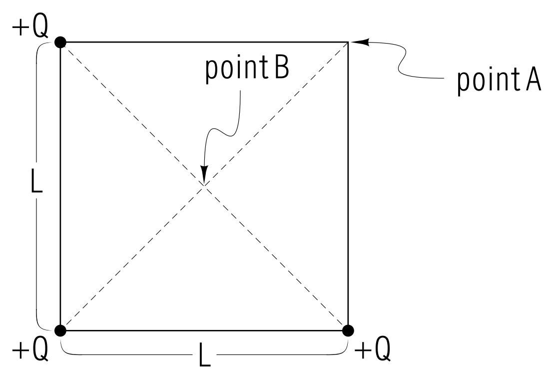
MISN-0-117

PARTICLE ENERGY IN AN ELECTROSTATIC FIELD



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PARTICLE ENERGY IN AN ELECTROSTATIC FIELD

by

J. Kovacs and P. Signell

Title: **Particle Energy in an Electrostatic Field**

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Input Skills:

1. Vocabulary: Coulomb's law (MISN-0-114); electrostatic field (0-115); conservative force field (0-21); electrostatic potential, volt (0-116); power, work, kinetic energy (0-20); rest mass (0-23).
2. Use the work-energy principle to calculate the change in kinetic energy of a particle acted on by conservative and non-conservative forces (MISN-0-20).
3. Determine the work done by an electrostatic field on a charged particle moving between two points, given the potential difference between those two points (MISN-0-116).

Output Skills (Knowledge):

K1. Vocabulary: ampere, battery, electric current, electron-volt, power (electrical).

Output Skills (Problem Solving):

S1. Use the conservation of energy to calculate the kinetic energy or speed of a charged particle when that particle falls through a given potential difference.

S2. Express the energy and mass of a particle in electron-volts (eV), million-electron-volts (MeV) and other multiples-of-a-thousand of the electron-volt.

S3. Calculate the power requirements associated with energy transfers from an electric field to particles for a beam of charged particles.

Post-Options:

1. "Conductivity and Resistance" (MISN-0-118).
2. "Examining the Charge Carriers: The Hall Effect" (MISN-0-149).

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1. Introduction

1a. Applying Conservation of Energy. The electrostatic field is much like the gravitational field, so the idea of conservation of energy that proved so useful in solving gravitational problems can be similarly used in solving electrostatic problems. Of course the force constant is different for gravitation and electrostatics, and the electrostatic force can be repulsive as well as attractive. However, the radial dependence of the two forces is the same and both are independent of the velocities of the interacting objects. This means that potential energy is a unique quantity for both, and that total energy is conserved for both. There is a difference in that in the gravitational case a mass always "falls" in the direction of the gravitational field, whereas in the electrostatic case a positive charge "falls" in the direction of the electric field but a negative charge "falls" in the opposite direction. Of course as either particle "falls" its potential energy decreases and its kinetic energy increases to keep its total energy constant.

1b. Force, Electric Field, Potential, Potential Energy. The terms "force," "electric field," "potential difference," and "potential energy difference" refer to four different concepts.

A non-zero value for "force" requires that a particle be present that is experiencing the force. Thus we say "the force on particle A is ...."

A non-zero value for "electric field" refers to a value at a point of space, whether a particle is there or not. Thus we say "the electric field at point A is ...."

A non-zero value for the "potential difference" between two points in space is the work per unit charge that must be expended to move a small "test" charge from one of the two points to the other.

A non-zero value for the "potential energy difference" refers to two points in space plus a specific particle: the value is the work that must be done to take the particle from one of the two points to the other.

As a specific example, the potential difference between space-points A and B might be 9.2 J/C and the electric field at A might be, say, 7.4 N/C.

⊳ Show that the potential energy difference between those two points for a particle with charge 0.1 C would be 0.92 J and the force on the particle when at A would be 0.74 N.

Since a joule per coulomb is also called a "volt," the potential difference could be quoted as 9.2 V and the electric field could be quoted as 7.4 V/m.

⊳ Show that an electron would have a potential energy difference of 9.2 electron-volts between the two points and would experience a force of 7.4 electron-volts per meter at point A (of course these values could also be stated in J and N).

