5. Now imagine the following experiment, but *don't do it yet.* What will happen to the image on the paper if you cover half of the mirror with your hand?

Prediction:____________________________

Test your prediction. If your prediction was incorrect, can you explain what happened?

6. Now imagine forming an image with a convex mirror (one that bulges outward), and that therefore bends light rays away from the central axis (i.e., is diverging). Draw a typical ray diagram.

Is the image real, or virtual? Will there be more than one type of image?

Prediction:____________________________

Test your prediction.

Exercise 3A: Object and Image Distances

Equipment:

optical benches

converging mirrors

illuminated objects

1. Set up the optical bench with the mirror at zero on the centimeter scale. Set up the illuminated object on the bench as well.

2. Each group will locate the image for their own value of the object distance, by finding where a piece of paper has to be placed in order to see the image on it. (The instructor will do one point as well.) Note that you will have to tilt the mirror a little so that the paper on which you project the image doesn't block the light from the illuminated object.

Is the image real or virtual? How do you know? Is it inverted, or uninverted?

Draw a ray diagram.

3. Measure the image distance and write your result in the table on the board. Do the same for the magnification.

4. What do you notice about the trend of the data on the board? Draw a second ray diagram with a different object distance, and show why this makes sense. Some tips for doing this correctly: (1) For simplicity, use the point on the object that is on the mirror's axis. (2) You need to trace two rays to locate the image. To save work, don't just do two rays at random angles. You can either use the on-axis ray as one ray, or do two rays that come off at the same angle, one above and one below the axis. (3) Where each ray hits the mirror, draw the normal line, and make sure the ray is at equal angles on both sides of the normal.

5. We will find the mirror's focal length from the instructor's data-point. Then, using this focal length, calculate a theoretical prediction of the image distance, and write it on the board next to the experimentally determined image distance.

Exercise 4A: How strong are your glasses?

This exercise was created by Dan MacIsaac.

Equipment:

eyeglasses

diverging lenses for students who don't wear glasses, or who use converging glasses

rulers and metersticks

scratch paper

marking pens

Most people who wear glasses have glasses whose lenses are diverging, which allows them to focus on objects far away. Such a lens cannot form a real image, so its focal length cannot be measured as easily as that of an converging lens. In this exercise you will determine the focal length of your own glasses by taking them off, holding them at a distance from your face, and looking through them at a set of parallel lines on a piece of paper. The lines will be reduced (the lens's magnification is less than one), and by adjusting the distance between the lens and the paper, you can make the magnification equal 1/2 exactly, so that two spaces between lines as seen through the lens fit into one space as seen simultaneously to the side of the lens. This object distance can be used in order to find the focal length of the lens.

1. Does this technique really measure magnification or does it measure angular magnification? What can you do in your experiment in order to make these two quantities nearly the same, so the math is simpler?

2. Before taking any numerical data, use algebra to find the focal length of the lens in terms of d_o, the object distance that results in a magnification of 1/2.

3. Use a marker to draw three evenly spaced parallel lines on the paper. (A spacing of a few cm works well.) Measure the object distance that results in a magnification of 1/2, and determine the focal length of your lens.

Exercise 5A: Double-Source Interference

1. Two sources separated by a distance $d = 2$ cm make circular ripples with a wavelength of $\lambda = 1$ cm. On a piece of paper, make a life-size drawing of the two sources in the default setup, and locate the following points:

