AP® Physics C: Mechanics Exam

SECTION I: Multiple Choice

2018

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 4OBP4-S

80

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
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

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

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

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

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

$B_s = \mu_0 n I$

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

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

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

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

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

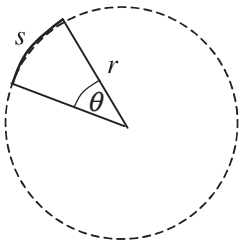
$a^2 + b^2 = c^2$

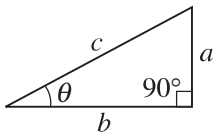
$\sin\theta = \frac{a}{c}$

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

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

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

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

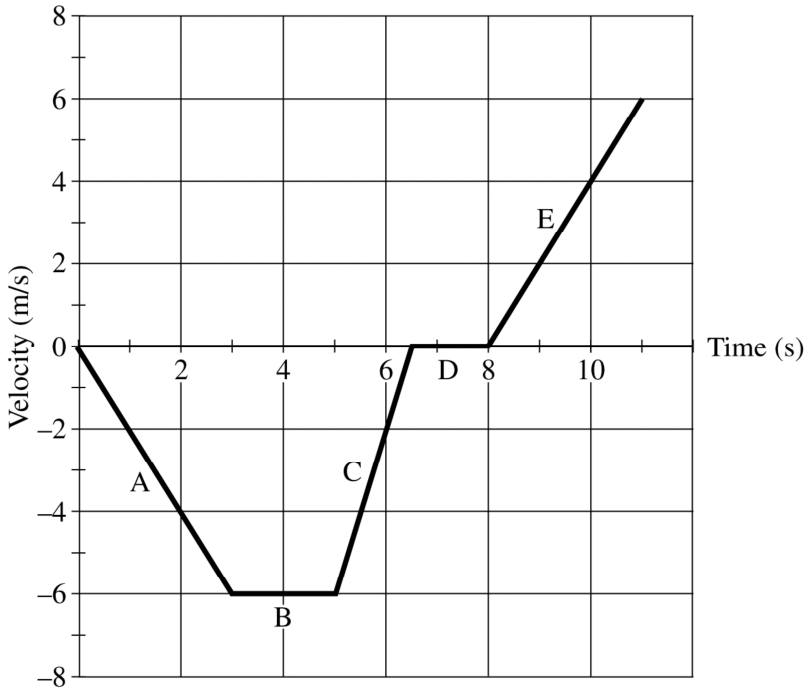
$\left|\vec{A} \times \vec{B}\right| = AB\sin\theta$

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.

Questions 1-2



An object is moving along a straight line. The object's velocity as a function of time is shown in the graph above.

1. During which of the labeled segments on the graph is the object moving but not accelerating?

   (A) A
   (B) B
   (C) C
   (D) D
   (E) E

2. The object has a speed of 2 m/s at which of the following times?

   (A) 1 s only
   (B) 6 s only
   (C) 9 s only
   (D) 4 s and 10 s only
   (E) 1 s, 6 s, and 9 s

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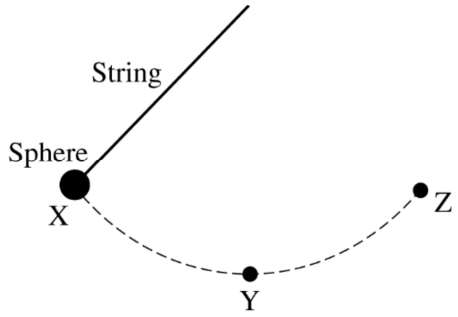
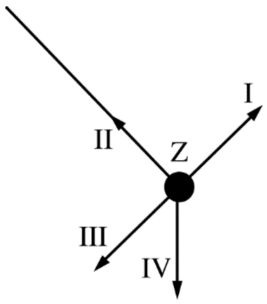
3. An object falls freely from rest under the influence of gravity. If air resistance is negligible, the ratio of the distances traveled during each 1-second time interval by the object during the first, second, and third seconds of its fall is

(A) 1:1:1
(B) 1:2:3
(C) 1:2:4
(D) 1:3:5
(E) 1:4:9

Questions 4-5

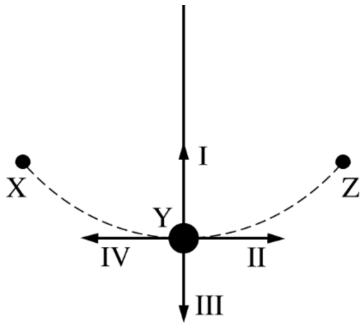


A sphere on the end of a string is released from rest at point X and swings through point Y to point Z, as shown in the figure above. Point Y is the lowest point for the sphere as it swings. Air resistance is negligible.



4. Four directions at point Z are indicated as I, II, III, and IV in the figure above. Which of the arrows best indicates the direction of the acceleration of the sphere at point Z?

(A) I
(B) II
(C) III
(D) IV
(E) The direction of the acceleration is undefined because the acceleration equals zero.



5. Four directions at point Y are indicated as I, II, III, and IV in the figure above. Directions I and III are vertical, II and IV are horizontal, and I is directed along the string. Which of the following best indicates the direction of the acceleration of the sphere at point Y?

(A) I
(B) II
(C) III
(D) IV
(E) The direction of the acceleration is undefined because the acceleration equals zero.

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GO ON TO THE NEXT PAGE.

6. A block of mass m is pulled by a rope along a horizontal surface with negligible friction. For time $t > 0$, the magnitude of the acceleration of the object as a function of time is given by the equation $a = Ae^{-kt}$, where A and k are positive constants. Which of the following expressions determines the impulse exerted on the block by the rope during the time interval $0 < t < t_1$?

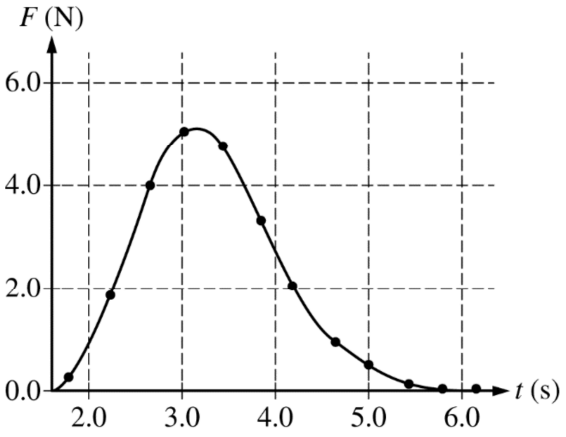
(A) $A\int_0^{t_1} e^{-kt}\,dt$

(B) $mA\dfrac{d}{dt}\left[e^{-kt}\right]_{t_1}$

(C) $A\dfrac{d}{dt}\left[e^{-kt}\right]_{t_1}$

(D) $mAt_1\left[e^{-kt}\right]$

(E) $mA\int_0^{t_1} e^{-kt}\,dt$



7. A 300 g cart with a force sensor attached starts at rest on a track. The force sensor exerts a force on the cart to speed it up. The graph above shows the force F exerted by the sensor on the cart as a function of time t. The change in the cart's momentum during the time interval shown is most nearly

(A) 4.0 N•s
(B) 8.5 N•s
(C) 13 N•s
(D) 25 N•s
(E) 30 N•s

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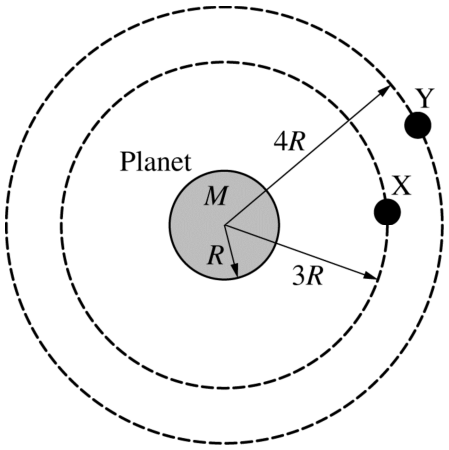
Questions 8-10



Identical satellites X and Y of mass m are in circular orbits around a planet of mass M. The radius of the planet is R. Satellite X has an orbital radius of $3R$, and satellite Y has an orbital radius of $4R$. The kinetic energy of satellite X is K_X.

