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AP® Physics C: Mechanics Exam

SECTION I: Multiple Choice

2015

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
45 minutes
Number of Questions
35
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
Calculator allowed

Instructions

Section I of this exam contains 35 multiple-choice questions. For these questions, fill in only the circles for numbers 1 through 35 on your answer sheet. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers and straightedges may be used in this section.

Indicate all of your answers to the multiple-choice questions on the answer sheet. No credit will be given for anything written in this exam booklet, but you may use the booklet for notes or scratch work. After you have decided which of the suggested answers is best, completely fill in the corresponding circle on the answer sheet. Give only one answer to each question. If you change an answer, be sure that the previous mark is erased completely. Here is a sample question and answer.

Sample Question	Sample Answer
Chicago is a (A) state (B) city (C) country (D) continent (E) village	Ⓐ ● Ⓒ Ⓓ Ⓔ

Use your time effectively, working as quickly as you can without losing accuracy. Do not spend too much time on any one question. Go on to other questions and come back to the ones you have not answered if you have time. It is not expected that everyone will know the answers to all of the multiple-choice questions.

Your total score on the multiple-choice section is based only on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

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Form I
Form Code 4KBP6-S

80

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DO NOT seal answer sheet inside

ADVANCED PLACEMENT PHYSICS C TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass, $m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude, $e = 1.60 \times 10^{-19}$ C
Neutron mass, $m_n = 1.67 \times 10^{-27}$ kg	1 electron volt, 1 eV $= 1.60 \times 10^{-19}$ J
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Speed of light, $c = 3.00 \times 10^{8}$ m/s
Avogadro's number, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{kg}^2$
Universal gas constant, $R = 8.31$ J/(mol·K)	Acceleration due to gravity at Earth's surface, $g = 9.8$ m/s^2
Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	

1 unified atomic mass unit, $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg} = 931 \text{ MeV}/c^2$

Planck's constant, $h = 6.63 \times 10^{-34}$ J·s $= 4.14 \times 10^{-15}$ eV·s

$hc = 1.99 \times 10^{-25}$ J·m $= 1.24 \times 10^{3}$ eV·nm

Vacuum permittivity, $\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\left(\text{N}\cdot\text{m}^2\right)$

Coulomb's law constant, $k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9} \left(\text{N}\cdot\text{m}^2\right)/\text{C}^2$

Vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A

Magnetic constant, $k' = \mu_0/(4\pi) = 1 \times 10^{-7}$ (T·m)/A

1 atmosphere pressure, $1 \text{ atm} = 1.0 \times 10^{5} \text{ N/m}^2 = 1.0 \times 10^{5}$ Pa

UNIT SYMBOLS								
	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	1/2	3/5	$\sqrt{2}/2$	4/5	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	4/5	$\sqrt{2}/2$	3/5	1/2	0
$\tan\theta$	0	$\sqrt{3}/3$	3/4	1	4/3	$\sqrt{3}$	∞

The following assumptions are used in this exam.

I. The frame of reference of any problem is inertial unless otherwise stated.
II. The direction of current is the direction in which positive charges would drift.
III. The electric potential is zero at an infinite distance from an isolated point charge.
IV. All batteries and meters are ideal unless otherwise stated.
V. Edge effects for the electric field of a parallel plate capacitor are negligible unless otherwise stated.

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

$v_x^2 = {v_{x0}}^2 + 2a_x (x - x_0)$

$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$\vec{F} = \frac{d\vec{p}}{dt}$

$\vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$

$\vec{p} = m\vec{v}$

$\left|\vec{F}_f\right| \le \mu \left|\vec{F}_N\right|$

$\Delta E = W = \int \vec{F} \bullet d\vec{r}$

$K = \frac{1}{2} m v^2$

$P = \frac{dE}{dt}$

$P = \vec{F} \bullet \vec{v}$

$\Delta U_g = mg\Delta h$

$a_c = \frac{v^2}{r} = \omega^2 r$

$\vec{\tau} = \vec{r} \times \vec{F}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$I = \int r^2 dm = \sum m r^2$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$v = r\omega$

$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$

$K = \frac{1}{2} I \omega^2$

$\omega = \omega_0 + \alpha t$

$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$

a = acceleration
E = energy
F = force
f = frequency
h = height
I = rotational inertia
J = impulse
K = kinetic energy
k = spring constant
ℓ = length
L = angular momentum
m = mass
P = power
p = momentum
r = radius or distance
T = period
t = time
U = potential energy
v = velocity or speed
W = work done on a system
x = position
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed
α = angular acceleration
ϕ = phase angle

$\vec{F}_s = -k\Delta\vec{x}$

$U_s = \frac{1}{2} k (\Delta x)^2$

$x = x_{\max} \cos(\omega t + \phi)$

$T = \frac{2\pi}{\omega} = \frac{1}{f}$

$T_s = 2\pi\sqrt{\frac{m}{k}}$

$T_p = 2\pi\sqrt{\frac{\ell}{g}}$

$\left|\vec{F}_G\right| = \frac{G m_1 m_2}{r^2}$

$U_G = -\frac{G m_1 m_2}{r}$

ELECTRICITY AND MAGNETISM

$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$

$\vec{E} = \frac{\vec{F}_E}{q}$

$\oint \vec{E} \bullet d\vec{A} = \frac{Q}{\varepsilon_0}$

$E_x = -\frac{dV}{dx}$

$\Delta V = -\int \vec{E} \bullet d\vec{r}$

$V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

$\Delta V = \frac{Q}{C}$

$C = \frac{\kappa\varepsilon_0 A}{d}$

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

$I = \frac{dQ}{dt}$

$U_C = \frac{1}{2} Q\Delta V = \frac{1}{2} C (\Delta V)^2$

$R = \frac{\rho\ell}{A}$

$\vec{E} = \rho\vec{J}$

$I = Nev_d A$

$I = \frac{\Delta V}{R}$

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

$\vec{F}_M = q\vec{v} \times \vec{B}$

$\oint \vec{B} \bullet d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\, d\vec{\ell} \times \hat{r}}{r^2}$

