0 \times 10^{-6})}{0.50} = 0.11$ J.

2.2 negative.

2.3 5.0 J (energy is conserved).

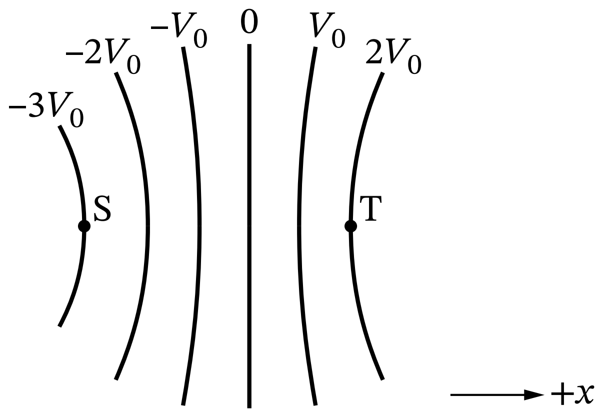
3.1 **B**.

3.2 **B**.

3.3 (a) $U = 8.99 \times 10^9 \times \dfrac{(4.0 \times 10^{-6})^2}{0.20} = 0.72$ J. (b) it is converted into kinetic energy as the like charges fly apart.

Question 4

4. Equipotential lines for a region with an electric field are shown.



A small sphere (not shown) with positive charge $+Q$ has initial speed v_S in the $+x$-direction and kinetic energy K_S when the sphere is at Point S. The sphere moves to Point T. The force from the electric field is the only force that is exerted on the sphere as the sphere moves between Points S and T.

The sphere has final speed v_T and kinetic energy K_T when the sphere is at Point T.

Part A

Indicate whether v_T is greater than, less than, or equal to v_S. Include one of the following relationships in your response.

- $v_T > v_S$
- $v_T < v_S$
- $v_T = v_S$

Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Part B

Derive an expression for K_T in terms of V_0, Q, K_S, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Part C

A new, small sphere of the same mass as the original sphere but with negative charge $-Q$ has the same initial speed v_S as the original sphere in the +x-direction when the sphere is at Point S. The force from the electric field is the only force that is exerted on the new sphere as the new sphere moves between Points S and T. The new sphere has kinetic energy K_{new} when the new sphere is at Point T.

Indicate whether K_{new} is greater than, less than, or equal to K_T. Include one of the following relationships in your response.

- $K_{new} > K_T$
- $K_{new} < K_T$
- $K_{new} = K_T$

Briefly **justify** your answer by referencing your derivation in part B.

STOP

END OF EXAM

Begin your response to **QUESTION 4** on this page.

4. (10 points, suggested time 20 minutes)

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$.
- Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(a) **Calculate** the ratio $\frac{K_2}{K_1}$.

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Continue your response to **QUESTION 4** on this page.

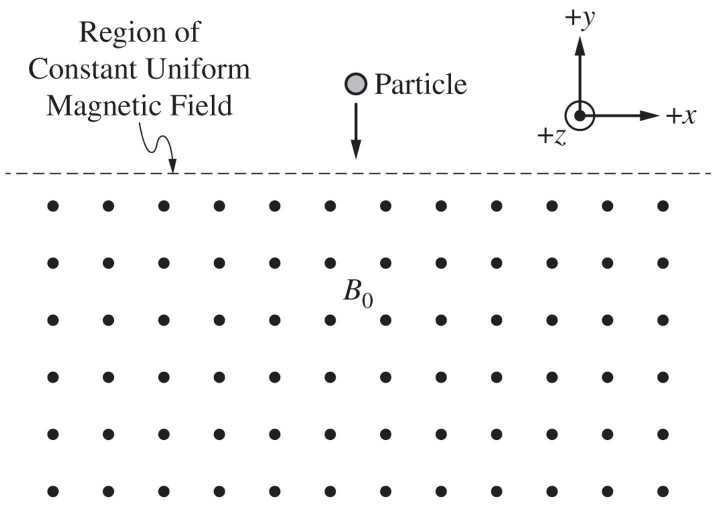


Figure 1

After exiting the device, the particles enter a large region of constant uniform magnetic field of magnitude B_0 that is directed in the $+z$-direction (out of the page), as shown in Figure 1. Each particle is moving in the $-y$-direction when entering the region, and each particle is moving in the $+y$-direction when exiting the region.

(b)

i. **Determine** an expression for the speed of Particle 2 in the region. Express your answer in terms of M, K_2, and physical constants, as appropriate.

ii. **Derive** an expression for the horizontal distance Δx between the locations where Particle 2 enters and leaves the region. Express your answer in terms of M, Q, K_2, B_0, and physical constants, as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 4** on this page.

(c) On the following diagram in Figure 2, **sketch** and clearly **label** the paths of both particles 1 and 2 in the region.

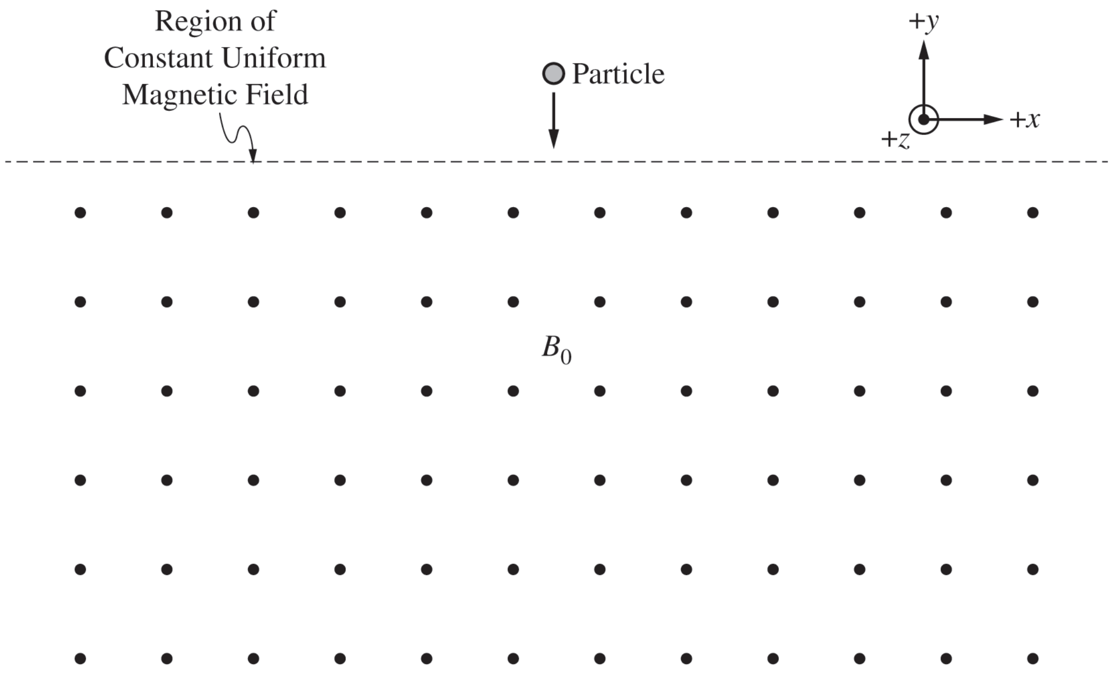


Figure 2

(d) A uniform electric field is added to the region such that Particle 1 of negative charge $-Q$ travels with constant speed in a straight line through the region. **Determine** the direction of the electric field.

GO ON TO THE NEXT PAGE.

STOP

END OF EXAM

(10 points, suggested time 20 minutes)

Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side length d, as shown. Point P is located equidistant from each vertex of the triangle.

Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed at the bottom-right vertex. The students make the following statements.

Student Y: "If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P."

Student Z: "To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex."