8. In terms of K_X, the gravitational potential energy of the planet-satellite X system is

   (A) $-2K_X$
   (B) $-K_X$
   (C) $-K_X/2$
   (D) $K_X/2$
   (E) $2K_X$

9. The kinetic energy of satellite X is K_X. The kinetic energy of satellite Y is K_Y. The ratio K_X/K_Y is

   (A) 1/4
   (B) 3/4
   (C) 1/1
   (D) 4/3
   (E) 4/1

10. Satellite X is moved to the same orbit as satellite Y by a force doing work on the satellite. In terms of K_X, the work done on satellite X by the force is

    (A) $-K_X/2$
    (B) $-K_X/4$
    (C) 0
    (D) $+K_X/4$
    (E) $+K_X/2$

---

11. Car A can travel around a curved section of road without skidding at a maximum constant speed of 10 m/s. When car B travels around the same curve without skidding at its maximum speed, it has twice the centripetal acceleration as car A. The maximum speed at which car B can safely travel around the curve is most nearly

    (A) 5.0 m/s
    (B) 10 m/s
    (C) 14 m/s
    (D) 20 m/s
    (E) 28 m/s

12. A car is traveling down the highway at speed v when the driver slams on the brakes and skids to a stop in a distance d. Assuming the same frictional force, how far would the car slide if its speed was $2v$?

    (A) $d/4$
    (B) $d/2$
    (C) d
    (D) $2d$
    (E) $4d$

13. A 3.0 kg block accelerates at 2.0 m/s^2 because of a constant net force. A block of unknown mass accelerates at 6.0 m/s^2 because of the same net force. What is the mass of the second block?

    (A) 9.0 kg
    (B) 4.0 kg
    (C) 3.0 kg
    (D) 1.5 kg
    (E) 1.0 kg

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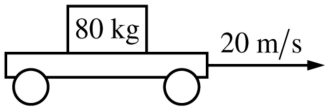

14. A cart is moving to the right with a constant speed of $20\ \text{m/s}$. A box of mass 80 kg moves with the cart without slipping. The coefficient of static friction between the box and cart is 0.30, and the coefficient of kinetic friction between the box and cart is 0.15. What are the magnitude and direction of the frictional force acting on the box as it moves with the cart?

(A) Zero
(B) 120 N to the right
(C) 120 N to the left
(D) 240 N to the right
(E) 240 N to the left

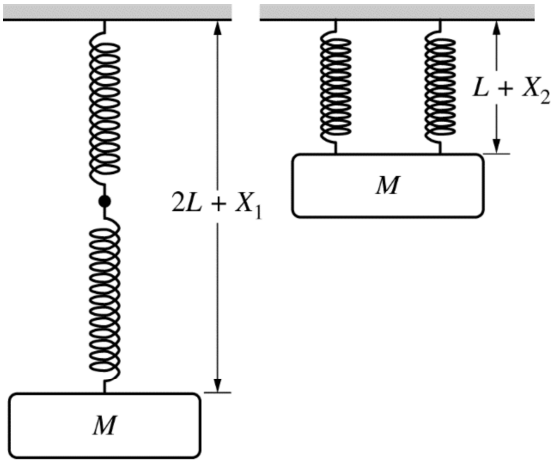

Figure 1 Figure 2

Note: Figure not drawn to scale.

15. A block of mass M is suspended from two identical springs of negligible mass, spring constant $k$and unstretched length L. First, one spring is attached to the end of the other spring. The block is then attached to the end of the second spring and slowly lowered to its equilibrium position. The two springs stretch a total distance of X_1, as shown in Figure 1 above. Next, the springs are hung side by side. The block is attached to the end of the springs and again slowly lowered to its equilibrium position. The springs each stretch a distance of X_2, as shown in Figure 2 above. Which of the following equations correctly shows the relationship between X_1 and X_2?

(A) $X_1 = X_2$
(B) $X_1 = \sqrt{2}X_2$
(C) $X_1 = 2X_2$
(D) $X_1 = 4X_2$
(E) $X_1 = 8X_2$

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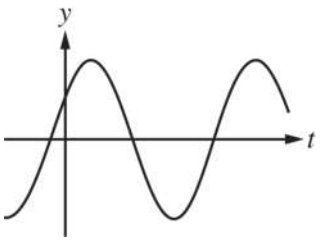
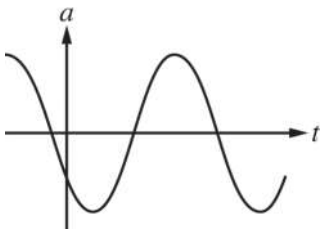
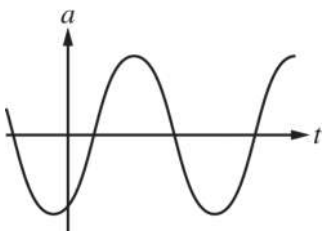
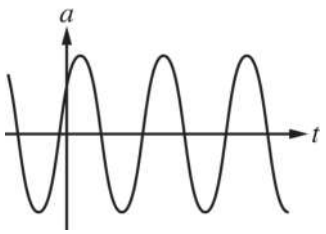
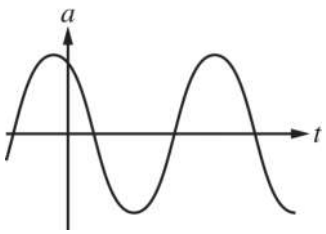


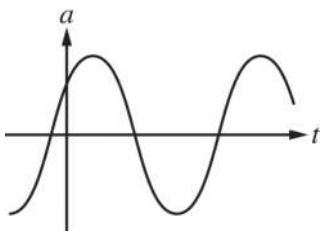
16. A block is hung vertically from an ideal spring. The block is pulled down and allowed to oscillate. The position y as a function for time t is shown in the graph above. Which of the following graphs best represents the acceleration a of the block as a function of time?

(A)


(B)


(C)


(D)


(E)


17. Two moons of equal mass are in circular orbits around a planet. Moon 1 orbits with a radius of r and moon 2 orbits with a radius of $3r$. What is the ratio of the magnitude of the planet's gravitational force on moon 2 to that on moon 1, $F_{G(\text{on } 2)} / F_{G(\text{on } 1)}$?

(A) 9/1
(B) 3/1
(C) 1/1
(D) 1/3
(E) 1/9

18. A comet moves in an elliptical orbit around the Sun. Which of the following is at a maximum when the comet is at its farthest distance from the Sun?

(A) Kinetic energy of the comet
(B) Speed of the comet
(C) Acceleration of the comet
(D) Gravitational potential energy of the Sun-comet system
(E) Total energy of the Sun-comet system

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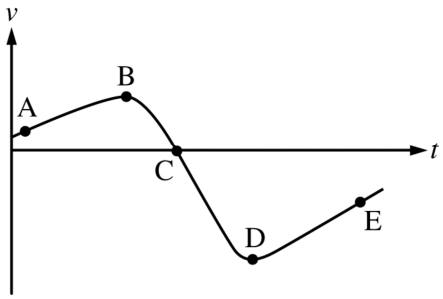
Questions 19-20



The graph above shows velocity as a function of time for a cart moving on a straight, horizontal track.

