Physics 9 — Wednesday, November 7, 2018

- For Monday, you read Eric Mazur's chapter 22 (Electric Interactions) — PDF on Canvas.
- For today, you read Giancoli ch16 (electric charge & E field)
- HW help sessions: Wed 4–6pm DRL $\boxed{\textbf{4C2}}$ (Bill), Thu 6:30–8:30pm DRL 2C8 (Grace)

There were too many blank expressions on people's faces on Monday when we discussed the COP of a heat pump or fridge or A/C, so let's review the most important point.

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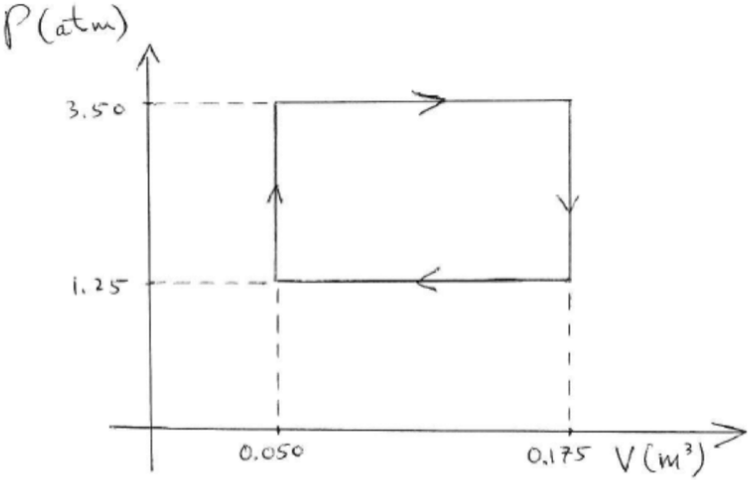
- What is the range of physically possible values for the efficiency of a heat engine?
- Can the COP of a heat pump be larger than one? Can the efficiency of an engine be larger than one?

One more confusing detail. In “US customary units,” instead rof directly using COP, one uses the (Seasonal) Energy Efficiency Ratio (SEER, or EER), where heat is measured in BTU, while work is measured in watt-hours.

Since a British Thermal Unit is 1055 J, a COP of 1.0 corresponds to an SEER of 3.4.

So if a very good COP value these days is around 4.0, then a very good SEER is around 13.6.

4*. The PV diagram for a certain (somewhat contrived, to keep the math simple) heat engine cycle is shown below. What is the efficiency ($\eta = (W_{\text{out}} - W_{\text{in}})/Q_{\text{in}}$) of this engine, if it exhausts $Q_{\text{out}} = 43.5$ kJ of thermal energy per cycle? (Remember 1 atm = 101325 N/m^2.)



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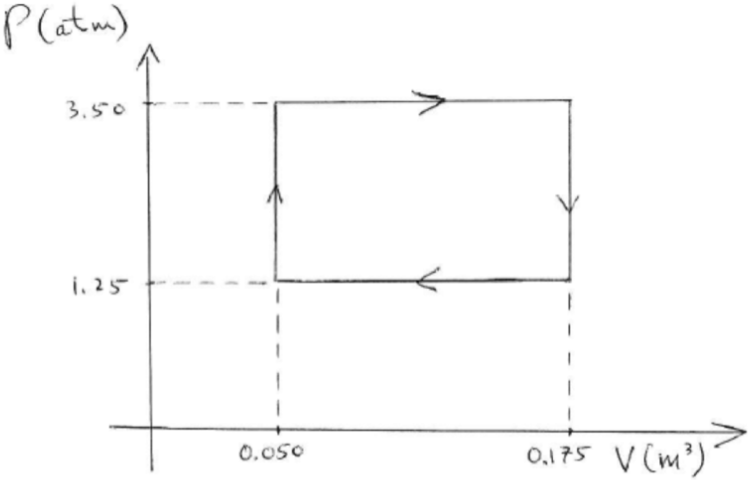

Answer: $W_{\text{out}} = 44.3$ kJ, $W_{\text{in}} = 15.8$ kJ,
$Qin = W_{\text{out}} + Q_{\text{out}} - W_{\text{in}} = 72.0$ kJ. $\eta = 0.396$.

In one cycle, a steady device transfers 1200×10^3 J of energy from a thermal reservoir at 600 K to a thermal reservoir at 300 K. (This is a pretty useless device: since $Q_{\rm out} = Q_{\rm in}$, we must have $W = 0$.) Find the change in entropy (after one complete cycle),

(a) For the device, and

(b) for the environment.

(Mazur writes $\Delta S = Q/(k_B T)$. Giancoli writes $\Delta S = Q/T$. Let's use Giancoli's convention here, since it makes the math easier.)

