AP® Physics B
2002 Scoring Guidelines

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General Notes About
2002 AP Physics Scoring Guidelines

1. The solutions contain the most common method(s) of solving the free-response questions, and the allocation of points for these solutions. Other methods of solution also receive appropriate credit for correct work.

2. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded.
   One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

3. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth one point, and a student's solution contains the application of that equation to the problem but the student does not write the basic equation, the point is still awarded.

4. The scoring guidelines typically show numerical results using the approximate value $g = 10 \text{ m/s}^2$ for ease of calculation, but use of 9.8 m/s^2 is of course also acceptable.

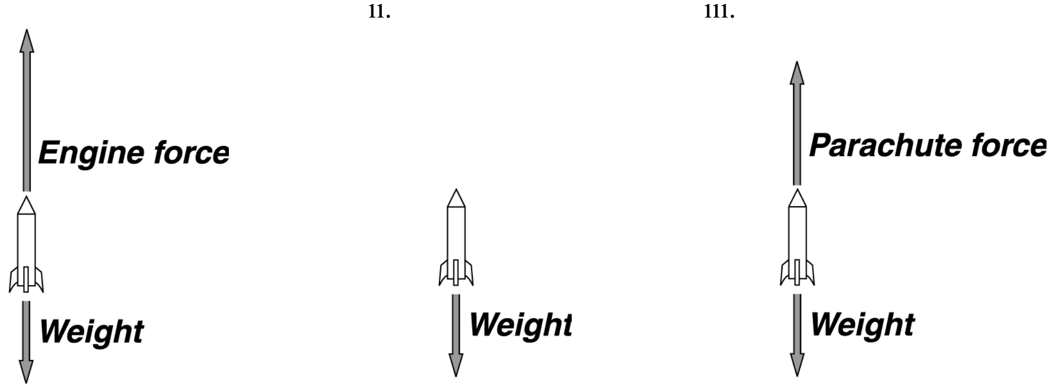
5. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. The exception is usually when rounding makes a difference in obtaining a reasonable answer. For example, in calculations of mass differences in a nuclear reaction, rounding to too few digits can lose the accuracy required to determine a mass difference.

Question 1

15 points total **Distribution of points**

(a) 5 points

i. ii. iii.



1 point for each properly drawn force with an appropriate and clear label, such as those above or letter labels like mg, W, F_e, or F_p — Total 5 points

For each diagram, one point was deducted for any incorrect forces or other vectors

(b & c) 7 points

These parts were scored together.
In solving parts (b) and (c), there were two frequently used methods of determining the average acceleration a while the engine is firing and the speed v_f attained when the engine stops. Both methods begin with determining the net force while the engine is firing, as shown below. They then determine the acceleration and velocity in different orders (methods 1 and 2 on the next page).

For applying the relationship between force and impulse to correctly determine the force exerted by the engine — 1 point

$J = F\ \Delta t$

$F_{engine} = J/\Delta t = (20.0\ \text{N}\cdot\text{s})/(2.0\ \text{s})$

$F_{engine} = 10\ \text{N}$

For subtracting to determine the net force on the rocket — 1 point

$F_{net} = F_{engine} - mg = 10\ \text{N} - (0.250\ \text{kg})(10\ \text{m/s}^2)$

$F_{net} = 7.5\ \text{N}$

Question 1 (cont'd.)

Distribution of points

(b & c) continued

<u>Method 1</u> - Determining first the velocity at the end of engine firing, then the average acceleration

Equating the total impulse to the change in momentum:

$F\ \Delta t = m\ \Delta v = m\left(v_f - v_i\right)$

(If a solution started with this expression but used an incorrect net force, one point was earned for applying the relationship between force and impulse)

$v_f - v_i = F\ \Delta t / m$

$v_f - 0 = (7.5\text{ N})(2.0\text{ s})/(0.250\text{ kg})$

For the correct value of the final velocity — 1 point

$v_f = 60\ \text{m/s}$

For using the kinematic equation for velocity to determine the acceleration — 1 point

$v_f = v_i + at$

$a = \left(v_f - v_i\right)/t$

$a = (60\ \text{m/s} - 0)/(2.0\text{ s})$

$a = 30\ \text{m/s}^2$

<u>Method 2</u> - Determining first the average acceleration, then the velocity at the end of engine firing