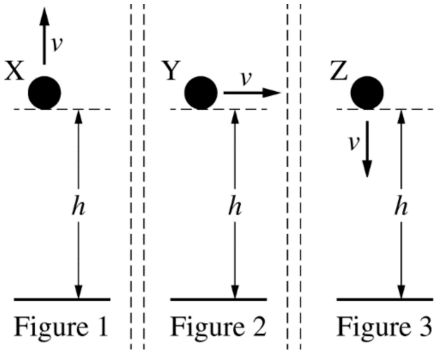
19. At which labeled point does the cart have the greatest speed?

(A) A
(B) B
(C) C
(D) D
(E) E

20. At which labeled point does the velocity of the cart change direction?

(A) A
(B) B
(C) C
(D) D
(E) E

Questions 21-22 are based on the following information.



Three identical spheres are thrown from the same height above the ground. Sphere X is thrown vertically up, sphere Y is thrown horizontally, and sphere Z is thrown vertically down, as shown in figures 1, 2, and 3 above, respectively. All three spheres are thrown with the same speed. Air resistance is negligible.

21. Which sphere or spheres initially collide with the ground with the greatest speed?

(A) Sphere X only
(B) Sphere Y only
(C) Sphere Z only
(D) Spheres X and Z only
(E) All three spheres collide with the same speed.

22. Assume the spheres collide elastically with the ground. Which of the following ranks the spheres based on the rebound height after they collide with the ground?

(A) X > Y > Z
(B) Y > (X = Z)
(C) Z > Y > X
(D) (X = Y) > Z
(E) (X = Z) > Y

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GO ON TO THE NEXT PAGE.

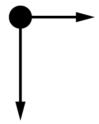
Questions 23-24

A block on a level horizontal surface of negligible friction is initially traveling at 20 m/s to the left. A horizontal force $\vec{F}$ is exerted to the right on the block for the time interval $0 < t < 0.10$ s. The magnitude of the force is given as a function of time t by the equation $F = \alpha t$, where $\alpha = 240$ N/s and t is in seconds.

23. Which of the following free-body diagrams best shows the forces acting on the block at time $t = 0.05$ s ?

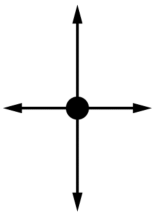
(A)

(B)

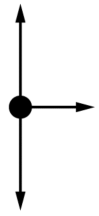


(C)

(D)



(E)



24. What is the magnitude of the change in momentum of the block due to the horizontal force?

(A) 1.2 kg•m/s

(B) 12 kg•m/s

(C) 24 kg•m/s

(D) 240 kg•m/s

(E) The change in momentum of the block cannot be determined without knowing the block's mass.

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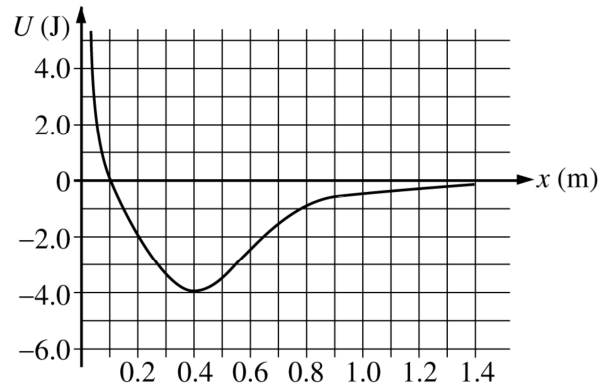
Questions 25-26



The variable x represents the position of particle A in a two-particle system. Particle B remains at rest. The graph above shows potential energy U of the system as a function of x.

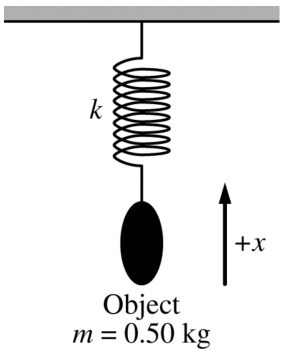
25. If the total energy of the system is -2.0 J, which of the following statements is true?

(A) The system has zero potential energy.
(B) Particle A has 2.0 J of kinetic energy.
(C) The system has 2.0 J of total mechanical energy.
(D) Particle A is always at $x = 0.40$ m.
(E) Particle A oscillates between $x = 0.20$ m and 0.65 m.

26. The x-component of the force on particle A when it is at $x = 0.15$ m is most nearly

(A) –20 N
(B) –2.0 N
(C) –1.0 N
(D) 2.0 N
(E) 20 N

Questions 27-28



A 0.50 kg object is attached to a vertical spring of constant k, as shown above. The object is pulled down and released. The object oscillates vertically. If up is the positive direction, the position x of the object as a function of time t is given by the formula $x = \beta \sin(\omega t + \varphi)$, where $\beta = 0.20$ m, $\omega = 4.0$ rad/s, and $\varphi = \pi/3$ rad.

27. The period of the oscillation for the object is most nearly

(A) 4.0 s
(B) 3.1 s
(C) 2.0 s
(D) 1.6 s
(E) 1.1 s

28. The magnitude of the maximum acceleration of the object as it oscillates is most nearly

(A) 8.0 m/s^2
(B) 6.4 m/s^2
(C) 3.2 m/s^2
(D) 0.80 m/s^2
(E) 0.013 m/s^2

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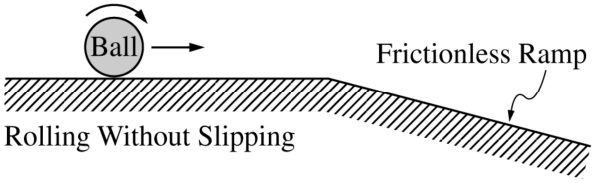
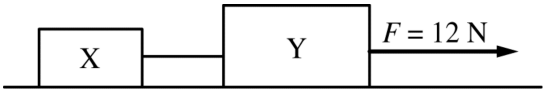


29. A ball, rolling without slipping on a horizontal surface, encounters a frictionless, downward-sloping ramp, as shown above. Which of the following correctly describes the motion of the ball on the ramp?

(A) Constant translational speed with no angular speed
(B) Increasing translational speed with no angular speed
(C) Increasing translational speed with constant nonzero angular speed
(D) Increasing translational speed with decreasing angular speed
(E) Increasing translational speed with increasing angular speed



30. Blocks X and Y of masses 3.0 kg and 5.0 kg, respectively, are connected by a light string and are both on a level horizontal surface of negligible friction. A force F = 12 N is exerted on block Y, as shown in the figure above. What is the tension in the string connecting the two blocks?

(A) 1.5 N
(B) 4.0 N
(C) 4.5 N
(D) 7.5 N
(E) 12 N

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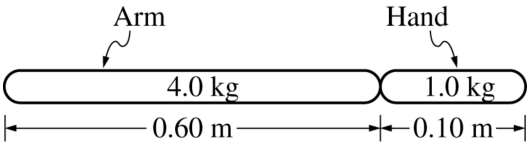
Questions 31-32

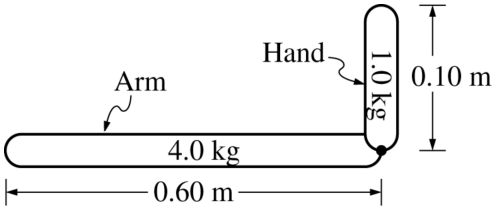


Note: Figure not drawn to scale.

In order to model the motion of an extinct ape, scientists measure its hand and arm bones. From shoulder to wrist, the arm bones are 0.60 m long and their mass is 4.0 kg. From wrist to the tip of the fingers, the hand bones are 0.10 m long and their mass is 1.0 kg. In the model above, each bone is assumed to have a uniform density.

31. When the arm and hand hang straight down, the distance from the shoulder to the center of mass of the arm-hand system is most nearly

(A) 0.25 m
(B) 0.35 m
(C) 0.37 m
(D) 0.50 m
(E) 0.93 m



Note: Figure not drawn to scale.