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Answer: $\Delta S_{\mathrm{env}} = \frac{Q_{\mathrm{output}}}{T_{\mathrm{output}}} - \frac{Q_{\mathrm{input}}}{T_{\mathrm{input}}} = \frac{1200\ \mathrm{kJ}}{300\ \mathrm{K}} - \frac{1200\ \mathrm{kJ}}{600\ \mathrm{K}} = 2000\ \mathrm{J/K}$

About HW problem 2 for HW08 (Reynolds number):

If **the same flow (volume per unit time)** of a fluid passes through both wide and narrow sections of the pipe/duct/river/etc., the narrow section is more likely to be turbulent, hence more likely to be noisy. If you only partially close off an HVAC duct, so that (approximately) the same air flow must pass (at higher speed) through a reduced area, the air flow makes more noise.

Reynolds number:

$$Re = \frac{2r\overline{v}\rho}{\eta} \propto r\overline{v}$$

Flow rate (volume/time):

$$Q = A\overline{v} = \pi r^2 \overline{v} \propto r^2 \overline{v}$$

Suppose $r_1 = R$, $\overline{v}_1 = V$, and $r_2 = 2R$. To get same flow, $Q_2 = Q_1$, you need $\overline{v}_2 = (V/4)$. Then

$$\frac{Q_2}{Q_1} = \frac{r_2^2\,\overline{v}_2}{r_1^2\,\overline{v}_1} = \frac{(2R)^2(V/4)}{(R)^2(V)} = 1$$

But

$$\frac{Re_2}{Re_1} = \frac{r_2\,\overline{v}_2}{r_1\,\overline{v}_1} = \frac{(2R)(V/4)}{(R)(V)} = \frac{1}{2}$$

Same flow through wider duct has smaller Reynolds number, so is less turbulent. Consistent with pictures of river. (This argument depends on same flow rate: if making the pipe bigger just allows a bigger flow, then you're not reducing turbulence.)

comparing electric and gravitational forces

- We learned at the beginning of the semester (and you probably also had learned in an earlier physics course) that the force of gravity:
  - is a field force that acts at a distance
  - is always “attractive” (never “repulsive”)
  - grows weaker with distance R, like $1/R^2$
  - is proportional to the product of the two masses
  - causes a dropped object to accelerate toward Earth’s center
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The gravitational force due to b acting ON a has magnitude

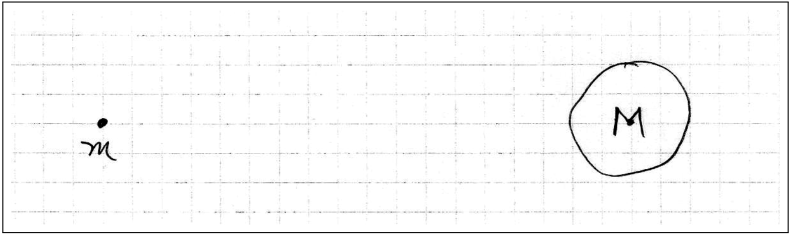
$$\vec{F}^{G}_{b,a} = G \, \frac{m_a \; m_b}{r_{ab}^2} \; \hat{r}_{ab}$$

The force acting ON a points from a toward b.

Object 1, of mass m, sits to the left of object 2, of mass M. The gravitational force between objects 1 and 2 has magnitude

$$F = \frac{GmM}{r_{12}^2}$$

where r_{12} is the distance between object 1 and object 2. What is the *direction* of the gravitational force **acting on object 1**? (Pretend that the objects are in outer space, so you can ignore Earth's gravity.)

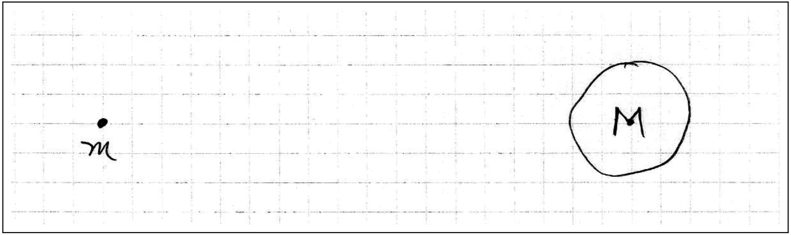


(A) up (B) down (C) right (D) left

Object 1, of mass m, sits to the left of object 2, of mass M. The gravitational force between objects 1 and 2 has magnitude

$$F = \frac{GmM}{r_{12}^2}$$

where r_{12} is the distance between object 1 and object 2. What is the *direction* of the gravitational force **acting on object 2**? (Pretend that the objects are in outer space, so you can ignore Earth's gravity.)



