Appendix 1: Exercises

Exercise 1A: Electric and Magnetic Forces

Apparatus:

In this exercise, you are going to investigate the forces that can occur among the following objects:

nails

magnets

small bits of paper

specially prepared pieces of scotch tape

To make the specially prepared pieces of tape, take a piece of tape, bend one end over to form a handle that won't stick to your hand, and stick it on a desk. Make a handle on a second piece, and lay it right on top of the first one. Now pull the two pieces off the desk and separate them.

Your goal is to address the following questions experimentally:

1. Do the forces get weaker with distance? Do they have some maximum range? Is there some range at which they abruptly cut off?

2. Can the forces be blocked or shielded against by putting your hand or your calculator in the way? Try this with both electric and magnetic forces, and with both repulsion and attraction.

3. Are the forces among these objects gravitational?

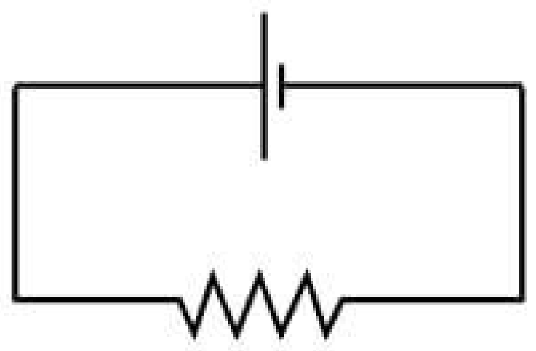
4. Of the many forces that can be observed between different pairs of objects, is there any natural way to classify them into general types of forces?

5. Do the forces obey Newton's third law?

6. Do ordinary materials like wood or paper participate in these forces?

Exercise 3A: Voltage and Current

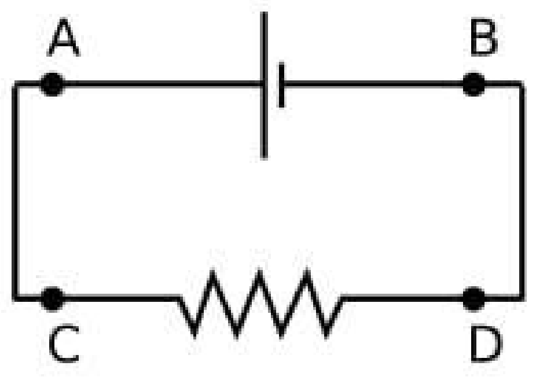
1. How many different currents could you measure in this circuit? Make a prediction, and then try it.



What do you notice? How does this make sense in terms of the roller coaster metaphor introduced in discussion question 3.3A?

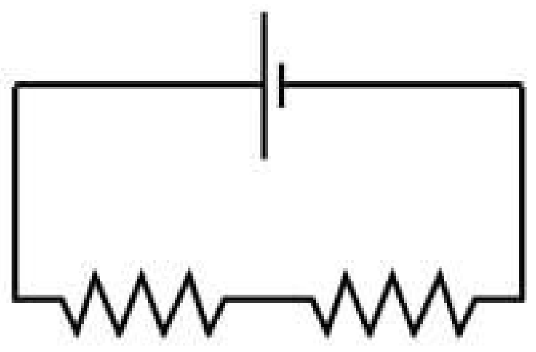
What is being *used up* in the resistor?

2. By connecting probes to these points, how many ways could you measure a voltage? How many of them would be different numbers? Make a prediction, and then do it.



What do you notice? Interpret this using the roller coaster metaphor, and color in parts of the circuit that represent constant voltages.

3. The resistors are unequal. How many *different* voltages and currents can you measure? Make a prediction, and then try it.



What do you notice? Interpret this using the roller coaster metaphor, and color in parts of the circuit that represent constant voltages.

Exercise 4A: The Loop and Junction Rules

Apparatus:

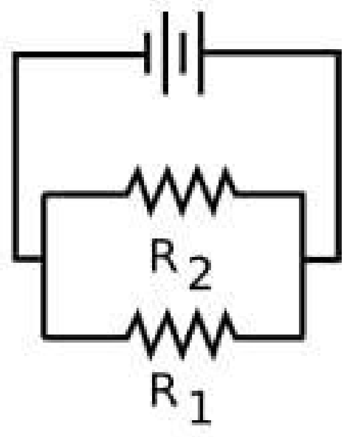
DC power supply

multimeter

resistors

1. The junction rule

Construct a circuit like this one, using the power supply as your voltage source. To make things more interesting, don't use equal resistors. Use nice big resistors (say 100 $k\Omega$ to 1 $M\Omega$) — this will ensure that you don't burn up the resistors, and that the multimeter's small internal resistance when used as an ammeter is negligible in comparison.



Insert your multimeter in the circuit to measure all three currents that you need in order to test the junction rule.

2. The loop rule

Now come up with a circuit to test the loop rule. Since the loop rule is always supposed to be true, it's hard to go wrong here! Make sure you have at least three resistors in a loop, and make sure you hook in the power supply in a way that creates non-zero voltage differences across all the resistors. Measure the voltage differences you need to measure to test the loop rule. Here it is best to use fairly small resistances, so that the multimeter's large internal resistance when used in parallel as a voltmeter will not significantly reduce the resistance of the circuit. Do not use resistances of less than about 100 Ω, however, or you may blow a fuse or burn up a resistor.

Exercise 4B: Reasoning About Circuits

The questions in this exercise can all be solved using some combination of the following approaches:

a) There is constant voltage throughout any conductor.

