AP® Physics C: Mechanics Exam

SECTION I: Multiple Choice

2016

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.

Form I
Form Code 4MBP4-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, $1\text{ eV} = 1.60 \times 10^{-19}$ 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, $h = 6.63 \times 10^{-34}\text{ J}\cdot\text{s} = 4.14 \times 10^{-15}\text{ eV}\cdot\text{s}$

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

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
ε = 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

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

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

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

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

$B_s = \mu_0 n I$

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

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

$\varepsilon = -L\frac{dI}{dt}$

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

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

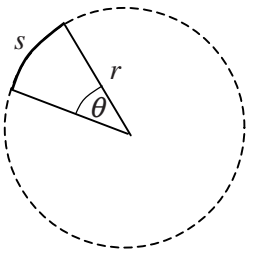
$a^2 + b^2 = c^2$

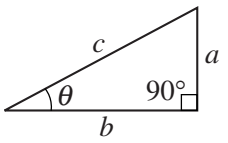
$\sin\theta = \frac{a}{c}$

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

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

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

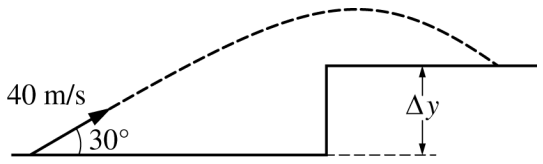
SECTION I

Time—45 minutes

35 Questions

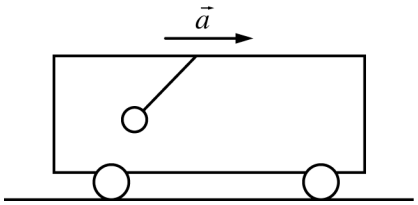
Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

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



1. A projectile is launched with a speed of $40\ \text{m/s}$ at an angle of $30°$ above the horizontal, as shown in the figure above. The projectile lands on a plateau 3 s later. The height Δy of the plateau is most nearly

   (A) 15 m
   (B) 30 m
   (C) 45 m
   (D) 60 m
   (E) 75 m



2. A small sphere hangs from a string attached to the ceiling of a uniformly accelerating train car. It is observed that the string makes an angle of $37°$ with respect to the vertical. The magnitude of the acceleration a of the train car is most nearly

   (A) $6.0\ \text{m/s}^2$
   (B) $7.5\ \text{m/s}^2$
   (C) $8.0\ \text{m/s}^2$
   (D) $10\ \text{m/s}^2$
   (E) $13\ \text{m/s}^2$

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3. Which of the following statements must be true for a falling object that has been dropped from rest near the surface of Earth?

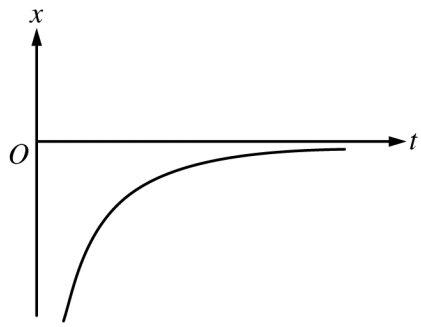
(A) The derivative of the distance the object falls with respect to time equals $9.8\ \text{m/s}^2$.

(B) The object falls a vertical distance of 9.8 m during the first second only.

(C) The object falls a vertical distance of 9.8 m during each second.

(D) The speed of the object as it falls is a constant $9.8\ \text{m/s}$.

(E) The speed of the object increases by $9.8\ \text{m/s}$ during each second.



4. The position x as a function of time t for an object moving in a straight line is shown in the graph above. Which of the following best describes the object's speed and direction of motion during the time interval shown?

	Speed	Direction of Motion
(A)	Decreasing	Positive
(B)	Increasing	Positive
(C)	Constant	Positive
(D)	Decreasing	Negative
(E)	Increasing	Negative

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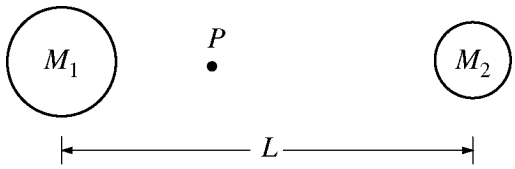
5. The force F exerted on a ball during a collision with a wall is given as a function of time t by the equation $F(t) = \alpha t - \beta t^2$, where $\alpha = 400$ N/s and $\beta = 4000$ N/s^2. The ball first contacts the wall at $t = 0$, and the collision lasts for 0.10 s. What is the magnitude of the change in momentum of the ball?