(A) up (B) down (C) right (D) left

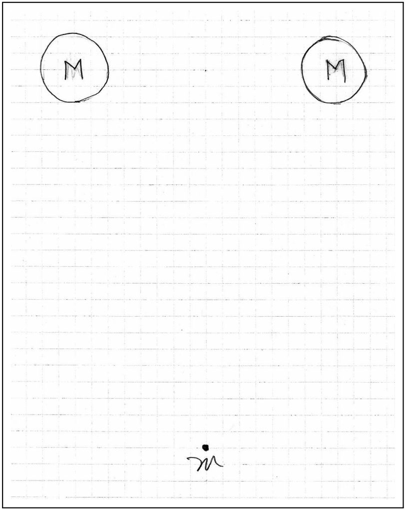
comparing electric and gravitational forces

The net gravitational force due to two objects b and c acting ON a is the vector sum of the individual forces ON a:

$$\vec{F}^{G}_{ON\ a} = G\,\frac{m_a\ m_b}{r^2_{ab}}\,\hat{r}_{ab} + G\,\frac{m_a\ m_c}{r^2_{ac}}\,\hat{r}_{ac}$$

where $\hat{r}_{ab}$ is the unit vector pointing from a toward b, and $\hat{r}_{ac}$ is the unit vector pointing from a toward c.

Objects 1 and 2, both of mass M, are at the top of the picture, separated from each other horizontally. Object 3, of mass m, is at the bottom of the picture, directly below the midpoint of objects 1 and 2. What is the direction of the gravitational force acting **on object 3** (the bottom object)? (Ignore Earth's gravity.)



(A) up

(B) down

(C) right

(D) left

(E) diagonal

comparing electric and gravitational forces

The electrical force:

- is a field force that acts at a distance
- can be either "attractive" or "repulsive"
- grows weaker with distance R, like $1/R^2$ (like gravity)
- is a long-range force, like gravity
- is proportional to the product of the two electric charges
- is what binds electrons to their atomic nuclei
- is stronger than gravity by a factor of roughly 10^{42} : that's 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000
- provides the energy content of food, fuel, chemical reactions
- is the underlying cause of everyday "contact" forces

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The electrostatic force due to b acting ON a is

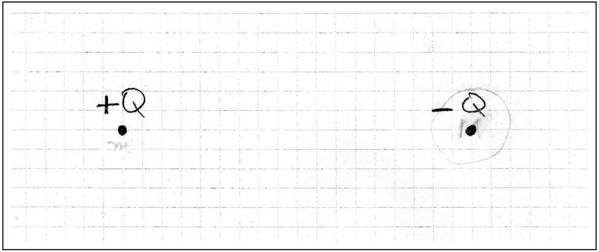
$$\vec{F}^{E}_{b,a} = -k\ \frac{q_a\ q_b}{r_{ab}^2}\ \hat{r}_{ab}$$

The force ON a points away from b for like charges and points toward b for opposite charges. (Opposites attract.)

Consider the two particles carrying identical electric charges (of the same sign), shown below. The force $\vec{F}^{E}_{12}$ (the force exerted BY 1 acting ON 2) points

(A) up (B) down (C) right (D) left (E) other direction

An object carrying positive charge, $+Q$, is placed to the left of an object carrying negative charge, $-Q$. The direction of the electrostatic force acting ON the left-hand charge is



(A) up (B) down (C) right (D) left (E) other direction

When the electric charge on each of two objects is doubled, the electric force between the two objects is

(A) The same.

(B) Doubled.

(C) Halved.

(D) Quadrupled.

(E) None of the above.

Two small objects are placed a large distance apart. Each object carries a positive charge. If the distance between the two objects is tripled, then the strength of the electrostatic repulsion between them will decrease by a factor of

(A) 3

(B) 6

(C) 8

(D) 9

(E) 12

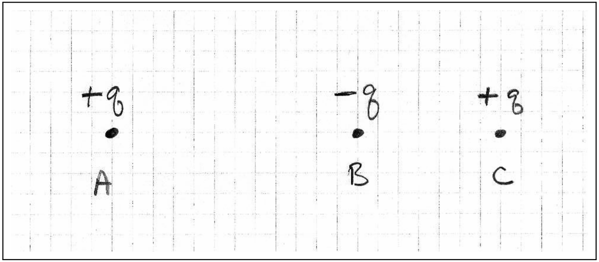
comparing electric and gravitational forces

The net electrostatic force of due to two objects b and c acting ON a is the vector sum of the individual forces ON a:

$$\vec{F}^{E}_{ON\ a} \;=\; -\,k\,\frac{q_a\;q_b}{r_{ab}^2}\,\hat{r}_{ab} \;-\; k\,\frac{q_a\;q_c}{r_{ac}^2}\,\hat{r}_{ac}$$

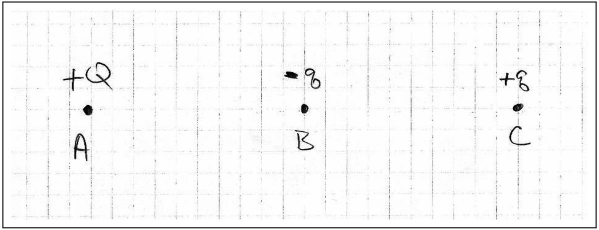
where $\hat{r}_{ab}$ is the unit vector pointing from a toward b, and $\hat{r}_{ac}$ is the unit vector pointing from a toward c.