For setting *ma* equal to the net force or some physical force in the problem — *1 point*

$F_{net} = ma$

$a = F_{net}/m = (7.5\text{ N})/(0.250\text{ kg})$

$a = 30\ \text{m/s}^2$

Using the kinematic equation for velocity:

$v_f = v_i + at$

$v_f = 0 + \left(30\ \text{m/s}^2\right)(2.0\text{ s})$

For the correct value of the final velocity — *1 point*

$v_f = 60\ \text{m/s}$

For using a correct kinematic equation to determine the height y_1 reached when the engine stops firing and for making correct substitutions — 1 point

$y_1 = y_i + v_i t + \frac{1}{2}at^2$ or $v_f^2 = v_i^2 + 2a\ \Delta y$

$y_1 = 0 + 0 + \frac{1}{2}\left(30\ \text{m/s}^2\right)(2\text{ s})^2$

$y_1 = 60\text{ m}$

$y_1 = \dfrac{v_f^2 - v_i^2}{2a} + y_i$

$y_1 = \dfrac{(60\ \text{m}/s)^2 - 0}{2\left(30\ \text{m/s}^2\right)} + 0$

$y_1 = 60\text{ m}$

Question 1 (cont'd.)

Distribution of points

(b & c) continued

For using a correct kinematic equation to determine the height y_2 traveled from when the engine stops firing to when the maximum height is attained, and making correct substitutions (This point could also be earned for correctly applying conservation of energy.) — 1 point

$v_f^2 = v_i^2 + 2g\ \Delta y$

$$y_2 = \frac{v_f^2 - v_i^2}{2g} + y_i$$

$$y_2 = \frac{0 - (60\ \text{m}/s)^2}{2\left(-10\ \text{m/s}^2\right)} + 0$$

$y_2 = 180\ \text{m}$

For adding the two distances to get the total height — 1 point

$y_{total} = y_1 + y_2 = 60\ \text{m} + 180\ \text{m}$

$y_{total} = 240\ \text{m}$

(d) 3 points

For using a correct kinematic equation to determine the time of travel from when the engine stops firing to when the maximum height is attained, and making correct substitutions — 1 point

$v_f = v_i - gt_2$

$$t_2 = \frac{v_f - v_i}{-g} = \frac{0 - 60\ \text{m/s}}{-10\ \text{m/s}^2}$$

$t_2 = 6.0\ \text{s}$

For adding the above to the time the rocket was firing — 1 point

$t_{total} = t_1 + t_2 = 2.0\ \text{s} + 6.0\ \text{s}$

For the correct value for the total time (i.e. the answer obtained from a completely correct solution to the entire problem) — 1 point

$t_{total} = 8.0\ \text{s}$

Question 2

15 points total	**Distribution of points**
(a) 1 point	
For a reasonable value of U read from the graph	1 point
$U \approx 0.05$ J	
	Alternate points
Alternate solution	
Using the equation for the potential energy of simple harmonic motion:	
$U = \frac{1}{2}kx^2$	
Using the distance of 10 cm at which the maximum value of 0.4 J for U occurs allows determination of the force constant k.	
$0.4\text{ J} = \frac{1}{2}k(0.1\text{ m})^2$	
$k = 80\ \text{N/m}$	
For determining the value of U at 4 cm	*1 point*
$U = \frac{1}{2}(80\ \text{N/m})(0.04\text{ m})^2$	
$U = 0.06$ J	
(b) 3 points	
For indicating that the maximum possible position in the $+x$-direction is 10 cm	1 point
For a complete explanation	2 points
A full-credit explanation would indicate either of the following: 1) The particle stops at this point (or that the kinetic energy is zero here) because all of the energy is in the form of potential energy. 2) The maximum potential energy cannot be greater than the total energy. Incomplete explanations (such as only saying that the potential energy is 0.4 J at 10 cm) received one point. However, only saying that the total energy is 0.4 J received no credit, since this is just a restatement of given information.	
(c) 3 points	
For a reasonable value of U read from the graph (between 0.18 J and 0.22 J) This point was also awarded for a correct calculation of U using the force constant determined in part (a).	1 point
For subtracting this value of U from the total energy to obtain the kinetic energy	1 point
For a consistent final answer	1 point
$K \approx 0.2$ J	

Question 2 (cont'd.)