(a) In a coherent, paragraph-length response, evaluate the accuracy of each student's statement. If any aspect of either student's statement is inaccurate, explain how to correct the student's statement. Support your evaluations using appropriate physics principles.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 4** on this page.

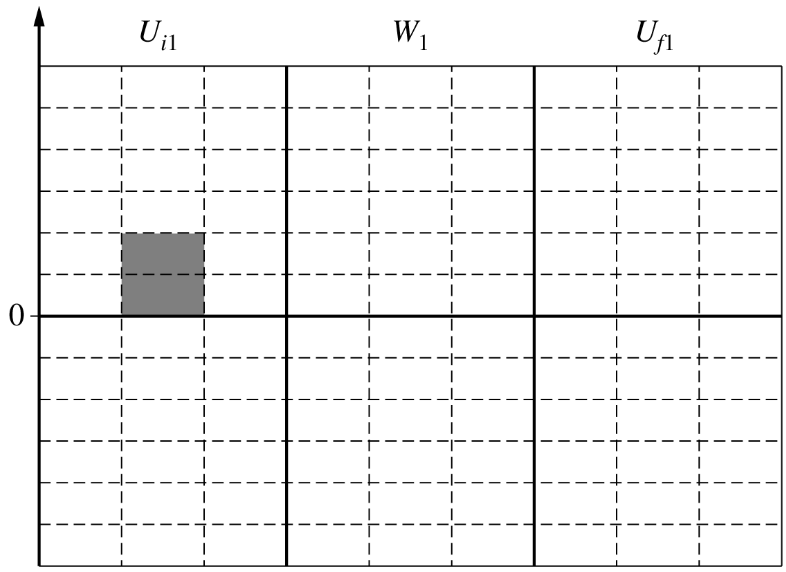
(b) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles when a third charged particle is brought from very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

i. In Scenario 1, a third particle with positive charge $+Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i1} of the system consisting of all three particles when the third particle with positive charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_1 required to move the third particle with positive charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f1} of the system consisting of all three particles when the third particle with positive charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 1

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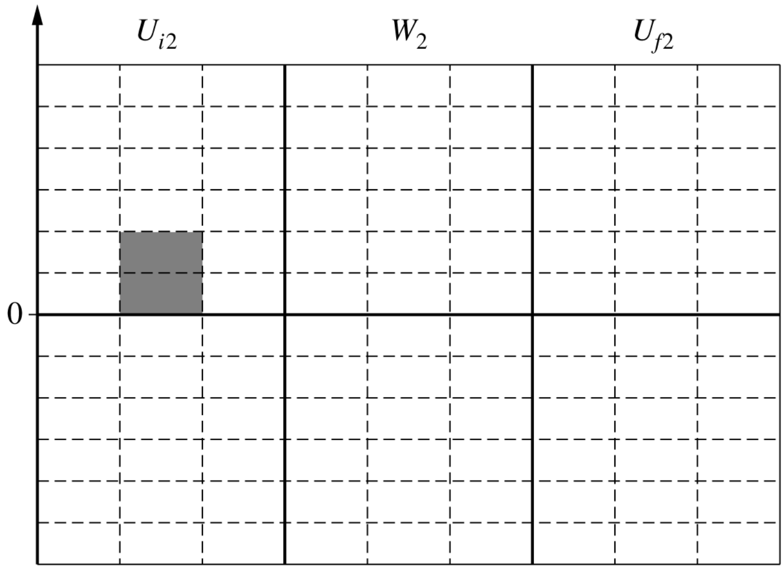
Continue your response to **QUESTION 4** on this page.

ii. In Scenario 2, a particle with negative charge $-Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i2} of the system consisting of all three particles when the particle with negative charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 2

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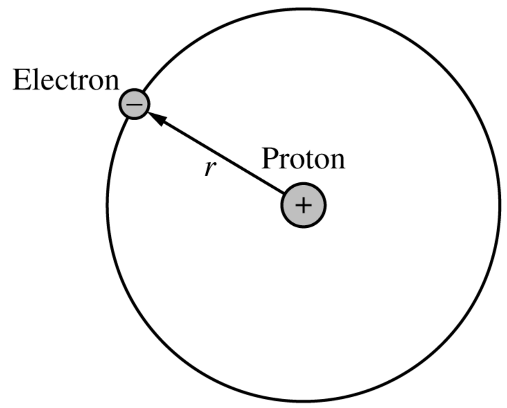
END OF EXAM

Begin your response to **QUESTION 3** on this page.



Note: Figure not drawn to scale.

. (12 points, suggested time 25 minutes)

A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(a) Derive an equation for the speed v of the electron in terms of r and physical constants, as appropriate.

(b) Derive an equation for the total energy of the atom in terms of r and physical constants, as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(c) When the hydrogen atom absorbs a photon, the electron moves to an orbit with a larger radius and the total energy of the atom increases. Is your equation for the energy derived in part (b) consistent with this description of the model of a hydrogen atom absorbing a photon? Explain why the equation is or is not consistent.

(d) Experiments show that a hydrogen atom can absorb a photon of frequency 3.2×10^{15} Hz.

i. Calculate the energy of a photon with this frequency.

ii. A student claims that when a hydrogen atom absorbs a photon at this frequency, the energy could be converted into mass, adding an electron to the atom. Calculate the amount of energy needed to create a particle with the mass of an electron and determine whether or not there is sufficient energy gained by the atom to add another electron.

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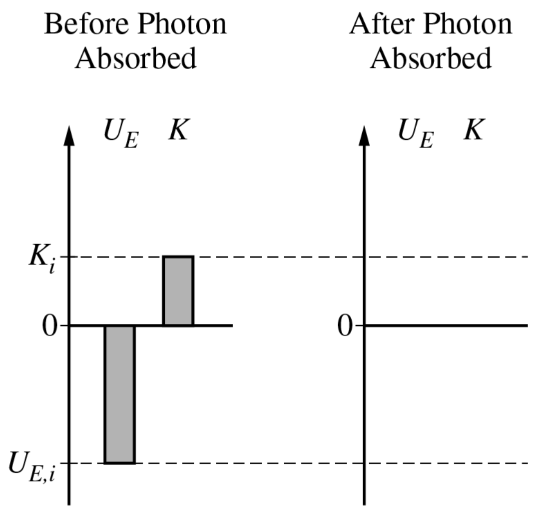
Continue your response to **QUESTION 3** on this page.



iii. The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

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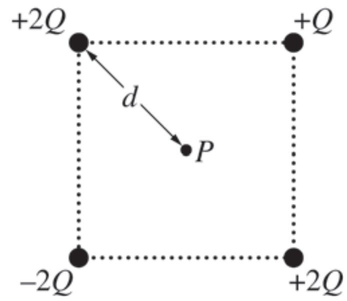
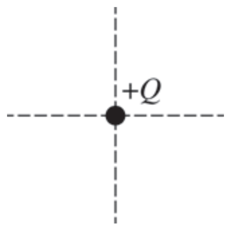


4. (10 points, suggested time 20 minutes)

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

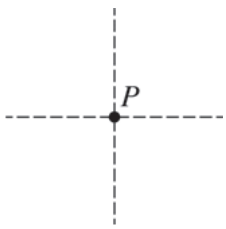
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.



(b)

i. Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P.

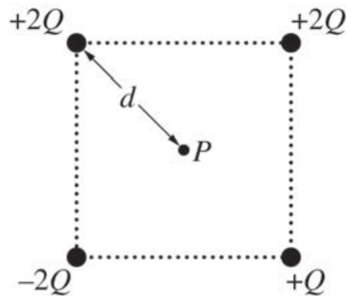
Draw Arrow



Calculate Electric Field

ii. Calculate the electric potential at point P due to all four objects.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.