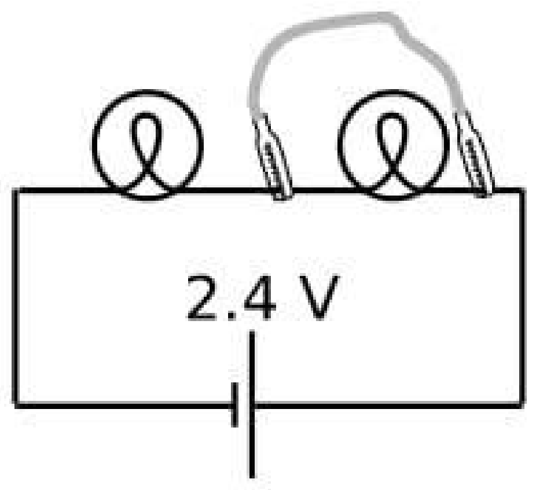
b) Ohm's law can be applied to any *part* of a circuit.

c) Apply the loop rule.

d) Apply the junction rule.

In each case, discuss the question, decide what you think is the right answer, and then try the experiment.

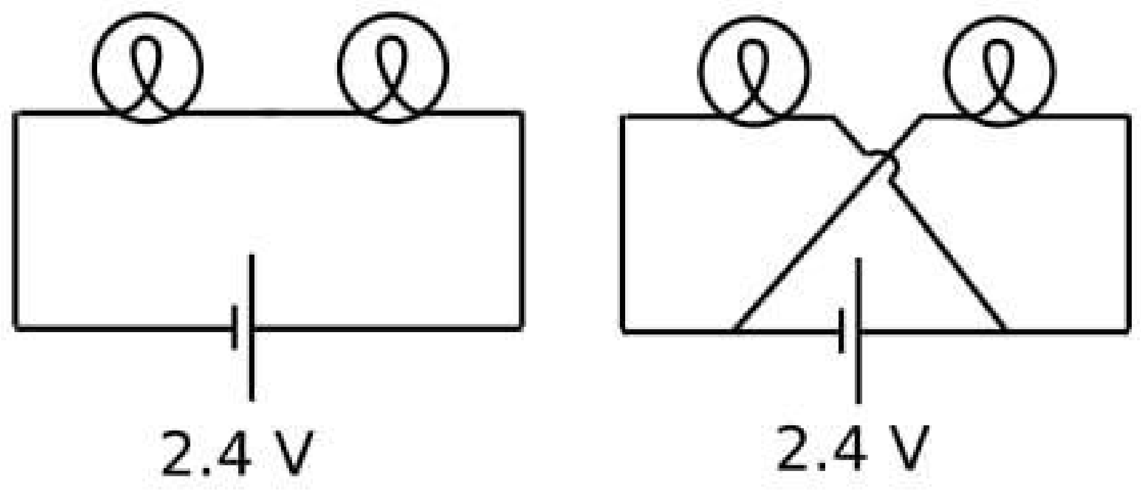
1. A wire is added in parallel with one bulb.



Which reasoning is correct?

- *Each bulb still has 1.2 V across it, so both bulbs are still lit up.*
- *All parts of a wire are at the same voltage, and there is now a wire connection from one side of the right-hand bulb to the other. The right-hand bulb has no voltage difference across it, so it goes out.*

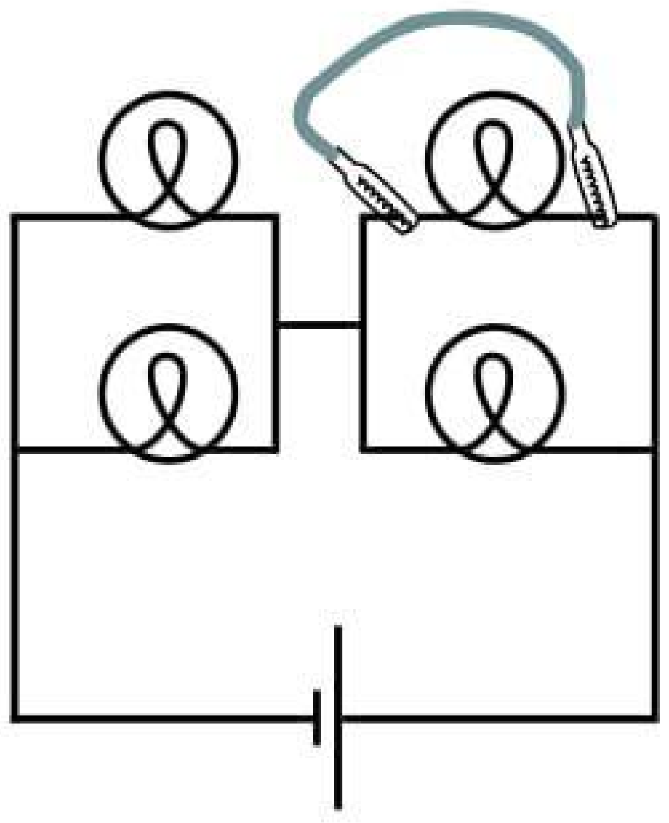
2. The series circuit is changed as shown.



Which reasoning is correct?

- *Each bulb now has its sides connected to the two terminals of the battery, so each now has 2.4 V across it instead of 1.2 V. They get brighter.*
- *Just as in the original circuit, the current goes through one bulb, then the other. It's just that now the current goes in a figure-8 pattern. The bulbs glow the same as before.*