		Distribution of points
(d)	4 points	
	For any indication that the potential energy is zero at $x = 0$	1 point
	For setting the kinetic energy equal to the total energy	1 point
	$K = \frac{1}{2}mv^2 = E_{total}$	
	$v = \sqrt{2E_{total}/m}$	
	For correctly substituting the energy and mass into the above equation	1 point
	$v = \sqrt{2(0.4\ \text{J})/(3.0\ \text{kg})}$	
	For the correct answer	1 point
	$v = 0.5\ \text{m/s}$	
(e)	4 points	
	Using the kinematic equation for the vertical motion:	
	$y_f = y_i + v_{0y}t - \frac{1}{2}gt^2$	
	For correctly substituting $v_{0y} = 0$	1 point
	Setting y_f also equal to zero and solving for t:	
	$t = \sqrt{2y_i/g} = \sqrt{2(0.5\ \text{m})/\left(10\ \text{m/s}^2\right)}$	
	For the correct value of t	1 point
	$t = 0.3\ \text{s}$	
	Using the equation for the horizontal distance:	
	$d = v_x t$	
	For correctly substituting the value of t above and the value of v_x from part (d)	1 point
	$d = (0.5\ \text{m/s})(0.3\ \text{s})$	
	For the correct answer	1 point
	$d = 0.2\ \text{m}$	

Question 3

15 points total | **Distribution of points**

(a) i. 3 points

For both a correct power formula and Ohm's law, either shown explicitly or applied	1 point
For a correct calculation of resistance	1 point
For a correct calculation of current	1 point

This point was awarded if an incorrect value for resistance was correctly used with 120 V.

The calculations can be done in slightly different ways and in different orders.
One example follows:

$P = IV$ and $I = \dfrac{V}{R}$, so $P = \dfrac{V^2}{R}$

$$R = \frac{V^2}{P} = \frac{(120\ \text{V})^2}{30\ \text{W}} = 480\ \Omega$$

$$I = \frac{V}{R} = \frac{120\ \text{V}}{480\ \Omega} = 0.25\ \text{A}$$

(a) ii. 2 points

For a correct calculation of resistance	1 point
For a correct calculation of current	1 point

This point was awarded if an incorrect value for resistance was correctly used with 120 V.

Again, the calculations can be done in slightly different ways and in different orders.
One example follows:

$$R = \frac{V^2}{P} = \frac{(120\ \text{V})^2}{40\ \text{W}} = 360\ \Omega$$

$$I = \frac{V}{R} = \frac{120\ \text{V}}{360\ \Omega} = 0.33\ \text{A}$$

(b) i. and ii. 4 points

These two parts were scored as a unit.

For showing by calculation or by statement that the resistance in part (b)i is assumed to be the same as in part (a)i, <u>and</u> the resistance in part (b)ii is assumed to be the same as in part (a)ii	1 point

This point could also be awarded to students who recognized the bulbs as non-ohmic and stated this clearly, specifying lower resistances to be used in the solution.

$R_{"30"} = 480\ \Omega$

$R_{"40"} = 360\ \Omega$

Question 3 (cont'd.)

Distribution of points

(b) i. and ii. continued

For adding both resistances to calculate the total series resistance R_{tot} used in the Ohm's law calculation of current — 1 point

$R_{tot} = 480\ \Omega + 360\ \Omega = 840\ \Omega$

For calculating the correct current in part (b)i, or for a current consistent with the total resistance calculated — 1 point

$I_{"30"} = I_{tot} = \dfrac{V}{R_{tot}} = \dfrac{120\ \text{V}}{840\ \Omega} = 0.14\ \text{A}$

For stating that the current in part (b)ii is the same as in part (b)i, whether or not the (b)i current is correct — 1 point

$I_{"40"} = I_{"30"} = I_{tot} = 0.14\ \text{A}$

(c) 3 points

__2__30 W bulb in the parallel circuit

__1__40 W bulb in the parallel circuit

__3__30 W bulb in the series circuit

__4__40 W bulb in the series circuit

For any order showing that both bulbs in parallel are brighter than both in series — 1 point