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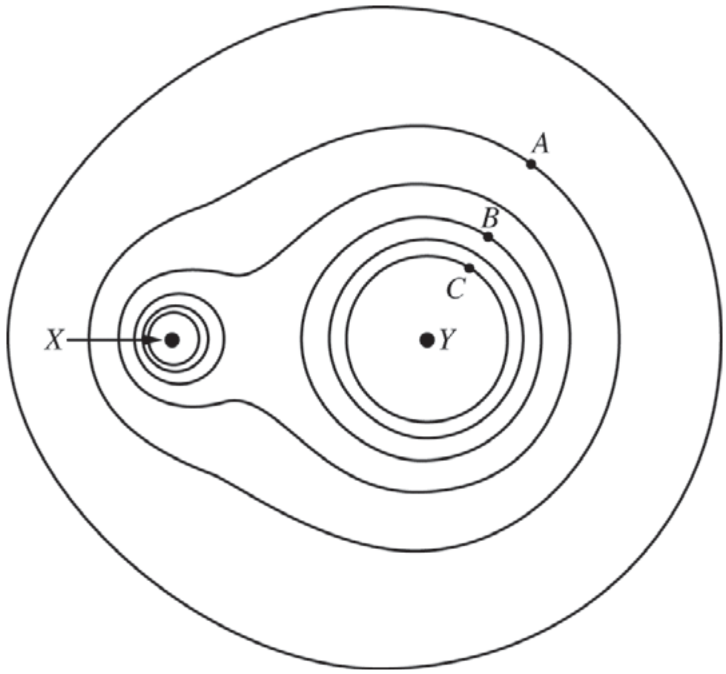


3. (12 points, suggested time 25 minutes)

The dots in the figure above represent two identical spheres, *X* and *Y,* that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere *Y* is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points *A* and *B*.

Potential at point *A* _______ Potential at point *B* _______

(b)

i. How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

ii. The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Let the potentials at the three labeled points be V_A , V_B , and V_C . A proton with charge $+q$ and mass *m* is released from rest at point *B*.

(c) Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

(d) At some time after being released from rest at point *B*, the proton has moved through a potential difference of magnitude 20 V.

i. Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.

ii. As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.

iii. Two students are discussing how and why the kinetic energy of the proton would change after it is released.

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.

10.5 Electric Potential

Name: ______________ Class: __________ Date: ____________ **Total: 11 marks**

KEY WORDS electric potential 电势 • potential difference 电势差 • electric field 电场

Objective

Build the skills to answer exam questions on **electric potential**.

You must be able to:

- define **electric potential 电势** (voltage) as potential energy per unit charge, $V = U/q$
- calculate the potential due to point charges, $V = k\frac{q}{r}$
- relate the **potential difference 电势差** to the work needed to move a charge
- connect the field to the potential (the field points toward decreasing potential)

1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ Electric potential

$V = \frac{U}{q}$, measured in volts — the potential energy per unit charge. For a point charge, $V = k\frac{q}{r}$, a **scalar** (just add potentials).

■ Work and potential difference

$W = q\,\Delta V$ to move a charge q through a potential difference ΔV.

■ Field and potential

The electric field points from **high** to **low** potential.

2 Practice

2.1 Find the potential 0.30 m from a +6.0 μC charge ($k = 8.99 \times 10^9$). [2]

2.2 State whether electric potential is a scalar or a vector quantity. [1]

2.3 Find the work needed to move a +2.0 μC charge through a potential difference of 100 V. [2]

3 Exam-style questions

3.1 Electric potential is [1]

- **A** potential energy per unit charge
- **B** force per unit charge
- **C** charge per unit energy
- **D** field $\times$ distance only

3.2 The electric field points in the direction of [1]

- **A** increasing potential
- **B** decreasing potential
- **C** zero potential
- **D** constant potential

3.3 A +3.0 μC charge sits at the origin.

(a) Find the potential 0.20 m from it. [3]

(b) Find the potential energy of a $+1.0\ \mu$C charge placed there. [1]

Solutions

2.1 $V = k\dfrac{q}{r} = 8.99 \times 10^9 \times \dfrac{6.0 \times 10^{-6}}{0.30} = 1.8 \times 10^5$ V.

2.2 a scalar.

2.3 $W = q\,\Delta V = 2.0 \times 10^{-6} \times 100 = 2.0 \times 10^{-4}$ J.

3.1 **A**.

3.2 **B**.

3.3 (a) $V = 8.99 \times 10^9 \times \dfrac{3.0 \times 10^{-6}}{0.20} = 1.35 \times 10^5$ V. (b) $U = qV = (1.0 \times 10^{-6})(1.35 \times 10^5) = 0.135$ J.

Begin your response to **QUESTION** [illegible] on this page.

(10 points, suggested time 20 minutes)

Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side length d, as shown. Point P is located equidistant from each vertex of the triangle.

Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed at the bottom-right vertex. The students make the following statements.

Student Y: “If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P.”

Student Z: “To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex.”

(a) In a coherent, paragraph-length response, evaluate the accuracy of each student’s statement. If any aspect of either student’s statement is inaccurate, explain how to correct the student’s statement. Support your evaluations using appropriate physics principles.

GO ON TO THE NEXT PAGE.

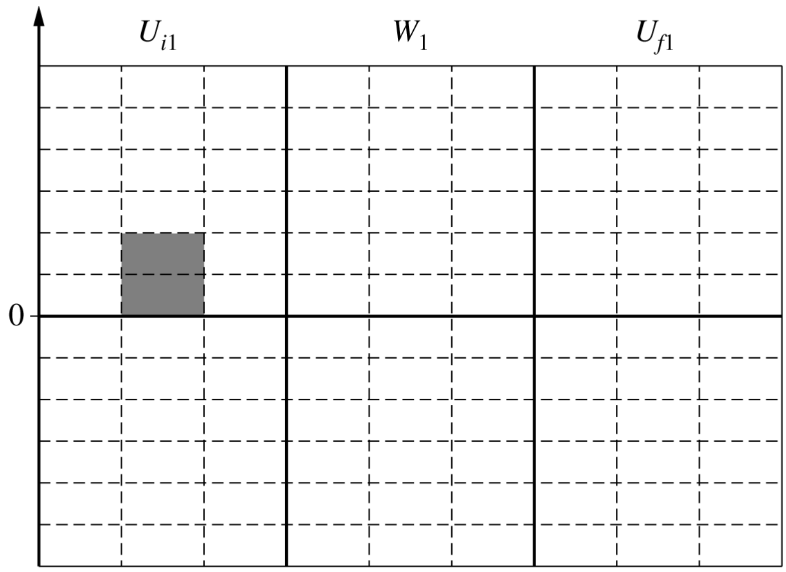
(b) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles when a third charged particle is brought from very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

i. In Scenario 1, a third particle with positive charge $+Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i1} of the system consisting of all three particles when the third particle with positive charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_1 required to move the third particle with positive charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f1} of the system consisting of all three particles when the third particle with positive charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 1

GO ON TO THE NEXT PAGE.