32. The arm is held in the horizontal position and the hand is bent at the wrist so the fingers point up, as shown in the figure above. The torque exerted by the weight of the hand with respect to the shoulder is most nearly

(A) 6 N•m
(B) 10 N•m
(C) 30 N•m
(D) 60 N•m
(E) 70 N•m

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Questions 33-34

An object moves along a straight line with a velocity v given as a function of time t by the equation $v(t) = \alpha t^2 + \beta t + \gamma$.

33. Which of the following expressions represents $\Delta x(t)$, the displacement of the object as a function of time t starting at time $t = 0$?

(A) 2α

(B) $\alpha t + \beta$

(C) $2\alpha t + \beta$

(D) $\alpha t^3/3 + \beta t^2/2 + \gamma t$

(E) $3\alpha t^3 + 2\beta t^2 + \gamma t$

34. Which of the following expressions represents $a(t)$, the acceleration of the object as a function of time t ?

(A) 2α

(B) $\alpha t + \beta$

(C) $2\alpha t + \beta$

(D) $\alpha t^3/3 + \beta t^2/2 + \gamma t$

(E) $3\alpha t^3 + 2\beta t^2 + \gamma t$

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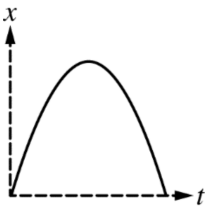
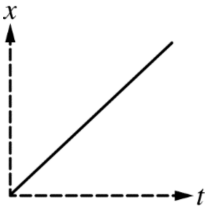
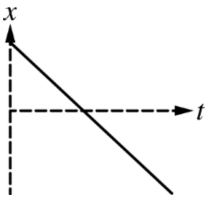
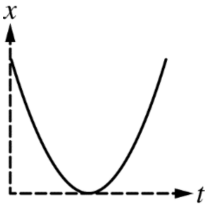
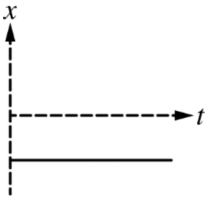
35. A cart is moving in the +x-direction and passes the origin when time t= 0. The cart then moves with decreasing speed, stops, and moves in the –x-direction with increasing speed. Which of the following graphs best represents the cart's position x as a function of time?

(A) 

(B) 

(C) 

(D) 

(E) 

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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

2018

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 4OBP4-S

80

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
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

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

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

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

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

$B_s = \mu_0 n I$

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

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

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

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

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

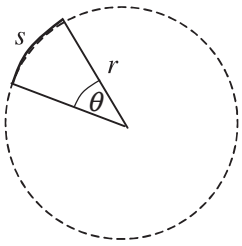
$a^2 + b^2 = c^2$

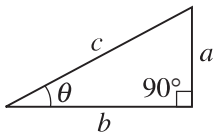
$\sin\theta = \frac{a}{c}$

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

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

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

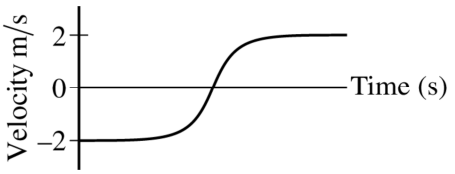
$\vec{A} \bullet \vec{B} = AB\cos\theta$

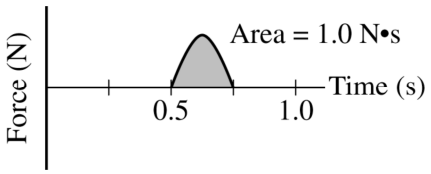
$\left|\vec{A} \times \vec{B}\right| = AB\sin\theta$

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.

1. A student sets up an experiment with a cart on a level horizontal track. The cart is attached with an elastic cord to a force sensor that is fixed in place on the left end of the track. A motion sensor is at the right end of the track, as shown in the figure above. The cart is given an initial speed of $v_0 = 2.0$ m/s and moves with this constant speed until the elastic cord exerts a force on the cart. The motion of the cart is measured with the motion detector, and the force the elastic cord exerts on the cart is measured with the force sensor. Both sensors are set up so that the positive direction is to the left. The data recorded by both sensors are shown in the graphs of velocity as a function of time and force as a function of time below.





(a) Calculate the mass m of the cart.

For time period from 0.50 s to 0.75 s, the force F the elastic cord exerts on the cart is given as a function of time t by the equation $F = A\sin(\omega t)$, where $A = 6.3$ N and $\omega = 12.6$ rad/s.

(b) Using the given equation, show that the area under the graph above is 1.0 N•s .

Question 1 continues on the next page.

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(c) The experiment is repeated using a different cord that exerts a larger average force on the cart. The cart starts and ends with the same speeds as those in the original experiment. Will the area for the graph of force as a function of time for the new cord be greater than, less than, or equal to the area for that of the original cord?

____ Greater than ____ Less than ____ Equal to

Justify your answer.

The elastic cord from the original experiment can be modeled as an ideal spring with force constant k.

(d) Derive an expression for the maximum change in length x_{MAX} for the cord. Express your answer in terms of m, k, v_0, and physical constants, as appropriate.

The student performs several trials of the experiment. For the first trial, the cart is empty. In each succeeding trial, a block is added to the cart. In all trials, the cart has an initial speed of $2.0\ \text{m/s}$ to the right, the cart rebounds to the left with a speed of $2.0\ \text{m/s}$, and the maximum change in length of the elastic cord is measured. The total mass M of the cart and the maximum change in length of the cord in each trial are recorded in the table below.

Total Mass of Cart M (kg)	x_{MAX} (m)		
0.25	0.142		
0.75	0.253		
1.25	0.349		
1.75	0.431		
2.25	0.465		

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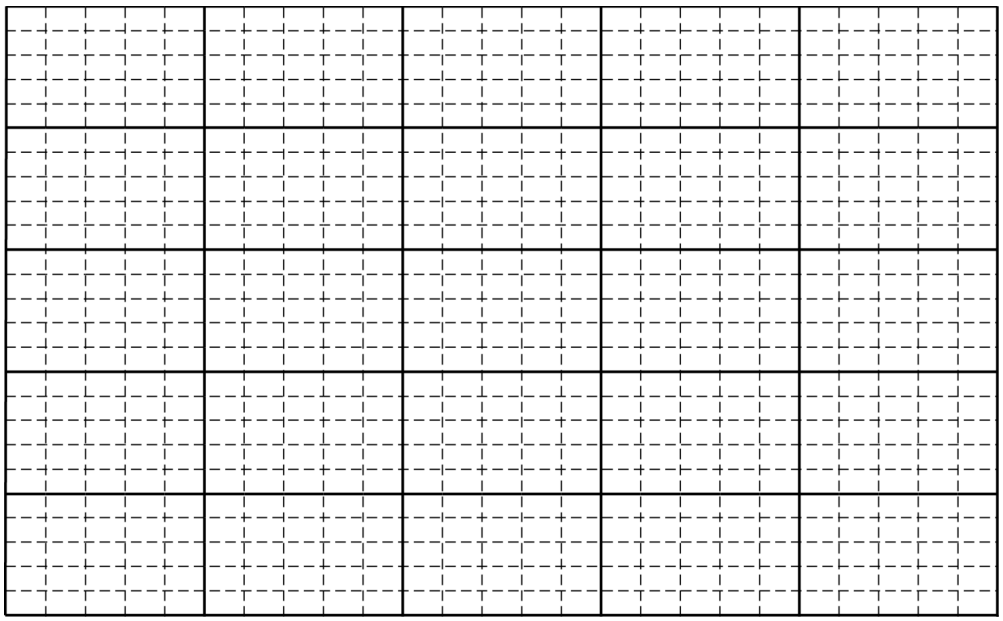
(e) Indicate below which quantities should be graphed to yield a straight line with a slope that could be used to calculate a numerical value for the force constant of the elastic cord k.