For any order showing the 40 W bulb in the parallel circuit is brighter than the 30 W bulb in the parallel circuit — 1 point

For any order showing the "30 W" bulb in the series circuit is brighter than the "40 W" bulb in the series circuit — 1 point

(d) i. 1 point

For a correct answer or calculation consistent with values reported in part (a) — 1 point

$P_{tot} = 30\ \text{W} + 40\ \text{W} = 70\text{W}$

OR $P_{tot} = \dfrac{V^2}{R_{tot}} = \dfrac{(120\ \text{V})^2}{206\ \Omega} = 70\ \text{W}$

OR $P_{tot} = \sum VI = (120\ \text{V})(0.25\ \text{A}) + (120\ \text{V})(0.33\ \text{A}) = 70\ \text{W}$

Question 3 (cont'd.)

Distribution of points

(d) ii. 2 points

For using values from part (b) correctly in the equations — 1 point
For correct answer or calculation consistent with values reported in part (b) — 1 point

$$P_{tot} = \frac{V^2}{R_{tot}} = \frac{(120\ \text{V})^2}{840\ \Omega} = 17\ \text{W}$$

OR $P_{tot} = \sum I^2 R = (0.14\ \text{A})^2(480\ \Omega) + (0.14\ \text{A})^2(360\ \Omega) = 17\ \text{W}$

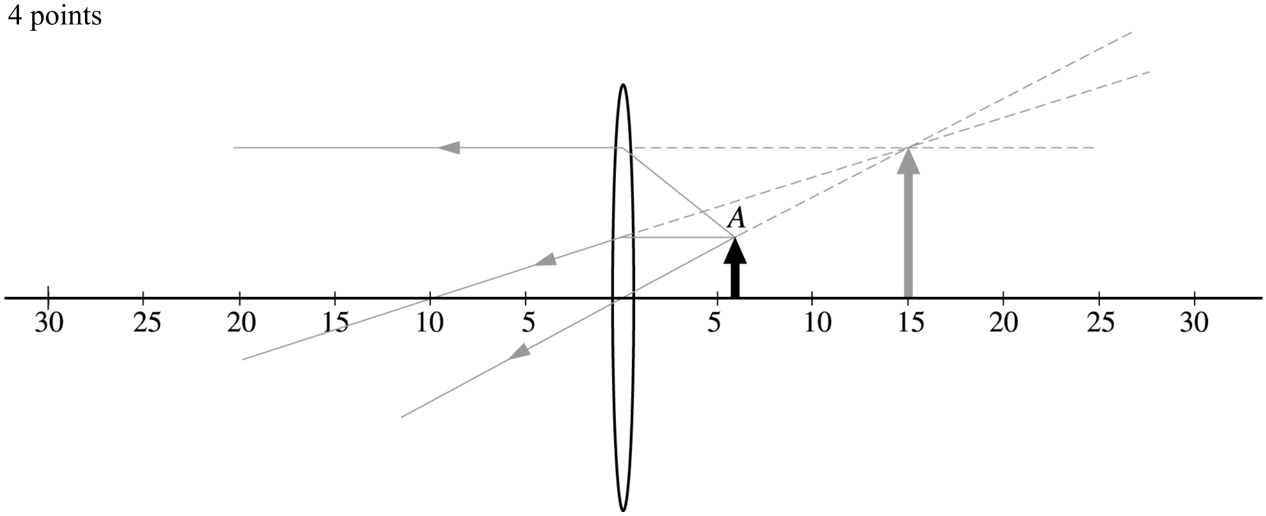
OR $P_{tot} = VI = (120\ \text{V})(0.14\ \text{A}) = 17\ \text{W}$

Note: Both points were awarded for the correct answer, 17 W, as long as it was consistent with the work in part (b). No points were awarded for answers of 70 W unless student's work clearly showed that it was obtained using a combination of values for *R*, *V*, and *I* consistent with part (b).