A. The point that is 10 wavelengths from source #1 and 10 wavelengths from source #2.

B. The point that is 10.5 wavelengths from #1 and 10.5 from #2.

C. The point that is 11 wavelengths from #1 and 11 from #2.

D. The point that is 10 wavelengths from #1 and 10.5 from #2.

E. The point that is 11 wavelengths from #1 and 11.5 from #2.

F. The point that is 10 wavelengths from #1 and 11 from #2.

G. The point that is 11 wavelengths from #1 and 12 from #2.

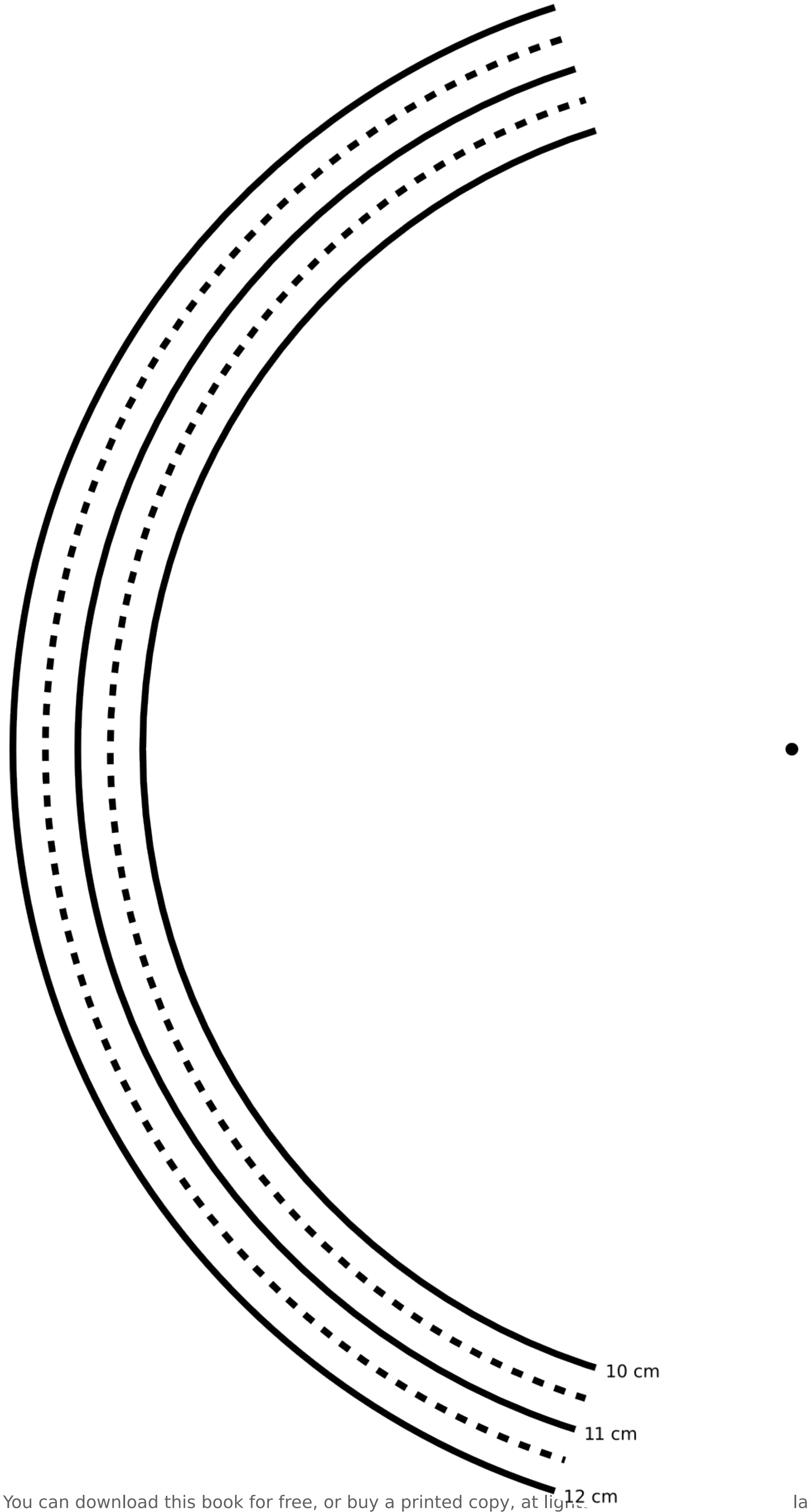
You can do this either using a compass or by putting the next page under your paper and tracing. It is not necessary to trace all the arcs completely, and doing so is unnecessarily time-consuming; you can fairly easily estimate where these points would lie, and just trace arcs long enough to find the relevant intersections.