Three charged objects, A,B,C, are placed in a horizontal row. Objects A and C are positively charged. Object B is negatively charged. All three charges have the same magnitude. What is the direction of the electric force exerted on object A ?



(A) up (B) down (C) right (D) left (E) zero (cancels)

Three charged objects, A,B,C, are placed in a horizontal row, equally spaced. Object B is negatively charged. Objects A and C are positively charged. The charge on object A is much larger than the charges on objects B and C. What is the direction of the electric force exerted on object B ?



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Electrostatic forces

i.e. forces due to electric charges that are not in motion

The electrostatic force due to b acting ON a is

$$\vec{F}^{\text{electric}}_{b\ ON\ a} = k\ \frac{q_a\ q_b}{r_{ab}^2}\ \hat{r}_{b\to a}$$

(or in Mazur's more abbreviated notation)

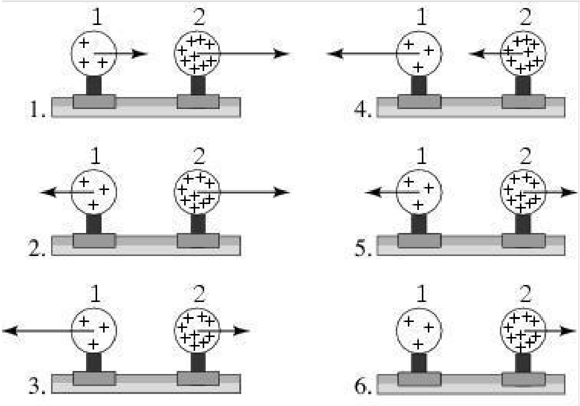
$$\vec{F}^{E}_{ba} = k\ \frac{q_a\ q_b}{r_{ab}^2}\ \hat{r}_{ba}$$

where $k = 9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}$.

The force ON a points away from b for like charges and points toward b for opposite charges. (Opposites attract, likes repel.)

(Ask yourself how you would rewrite this equation to get the force due to a acting on b.)

Two uniformly charged spheres are firmly fastened to (and electrically insulated from) frictionless pucks on an air table. The charge on sphere 2 is three times the charge on sphere 1. Which force diagram correctly shows the magnitude and direction of the electrostatic forces?



(A) 1 (B) 2 (C) 3 (D) 4 (E) 5 (F) 6 (G) none

How would you change the last picture if both spheres were negatively charged?

How would you change the last picture if one sphere were positively charged and one were negatively charged?

- Matter is made up of atoms: positively charged nuclei (protons and neutrons), surrounded by a cloud of electrons.
- Elementary charge $e = 1.6 \times 10^{-19}\ \mathrm{C}$.
- Proton has positive charge $(+e)$. Neutron is uncharged (electrically neutral). Electron has negative charge $(-e)$.
- In an insulator (glass, plastic, rubber, cloth, etc.), electrons tend to be stuck to their own atoms.
- In a solid conductor (e.g. metal), electrons can freely move around within the conductor, whereas the positive ions are fixed in place in a lattice-like pattern.
- In a liquid conductor (e.g. impure water), positive and negative ions can both move around freely.
- Chemical bonds involve the transfer of electrons from one atom to another, or the sharing of electrons between atoms.
- When a chemical bond is formed between two unlike materials, electrons tend to be more closely attracted to one kind of atom than the other.
- If you rub unlike insulators together, you transfer some electrons to whichever material more closely attracts electrons.

- http://en.wikipedia.org/wiki/Triboelectric_effect
- fur + plastic leaves negative charge on plastic
- cotton + acrylic leaves positive charge on acrylic
- Rubbing just about any other insulating material against a rubber balloon leaves negative charge on the rubber balloon!

- Only a tiny fraction of the electrons are transferred, but this tiny fraction results in a *surplus* of electrons on one material and a surplus of positive ions on the other material.

- Surplus electrons deposited on an insulator are stuck where they were deposited, unless you rub them off.
- But surplus electrons deposited on a conductor will spread out, to try to get as far away from one another as possible.
- Since your body contains a lot of water (but not pure water), you are a pretty good conductor (but dry skin is an insulator). So surplus electrons deposited on me will try to spread out as far as possible!

Triboelectric series (who knew?!)

most positively charged
air
human skin (dry)
leather
rabbit fur
glass
quartz
mica
human hair
nylon
wool
lead
cat fur
silk
aluminum
paper
(small positive charge)

(small negative charge)
wood
rubber balloon
resins
hard rubber
nickel, copper
brass, silver
gold, platinum
synthetic rubber
polyester
styrofoam
plastic wrap
scotch tape
vinyl
teflon
silicone rubber
most negatively charged

Be sure to put a “handle” on the end of your bottom piece of tape, so that it is easy to remove it from your desk at the end of class. If we leave tape stuck to the desks at the end of class, the housekeeping folks may put an end to our experiments . . . .