Question 4

15 points total **Distribution of points**

(a) 4 points



For any two correct rays through the lens	2 points
Two of the three principal rays shown on the diagram above were expected. One point was subtracted for additional incorrect rays. No credit was awarded for reflected rays.	
For correct extension of the rays backward	1 point
For showing the image with correct size, position, and orientation	1 point

(b) 2 points

For stating that the image is virtual, or for stating a choice consistent with the ray diagram in part (a)	1 point
If there were no supporting diagrams or calculations, virtual was the only accepted answer.	
For a correct explanation consistent with the choice given, such as:	1 point
The light rays diverge on the left side of the lens, but appear to come from a point behind the object. OR The image is on the same side of the lens as the object. OR The object is placed between the converging lens and the focal point. This point was not awarded if additional wrong statements were part of the response.	

(c) 3 points

For the lens equation OR for the lens equation with substituted quantities	1 point
$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ OR $\frac{1}{s_i} = \frac{1}{10\ \text{cm}} - \frac{1}{6\ \text{cm}}$	
For the correct solution	2 points
$s_i = -15$ cm (Minus sign was not necessary to receive full credit.) Only 1 of the 2 answer points was awarded for the correct number without units.	

Question 4 (cont'd.)

	Distribution of points
(c) continued	
Alternate Solution	*Alternate points*
Let x_o = distance from object to focal point and x_i = distance from image to focal point.	
For the correct formula	*1 point*
$\dfrac{x_i}{f} = \dfrac{f}{x_o}$	
For correct substitutions	*1 point*
$\dfrac{x_i}{10\ \text{cm}} = \dfrac{10\ \text{cm}}{10\ \text{cm} - 6\ \text{cm}}$	
$x_i = \dfrac{(10\ \text{cm})^2}{4\ \text{cm}} = 25\ \text{cm}$	
$s_i = 25\ \text{cm} - 10\ \text{cm}$	
For the correct answer	*1 point*
$s_i = 15\ \text{cm}$	

(d) 2 points

For the correct image size to object size ratio with no units, or with units that cancel	2 points
$\dfrac{h_i}{h_o} = \dfrac{s_i}{s_o} = \dfrac{15\ \text{cm}}{6\ \text{cm}} = \dfrac{5}{2}$	

Notes:
Students could use either a calculation or a ray diagram to arrive at the final answer.
1 point only was awarded if the correct ratio was imbedded in extra calculations or if units were provided for the answer (for example, 2.5 cm).
No points were given for giving the object size to image size ratio.

(e) 4 points

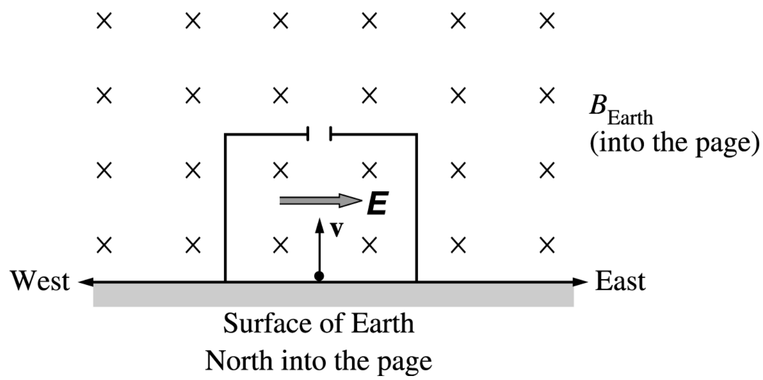
Since the question asked for a description, a verbal response was expected, although the image position, size, and orientation could be determined from either a calculation or a ray diagram.

For the correct position:	
Image on the opposite side of the lens from the object	1 point
Distance from the image to the lens in the range 20 cm ± 3 cm	1 point
For the correct size: image size same as object size, or for size consistent with value for position	1 point
For the correct orientation: image is inverted	1 point

Question 5

10 points total | **Distribution of points**

(a) 3 points



For drawing the electric field vector to the right (labeled as E or unlabeled) and parallel to the base of the box — 1 point

For demonstrating an understanding of the physics involved in balancing the magnetic <u>force</u> with an electric <u>force</u>, and for demonstrating an understanding that the electric force and electric field are in the same direction for a proton — 2 points

<u>Note</u>: It was possible to misapply the right-hand rule and obtain an electric field vector to the left, thus not receiving the first point, but still receive 1 or 2 points for the explanation if it was consistent with this direction of the electric field vector.