What do these points correspond to in the real wave pattern?

2. Make a fresh copy of your drawing, showing only point F and the two sources, which form a long, skinny triangle. Now suppose you were to change the setup by doubling d, while leaving λ the same. It's easiest to understand what's happening on the drawing if you move both sources outward, keeping the center fixed. Based on your drawing, what will happen to the position of point F when you double d? Measure its angle with a protractor.

3. In part 2, you saw the effect of doubling d while leaving λ the same. Now what do you think would happen to your angles if, starting from the standard setup, you doubled λ while leaving d the same?_________

4. Suppose λ was a millionth of a centimeter, while d was still as in the standard setup. What would happen to the angles? What does this tell you about observing diffraction of light?


10 cm
11 cm
12 cm

Exercise 5B: Single-slit diffraction

Equipment:

rulers

computer with web browser

The following page is a diagram of a single slit and a screen onto which its diffraction pattern is projected. The class will make a numerical prediction of the intensity of the pattern at the different points on the screen. Each group will be responsible for calculating the intensity at one of the points. (Either 11 groups or six will work nicely – in the latter case, only points a, c, e, g, i, and k are used.) The idea is to break up the wavefront in the mouth of the slit into nine parts, each of which is assumed to radiate semicircular ripples as in Huygens' principle. The wavelength of the wave is 1 cm, and we assume for simplicity that each set of ripples has an amplitude of 1 unit when it reaches the screen.

1. For simplicity, let's imagine that we were only to use two sets of ripples rather than nine. You could measure the distance from each of the two points inside the slit to your point on the screen. Suppose the distances were both 25.0 cm. What would be the amplitude of the superimposed waves at this point on the screen?

Suppose one distance was 24.0 cm and the other was 25.0 cm. What would happen?

What if one was 24.0 cm and the other was 26.0 cm?

What if one was 24.5 cm and the other was 25.0 cm?

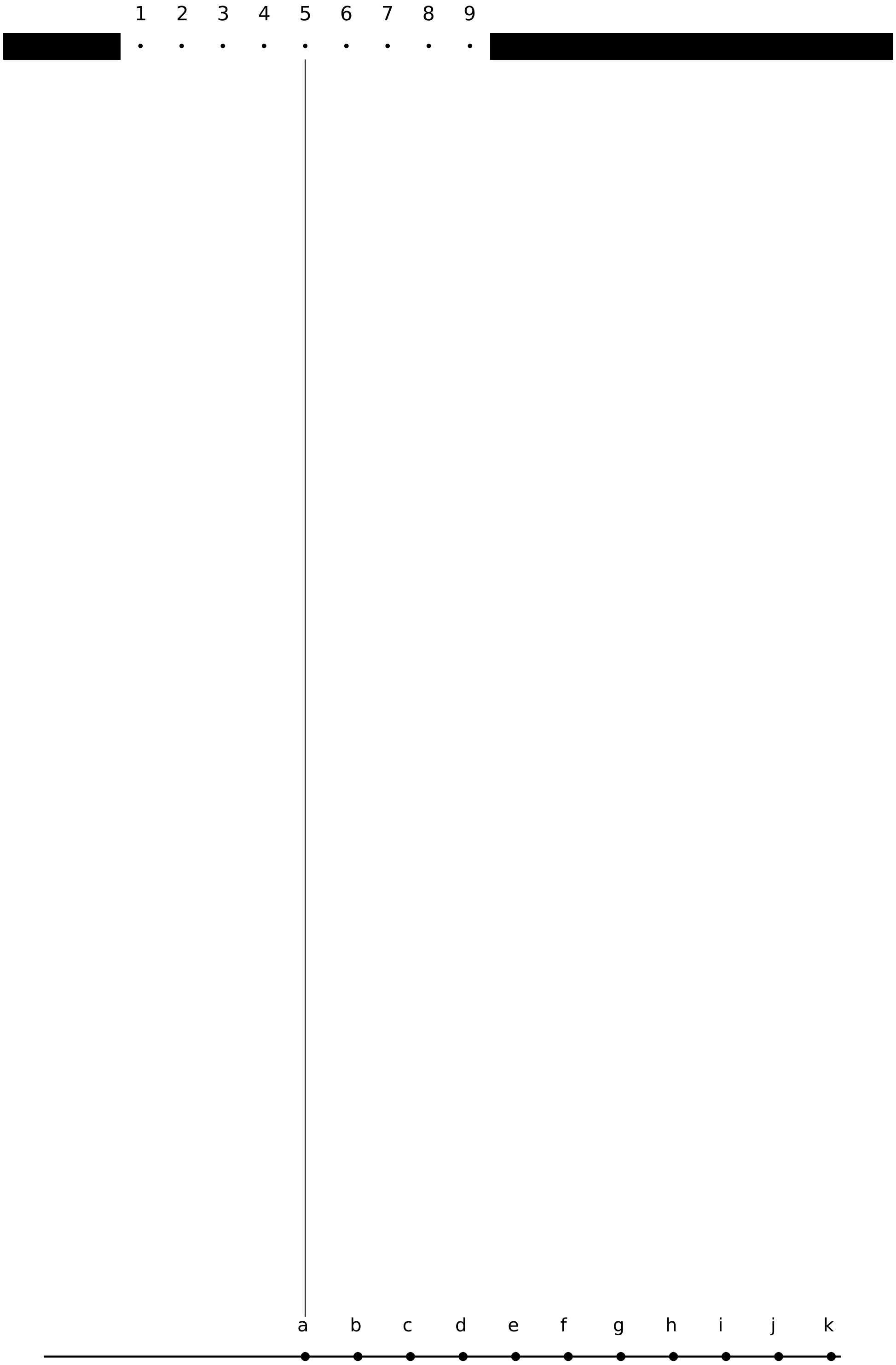
In general, what combinations of distances will lead to completely destructive and completely constructive interference?