1c. Potential Energy and Potential Energy Difference. A definite value for a particle's *kinetic* energy allows you to calculate that particle's speed, but a definite value for the particle's *potential* energy, by itself, tells you nothing. You must know where the potential energy is defined to be zero or else you must know the *potential difference* through which the particle has moved since its characteristics were last known. For example, it is meaningful to ask how much the particle's speed *changes* when its potential energy *changes* by a specified amount just as it is meaningful to ask how much a particle's speed changes when it falls from one altitude to another.

2. Energy Conservation

2a. Electrostatic Fields Conserve Energy. Because the force exerted on a charged particle by an electrostatic field is conservative, the electrostatic potential energy plus the kinetic energy for the charged particle in the electrostatic field is a constant, provided no other forces act on the particle.

2b. Gravitational Field and Potential. As a guide to defining electrostatic potential energy, we here review the reasoning we use in the gravitational case. As a concrete example, consider raising a mass from a point A above the floor to a point B that is higher above the floor. As we do work on the mass in raising it, the mass's gravitational potential energy increases. That is, we do positive work on the system and we increase its potential energy in moving it from point A to point B:[1]

$$\text{grav'l pot. energy diff.} \; = W_{\text{us on mass, } B\leftarrow A} = \int_A^B \vec{F}_{\text{us on mass}} \cdot d\vec{r}\,. \quad (1)$$

We now define the "gravitational potential difference" in going from point A to point B, $V_{\text{grav},BA}$, as the potential energy difference per unit mass in moving a small "test" mass from point A to point B, and we define the gravitational field at a point A in space, $\vec{\mathcal{G}}(\vec{r}_A)$, as the force per unit mass on a small "test" mass placed at point A. Then Eq. (1) can be written:

$$V_{grav,BA} = -\int_A^B \vec{\mathcal{G}} \cdot d\vec{r}\,, \quad (2)$$

where we have used the fact that the gravitational force on the mass is equal but opposite to the force we exerted on it as we raised it higher above the floor. Since signs are important, we now switch away from the ambiguous term "the potential difference between A and B" and start calling the same quantity "the (gravitational) potential at point B with respect to point A." We read Eq. (2) as "the (gravitational) potential at point B with respect to point A is the negative of the work per unit mass done by the field when a small "test" mass is taken from point A to point B."

▷ Check the signs in Eq. (2) by noting that when an object "falls" under the sole influence of gravity, so its motion is in the same direction as the field, the object's potential energy decreases while its kinetic energy increases.

2c. Electrostatic Field and Potential. In analogy with the gravitational case, we define the electric field at a point A as the force per unit charge on a small test charge placed at that point. We define the (electrostatic) potential of point B with respect to point A, V_{BA}, as the negative of the work per unit charge done by the field when a small test

[1]The relationship between the work integral and potential energy is the topic of MISN-0-21.

charge is taken from point A to point B:[2]

$$V_{BA} = -\int_A^B \vec{E} \cdot d\vec{r}\,. \quad (3)$$

▷ Check the signs in Eq. (3) by noting that when a positive charge "falls" from a point A to a point B under the sole influence of the electric field, its motion is in the same direction as the electric field so the charge's potential energy decreases while its kinetic energy increases.

2d. Conservation of Energy. With only conservative forces acting, a particle's total energy remains constant while it travels from some point A to some point B. Then:

$$\text{total energy at } A = \text{total energy at } B\,,$$

or:

$$\text{change in total energy } \; = 0\,.$$

Since the particle's total energy is the sum of its kinetic and potential energies, we can express its non-change in total energy this way:

$$\text{change in kinetic energy} + \text{change in potential energy} = 0\,.$$

This is usually written in a *delta notation* where the Greek letter Δ denotes the words "change in"[3] and we use the symbols $E_{\rm k}$ and $E_{\rm p}$ to refer to the particle's kinetic and potential energies, respectively:

$$\Delta E_{\rm k} + \Delta E_{\rm p} = 0\,.$$

Assuming Q for the charge on the particle being moved from A to B, that expression can be written in terms of the change in potential:

$$\Delta E_{\rm k} + Q\Delta V = 0\,.$$

It is also interesting to put in the space-point designators explicitly,

$$E_{{\rm k},B} - E_{{\rm k},A} + QV_{BA} = 0\,,$$

[2]Professionals in science and technology describe V_{BA} in various ways:

- "V_{BA} is the potential of B with respect to A."
- "V_{BA} is the potential difference between point B and point A."
- "V_{BA} is the potential of point B with A as the reference point."
- "V_{BA} is the voltage at point B with point A as ground."