(A) 0
(B) 0.67 kg•m/s
(C) 3.33 kg•m/s
(D) 3.60 kg•m/s
(E) The change in momentum of the ball cannot be determined without knowing the mass of the ball.



6. Two spheres of uniform density are located a distance L apart, as shown in the figure above. The left sphere has a mass M_1, and the right sphere has a mass M_2. The center of mass of the two spheres is labeled point P. Which of the following is a correct expression for the distance from point P to the center of the left sphere?

(A) $\frac{M_1}{M_2}L$
(B) $\frac{(M_1 + M_2)}{M_1}L$
(C) $\frac{(M_1 + M_2)}{M_2}L$
(D) $\frac{M_2}{(M_1 + M_2)}L$
(E) $\frac{M_1}{(M_1 + M_2)}L$

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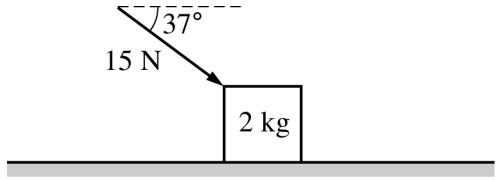
Questions 7-8



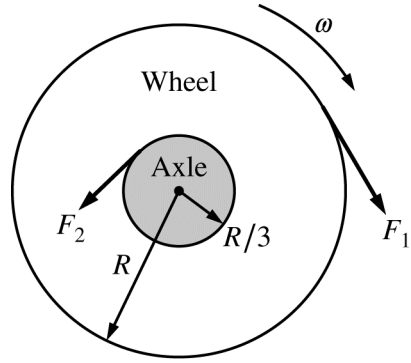
A 2 kg block is initially at rest on a horizontal frictionless table. A force of 15 N is then exerted on the block at an angle of $37°$ to the horizontal, as shown above.

7. The change in the kinetic energy of the block after moving a distance of 3 m is most nearly

(A) 60 J
(B) 45 J
(C) 36 J
(D) 27 J
(E) 24 J

8. The magnitude of the force exerted on the block by the table is most nearly

(A) 35 N
(B) 32 N
(C) 29 N
(D) 20 N
(E) 11 N



Note: Vectors not drawn to scale.

9. A wheel of radius R is fixed to an axle of radius $R/3$ and rotates at constant angular speed ω, as shown in the figure above. A force of magnitude F_1 is applied tangent to the outer edge of the wheel. A second force of magnitude F_2 is applied tangent to the edge of the axle to keep the wheel rotating at constant angular speed ω. The magnitude F_2 is equal to

(A) $F_1/9$
(B) $F_1/3$
(C) F_1
(D) $3F_1$
(E) $9F_1$

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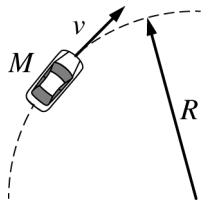
Questions 10-11



On a level horizontal table, a toy race car of mass M moves with constant speed v around a flat circular racetrack of radius R.

10. Which of the following best represents the minimum coefficient of static friction required for the race car to continue to follow the circular path shown?

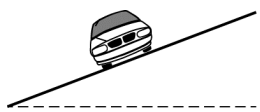
(A) $\frac{Rg}{v^2}$

(B) $\frac{Mv^2}{R}$

(C) $\frac{v^2}{g}$

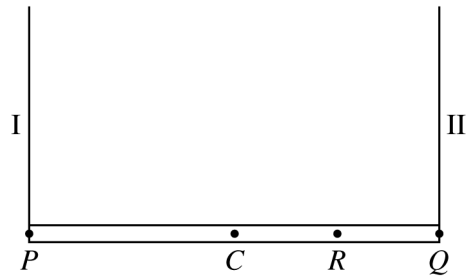
(D) $\frac{v^2}{Rg}$

(E) $\frac{v^2}{2Rg}$



11. The car is now going around a banked curve, as shown in the figure above. The banked curve is higher toward the outside of the circular turn. The car can now travel at a higher speed without sliding because the banked curve

(A) increases the coefficient of friction between the car and the track.
(B) increases the momentum of the car.
(C) allows a component of the normal force to point toward the center of the track.
(D) allows a component of the weight of the car to point toward the center of the track.
(E) allows gravity to do work on the car.