(b) 2 points

For indicating that the magnetic force and electric force are equal in magnitude, $F_B = F_E$, and thus $evB_{Earth} \sin\theta = eE$ — 1 point

The velocity and magnetic field are perpendicular to each other, i.e. $\theta = 90°$, so $\sin\theta = 1$

For the correct solution of the above equation for speed in terms of the fields — 1 point

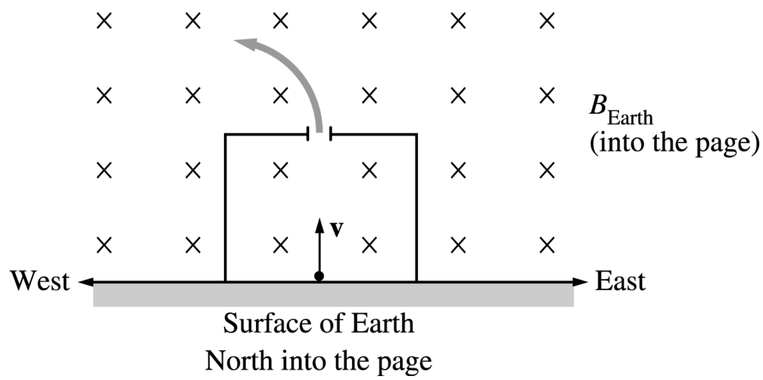
$$v = \frac{E}{B_{Earth}}$$

<u>Note</u>: Since the question asked for the speed "in terms of the fields and the given quantities", and since **v** was unintentionally a given quantity, 2 points were also awarded for realizing that the forces balance and thus the speed remains the same as its initial value, the magnitude of **v.**

Question 5 (cont'd.)

Distribution of points

(c) 2 points



For sketching a path that moves to the west (i.e. to the left)	1 point
For having the path start out concave downward (either west or east) as soon as the proton leaves the box, and continuing that way for a short distance	1 point

(d) 3 points

For realizing that there is a single force accelerating the proton and that Newton's 2nd law applies — 1 point

$F = m_p a$

For knowing that the force is magnetic and substituting its value into Newton's 2nd law — 1 point

$evB_{Earth} = m_p a$

For solving for a correctly — 1 point

$a = \dfrac{evB_{Earth}}{m_p}$

Note: By substituting $\upsilon = \dfrac{E}{B_{Earth}}$ from part (b), the final answer may be expressed as $a = \dfrac{eE}{m_p}$, because those are also given quantities, but full credit was awarded only if it was clearly shown that the force accelerating the proton is the magnetic force.

Question 5 (cont'd.)

Distribution of points

(d) continued

Alternate Solution — *Alternate points*

There were several variations of an alternate solution all involving the use of the idea that a particle in a magnetic field with velocity perpendicular to the field will move in a circle of radius r at constant speed, and with centripetal acceleration $a = \frac{v^2}{r}$.

The following is one example.

For realizing that the force accelerating the proton is centripetal — *1 point*

$$F = m_p a = \frac{m_p v^2}{r}$$

For knowing that the force is magnetic and substituting its value into the equation above — *1 point*

$$evB_{Earth} = \frac{m_p v^2}{r}$$

Solving for r:

$$r = \frac{m_p v}{eB_{Earth}}$$

Substituting this value of r into the equation $a = \frac{v^2}{r}$:

$$a = \frac{v^2}{\left(\frac{m_p v}{eB_{earth}}\right)}$$

For correct answer — *1 point*

$$a = \frac{evB_{Earth}}{m_p}$$

<u>Note</u>: Other variations of this general approach could also receive full credit if correct

Question 6

10 points total | **Distribution of points**

(a) 3 points

For a correct verbal description of the method used to determine the spring constant (One point could be awarded for an incomplete description)	2 points
For an appropriate equation for *k*, or a verbal representation of the equation	1 point

Example 1: Measure the unstretched length of the spring. Hang it with the object at rest and measure the stretched length. Call the difference in these lengths ℓ. Equating the weight of the object and the force exerted by the extended spring gives $mg = k\ell$ from which *k* can be determined.