Can you estimate the answer in the case where the distances are 24.7 and 25.0 cm?

2. Although it is possible to calculate mathematically the amplitude of the sine wave that results from superimposing two sine waves with an arbitrary phase difference between them, the algebra is rather laborious, and it become even more tedious when we have more than two waves to superimpose. Instead, one can simply use a computer spreadsheet or some other computer program to add up the sine waves numerically at a series of points covering one complete cycle. This is what we will actually do. You just need to enter the relevant data into the computer, then examine the results and pick off the amplitude from the resulting list of numbers. You can run the software through a web interface at `http://lightandmatter.com/cgi-bin/diffraction1.cgi`.

3. Measure all nine distances to your group's point on the screen, and write them on the board - that way everyone can see everyone else's data, and the class can try to make sense of why the results came out the way they did. Determine the amplitude of the combined wave, and write it on the board as well.

The class will discuss why the results came out the way they did.


1
2
3
4
5
6
7
8
9
a
b
c
d
e
f
g
h
i
j
k

Exercise 5C: Diffraction of Light

Equipment:

slit patterns, lasers, straight-filament bulbs

station 1

You have a mask with a bunch of different double slits cut out of it. The values of w and d are as follows:

pattern A	w=0.04 mm	d=.250 mm
pattern B	w=0.04 mm	d=.500 mm
pattern C	w=0.08 mm	d=.250 mm
pattern D	w=0.08 mm	d=.500 mm

Predict how the patterns will look different, and test your prediction. The easiest way to get the laser to point at different sets of slits is to stick folded up pieces of paper in one side or the other of the holders.

station 2

This is just like station 1, but with single slits:

pattern A	w=0.02 mm
pattern B	w=0.04 mm
pattern C	w=0.08 mm
pattern D	w=0.16 mm

Predict what will happen, and test your predictions. If you have time, check the actual numerical ratios of the w values against the ratios of the sizes of the diffraction patterns

station 3

This is like station 1, but the only difference among the sets of slits is how many slits there are:

pattern A	double slit
pattern B	3 slits
pattern C	4 slits
pattern D	5 slits

station 4

Hold the diffraction grating up to your eye, and look through it at the straight-filament light bulb. If you orient the grating correctly, you should be able to see the $m = 1$ and $m = -1$ diffraction patterns off the left and right. If you have it oriented the wrong way, they'll be above and below the bulb instead, which is inconvenient because the bulb's filament is vertical. Where is the $m = 0$ fringe? Can you see $m = 2$, etc.?