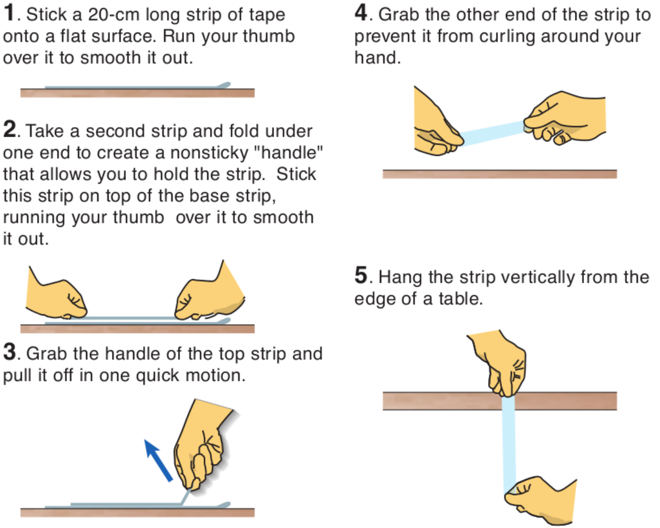


Figure 22.3 Procedure for making strips of transparent tape that interact electrically. The lower strip is used to provide a standard surface—the top side of a piece of tape — because surface properties may vary from one tabletop or desktop to another.

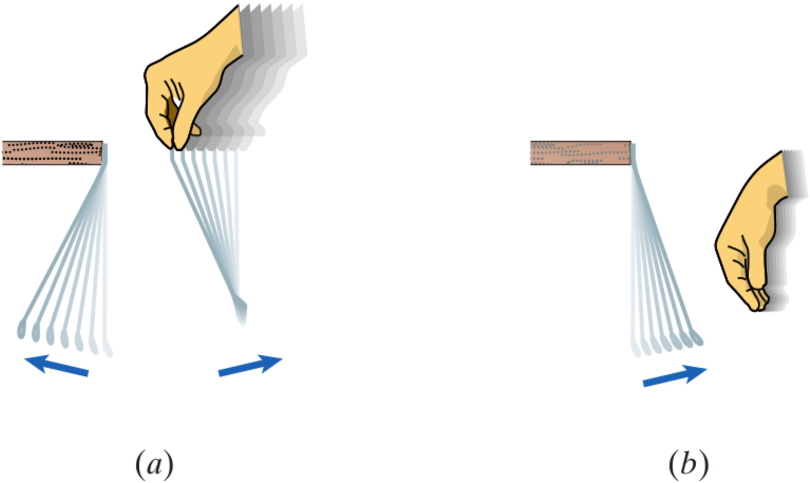


Figure 22.4 A strip of tape is (a) repelled by a second strip and (b) attracted to your hand.

22.4 (*a*) Prepare a charged strip of transparent tape as described in Figure 22.3 and then suspend the strip from the edge of your desk. Verify that the tape interacts as you would expect with your hand, with a strip of paper, and with another charged strip of tape. (*b*) Rub your fingers along the hanging strip to remove all the charge from it and then verify that it no longer interacts with your hand. If it does interact, rub again until it no longer interacts. (*c*) Predict and then verify experimentally how the uncharged suspended strip interacts with a strip of paper and with a charged strip of tape.

To restore the charge on a discharged strip, stick the strip on top of the base strip from which you pulled it off (step 1 in Figure 22.3), smooth it out, and then quickly pull it off again. You can recharge a strip quite a few times before it loses its adhesive properties. Once the tape does lose its adhesiveness, however, recharging it becomes impossible. It is generally a good idea to rub your finger over the base strip before you reuse it to make sure that it, too, is uncharged.

22.5 Recharge the discharged strip from Checkpoint 22.4 and verify that it interacts as before with your hand, with a strip of paper, and with another charged strip of tape.

A discharged tape strip interacts in the same way as objects that carry no charge. Such objects are said to be electrically **neutral**. They do not interact electrically with other neutral objects, but they do interact electrically with charged objects. We shall examine this surprising fact in more detail in Section 22.4.

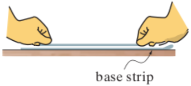
Where does the electrical charge on a charged tape strip come from? Is charge *created* when two strips are pulled apart as in Figure 22.3? This is something we can check by sticking two strips of tape together, rubbing with our fingers to remove all charge from the combination, and then quickly separating the two strips (Figure 22.5).

22.6 Follow the procedure illustrated in Figure 22.5 to separate a pair of charged strips. (*a*) How does strip B interact with a neutral object? How does strip T interact with a neutral object? (*b*) Create a third charged strip and see how it interacts with strip B and with strip T. (*c*) Is strip T charged? (*d*) Is strip B charged? (*e*) Check what happens to the interactions with B and T strips when you discharge a B or a T strip by rubbing your fingers along its length.