Vertical axis: _____

Horizontal axis: _____

Use the remaining columns in the table on the previous page, as needed, to record any quantities that you indicated that are not given.

(f) Plot the data points for the quantities indicated in part (e) on the graph below. Clearly scale and label all axes, including units as appropriate. Draw a straight line that best represents the data.



(g) Use the best-fit line to calculate the force constant k of the elastic cord.

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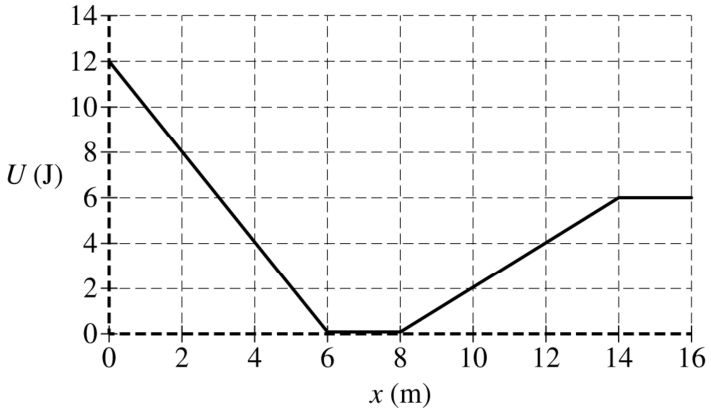

2. The variable x represents the position of particle A in a two-particle system. Particle B remains at rest. The above graph shows the potential energy $U(x)$ of the system as a function of position x of particle A, which has a mass of 0.40 kg. Particle A is released from rest at the position x = 2.0 m. Assume positive to be toward the right.

(a) Calculate the speed of particle A when it reaches position x = 14.0 m.

(b)

i. Calculate the magnitude of the acceleration of particle A when it reaches position x= 3.0 m.

ii. What is the direction of the acceleration of particle A when it reaches position x= 3.0 m?

____ Left ____ Right

(c) Determine the magnitude of the acceleration of particle A when it reaches position x = 7.0 m.

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(d) Particle A is again released from rest at the position $x = 2.0$ m.

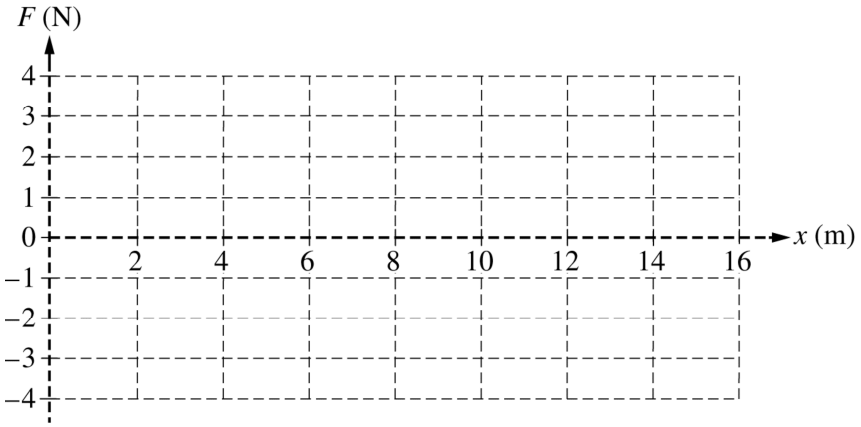
i. Calculate the elapsed time for particle A to travel from position $x = 2.0$ m to position $x = 6.0$ m.

ii. Calculate the elapsed time for particle A to travel from position $x = 6.0$ m to position $x = 8.0$ m.

iii. Calculate the elapsed time for particle A to travel from position $x = 8.0$ m to position $x = 14$ m.

(e) Particle A is now placed at position $x = 7.0$ m. In order for particle A to reach the position $x = 16.0$ m and to be moving at a speed of $1.0\ \text{m/s}$, what initial speed should particle A be given at its new initial position of $x = 7.0$ m?

(f) On the grid below, carefully draw a graph of the force F acting on particle A as a function of x for the range $0 < x < 16$ m.



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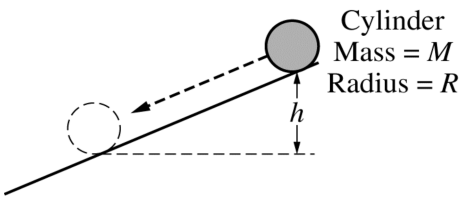


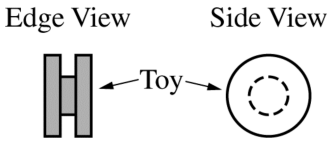
3. A cylinder of mass M and radius R is released from rest at the top of an inclined plane, as shown above. The cylinder rolls without slipping down the incline. The rotational inertia of the cylinder is $MR^2/2$.

   (a) Derive an expression for the angular momentum of the cylinder about its center of mass when it has rolled a vertical distance h. Express your answer in terms of M, R, h, and physical constants, as appropriate.

   (b) Is the angular momentum of the cylinder conserved as the cylinder rolls down the vertical distance h ?

   ____ Yes ____ No

   Justify your answer.



A child's toy is composed of 3 narrow cylinders attached around a common axis through their centers, as shown above. The central cylinder has a mass M and radius R. Each of the two outer cylinders has a mass M and radius $2R$.

(c) Derive an expression for the rotational inertia of the toy around its center. Express your answer in terms of M, R, and physical constants, as appropriate.

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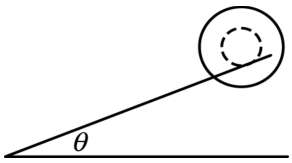
GO ON TO THE NEXT PAGE.



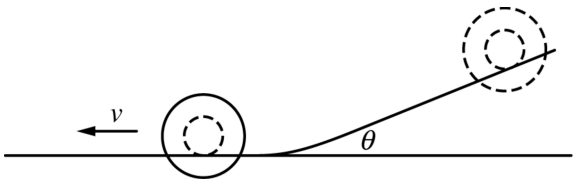
The toy is placed on a narrow track that is inclined at an angle of θ above the horizontal. Only the central cylinder is in contact with the track, as shown above. The toy rolls without slipping down the track.

(d)

i. On the dot below, which represents the toy, draw and label the forces (not components) that act on the toy. The dashed line is parallel to the narrow track. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

ii. Derive an expression for the linear acceleration of the toy as it rolls down the track. Express your answer in terms of M, R, θ, and physical constants, as appropriate.

iii. Determine the force of friction exerted on the toy as it rolls down the track. Express your answer in terms of M, R, θ, and physical constants, as appropriate.



(e) The toy reaches the bottom of the incline and rolls at constant speed v along a horizontal section of the track, as shown above. Derive an expression for the total kinetic energy of the toy while it is rolling. Express your answer in terms of M, R, v, and physical constants, as appropriate.

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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.**

AP Physics C Mechanics

2018

APPENDIX - ANSWERS

Matching multiple-choice answers and free-response scoring follow.

Multiple-Choice Answer Key

The following contains the answers to
the multiple-choice questions in this exam.

Answer Key for AP Physics C: Mechanics

Practice Exam, Section I

Question 1: B
Question 2: E
Question 3: D
Question 4: C
Question 5: A
Question 6: E
Question 7: B
Question 8: A
Question 9: D
Question 10: D
Question 11: C
Question 12: E
Question 13: E
Question 14: A
Question 15: D
Question 16: A
Question 17: E
Question 18: D
Question 19: D
Question 20: C
Question 21: E
Question 22: E
Question 23: E
Question 24: A
Question 25: E
Question 26: E
Question 27: D
Question 28: C
Question 29: C
Question 30: C
Question 31: C
Question 32: A
Question 33: D
Question 34: C
Question 35: A

Free-Response Scoring Guidelines

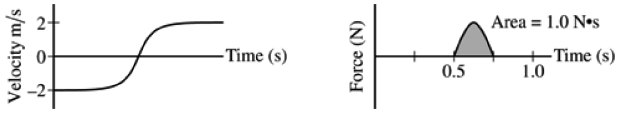
The following contains the scoring guidelines
for the free-response questions in this exam.

