Snapshot:

Review Problems for Elementary Physics 42

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Contents

This review guide is NOT sorted or made unique – it is the simple union of all the problems in my problem repository. Some problems that I give "a lot" (such as Maxwell's Equations) may be represented many times. Others may occur only once. To a certain extent this reflects their frequency of occurrence and hence the weight I give to the material being tested. This can be used as a clue for how best to spend your limited study time – if something is here three or four times in various forms it is a good idea to know how to do it. If it is here only once, you *might* get a way without knowing it, although of course you should try not to have to take that sort of risk.

Note well that I *always* make up a new problem or two for just about any exam I give, so this list is not and cannot be totally complete. Still, if you can do all of these problems you are likely to be able to do any of the new problems I make up (or at least do as well as any students on those problems).

This whole course emphasizes problem solving and derivation as a route to a deep conceptual understanding of the material. By the time you can work *all* of these problems *quickly* you will be well on your way to true mastery of the material.

Enjoy!

1 Laws of Nature and Fundamental Definitions

1. What is Coulomb's Law?
2. What is Gauss's Law for Electricity?
3. What is the energy density η of the electric field $\vec{E}$?
4. What is the potential energy of an electric dipole $\vec{p}$ in an electric field $\vec{E}$?
5. What is the torque $\vec{\tau}$ acting on an electric dipole $\vec{p}$ in an electric field $\vec{E}$?
6. What is the force $\vec{F}$ acting on an electric dipole $\vec{p}$ in a *uniform* electric field $\vec{E}$?
7. What is the net force on a charged particle q moving with velocity $\vec{v}$ in a magnetic field $\vec{B}$? Draw a picture to illustrate its relative direction.
8. What is the "Lorentz Force Law" (the law that relates the electromagnetic force on a charged particle q moving at velocity $\vec{v}$ in an electric field $\vec{E}$ and magnetic field $\vec{B}$?
9. What is Ohm's Law?
10. What is the defining relation for Capacitance?
11. What is the Biot-Savart Law?
12. What is Ampere's Law (without displacement current)?
13. What is Ampere's Law (with displacement current)?
14. What is Faraday's Law? Circle Lenz's Law within.
15. What is the thin lens equation?
16. What is the equation one uses to locate images formed with a mirror of radius r?

17. What is the “lensmaker’s formula”?
18. What is Snell’s Law?
19. What is the Fermat Principle?
20. What happens at the Curie Temperature of a magnetic material?
21. What is the Poynting vector? What do we call its absolute magnitude?
22. What is Fresnel diffraction?
23. What is Fraunhofer diffraction?
24. What is the Rayleigh criterion for resolution?
25. Draw the phasor diagram used to determine the E-field amplitude from two point sources separated by a distance d on a distant screen (Fraunhofer condition). What is the phase difference δ in terms of d and θ?
26. Draw the phasor diagram used to determine the E-field amplitude from three point sources separated by a distance d on a distant screen (Fraunhofer condition). What is the phase difference δ in terms of d and θ?
27. Draw the phasor diagram used to determine the E-field amplitude from a slit of width a on a distant screen (Fraunhofer condition). What is the phase difference ϕ in terms of a and θ?
28. What is the angular magnification produced by a simple magnifier with focal length f?
29. What is the near point distance of the human eye (both what *is* it and what is its presumed/approximate value)?
30. Draw a representation of a nearsighted eye, indicating the focal length of its relaxed lens. Then draw the eye with the appropriate corrective lens in front and indicate how it fixes the problem.
31. Draw a representation of a farsighted eye, indicating the focal length of its relaxed lens. Then draw the eye with the appropriate corrective lens in front and indicate how it fixes the problem.

32. What is "dispersion" in the theory of refracted light?

33. If a beam of light has speed c, frequency f, and wavelength λ in a vaccuum, what are its speed, frequency and wavelength in a medium with index of refraction n?

34. What is the formula for the critical angle (of total internal reflection) for a beam of light going from medium 1 to medium 2 with $n_1 > n_2$?

35. What is the speed of light in terms of ϵ_0 and μ_0?

36. What is the relation between E and B in an electromagnetic wave?

37. What is the formula for the intensity of radiation from a dipole oriented along the $\hat{z}$-direction?

38. If vertically polarized light of intensity I_0 strikes a polarizing filter with a transmission axis at an angle θ with respect to the vertical, what is the intensity of the transmitted light (Malus' Law)?

39. A transformer has N_1 turns in its primary winding and N_2 turns in its secondary winding. If it has an alternating voltage V_1 applied across its primary, what would one expect to measure for V_2 across its secondary?

2 Short Answer Questions

1. What is Coulomb's Law? (Equation and figure ok, or in words.)

2. What is Gauss's Law? To get full credit for this, it needs to be written *exactly* the way I write it in class, with all the little vector arrows, hats,

loopy thingies and so forth. An illustrative figure should accompany.

3. What is the relationship between electric field and electric potential? (A couple of mathematical equations would be good, possibly accompanied by a picture.)

4. What is the total capacitance of three capacitors C_1, C_2, and C_3 in *series*?

5. True or False. If false, change *one* (interesting!) *word* to make it true. (No fair just changing "is" to "is not".): The potential is always *zero*

inside a conductor at electrostatic equilibrium.

6. List three ways a dielectric is useful in capacitor design.

7. What are Maxwell's Equations? Give me equation, name, picture, comment about significance or important experimental result if any. Circle and label the Maxwell Displacement Current and Lenz's Law.

   (a)

   (b)

   (c)

   (d)

8. What is the potential energy of a magnetic dipole placed in a magnetic field? For a couple of bonus points, write an exact expression for the magnetic *force* on the dipole.

9. The average power output of Mr. Sun is roughly $P_{\rm sun} = 3.83 \times 10^{26}$ watts. We (Mr. Earth) are roughly $R_{\rm earthorbit} = 1.5 \times 10^{11}$ meters away. Mr. Earth itself is about $R_{\rm earth} = 6.4 \times 10^{6}$ meters in radius. The mean temperature of Mr. Earth today is approximately 300° K. Three hundred years ago (during the "Little Ice Age" that struck Europe) the mean temperature was perhaps 1.5° C lower. If we make the most naive possible assumption (that that average global temperature is directly proportional to the total energy that strikes it in a year from Mr. Sun), find the variation in solar power output that would suffice to "explain" global warming without recourse to the greenhouse effect.

   In fact, it has been estimated that the solar constant varies by about 0.5%, with 70 year dips of that amount every 300 year cycle. It's just about time to get the woolies out of drawers again...

10. The average power output of Mr. Sun is roughly $P_{\text{sun}} = 3.83 \times 10^{26}$ watts. We (Mr. Earth) are roughly $R_{\text{earth orbit}} = 1.5 \times 10^{11}$ meters away. Mr. Earth itself is about $R_{\text{earth}} = 6.4 \times 10^{6}$ meters in radius. Just for grins, approximately how *much* solar energy strikes the earth in a year? [Note: You don't have to give me a number (although you certainly may), but you must draw the right picture and give me an answer that makes dimensional and logical sense in terms of P_{sun}, R_{earth}, $R_{\text{earth orbit}}$, and $T \approx \pi \times 10^{7}$ (seconds per year).]

11. What is the energy density η_E of the electric field $\boldsymbol{E}$?

12. What is the definition of the Poynting vector (in terms of the fields and electomagnetic constants)? For one extra point, what is its magnitude also called?

13. What is the lensmaker's formula in terms of n, r_1, r_2 (the index of refraction and radii of curvature of the first and second thin lensing surfaces. (Note: If you do not remember or do remember but want more credit, and have time to derive it on one of the extra sheets, the derivation will be worth 10 *extra* points!)

14. What happens at the Curie Temperature of a magnetic material?

15. What is Fraunhofer diffraction? Why do we prefer to assume that the Fraunhofer conditions are satisfied when doing diffraction or interference problems?

16. Draw the phasor diagrams for the first four *interference minima* produced by five slits. Two are easy. Two will require meditation on the phrase “Twinkle, twinkle, little....”.

17. What are the four values of $\delta = kd\sin\theta$ for the first four *interference minima* produced by five slits. Should be able to read them right off the phasor pictures...

18. Draw a representation of a nearsighted eye, indicating the focal length of the relaxed lens. Then draw the eye with the appropriate corrective lense in front and indicate with rays how it “fixes” the problem.

19. Why are transformer cores generally made of thin slices of laminated iron separated by a thin insulating layer? I'm interested in knowing “why laminated”, not “why iron” (although feel free to answer both).

20. Dielectric materials are generally used when designing capacitors for several excellent reasons. Give two. Heck, give three if you can (you should be able to) and get an extra point in the process.

21. You are out fishing and your polarized sunglasses do great job of reducing reflected glare off the water in the late afternoon. Do they *also* reduce the *scattered* glare from the sky above the horizon at noon? No good just answering yes or no, have to draw a picture to indicate why to get credit.

22. Roger (who owns a motorcycle repair shop in Eastern North Carolina) hears about magnetic monopoles and decides to build one and end all the confusion. He gets a few hundred bar magnets and glues them all hedgehog-fashion onto a sphere so that the north poles face out and the sphere is tightly packed and covered. He reasons that the field of the south poles will meet in the middle and cancel out, while the north pole fields will look just like a monopole.

    If the total summed pole strengths ("magnetic charge" of the north poles as determined by their magnetic dipole moments) of all the bar magnets is Q_m, approximately what magnetic field will Roger observe one meter away from his "monopole"? Why? (Draw a picture, invoke a law, something...).

23. What does a diamagnetic material do when placed in a magnetic field? For an extra point, when do "perfect" diamagnets occur in nature? For two extra points name the effect that most dramatically demonstrates the diamagnetism (which involves hovering magnets).

24. What is Rayleigh's criterion for the angular separation of two objects such that their images are minimally resolved if the light from the objects has wavelength λ and passes through a circular aperture of

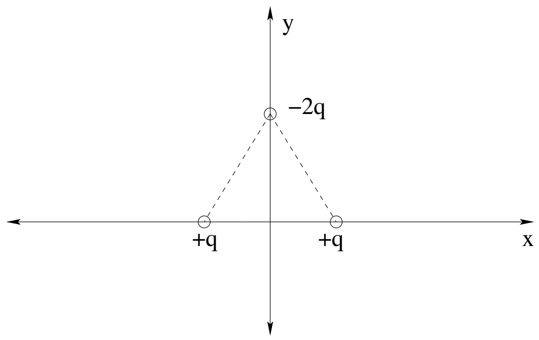
diameter $D \gg \lambda$?

25. True or False: A conductor carrying an electric current has no electric field inside.

26. Draw an approximate graph of the average power $P_{\mathrm{av}}(\omega)$ dissipated in a series LRC AC circuit when $Q = 20$. The figure should not be insanely out of scale for the value of Q.

3 Electric Field

3.1

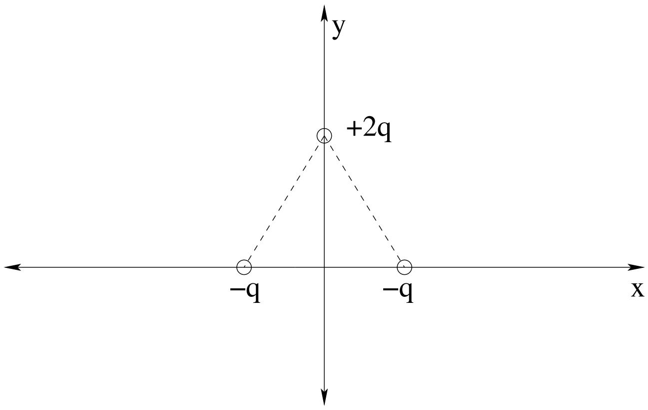


Charges of $+q$ are located at the two bottom corners of an equilateral triangle with sides of length a. A charge of $-2q$ is at that top corner. This arrangement of charge can be considered two dipoles oriented at 60° with respect to one another.

a) Find the electric field (magnitude and direction) at an arbitrary point on the y-axis above/outside the triangle.

b) What are the first two terms in the binomial-theorem-derived series for the electric field evaluated *far* from the charges, i.e. – for $y >> a$[1]?

[1]Hint: since the net charge balances (=0), we expect no monopolar part (like $1/x^2$). Since the dipoles do not quite balance, we might see a dipolar part (like $1/x^3$). However, since the dipoles are not parallel we might expect to see a significant *quadrupolar* term that varies like $1/x^4$ as well.

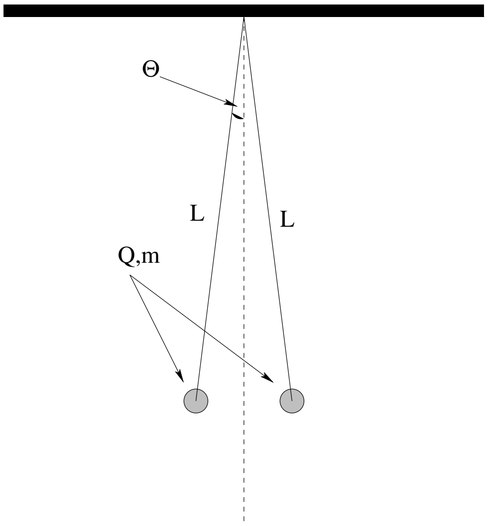


Charges of $-q$ are located at both $y = a$ and $y = -a$, and a charge of $+2q$ is located at $y = 0$ on the y-axis. This arrangement of charge can be visualized as two opposing dipoles.

a) Find the electric field (magnitude and direction) at an arbitrary point on the x-axis.

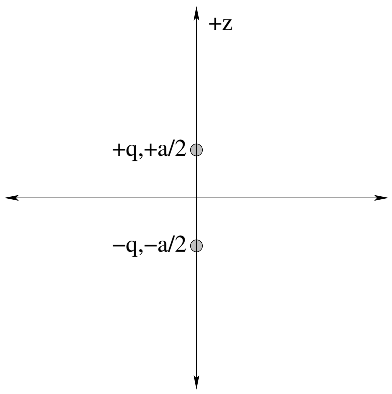
b) What is *nonzero* term in the expansion of the electric field evaluated *far* from the charges, i.e. – for $x >> a$? Your answer should be a series of terms in inverse powers of x.

3.2



Two positively charged pith balls of mass m each have a charge Q and are suspended by insulating (massless) lines of length L from a common point as shown. Assume that L is long enough that θ at the top is a small angle. Find θ such that the pith balls are in static equilibrium in terms of k, Q, m, L and of course g.

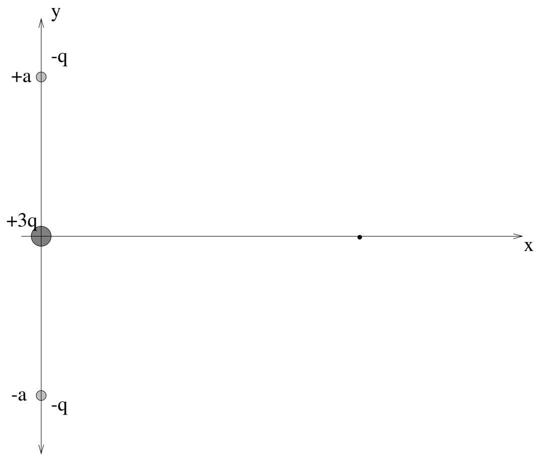
3.3



Charges of $\pm q$ are located at both $z = \pm a/2$, respectively. This arrangement forms a electric dipole.

a) Find both the electric potential and electric field (magnitude and direction) at an arbitrary point $z > a/2$ on the z-axis.

b) What is the first *nonzero* term in the expansion of the electric field evaluated *far* from the charges, i.e. – for $z \gg a/2$?