12. A horizontal uniform plank is supported by ropes I and II at points P and Q, respectively, as shown above. The two ropes have negligible mass. The tension in rope I is 150 N. The point at which rope II is attached to the plank is now moved to point R halfway between point Q and point C, the center of the plank. The plank remains horizontal. Which of the following are most nearly the new tensions in the two ropes?

	Tension in I	Tension in II
(A)	75 N	225 N
(B)	100 N	200 N
(C)	112.5 N	112.5 N
(D)	112.5 N	187.5 N
(E)	150 N	300 N

13. The potential energy U as a function of the position x of an object is given by $U(x) = -400/x$, where U is in joules and x is in meters. The object is released from rest at position $x = 30$ m and is free to move along the x-axis. When the object has moved a distance of 10 m from its initial position, the magnitude of the force associated with this potential energy function is

(A) 20 N
(B) 10 N
(C) 4.0 N
(D) 1.0 N
(E) 0.25 N

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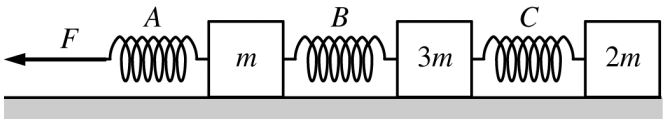
14. A student pushes a box across a rough horizontal floor. If the amount of work done by the student on the box is 100 J and the amount of energy dissipated by friction is 40 J, what is the change in kinetic energy of the box?

(A) 0 J
(B) 40 J
(C) 60 J
(D) 100 J
(E) 140 J



15. Three blocks of masses m, $3m$, and $2m$ resting on a frictionless horizontal surface are connected to identical ideal springs, as shown above. A force of magnitude F directed to the left is then applied to the left end of spring A. Which spring is stretched the most when the blocks are all moving with the same acceleration?

(A) A
(B) B
(C) C
(D) None, because the springs do not stretch.
(E) None, because the springs all stretch the same amount.

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16. At time $t = 0$, a ball is thrown with initial speed v_0 at an angle θ above the horizontal. Air resistance is negligible. Which of the following best represents the speed of the ball as a function of time t while the ball is in flight?

(A) $v_0 \sin\theta - gt$

(B) $v_0 \cos\theta - gt$

(C) $\sqrt{v_0^2 \cos^2\theta + (v_0 \sin\theta - gt)^2}$

(D) $\sqrt{(v_0 \cos\theta - gt)^2 + v_0^2 \sin^2\theta}$

(E) $\sqrt{(v_0 \cos\theta - gt)^2 + (v_0 \sin\theta - gt)^2}$

17. The position x of an object is given as a function of time t by the equation $x = 8 + 4t - 6t^3$, where x is in meters and t is in seconds. What is the maximum positive velocity attained by this object?

(A) 4 m/s
(B) 8 m/s
(C) 18 m/s
(D) 36 m/s
(E) There is no maximum positive velocity because the object never moves in the positive direction.

18. Two balls, A and B, have the same mass and diameter but are made from different types of rubber. The balls are dropped from the same height above the floor. After colliding with the floor, ball A bounces higher than ball B bounces. Which of the following quantities must necessarily be larger for ball A than for ball B ?

(A) The average force exerted by the floor
(B) The amount of time in contact with the floor
(C) The impulse exerted by the floor
(D) The momentum just before colliding with the floor
(E) The kinetic energy just before colliding with the floor

19. Object A of mass M is moving east at speed v. It collides with object B of mass $2M$ that was initially at rest. The motion of the objects before and after the collision is along the same line. After the collision, object A is moving west at a speed of $v/3$. What is the speed of object B immediately after the collision?

(A) $v/3$
(B) $v/2$
(C) $2v/3$
(D) v
(E) $2v$

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Questions 20-21

A wheel of mass m, which has a rotational inertia I and a radius r, rotates with an angular speed ω about an axis through its center. A retarding force F is applied tangentially to the rim of the wheel.