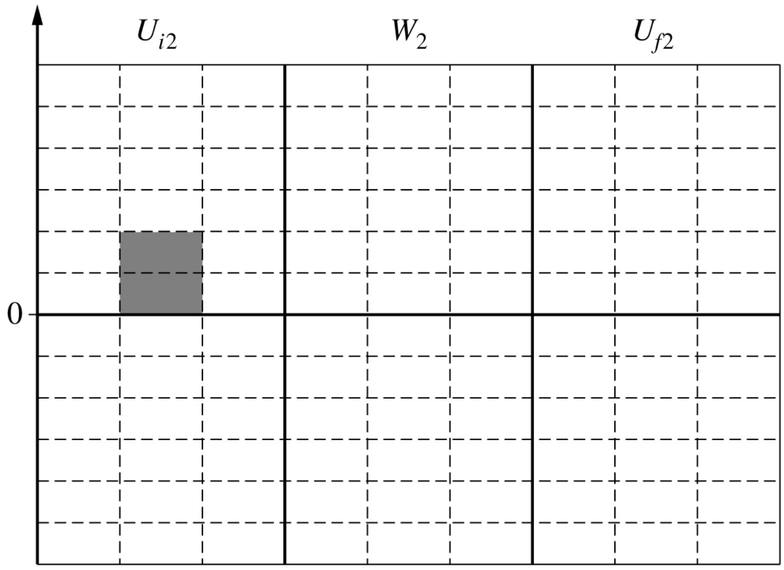
Continue your response to **QUESTION 4** on this page.

ii. In Scenario 2, a particle with negative charge $-Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i2} of the system consisting of all three particles when the particle with negative charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 2

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STOP

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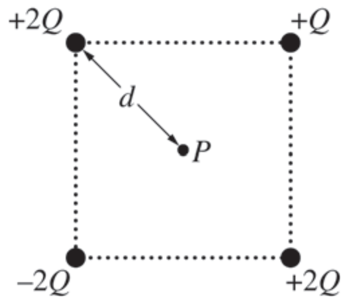
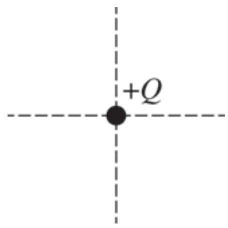


4. (10 points, suggested time 20 minutes)

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

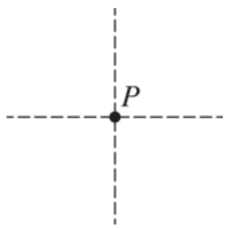
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.



(b)

i. Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P.

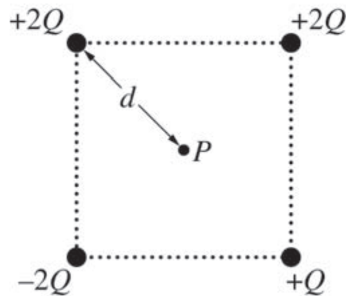
Draw Arrow



Calculate Electric Field

ii. Calculate the electric potential at point P due to all four objects.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.



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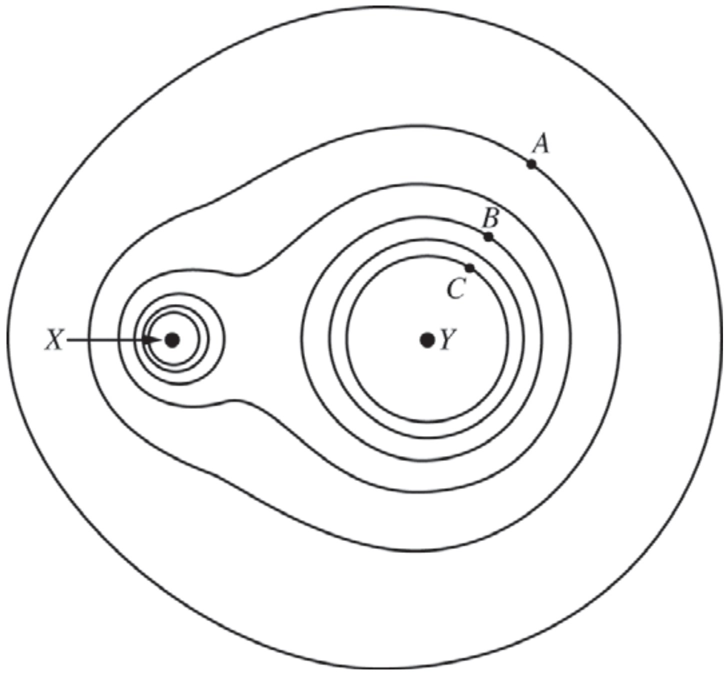
END OF EXAM



3. (12 points, suggested time 25 minutes)

The dots in the figure above represent two identical spheres, *X* and *Y,* that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere *Y* is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points *A* and *B*.

Potential at point *A* _______ Potential at point *B* _______

(b)

i. How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

ii. The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Let the potentials at the three labeled points be V_A , V_B , and V_C . A proton with charge $+q$ and mass *m* is released from rest at point *B*.

(c) Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

(d) At some time after being released from rest at point B, the proton has moved through a potential difference of magnitude 20 V.

i. Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.

ii. As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.

iii. Two students are discussing how and why the kinetic energy of the proton would change after it is released.

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.

10.6 Capacitors

Name: ____________ Class: ________ Date: __________ **Total: 11 marks**

KEY WORDS capacitor 电容器 • capacitance 电容 • conductor 导体

Objective

Build the skills to answer exam questions on **capacitors**.

You must be able to:

- describe a **capacitor 电容器** as two conductors storing equal and opposite charge
- apply the defining relation for **capacitance 电容**, $C = Q/V$
- relate a parallel-plate capacitor's capacitance to plate area and separation
- calculate the **energy stored** in a capacitor, $U = \frac{1}{2}CV^2$

1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ Capacitance

$C = \dfrac{Q}{V}$, measured in farads. A bigger capacitor stores more charge at the same voltage.

■ Parallel plates

Capacitance rises with a **larger plate area** and a **smaller separation**.

■ Energy stored

$U = \frac{1}{2}CV^2$. A 2.0 μF capacitor at 10 V: $Q = CV = 2.0 \times 10^{-5}$ C, $U = \frac{1}{2}(2.0 \times 10^{-6})(10)^2 = 1.0 \times 10^{-4}$ J.

2 Practice

2.1 A capacitor stores 6.0×10^{-4} C at 12 V. Find its capacitance. [2]

2.2 State how the capacitance changes if the plates are moved closer together. [1]

2.3 Find the energy stored in a 5.0 μF capacitor at 20 V. [2]

3 Exam-style questions

3.1 Capacitance is defined as [1]

- **A** QV
- **B** Q/V
- **C** V/Q
- **D** $\frac{1}{2}QV$

3.2 The energy stored in a capacitor is [1]

- **A** CV
- **B** $\frac{1}{2}CV^2$
- **C** Q/V
- **D** QV^2

3.3 A 100 μF capacitor is charged to 50 V.

(a) Find the charge stored. [2]

(b) Find the energy stored. [2]

Solutions

2.1 $C = \dfrac{Q}{V} = \dfrac{6.0 \times 10^{-4}}{12} = 5.0 \times 10^{-5}$ F.

2.2 it increases (smaller separation gives larger capacitance).

2.3 $U = \frac{1}{2}CV^2 = \frac{1}{2}(5.0 \times 10^{-6})(20)^2 = 1.0 \times 10^{-3}$ J.

3.1 **B**.

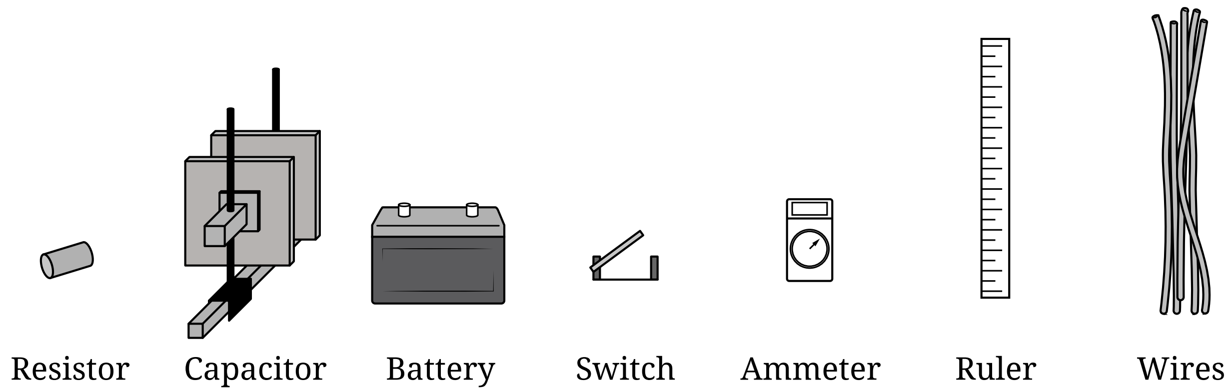
3.2 **B**.