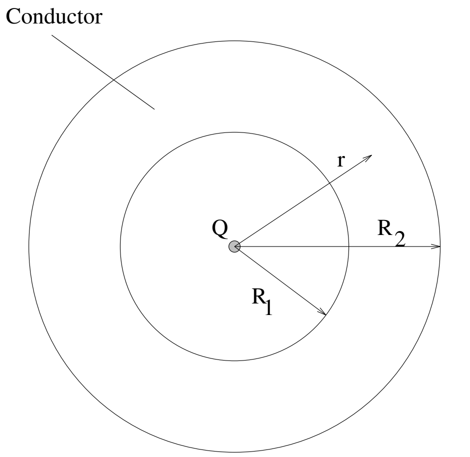


3.4

Charges of $-q$ are located at both $y = a$ and $y = -a$, and a charge of $+3q$ is located at $y = 0$ on the y-axis. This arrangement of charge can be visualized as two opposing dipoles plus a charge at the center.

a) Find the electric field (magnitude and direction) at an arbitrary point on the x-axis.

b) What are the first two *nonzero* terms in the electric field evaluated *far* from the charges, i.e. – for $x >> a$? Your answer should be a series of terms in inverse powers of x.

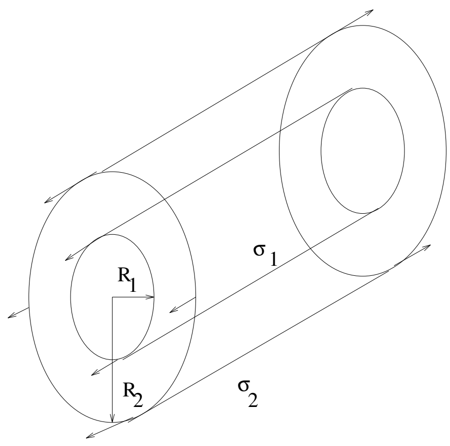


3.5

A conducting shell concentrically surrounds a point charge of magnitude Q located at the origin. The inner radius of the shell is R_1 and the outer radius R_2.

a) Find the electric field $\vec{E}$ at all points in space (you should have three answers for three distinct regions).

b) Find the surface charge density σ on the inner surface of the conductor. Justify your answer with Gauss's law.



3.6

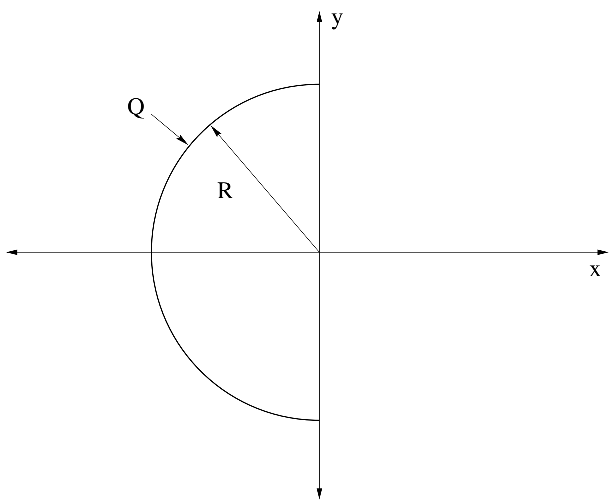
Two infinitely long, cylindrical conducting shells are concentrically arranged as shown above. The inner shell has a radius R_1 and the outer shell the radius R_2. The inner shell has a charge per unit area σ_1, and the outer shell a charge per unit area σ_2.

a) Find the electric field $\vec{E}$ at all points in space (you should have three answers for three distinct regions).

b) Find the surface charge density σ_2 (in terms of σ_1, R_1, R_2, etc.) that causes the field to vanish everywhere but in between the two shells. *Justify your answer with Gauss's law.*

4 Gauss's Law

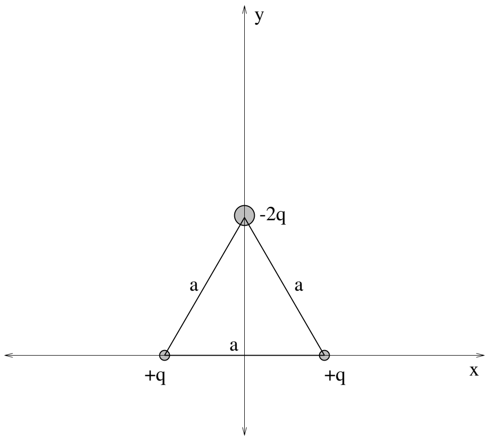
4.1



A half-ring of total charge Q and radius R sits symmetrically across the x-axis around the origin as shown in the figure above.

1. Find the electric field at the origin (magnitude and direction) from direct integration.

2. What is the electric potential at the origin?



4.2

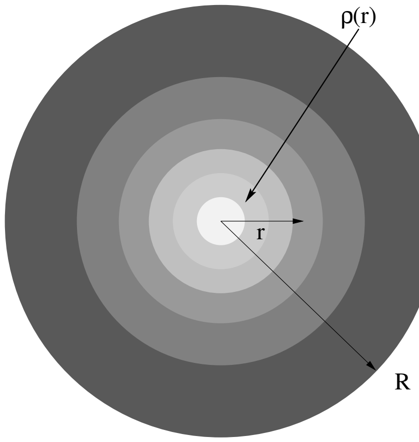
Charges of $+q$ are located at the two bottom corners of an equilateral triangle with sides of length a. A charge of $-2q$ is at that top corner. This arrangement of charge can be considered two dipoles oriented at 60° with respect to one another.

a) Find the electric field (magnitude and direction) at an arbitrary point on the y-axis above/outside the triangle.

b) What are the first two surviving terms in the binomial-theorem-derived series for the electric field evaluated *far* from the charges, i.e. – for $y >> a^2$?

[2]Hint: since the net charge balances (=0), we expect no monopolar part (like $1/x^2$). Since the dipoles do not quite balance, we might see a dipolar part (like $1/x^3$). However, since the dipoles are not parallel we might expect to see a significant *quadrupolar* term that varies like $1/x^4$ as well.

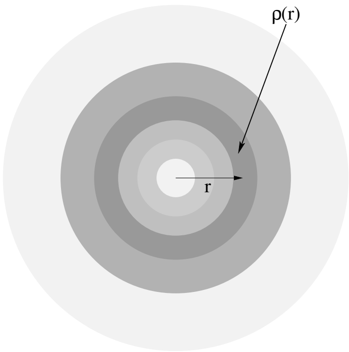
4.3



Find the electric field and electric potential at all points in space of a sphere with radial charge density:

$$\rho(r) = \rho_0 r \qquad r \leq R$$
$$\rho(r) = 0 \qquad r > R$$

4.4

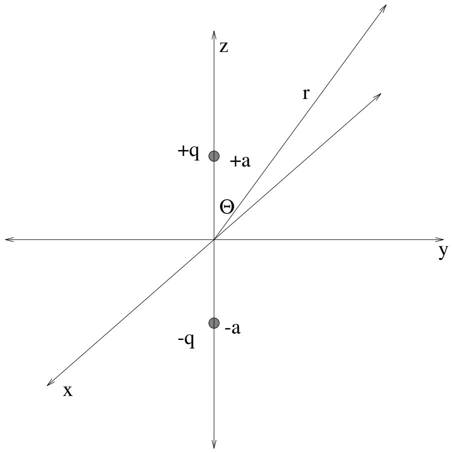


Find the electric field at all points in space of a spherical charge distribution with radial charge density:

$$\rho(r) = \rho_0 \frac{e^{-r/2a}}{r^2}$$

For extra credit, determine ρ_0 such that the total charge Q in the distribution is $-e$.

This is the charge distribution of the electron cloud about a hydrogen atom in the ground state. Remember, if you can't quite see how to do the integral (which is actually pretty easy) set the problem up, systematically – following the steps outlined in class – until all that is LEFT is doing the integral, to end up with most of the credit.



5 Electric Potential

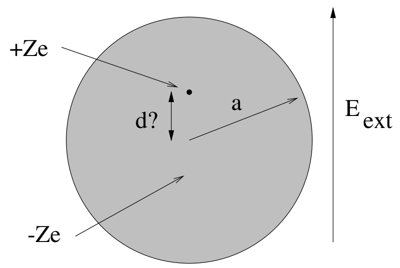
5.1

A point charge of $-q$ is located at $z = -a$ on the z-axis and a point charge of $+q$ is located at $z = +a$.

1. (10 points) Write down the potential at an arbitrary point in space in spherical coordinates (r, θ, ϕ).
2. (10 points) What is the leading term in the expansion of the potential for $r \gg a$, expressed in terms of the dipole moment?

(Note: Obviously, I *really do* want you to learn to do this one, since I did a bunch of it in lecture and asked you to finish the rest on your own. You derive a very fundamental result that will be useful to you in the years to come....so much that I'll give two hints. One is use the law of cosines to determine the distance from e.g. $+q$ to the point of observation in terms of r, a, and θ only. Second is to use the binomial expansion to extract the leading order potential term(s) for each charge and add them until you get the overall leading order term that *survives* – the first term or two might well cancel.)

5.2

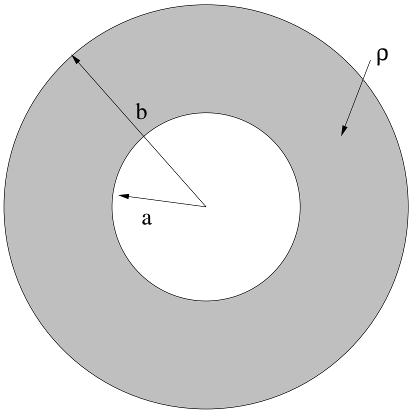


A simple model for an atom has a tiny (point-like) nucleus with charge $+Ze$ is located at the center of a uniform sphere of charge with radius a and total charge -Ze. The atom is placed in a uniform electric field which displaces the nucleus as shown. Find:

a) The equilibrium separation d of the nucleus from the center of the spherical electron cloud;

b) The *average* polarization density $\boldsymbol{P}$ (dipole moment per unit volume) of a solid made up of these atoms, assuming that the atoms are arranged so that they "touch" in a simple cubic lattice (a three dimensional array where atoms sit at positions (x, y, z) where all three coordinates are integer multiples of $2R$).

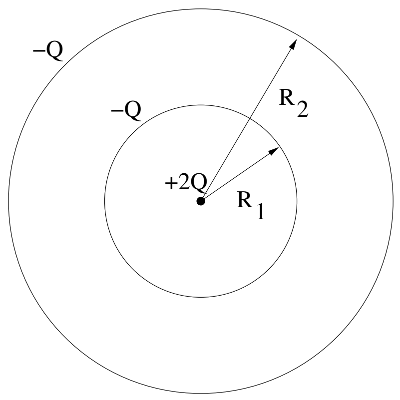
Remember, this polarization density can be related to the total electric field inside the conductor by a relation like $\boldsymbol{P} = \chi_e \epsilon_0 \boldsymbol{E}$ where χ_e is called the *electric susceptibility* of the material. This in turn lets you completely understand κ, the dielectric constant of the model material.



5.3

A spherical shell of inner radius a and outer radius b contains a uniform distribution of charge with charge density ρ.

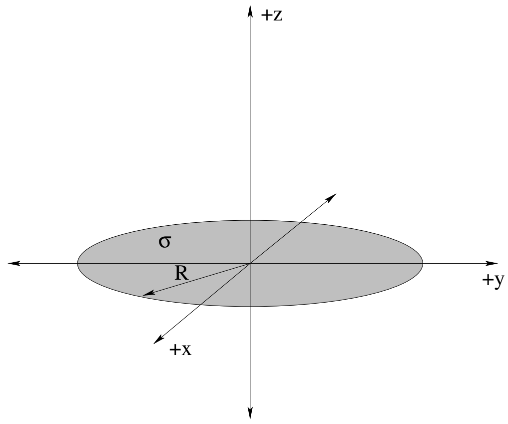
Find the field and potential at all points in space.



5.4

Two spherical shells with radii R_1 and R_2 respectively concentrically surround a point charge. The central point charge has magnitude $2Q$. Both the spherical shells have a charge of $-Q$ (each) distributed uniformly upon the shells.

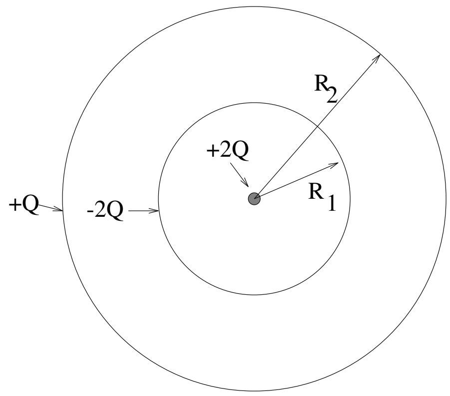
Find the field and potential at all points in space. Show your work – even if you can just write the answer(s) down for each region, briefly sketch the methodology used to get the answers.



5.5

Find the electric potential on the (z) axis of a disk of charge of radius R with uniform surface charge distribution σ.

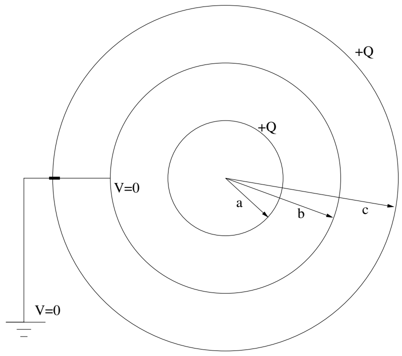
For extra credit (if you have time) find the electric field on the z-axis.



5.6

Find the potential $V(r)$ at all points in space for the arrangement of charge pictured above, where there is a point charge $+2Q$ at the origin, a charge uniformly distributed $-2Q$ on the inner shell (radius R_1), and a charge $+Q$ uniformly distributed on the outer shell (radius R_2). You will need three different answers for the three distinct regions of space.

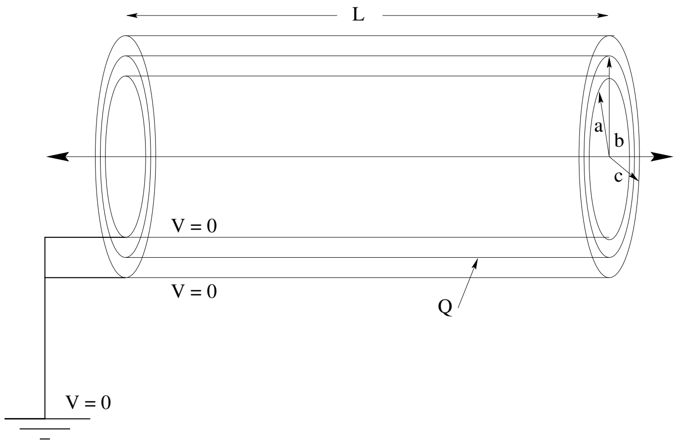
5.7



A charge of $+Q$ is placed on the innermost and outermost of three concentric conducting spherical shells. The middle shell is grounded via a thin wire that passes through an insulated hole in the outer shell and hence has a potential (relative to ∞) of 0.

a) Find the charge Q_s on the middle shell in terms of k, Q, and the given radii a, b and c.

b) Find the potential at all points in space (in each region where there is a distinct field). You may express your answers algebraically in terms of Q_s to make life a bit simpler (and independent of your answer to part a).