AP® PHYSICS C: MECHANICS
2018 SCORING GUIDELINES

Question 1

15 points total **Distribution of points**

A student sets up an experiment with a cart on a level horizontal track. The cart is attached with an elastic cord to a force sensor that is fixed in place on the left end of the track. A motion sensor is at the right end of the track, as shown in the figure above. The cart is given an initial speed of $v_0 = 2.0\ \text{m/s}$ and moves with this constant speed until the elastic cord exerts a force on the cart. The motion of the cart is measured with the motion detector, and the force the elastic cord exerts on the cart is measured with the force sensor. Both sensors are set up so that the positive direction is to the left. The data recorded by both sensors are shown in the graphs of velocity as a function of time and force as a function of time below.



(a) 2 points

Calculate the mass m of the cart.

For correctly using the area under the graph to calculate the mass of the cart		1 point
$J = Area = \Delta p = m(v_2 - v_1)$		
For a correct answer with units		1 point
$m = \dfrac{Area}{(v_2 - v_1)} = \dfrac{(1.0\ \text{N•s})}{(2.0\ \text{m/s} - (-2.0\ \text{m/s}))}$		
$m = 0.25\ \text{kg}$		

For time period from 0.50 s to 0.75 s, the force F the elastic cord exerts on the cart is given as a function of time t by the equation $F = A\sin(\omega t)$, where $A = 6.3\ \text{N}$ and $\omega = 12.6\ \text{rad/s}$.

(b) 2 points

Using the given equation, show that the area under the graph above is $1.0\ \text{N•s}$.

For relating the time integral of given equation to the area under the curve		1 point
For applying the correct limits of integration		1 point
$J = Area = \int_{0.50}^{0.75} A\sin(\omega t)dt$		
$J = -\dfrac{A}{\omega}[\cos(\omega t)]_{0.50}^{0.75} = -\dfrac{(6.3\ \text{N})}{(12.6\ \text{rad/s})}[\cos(12.6t)]_{0.50}^{0.75}$		
$J = -(0.50)(\cos[(12.6)(0.75)] - \cos[(12.6)(0.50)])$		
$J = 1.0\ \text{N•s}$		

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Question 1 (continued)

Distribution of points

(c) 2 points

The experiment is repeated using a different cord that exerts a larger average force on the cart. The cart starts and ends with the same speeds as those in the original experiment. Will the area for the graph of force as a function of time for the new cord be greater than, less than, or equal to the area for that of the original cord?

____ Greater than ____ Less than ____ Equal to

Justify your answer.

For selecting "Equal to" with an attempt at a relevant justification		1 point
For a correct justification		1 point
Example: Since the cart starts and ends at the same velocity, the impulse on the cart will be the same so the area under the graph will be the same. Note: If the wrong selection is made, the justification is ignored.		

The elastic cord from the original experiment can be modeled as an ideal spring with force constant k .

(d) 2 points

Derive an expression for the maximum change in length x_{MAX} for the cord. Express your answer in terms of $m,\ k,\ v_0$, and physical constants, as appropriate.

For correctly using conservation of energy		1 point
$U_{\text{MAX}} = K_{\text{MAX}}$		
$\frac{1}{2}kx_{\text{MAX}}^2 = \frac{1}{2}mv_0^2$		
For a correct answer		1 point
$x_{\text{MAX}} = v_0\sqrt{\frac{m}{k}}$		

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Question 1 (continued)

Distribution of points

The student performs several trials of the experiment. For the first trial, the cart is empty. In each succeeding trial, a block is added to the cart. In all trials, the cart has an initial speed of $2.0\ \text{m/s}$ to the right, the cart rebounds to the left with a speed of $2.0\ \text{m/s}$, and the maximum change in length of the elastic cord is measured. The total mass M of the cart and the maximum change in length of the cord in each trial are recorded in the table below.

Total Mass of Cart M (kg)	x_{MAX} (m)		
0.25	0.142		
0.75	0.253		
1.25	0.349		
1.75	0.431		
2.25	0.465		

(e) 1 point

Indicate below which quantities should be graphed to yield a straight line with a slope that could be used to calculate a numerical value for the force constant of the elastic cord k.

Vertical axis: _____

Horizontal axis: _____

Use the remaining columns in the table on the previous page, as needed, to record any quantities that you indicated that are not given.

For correctly indicating two variables that will yield a straight line that could be used to determine a value for k		1 point
Example: Vertical Axis: x_{MAX} *Horizontal Axis:* $\sqrt{m}$		
Note: Student earns full credit if axes are reversed or if they use another acceptable combination		

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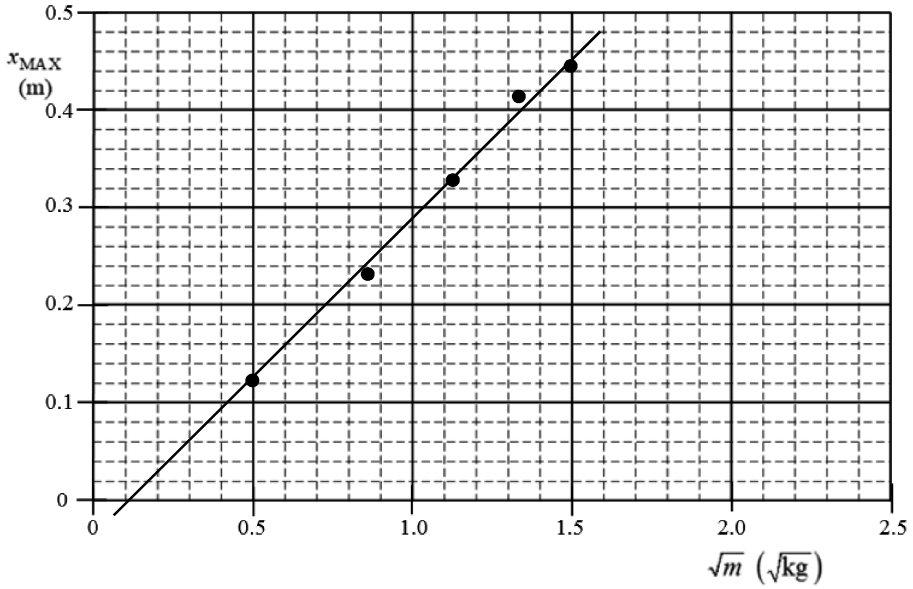
Question 1 (continued)

Distribution of points

(f) 4 points

Plot the data points for the quantities indicated in part (e) on the graph below. Clearly scale and label all axes, including units as appropriate. Draw a straight line that best represents the data.



For a correct scale that uses more than half the grid		1 point
For correctly labeling the axis with variables and units consistent with part (e) Note: Student earns full credit if axes are reversed		1 point
For correctly plotting data		1 point
For drawing a straight line consistent with the plotted data		1 point

(g) 2 points

Use the best-fit line to calculate the force constant k of the elastic cord.