20. Which of the following is equal to the magnitude of the angular acceleration of the wheel?

(A) $\frac{F\omega}{m}$

(B) $\frac{Fr}{I}$

(C) $\frac{\omega^2}{r}$

(D) $I\omega$

(E) ωr

21. The retarding force F finally stops the rotation of the wheel. Which of the following best represents the total reduction in mechanical energy in the process of stopping the wheel?

(A) Fr

(B) $I\omega^2$

(C) $\omega^2 r$

(D) Fr^2

(E) $\frac{1}{2}I\omega^2$

22. An airplane travels horizontally at a constant velocity $\vec{v}$. An object is dropped from the plane, and one second later another object is dropped from the plane. If air resistance is negligible, what happens to the vertical distance between the two objects while they are both falling?

(A) It increases.
(B) It decreases.
(C) It remains the same.
(D) It depends on the mass of the objects.
(E) It depends on the horizontal speed of the plane.

23. A boat moves across a river. The river's velocity relative to the land is $\vec{v}_{RL}$, and the boat's velocity relative to the river is $\vec{v}_{BR}$. Which of the following best represents the velocity of the boat relative to the land?

(A) $\vec{v}_{BR} + \vec{v}_{RL}$

(B) $\vec{v}_{BR} - \vec{v}_{RL}$

(C) $-\vec{v}_{BR} + \vec{v}_{RL}$

(D) $|\vec{v}_{BR}| + |\vec{v}_{RL}|$

(E) $|\vec{v}_{BR}| - |\vec{v}_{RL}|$

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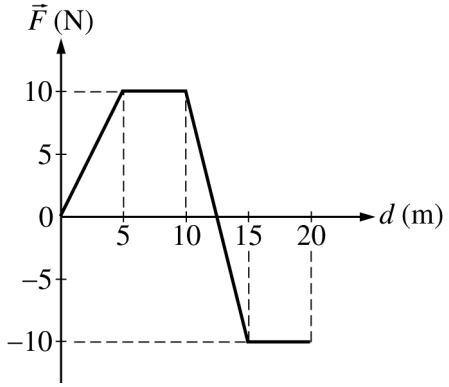
Questions 24-25

The following graph shows the force $\vec{F}$ exerted on a 2 kg object as a function of the distance d that the object travels. The object is at rest at $d = 0$ and travels on a horizontal, frictionless surface along the line of action of the force.



24. The work done on the object by the force $\vec{F}$ during the first 10 m of travel is most nearly

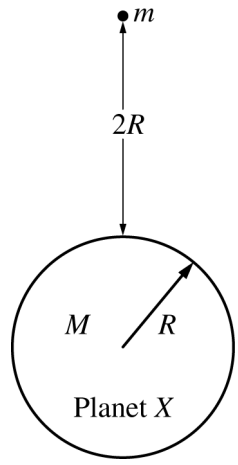
(A) 7.5 J
(B) 10 J
(C) 50 J
(D) 75 J
(E) 100 J

25. The kinetic energy of the 2 kg object when d equals 20 m is the same as when d is most nearly

(A) 0 m
(B) 5 m
(C) 10 m
(D) 12.5 m
(E) 15 m

26. The acceleration due to gravity on the surface of the Moon is about $1/6$ of that on the surface of Earth. An astronaut weighs 600 N on Earth. The astronaut's mass on the Moon is most nearly

(A) 600 kg
(B) 360 kg
(C) 100 kg
(D) 60 kg
(E) 10 kg



27. Planet X has a mass M, radius R, and no atmosphere. An object of mass m is located a distance $2R$ above the surface of planet X, as shown in the figure above. The object is released from rest and falls to the surface of the planet. What is the speed of the object just before it reaches the surface of planet X ?