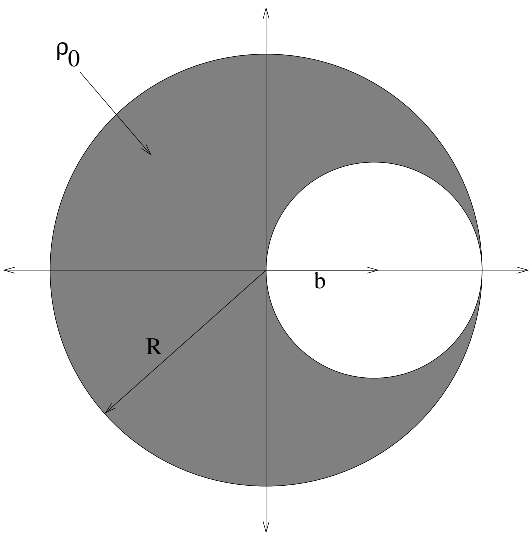
5.8

Three cylindrical conducting shells of radii $a < b < c$ and of length $L \gg c$ are placed in a concentric configuration as shown. The middle shell is given a total charge Q, and both the inner and outer shells are grounded (connected by a thin wire to each other and to something at a potential of “0”). Find:

a) The total charge on the *inner* shell, in terms of a, b, c, L, Q and k.

b) The potential on the middle shell. In what direction does the field point in between a and b and in between b and c?

5.9

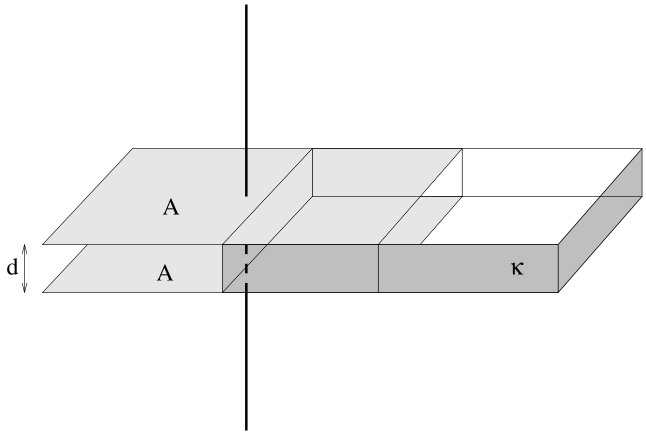


A sphere of uniform charge density ρ_0 has a hole of radius $b = R/2$ centered on $x = b$ cut out of it as shown in the figure.

a) Find the electric field **vector** inside the hole.

b) What do you *expect* to be the first two terms in the electric field expansion at an arbitrary point $x \gg R$ on the x axis? Note that you can *either* guess this answer based on what you know of multipolar fields *or* you can evaluate the field exactly (which is pretty easy) and do a binomial expansion through two surviving terms.

Hint: Remember, you can think of this as a superposition problem for two spheres, one with uniform charge density ρ_0 and one with uniform charge density $-\rho_0$.



6 Capacitance

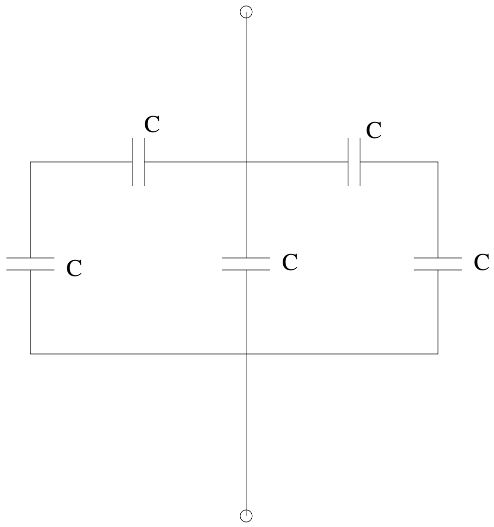
6.1

A parallel plate capacitor is constructed from two square conducting plates of with an area of A, separated by a distance of d. An insulating slab of thickness d and a dielectric constant κ is inserted so that it half-fills the space between the plates. Find:

1. (15 points) the capacitance of this arrangement;

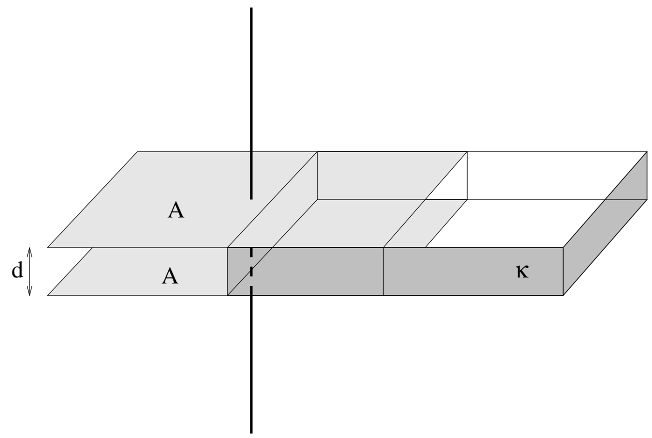
2. (5 points) the electrostatic force on the dielectric slab when a potential V is maintained across the capacitor. Does it pull the dielectric in between the plates or push it out from between them?

6.2



1. Find the total effective capacitance between the two contacts (the round circles at the top and the bottom) of the arrangement of capacitors drawn above. Naturally, show all work.

2. If a potential V is connected across the contacts, indicate the *relative* size of the charge on each capacitor. (It will probably be easiest if you give your answers in terms of $Q = CV$.)



6.3

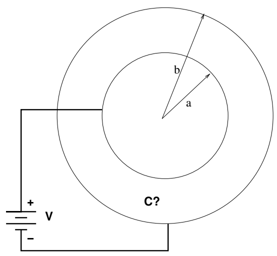
A parallel plate capacitor is constructed from two square conducting plates of with an area of A, separated by a distance of d. An insulating slab of thickness d and a dielectric constant κ is inserted so that it half-fills the space between the plates.

a) Find the capacitance of this arrangement. Clearly indicate the basic principles and definitions you are using, e.g. the definition of capacitance, the equation that defines the effect of a dielectric on the electric field and so forth.

b) Find the electrostatic force on the dielectric slab when a fixed charge of $\pm Q$ is placed on the two plates of the capacitor. If you cannot do this, for partial credit at least indicate on physical grounds whether the force pulls the dielectric in between the plates (trying to fill the space between them) or pushes it out from between them and explain your reasoning.

Hint: Consider the relation between force and potential energy.

6.4

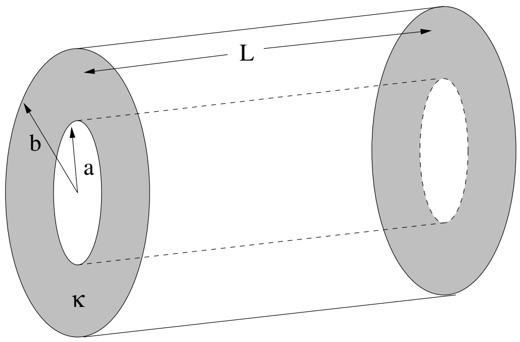


A spherical capacitor has inner radius a and outer radius b

a) Find (derive!) its capacitance of this arrangement. *Show All Work!*

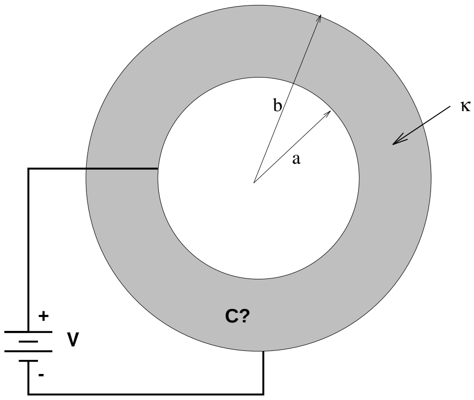
b) Show that when $b = a + \delta$ with $\delta \ll a$ the capacitance has the limiting form $C = \epsilon_0 A/\delta$ where A is the area of the inner sphere and δ is the separation of the shells.

6.5



Derive C for the cylindrical capacitor drawn above, with inner radius a, outer radius b, length L, filled with a dielectric of dielectric constant κ. *Show all work!* You must follow the progression $\vec{E} \rightarrow \Delta V \rightarrow C$, inserting or using the important property of the dielectric either at the beginning or the end.

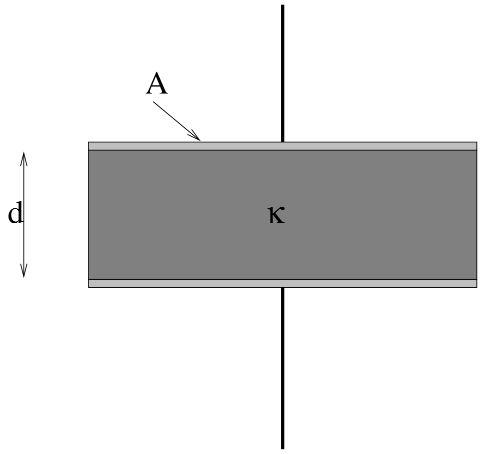
6.6



A spherical capacitor with inner radius a and outer radius b has the space in between filled with a dielectric with dielectric constant κ. Find:

- The field between the shells
- The charge on the inner and outer shells
- The capacitance of this arrangement.

Show All Work!

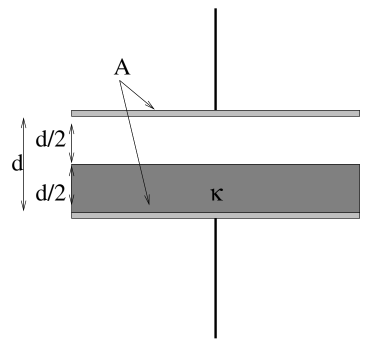


6.7

A parallel plate capacitor has cross sectional area A and separation d. A dielectric material with dielectric constant κ of thickness d and area A fills the space in between as shown.

Suppose a potential V is connected across this capacitor. Find the electric field inside the dielectric, the free charge (and hence the capacitance), and the bound charge on the surface of the dielectric. *Show all work!*

6.8

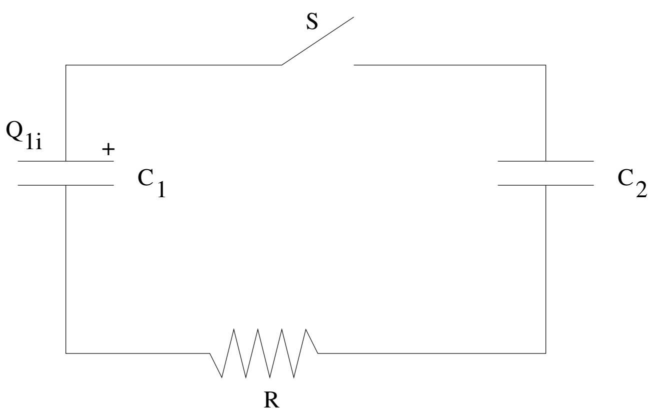


A parallel plate capacitor has cross sectional area A and separation d. A dielectric material with dielectric constant κ of thickness $d/2$ and area A half fills the space in between as shown.

Find the capacitance of this arrangement. *Show all work!*.

7 Resistors and RC Circuits

7.1

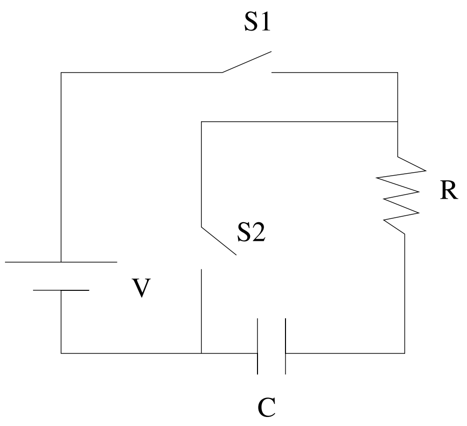


A pair of capacitors C_1 and C_2 is connected as shown, with a resistance R in between them. Initially, the first capacitor carries a total charge Q_{1i} and the second one is uncharged, $Q_{2i} = 0$. At $t = 0$ the switch is closed. Find:

a) The equilibrium ($t = \infty$) charges on the two capacitors, Q_{1f} and Q_{2f}.

b) Using Kirchoff's laws for this arrangement, find the time constant for the equilibration process. Note that you do NOT have to solve the DE, just formulate it with dt and some arrangement of R, C_1, and C_2 on the other side.

c) For extra credit, either solve the DE (it is integrable, although a bit messy) or GUESS what its solution is, based on your answers to a) and b). To do the latter, try visualizing what $Q_1(t)$ and $Q_2(t)$ will formally look like – it is just a matter of setting the various constants so that the asymptotic (final) and initial conditions are correctly represented and the approach to those conditions has the right time dependence.



7.2

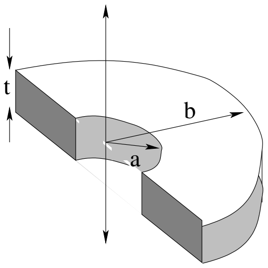
In the circuit above, R = 100Ω and C = 1μFarad, and V = 10 volts. The capacitor is initially uncharged. To simplify arithmetic to the finger and toe level, answers given algebraically in terms of powers of e are acceptable – no calculators should be strictly necessary although you can smoke 'em if you got 'em.

a) At time $t = 0$, switch 1 is closed. What is the charge on the capacitor as a function of time?

b) At time $t = 300$ microseconds, switch 1 is opened and switch 2 is closed. What is the voltage across the capacitor as a function of time.

c) At time $t = 500$ microseconds (from $t = 0$ in part a) switch 2 is opened. How much energy is stored in the capacitor at that time?

7.3



A printed circuit board contains a resistor formed of a semicircular bend of resistive material (resistivity ρ) of thickness t, inner radius a and outer radius b as shown in the figure above. Copper traces maintain a constant voltage V across the semicircular resistor. Find (in terms of the givens):

a) the resistance R of the resistor – be sure to indicate the basic formulae you are starting from for partial credit in case you can't quite get the integral right (it is like the integral in a homework problem);

b) the energy dissipated as heat in the resistor in s seconds. Again, if you cannot find R in terms of the givens (or have little confidence in your answer), you may use R and other given quantities to answer b) for at least partial credit.

Check the Units of Your Answers!

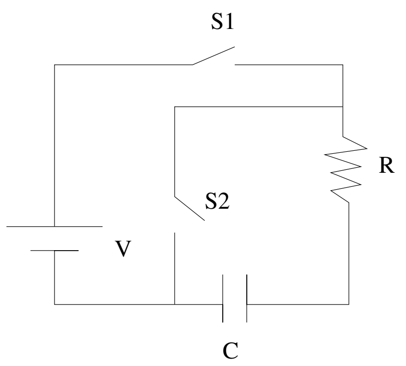
7.4

You are given a box containing a digital meter that measures current. It reads 100.0 when a current of 0.1 mA is passed through it. It has a resistance of 10 Ω. The box also contains assorted resistors in powers of 10 Ω, e.g. $\ldots \mathrm{R}_{-6} = 10^{-6}\Omega$, $\mathrm{R}_{-5} = 10^{-5}\Omega$, $\ldots$, $\mathrm{R}_{6} = 10^{6}\Omega$, $\ldots$ with at least ten resistors available at each size. The resistors are only good to 10%, though, so there is no point in trying make combinations with more than one significant digit out of different powers. Use this material to design:

a) An ammeter that makes the digital scale read Amps (that is, read (approximately) 100.0 when a current of 100.0 A is flowing into it). Draw it, label all parts, and show your reasoning.

b) A voltmeter that makes the digital scale read Volts (that is, read 100.0 with it is placed across 100 volts). Draw it, label all parts, and show your reasoning.