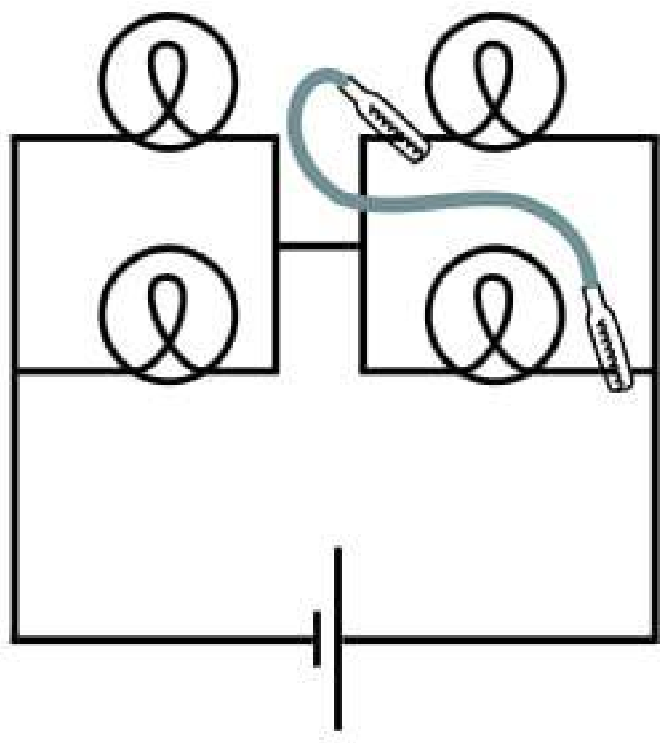
3. A wire is added as shown to the original circuit.



What is wrong with the following reasoning?

The top right bulb will go out, because its two sides are now connected with wire, so there will be no voltage difference across it. The other three bulbs will not be affected.

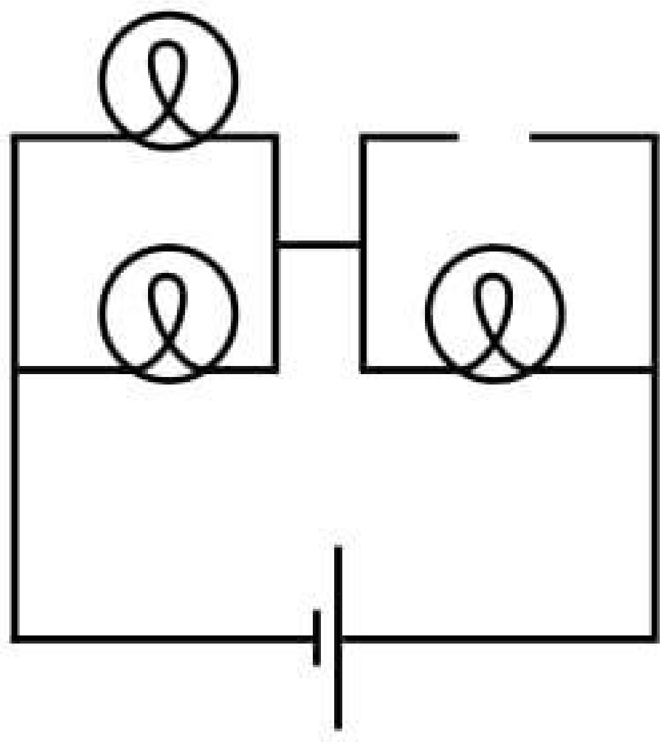
4. A wire is added as shown to the original circuit.



What is wrong with the following reasoning?

The current flows out of the right side of the battery. When it hits the first junction, some of it will go left and some will keep going up The part that goes up lights the top right bulb. The part that turns left then follows the path of least resistance, going through the new wire instead of the bottom bulb. The top bulb stays lit, the bottom one goes out, and others stay the same.

5. What happens when one bulb is unscrewed, leaving an air gap?



Exercise 5A - Field Vectors

Apparatus:

3 solenoids

DC power supply

compass

ruler

cut-off plastic cup

At this point you've studied the gravitational field, **g**, and the electric field, **E**, but not the magnetic field, **B**. However, they all have some of the same mathematical behavior: they act like vectors. Furthermore, magnetic fields are the easiest to manipulate in the lab. Manipulating gravitational fields directly would require futuristic technology capable of moving planet-sized masses around! Playing with electric fields is not as ridiculously difficult, but static electric charges tend to leak off through your body to ground, and static electricity effects are hard to measure numerically. Magnetic fields, on the other hand, are easy to make and control. Any moving charge, i.e. any current, makes a magnetic field.

A practical device for making a strong magnetic field is simply a coil of wire, formally known as a solenoid. The field pattern surrounding the solenoid gets stronger or weaker in proportion to the amount of current passing through the wire.