[3]The "change in" a quantity is here defined as the quantity's final value minus its initial value, just as in Mechanics, Heat, etc.

and solve for the kinetic energy at point B:

$$E_{k,B} = E_{k,A} - QV_{BA}\,. \tag{4}$$

Think about what Eq. (4) says: the kinetic energy of the particle at point B is the kinetic energy it had at point A minus the change in its electrostatic potential energy in going from A to B. Fow example: if the particle went "down hill" in terms of its potential energy, so the change in potential energy was negative, then the particle gained kinetic energy.

▷ Determine that a proton, starting from rest and falling through a potential difference[4] of 100 volts, will acquire a kinetic energy of 1.6×10^{-17} J. This may seem to be a very minute amount of energy, which it is. However, because the proton's mass is quite small (compared with masses we commonly encounter in the macroscopic world) it acquires a speed of 1.38×10^5 m/s, a relatively large speed (for the proton's characteristics see the Appendix or the Glossary).

2e. Non-conservative Forces Do Not Conserve Energy. When non-conservative forces as well as the electrostatic field act on a particle, total particle energy (kinetic energy plus electrostatic potential energy) is no longer a constant. In such cases we must use the work-energy principle to determine how these non-conservative forces affect the energy of the particle. We often think of a non-conservative force as an "external agent," either adding energy to or taking energy from the system.

3. The Electron-Volt

3a. Atomic and Subatomic Energies. As the illustrative calculation at the end of Sect. 1b hinted, the *joule* is awkwardly large to use as a unit of energy for the energies that atomic and subatomic particles normally have. It's as awkward for those cases as it would be to have the earth's mass as the standard unit of mass, where a 160 pound person's mass would be expressed as 1.21×10^{-23} earth masses. For atomic particles, such as the proton and the electron, it is more convenient to use the much smaller unit of energy called the electron-volt, abbreviated eV. The electron-volt is defined as the amount of energy an electron receives (or loses) when it moves between two points that differ in potential by one volt. Because this energy change is the electron's charge times a potential difference [see Eq. (1)] we can see that this amount of energy in joules is

$$1\,\text{eV} = Q_{\text{electron}}(1\,\text{V}) = (1.602 \times 10^{-19}\,\text{C})(\text{V})\,,$$

[4]This describes going from a point of higher potential to one of lower potential.

$$1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}\,,$$

and is numerically equal to the electronic charge in coulombs. For the numerical example encountered at the end of Sect. 2d, the more convenient answer would have been that the proton acquired a kinetic energy of 100 eV.

3b. Atomic and Subatomic Masses. The rest mass of atomic and subatomic particles is also commonly expressed in energy units for which the electron-volt is again convenient. Recall that the energy associated with a mass m is mc^2, where c is the numerical value of the speed of light.[5] The rest mass of the proton is 1.67×10^{-27} kg and its rest energy is 1.50×10^{-10} J. Expressed in electron-volts the rest energy is 9.38×10^8 eV or 938 million electron-volts (MeV), so the rest mass of the proton is $938\,\text{MeV}/c^2$. Similarly, the electron's rest mass is $0.511\,\text{MeV}/c^2$. The elementary particles, which are considered the building blocks of all matter, when referred to, commonly have their masses given in the above units.