For correctly calculating the slope from the best-fit line and not the data points		1 point
Example: slope $= \dfrac{\Delta x_{\max}}{\Delta\sqrt{m}} = \dfrac{(0.40 - 0.20)\ \text{m}}{(1.32 - 0.70)\ \sqrt{kg}} = 0.34\ \text{m}/\sqrt{kg}$		
(linear regression slope $= 0.33\ \text{m}/\sqrt{kg}$)		
For correctly relating the slope to the force constant k		1 point
Example: slope $= \dfrac{v_0}{\sqrt{k}}\ \therefore\ k = \dfrac{v_0^2}{(\text{slope})^2} = \dfrac{(2.0\ \text{m/s})^2}{(0.34\ \text{m}/\sqrt{kg})^2}$		
$k = 34.6\ \text{N/m}$		
(linear regression $k = 36.7\ \text{N/m}$ **)**		

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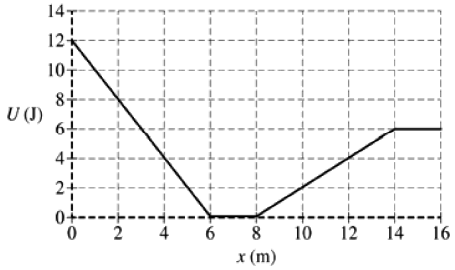
Question 2

15 points total **Distribution of points**



The variable x represents the position of particle A in a two-particle system. Particle B remains at rest. The above graph shows the potential energy $U(x)$ of the system as a function of position x of particle A, which has a mass of 0.40 kg. Particle A is released from rest at the position $x = 2.0$ m. Assume positive to be toward the right.

(a) 2 points

Calculate the speed of particle A when it reaches position $x = 14.0$ m.

For correctly using conservation of energy		1 point
$U_1 + K_1 = U_2 + K_2$		
$U_1 + 0 = U_2 + \frac{1}{2}mv^2$		
For correctly substituting values from the graph into the equation above		1 point
$(8\text{ J}) = (6\text{ J}) + \left(\frac{1}{2}\right)(0.40\text{ kg})v^2$		
$v = 3.16\text{ m/s}$		

(b)

i) 2 points

Calculate the magnitude of the acceleration of particle A when it reaches position $x = 3.0$ m.

For correctly relating the slope of the line to the force exerted on the particle		1 point
$F = -\text{slope} = -\frac{(U_2 - U_1)}{(x_2 - x_1)} = -\frac{(12 - 0)\text{J}}{(0 - 6)\text{m}} = 2.0\text{ N}$		
For using Newton's second law to calculate the acceleration of the particle		1 point
$a = \frac{F}{m} = \frac{(2.0\text{ N})}{(0.40\text{ kg})} = 5.0\text{ m/s}^2$		
Note: point is awarded for -5.0 m/s^2		

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2018 SCORING GUIDELINES

Question 2 (continued)

Distribution of points

(b) con't

i) con't

Alternate Solution		*Alternate Points*
Solving for two velocities between 2.0 m and 6.0 m		*1 point*
$v_1 = 0$		
$U_1 + K_1 = U_2 + K_2 \therefore (8\text{ J}) + 0 = 0 + \frac{1}{2}(0.40\text{ kg})v_2^2$		
$v_2 = 6.32\text{ m/s}$		
For using a correct kinematic equation to find acceleration		*1 point*
$v_2^2 = v_1^2 + 2ad \therefore a = \frac{v_2^2}{2d} = \frac{(6.32\text{ m/s})^2}{(2)(4.0\text{ m})} = 5.0\text{ m/s}^2$		
Note: point is awarded for -5.0 m/s^2		

ii) 1 point

What is the direction of the acceleration of particle A when it reaches position $x = 3.0$ m?

____ Left ____ Right

For selecting answer consistent with part (b)(i)		1 point

(c) 1 point

Determine the magnitude of the acceleration of particle A when it reaches position $x = 7.0$ m.

For a correct answer		1 point
$F = -\text{slope} = 0 \therefore a = 0$		
Note: credit is given even if no work is shown		

(d) Particle A is again released from rest at the position $x = 2.0$ m.

i) 2 points

Calculate the elapsed time for particle A to travel from position $x = 2.0$ m to position $x = 6.0$ m.

For using a correct kinematic equation to calculate the time		1 point
$d = v_1 t + \frac{1}{2}at^2 = 0 + \frac{1}{2}at^2$		
For correctly substituting acceleration from part (b)(i) into equation above		1 point
$t = \sqrt{\frac{2d}{a}} = \sqrt{\frac{(2)(6.0 - 2.0)\text{m}}{(5.0\text{ m/s}^2)}} = 1.26\text{ s}$		

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Question 2 (continued)

Distribution of points

(d) con't

i) con't

Alternate Solution		*Alternate Points*
For correctly using the energy equation to solve for the speed at 6.0 m (or using the value from alternate solution part (b)(i)		*1 point*
$U_1 + K_1 = U_2 + K_2 \therefore (8\text{ J}) + 0 = 0 + \frac{1}{2}(0.40\text{ kg})v_2^2$		
$v_2 = 6.32\text{ m/s}$		
For correctly substituting velocity above and acceleration from part (b)(i) into an appropriate kinematic equation		*1 point*
$v_2 = v_1 + at \therefore t = \frac{v_2 - v_1}{a} = \frac{(6.32\text{ m/s} - 0)}{(5.0\text{ m/s}^2)} = 1.26\text{ s}$		

ii) 2 points

Calculate the elapsed time for particle A to travel from position $x = 6.0$ m to position $x = 8.0$ m.

For using a correct kinematic equation to determine the speed at $x = 6.0$ m or using the velocity at 6.0 m from alternate solutions part (b)(i) or (d)(i)		1 point
$v_2^2 = v_1^2 + 2ad = 0 + 2ad$		
$v_2 = \sqrt{2ad} = \sqrt{(2)(5.0\text{ m/s}^2)(6.0 - 2.0)\text{m}}$		
$v_2 = 6.32\text{ m/s}$		
For using a kinematic equation for zero acceleration to calculate the time		1 point
$d = vt$		
$t = \frac{d}{v} = \frac{(8.0 - 6.0)\text{m}}{(6.32\text{ m/s})}$		
$t = 0.32\text{ s}$		
Alternate Solution		*Alternate Points*
For correctly using the energy equation to solve for the speed at 6.0 m (or using the value from alternate solution part (b)(i)		*1 point*
$U_1 + K_1 = U_2 + K_2 \therefore (8\text{ J}) + 0 = 0 + \frac{1}{2}(0.40\text{ kg})v_2^2$		
$v_2 = 6.32\text{ m/s}$		
For using a kinematic equation with zero acceleration to calculate the time		*1 point*
$d = vt$		
$t = d/v = (8.0 - 6.0)\text{m}/(6.32\text{ m/s})$		
$t = 0.32\text{ s}$		

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Question 2 (continued)

Distribution of points

(d) con't

iii) 1 point

Calculate the elapsed time for particle A to travel from position $x = 8.0$ m to position $x = 14$ m.

For using a correct kinematic equation to calculate the time		1 point
$d = \frac{1}{2}(v_1 + v_2)t$		
$t = \frac{2d}{(v_1 + v_2)} = \frac{(2)(14 - 8.0)\text{m}}{(6.32\ \text{m/s} + 3.16\ \text{m/s})}$		
$t = 1.26$ s		

(e) 1 points

Particle A is now placed at position $x = 7.0$ m. In order for particle A to reach the position $x = 16.0$ m and to be moving at a speed of $1.0\ \text{m/s}$, what initial speed should particle A be given at its new initial position of $x = 7.0$ m?