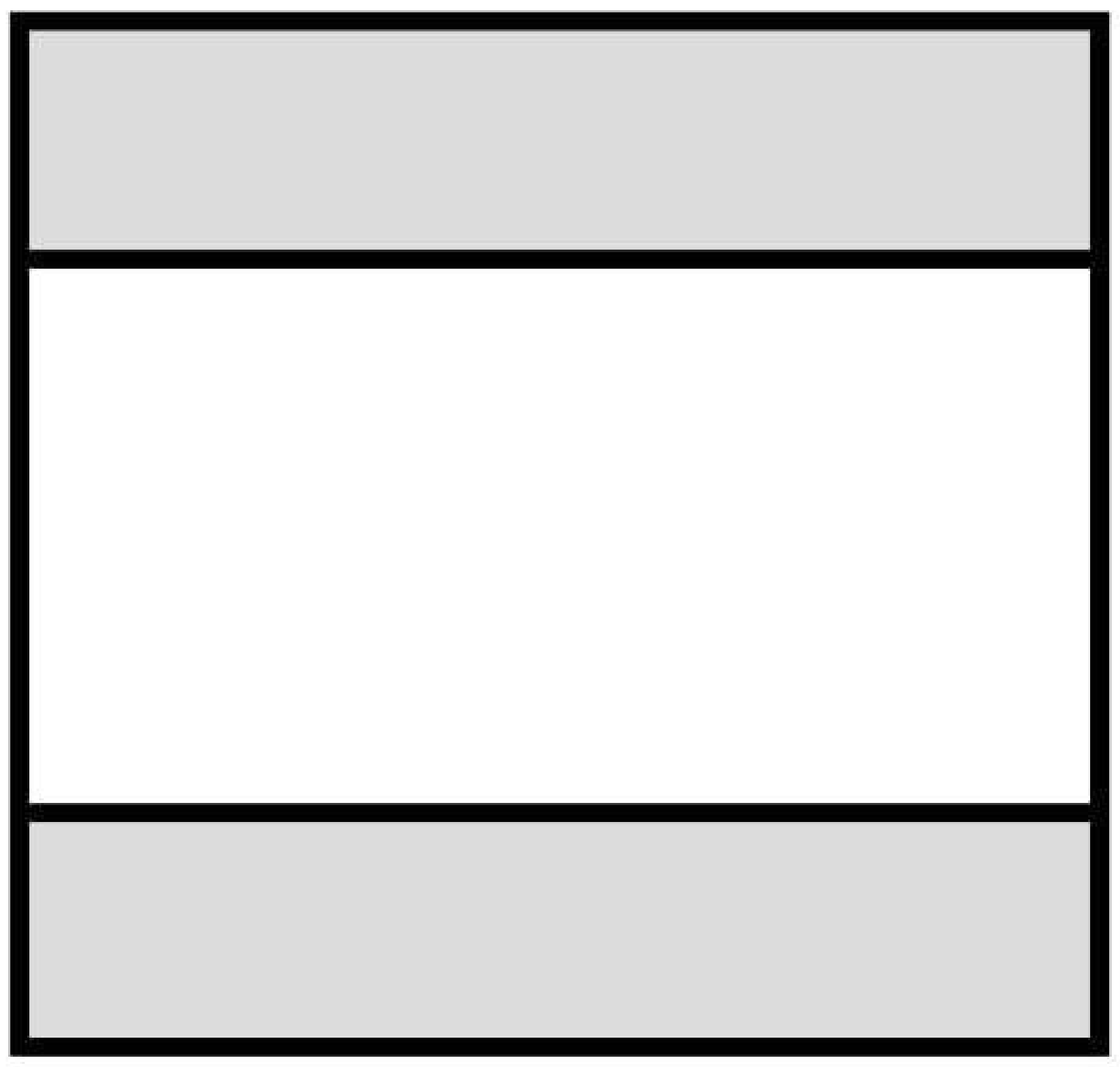
1. With a single solenoid connected to the power supply and laid with its axis horizontal, use a magnetic compass to explore the field pattern inside and outside it. The compass shows you the field vector's direction, but not its magnitude, at any point you choose. Note that the field the compass experiences is a combination (vector sum) of the solenoid's field and the earth's field.

2. What happens when you bring the compass extremely far away from the solenoid?

What does this tell you about the way the solenoid's field varies with distance?

Thus although the compass doesn't tell you the field vector's magnitude numerically, you can get at least some general feel for how it depends on distance.

3. Make a sea-of-arrows sketch of the magnetic field in the horizontal plane containing the solenoid's axis. The length of each arrow should at least approximately reflect the strength of the magnetic field at that point.



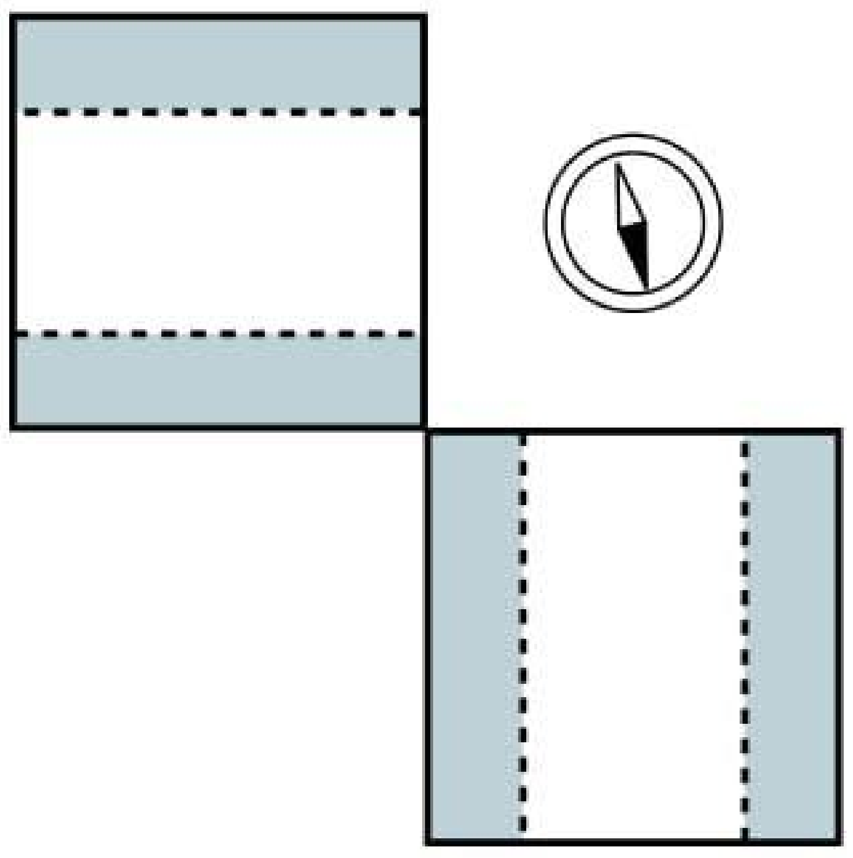
Does the field seem to have sources or sinks?

4. What do you think would happen to your sketch if you reversed the wires?

Try it.

5. Now hook up the two solenoids in parallel. You are going to measure what happens when their two fields combine in the at a certain point in space. As you've seen already, the solenoids' nearby fields are much stronger than the earth's field; so although we now theoretically have three fields involved (the earth's plus the two solenoids'), it will be safe to ignore the earth's field. The basic idea here is to place the solenoids with their axes at some angle to each other, and put the compass at the intersection of their axes, so that it is the same distance from each solenoid. Since the geometry doesn't favor either solenoid, the only factor that would make one solenoid influence the compass more than the other is current. You can use the cut-off plastic cup as a little platform to bring the compass up to the same level as the solenoids' axes.