(A) $\sqrt{\frac{2GM}{3R}}$

(B) $\sqrt{\frac{4GM}{3R}}$

(C) $\sqrt{\frac{8GM}{3R}}$

(D) $\sqrt{\frac{3GM}{R}}$

(E) $\sqrt{\frac{6GM}{R}}$

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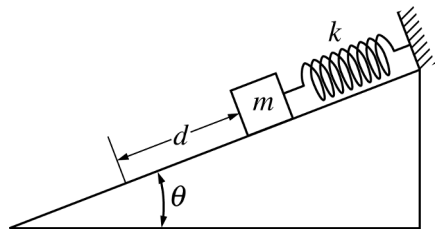
28. A ball is kicked from the ground with an initial speed v_0 at an angle θ above the horizontal. Which of the following best describes the magnitudes of the velocity and acceleration of the ball when it reaches the highest point of its trajectory?

	Velocity	Acceleration
(A)	0	0
(B)	$v_0 \cos\theta$	0
(C)	$v_0 \sin\theta$	0
(D)	$v_0 \cos\theta$	9.8 m/s^2
(E)	$v_0 \sin\theta$	9.8 m/s^2



29. A block of mass m is attached to a spring and placed on an inclined plane. The spring has a spring constant k, and there is negligible friction between the block and inclined plane. The block is released from rest at the position shown in the figure above with the spring initially unstretched. What distance d does the block slide down the plane before coming momentarily to rest?

(A) $\frac{2mg}{k}$

(B) $\frac{mg}{k}$

(C) $\frac{mg\sin\theta}{k}$

(D) $\frac{2mg\sin\theta}{k}$

(E) $\sqrt{\frac{mg\sin\theta}{k}}$

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30. A 5.0 kg object suspended on a spring oscillates such that its position x as a function of time t is given by the equation $x(t) = A\cos(\omega t)$, where $A = 0.80$ m and $\omega = 2.0\ \text{s}^{-1}$. What is the magnitude of the maximum net force on the object during the motion?

(A) 3.2 N
(B) 4.0 N
(C) 8.0 N
(D) 12.8 N
(E) 16.0 N

31. Consider Earth to be stationary, and the Moon as orbiting Earth in a circle of radius R. If the masses of Earth and the Moon are M_E and M_M, respectively, which of the following best represents the total mechanical energy of the Earth-Moon system?

(A) $\frac{GM_EM_M}{2R}$

(B) $\frac{GM_EM_M}{R}$

(C) $-\frac{GM_EM_M}{2R}$

(D) $-\frac{GM_EM_M}{R}$

(E) $-\frac{2GM_EM_M}{R}$

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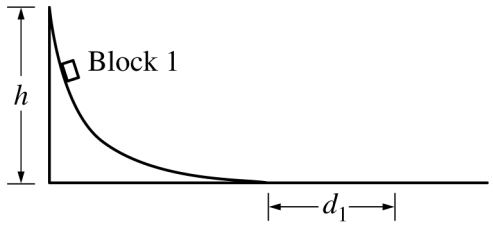
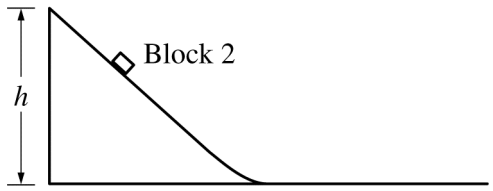
32. A small rock is launched straight upward from the surface of a planet with no atmosphere. The initial speed of the rock is twice the escape speed v_e of the rock from the planet. If gravitational effects from other objects are negligible, the speed of the rock at a very great distance from the planet will approach a value of

(A) zero
(B) $v_e/2$
(C) v_e
(D) $\sqrt{2}v_e$
(E) $\sqrt{3}v_e$





33. Identical blocks 1 and 2 start from rest at height h and travel down two differently shaped tracks onto identical rough horizontal surfaces, as shown in the figures above. Both tracks are frictionless, and both blocks make a smooth transition onto the rough horizontal surfaces. Block 1 comes to rest at a horizontal distance d_1 from the bottom of the track. Which of the following best describes and explains the horizontal distance d_2 that block 2 travels before coming to rest?