4. Accelerating a Stream of Particles

4a. Electrons Are Accelerated by a Potential Difference. If an electron traverses a gap, across which there is a potential difference of 6 volts, the electron gains 6 electron-volts of energy. We assume that the potential difference across that gap is maintained by some external source regardless of whether the electron is present and traverses the gap or not.[6] If many electrons traverse the gap in a given unit of time the power[7] required to accelerate the electrons is determined directly from the amount of energy each electron gains and the number of electrons per second that are accelerated. The number of electrons per second being accelerated is usually expressed in charge units rather than an actual count of electrons. This is referred to as the "beam." If it is expressed as charge per unit time it is referred to as the beam "current." The SI unit of electric current is the "ampere" and it is one coulomb per second passing the point at which it is being measured. Related commonly used

[5]See "Relativistic Energies: Thresholds for Particle Reactions, Binding Energies."

[6]An electrostatic condenser or capacitor is an example of a potential difference maintained across a gap by virtue of separation of charge. Any charged particle leaking across the gap decreases the potential difference. An outside source of potential, a battery, must be used to provide the energy to maintain the potential difference. See (MISN-0-135) for a discussion of capacitors.

[7]See "Work, Kinetic Energy, Work-Energy Principle, Power" (MISN-0-20).

units: the milliampere, 10^{-3} amperes, and microamperes, 10^{-6} amperes.

▷ Each electron has a charge of -1.6×10^{-19} C. Show that in a one ampere current of electrons there are 6.24×10^{18} electrons passing any given space-point each second. *Help: [S-6]*

4b. Examples of Particle Accelerators. In an X-ray machine, a steady stream of fast moving electrons is needed to produce a steady beam of X-rays. The X-rays are produced when the electrons impinge upon and are stopped by a metal target. The X-rays' energy[8] comes from the kinetic energy the electrons had when they were stopped. Where did the electron energy come from? The electrons received their energy from the electric field as they traveled across a high voltage gap between a region of low potential to a region of high potential. (Note that electrons, being negatively charged, gain energy when they rise in potential). How much energy depends upon the current of particles. This above illustration is but one example of many involving the acceleration of particles by means of electric fields. Particle accelerators used in basic physics experiments, electron microscopes, and TV picture tubes are some others.

4c. Power Requirements of Particle Accelerators. We can determine the power requirements of such systems from the basic fact that energy must be conserved. If a current I of charged particles are accelerated by a potential difference V, as in the X-ray apparatus discussed earlier, then each unit of charge in the beam receives V energy as it traverses the potential drop. To get the energy acquired per second by the entire beam, we must multiply the energy acquired by a unit charge by the amount of charge per second in the beam, the current I. Consequently, the beam acquired power, energy per second, of $V \times I$. and this must be supplied by an external power source:

$$P = V\,I\,, \tag{5}$$

where P is the power required to maintain a beam-current I traversing a potential difference V.

Acknowledgments

Preparation of this module was supported in part by the National Science Foundation, Division of Science Education Development and Research, through Grant #SED 74-20088 to Michigan State University.We would like to thank Professor James Linnemmann for suggesting a number of improvements in this module.

[8]The energy associated with X-rays and other quanta of electromagnetic radiation is discussed in "Characteristics of Photons" (MISN-0-212) and "The Photoelectric Effect" (MISN-0-213).

Glossary

- **ampere**: the SI unit of electric current; one ampere is one coulomb per sec.

- **battery**: technically, a group of cells that can store energy chemically and release it electrically at a fairly constant potential difference. Most cells contribute about 1.5 V each, including lead-acid cells, carbon-zinc cells, alkaline cells, and gel cells, although rechargeables produce a slightly lower voltage. Thus a 1.5 V flashlight "battery" contains one cell, a 9 V "walkman" battery contains 6, and a normal 12 V car battery contains 8.

- **current**: for a beam, the amount of electric charge per second passing some point along the path of the beam.

- **electron**: an elementary particle, the common carrier of electricity in electric circuits. Each electron has a mass of $9.1093897 \times 10^{-31}$ kg and a charge of $-1.60217733 \times 10^{-19}$ C. Electrons are the sole constituents of the non-nucleus part of any except very rare atoms.

- **electron-volt**: a unit of energy equal to the energy acquired by an electron as it moves through a potential difference of one volt; abbreviated eV; eV $= 1.6 \times 10^{-19}$ J. By tradition, 10^6 eV is called "million electron volts," not "mega electron volts."