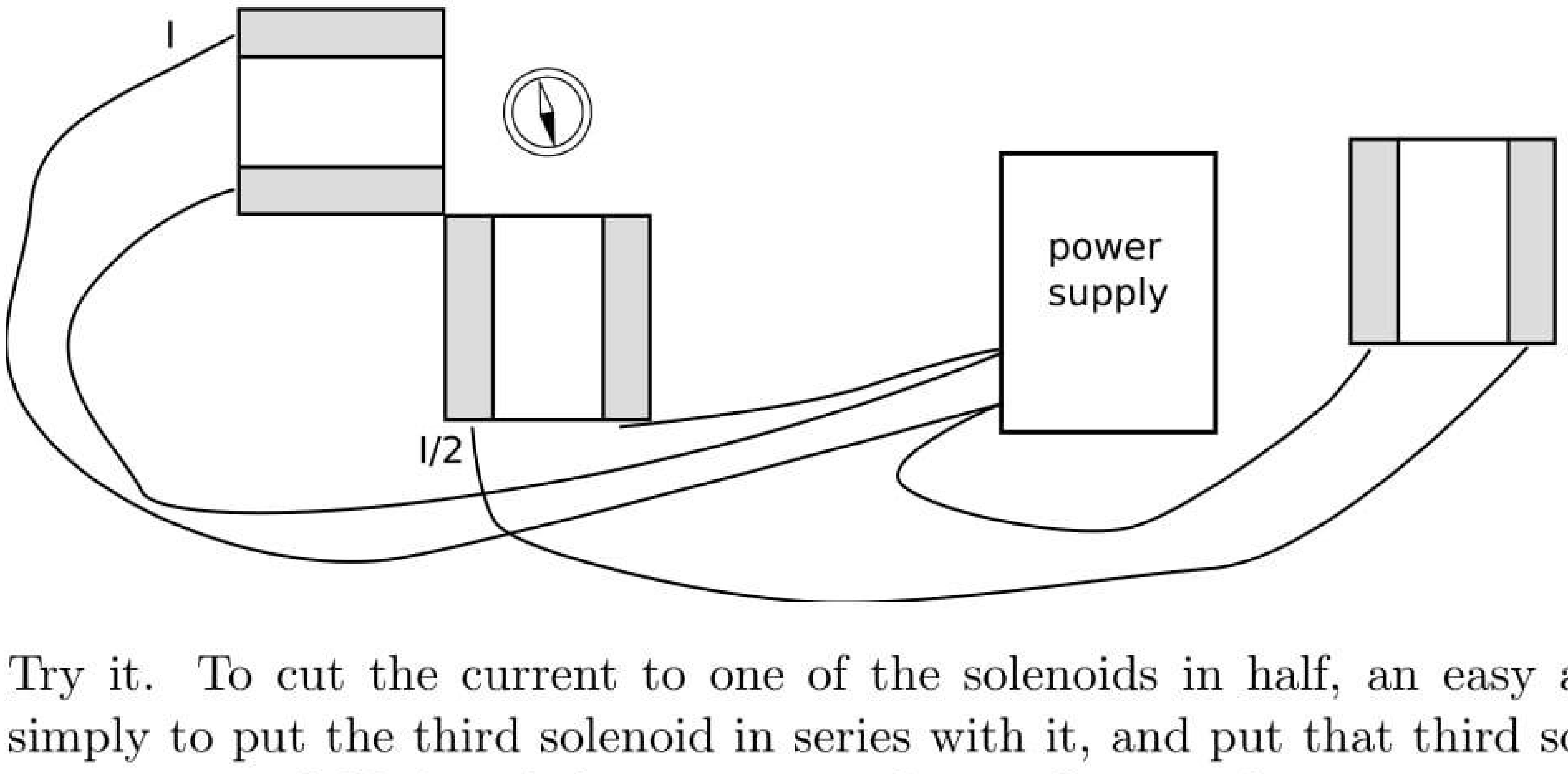
a)What do you think will happen with the solenoids' axes at 90 degrees to each other, and equal currents? Try it. Now represent the vector addition of the two magnetic fields with a diagram. Check your diagram with your instructor to make sure you're on the right track.



b) Now try to make a similar diagram of what would happen if you switched the wires on one of the solenoids.

After predicting what the compass will do, try it and see if you were right.

c)Now suppose you were to go back to the arrangement you had in part a, but you changed one of the currents to half its former value. Make a vector addition diagram, and use trig to predict the angle.



Try it. To cut the current to one of the solenoids in half, an easy and accurate method is simply to put the third solenoid in series with it, and put that third solenoid so far away that its magnetic field doesn't have any significant effect on the compass.

Exercise 6A - Polarization

Apparatus:

calcite (Iceland spar) crystal

polaroid film

1. Lay the crystal on a piece of paper that has print on it. You will observe a double image. See what happens if you rotate the crystal.

Evidently the crystal does something to the light that passes through it on the way from the page to your eye. One beam of light enters the crystal from underneath, but two emerge from the top; by conservation of energy the energy of the original beam must be shared between them. Consider the following three possible interpretations of what you have observed:

(a) The two new beams differ from each other, and from the original beam, only in energy. Their other properties are the same.

(b) The crystal adds to the light some mysterious new property (not energy), which comes in two flavors, X and Y. Ordinary light doesn't have any of either. One beam that emerges from the crystal has some X added to it, and the other beam has Y.

(c) There is some mysterious new property that is possessed by all light. It comes in two flavors, X and Y, and most ordinary light sources make an equal mixture of type X and type Y light. The original beam is an even mixture of both types, and this mixture is then split up by the crystal into the two purified forms.