(A) $d_2 < d_1$, because block 2 reaches its maximum speed later than block 1
(B) $d_2 < d_1$, because block 2 has a lower maximum speed than block 1
(C) $d_2 = d_1$, because the blocks have the same mass
(D) $d_2 = d_1$, because the blocks start at the same height
(E) $d_2 > d_1$, because the track for block 2 is shorter

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	Mass (kg)	Area $\left(\text{cm}^2\right)$	μ_s
Block 1	0.75	75	0.20
Block 2	3.0	100	0.40

34. In an experiment, two blocks of different roughness are placed on the same rough wooden board. The table above shows three values for each block: the mass, the area of the block in contact with the board, and the coefficient of static friction μ_s between the block and the board. The experiment begins with the board horizontal. One end of the board is then slowly raised. Which of the following correctly identifies the block that will start sliding down the board first and why?
    (A) Block 1, because it has less mass per unit area
    (B) Block 1, because the coefficient of friction is smaller
    (C) Block 2, because it has greater mass
    (D) Block 2, because it has a smaller surface area
    (E) Block 2, because the coefficient of friction is larger

35. An equation for the motion of an object is given as $2vt - 4x = Bt^2$, where B is a constant. The variable v indicates velocity, in meters per second; t indicates time, in seconds; and x indicates displacement, in meters. What is the unit of measure for B ?
    (A) s
    (B) m/s
    (C) m/s^2
    (D) $\text{m}^2\text{/s}$
    (E) $\text{m}^2\text{/s}^2$

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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**

AP® Physics C: Mechanics Exam

SECTION II: Free Response

2016

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 4MBP4-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, $1\text{ eV} = 1.60 \times 10^{-19}$ 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, $h = 6.63 \times 10^{-34}\text{ J}\cdot\text{s} = 4.14 \times 10^{-15}\text{ eV}\cdot\text{s}$

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

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
ε = 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

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

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

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

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

$B_s = \mu_0 n I$

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

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

$\varepsilon = -L\frac{dI}{dt}$

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

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

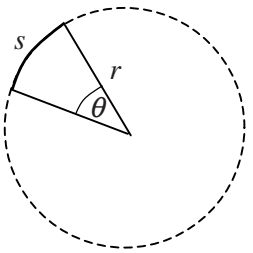
$a^2 + b^2 = c^2$

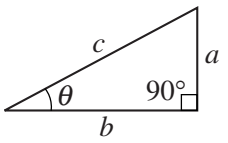
$\sin\theta = \frac{a}{c}$

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

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

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

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

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

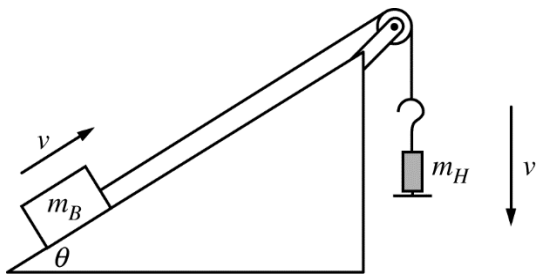
PHYSICS C: MECHANICS

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.

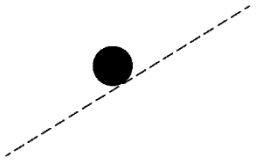


Mech.1.

A block of mass m_B is being pulled up a ramp by a hanging object of mass m_H, as shown in the figure above. The blocks are attached to each other by a light string that passes over a pulley of negligible mass and friction. Both the block and the hanging object are moving at constant speed, and the angle of the ramp with the horizontal is θ. The coefficient of kinetic friction between the block and the ramp is μ_k.

(a) On the dots below, which represent the block and the hanging object, draw and label the forces (not components) that act on the block and the hanging object. Each force must be represented by a distinct arrow starting on, and pointing away from, the appropriate dot.

Block



Hanging Object



(b) Derive an expression for the mass m_H of the hanging object. Express your answer in terms of m_B, θ, μ_k, and physical constants, as appropriate. 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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GO ON TO THE NEXT PAGE.

It is determined that $m_B = 2.0$ kg, $\theta = 30^\circ$, and $\mu_k = 0.10$. While the block is moving up the ramp and the hanging object is moving downward, the string is suddenly cut.

(c)

i. Calculate the magnitude of the acceleration of the block immediately after the string is cut.

ii. What is the direction of the acceleration of the block immediately after the string is cut?

____ Up the ramp _____ Down the ramp

____ No direction, because the acceleration is zero

iii. Determine the magnitude of the acceleration of the hanging object immediately after the string is cut.