For correctly using conservation of energy to calculate the speed		1 point
$U_1 + K_1 = U_2 + K_2$		
$0 + \frac{1}{2}m_1v_1^2 = U_2 + \frac{1}{2}m_2v_2^2$		
$\left(\frac{1}{2}\right)(0.40\ \text{kg})v_1^2 = (6\ \text{J}) + \left(\frac{1}{2}\right)(0.40\ \text{kg})(1.0\ \text{m/s})^2$		
$v = 5.57\ \text{m/s}$		

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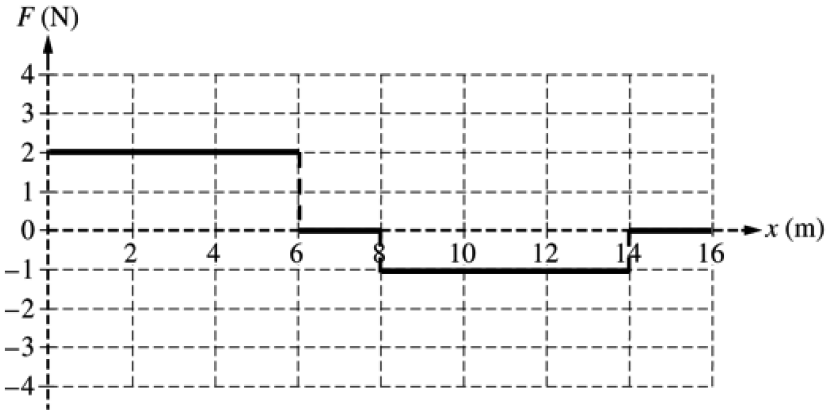
Question 2 (continued)

Distribution of points

(f) 3 points

On the grid below, carefully draw a graph of the force F acting on particle A as a function of x for the range $0 < x < 16$ m.



For a horizontal line at $F = 2$ N from $x = 0$ m to $x = 6$ m		1 point
For a horizontal line at $F = 0$ from $x = 6$ m to $x = 8$ m and from $x = 14$ m to $x = 16$ m		1 point
For a horizontal line at $F = –1$ N from $x = 8$ m to $x = 14$ m		1 point
Note: Two points earned if shape and magnitudes are correct but graph is inverted		

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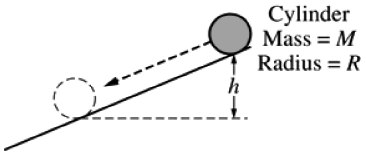
Question 3

15 points total **Distribution of points**



A cylinder of mass M and radius R is released from rest at the top of an inclined plane, as shown above. The cylinder rolls without slipping down the incline. The rotational inertia of the cylinder is $MR^2/2$.

(a) 3 points

Derive an expression for the angular momentum of the cylinder about its center of mass when it has rolled a vertical distance h. Express your answer in terms of M, R, h, and physical constants, as appropriate.

For correctly using conservation of energy		1 point
$U_{g1} + K_1 = U_{g2} + K_2$		
$U_{g1} + 0 = 0 + K_2$		
$mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$		
For correctly substituting into equation above for both linear and rotational kinetic energy		1 point
$Mgh = \frac{1}{2}M(R\omega)^2 + \frac{1}{2}\left(\frac{MR^2}{2}\right)\omega^2$		
$gh = \frac{3}{4}R^2\omega^2$		
$\omega = \sqrt{\frac{4gh}{3R^2}}$		
For correctly substituting into the equation for angular momentum		1 point
$L = I\omega = \left(\frac{MR^2}{2}\right)\left(\sqrt{\frac{4gh}{3R^2}}\right)$		
$L = MR\sqrt{\frac{gh}{3}}$		

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Question 3 (continued)

Distribution of points

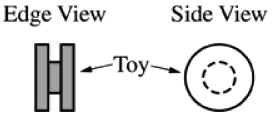
(b) 1 point

Is the angular momentum of the cylinder conserved as the cylinder rolls down the vertical distance h ?

____ Yes ____ No

Justify your answer.

Selecting "No"		
For a correct justification		1 point
Example: The frictional force exerts an external torque on the cylinder therefore the angular momentum of the cylinder is not conserevd.		
Example: The angular velocity is changing with h; therefore, L is changing.		



A child's toy is composed of 3 narrow cylinders attached around a common axis through their centers, as shown above. The central cylinder has a mass M and radius R. Each of the two outer cylinders has a mass M and radius $2R$.

(c) 2 points

Derive an expression for the rotational inertia of the toy around its center. Express your answer in terms of M, R, and physical constants, as appropriate.

For setting the total rotational inertia for the toy equal to the sum of the rotaional inertias of the three cylinders		1 point
$I_{tot} = 2I_{OUTER} + I_{INNER} = 2\left(\frac{MR^2}{2}\right)_{OUTER} + \left(\frac{MR^2}{2}\right)_{INNER}$		
$I_{tot} = 2\left(\frac{M(2R)^2}{2}\right) + \left(\frac{MR^2}{2}\right) = 4MR^2 + \frac{MR^2}{2}$		
For a correct answer:		1 point
$I_{tot} = \frac{9}{2}MR^2$		

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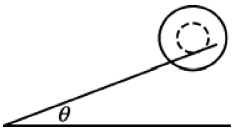
Question 3 (continued)

Distribution of points

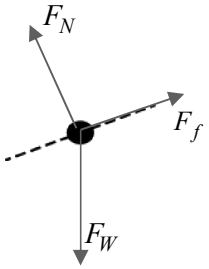


The toy is placed on a narrow track that is inclined at an angle of θ above the horizontal. Only the central cylinder is in contact with the track, as shown above. The toy rolls without slipping down the track.

(d)

i) 3 points

On the dot below, which represents the toy, draw and label the forces (not components) that act on the toy. The dashed line is parallel to the narrow track. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



For correctly drawing a vector representing the normal force perpendicular to the dashed line		1 point
For correctly drawing a vector representing the weight of the toy directed straight down		1 point
For correctly drawing a vector representing the frictional force directed up the incline		1 point
Note: A maximum of two points can be earned if there are any extraneous vectors		

ii) 3 points

Derive an expression for the linear acceleration of the toy as it rolls down the track. Express your answer in terms of M, R, θ, and physical constants, as appropriate.

For correctly using Newton's second law in linear form for the toy on the incline		1 point
$F = ma \therefore (3M)g(\sin\theta) - F_f = (3M)a$		
For correctly using Newton's second law in rotational form for the toy on the incline		1 point
$\tau = I\alpha \therefore F_f R = I\alpha \therefore F_f R = \left(\frac{9}{2}MR^2\right)\left(\frac{a}{R}\right) \therefore F_f = \frac{9}{2}Ma$		
For combining the two equation above to calculate the acceleration		1 point
$3Mg(\sin\theta) - \frac{9}{2}Ma = 3Ma \therefore 3g(\sin\theta) = \frac{15}{2}a$		
$a = \frac{2}{5}g(\sin\theta)$		

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Question 3 (continued)

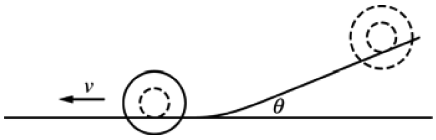
Distribution of points

(d) Con't

iii) 1 point

Determine the force of friction exerted on the toy as it rolls down the track. Express your answer in terms of M, R, θ, and physical constants, as appropriate.

For an answer consistent with part (d)(ii)		1 point
$F_f = \frac{9}{2}M\left(\frac{2}{5}g(\sin\theta)\right) = \frac{9}{5}Mg(\sin\theta)$		



(e) 2 points

The toy reaches the bottom of the incline and rolls at constant speed v along a horizontal section of the track, as shown above. Derive an expression for the total kinetic energy of the toy while it is rolling. Express your answer in terms of M, R, v, and physical constants, as appropriate.

For using both rotational and linear kinetic energy for the total kinetic energy of the toy		1 point
$K = K_L + K_R = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$		
For correctly substituting for both the rotational inertia, the mass, and $\omega = v / R$ into the equation above		1 point
$K = \frac{1}{2}(3M)v^2 + \frac{1}{2}\left(\frac{9}{2}MR^2\right)\omega^2 = \frac{3}{2}Mv^2 + \frac{9}{4}MR^2\left(\frac{v}{R}\right)^2 = \frac{15}{4}Mv^2$		

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