In parts 2 and 3 you'll make observations that will allow you to figure out which of these is correct.

2. Now place a polaroid film over the crystal and see what you observe. What happens when you rotate the film in the horizontal plane? Does this observation allow you to rule out any of the three interpretations?

3. Now put the polaroid film under the crystal and try the same thing. Putting together all your observations, which interpretation do you think is correct?

4. Look at an overhead light fixture through the polaroid, and try rotating it. What do you observe? What does this tell you about the light emitted by the lightbulb?

5. Now position yourself with your head under a light fixture and directly over a shiny surface,

such as a glossy tabletop. You'll see the lamp's reflection, and the light coming from the lamp to your eye will have undergone a reflection through roughly a 180-degree angle (i.e. it very nearly reversed its direction). Observe this reflection through the polaroid, and try rotating it. Finally, position yourself so that you are seeing glancing reflections, and try the same thing. Summarize what happens to light with properties X and Y when it is reflected. (This is the principle behind polarizing sunglasses.)

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Appendix 3: Hints and Solutions

Answers to Self-Checks

Answers to Self-Checks for Chapter 1

Page 17, self-check A: Either type can be involved in either an attraction or a repulsion. A positive charge could be involved in either an attraction (with a negative charge) or a repulsion (with another positive), and a negative could participate in either an attraction (with a positive) or a repulsion (with a negative).

Page 18, self-check B: It wouldn't make any difference. The roles of the positive and negative charges in the paper would be reversed, but there would still be a net attraction.

Page 28, self-check C: Yes. In U.S. currency, the quantum of money is the penny.

Page 56, self-check A: Thomson was accelerating electrons, which are negatively charged. This apparatus is supposed to accelerated atoms with one electron stripped off, which have positive net charge. In both cases, a particle that is between the plates should be attracted by the forward plate and repelled by the plate behind it.

Page 66, self-check B: The hydrogen-1 nucleus is simple a proton. The binding energy is the energy required to tear a nucleus apart, but for a nucleus this simple there is nothing to tear apart.

Answers to Self-Checks for Chapter 3

Page 92, self-check A: The large amount of power means a high rate of conversion of the battery's chemical energy into heat. The battery will quickly use up all its energy, i.e., "burn out."

Answers to Self-Checks for Chapter 5

Page 129, self-check A: The reasoning is exactly analogous to that used in example 1 on page 126 to derive an equation for the gravitational field of the earth. The field is $F/q_t = (kQq_t/r^2)/q_t = kQ/r^2$.

Page 134, self-check B:

$$
\begin{aligned}
E_x &= -\frac{\mathrm{d}V}{\mathrm{d}x} \\
&= -\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{kQ}{r}\right) \\
&= \frac{kQ}{r^2}
\end{aligned}
$$

Page 136, self-check C: (a) The voltage (height) increases as you move to the east or north. If we let the positive x direction be east, and choose positive y to be north, then $\mathrm{d}V/\mathrm{d}x$ and $\mathrm{d}V/\mathrm{d}y$ are both positive. This means that E_x and E_y are both negative, which makes sense, since the water is flowing in the negative x and y directions (south and west).
(b) The electric fields are all pointing away from the higher ground. If this was an electrical map, there would have to be a large concentration of charge all along the top of the ridge, and especially at the mountain peak near the south end.

Answers to Self-Checks for Chapter 6

Page 152, self-check A: An induced electric field can only be created by a *changing* magnetic field. Nothing is changing if your car is just sitting there. A point on the coil won't experience a changing magnetic field unless the coil is already spinning, i.e., the engine has already turned over.

Answers to Self-Checks for Chapter A

Page 171, self-check A: Yes. The mass has the same kinetic energy regardless of which direction it's moving. Friction coverts mechanical energy into heat at the same rate whether the mass is sliding to the right or to the left. The spring has an equilibrium length, and energy can be stored in it either by compressing it ($x < 0$) or stretching it ($x > 0$).

Page 171, self-check B: Velocity, v, is the rate of change of position, x, with respect to time. This is exactly analogous to $I = \Delta q/\Delta t$.

Page 180, self-check C: The impedance depends on the frequency at which the capacitor is being driven. It isn't just a single value for a particular capacitor.

Solutions to Selected Homework Problems

Solutions for Chapter 2

Page 75, problem 6: (a) In the reaction $\mathrm{p}+\mathrm{e}^- \rightarrow \mathrm{n}+\nu$, the charges on the left are $e+(-e) = 0$, and both charges on the right are zero. (b) The neutrino has negligible mass. The masses on the left add up to less than the mass of the neutrino on the right, so energy would be required from an external source in order to make this reaction happen.

Solutions for Chapter 3

Page 104, problem 12: Δt= Dq/ I $= e/I = 0.160\ \mu$s.

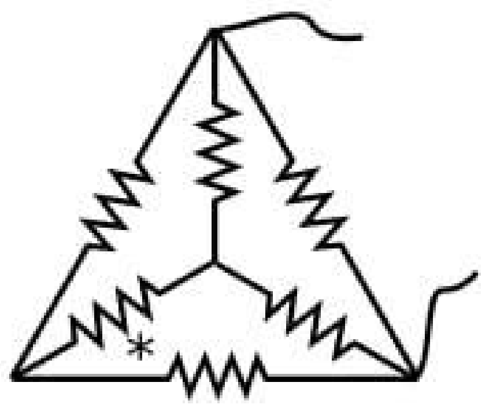
Page 104, problem 13: (a) The change in PE is $e\Delta\mathrm{V}$, so the KE gained is $(1/2)mv^2 = eV$. Solving for v and plugging in numbers, we get 5.9×10^7 m/s. This is about 20% of the speed of light. (Since it's not that close to the speed of light, we'll get a reasonably accurate answer without taking into account Einstein's theory of relativity.)