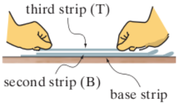
As this checkpoint shows, separating an uncharged pair of strips produces two charged ones, but the behavior of strip B is different from that of the other strips we have encountered so far!

22.7 Make two charged pairs of strips (B and T) following the procedure illustrated in Figure 22.5. Investigate the interaction of B with T, T with T, and B with B.

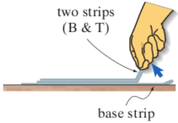
1. Run your finger over the base strip and stick a second strip with a handle on top of it. Press down and smooth it out. Write “B” on the handle of the top strip.



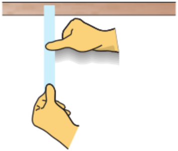
2. Stick a third strip on top. Press down and smooth it out. Write “T” on the handle of the top strip.



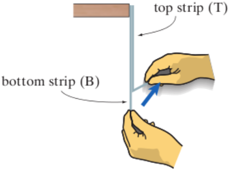
3. Grab the handles of the top two strips and **very slowly** pull the combination as one unit off the base strip leaving the base strip stuck on the table.



4. Stick the combination to the edge of a table with the handles at the bottom and rub your thumb over it until completely discharged.



5. Holding the bottom strip, grab the handle of the top strip and quickly pull the top strip off the bottom one.



6. Stick the top strip to the edge of the table 0.5 m away from the bottom strip.

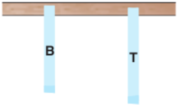


Figure 22.5 Procedure for making strips of transparent tape carrying opposite charge.

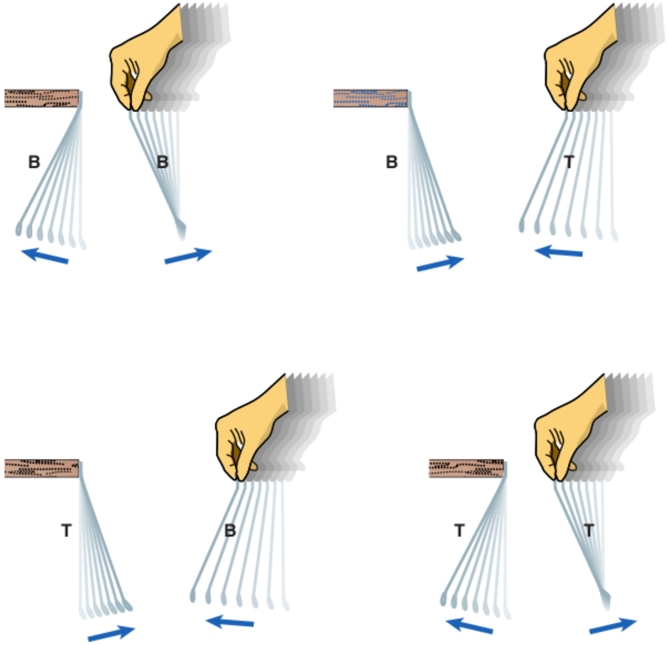


Figure 22.6 Interactions of B and T charged strips.

opposite charge. Combining these equal amounts of opposite charge produces zero charge. These observations indicate that all neutral matter contains equal amounts of positive and negative charge. The two types of charge are called **positive** and **negative charges**. The definition of negative charge is as follows:*

> *Negative charge is the type of charge acquired by a plastic comb that has been passed through hair a few times.*

22.9 Does the B strip you created in Checkpoint 22.8 carry a positive charge or a negative charge?

When two neutral objects touch, some charge can be transferred from one object to the other, with the result that one object ends up with a surplus of one type of charge and the other object ends up with an equal surplus of the other type of charge. For example,

Troubleshooting B and T strips

If your experiment with B and T strips doesn't work as expected, check the following:

1. You must pull off the combination in step 3 of Figure 22.5 *very* slowly. (The amount of charge that builds up on the strips is roughly proportional to the speed at which you separate them.) Be sure to remove *all* charge before proceeding.

2. Separating the B and T strips, on the other hand, must be done fairly raplidly. (If you do it too fast, however, so much charge may build up on your strips that it becomes hard to prevent them from being attracted to your hands. If they curl around and touch your hands, you must start over.)

3. Avoid any air currents on the suspended strips.

4. If the humidity of the air is high, the strips may lose their charge rapidly; you may need to repeat the experiment in a drier environment.

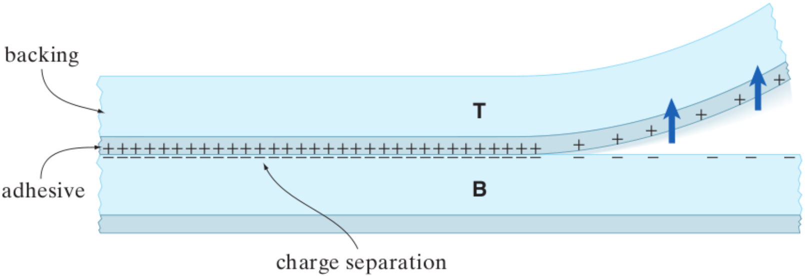


Figure 22.17 Chemical bonds between two strips of tape are responsible for transfer of electrons from the top strip to the bottom strip. When the strips are separated, some of these electrons remain on the bottom strip, giving it a negative charge and the top strip a positive charge.