- **power (electrical)**: the rate at which energy is consumed in an electrical system, usually expressed as $P = dE/dt = VI$ where E is energy (not electric field) and V is the potential drop suffered by a beam of charged particles constituting an electric current I. If V is in volts and I is in amperes, P is in watts (joules per second). For power to be consumed, work must be done on the system or energy must be fed in from some other source (such as chemical energy from a battery).

- **proton**: one of the two main constituents (along with the neutron), of any atom's nucleus. A free proton is stable, in contrast to the neutron, but each is made up of three quarks. The proton has a mass of $1.6726231 \times 10^{-27}$ kg and a charge of $1.60217733 \times 10^{-19}$ C, a charge that is exactly equal and opposite to that of the electron.

- **test charge**: a charge sufficiently small so that its introduction at a point in space does not cause any change in the electric field at that point.
- **test mass**: a mass sufficiently small so that its introduction at a point in space does not cause any change in the gravitational field at that point.

PROBLEM SUPPLEMENT

Note: Problems 7 and 8 also occur in this module's *Model Exam*.

1. Calculate the kinetic energy in joules acquired by a proton starting from rest and falling through a potential difference of 150 volts. Also calculate the proton's final speed. *Help: [S-5]*

2. 

   A charge $Q_1 = -8.0 \times 10^{-6}$ C is located at $x = -0.50$ m, $y = 0.00$ m, and a charge $Q_2 = +4.0 \times 10^{-6}$ C is located at the point $x = +1.6$ m, $y = 0.0$ m. Due to the field set up by this system of charges:

   a. What is the potential difference between the origin ($x = 0$ m, $y = 0$ m) and the point $x = 0.0$ m, $y = +1.2$ m on the y-axis?

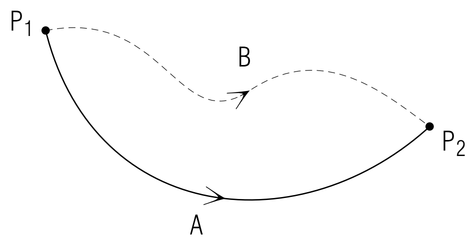
   b. Which point is at the higher potential?

   c. Suppose a charge $Q' = -2.0 \times 10^{-6}$ C goes from the origin to the point $x = 0.0$ m, $y = +1.2$ m. How much work is done by the electric field?

   d. If an external agent (you with a pair of tweezers?) took the charged particle Q' of part (c) from an infinite distance away (starting it at rest) and placed it (at rest) at the origin, determine the work that would have to be done by this external agent. *Help: [S-3]*

   e. If this same particle, Q', with mass= 0.0040 kg, had instead a speed of 1.0×10^1 m/s at the instant it got to the origin, then how much work would have been done by the external agent? *Help: [S-4]*

3. Express the answer to part (c) of Problem 2 in electron-volts (eV), and million electron-volts (MeV), and giga electron-volts (GeV).

4. 

Asume some point P_3 (not shown) as the reference point where the electrostatic potential is taken to be zero. A charged particle Q moves from point P_1 where the potential is V_1 to a point P_2 where the potential is V_2 along either path A or path B shown in the sketch above. It moves in such a way that its speed is negligible at both P_1 and P_2.

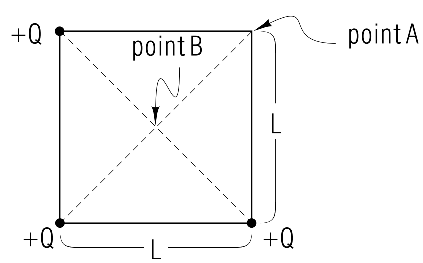
a. How much work is done by the electric field in going along path A?

b. Because there was no kinetic energy imparted to the charged particle, there must have been another force, applied by some external agent, acting on the particle. How much work was done by the external agent?

c. Repeat part (a) but for going from $P_1 \to P_2$ along path B.

d. Repeat part (b) but for path B.

e. Suppose the particle Q goes from $P_1 \to P_2$ along path A then from $P_2 \to P_1$ along path B, how much work is done by the field?

5. 