Page 105, problem 16: It's much more practical to measure voltage differences. To measure a current, you have to break the circuit somewhere and insert the meter there, but it's not possible to disconnect the circuits sealed inside the board.

Solutions for Chapter 4

Page 120, problem 11: In series, they give 11 kΩ. In parallel, they give $(1/1\ \mathrm{k}\Omega + 1/10\ \mathrm{k}\Omega)^{-1} = 0.9\ \mathrm{k}\Omega$.

Page 121, problem 12: The actual shape is irrelevant; all we care about it what's connected to what. Therefore, we can draw the circuit flattened into a plane. Every vertex of the tetrahedron is adjacent to every other vertex, so any two vertices to which we connect will give the same resistance. Picking two arbitrarily, we have this:



This is unfortunately a circuit that cannot be converted into parallel and series parts, and that's what makes this a hard problem! However, we can recognize that by symmetry, there is zero current in the resistor marked with an asterisk. Eliminating this one, we recognize the whole arrangement as a triple parallel circuit consisting of resistances R, $2R$, and $2R$. The resulting resistance is $R/2$.

Solutions for Chapter 5

Page 141, problem 9: Proceeding as suggested in the hint, we form concentric rings, each one extending from radius b to radius $b + \mathrm{d}b$.The area of such a ring equals its circumference multipled by $\mathrm{d}b$, which is $(2\pi b)\mathrm{d}b$. Its charge is thus $2\pi\sigma b\mathrm{d}b$. Plugging this in to the expression from problem 8 gives a contribution to the field $\mathrm{d}E = 2\pi\sigma bka(a^2 + b^2)^{-3/2}\mathrm{d}b$. The total field is found by integrating this expression. The relevant integral can be found in a table.

$$\begin{aligned}
E &= \int_0^\infty \mathrm{d}E = 2\pi\sigma bka(a^2+b^2)^{-3/2}\mathrm{d}b \\
&= 2\pi\sigma ka \int_0^\infty b(a^2+b^2)^{-3/2}\mathrm{d}b \\
&= 2\pi\sigma ka \left[-\left(a^2+b^2\right)^{-1/2}\right]_{b=0}^{\infty} \\
&= 2\pi\sigma k
\end{aligned}$$

Page 141, problem 11: Let the square's sides be of length a. The field at the center is the vector sum of the fields that would have been produced individually by the three charges. Each of these individual fields is kq/r^2, where $r_1 = a/\sqrt{2}$ for the two charges q_1, and $r_2 = a/2$ for q_2. Vector addition can be done by adding components. Let x be horizontal and y vertical. The y

components cancel by symmetry. The sum of the x components is

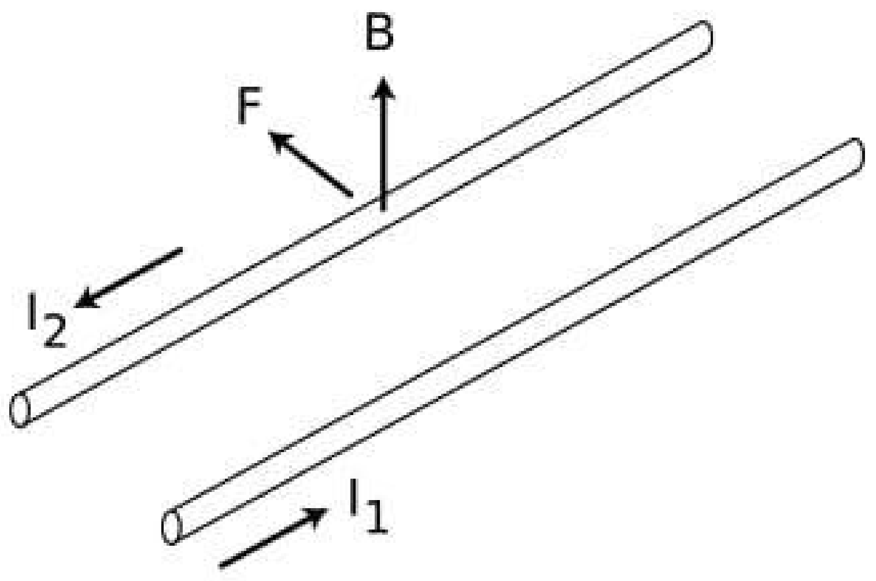
$$E_x = \frac{kq_1}{r_1^2}\cos 45\,^\circ + \frac{kq_1}{r_1^2}\cos 45\,^\circ - \frac{kq_2}{r_2^2} \qquad .$$

Substituting $\cos 45\,^\circ = 1/\sqrt{2}$ and setting this whole expression equal to zero, we find $q_2/q_1 = 1/\sqrt{2}$.

Solutions for Chapter 6

Page 164, problem 13: (a) Current means how much charge passes by a given point per unit time. During a time interval $\Delta\mathrm{t}$, all the charge carriers in a certain region behind the point will pass by. This region has length $v\Delta t$ and cross-sectional area A, so its volume is $Av\Delta\mathrm{t}$, and the amount of charge in it is $Avnq\Delta\mathrm{t}$. To find the current, we divide this amount of charge by $\Delta\mathrm{t}$, giving $I = Avnq$. (b) A segment of the wire of length L has a force QvB acting on it, where $Q = ALnq$ is the total charge of the moving charge carriers in that part of the wire. The force per unit length is $ALnqvB/L = AnqvB$. (c) Dividing the two results gives $F/L = IB$.

Page 165, problem 14: (a) The figure shows the case where the currents are in opposite directions.