7.5



In the circuit above, assume R, C, and V are given. Derive all your answers for up to five bonus points, but you may just give the answers below for full credit. All answers may be expressed in terms of powers of e.

a) At time $t = 0$, switch 1 is closed. What is the *charge* on the capacitor as a function of time in terms of the given quantities.

b) After a very long time ($\gg RC$) switch 1 is opened and switch 2 is closed. What is the *voltage* across the capacitor as a function of time.

c) At time $t = 2RC$ switch 2 is opened. How much energy is stored in the capacitor at that time?

7.6

A large Leyden jar (capacitor) is surrounded by dry air so that the net resistance between its charged and grounded terminal is approximately $10^{1}0\ \Omega$. It is charged up to 50,000 volts by a Wimshurst generator (at which time it contains 0.005 Coulombs of charge). It is then disconnected and left there by a negligent physics instructor. 33 1/3 minutes later, an astrophysics professor comes into the room and, seeking to move the jar, grabs the ungrounded, charged, central terminal. How much charge seeks ground through this hapless soul's body? How much stored energy is dissipated in the process? (You can solve this algebraically if you have no calculator handy.)

Ouch! These are not unrealistic parameters. Leyden jars can be very, very dangerous for hours after they are charged up.

8 Magnetic Forces

8.1

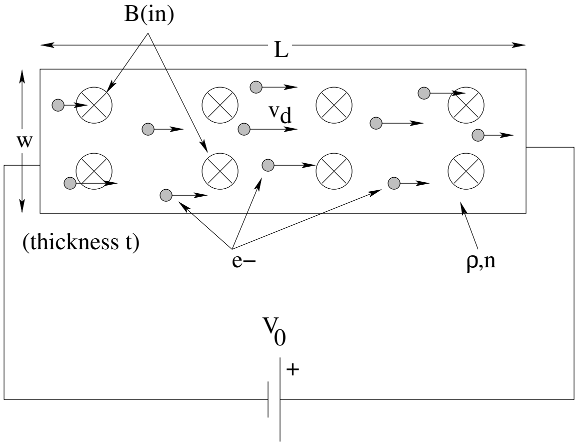
A particle of charge q and mass m has momentum (magnitude) $p = mv$ and kinetic energy $K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$. If the particle moves in a circular orbit of radius r perpendicular to a uniform magnetic field of magnitude B, show that:

- $p = Bqr$
- $K = \frac{B^2q^2r^2}{2m}$
- The angular momentum magnitude $L = Bqr^2$.

8.2

A beam of particles with velocity $\vec{v}$ enters a region of uniform magnetic field $\vec{B}$ that makes a small angle θ with $\vec{v}$. Show that after a particle moves a distance $\frac{2\pi m}{qB} v \cos(\theta)$ measured along the direction of $\vec{B}$, the velocity of the particle is in the same direction as it was when it entered the field. (Look familiar:-)

8.3

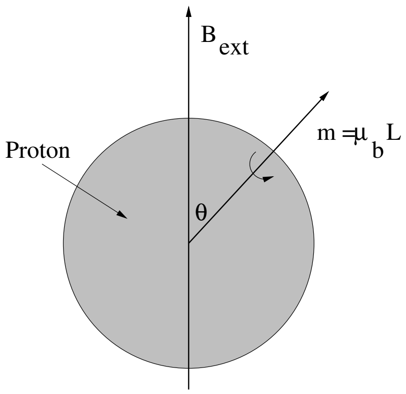


A rectangular metal strip of length L, width w, and thickness t sits in a uniform magnetic field B perpendicular to the strip and into the page as shown. The material has resistivity ρ and a free (conducting) *electron* (charge $q = -e$) density of n. A voltage V_0 is connected across the strip so that the *electrons* travel from left to right as shown.

a) Find an expression for the Hall potential (the potential difference across the strip from top to bottom) in terms of the given quantities.

b) Is the top of the strip at *higher* or *lower* potential than the bottom?

Hints: you'll have to start by relating I (the current in the strip) to the givens, and then translate that into a form involving the drift velocity v_d. From v_d and your knowledge of magnetic forces you should be able to determine the electric field and then the potential across the strip in the steady state.



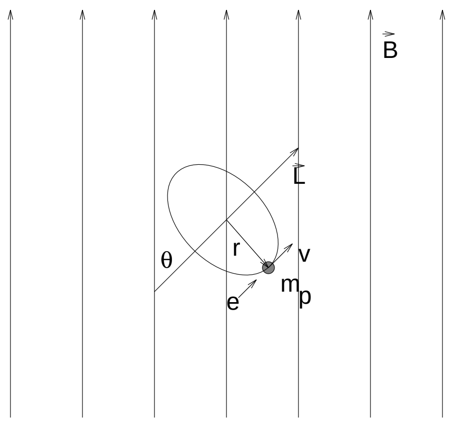
8.4

A proton (charge $+e$) with mass m_p has an intrisic angular momentum given by $\vec{L}$ and a magnetic moment given by $\vec{m} = \mu_B \vec{L}$. When the proton is placed in a uniform magnetic field of strength B so that $\vec{L}$ makes an angle of θ with $\vec{B}$, the angular momentum precesses around $\vec{B}$.

a) Find the angular frequency ω_p with which the angular momentum precesses. Indicate the direction of precession on the figure above (into or out of page, as drawn).

b) For extra credit, **derive** μ_B. One way you might proceed is to simply derive $\vec{m}$ and $\vec{L}$ separately for the proton, assuming uniform mass and charge distribution and a common angular velocity $\vec{\omega}$. A better way to proceed might be to relate dm_z (along the axis of rotation) to dL_z (ditto) assuming axial symmetry so that $\vec{L}$ is parallel to $\vec{\omega}$.

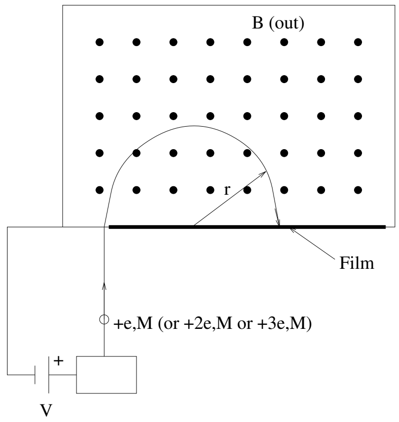
8.5



A proton (charge $+e$) with mass m_p is in a circular orbit of radius r such that it has an angular momentum given by $\vec{L}$. The orbiting proton has a magnetic moment $\vec{m}$ parallel to its angular momentum. When the orbiting proton is placed in a uniform magnetic field of strength B so that $\vec{L}$ makes an angle of θ with $\vec{B}$, the angular momentum precesses around $\vec{B}$. Find:

a) The magnetic moment of the orbit in terms of $\vec{L}$;

b) The angular frequency with which the angular momentum precesses.

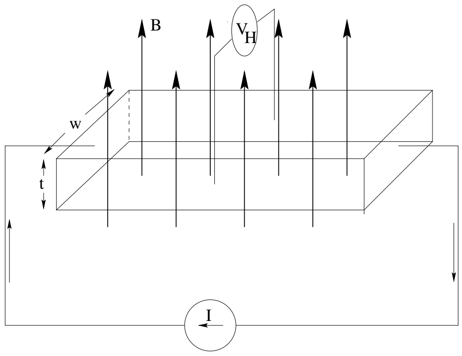


8.6

In the mass spectrograph above, the goo in the source chamber contains molecules of mass M that are ionized to have charges of $+e$, $+2e$ or $+3e$ at the source. The particles then fall through a potential of V and enter the uniform B field in the box.

a) Derive an expression for the radius r at which a fragment of charge-to-mass ratio of m/q hits.

b) Use this expression to find r for each of the three possible ionization charges, and draw a picture of the bars produced on the film to a reasonable scale.

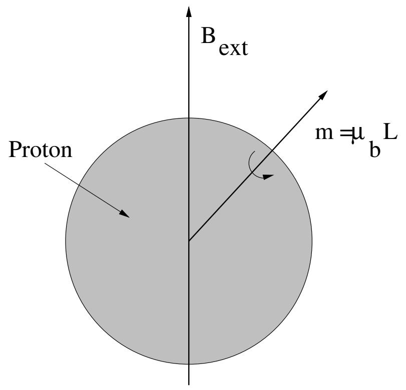


Voltage V_H measured across w
Magnetic Field B perpendicular to strip as shown
Current I measured through strip in direction shown

8.7

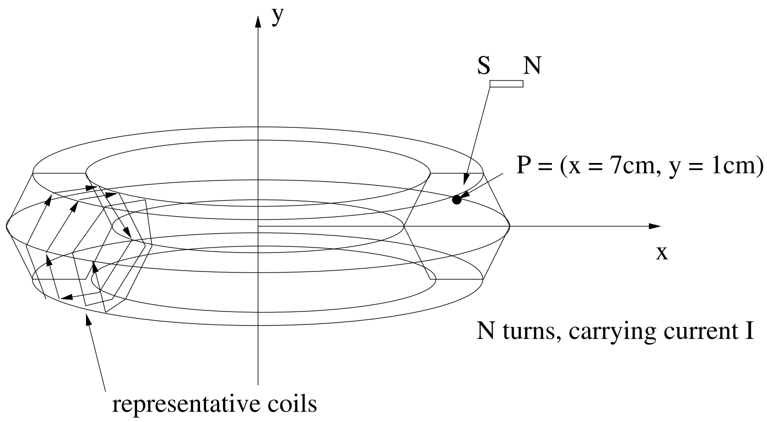
The apparatus for measuring the Hall effect is shown above. Consider a charge carrier q (to keep you from having to mess with the negative charge on the real charge carriers – electrons) moving through the apparatus in a material with an unknown n charge carriers per unit volume. **Derive** an expression for n, given I, V_H, t, B, w and q. Note that I'd have to consider you moderately insane to have memorized this result (I certainly haven't) but by considering the strip to be a region of self-maintaining crossed fields and relating the current to the drift velocity you should be able to get it fairly easily.

8.8



A model for a proton (charge $+e$) with mass m_p has an intrinsic angular momentum given by $\vec{L}$ and a magnetic moment given by $\vec{m} = \mu_B \vec{L}$ (where $\mu_B = Q/2M$ for reasons you should completely understand). When the proton is placed in a uniform magnetic field of strength B so that $\vec{L}$ makes an angle of θ with $\vec{B}$, the angular momentum precesses around $\vec{B}$.

Find (*derive*) the angular frequency with which the angular momentum precesses. Indicate the direction of precession on the figure above (into or out of page, as drawn).



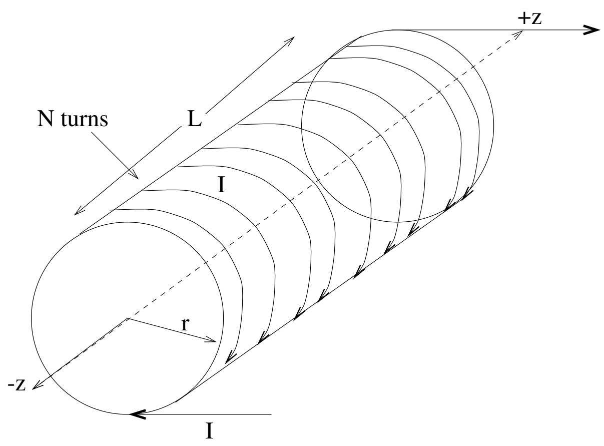
9 Magnetic Fields and Ampere's Law

9.1

a) Find the magnetic field at the point labelled P in the toroidal solenoid pictured above, when $N = 1000$ turns and $I = 10$ amps. Indicate its direction on the picture.

b) If a bar magnet (magnetic dipole with length l and pole strength q) is placed so that its south pole is at P and its north pole is oriented outward along x (as shown) what is the approximate *direction* of the net force on the dipole?

9.2



A solenoid has length L, N turns, and radius r is centered on the z-axis. A current I is driven through the solenoid.

a) *Derive* the magnetic field $\vec{B}$ inside the solenoid, neglecting end effects. Draw the direction of the field lines in on your picture.

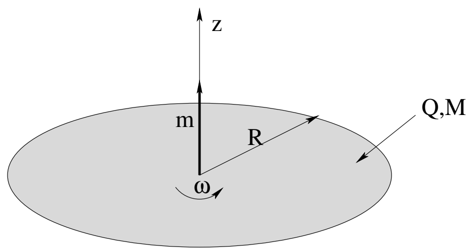
b) *Derive* the self-inductance of the solenoid.

In both cases, start from fundamental principles, equations, laws or definitions and clearly state what they are; do not just put down a remembered answer.

9.3

Using the Biot-Savart law, find the magnetic field at an arbitrary point on the z-axis of a circular loop or radius a carrying a current I counterclockwise around the z-axis and centered on the origin in the x-y plane. Draw the arrangement in the space provided above, of course. Show all work – don't just write the answer down even. Then find the field in the limit that $z \gg a$ and show that it is the familiar field of a (magnetic) dipole on its axis.

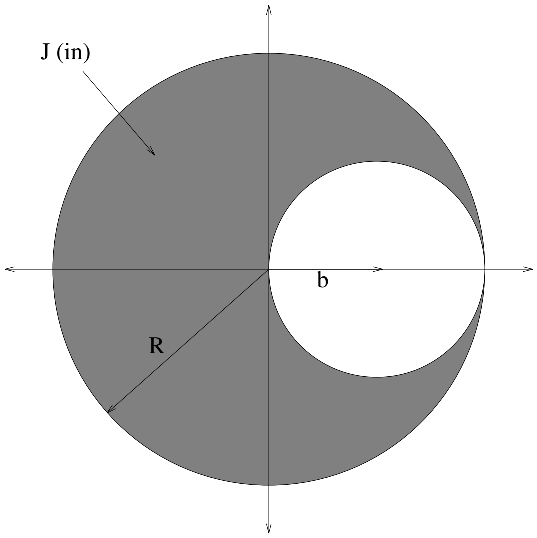
9.4



A flat disk of radius R with uniform surface charge density $\sigma_q = \frac{Q}{\pi R^2}$ and surface mass density $\sigma_m = \frac{M}{\pi R^2}$ is rotating at angular velocity ω.

Show that its magnetic moment $\vec{m} = \mu_B \vec{L}$ with $\mu_B = \frac{Q}{2M}$.