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* Depending on the type of adhesive and the material of the backing, the transfer of electrons can also be in the other direction.

Who wants a great photo to share with friends?

The net force ON a due to a set of N charged objects is

$$\vec{F}^E_a = k \sum_{i=1}^{N} \frac{q_i \; q_a}{r_{ia}^2} \; \hat{r}_{ia}$$

where r_{ia} is the distance from object i to object a and $\hat{r}_{ia}$ is the **unit vector** pointing from object i toward object a.

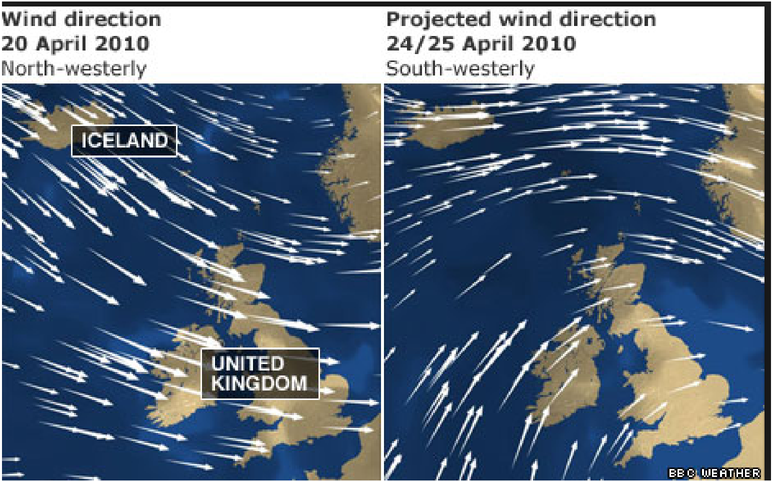
We'll spend some class time on Friday talking about unit vectors and generally refreshing your memory about working with vectors. For the moment, we'll just draw arrows.

Math reminder: the unit vector pointing in direction $\vec{r} = (x, y, z)$ is

$$\hat{r} = \frac{\vec{r}}{r} = \frac{(x, y, z)}{\sqrt{x^2 + y^2 + z^2}}$$

So $\hat{r}$ points in the same direction as $\vec{r}$, but $\hat{r}$ has a length of 1.

The **electric field** associates, with each position in space, a magnitude and a direction of the electrostatic force that a small positive "test charge" would feel if it were placed at that position.



A "field map" of wind velocity is familiar from a weather map. Each position in space gets a vector indicating wind velocity.

Electric field (E)

$\vec{E}(x, y, z)$ is force-per-unit-charge that a "test charge" q, if placed at position $\vec{r} = (x, y, z)$, would feel as a result of the other charges.

If we put an object of charge Q at the origin, the force on q is

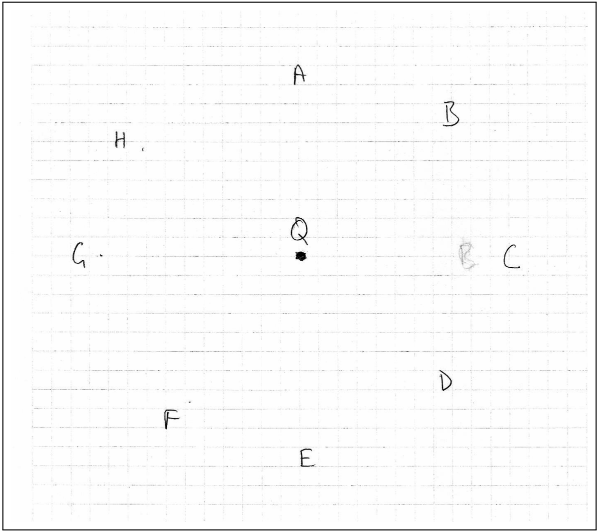
$$\vec{F}_q = k\,\frac{Qq}{r_{Qq}^2}\,\hat{r}_{Qq} = +k\,\frac{qQ}{r^2}\,\hat{r}$$