The field vector shown is one made by wire 1, which causes an effect on wire 2. It points up because wire 1's field pattern is clockwise as view from along the direction of current I_1. For simplicity, let's assume that the current I_2 is made by positively charged particles moving in the direction of the current. (You can check that the final result would be the same if they were negatively charged, as would actually be the case in a metal wire.) The force on one of these positively charged particles in wire 2 is supposed to have a direction such that when you sight along it, the B vector is clockwise from the v vector. This can only be accomplished if the force on the particle in wire 2 is in the direction shown. Wire 2 is repelled by wire 1.

To verify that wire 1 is also repelled by wire 2, we can either go through the same type of argument again, or we can simply apply Newton's third law.

Simialar arguments show that the force is attractive if the currents are in the same direction.

(b) The force on wire 2 is $F/L = I_{2B}$, where $B = \mu_o I_1/2\pi r$ is the field made by wire 1 and r is the distance between the wires. The result is

$$F/L = \mu_o I_1 I_2/2\pi r \qquad .$$

Page 166, problem 19: (a) Based on our knowledge of the field pattern of a current-carrying loop, we know that the magnetic field must be either into or out of the page. This makes sense, since that would mean the field is always perpendicular to the plane of the electrons' motion; if it was in their plane of motion, then the angle between the v and B vectors would be changing all the time, but we see no evidence of such behavior. With the field turned on, the force vector is apparently toward the center of the circle. Let's analyze the force at the moment when the electrons have started moving, which is at the right side of the circle. The force is to the left. Since the electrons are negatively charged particles, we know that if we sight along the force vector, the B vector must be counterclockwise from the v vector. The magnetic field must be out of the page. (b) Looking at figure g on page 147, we can tell that the current in the coils must be counterclockwise as viewed from the perspective of the camera. (c) Electrons are negatively charged, so to produce a counterclockwise current, the electrons in the coils must be going clockwise. (d) The current in the coils is keep the electrons in the beam from going straight, i.e. the force is a repulsion. This makes sense by comparison with problem 14: the coil currents and vacuum tube currents are counterrotating, which causes a repulsion.

Page 166, problem 20: Yes. For example, the force vanishes if the particle's velocity is parallel to the field, so if the beam had been launched parallel to the field, it would have gone in a straight line rather than a circle. In general, any component of the velocity vector that is out of the plane perpendicular to the field will remain constant, so the motion can be helical.

Page 166, problem 22: The trick is to imagine putting together two identical solenoids to make one double-length solenoid. The field of the doubled solenoid is given by the vector sum of the two solenoids' individual fields. At points on the axis, symmetry guarantees that the individual fields lie along the axis, and similarly for the total field. At the center of one of the mouths, we thus have two parallel field vectors of equal strength, whose sum equals the interior field. But the interior field of the doubled solenoid is the same as that of the individual ones, since the equation for the field only depends on the number of turns per unit length. Therefore the field at the center of a solenoid's mouth equals exactly half the interior field.

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Useful Data

Metric Prefixes

M-	mega-	10^6
k-	kilo-	10^3
m-	milli-	10^{-3}
μ- (Greek mu)	micro-	10^{-6}
n-	nano-	10^{-9}
p-	pico-	10^{-12}
f-	femto-	10^{-15}

(Centi-, 10^{-2}, is used only in the centimeter.)

Notation and Units

quantity	unit	symbol
distance	meter, m	$x, \Delta x$
time	second, s	$t, \Delta t$
mass	kilogram, kg	m
density	kg/m^3	ρ
velocity	m/s	$\mathbf{v}$
acceleration	m/s^2	$\mathbf{a}$
force	N = kg$\cdot$m/s^2	$\mathbf{F}$
pressure	Pa=1 N/m^2	P
energy	J = kg$\cdot$m^2/s^2	E
power	W = 1 J/s	P
momentum	kg$\cdot$m/s	$\mathbf{p}$
period	s	T
wavelength	m	λ
frequency	s^{-1} or Hz	f
charge	coulomb, C	q
voltage	volt, 1 V = 1 J/C	V
current	ampere, 1 A = 1 C/s	I
resistance	ohm, 1 Ω = 1 V/A	R
capacitance	farad, 1 F = 1 C/V	C
inductance	henry, 1 H = 1 V$\cdot$s/A	L
electric field	V/m or N/C	E
magnetic field	tesla, 1 T = 1 N$\cdot$s/C$\cdot$m	B

Fundamental Constants

gravitational constant	$G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$
Coulomb constant	$k = 8.99 \times 10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$
quantum of charge	$e = 1.60 \times 10^{-19}\ \text{C}$
speed of light	$c = 3.00 \times 10^{8}\ \text{m/s}$

Conversions

Nonmetric units in terms of metric ones:

1 inch = 25.4 mm (by definition)
1 pound-force = 4.5 newtons of force
(1 kg) $\cdot g$ = 2.2 pounds-force
1 scientific calorie = 4.18 J
1 kcal = 4.18×10^3 J
1 gallon = 3.78×10^3 cm^3
1 horsepower = 746 W

When speaking of food energy, the word "Calorie" is used to mean 1 kcal, i.e., 1000 calories. In writing, the capital C may be used to indicate 1 Calorie=1000 calories.

Relationships among U.S. units:
1 foot (ft) = 12 inches
1 yard (yd) = 3 feet
1 mile (mi) = 5280 feet

Earth, Moon, and Sun

body	mass (kg)	radius (km)	radius of orbit (km)
earth	5.97×10^{24}	6.4×10^{3}	1.49×10^{8}
moon	7.35×10^{22}	1.7×10^{3}	3.84×10^{5}
sun	1.99×10^{30}	7.0×10^{5}	—

Subatomic Particles

particle	mass (kg)	radius (fm)
electron	9.109×10^{-31}	$\lesssim 0.01$
proton	1.673×10^{-27}	~ 1.1
neutron	1.675×10^{-27}	~ 1.1

The radii of protons and neutrons can only be given approximately, since they have fuzzy surfaces. For comparison, a typical atom is about a million fm in radius.