(d) Assume the block is moving up the ramp at 2.0 m/s when the string is cut. Calculate how far the block travels up the ramp from the time the string is cut until the block stops, assuming there is sufficient distance on the ramp.

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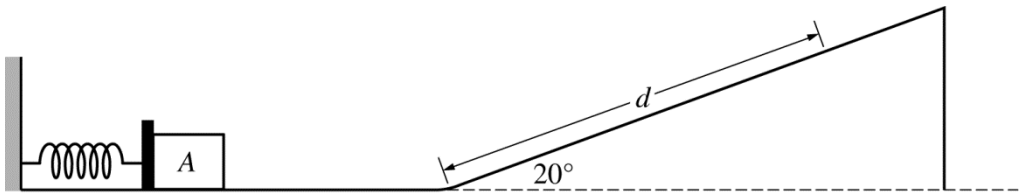


Note: Figure not drawn to scale.

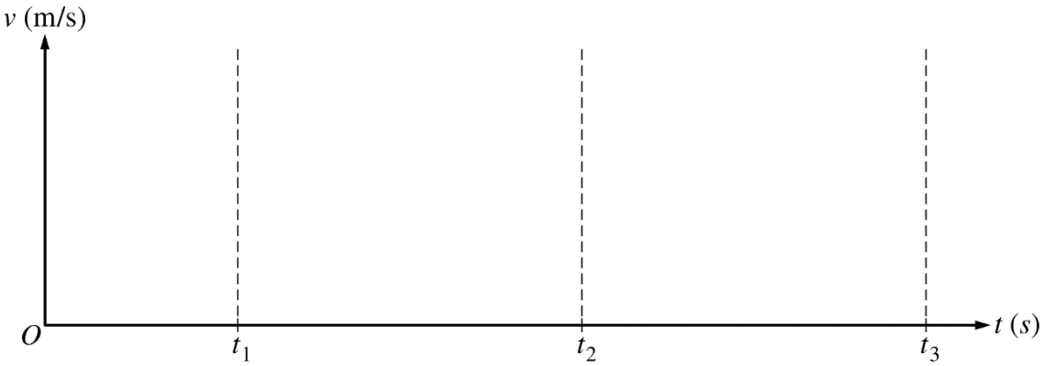
Mech.2.

An experiment is performed on a frictionless surface consisting of a horizontal section and a ramp inclined at a $20°$ angle. Block A of mass 3.0 kg rests on the horizontal section against but not attached to an ideal spring at its equilibrium length, as shown in the figure above. The spring has a spring constant of $k = 700\ \text{N/m}$. Block A is pushed to the left, compressing the spring 0.15 m, and then released.

(a) Calculate the speed of block A when it leaves the spring.

(b) Calculate the maximum distance d block A travels up the ramp.

(c) On the axis below, sketch a graph of the speed v of block A as a function of time t from $t = 0$ to $t = t_3$. Block A is released at time $t = 0$, loses contact with the spring at time $t = t_1$, transitions to the ramp at time $t = t_2$, and reaches its maximum height at time $t = t_3$.



Note: Time intervals not to scale.

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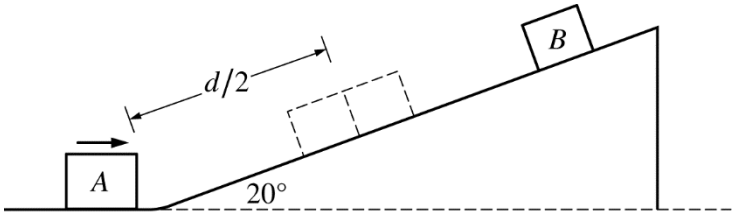

Note: Figure not drawn to scale.

In a second experiment, block *B*, of mass 0.50 kg, is placed on the ramp a distance of *d* from the bottom of the ramp and held in place. Block *A* is released from the spring as in the first experiment. Block *B* is released from rest so that it collides with block *A* as block *A* travels up the ramp. The two blocks collide at a distance of $d/2$ up the ramp. The blocks stick together after the collision.

(d)

i. Calculate the speed of the two blocks immediately after the collision.

ii. In what direction, if any, are the two blocks moving immediately after the collision?