3.3 (a) $Q = CV = (100\times10^{-6})(50) = 5.0\times10^{-3}$ C. (b) $U = \frac{1}{2}CV^2 = \frac{1}{2}(100\times10^{-6})(50)^2 = 0.125$ J.

Question 3

3. In Experiment 1, a student is given a resistor of unknown resistance and an air-filled parallel-plate capacitor of unknown capacitance. The student is asked to predict the expected time constant τ of a circuit if these two circuit elements were connected in series with a battery. The student has access to a battery of known emf, a switch, an ammeter, a ruler, and wires, as shown in Figure 1. The plates of the capacitor are square, and the separation between the plates is small compared to the dimensions of the plates. The capacitor is initially uncharged. Assume that the dielectric constant of air is 1.

Figure 1



Note: Figure not drawn to scale.

A. Describe a procedure for collecting data that would allow the student to determine the expected time constant τ. In your description, include the measurements to be made. Include any steps necessary to reduce experimental uncertainty.

B. Describe how the collected data could be analyzed to determine τ. Include references to appropriate equations and to relationships between measured and known quantities.

C. In Experiment 2, the student is asked to determine the capacitance C of a new parallel-plate capacitor. For each trial, the absolute value $|\Delta V|$ of the potential difference across the capacitor is varied and the charge q stored on one plate of the fully charged capacitor is measured. Table 1 contains the data collected.

Table 1

$\lvert\Delta V\rvert$ (V)	$q\ (\times 10^{-10}\ \text{C})$
3.0	2.4
5.0	4.2
7.2	5.6
8.0	6.6
10.0	8.0

i. **Indicate** two quantities, either measured quantities from Table 1 or additional calculated quantities, that could be graphed to produce a straight line that could be used to determine C.

Vertical axis: ______ Horizontal axis: ______

ii. On the grid provided, create a graph of the quantities indicated in part C (i).

- Use Table 2 to record the measured or calculated quantities that you will plot.
- Clearly **label** the axes, including units as appropriate.
- **Plot** the points you recorded in Table 2.

iii. **Draw** a best-fit line for the data graphed in part C (ii).

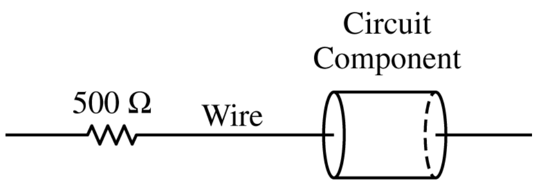
D. Using the best-fit line that you drew in part C (iii), **calculate** an experimental value for capacitance C.

2. (12 points, suggested time 25 minutes)

Students are given an unknown circuit component that is connected in series to a resistor with known resistance $500\,\Omega$.

(a) The students are asked to experimentally determine whether the component is a resistor or an uncharged capacitor.

i. Complete the following diagram to show how to use standard circuit equipment to determine whether the component is a resistor or an uncharged capacitor.



ii. Describe an experimental procedure to determine whether the component is a resistor or an uncharged capacitor. Refer to the circuit equipment in the diagram drawn in part (a)(i).

iii. What results would the students expect if the component is an uncharged capacitor? Support your answer in terms of potential difference and charge.

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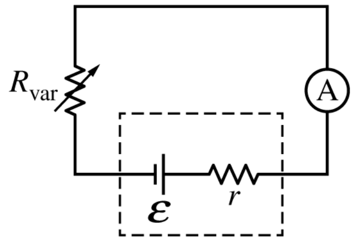
Continue your response to **QUESTION 2** on this page.



The students conduct a different experiment to determine the emf $\mathcal{E}$ of a battery that is not ideal and has internal resistance $r = 30\,\Omega$. The battery is connected to a variable resistor in a circuit, as shown. The students measure the current I through the circuit for different values of resistance R_{var} of the variable resistor that is connected to the battery. The following table contains the data collected.

I (A)	R_{var} (Ω)		
0.087	200		
0.060	300		
0.042	450		
0.027	700		
0.016	1200		

(b)

i. Write an equation describing the circuit in terms of $\mathcal{E}$, I, r, and R_{var}.

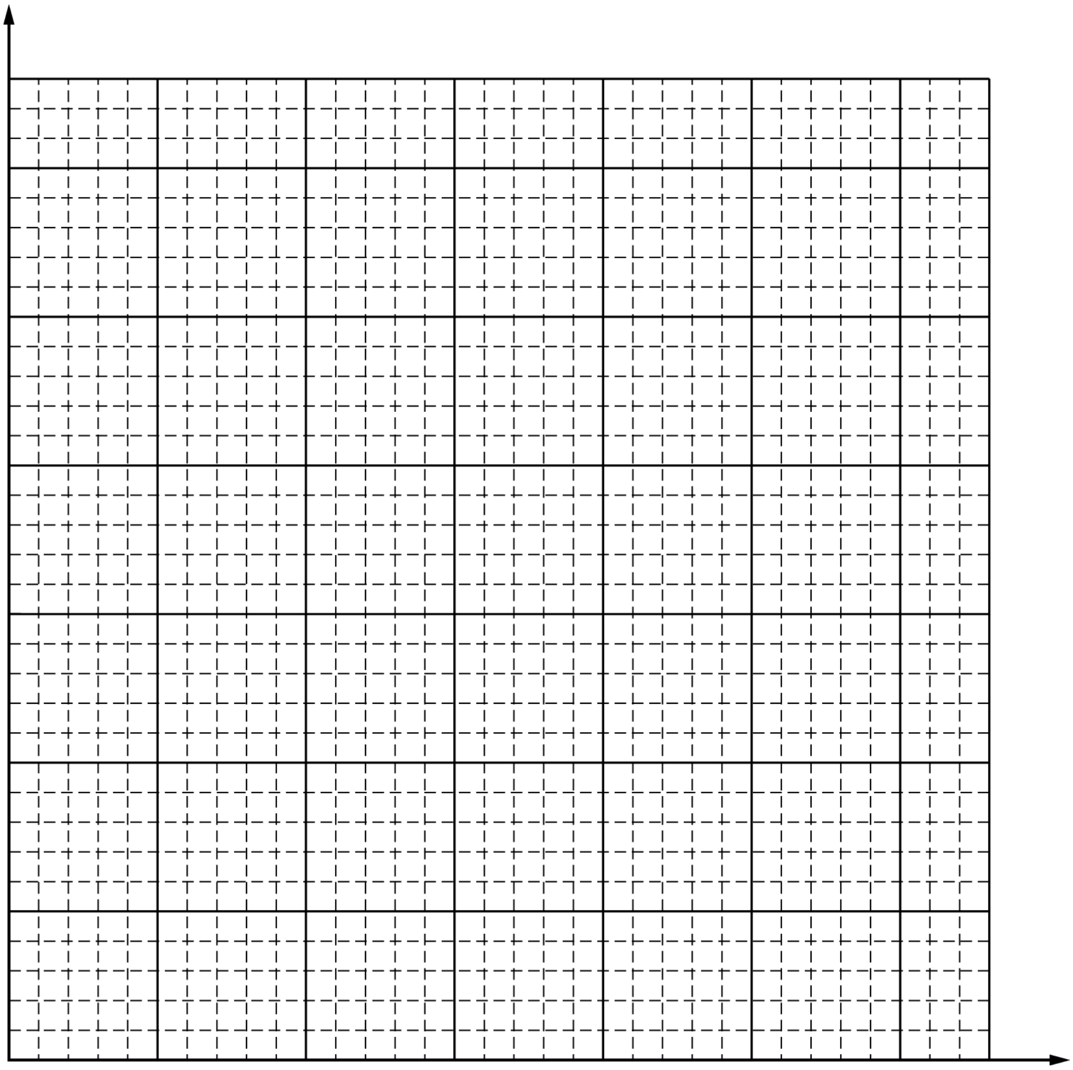
ii. Which quantities could be graphed to yield a straight line that could be used to calculate a numerical value for the emf $\mathcal{E}$ of the battery?