$\vec{F} = \int I\, d\vec{\ell} \times \vec{B}$

$B_s = \mu_0 n I$

$\Phi_B = \int \vec{B} \bullet d\vec{A}$

$\mathcal{E} = \oint \vec{E} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\mathcal{E} = -L\frac{dI}{dt}$

$U_L = \frac{1}{2} L I^2$

ADVANCED PLACEMENT PHYSICS C EQUATIONS

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

$A = \frac{1}{2}bh$

Circle

$A = \pi r^2$

$C = 2\pi r$

$s = r\theta$

Rectangular Solid

$V = \ell wh$

Cylinder

$V = \pi r^2 \ell$

$S = 2\pi r\ell + 2\pi r^2$

Sphere

$V = \frac{4}{3}\pi r^3$

$S = 4\pi r^2$

Right Triangle

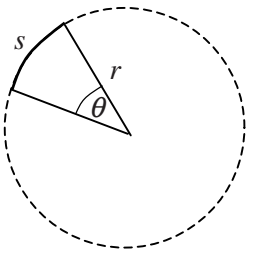
$a^2 + b^2 = c^2$

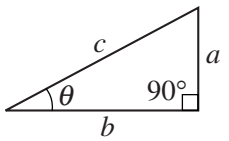
$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

$\tan\theta = \frac{a}{b}$

A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius
s = arc length
θ = angle





CALCULUS

$$\frac{df}{dx} = \frac{df}{du}\frac{du}{dx}$$

$$\frac{d}{dx}\left(x^n\right) = nx^{n-1}$$

$$\frac{d}{dx}\left(e^{ax}\right) = ae^{ax}$$

$$\frac{d}{dx}(\ln ax) = \frac{1}{x}$$

$$\frac{d}{dx}[\sin(ax)] = a\cos(ax)$$

$$\frac{d}{dx}[\cos(ax)] = -a\sin(ax)$$

$$\int x^n\,dx = \frac{1}{n+1}x^{n+1},\ n \neq -1$$

$$\int e^{ax}\,dx = \frac{1}{a}e^{ax}$$

$$\int \frac{dx}{x+a} = \ln|x+a|$$

$$\int \cos(ax)\,dx = \frac{1}{a}\sin(ax)$$

$$\int \sin(ax)\,dx = -\frac{1}{a}\cos(ax)$$

VECTOR PRODUCTS

$\vec{A}\bullet\vec{B} = AB\cos\theta$

$\left|\vec{A}\times\vec{B}\right| = AB\sin\theta$

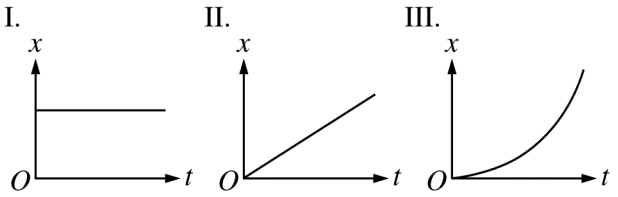
PHYSICS C: MECHANICS
SECTION I
Time—45 minutes
35 Questions

Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

Note: To simplify calculations, you may use $g = 10\,\text{m/s}^2$ in all problems.

Questions 1-3

The graphs below show position x plotted as a function of time t for each of three objects constrained to move along a straight, level path.



1. In which of the graphs is the magnitude of the momentum of the object increasing?

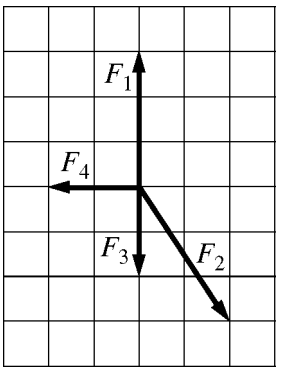
   (A) II only
   (B) III only
   (C) I and II
   (D) I and III
   (E) II and III

2. In which of the graphs does the object have a constant nonzero kinetic energy?

   (A) I only
   (B) II only
   (C) III only
   (D) I and II
   (E) I and III

3. In which of the graphs is the net force on the object zero?

   (A) I only
   (B) III only
   (C) I and II only
   (D) II and III only
   (E) I, II, and III



4. The coplanar forces F_1, F_2, F_3, and F_4 represented above can act on an object. If the object is initially at rest, which combination of the forces would result in static equilibrium?

   (A) F_1 and F_3 only
   (B) F_1, F_2, and F_4 only
   (C) F_2, F_3, and F_4 only
   (D) All four forces
   (E) No combination of the forces would result in equilibrium.

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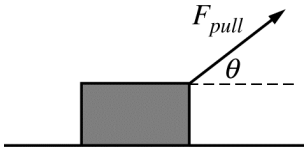

5. A block of mass M is being pulled to the right at a constant speed with a pull force F_{pull} that is at an angle of θ with respect to the horizontal, as shown in the figure above. The force of friction acting on the block has magnitude f. What is the magnitude of F_{pull}?

   (A) $f\cos\theta$
   (B) $f\sin\theta$
   (C) f
   (D) $f/\cos\theta$
   (E) $f/\sin\theta$

Questions 6-8

An astronaut hits a golf ball of mass m on the Moon, where there is no atmosphere and the acceleration due to gravity is $g/6$, where g is the acceleration due to gravity on Earth. Assume that the golf club is in contact with the ball for a time t. Just after losing contact with the club, the ball has an initial speed v directed at an angle θ above the horizontal.