Station 5 has the same equipment as station 4. If you're assigned to station 5 first, you should actually do activity 4 first, because it's easier.

station 5

Use the transformer to increase and decrease the voltage across the bulb. This allows you to control the filament's temperature. Sketch graphs of intensity as a function of wavelength for various temperatures. The inability of the wave model of light to explain the mathematical shapes of these curves was historically one of the reasons for creating a new model, in which light is both a particle and a wave.

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Appendix 3: Hints and Solutions

Answers to Self-Checks

Answers to Self-Checks for Chapter 1

Page 22, self-check A: Only 1 is correct. If you draw the normal that bisects the solid ray, it also bisects the dashed ray.

Answers to Self-Checks for Chapter 2

Page 30, self-check A: You should have found from your ray diagram that an image is still formed, and it has simply moved down the same distance as the real face. However, this new image would only be visible from high up, and the person can no longer see his own image.

Page 35, self-check B: Increasing the distance from the face to the mirror has decreased the distance from the image to the mirror. This is the opposite of what happened with the virtual image.

Answers to Self-Checks for Chapter 3

Page 48, self-check A: At the top of the graph, d_i approaches infinity when d_o approaches f. Interpretation: the rays just barely converge to the right of the mirror.

On the far right, d_i approaches f as d_o approaches infinity; this is the definition of the focal length.

At the bottom, d_i approaches negative infinity when d_o approaches f from the other side. Interpretation: the rays don't quite converge on the right side of the mirror, so they appear to have come from a virtual image point very far to the left of the mirror.

Answers to Self-Checks for Chapter 4

Page 65, self-check A: (1) If n_1 and n_2 are equal, Snell's law becomes $\sin\theta_1 = \sin\theta_2$, which implies $\theta_1 = \theta_2$, since both angles are between 0 and $90\,^\circ$. The graph would be a straight line along the diagonal of the graph. (2) The graph is farthest from the diagonal when the angles are large, i.e., when the ray strikes the interface at a grazing angle.

Page 69, self-check B: (1) In 1, the rays cross the image, so it's real. In 2, the rays only appear to have come from the image point, so the image is virtual. (2) A rays is always closer to the normal in the medium with the higher index of refraction. The first left turn makes the ray closer to the normal, which is what should happen in glass. The second left turn makes the ray farther from the normal, and that's what should happen in air. (3) Take the topmost ray as an example. It will still take two right turns, but since it's entering the lens at a steeper angle, it will also leave at a steeper angle. Tracing backward to the image, the steeper lines will meet closer to the lens.

Answers to Self-Checks for Chapter 5

Page 83, self-check A: It would have to have a wavelength on the order of centimeters or meters, the same distance scale as that of your body. These would be microwaves or radio waves. (This effect can easily be noticed when a person affects a TV's reception by standing near the antenna.) None of this contradicts the correspondence principle, which only states that the wave model must agree with the ray model when the ray model is applicable. The ray model is not applicable here because λ/d is on the order of 1.

Page 85, self-check B: At this point, both waves would have traveled nine and a half wavelengths. They would both be at a negative extreme, so there would be constructive interference.

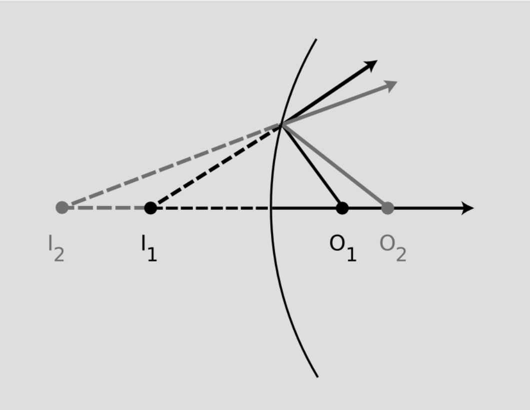
Page 89, self-check C: Judging by the distance from one bright wave crest to the next, the wavelength appears to be about 2/3 or 3/4 as great as the width of the slit.