Example 2: Set the hanging mass into oscillation. Determine the period *T* by timing *n* oscillations and dividing that time by *n*. The equation $T = 2\pi\sqrt{m/k}$ can then be used to find *k*.

Example 3: Hold the object at the position where the spring is unstretched and then release it. Measure the maximum distance *h* it falls. Equating maximum potential and kinetic energies, $mgh = \frac{1}{2}kh^2$, allows determination of *k*.

(b) 2 points

For a correct observation that includes an indication of whether the change is an increase or decrease	1 point
For a correct explanation of the change	1 point

Example 1: The spring is stretched less when the object is at rest in the fluid. The fluid exerts an upward buoyant force on the object. Since the net force on the object is still zero, the spring does not need to exert as much force as before, and thus stretches less.

Example 2: If the spring oscillates in the fluid, its period will be greater. The fluid exerts a drag force on the object in the direction opposite to its motion, and thus slows it down.

Question 6 (cont'd.)

15 points total **Distribution of points**

(c & d) 5 points

These parts were scored together. The following describe the criteria for receiving each of the possible scores.

5 points A complete and accurate explanation of a correct experimental method, with correct equations and definitions of symbols

4 points A mostly complete response, with only one or two errors in the explanation or equations
This was the maximum possible score if the student incorrectly used the volume of displaced fluid.

3 points Partially complete response with one or two major errors
OR A complete description of the method (part (c)) with no mathematical treatment (part (d))
OR A complete mathematical treatment with symbol definitions (part (d)) with no description of the method (part (c))

2 points An incomplete explanation and presentation, but one that shows some understanding of the principles involved

1 point An explanation and presentation that shows very little understanding of the principles involved

The following is one example of a correct method.

1) Measure the length of the spring when the object is immersed in the liquid, and subtract the unstretched length to determine the amount the spring is stretched. This will allow calculation of the force exerted by the spring on the object.
2) The volume of fluid displaced is equal to the volume of the object, which can be determined from the given mass and density of the object.
3) The buoyant force on the object is equal to the difference of the object's weight and the force exerted by the spring.
4) The buoyant force also equals the weight of the displaced fluid, which equals the product of the fluid density, displaced volume, and g.

Question 6 (cont'd.)

15 points total | **Distribution of points**

(c & d) continued

Symbol	Physical quantity
m	Mass of object
g	Acceleration due to gravity
k	Spring constant
ℓ	Amount of spring stretch when <u>not</u> immersed
ℓ_w	Amount of spring stretch when immersed
V	Volume (of both object and displaced fluid)
D	Density of object
ρ	Density of fluid
$F_{bouyant}$	Buoyant force on object
F_{spring}	Spring force on object
w_{fluid}	Weight of fluid displaced
m_{fluid}	Mass of fluid displaced

Equation to determine the spring constant

$mg = k\ell$

Equations corresponding to points 1 through 4 in the method described on the previous page:

$F_{spring} = k\ell_w$

$V = m/D$

$F_{bouyant} = mg - F_{spring} = mg - k\ell_w$

$F_{bouyant} = w_{fluid} = m_{fluid}\,g = \rho V g$

Solving for ρ (which was not required):

$\rho V g = mg - k\ell_w$

$\rho V g = mg - \frac{mg}{\ell}\ell_w = mg\left(1 - \frac{\ell_w}{\ell}\right)$

$\rho = \frac{m}{V}\left(1 - \frac{\ell_w}{\ell}\right) = \frac{m}{m/D}\left(1 - \frac{\ell_w}{\ell}\right)$

$\rho = D\left(1 - \frac{\ell_w}{\ell}\right)$

Question 7

10 points total | **Distribution of points**

(a) 2 points

For a correct equation for the energy of a photon in terms of wavelength (or an equivalent set of equations that will allow such a determination) — 1 point

$$E = \frac{hc}{\lambda}$$

$$E_{\gamma i} = \frac{\left(6.63\times10^{-34}\ \text{J}\cdot\text{s}\right)\left(3.00\times10^{8}\ \text{m/s}\right)}{2.0\times10^{-11}\ \text{m}}$$