6. What is the magnitude of the average force exerted by the club on the ball during contact?

   (A) mv
   (B) $mv\cos\theta$
   (C) $\frac{mv}{t}$
   (D) $\frac{mg}{6}$
   (E) $\frac{mg}{6}\cos\theta$

7. What is the work done by the club on the ball?

   (A) $\frac{1}{2}mv^2$
   (B) $\frac{1}{2}m(v\sin\theta)^2$
   (C) $\frac{1}{2}m(v\cos\theta)^2$
   (D) $6\left(\frac{1}{2}mv^2\right)$
   (E) $\left(\frac{1}{6}\right)\left(\frac{1}{2}mv^2\right)$

8. What is the maximum height above the Moon's surface attained by the ball?

   (A) vt
   (B) $6vt$
   (C) $\frac{v^2}{2g}$
   (D) $\frac{(v\sin\theta)^2}{2g}$
   (E) $6\left[\frac{(v\sin\theta)^2}{2g}\right]$

---

9. A simple pendulum of length L has a period T. What is the length of another simple pendulum of period $2T$, assuming that both pendulums swing with small amplitude?

   (A) $\frac{1}{2}L$
   (B) L
   (C) $\sqrt{2}L$
   (D) $2L$
   (E) $4L$

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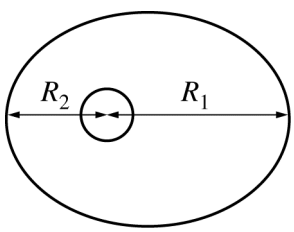
10. Pendulum 1 is displaced by a very small angle θ_1, is released from rest, and oscillates with a period T_1. Pendulum 2 is identical to pendulum 1, but it is displaced by a very small angle θ_2, is released from rest, and oscillates with a period T_2, where $\theta_1 > \theta_2$. Using the small angle approximation, how do the periods T_1 and T_2 compare?

(A) $T_1 > T_2$
(B) $T_1 = T_2$
(C) $T_1 < T_2$
(D) It cannot be determined without knowing the values of θ_1 and θ_2.
(E) It cannot be determined without knowing the length of the pendulums.

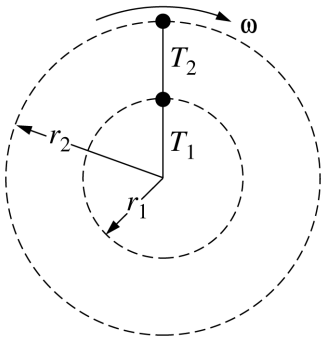
11. A newly discovered planet has three times the mass and five times the radius of Earth. What is the ratio of the acceleration due to gravity at the surface of the new planet to the acceleration due to gravity at the surface of Earth?

(A) $3/25$
(B) $3/5$
(C) $5/9$
(D) $9/5$
(E) $25/3$



12. A satellite is in an elliptical orbit about a planet, as shown in the figure above. At apogee, a distance R_1 from the planet, the satellite's angular speed is ω. What is the angular speed of the satellite at perigee, a distance $R_2 = R_1/2$ from the planet?

(A) $(1/4)\omega$
(B) $(1/2)\omega$
(C) $(1/\sqrt{2})\omega$
(D) 2ω
(E) 4ω



13. Two objects of equal mass m are tied to a string and placed on a horizontal frictionless tabletop. The string and objects spin with angular velocity ω so that the objects move in circles of radius r_1 and r_2, as shown above. The tensions T_1 and T_2 must satisfy which of the following relations?

(A) $T_1 - T_2 = m\omega^2 r_1$
(B) $T_2 - T_1 = m\omega^2 r_1$
(C) $T_1 + T_2 = m\omega^2 r_2$
(D) $T_1 + T_2 = m\omega^2 r_1$
(E) $T_1 = T_2$

14. A block of mass 3 kg is swung on a cord in a horizontal circle of radius 2 m. The speed of the block is 6 m/s. The magnitude of the acceleration of the block is most nearly

(A) zero
(B) 10 m/s^2
(C) 18 m/s^2
(D) 36 m/s^2
(E) 54 m/s^2

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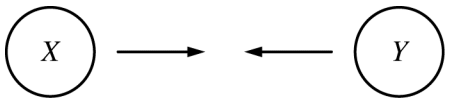
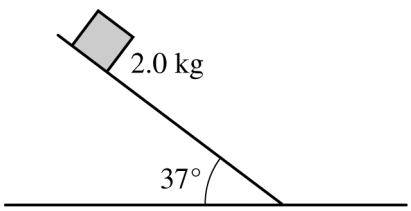


15. Two 1.0 kg balls have a perfectly elastic head-on collision, as shown in the figure above. Before the collision, ball *X* has a velocity of 2.0 m/s to the right and ball *Y* has a velocity of 4.0 m/s to the left. After the collision, ball *X* has a velocity of

(A) 0 m/s
(B) 2.0 m/s to the right
(C) 2.0 m/s to the left
(D) 4.0 m/s to the right
(E) 4.0 m/s to the left

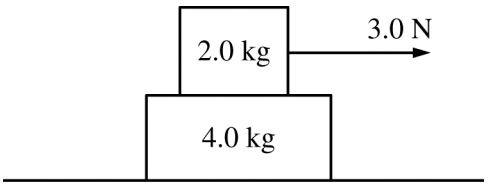
16. An object of mass m and velocity $3v$ toward the east has a completely inelastic collision with an object of mass $2m$ and velocity $2v$ toward the north. After the collision, the momentum of the combined object has a magnitude of

(A) $5mv$
(B) $7mv$
(C) $10mv$
(D) $12mv$
(E) $15mv$



17. A 2.0 kg block is released from rest at the top of a rough plane inclined at 37° to the horizontal, as shown above. The block slides down the incline with an acceleration of 4.0 m/s^2. What is the approximate magnitude of the force of friction on the block as it slides down the incline?

(A) 4.0 N
(B) 6.0 N
(C) 10 N
(D) 12 N
(E) 20 N



18. A 2.0 kg box is on top of a 4.0 kg box that is placed on a frictionless surface, as shown in the figure above. A 3.0 N force is applied to the top box. What is the minimum coefficient of friction between the two boxes needed to keep them moving together?