Three point charges, each of charge $Q = +3.00 \times 10^{-6}$ C are situated on three of the corners of a square of side $L = 0.200$ meters.

a. Calculate the mechanical work that must be done to move a charge $q = +5.0 \times 10^{-7}$ C from the other corner, point A, to the center of the square, point B.

b. Where does the energy for doing this work come from?

c. Where does the energy go if q is at rest both before it is moved from A and after it is at B?

d. Suppose charge q was at rest at point A and had a kinetic energy of 0.150 joules at point B. What is the total energy that must be expended to move this charge from A to B?

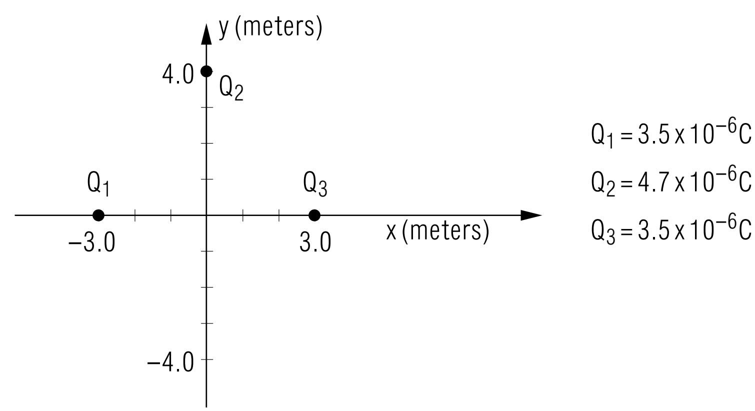
e. Where does this energy come from?

f. Where does it go?

6. A 10.0 milliampere beam of doubly-charged helium nuclei (alpha particles) was accelerated through a potential difference of 1.0×10^1 KV.

a. Determine the kinetic energy per beam particle after this acceleration. (Assume the α-particles start from rest. By "doubly-charged" is meant having twice the charge of the proton). Express your answer in joules and electron-volts.

b. How much power must be supplied to maintain such a process?

7. 

Three charges (Q_1, Q_2, and Q_3) are located on a cartesian axis as shown above. A fourth charge, $Q_4 = -2.8 \times 10^{-6}$ C, initially at rest at the point (0,-4), moves to the origin under the influence of the electrostatic field alone. Its mass is 7.3×10^{-8} kg.

a. Calculate the change in electrostatic potential energy of the particle.

b. What is the speed of the particle at the origin?

8. A beam of electrons is accelerated from rest through a potential difference of 15,000 V. The current of the beam is 2.5 mA.

a. What is the final kinetic energy of the electrons in the beam? Express your answer in joules and electron-volts.

b. Calculate the final speed of the electrons.

c. How much power is required to produce this current?

Brief Answers:

1. $E = 2.4 \times 10^{-17}$ J; $v = 1.7 \times 10^5$ m/s

2. a. 8.4×10^4 V *Help: [S-1]* (the answer is NOT 9.3×10^4 V)

   b. The point $y = 1.2$ m, $x = 0.0$ m is at the higher potential (both are at negative potential, but the point at $y = +1.2$ m is closer to zero potential).

   c. $+0.17$ J

   d. 0.24 J *Help: [S-2]*

   e. 0.44 J

3. 1.05×10^{18} MeV, 1.05×10^{12} MeV, 1.05×10^9 GeV

4. a. $Q(V_1 - V_2)$

   b. $Q(V_2 - V_1)$

   c. $Q(V_1 - V_2)$

   d. $Q(V_2 - V_1)$

   e. zero

5. a. 0.104 J (The answer is NOT negative.)

   b. From the external agent that moved q from A to B.

   c. Into the potential energy of the system, which increases.

   d. 0.254 J

   e. From the external agent.

   f. Into the potential energy of the system, which increases, and into the kinetic energy of the particle q, which also increases.

6. a. 3.2×10^{-15} J or 2.0×10^4 eV

   b. 1.0×10^2 watts

7. a. -3.8×10^{-2} J

   b. 1.0×10^3 m/s

8. a. 2.4×10^{-15} J or 15,000 eV (or 15 KeV)

   b. 7.3×10^7 m/s

   c. 38 W

SPECIAL ASSISTANCE SUPPLEMENT

S-1 *(from PS, problem 2)*

The sign of the potential difference depends on which difference you take.