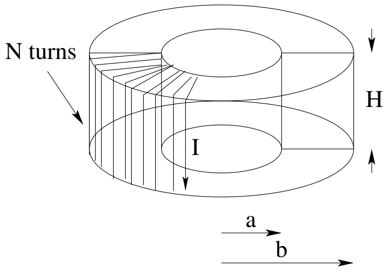
9.5



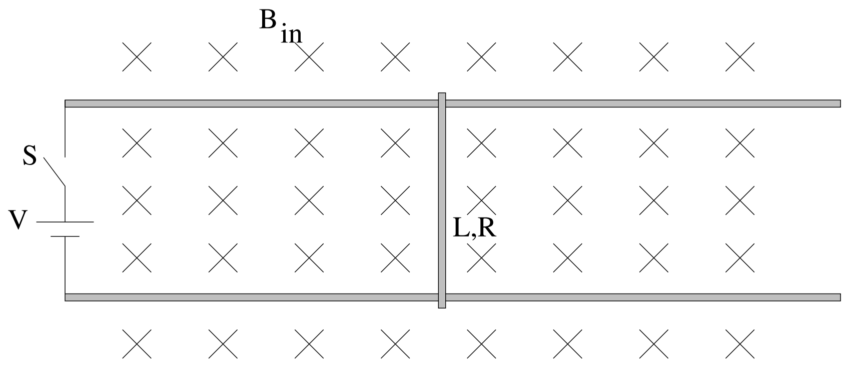
A cylindrical long straight wire of radius R has a cylindrical long straight hold of radius $b = R/2$ and carries a current density of $\vec{\mathbf{J}}$ into the page as drawn. Find the magnetic field (magnitude and direction) at an arbitrary point inside the hole.

10 Inductance and Faraday's Law

10.1



Find the self-inductance L of a toroidal solenoid with a rectangular cross-section (height H, inner radius a, outer radius b) and N turns. Presume that the wires are wrapped uniformly all the way around and carry a current of (for example) I.



10.2

A rod of mass m, resistance R and length L is sitting at rest on frictionless rails in a magnetic field as shown. At $t = 0$, the switch S is closed and a voltage V applied across the rails. Show all work while deriving the following results, clearly indicating the physical law used and reasoning process. Neatness and clarity count.

a) What is the net voltage across the resistance R as a function of $|\vec{v}|$?

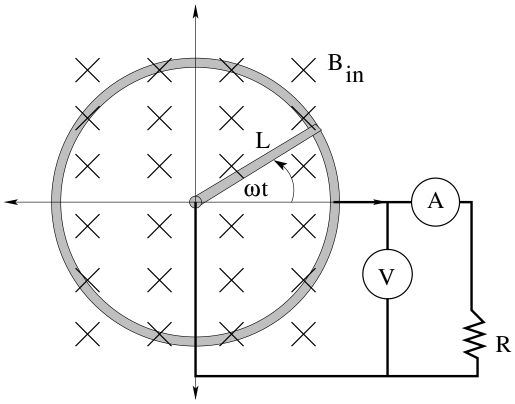
b) What is the current I in the loop as a function of $\vec{v}$?

c) What is the force $\vec{F}$ on the rod as a function of $\vec{v}$?

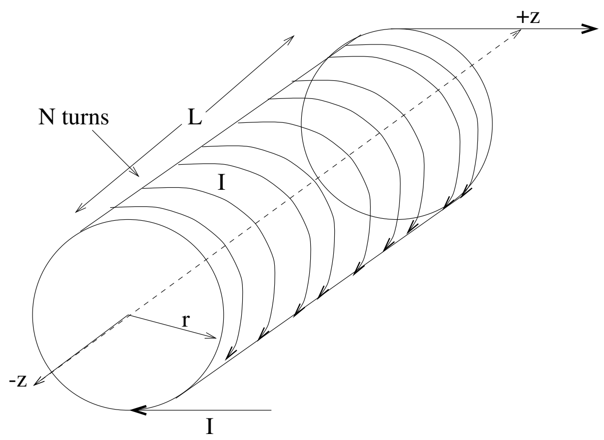
d) What is the terminal velocity of the rod as $t \to \infty$?

10 points of extra Credit: Solve the first order, linear, ordinary, inhomogeneous differential equation and find the velocity of the rod $\vec{v}(t)$ as a function of time. Draw a qualitatively correct curve showing this function and show how it corresponds to your answer to d).

10.3



A rod of length L is pivoted at one end and swings around at an angular frequency ω with its other end sliding along a circular conducting track. A magnetic field B_{in} is oriented perpendicular to the plane of rotation of the rod as shown. The pivot point and the outer ring are connected by (fixed) wires across a resistance R with a voltmeter and ammeter inserted in the circuit as shown. What do the voltmeter and ammeter read?



10.4

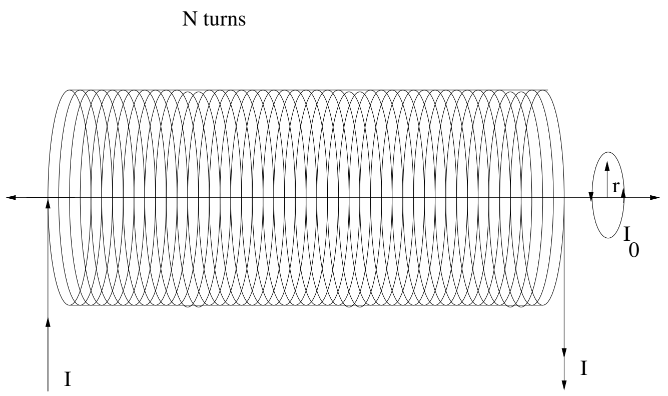
A solenoid is built of length L with N turns and a radius of r. A current I is driven through the solenoid. **Derive from basic laws and definitions**:

a) The magnetic field $\vec{B}$ inside the solenoid, neglecting end effects (magnitude and direction, given the direction of current flow drawn).

b) The magnetic flux ϕ_m through the solenoid, as a function of I?

c) What is the self-inductance of the solenoid?

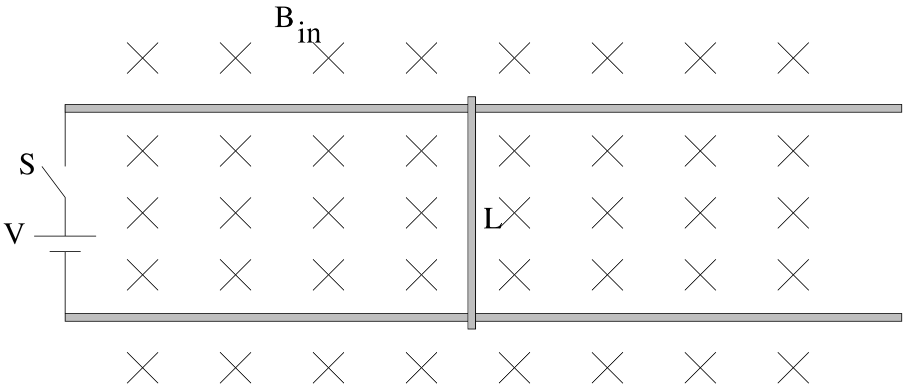
You might prefer to draw your own picture(s) to facilitate the work.



10.5

a) Find the magnetic field inside the solenoid pictured above, when $N = 1000$ turns and $I = 10$ amps, assuming that it is "much longer than its diameter". Indicate its direction on the picture.

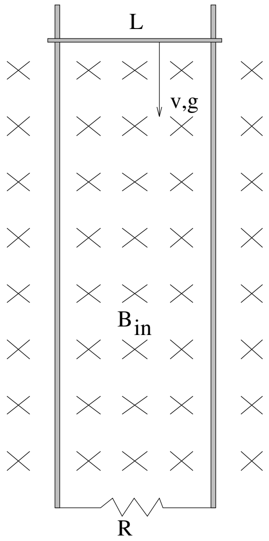
b) If a current loop of radius r carrying a current I_0 is placed near the end of the solenoid as shown, should it experience a force? Why or why not?



10.6

A rod of mass m, resistance R and length L is sitting at rest on frictionless rails in a magnetic field as shown. At $t = 0$, the switch S is closed and a voltage V applied across the rails. Find the velocity of the rod as a function of time from a combination of Newton's laws, Ohm's law, and Faraday's law. If you are clueless (in spite of this being a homework problem and very similar to a quiz problem) at least tell me what all those laws and the terminal velocity *are* for most of the credit.

10.7



A rod of length L and mass m slides on frictionless conducting guides down vertical rails, connected at the bottom, that enclose a uniform magnetic field of magnitude B as shown, starting at rest at $t = 0$. The loop formed by the rod and rails has a total resistance of R. **Gravity** makes the rod fall. Find:

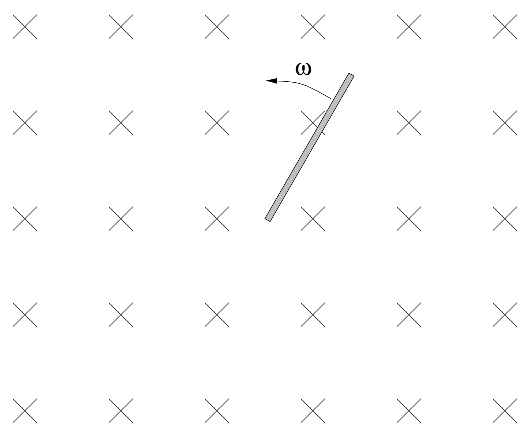
a) The current $I(v)$ induced in the rod when the speed of the rod is v (down). Indicate the direction on the figure above.

b) The **net** force on the rod as a function of v.

c) The "terminal velocity" of the rod $\boldsymbol{v}_t$.

d) For extra credit, explicitly solve the equations of motion and find $v(t)$ for all times, assuming of course that it hasn't yet fallen off of the rails.

10.8

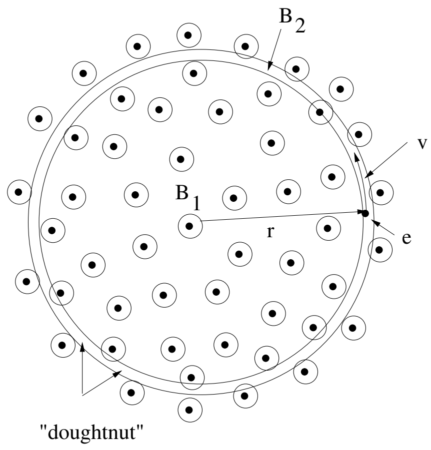


A conducting bar of length L rotates at an angular frequency ω in a uniform, perpendicular magnetic field as shown.

b) Find the forces acting on a charge $+q$ in the rod (magnitude and direction) at the radius r. What causes these forces and what direction do they point?

a) Find the potential difference developed between the central end of the rod and a point at radius r on the rotating rod.

c) Discuss the *qualitative* distribution of charge in the (presumed neutrally charged) rod, assuming that it is in equilibrium (has been rotating for a long time). Draw a qualitative graph of $\rho(r)$, the charge density as a function of r to support your assertions. That is, you don't have to have exactly the right functional form but your curve should have all the right features.



10.9

A Betatron (pictured above with field out of the page) works by increasing a uniform magnetic field in such a way that electrons of charge e and mass m inside the "doughnut" tube are accelerated by the E-field produced by induction from the average time-dependent magnetic field $B_1(t)$ inside r (via Faraday's law) while the average magnitude of the magnetic field at the radius $B_2(t)$ bends the electrons around in the constant radius circle of radius r.

This problem solves for the "betatron condition" which relates $B_1(t)$ to $B_2(t)$ such that both things can simultaneously be true.

a) First, assuming that the electrons go around in circles of radius r and are accelerated by an $\vec{E}$ field produced by Faraday's law from the average field B_1 inside that radius, solve for that induced E field in terms of B_1 and r.

b) Second, assuming that the electrons are bent into a circle of radius r by the average field at that radius, B_2, relate B_2 to the momentum $p = mv$ and charge e of the electron, and the radius r.

c) Third, noting that the force F from the E-field acting on the electron with charge e in part a) is equal to the time rate of change of p in the result of b) substitute, cancel stuff, and solve for dB_1/dt in terms of dB_2/dt. If you did things right, the units will make sense and the relationship will only involve dimensionless numbers, not e or m.

Cool! You've just figured out how to build one of the world's cheapest electron accelerators! Or perhaps not....

11 Maxwell's Equations and Light

11.1

Invent and compare spaceships (draw them in the blank space above) that are driven according to the following (ideal) criteria. The actual source of power is e.g. a small fusion plant onboard the spaceship.

a) Suppose a spaceship is powered by a laser that emits 1000 Watts in a beam 1 cm^2 in cross-sectional area. What is the recoil force (per KW) exerted by the laser?

b) Suppose instead the spaceship is powered by throwing mass. If it throws 1000 small beads per second, each with mass $m = 1$ gram and with a kinetic energy of 1 Joule per bead (so the power required to operate it is still 1000 Watts), what is the average force (per KW) exerted by the mass-driver?

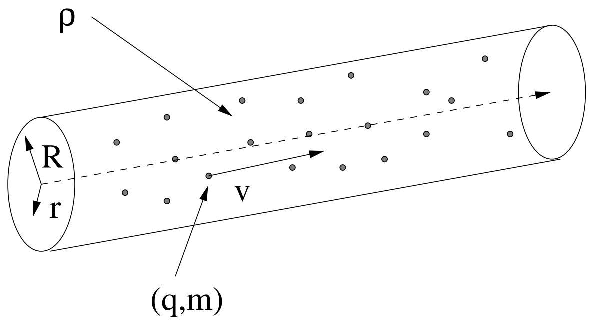
11.2

You need to decide whether or not to buy a solar panel for your house (or if you prefer, if solar cells are an economically viable way to produce electricity compared to burning fossil fuels). Use the facts below and your understanding of light energy to *estimate* whether or not you will invest in a panel based energy system.

- The sun produces 4×10^{26} Watts of power and is 1.5×10^{11} meters away from the earth.
- Only about 70% of this makes it down through the atmosphere on a clear day at the equator.
- On average, at our latitude the sun will strike your panel at an angle of 45%.
- The solar panel converts sunlight into electrical energy and stores it into a battery to be recovered later at an overall efficiency of about 10%.
- Electricity can be purchased from a power company at a cost of \$0.10 kW-hour (what is that in joules?).
- A 1 m^2 solar panel and associated battery storage system cost approximately \$1000.

If you collect an average of six hours of sunlight a day, roughly how long would it take to recover the cost of a panel? Show *all* of your reasoning, supporting it with figures and diagrams as needed. Note that to be *completely* fair, you'd need to add in the cost of borrowing the money for the panel in which case the answer might well be "never", but let's go with the easy answer first.

You may make "reasonable" simplifying assumptions to make your arithmetic easier as you proceed as long as you are very clear as to what they are, e.g. – six hours is 0.25 days, $0.25 * 365 \approx 100$ days...

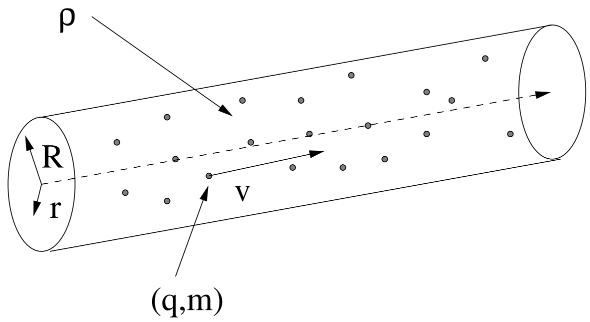


11.3

Beam Dynamics: Each part of this problem (a and b) will be graded separately. You do not need to get the first part right to do the second part, but obviously you need to get both parts right to get the extra credit.