(A) 0.10
(B) 0.15
(C) 0.30
(D) 0.50
(E) 1.0

Questions 19-20

A juggler has three objects in the air simultaneously. The masses of the objects are m, $2m$, and $3m$. At a particular instant, their respective vertical velocities are $\vec{v}$, 0, and $-\vec{v}$, where positive velocity is upward.

19. What is the magnitude of the acceleration of the center of mass of the three-object system at this instant?

(A) zero
(B) $g/6$
(C) $g/3$
(D) $g/2$
(E) g

20. What is the velocity of the center of mass of the three-object system at this instant?

(A) $-\vec{v}/2$
(B) $-\vec{v}/3$
(C) zero
(D) $\vec{v}/3$
(E) $\vec{v}/2$

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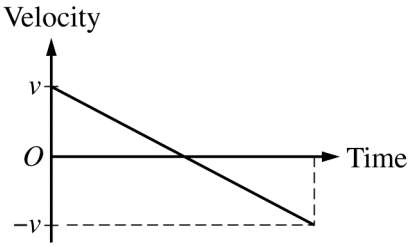
21. In a classroom demonstration, a teacher has a coin and feather in a long tube. The teacher uses a vacuum pump to remove all the air from the tube. The feather and coin are then dropped from the top of the tube at the same time. Which of the following describes what happens and why?

(A) The coin hits the bottom of the tube first because it weighs more.
(B) The coin hits the bottom of the tube first because it is more dense.
(C) The feather hits the bottom of the tube first because it weighs less.
(D) The coin and feather hit the bottom of the tube at the same time because they weigh the same.
(E) The coin and feather hit the bottom of the tube at the same time because they have the same acceleration.



22. The graph above shows velocity versus time for an object moving in a straight line, initially in the $+x$ direction. Which of the following is true for the motion of the object for the entire time shown on the graph?

(A) Its speed decreases with constant acceleration.
(B) Its speed increases with constant acceleration.
(C) Its speed decreases with acceleration that also decreases in magnitude.
(D) Its speed decreases to zero, then increases as the object moves in the $-x$ direction.
(E) Its acceleration decreases at a constant rate to zero, then increases at a constant rate.

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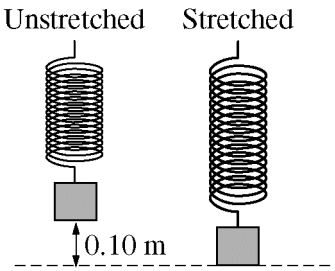
Questions 23-24

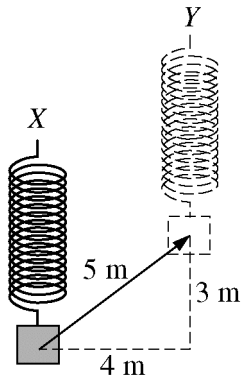


Note: Figure not drawn to scale.

A block is hung vertically from a spring of force constant 50 N/m and slowly lowered to equilibrium, stretching the spring by 0.10 m, as shown in the figure above.

23. If instead of being lowered slowly to equilibrium, the block—still attached to the spring—was released from rest and allowed to fall, which of the following would happen?

(A) It would descend 0.10 m and remain at that position.
(B) It would descend 0.10 m and then reverse its direction of motion.
(C) It would descend 0.20 m and remain at that position.
(D) It would descend 0.20 m and then reverse its direction of motion.
(E) It would descend more than 0.20 m and then reverse its direction of motion.



Note: Figure not drawn to scale.

24. The spring and attached block are allowed to come to rest at position *X* and are then moved to rest at position *Y* along the diagonal path shown above. What is the work done on the block by the spring in moving it along this path?

(A) 0 J
(B) 15 J
(C) 20 J
(D) 25 J
(E) It cannot be determined without being given the value of the mass of the block.

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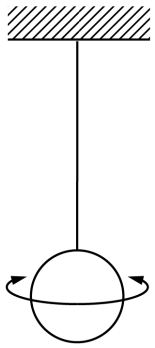


25. The sphere shown above, which hangs from a rigid wire, is given a twist and set into angular harmonic motion. The resulting equation of motion of the oscillating sphere is $\theta(t) = 0.1\cos(2t)$, where θ is in radians and t is in seconds. If the rotational inertia of the sphere is $10\ \text{kg}\cdot\text{m}^2$, then the torsion constant of the wire is most nearly

(A) $7\ \text{kg}\cdot\text{m}^2/\text{s}^2$
(B) $20\ \text{kg}\cdot\text{m}^2/\text{s}^2$
(C) $30\ \text{kg}\cdot\text{m}^2/\text{s}^2$
(D) $40\ \text{kg}\cdot\text{m}^2/\text{s}^2$
(E) $50\ \text{kg}\cdot\text{m}^2/\text{s}^2$

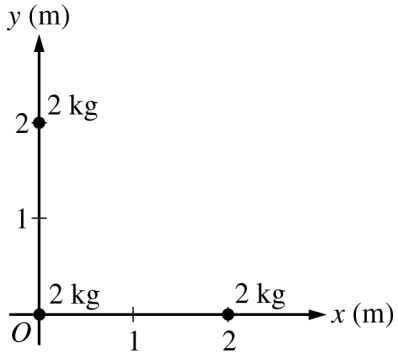
26. Assuming air resistance is negligible, how does a diver doing flips off a diving board change rotational speed in midair?

(A) By changing rotational inertia
(B) By maintaining a constant linear speed
(C) By changing linear momentum
(D) By exerting a net torque
(E) By changing angular momentum

27. A toy spacecraft is launched directly upward. When the toy reaches its highest point, a spring is released and the toy splits into two parts with masses of 0.01 kg and 0.09 kg, respectively. Immediately after the separation, the 0.01 kg part moves horizontally due east. Air resistance is negligible. True statements about the 0.09 kg part include which of the following?