Horizontal Axis:________________ Vertical Axis:________________

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 2** on this page.

iii. Plot the data points for the quantities indicated in part (b)(ii) on the following graph. Clearly scale and label all axes, including units. Draw a straight line that best represents the data.
You may use the blank columns in the table for any quantities you graph other than the given data.



iv. Using the graph from part (b)(iii), determine the emf $\mathcal{E}$ of the battery.

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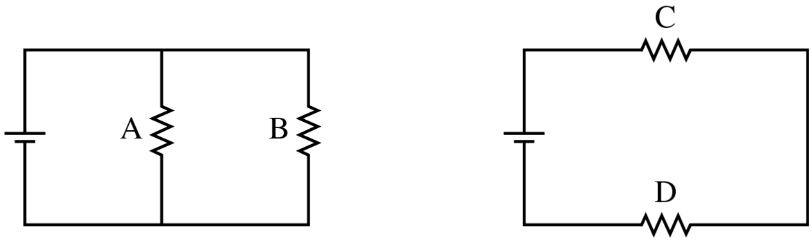
Begin your response to **QUESTION 2** on this page.



2. (12 points, suggested time 25 minutes)

Students perform an experiment with a battery and four resistors, A, B, C, and D. The resistance of resistors A and C is $R_A = R_C = R$. The resistance of resistors B and D is $R_B = R_D = 2R$. The students create the two circuits shown above and measure the potential differences ΔV_A, ΔV_B, ΔV_C, and ΔV_D across resistors A, B, C, and D, respectively.

(a) From greatest to least, rank the magnitudes of the potential differences across the resistors. Use "1" for the greatest magnitude, "2" for the next greatest magnitude, and so on. If any potential differences have the same magnitude, use the same number for their ranking.

____ΔV_A ____ΔV_B ____ΔV_C ____ ΔV_D

Justify your answer.

In another experiment, the students have a capacitor with unknown capacitance C_U. They want to determine C_U by using a battery of potential difference 4.5 V and several other capacitors of known capacitance. They create circuits with the battery, the unknown capacitor, and one of the capacitors of known capacitance. The students wait until the capacitors are fully charged and then record the potential difference ΔV_{known} across the known capacitor and the potential difference ΔV_U across the unknown capacitor. Their data are shown in the table on the following page.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 2** on this page.

Known Capacitance of Capacitors (μF)	ΔV_{known} (V)	ΔV_U (V)		
200	0.91	3.53		
300	0.65	3.74		
400	0.51	3.95		
500	0.42	4.06		
600	0.36	4.17		

(b)

i. Calculate the amount of charge on the capacitor of known capacitance of 200 μF in the students' experiment.

ii. Briefly explain why the data in the table provide evidence that the capacitors are connected in series.

iii. Briefly explain why connecting the capacitors in parallel would not provide enough information to determine the capacitance of the unknown capacitor if the only measuring device available is a voltmeter.

GO ON TO THE NEXT PAGE.

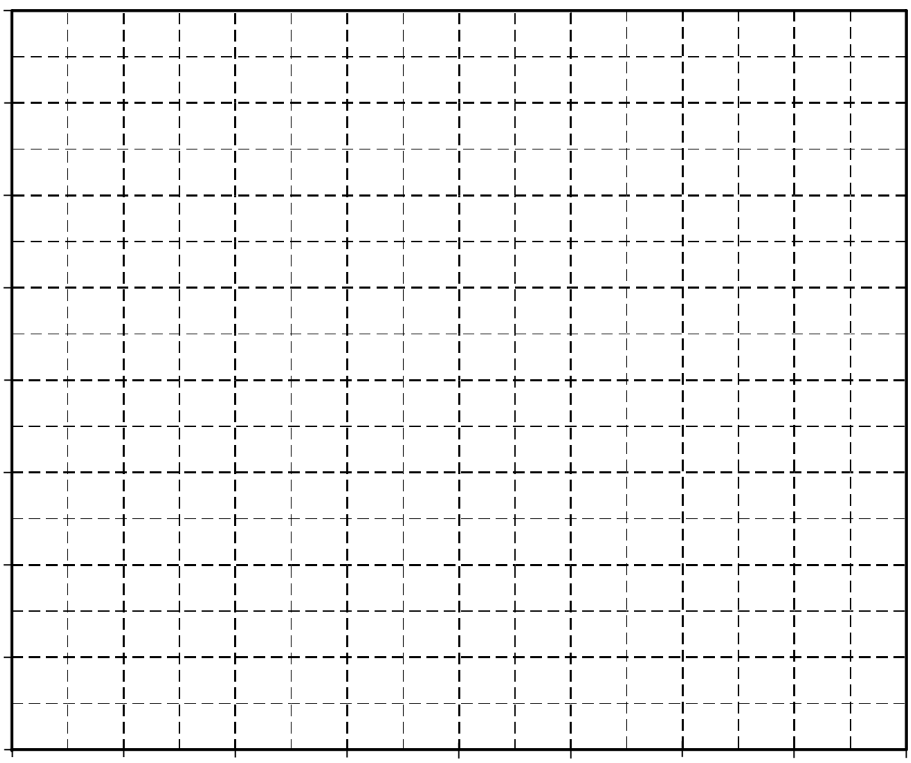
Continue your response to **QUESTION 2** on this page.

(c) The students want to produce a linear graph of the data so that the capacitance C_U of the unknown capacitor can be determined from the slope of the best-fit line for the data.

i. Indicate two quantities that could be plotted to produce the desired graph. Use the empty columns of the data table in part (b) to record any values that you need to calculate.

Vertical axis ____________________ Horizontal axis ____________________

ii. Label the axes below and provide an appropriate scale with units. Plot the data points for the quantities indicated in part (c)(i) on the axes and draw a best-fit line.



iii. Using your best-fit line, determine the capacitance of capacitor C_U.

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4. (10 points, suggested time 20 minutes)

Some students are investigating the behavior of a circuit with four components in series: a resistor of resistance R, a capacitor of capacitance C, a battery with potential difference $\mathcal{E}$, and a switch. Initially, the capacitor is uncharged and the switch is open.

(a)

i. Determine the current in the resistor and the potential difference across the capacitor immediately after the switch is closed.

ii. Determine the current in the resistor and the potential difference across the capacitor a long time after the switch is closed.

(b) The switch is opened, the capacitor is discharged, and a second, identical capacitor is added to the circuit in series with the other components. The switch is then closed again.

i. A long time after the switch is closed, the energy stored in the single capacitor in the original circuit is U_1, and the total energy stored in the two capacitors in the new circuit is U_2. Calculate the ratio U_1/U_2.

ii. The two capacitors in series are to be replaced with a single capacitor that will have the same energy U_2. Indicate a plate area and a distance between the plates for the new capacitor, compared with one of the original capacitors, that will accomplish this. Support your reasoning using appropriate physics principles and/or mathematical models.