Page 90, self-check D: Since the wavelengths of radio waves are thousands of times longer, diffraction causes the resolution of a radio telescope to be thousands of times worse, all other things being equal. (To compensate for the wavelength, it's desirable to make the telescope very large, as in figure y on page 90.)

Solutions to Selected Homework Problems

Solutions for Chapter 3

Page 57, problem 2: See the ray diagram below. Decreasing θ_o decreases θ_i, so the equation $\theta_f = \pm\theta_i + \pm\theta_o$ must have opposite signs on the right. Since θ_o is bigger than θ_i, the only way to get a positive θ_f is if the signs are $\theta_f = -\theta_i + \theta_o$. This gives $1/f = -1/d_i + 1/d_o$.



Page 58, problem 10: (a) The object distance is less than the focal length, so the image is virtual: because the object is so close, the cone of rays is diverging too strongly for the mirror to bring it back to a focus. (b) Now the object distance is greater than the focal length, so the image is real. (c),(d) A diverging mirror can only make virtual images.

Solutions for Chapter 4

Page 75, problem 13: Since d_o is much greater than d_i, the lens-film distance d_i is essentially the same as f. (a) Splitting the triangle inside the camera into two right triangles, straightforward trigonometry gives

$$\theta = 2\tan^{-1}\frac{w}{2f}$$

for the field of view. This comes out to be 39° and 64° for the two lenses. (b) For small angles, the tangent is approximately the same as the angle itself, provided we measure everything in radians. The equation above then simplifies to

$$\theta = \frac{w}{f}$$

The results for the two lenses are .70 rad = 40°, and 1.25 rad = 72°. This is a decent approximation.

(c) With the 28-mm lens, which is closer to the film, the entire field of view we had with the 50-mm lens is now confined to a small part of the film. Using our small-angle approximation $\theta = w/f$, the amount of light contained within the same angular width θ is now striking a piece of the film whose linear dimensions are smaller by the ratio 28/50. Area depends on the square of the linear dimensions, so all other things being equal, the film would now be overexposed by a factor of $(50/28)^2 = 3.2$. To compensate, we need to shorten the exposure by a factor of 3.2.

Page 77, problem 20: One surface is curved outward and one inward. Therefore the minus sign applies in the lensmaker's equation. Since the radii of curvature are equal, the quantity $1/r_1 - 1/r_2$ equals zero, and the resulting focal length is infinite. A big focal length indicates a weak lens. An infinite focal length tells us that the lens is infinitely weak — it doesn't focus or defocus rays at all.

Index

Useful Data

Metric Prefixes

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

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

Notation and Units

quantity	**unit**	**symbol**
distance	meter, m	$x, \Delta x$
time	second, s	$t, \Delta t$
mass	kilogram, kg	m
density	kg/m^3	ρ
velocity	m/s	$\mathbf{v}$
acceleration	m/s^2	$\mathbf{a}$
force	N = kg·m/s^2	$\mathbf{F}$
pressure	Pa=1 N/m^2	P
energy	J = kg·m^2/s^2	E
power	W = 1 J/s	P
momentum	kg·m/s	$\mathbf{p}$
period	s	T
wavelength	m	λ
frequency	s^{-1} or Hz	f
focal length	m	f
magnification	unitless	M
index of refraction	unitless	n

Fundamental Constants

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

Conversions

Nonmetric units in terms of metric ones:

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

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

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

Some Indices of Refraction

substance	**index of refraction**
vacuum	1 by definition
air	1.0003
water	1.3
glass	1.5 to 1.9
diamond	2.4

Note that indices of refraction, except in vacuum, depend on wavelength. These values are about right for the middle of the visible spectrum (yellow).

Subatomic Particles

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

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