I. It could move north immediately after the spring is released.
II. It takes longer to reach the ground than does the 0.01 kg part.
III. It strikes the ground closer to the launch point than does the 0.01 kg part.

(A) I only
(B) III only
(C) I and II only
(D) II and III only
(E) I, II, and III



28. A system consists of three 2 kg objects located at coordinates (0, 2), (0, 0), and (2, 0), as shown in the figure above. What are the coordinates (x, y) of the center of mass of the system?

(A) $(1/2\ \text{m},\ 1/2\ \text{m})$
(B) $(2/3\ \text{m},\ 2/3\ \text{m})$
(C) $(3/4\ \text{m},\ 3/4\ \text{m})$
(D) $(1\ \text{m},\ 1\ \text{m})$
(E) $(4/3\ \text{m},\ 4/3\ \text{m})$

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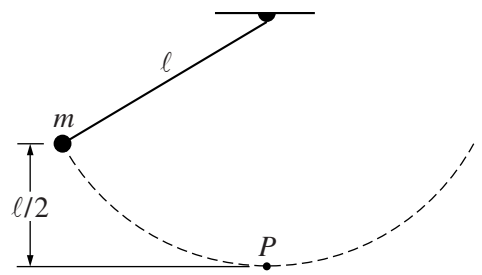
Questions 29-30 refer to the following.



A ball of mass m, suspended by a cord of length ℓ, is displaced along its arc until it is elevated a vertical distance of $\ell/2$ above its lowest position at point P, as shown above. The ball is then released from rest and swings like a simple pendulum.

29. The speed of the ball as it swings through point P is

(A) $\sqrt{g\ell}$

(B) $\sqrt{2g\ell}$

(C) $\sqrt{mg\ell}$

(D) $\frac{mg\ell}{2}$

(E) $mg\ell$

30. If air resistance and friction in the pivot are negligible, quantities that are conserved as the ball swings back and forth include which of the following?

I. Mechanical energy of the ball-Earth system
II. Linear momentum of the ball
III. Angular momentum of the ball about the pivot point

(A) I only
(B) II only
(C) I and III only
(D) II and III only
(E) I, II, and III

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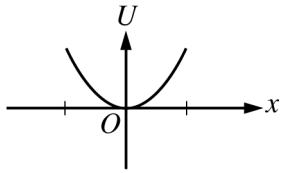
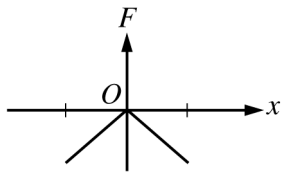
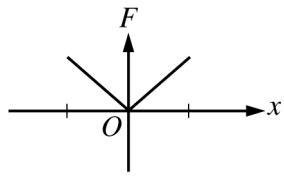
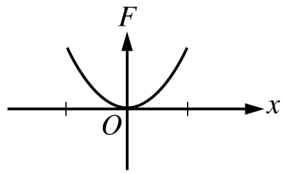
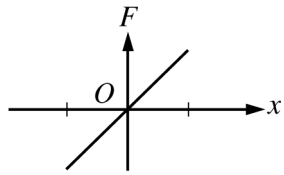


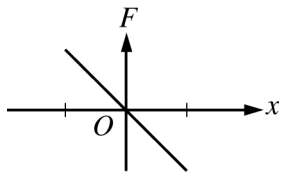
31. The graph above shows potential energy U versus position x for an object. Which of the following graphs shows the force F exerted on the object as a function of position x ?

(A)


(B)


(C)


(D)


(E)


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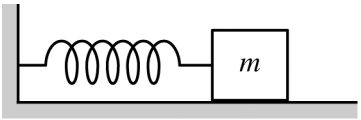

32. A block of mass m on a horizontal surface is attached to one end of a horizontal spring. The other end of the spring is fixed, as shown in the figure above. The block oscillates with negligible friction and an amplitude of 4.0 cm. How far from the equilibrium position is the block when the kinetic energy of the block is three times the potential energy of the system?

(A) 1 cm
(B) $\sqrt{2}$ cm
(C) 2 cm
(D) $2\sqrt{2}$ cm
(E) 3 cm

33. An Earth satellite in a circular orbit of radius R has a period T. What is the period of an Earth satellite in a circular orbit of radius $4R$?

(A) T
(B) $2T$
(C) $4T$
(D) $6T$
(E) $8T$

34. The net force on an object initially moving along the positive x-axis is given by $F(t) = \left(4t - t^3\right)$ for $t > 0$, where F is in newtons and along the x-axis, and t is in seconds. At what time does the object reach its maximum positive velocity?

(A) $\frac{3}{4}$ s
(B) $\frac{4}{3}$ s
(C) 2 s
(D) $\sqrt{6}$ s
(E) 3 s

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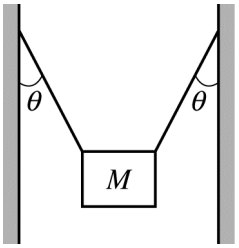

35. A heavy sign of mass M is hung between two buildings from two supporting wires, each making an angle θ with the vertical, as shown in the figure above. What is the tension in each wire?

(A) $\frac{Mg}{2\sin\theta}$

(B) $\frac{Mg}{2\cos\theta}$

(C) $\frac{Mg}{\sin\theta}$

(D) $\frac{2Mg}{\sin\theta}$

(E) $\frac{2Mg}{\cos\theta}$

S T O P

END OF MECHANICS SECTION I

IF YOU FINISH BEFORE TIME IS CALLED,
YOU MAY CHECK YOUR WORK ON MECHANICS SECTION I ONLY.

DO NOT TURN TO ANY OTHER TEST MATERIALS.

MAKE SURE YOU HAVE DONE THE FOLLOWING.