The students are then asked to design two circuits each containing a switch, a battery with a small internal resistance, a lightbulb, and a capacitor. In arrangement 1, the bulb should gradually light up after the switch is closed, becoming brightest after the switch has been closed a long time. In arrangement 2, the bulb should be brightest when the switch is first closed, getting dimmer with time, and going out completely when the switch has been closed for a long time.

(c) Using standard symbols, draw two circuit diagrams, one showing a possible circuit for arrangement 1 and the other showing a possible circuit for arrangement 2. Justify your circuit diagrams with a paragraph-length explanation referring to the properties of lightbulbs and capacitors in circuits and the conservation of energy and/or the conservation of charge.

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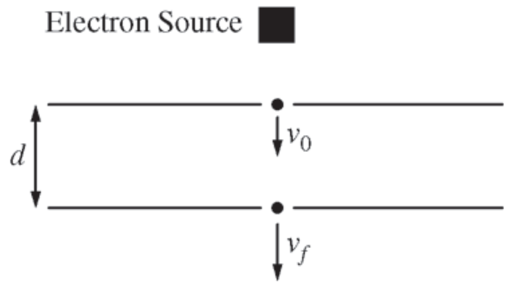
END OF EXAM



Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

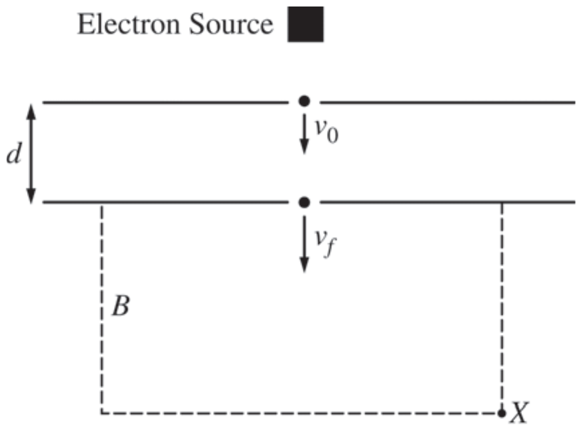
The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010\ \text{m}$. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6\ \text{m/s}$, take $1.49\ \text{ns}$ to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\ \text{m/s}$.

(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

(b) Calculate the magnitude of the electric field between the plates.

(c) Calculate the magnitude of the charge on each plate.

(d) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude B that is perpendicular to the page. The electrons then leave the magnetic field at point X.



Note: Figure not drawn to scale.

i. On the figure above, sketch the path of the electrons from the bottom plate to point X. Explain why the path has the shape that you sketched.

ii. Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

STOP

END OF EXAM

10.7 Conservation of Electric Energy

Name: ____________ Class: ________ Date: __________ **Total: 11 marks**

KEY WORDS conservation of energy 能量守恒 • electric potential 电势 • electric potential energy 电势能 • potential difference 电压 • capacitor 电容器

Objective

Build the skills to answer exam questions on **conservation of electric energy**.

You must be able to:

- apply **conservation of energy 能量守恒** to a charge accelerated through a potential difference
- relate the kinetic energy gained to the work done by the field, $\Delta KE = q\,\Delta V$
- analyse energy transfers in systems of charges, fields, and capacitors

1 Worked examples

Study these first. Each one shows the method for a question type used later.

Energy from a potential difference

A charge q moved through a potential difference ΔV has work $q\,\Delta V$ done on it, so $\Delta KE = q\,\Delta V$ if nothing else acts.

Accelerating a charge

An electron accelerated through ΔV gains kinetic energy $e\,\Delta V$; setting this equal to $\frac{1}{2}mv^2$ gives its speed.

Example

A +2.0 μC charge through 500 V: $\Delta KE = (2.0 \times 10^{-6})(500) = 1.0 \times 10^{-3}$ J.

2 Practice

2.1 A charge of 5.0×10^{-6} C moves through a potential difference of 200 V. Find the kinetic energy it gains. [2]

2.2 State the energy conversion when a charge accelerates through a potential difference. [1]

2.3 An electron ($q = 1.6 \times 10^{-19}$ C) is accelerated through 100 V. Find the kinetic energy it gains. [2]

3 Exam-style questions

3.1 A charge q accelerated through a potential difference ΔV gains kinetic energy [1]

- **A** $q\,\Delta V$
- **B** $q/\Delta V$
- **C** $\frac{1}{2}q\,\Delta V^2$
- **D** $\Delta V/q$

3.2 As a positive charge moves from high to low potential, its kinetic energy [1]

- **A** decreases
- **B** increases
- **C** stays constant
- **D** becomes zero

3.3 A proton ($q = 1.6 \times 10^{-19}$ C, $m = 1.67 \times 10^{-27}$ kg) is accelerated from rest through 1000 V.

(a) Find the kinetic energy it gains. [2]

(b) Find its final speed. [2]

Solutions

2.1 $\Delta KE = q\,\Delta V = (5.0 \times 10^{-6})(200) = 1.0 \times 10^{-3}$ J.

2.2 electric potential energy is converted into kinetic energy.

2.3 $\Delta KE = (1.6 \times 10^{-19})(100) = 1.6 \times 10^{-17}$ J.

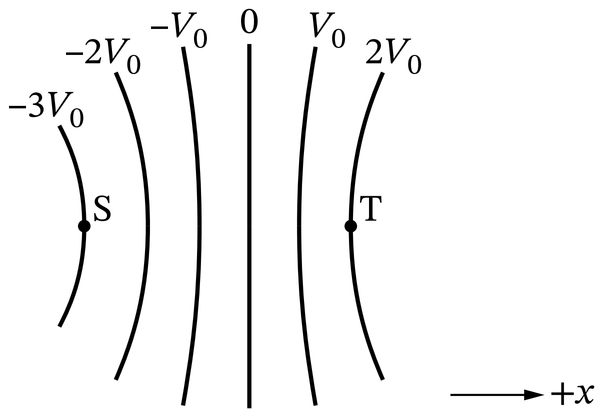
3.1 **A**.

3.2 **B**.

3.3 (a) $\Delta KE = q\,\Delta V = (1.6 \times 10^{-19})(1000) = 1.6 \times 10^{-16}$ J. (b) $\frac{1}{2}mv^2 = 1.6 \times 10^{-16} \Rightarrow$ $v = \sqrt{\dfrac{2(1.6 \times 10^{-16})}{1.67 \times 10^{-27}}} = 4.4 \times 10^5$ m s^{-1}.

Question 4

4. Equipotential lines for a region with an electric field are shown.



A small sphere (not shown) with positive charge $+Q$ has initial speed v_S in the $+x$-direction and kinetic energy K_S when the sphere is at Point S. The sphere moves to Point T. The force from the electric field is the only force that is exerted on the sphere as the sphere moves between Points S and T.

The sphere has final speed v_T and kinetic energy K_T when the sphere is at Point T.

Part A

Indicate whether v_T is greater than, less than, or equal to v_S. Include one of the following relationships in your response.

- $v_T > v_S$
- $v_T < v_S$
- $v_T = v_S$

Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Part B

Derive an expression for K_T in terms of V_0, Q, K_S, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Part C

A new, small sphere of the same mass as the original sphere but with negative charge $-Q$ has the same initial speed v_S as the original sphere in the $+x$-direction when the sphere is at Point S. The force from the electric field is the only force that is exerted on the new sphere as the new sphere moves between Points S and T. The new sphere has kinetic energy K_{new} when the new sphere is at Point T.

Indicate whether K_{new} is greater than, less than, or equal to K_T. Include one of the following relationships in your response.