S-2 *(from PS, problem 2d)*

Notice that the work done on the particle by the electric field is opposite in sign to the work done by the external agent.

S-3 *(from PS, problem 2d)*

If the particle starts at rest and ends up at rest, the net change in kinetic energy is zero. Then the work done by the external force, against the electrostatic force, is just the potential difference times the charge on the moved particle. The potential difference can be calculated straightforwardly using the method developed in *MISN-0-116*. If you still cannot get the answer: *Help: [S-7]*.

S-4 *(from PS, problem 2e)*

$W_{\rm total} = W_{\rm external} + W_{\rm field} = \Delta E_K$

S-5 *(from PS, problem 1)*

If you don't know where to find the characteristics of the proton, you did not read the text. Do it!

S-6 *(from TX, 4a)*

$$\text{current} \; = \frac{\text{charge}}{\text{time}} = \frac{\text{charge}}{\text{electron}} \times \frac{\text{electrons}}{\text{time}}$$

where the first fraction above should be read as "charge per unit time," the second fraction should be read as "charge per electron," and the third as "electrons (passing the point) per unit time." You should construct such equalities, as needed, without being told to.

S-7 *(from AS, S-3)*

$$W_{0,\infty} = (9.0\times10^{9}\,\mathrm{N\,m^2/C^2})(-2.0\times10^{-6}\,\mathrm{C})\cdot \left(\frac{-8.0\times10^{-6}\,\mathrm{C}}{0.5\,\mathrm{m}} + \frac{4.0\times10^{-6}\,\mathrm{C}}{1.6\,\mathrm{m}}\right)$$

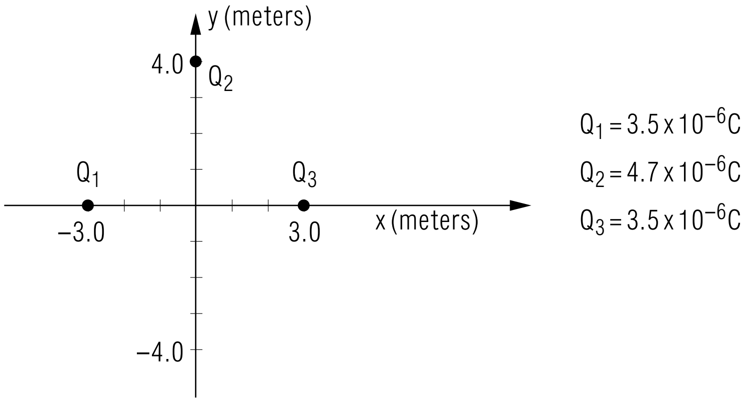
MODEL EXAM

$k_e = 8.99 \times 10^9\,\mathrm{N\,m^2/\,C^2}$; $m_{\text{electron}} = 9.11 \times 10^{-31}\,\mathrm{kg}$

$e = 1.6 \times 10^{-19}\,\mathrm{C}$; $eV = 1.6 \times 10^{-19}\,\mathrm{J}$

1. See Output Skill K1 in this module's *ID Sheet*.

2.



Three charges (Q_1, Q_2, and Q_3) are located on a cartesian axis as shown above. A fourth charge, $Q_4 = -2.8 \times 10^{-6}\,\mathrm{C}$, initially at rest at the point (0,-4), moves to the origin under the influence of the electrostatic field alone. Its mass is $7.3 \times 10^{-8}\,\mathrm{kg}$.

a. Calculate the change in electrostatic potential energy of the particle.

b. What is the speed of the particle at the origin?

3. A beam of electrons is accelerated from rest through a potential difference of 15,000 V. The current of the beam is 2.5 mA.

a. What is the final kinetic energy of the electrons in the beam? Express your answer in joules and electron-volts.

b. Calculate the final speed of the electrons.

c. How much power is required to produce this current?

Brief Answers:

1. See this module's *text*.

2. See Problem 7 in this module's *Problem Supplement*.

3. See Problem 8 in this module's *Problem Supplement*.