- **PLACED YOUR AP NUMBER LABEL ON YOUR ANSWER SHEET**
- **WRITTEN AND GRIDDED YOUR AP NUMBER CORRECTLY ON YOUR ANSWER SHEET**
- **TAKEN THE AP EXAM LABEL FROM THE FRONT OF THIS BOOKLET AND PLACED IT ON YOUR ANSWER SHEET**

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AP® Physics C: Mechanics Exam

SECTION II: Free Response

2015

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
45 minutes
Number of Questions
3
Percent of Total Score
50%
Writing Instrument
Either pencil or pen with black or dark blue ink
Electronic Device
Calculator allowed
Weight
The questions are weighted equally.

IMPORTANT Identification Information

PLEASE PRINT WITH PEN:

1. First two letters of your last name ☐☐
   First letter of your first name ☐
2. Date of birth
   ☐☐ Month ☐☐ Day ☐☐☐☐ Year
3. Six-digit school code
   ☐☐☐☐☐☐
4. Unless I check the box below, I grant the College Board the unlimited right to use, reproduce, and publish my free-response materials, both written and oral, for educational research and instructional purposes. My name and the name of my school will not be used in any way in connection with my free-response materials. I understand that I am free to mark "No" with no effect on my score or its reporting.
   No, I do not grant the College Board these rights. ☐

Instructions

The questions for Section II are printed in this booklet. You may use any blank space in the booklet for scratch work, but you must write your answers in the spaces provided for each answer. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers, and straightedges may be used in this section.

All final numerical answers should include appropriate units. Credit for your work depends on demonstrating that you know which physical principles would be appropriate to apply in a particular situation. Therefore, you should show your work for each part in the space provided after that part. If you need more space, be sure to clearly indicate where you continue your work. Credit will be awarded only for work that is clearly designated as the solution to a specific part of a question. Credit also depends on the quality of your solutions and explanations, so you should show your work.

Write clearly and legibly. Cross out any errors you make; erased or crossed-out work will not be scored. You may lose credit for incorrect work that is not crossed out.

Manage your time carefully. You may proceed freely from one question to the next. You may review your responses if you finish before the end of the exam is announced.

Form I
Form Code Z-4FBP2-S

ADVANCED PLACEMENT PHYSICS C TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass,	$m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude,	$e = 1.60 \times 10^{-19}$ C
Neutron mass,	$m_n = 1.67 \times 10^{-27}$ kg	1 electron volt,	1 eV $= 1.60 \times 10^{-19}$ J
Electron mass,	$m_e = 9.11 \times 10^{-31}$ kg	Speed of light,	$c = 3.00 \times 10^{8}$ m/s
Avogadro's number,	$N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant,	$G = 6.67 \times 10^{-11}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{kg}^2$
Universal gas constant,	$R = 8.31$ J/(mol·K)	Acceleration due to gravity at Earth's surface,	$g = 9.8$ m/s^2
Boltzmann's constant,	$k_B = 1.38 \times 10^{-23}$ J/K		

1 unified atomic mass unit,	1 u $= 1.66 \times 10^{-27}$ kg $= 931$ MeV/c^2
Planck's constant,	$h = 6.63 \times 10^{-34}$ J·s $= 4.14 \times 10^{-15}$ eV·s
	$hc = 1.99 \times 10^{-25}$ J·m $= 1.24 \times 10^{3}$ eV·nm
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}$ C$^2/\left(\text{N}\cdot\text{m}^2\right)$
Coulomb's law constant,	$k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{C}^2$
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A
Magnetic constant,	$k' = \mu_0/(4\pi) = 1 \times 10^{-7}$ (T·m)/A
1 atmosphere pressure,	1 atm $= 1.0 \times 10^{5}$ N/m^2 $= 1.0 \times 10^{5}$ Pa

UNIT SYMBOLS								
	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	1/2	3/5	$\sqrt{2}/2$	4/5	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	4/5	$\sqrt{2}/2$	3/5	1/2	0
$\tan\theta$	0	$\sqrt{3}/3$	3/4	1	4/3	$\sqrt{3}$	∞

The following assumptions are used in this exam.

I. The frame of reference of any problem is inertial unless otherwise stated.
II. The direction of current is the direction in which positive charges would drift.
III. The electric potential is zero at an infinite distance from an isolated point charge.
IV. All batteries and meters are ideal unless otherwise stated.
V. Edge effects for the electric field of a parallel plate capacitor are negligible unless otherwise stated.

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

$v_x^2 = {v_{x0}}^2 + 2a_x (x - x_0)$

$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$\vec{F} = \frac{d\vec{p}}{dt}$

$\vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$

$\vec{p} = m\vec{v}$

$\left|\vec{F}_f\right| \le \mu \left|\vec{F}_N\right|$

$\Delta E = W = \int \vec{F} \bullet d\vec{r}$

$K = \frac{1}{2} m v^2$

$P = \frac{dE}{dt}$

$P = \vec{F} \bullet \vec{v}$

$\Delta U_g = mg\Delta h$

$a_c = \frac{v^2}{r} = \omega^2 r$

$\vec{\tau} = \vec{r} \times \vec{F}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$I = \int r^2 dm = \sum m r^2$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$v = r\omega$

$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$

$K = \frac{1}{2} I \omega^2$

$\omega = \omega_0 + \alpha t$

$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$

a = acceleration
E = energy
F = force
f = frequency
h = height
I = rotational inertia
J = impulse
K = kinetic energy
k = spring constant
ℓ = length
L = angular momentum
m = mass
P = power
p = momentum
r = radius or distance
T = period
t = time
U = potential energy
v = velocity or speed
W = work done on a system
x = position
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed
α = angular acceleration
ϕ = phase angle