- $K_{new} > K_T$
- $K_{new} < K_T$
- $K_{new} = K_T$

Briefly **justify** your answer by referencing your derivation in part B.

STOP

END OF EXAM

Begin your response to QUESTION 4 on this page.

(10 points, suggested time 20 minutes)

Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side length d, as shown. Point P is located equidistant from each vertex of the triangle.

Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed at the bottom-right vertex. The students make the following statements.

Student Y: “If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P.”

Student Z: “To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex.”

(a) In a coherent, paragraph-length response, evaluate the accuracy of each student’s statement. If any aspect of either student’s statement is inaccurate, explain how to correct the student’s statement. Support your evaluations using appropriate physics principles.

GO ON TO THE NEXT PAGE.

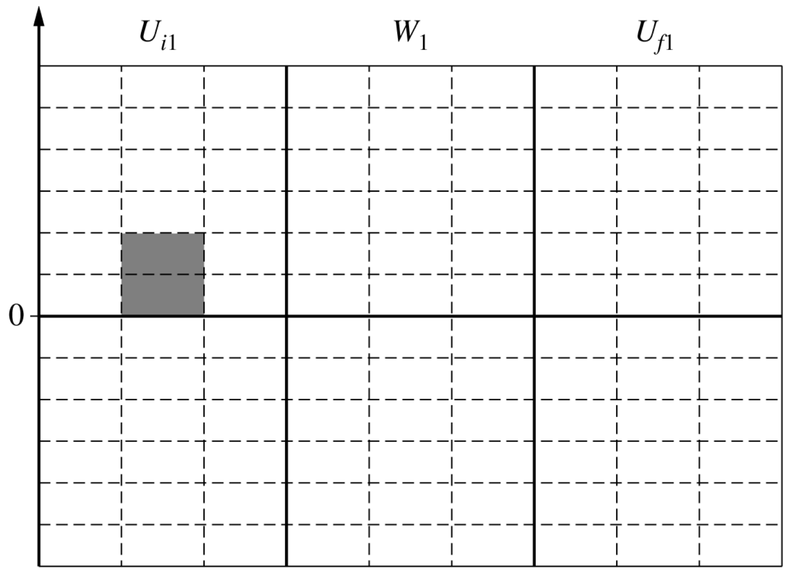
(b) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles when a third charged particle is brought from very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

i. In Scenario 1, a third particle with positive charge $+Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i1} of the system consisting of all three particles when the third particle with positive charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_1 required to move the third particle with positive charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f1} of the system consisting of all three particles when the third particle with positive charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 1

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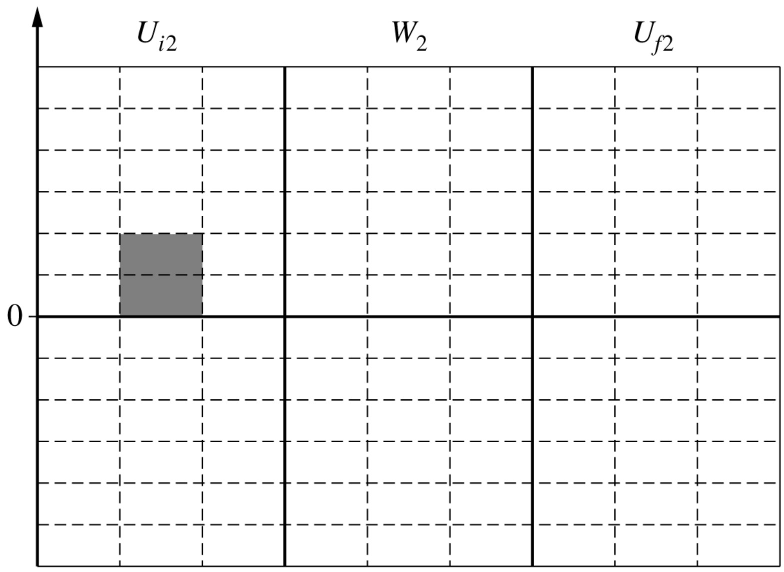
Continue your response to **QUESTION 4** on this page.

ii. In Scenario 2, a particle with negative charge $-Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i2} of the system consisting of all three particles when the particle with negative charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.



Scenario 2

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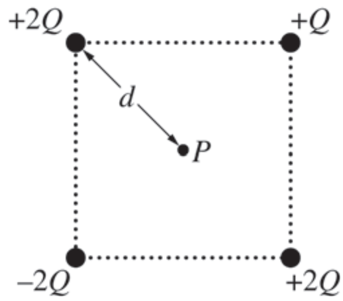
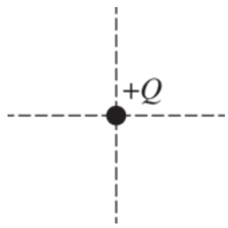
END OF EXAM



4. (10 points, suggested time 20 minutes)

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

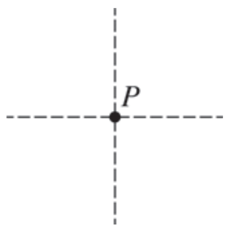
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.



(b)

i. Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P.

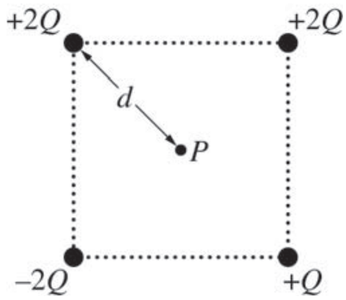
Draw Arrow



Calculate Electric Field

ii. Calculate the electric potential at point P due to all four objects.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.



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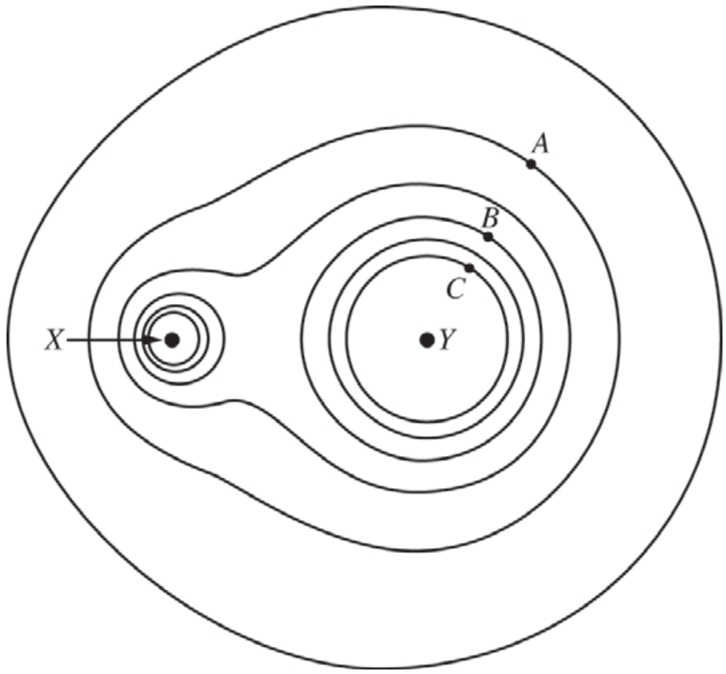
END OF EXAM



3. (12 points, suggested time 25 minutes)

The dots in the figure above represent two identical spheres, X and Y, that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere Y is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points A and B.

Potential at point A _______ Potential at point B _______

(b)

i. How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

ii. The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Let the potentials at the three labeled points be V_A, V_B, and V_C. A proton with charge $+q$ and mass m is released from rest at point B.

(c) Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

(d) At some time after being released from rest at point B, the proton has moved through a potential difference of magnitude 20 V.

i. Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.

ii. As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.

iii. Two students are discussing how and why the kinetic energy of the proton would change after it is released.

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.