A cylindrical beam of particles each with charge q and mass m has a uniform initial (charge) density ρ and radius R. Each particle in the beam is initially travelling with velocity v parallel to the beam's axis. We will discuss the stability of this beam by examining the forces on a particle travelling in the beam at a distance $r < R$ from the axis (the center of the cylinder).

a) Find the force on a particle at radius r caused by the other particles in the beam. You will need to use Gauss's law to calculate the electric field at radius r. Describe your work, and do not skip steps; show that you understand Gauss's law. Make a sketch as needed. .



11.4

Beam Dynamics: Each part of this problem (a and b) will be graded separately. You do not need to get the first part right to do the second part, but obviously you need to get both parts right to get the extra credit.

A cylindrical beam of particles each with charge q and mass m has a uniform initial (charge) density ρ and radius R. Each particle in the beam is initially travelling with velocity v parallel to the beam's axis. We will discuss the stability of this beam by examining the forces on a particle travelling in the beam at a distance $r < R$ from the axis (the center of the cylinder).

b) Find the magnetic force on a particle at radius r caused by the other particles in the beam. Use Ampere's law to calculate the magnetic field. Describe your work, and do not skip steps; show that you understand Ampere's law. Make a sketch.

c) (5 points extra credit) At what beam velocity do the forces in a) and b) exactly balance? Given the unbalanced electric force *in the rest frame of the particles* from a), offer a hypothesis that can explain both measurements.

12 AC Circuits

12.1

Draw a *series* LRC circuit above with an alternating voltage $V_0 \cos(\omega t)$, clearly labeling the (presumably given) L, R, and C.

a) Draw the phasor diagram that represents Kirchhoff's rule for the voltages around the loop.

b) Draw the phasor diagram for the impedance Z and write down its value in terms of the givens. Also indicate the value of the phase angle δ in terms of the givens.

c) What is the resonant frequency ω_0 for the circuit in terms of the givens?

d) Draw a semi-quantitatively correct graph of the average power $P(\omega)$ delivered to the circuit for $Q = 10$, clearly indicating the location of ω_0. At the very least, the graph scales should be arguably consistent with the value of Q.

12.2

Draw a *parallel* LRC circuit above with an alternating voltage $V_0 \cos(\omega t)$, clearly labeling the (presumably given) L, R, and C.

a) Draw the phasor diagram that represents Kirchhoff's rule for the currents around the loop. What is the form of the total current as a function of time?

b) Draw the phasor diagram from which the impedance Z can be determined and write down its value in terms of the givens. Also indicate the value of the phase angle δ in terms of the givens.

c) What is the resonant frequency ω_0 for the circuit in terms of the givens?

d) Does the average power delivered to the circuit depend on ω? Why or why not?

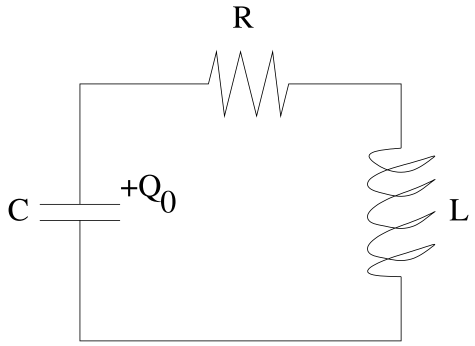
12.3

(20 pts)

You are building an FM radio ($f \approx 100$ MHz) and have a power supply and circuitry that generates annoying harmonics in the low frequencies (especially 60 Hz, but also AM stations around 1 MHz contribute) that contaminate your high frequency output and causes your signal to "buzz'. Naturally, you have a parts box that contains resistors and capacitors. The range of resistors available runs from 1 Ohm through 100,000 Ohms (to one significant digit – don't bother with resistances like 3.845 Ohms as their rated value is generally accurate only to 10% or so anyway – call it 4 Ohms instead), and you have capacitors that range from 1 microfarad to 1 picofarad, but only in multiples of ten (e.g. 10^{-6} farads, 10^{-7} farads, ..., 10^{-12} farads).

Design a "high pass" filter built from one resistor and one capacitor (where you get to choose suitable values for R and C as well as their arrangement) that will output more than half the input voltage for all frequencies greater than 10 MHz but strongly attenuates the output voltage for frequencies more than a bit less than this, and derive the expression (for your circuit) for $V_{\rm out}/V_{\rm in}$ as a function of R, C and ω. Draw the circuit in the space above, of course, clearly indicating where $V_{\rm in}$ and $V_{\rm out}$ go.

(Hints and Notes: This *was* a homework problem, so you *should* know what a high pass filter is. If you don't remember exactly, consider a series combination of R and C and think about what happens to the voltage drops across each one as a function of ω. Your "output voltage" will come from a parallel connection across one or the other.)



12.4

At time $t = 0$ the capacitor in the LRC circuit above has a charge Q_0 and the current in the wire is $I_0 = 0$ (there is no current in the wire). Find $Q(t)$, and draw a qualitatively correct picture of $Q(t)$ in the case that the oscillation is only weakly damped. Show all your work. Remember that $Q(t)$ is real.

12.5

Draw a series LRC circuit connected across an alternating voltage source. Suppose $R = 40\Omega$, $C = 0.2\mu$f, $L = 0.80m$H, and the frequency of the applied voltage is $\omega = 10^5$ radians/second. What is:

a) The impedance Z of the circuit?

b) The resonant frequency of the circuit, ω_0?

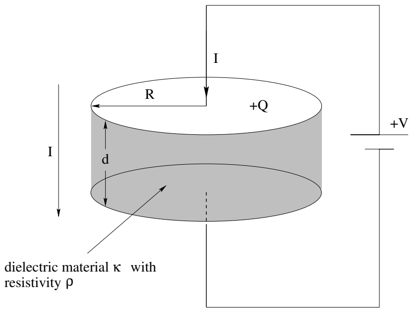
12.6

Draw a parallel LRC circuit connected across an alternating voltage source. Suppose you are given R, C, L, and an applied voltage $V_0 \sin(\omega t)$. What is:

a) The impedance Z of the circuit?

b) The power $P(t)$ dissipated by the resistor?

12.7



Our archetypical model for a resistor is drawn above: two circular "perfectly conducting" plates (metal contacts) with radius R, separated at a distance d by a material with resistivity ρ.

a) In a steady state situation where a DC voltage V is applied as shown, find the field $\vec{E}$ inside the resistive material.

b) Find the current density $\vec{J}$ inside the resistive material.

c) From Ampere's law, find the magnetic field as a function of r in the region between the plates.

d) From your answers to a) and c), find the Poynting vector $\vec{S}$ (magnitude and direction) as a function of r in the region in between the plates.

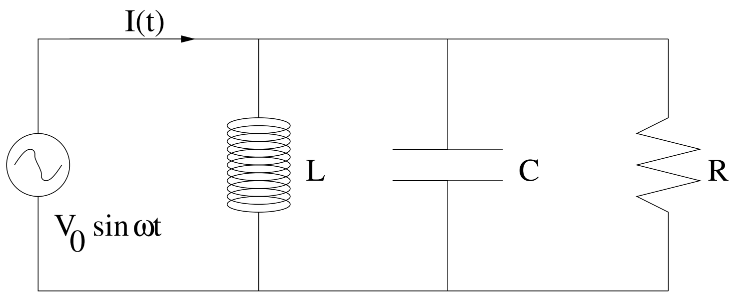
e) NOW show that:

$$\oint_A \vec{S} \cdot \hat{n} dA = -I^2 R$$

where A is the outer surface of the resistor and $\hat{n}$ is its outward-directed normal unit vector.

Thus the heat that appears in the resistor *can* be thought of as the electromagnetic field energy that flows in through its outer surface!

Solution Page

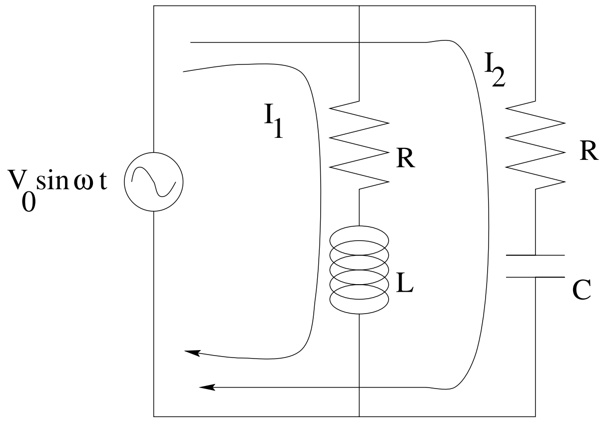


12.8

A *parallel* LRC circuit connected across a variable AC voltage source $V = V_0 \sin(\omega t)$ is drawn above. Find (in terms of L, R, C, V_0, ω and any quantities you define in terms of these such as χ_L or χ_c):

a) The current $I_{L,R,C}(t)$ in each element of the circuit. Don't forget the phase shifts (if any), and note that we are getting *current* from *voltage* – be careful!

b) Now find the current $I(t)$ in the primary supply wire (as shown in the figure above) with all terms, e.g. any required phase δ, and the impedance Z defined and (at the end) numerically evaluated. You will probably need to draw the appropriate phasor diagram to help you figure this out unless you managed to memorize the entire LRC circuit chapter results.



12.9

a) Draw (two) qualitatively correct phasor diagrams that show the voltage drops and gains for each of the two loops shown. Be sure to correctly indicate the phases of the currents I_1 and I_2 relative to the phase of the applied voltage and the voltage drop across each element.

b) Write the Kirchoff's Law (Voltage) for each of the two loops shown that corresponds to your phasor diagram.

c) From a) and b), find the impedance of each loop Z_1 and Z_2, the current phase of each loop δ_1 and δ_2, and write down an expression for $I_1(t)$ and $I_2(t)$. Try to work neatly enough that I can grade this.

d) For extra credit, use Kirchoff's Law (current) to find the total impedance of the circuit, the total current provided by the voltage, and the total power provided by the voltage.

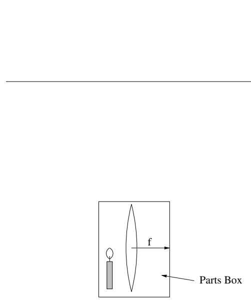
13 Geometric Optics and Polarization

13.1

Indicate, with pictures and/or a short descriptions, how light is polarized by absorption, by reflection, and by scattering. Derive and explain the formula for the Brewster angle (telling us what the Brewster angle is). Derive and explain Malus's law, which quantitatively describes how much light polarized in one direction passes through a filter whose transmission axis is rotated through an angle θ with respect to that direction.

13.2

Derive Snell's Law. You may use either the wave picture (that I gave in class) or the Fermat principle (which was on your homework). For a bit of extra credit, do it both ways. Be sure to give the definition of index of refraction.



13.3

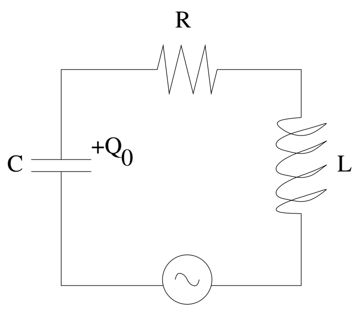
You have a candle and a lens with a focal length of 15 cm. You wish to cast a real image of the candle upon a screen. You want the image size (magnitude) to be exactly two times the size of the actual candle.

a) Find s and s' such that this kind of image can be formed.

b) Carefully place the components on the figure above and draw a ray diagram to locate the image, to scale, in agreement with your answers to a. Be sure to include the 3 rays that uniquely specify the image location.

Don't burn yourself on the candle.

13.4

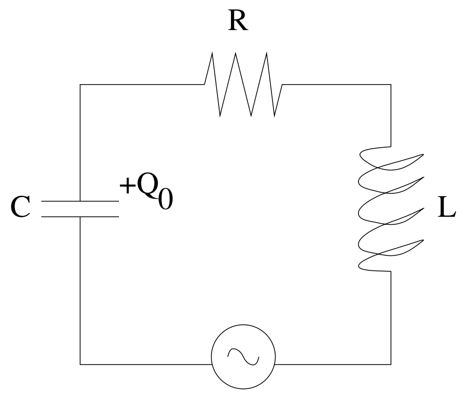


The LRC circuit above is connected to an alternating voltage $V_0 \cos(\omega t)$ and the circuit is run until it is in a steady state. Assume that the current in this circuit is given by $I_0 \cos(\omega t - \delta)$.

1. Draw the phasor diagram that represents Kirchoff's voltage rule for the circuit, clearly marking the voltage drops across each circuit element that sum to the total applied voltage. Clearly label e.g. δ.

2. Draw the related figure for the impedance Z for the circuit. Write the impedance in terms of R, L, C and ω.

3. Draw a *qualitatively* correct figure of $P_{\text{av}}(\omega)$ (the average power as a function of ω) for the oscillator if it has $Q = 10$ and a resonant frequency ω_0.



13.5

The LRC circuit above is connected to an alternating voltage $V_0 \sin(\omega t)$ and the circuit run until it is in a steady state.

1. Write Kirchoff's voltage rule for this circuit loop.

2. Draw the phasor diagram for the voltage, noting that the current must be in phase with the voltage across the resistor.

3. From this phasor diagram and the relations between maximum current, reactance or resistance of the circuit elements, and the maximum voltage drop across them, deduce and draw the phasor diagram for the impedance Z of the circuit.

4. Draw a *qualitatively* correct figure of $P_{\text{av}}(\omega)$ (the average power as a function of ω) for the oscillator if it has $Q = 10$ and a resonant frequency ω_0.

13.6

It is sunset on a clear day. You are wearing your trusty polaroid sunglasses. You look straight overhead and the sky is somewhat dark. You slowly turn your body to the right (continuing to look up) and the sky gradually lightens to become maximally bright. At this moment your body is facing(circle correct answer):

1. North
2. East
3. South
4. West
5. East or West
6. North or South
7. Cannot tell from information given

Draw a set of diagrams and write a paragraph or two showing ALL OF THE PHYSICS that explains your answer – include descriptions BOTH of the polaroid sunglasses themselves and the light scattering off of molecules in the atmosphere overhead.

13.7

Light propagates down a light fiber by reflecting off the walls.

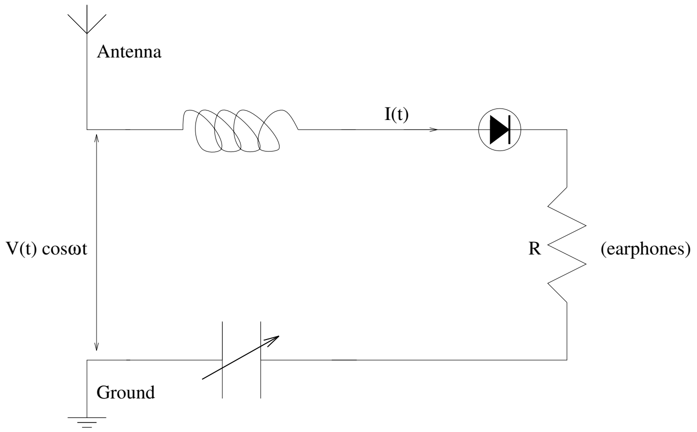
a) Assuming that the fiber has an index of refraction of $n = 1.4$, what is the critical angle of incidence such that light will remain trapped in the fiber?

b) Indicate how you *think* light might be polarized in the fiber after propagating a few meters (and bouncing several times off the walls). Show the polarization direction(s) in cross section. Indicate WHY you think the light would be polarized that way.