$\vec{F}_s = -k\Delta\vec{x}$

$U_s = \frac{1}{2} k (\Delta x)^2$

$x = x_{\max} \cos(\omega t + \phi)$

$T = \frac{2\pi}{\omega} = \frac{1}{f}$

$T_s = 2\pi\sqrt{\frac{m}{k}}$

$T_p = 2\pi\sqrt{\frac{\ell}{g}}$

$\left|\vec{F}_G\right| = \frac{G m_1 m_2}{r^2}$

$U_G = -\frac{G m_1 m_2}{r}$

ELECTRICITY AND MAGNETISM

$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$

$\vec{E} = \frac{\vec{F}_E}{q}$

$\oint \vec{E} \bullet d\vec{A} = \frac{Q}{\varepsilon_0}$

$E_x = -\frac{dV}{dx}$

$\Delta V = -\int \vec{E} \bullet d\vec{r}$

$V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

$\Delta V = \frac{Q}{C}$

$C = \frac{\kappa \varepsilon_0 A}{d}$

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

$I = \frac{dQ}{dt}$

$U_C = \frac{1}{2} Q\Delta V = \frac{1}{2} C (\Delta V)^2$

$R = \frac{\rho\ell}{A}$

$\vec{E} = \rho\vec{J}$

$I = Nev_d A$

$I = \frac{\Delta V}{R}$

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

$\vec{F}_M = q\vec{v} \times \vec{B}$

$\oint \vec{B} \bullet d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\, d\vec{\ell} \times \hat{r}}{r^2}$

$\vec{F} = \int I\, d\vec{\ell} \times \vec{B}$

$B_s = \mu_0 n I$

$\Phi_B = \int \vec{B} \bullet d\vec{A}$

$\mathcal{E} = \oint \vec{E} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\mathcal{E} = -L\frac{dI}{dt}$

$U_L = \frac{1}{2} L I^2$

ADVANCED PLACEMENT PHYSICS C EQUATIONS

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

$A = \frac{1}{2}bh$

Circle

$A = \pi r^2$

$C = 2\pi r$

$s = r\theta$

Rectangular Solid

$V = \ell wh$

Cylinder

$V = \pi r^2 \ell$

$S = 2\pi r\ell + 2\pi r^2$

Sphere

$V = \frac{4}{3}\pi r^3$

$S = 4\pi r^2$

Right Triangle

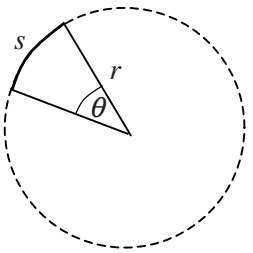
$a^2 + b^2 = c^2$

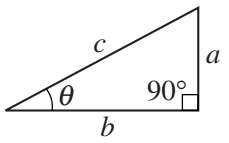
$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

$\tan\theta = \frac{a}{b}$

A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius
s = arc length
θ = angle





CALCULUS

$$\frac{df}{dx} = \frac{df}{du}\frac{du}{dx}$$

$$\frac{d}{dx}\left(x^n\right) = nx^{n-1}$$

$$\frac{d}{dx}\left(e^{ax}\right) = ae^{ax}$$

$$\frac{d}{dx}(\ln ax) = \frac{1}{x}$$

$$\frac{d}{dx}[\sin(ax)] = a\cos(ax)$$

$$\frac{d}{dx}[\cos(ax)] = -a\sin(ax)$$

$$\int x^n\,dx = \frac{1}{n+1}x^{n+1},\ n \neq -1$$

$$\int e^{ax}\,dx = \frac{1}{a}e^{ax}$$

$$\int \frac{dx}{x+a} = \ln|x+a|$$

$$\int \cos(ax)\,dx = \frac{1}{a}\sin(ax)$$

$$\int \sin(ax)\,dx = -\frac{1}{a}\cos(ax)$$

VECTOR PRODUCTS

$\vec{A}\bullet\vec{B} = AB\cos\theta$

$\left|\vec{A}\times\vec{B}\right| = AB\sin\theta$

PHYSICS C: MECHANICS
SECTION II
Time—45 minutes
3 Questions

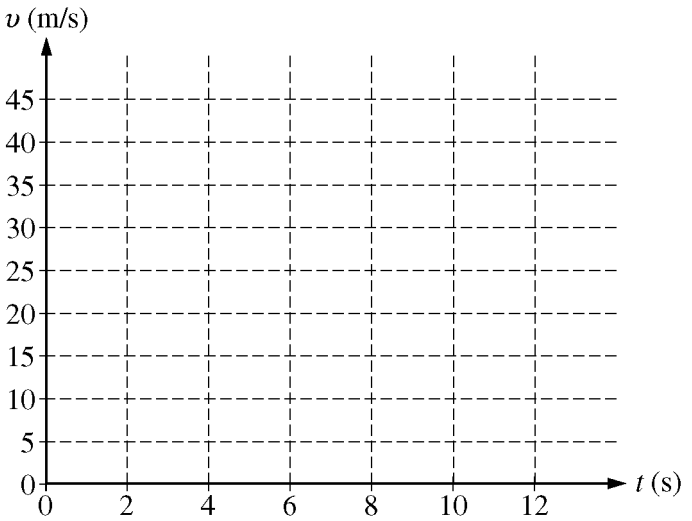
Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

Mech. 1.

A new sports car is undergoing acceleration tests to determine its specifications. The following data on speed v versus time t are recorded for the car as it accelerates from rest along a straight track.

v (m/s)	0	14	23	30	35	39
t (s)	0	2	4	6	8	10

(a) On the axes below, plot v as a function of t and sketch a curve that best represents the data.



(b) Answer each of the following for the time period $t = 0$ s to $t = 10$ s.

i. Does the speed of the car increase, decrease, or stay the same?

____ Increase ____ Decrease ____ Stay the same

Justify your answer.

ii. Does the acceleration of the car increase, decrease, or stay the same?

____ Increase ____ Decrease ____ Stay the same

Justify your answer.