So the electric field $\vec{E}(\vec{r})$ is

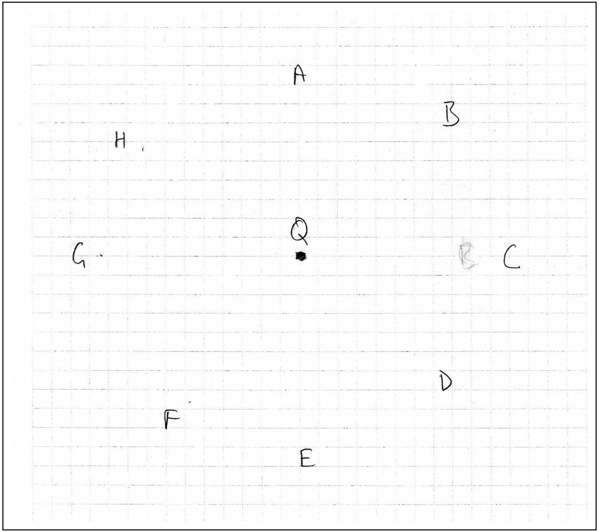
$$\vec{E}(x, y, z) = \frac{\vec{F}_{\text{on q}}}{q} = k\,\frac{Q}{r^2}\,\hat{r}$$

The magnitude of $\vec{E}$ falls off like $1/r^2$, and (for positive Q) $\vec{E}$ points away from Q. $\vec{E}$ points away from positive source charges and points toward negative source charges.

(Try this on a sheet of paper, and compare your drawing with your neighbor's drawing.) I place **a single object** of positive charge $Q > 0$ at the origin. Draw arrows to indicate the direction of the electric field at the points A,B,C,D,E,F,G,H.



(Try this on a sheet of paper, and compare your drawing with your neighbor's drawing.) I place a single object of **negative** charge $Q < 0$ at the origin. Draw arrows to indicate the direction of the electric field at the points A,B,C,D,E,F,G,H.



Electric field due to N charged objects $Q_1, Q_2, \ldots, Q_N$

Just as the force experienced by a test charge q (positioned at point P) is the vector sum of the forces due to the other charges, the electric field $\vec{E}$ (evaluated at point P) due to N charged objects is the vector sum of the contributions from each charge:

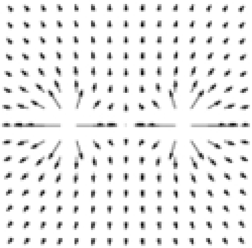
$$\vec{E}(P) \;=\; \sum \frac{\vec{F}_{\mathrm{on\ q}}}{q} \;=\; k \sum_{i=1}^{N} \frac{Q_i}{r_{iP}^2}\, \hat{r}_{iP}$$

That implies that the electric field due to N different source objects is just the *superposition* (i.e. the vector sum) of the electric fields due to the individual sources.

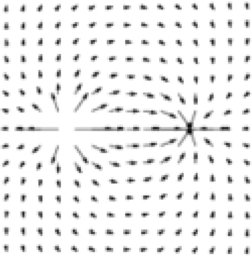
(Draw $\vec{E}$ surrounding $Q > 0$ and surrounding $Q < 0$.)

A positively charged particle is placed at $(x = -1, y = 0)$ and a negatively charged particle (having charge of the same magnitude) is placed at $(x = +1, y = 0)$. Which diagram correctly shows the electric field in the region surrounding these two charged particles?

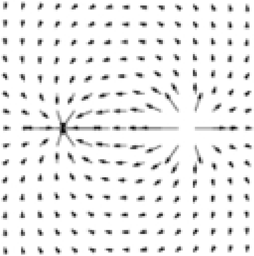
1.



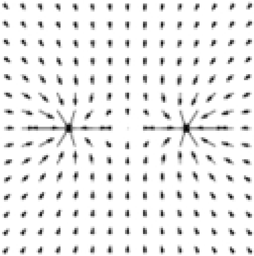
2.



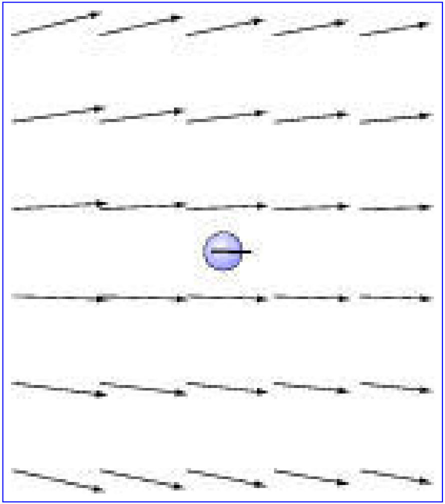
3.



4.



A negatively charged object is placed in an electric field as shown below. The direction of the electostatic force on the object is



(A) to the right

(B) to the left

(C) neither right nor left

(D) depends on whether the field was created by a positively or negatively charged object

(E) There is no force on the object at the location shown in the figure.

Physics 9 — Wednesday, November 7, 2018

- For Monday, you read Eric Mazur's chapter 22 (Electric Interactions) — PDF on Canvas.
- For today, you read Giancoli ch16 (electric charge & E field)
- HW help sessions: Wed 4–6pm DRL $\boxed{\textbf{4C2}}$ (Bill), Thu 6:30–8:30pm DRL 2C8 (Grace)