For a correct answer — 1 point

$$E_{\gamma i} = 9.9\times10^{-15}\ \text{J}$$

(b) 2 points

For a correct equation for the momentum of a photon (or an equivalent set of equations that will allow such a determination) — 1 point

$$p = \frac{E}{c} \qquad \text{or} \qquad p = \frac{h}{\lambda}$$

Using the second equation:

$$p_{\gamma i} = \frac{6.63\times10^{-34}\,\text{J}\cdot\text{s}}{2.0\times10^{-11}\ \text{m}}$$

For the correct answer — 1 point

$p_{\gamma i} = 3.3\times10^{-23}\ \text{kg}\cdot\text{m/s}$ or equivalent in other units (e.g. $6.2\times10^{4}\ \text{eV}/c$)

(c) 3 points

For indicating that the photon wavelength increased — 1 point

For indicating that the photon energy or momentum is decreased due to the interaction — 1 point
This point was <u>not</u> awarded if the student gave an incorrect explanation of the reason for these decreases.

For indicating that there is an inverse relationship between the wavelength and either energy or momentum — 1 point

Question 7 (cont'd.)

	Distribution of points
(d) 3 points	
For indicating that conservation of momentum is applicable	1 point
For further work applying conservation of momentum that indicates that the momentum of the final photon is in the direction opposite to that of the initial momentum (e.g. correctly including a minus sign in calculations)	1 point

$p_{ei} + p_{\gamma i} = p_{ef} - p_{\gamma f}$

$p_{ei} = 0$ and $p_{\gamma f}$ can be determined by using the given expression for $\Delta\lambda$ to calculate the wavelength of the final photon

$$\lambda_f = \lambda_i + \Delta\lambda = \lambda_i + \frac{2h}{m_e c}$$

$$\lambda_f = 2.0\times10^{-11}\ \text{m} + \frac{2\left(6.63\times10^{-34}\ \text{J}\cdot\text{s}\right)}{\left(9.11\times10^{-31}\ \text{kg}\right)\left(3.00\times10^{8}\ \text{m/s}\right)} = 2.5\times10^{-11}\ \text{m}$$

$$p_{\gamma f} = \frac{h}{\lambda_f} = \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{2.5\times10^{-11}\ \text{m}}$$

$$p_{\gamma f} = 2.7\times10^{-23}\ \text{kg}\cdot\text{m/s}$$

$$p_{ef} = p_{\gamma i} + p_{\gamma f} = 3.3\times10^{-23}\ \text{kg}\cdot\text{m/s} + 2.7\times10^{-23}\ \text{kg}\cdot\text{m/s}$$

For a correct final answer, including units — 1 point

$$p_{ef} = 6.0\times10^{-23}\ \text{kg}\cdot\text{m/s}$$

	Alternate points
Alternate solution	
For indicating that conservation of energy is applicable	*1 point*
For further work applying conservation of energy correctly	*1 point*

$E_{ei} + E_{\gamma i} = E_{ef} + E_{\gamma f}$

$E_{ei} = 0$ and $E_{\gamma f}$ can be determined by using the given expression for $\Delta\lambda$ to calculate the wavelength of the final photon (as shown above)

$$E_{\gamma f} = \frac{hc}{\lambda_f} = \frac{\left(6.63\times10^{-34}\ \text{J}\cdot\text{s}\right)\left(3.00\times10^{8}\right)}{2.5\times10^{-11}\ \text{m}} = 8.0\times10^{-15}\ \text{J}$$

$$E_{ef} = E_{\gamma i} - E_{\gamma f} = 9.9\times10^{-15}\ \text{J} - 8.0\times10^{-15}\ \text{J} = 1.9\times10^{-15}\ \text{J}$$

$$E_{ef} = \frac{1}{2}m_e v_{ef}^2 = \frac{1}{2}\frac{p_{ef}^2}{m_e}$$

$$p_{ef} = \sqrt{2m_e E_{ef}} = \sqrt{2\left(9.11\times10^{-31}\ \text{kg}\right)\left(1.9\times10^{-15}\ \text{J}\right)}$$

For a correct final answer, including units — *1 point*

$$p_{ef} = 5.9\times10^{-23}\ \text{kg}\cdot\text{m/s}$$