13.8

a) Unpolarized light is incident on the surface of diamond (n = 2.4). Some of the light is reflected from the diamond; the rest penetrates the diamond surface and is refracted. Find the angle at which the reflected light is *completely* polarized and indicate the direction of polarization on a suitable figure.

b) Diamond is interesting for another reason. It "traps light" and reflects it internally many times as it bounces from facet to facet. Explain how a diamond (with n = 2.4) traps more light more than a piece of glass (n = 1.5). Your answer should be at least partly quantitative.

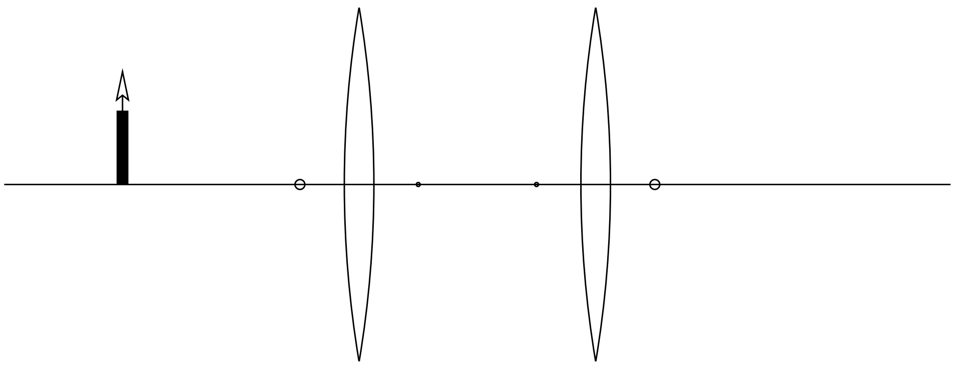


13.9

One kind of simple crystal radio consists of the *series* LRC circuit drawn above. The antenna-to-ground connection represents an amplitude-modulated AC voltage source $V = V(t)\cos(\omega t)$ where $\omega = 2\pi \times 10^6$ radians/sec. The diode (in series with the earphone of resistance R) is a circuit element that only lets current flow in the direction of the arrow – a one-way gate. The capacitor can be varied to tune the radio.

a) How should the capacitor be set (with respect to the value of L) to tune the radio to deliver the maximum current through the earphones (resistance R) and what is that maximum current? Assume that the diode has negligible resistance and capacitance and that the amplitude-modulation is slow relative to ω^{-1}.

b) Describe qualitatively, with a suitable picture or figure, how the diode allows the amplitude-modulated signal ($V(t)$) to be extracted from the carrier frequency ω.



14 More Optics (mostly)

14.1

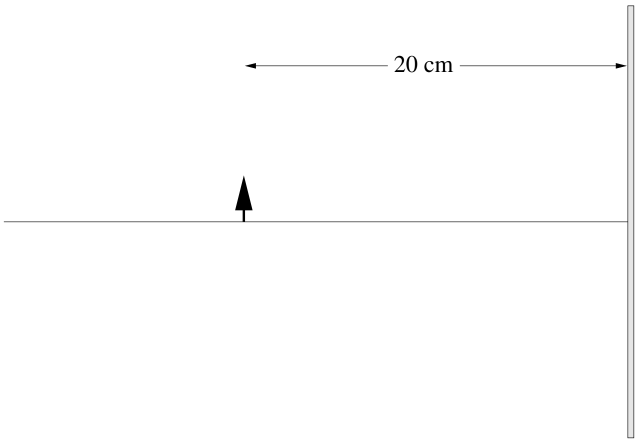
A candle 20 cm high is placed 40 cm in front of the center of a thin lens. This lens has a focal length of 10 cm. A second thin lens, also with a focal length of 10 cm, is placed 40 cm from the first. Find:

a) The location s' of the image due to the **first** lens and its magnification. Indicate whether the image is real or virtual.

b) The location s'' of the image (of the image of the first lens) of the **second** lens. Find the overall magnification, and indicate if the final image is real or virtual.

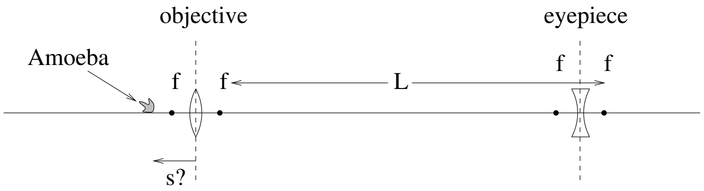
c) Draw a ray diagram to locate the image in agreement with your answers to a and b. Be sure to include and label 3 rays that uniquely specify the image locations.

14.2



There is an object 20 cm away from a screen. Using a concave mirror, I would like to throw an image of this object upon the screen that is three times larger than the object itself. Find the location of the mirror (with respect to object and screen and the focal length of the mirror necessary to accomplish this. Draw the corresponding ray diagram.

14.3



The arrangement of lenses that makes up a "Gallilean" compound microscope is pictured above. The focal lengths of the objective and eyepiece lenses are $f_o = 1$ cm and $f_e = -1$ cm. The tube length is $L = 20$ cm.

a) Find s (the object distance from the objective lens) such that the final image viewed by the eye is in focus (at infinity, as imaged by the eyepiece).

b) Draw the ray diagram from which you can find the overall magnification. NOTE WELL the tube length goes to the second (negative) focal point of the eyepiece. Why?

c) From this diagram, find the overall magnification. Explain each part (that is, what are the separate roles of the objective and eyepiece).

d) What is the advantage of this kind of microscope compared to one with two converging lenses?

14.4

Draw below a Gallilean telescope (one built with a converging primary lens and a *diverging* eyepiece lens). Draw it to scale so that the overall angular magnification is $M = 10$. Derive (with a figure and the correct rays and triangles and angles) its magnification in terms of f_p, f_e, and any other parameters you think necessary. Remember, f_e is *negative* for a Gallilean telescope – be sure to specify whether the brain perceives the final image right side up or upside down so that there is no ambiguity.

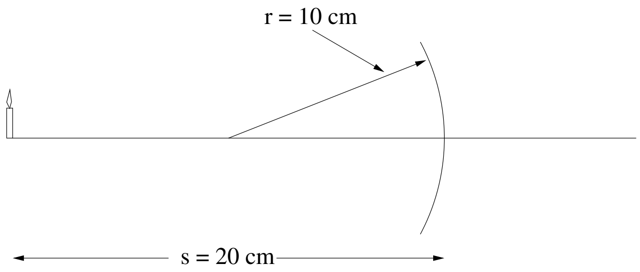
Note that the rays used to derive the magnfication are tricky for a diverging eyepiece, so be careful.

14.5

a) Design a microscope with a tube length $\ell = 10$ cm and a magnification of 500. Draw it below to scale. Derive its magnification in terms of f_o (the objective lens) , f_e, ℓ, and any other parameters you think necessary. You may pick f_o and f_e to have any “sensible” values, and can make the microscope invert the image or not as you wish.

b) Determine where (that is, the actual position in cm) one has to place the object in front of the objective lens in order for the relaxed, normal eye to view its image at infinity through the eyepiece. Note that this answer will depend (obviously) on f_o and other parameters, so the number answer is less important than the algebra (which is what will be checked).

14.6



The mirror above has a radius of curvature $r = 10$ cm. A candle is placed at $s = 20$ cm as shown. Find:

- The focal length of the mirror (draw the focal point in on the diagram above).
- The location s' of the image in centimeters.
- The magnification of the image.
- State whether the image is real or virtual, erect or inverted.
- Draw the ray diagram for this arrangement using the three "named" rays used for both lenses and mirrors as shown in class. Obviously it should validate your answers to the above.

14.7

This problem will be solved algebraically in terms of the positive length $f > 0$. If it pleases you to make this length definite, say 10 cm, feel free, but it is not necessary.

A small object is placed $2f$ in front of a *diverging* (convex) mirror with focal length $-f$ – negative because it is diverging. Determine (in terms of f where appropriate):

1. The image distance s'.
2. The magnification m.
3. The kind of image (erect/inverted, real/virtual).

Draw a **neat ray diagram** for the arrangement using (and labelling!) the three standard rays covered in class to locate the image. It should at least approximately correspond to your numerical results above. It's a good idea to use a straightedge of some sort, and try to make the size of the diagram reasonable so it clearly illustrates the problem.

14.8

A physics professor hands you a box that contains the following material: lens A with $f_A = 100$ cm, lens B with $f_B = 200$ cm, lens C with $f_C = -2$ mm, lens D with $f_D = 5$ mm and lens E with $f_E = -5$ mm. There are also 4 meter sections of PVC pipe that fit each lens and that can be cut with a handy hacksaw, sleeves that nest the PVC pipe sections together, some glue, focus gears (that can be used to move the eyepiece lens small distances along its axis), and things like that.

a) Create a rough design in the space above for a refracting telescope with an angular magnification $M = -200$, made using this material and equipment. Clearly indicate the lenses you use and their arrangement in the tube(s).

b) Draw below a simple ray diagram from which the angular magnification of a general refracting telescope of the sort you design can be evaluated. It need not be precisely to scale.

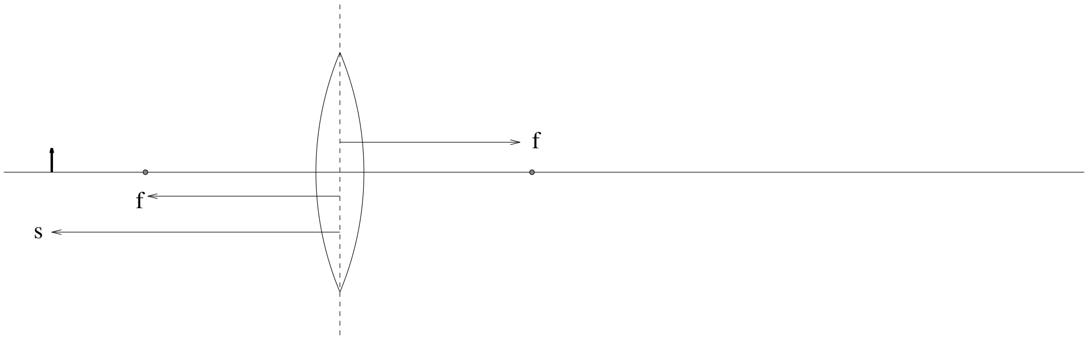
Note that this telescope will only be used to look relatively *distant* objects.

14.9

A physics professor hands you a box that contains the following material: (mounted) lens A with $f_A = 10$ cm, lens B with $f_B = 1$ cm, lens C with $f_C = 5$ mm and lens D with $f_D = -2$ mm. There is also a piece of tubing 15 cm long that fits the lens mounts exactly and can be cut to any length you like with the enclosed hacksaw, a focus gear (that can be used to move the objective lens mount small distances along its axis in the tube), glue, screws, a slide/tube mounting bracket, and things like that.

Create a rough design in the space above for a simple microscope with a magnification of $M = -500$ using this material and equipment. Clearly indicate the lenses you use and their arrangement in the tube.

14.10

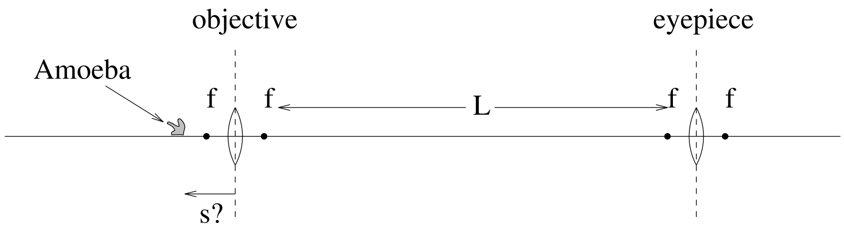


A candle 10 cm high is placed 75 cm in front of the center of a thin lens. The lens has a focal length of 50 cm.

a) Find the location s' of the image, its magnification, and indicate whether the image is real or virtual.

b) Draw a ray diagram to locate the image in agreement with your answers to a. Be sure to include the 3 rays that uniquely specify the image location.

14.11



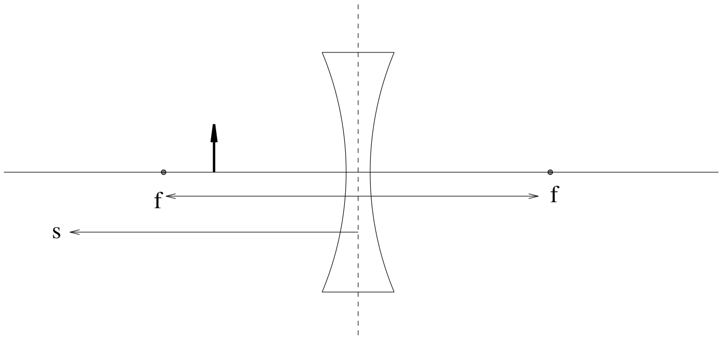
The arrangement of lenses that makes up a compound microscope is pictured above. The focal lengths of the objective and eyepiece lenses are $f_o = f_e = f = 1$ cm. The tube length is $L = 9$ cm.

a) Find s (the object distance from the objective lens) such that the final image viewed by the eye is in focus (at infinity, as imaged by the eyepiece).

b) Draw the ray diagram from which you can find the overall magnification (try to use a straight edge to do this).

c) From this diagram and your knowledge of the separate purposes of the two lenses, find the overall magnification. Explain each part (that is, what are the separate roles of the objective and eyepiece).

14.12



A candle 20 cm high is placed 60 cm in front of the center of a thin lens. The lens has a focal length of -80 cm.

a) Find the location s' of the image, its magnification, and indicate whether the image is real or virtual.

b) Draw a ray diagram to locate the image in agreement with your answers to a. Be sure to include 3 rays that uniquely specify the image location.

15 Physical/Wave Optics

15.1

Two vertical slits of width 1500 nanometers (nm) are separated (center to center) by a distance of 2500 nm and illuminated by light of wavelength 500 nm. The light which passes through is then projected on a distant screen. Find:

a) The location (angles θ) of all **diffraction minima**.

b) The location of all **interference minima**.

c) The location of all **interference maxima**.

d) Finally, draw a properly proportional figure of the resulting interference pattern between 0 and $\pi/2$ (on either side), indicating the maximum intensity in terms of the central maximum intensity that would result from a single slit.

15.2

All angles in the parts a-c may be expressed by means of tables of inverse trigonometric functions of simple fractions, e.g. $\cos^{-1}(1/2)$, $sin^{-1}(2/7)$, etc.

Two vertical slits of width $a = 1200$ nanometers (nm) are separated (center to center) by a distance of $d = 3000$ nm and illuminated by light of wavelength $\lambda = 600$ nm. The light which passes through is then projected on a distant screen. Find:

a) The location (angles θ) of all **diffraction minima**.

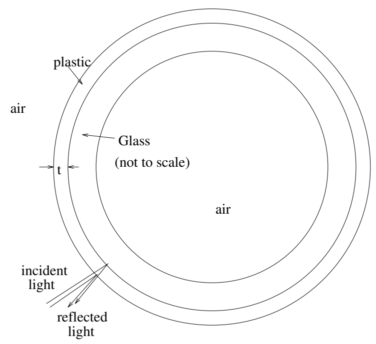
b) The location of all **interference minima**.

c) The location of all **interference maxima**.

d) Finally, draw a properly proportional figure of the resulting interference pattern between 0 and $\pi/2$ (on either side), indicating the maximum intensity in terms of the central maximum intensity that would result from a single slit.

e) For five points of extra credit, write down the algebraic expression for $I(\theta)$ in terms of I_0 (the central intensity of a single slit), defining all variables used (like ϕ and δ) in terms of a, d, λ and θ.