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(c) Explain how you would use your graph in part (a) to find the distance traveled by the car between $t = 2$ s and $t = 8$ s.

The equation for the speed v of the car as a function of time t found from the graph is $v(t) = -0.3t^2 + 7t$, where v is in meters per second and t is in seconds.

(d) Derive an expression for the acceleration of the car $a(t)$ as a function of time t.

(e) Calculate the position of the car as a function of time, $x(t)$, assuming that the car starts from rest at the origin of a coordinate system.

(f) Calculate the distance traveled by the car between $t = 2$ s and $t = 8$ s.

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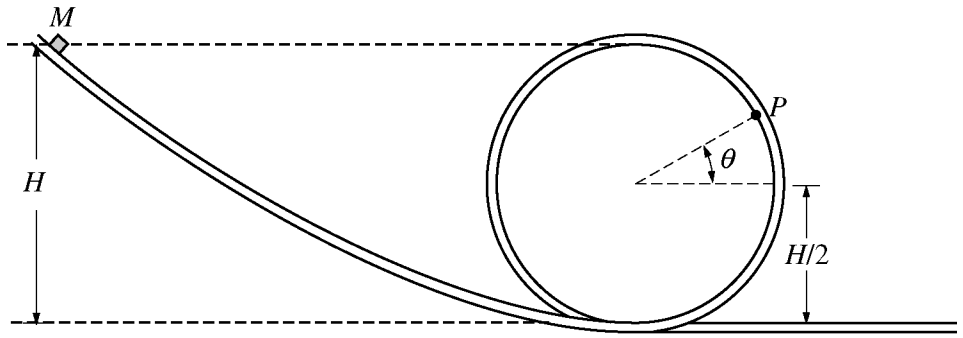
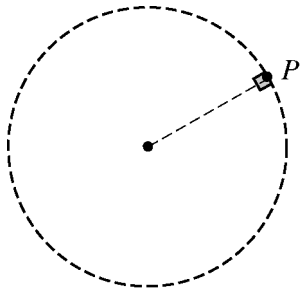


Mech. 2.

The model of a roller coaster shown above consists of a ramp and a circular loop. A small block of mass M starts from height H with speed $v = 0$ and slides without friction down the ramp and around the inside of the loop of radius $H/2$. Position P is a point on the loop at an angle θ with the horizontal, as shown above. Express all algebraic answers in terms of M, H, θ, and fundamental constants, as appropriate.

(a) Derive an expression for the speed of the block at position P.

(b) On the following diagram, draw and label vectors to represent the forces (not components) on the block when it is at position P. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot at position P.



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(c) Derive an expression for the magnitude of the force exerted by the loop on the block when it is at position *P*. If you need to draw anything other than what you have shown in part (b) to assist in your solution, use the space below. Do NOT add anything to the figure in part (b).

(d) Calculate the angle θ_L, in degrees, at which the block leaves the loop.

(e) The small block is replaced with a small sphere that also starts at height *H*. Now there is enough friction to allow the sphere to roll down the ramp without slipping. Identify how the new angle θ_n at which the sphere leaves the loop compares with the angle θ_L calculated in part (d).

____ $\theta_n < \theta_L$ ____ $\theta_n = \theta_L$ ____ $\theta_n > \theta_L$

Explain your reasoning.

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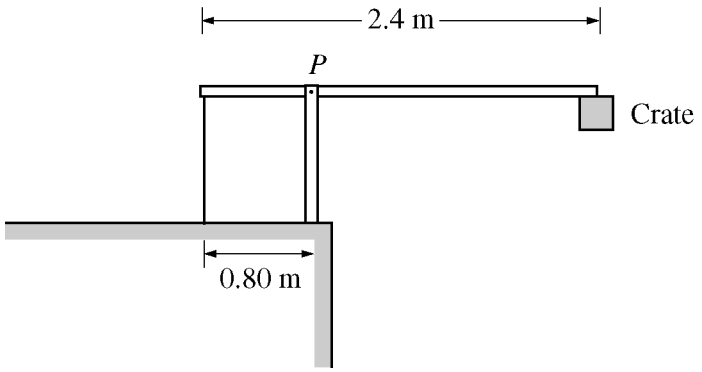
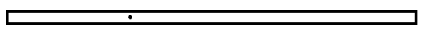


Mech. 3.

A uniform, rigid, thin board that is 2.4 m long and weighs 200 N is attached to a post by a pivot at point *P* and hangs over the edge of a building, as shown above. A crate weighing 400 N is attached to the right end of the board. The left end of the board, 0.80 m from the pivot, is attached to a light vertical wire anchored at the other end to keep the board from rotating.

(a) On the diagram below, draw and label vectors to represent all the forces (not components) acting on the board. Show each force vector originating at its point of application.



(b) Calculate the magnitudes of the forces exerted on the board by the post and by the wire. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figure in part (a).

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(c) The rotational inertia of the board alone about its center is $\frac{1}{12}ML^2$, where M is the mass of the board and L is its length. Calculate the rotational inertia of the combined board-crate system about point P.

(d) Suppose that the wire breaks and the board begins to pivot about point P. Calculate each of the following.

i. The magnitude of the initial angular acceleration of the board-crate system

ii. The magnitude of the initial linear acceleration of the left end of the board

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THIS PAGE MAY BE USED FOR SCRATCH WORK.

STOP

END OF EXAM

THE FOLLOWING INSTRUCTIONS APPLY TO THE COVERS OF THE SECTION II BOOKLET.

- **MAKE SURE YOU HAVE COMPLETED THE IDENTIFICATION INFORMATION AS REQUESTED ON THE FRONT AND BACK COVERS OF THE SECTION II BOOKLET.**
- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE COVER.**
- **MAKE SURE YOU HAVE USED THE SAME SET OF AP NUMBER LABELS ON ALL AP EXAMS YOU HAVE TAKEN THIS YEAR.**