____ Up the ramp ____ Down the ramp

____ Undefined, because the blocks momentarily come to rest after the collision

(e)

i. Calculate the magnitude of the impulse exerted on block *A* by block *B*.

ii. In what direction, if any, is the impulse exerted on block *A* by block *B* ?

____ Up the ramp ____ Down the ramp

____ Undefined, because the impulse is zero

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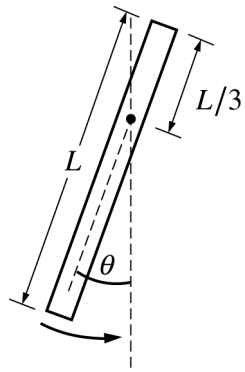

Mech.3.

A uniform rod of mass M and length L is pivoted at a point a distance $L/3$ from the top end, as shown above. The rod is pulled back so that it makes a small angle with the vertical and is then released.

(a) Using integral calculus, show that the rotational inertia for the rod around its pivot is $ML^2/9$.

(b)

i. Using Newton's 2nd law in rotational form, write but do NOT solve a differential equation in terms of M, L, and physical constants, as appropriate, that can be used to determine the angular displacement theta as a function of time t.

ii. Using the differential equation from part (b)i, show that the period of oscillation for the rod is given by the expression $T = 2\pi\sqrt{\frac{2L}{3g}}$.

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An experiment is performed with thin, uniform metal rods of different lengths, each pivoted around a point one third the length of the rod from the top end and used as a physical pendulum, as shown in the figure on the previous page. Each rod is pulled back so that it makes a small angle with the vertical and is then released, and the period of oscillation is measured. The data are recorded in the table below.

Length (m)	0.5	1.0	1.5	2.0	2.5
Period (s)	1.2	1.6	2.0	2.3	2.6

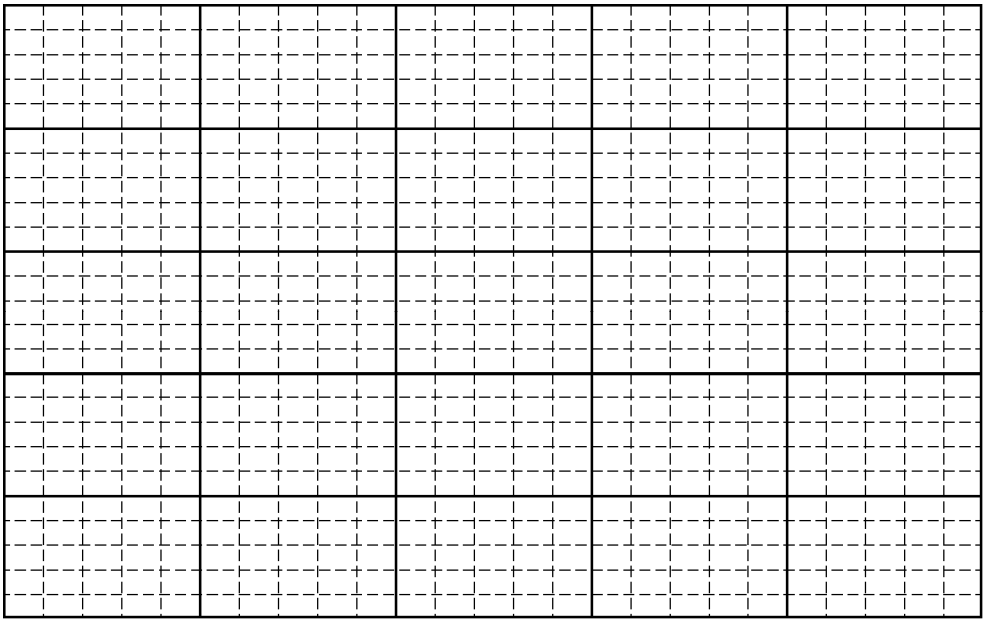
(c) Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the acceleration due to gravity g.

Horizontal axis: _____

Vertical axis: _____

Use the remaining rows in the table above, as needed, to record any quantities that you indicated that are not given.

(d) Plot the straight line data points on the graph below. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



(e) Using your straight line, determine an experimental value for g.

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STOP

END OF EXAM

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- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE COVER.**
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