15.3

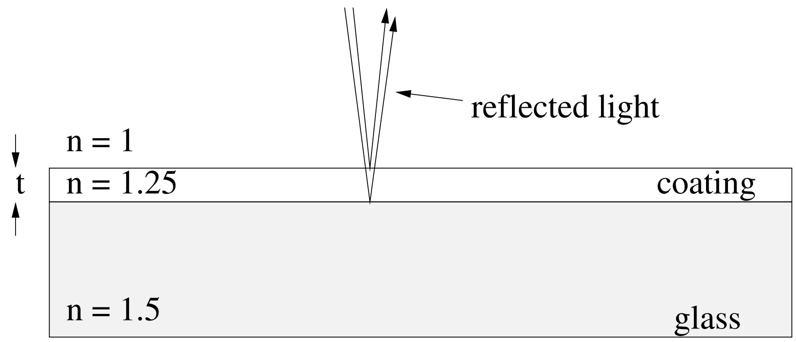


A Christmas tree ornament is constructed by vapor-depositing a thin, transparent film (with $n = 1.25$) on a "thick" (~ 2 mm) spherical glass ($n = 1.5$) bubble as drawn schematically above. The thin plastic film is not quite uniform in thickness, and this variation produces brilliant streaks of color in the reflected light.

a) What does the light reflected from the ornament look like where $t \sim 0$ (or $t \ll \lambda$, at any rate). Explain the physics behind your answer with a single sentence and/or diagram.

b) At what thickness $t \sim \lambda > 0$ of the film will the reflected light first have a constructive interference *maximum* at $\lambda = 550$ nm (where λ, recall, is the wavelength in free space where $n = 1$)?

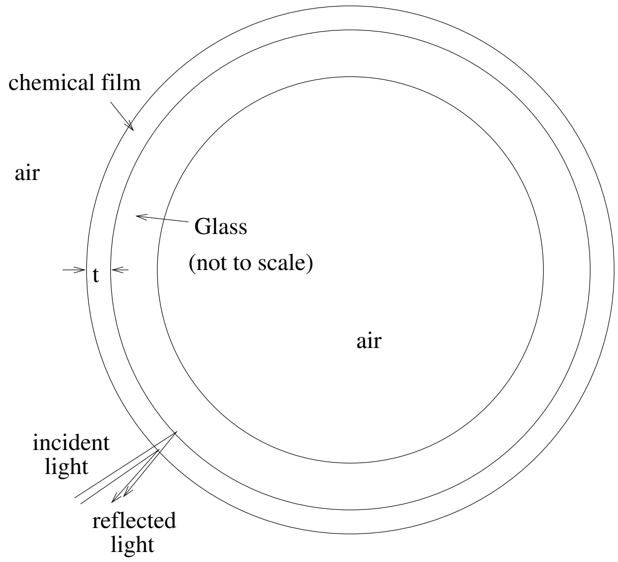
c) At that thickness, will any other visible wavelengths have an interference maximum or minimum? Justify your answer – just 'yes' or 'no' (even if correct) are incorrect.



15.4

You would like to eliminate the reflected light from a flat glass pane for perpendicularly incident light of wavelength 550 nm. The index of refraction of the glass is $n_g = 1.5$, and the index of refraction of the coating material to be used is $n_c = 1.25$. What minimum thickness t of the coating material will have the desired effect? (Try to show your reasoning, and don't forget "details".)

15.5



A Christmas tree ornament is constructed by vapor-depositing a chemical film (with n = 1.7) on a "thick" ($\sim$ 2 mm) spherical glass (n = 1.5) bubble as drawn schematically above. The thin chemical film is not uniform in thickness, and its variation in the range 0-2 microns (micrometers) produces brilliant streaks of color in the reflected light.

a) What is the smallest (nontrivial) mean thickness t of the film such that reflected light to has a constructive interference *maximum* in the center of the visible spectrum (λ = 400-700 nm in free space where $n = 1$).

b) When the film first starts to deposit on the glass (and has a thickness t of only a few nanometers) does the film on the bulb turn shiny (constructively reflecting all wavelengths) or transparent (destructively reflecting all wavelengths)? Explain.

15.6

Light with wavelength $\lambda = 700$ nm passes through two slits of a width $a = 1400$ nm. The centerpoints of these two slits are separated by a distance of $d = 3500$ nm. The light then travels a long distance and falls on a screen. It is *not* necessary (for once) to derive or justify the equation(s) you use below, but if you do you will get partial credit even if your numerical answers are wrong.

a) Write down (or derive) the algebraic formula for the intensity of the combined interference-diffraction pattern for this arrangement.

b) Write down (or derive) the formula from which the angles at which diffraction minima occur can be found, and apply it to find *all* these angles (put them in a table).

c) Write down (or derive) the formulas from which the angles at which interference maxima and minima occur, and apply them to find **the first three of each** (only) (put them in a table).

d) Draw a qualitatively correct picture of the expected diffraction/integration pattern $I(\theta)$.

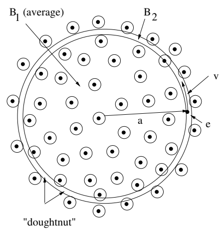
15.7

Light with wavelength $\lambda = 300$ nm passes through two slits of a width $a = 900$ nm. The centerpoints of these two slits are separated by a distance of $d = 2700$ nm. The light then travels a long distance and falls on a screen. It is *not* necessary (for once) to derive or justify the equation(s) you use below, but if you do you will get partial credit even if your answers are wrong.

a) Write down (or derive) the formula from which the angles at which diffraction minima occur can be found, and apply it to find *all* these angles (put them in a table).

b) Write down (or derive) the formulas from which the angles at which interference maxima and minima occur, and apply them to find the first three of each (put them in a table).

c) Draw a qualitatively correct picture of the expected diffraction/integration pattern $I(\theta)$.



15.8

A Betatron is pictured above (with field out of the page). It works by increasing a non-uniform magnetic field $\vec{B}(r)$ in such a way that electrons of charge e and mass m inside the "doughnut" tube are accelerated by the E-field produced by induction (via Faraday's law) from the "average" time-dependent magnetic field $B_1(t)$ inside a, while the magnitude of the magnetic field at the radius a, $B_2(t) = |\vec{B}(a,t)|$, bends those same electrons around in the circle of (constant) radius a.

This problem solves, in simple steps, for the "betatron condition" which relates $B_1(t)$ to $B_2(t)$ such that both things can simultaneously be true.

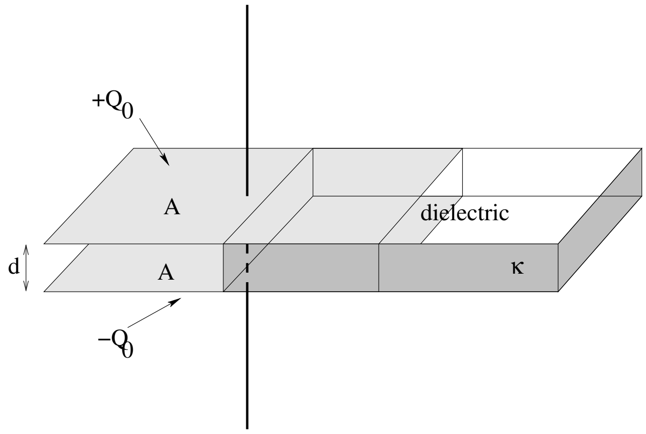
a) The electrons go around in circles of radius a and are accelerated by an $\vec{E}$ field produced by Faraday's law. We will define the (magnitude of the) average field B_1 by $\phi_m = B_1(\pi a^2) = \int_{(r<a)} \vec{B}(r) \cdot \hat{n} dA$. What is the induced E field (tangent to the circle) in terms of B_1 and a?

(Problem continued on next page!)

b) The electrons (at their instantaneous speed v tangent to the circle) are bent into the circle of radius a by the field B_2. Relate B_2 to the magnitude of the momentum $p = mv$, the charge e of the electron, and the radius a.

c) The force $\vec{F}$ from the E-field acting on the electron with charge e in the direction of its motion is equal to the time rate of change of the magnitude of its momentum p (if Newton did not live in vain). Substitute, cancel stuff, and solve for $\frac{dB_1}{dt}$ in terms of $\frac{dB_2}{dt}$. If you did things right, the units will make sense and the relationship will only involve dimensionless numbers, not e or m.

Cool! You've just figured out how to build one of the world's cheapest electron accelerators! Or perhaps not....



16 Misc

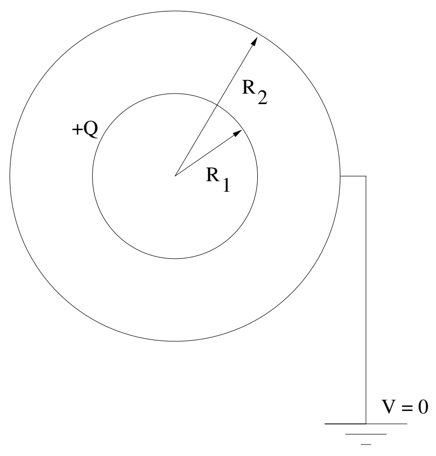
16.1

A parallel plate capacitor is constructed from two square conducting plates of with an area of A, separated by a distance of d. An insulating slab of thickness d and a dielectric constant κ is inserted so that it half-fills the space between the plates as shown. Find:

1. The capacitance of this arrangement;

2. The electrostatic force on the dielectric slab when a the capacitor carries a total charge (fixed) Q_0 on the top plate and $-Q_0$ on the bottom plate.

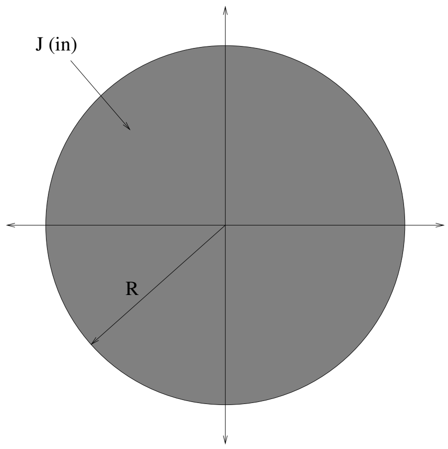
3. For extra credit, would the direction of the force be the same if a constant voltage ΔV were applied across the plates? Indicate *why* if you try to answer this one.



16.2

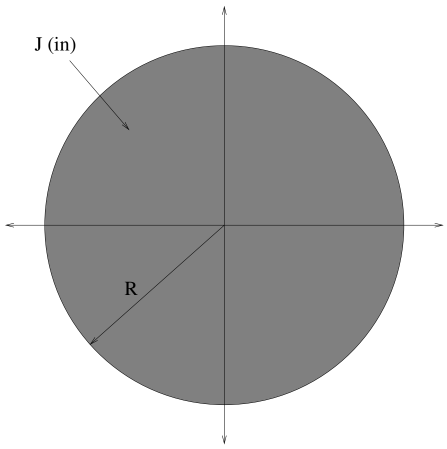
Two concentric spherical conducting shells of radii R_1 and R_2 are arranged as shown. The inner shell is given a total charge $+Q$. The outer shell is grounded (connected to a conductor at zero potential) as shown.

Find the potential and field at all points in space. Show all work – don't just write down answers even if you can "see" what the answers must be.



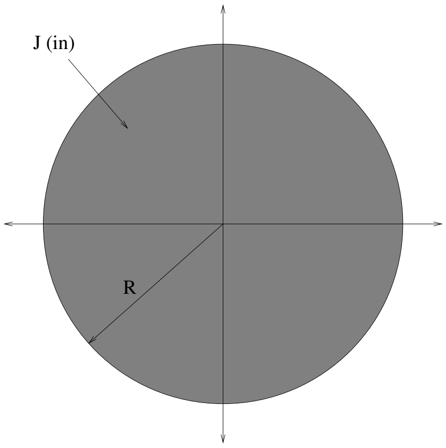
16.3

A cylindrical long straight wire of radius R has a cylindrical long straight hold of radius $b = R/2$ and carries a current density of $\vec{\mathbf{J}}$ into the page as drawn. Find the magnitude of the magnetic field for arbitrary $r > R$ (region I) and $r < R$ (region II). Indicate the direction of the magnetic field in these regions on the diagram above.

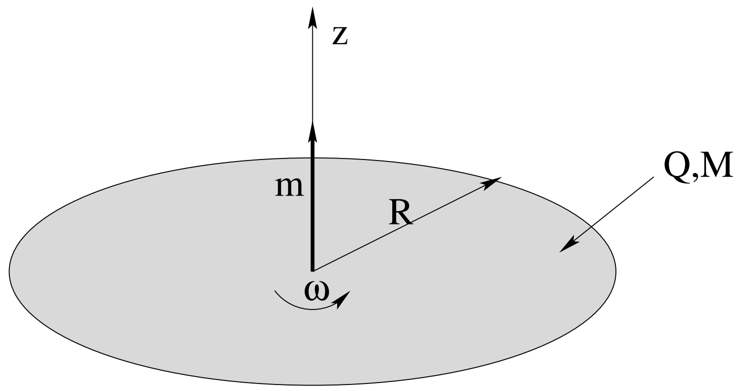


16.4

A cylindrical long straight wire of radius R carries a current density of $\vec{\mathbf{J}}$ into the page as drawn. Find the magnetic field (magnitude and direction) at arbitrary points inside and outside the wire. Show all work and clearly label the law or rule used to find the answer.



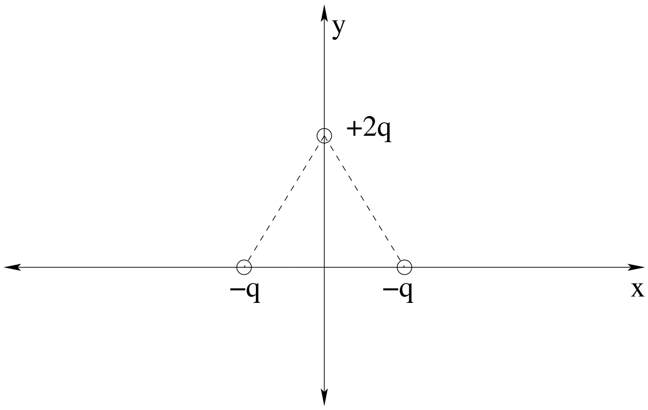
16.5



16.6

A flat disk of radius R and mass M with uniform surface charge density $\sigma_q = \frac{Q}{\pi R^2}$ is rotating at angular velocity ω about the z-axis as shown.

Find its magnetic field at an arbitrary point on the z-axis.



16.7

Charges of $-q$ are located at both $y = a$ and $y = -a$, and a charge of $+2q$ is located at $y = 0$ on the y-axis. This arrangement of charge can be visualized as two opposing dipoles.

a) Find the electric field (magnitude and direction) at an arbitrary point on the x-axis.

b) What is *nonzero* term in the expansion of the electric field evaluated *far* from the charges, i.e. – for $x >> a$? Your answer should be a series of terms in inverse powers of x.

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