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 55, 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 65, 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 91, 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 131, self-check A: The reasoning is exactly analogous to that used in example 1 on page 128 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 137, 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 139, 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 154, 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 175, 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 175, 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 185, 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.

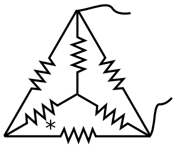
Page 104, problem 13: (a) The change in PE is $e\Delta\text{V}$, so the KE gained is $(1/2)mv^2 = eV$. Solving for v and plugging in numbers, we get 5.9×10^7 m/s. This is about 20% of the speed of light. (Since it's not that close to the speed of light, we'll get a reasonably accurate answer without 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 122, problem 11: In series, they give 11 kΩ. In parallel, they give $(1/1\ \text{k}\Omega+1/10\ \text{k}\Omega)^{-1} = 0.9\ \text{k}\Omega$.

Page 123, 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 144, 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 144, 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

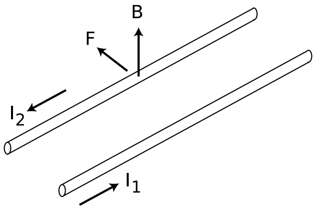
$$E_x = \frac{kq_1}{r_1^2}\cos 45\,^\circ + \frac{kq_1}{r_1^2}\cos 45\,^\circ - \frac{kq_2}{r_2^2} \qquad .$$

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 168, problem 13: (a) Current means how much charge passes by a given point per unit time. During a time interval Δt, 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 $Av\Delta$t, and the amount of charge in it is $Avnq\Delta$t. To find the current, we divide this amount of charge by Δt, 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 169, 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 170, 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 i on page 149, 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 170, 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 170, 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.

Index

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·m/s^2	$\mathbf{F}$
pressure	Pa=1 N/m^2	P
energy	J = kg·m^2/s^2	E
power	W = 1 J/s	P
momentum	kg·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·s/A	L
electric field	V/m or N/C	E
magnetic field	tesla, 1 T = 1 N·s/C·m	B

Fundamental Constants

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