International Physics Olympiad:

Examination Area: Mechanics

Contents

Exam Instructions

IPho 2019: Mechanics

Read through the following examination instructions very carefully

Section I: At a Glance

Total Time:
45 minutes
Number of Questions:
35
Percent of Total Score:
50%
Writing Instrument:
Pencil required
Electronic Device:
None allowed

Section II: 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.

Section I: Multiple Choice Booklet 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 that may be helpful is in the booklet. 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.

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.

Section II: Free Response Booklet 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.

Student Answer Sheet for the Multiple-Choice Section

2019 Answer Sheet

Write your name here

B123456789T

Write your name here

NAME AND EXAM AREA — COMPLETE THIS AREA AT EVERY EXAM.

USE NO. 2 PENCIL ONLY

To maintain the security of the exam and the validity of my score, I will allow no one else to see the multiple-choice questions. I will seal the multiple-choice booklet when asked to do so, and I will not discuss these questions with anyone at any time after the completion of the section. I am aware of and agree to the Program's policies and procedures including using testing accommodations (e.g., extended time, computer, etc.) only if I have been preapproved by Board Services for Students with Disabilities.

A. SIGNATURE Sign your legal name as it will appear on your college applications. Date

B. LEGAL NAME Omit apostrophes, Jr., II.

Legal Last Name — First 15 Letters | Legal First Name — First 12 Letters | MI

C. YOUR IPHO NUMBER

D. EXAM DATE Month

E. EXAM START TIME AM PM

F. MULTIPLE-CHOICE BOOKLET SERIAL NUMBER S

G. ONLINE PROVIDER CODE

H. I AM TAKING USING THIS ANSWER SHEET Print Exam Name: Print Form: Print Form Code:

STUDENT INFORMATION AREA — COMPLETE THIS AREA ONLY ONCE.

I. DATE OF BIRTH Month Day Year

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

J. SEX

- Female
- Male

K. CURRENT GRADE LEVEL

- Pre-9th
- 9th
- 10th
- 11th
- 12th
- Post-12th

L. SOCIAL SECURITY NUMBER (Optional)

M. EXPECTED DATE OF COLLEGE ENTRANCE

- Fall
- Winter/Spring
- Summer
- Undecided

2019 2013 2014 2015

N. STUDENT SEARCH SERVICE®

I want the College Board to send information about me to colleges, universities and government scholarship programs interested in students like me.

Yes No

O. WHICH LANGUAGE DO YOU KNOW BEST?

- English
- English and another language about the same
- Another language

P. ETHNICITY/RACE

- American Indian or Alaska Native
- Asian, Asian American or Pacific Islander
- Black or African American
- Mexican or Mexican American
- Puerto Rican
- Other Hispanic, Latino or Latin American
- White
- Other

Q. PARENTAL EDUCATION LEVEL

Father/Male Guardian	Mother/Female Guardian	
		Grade school
		Some high school
		High school diploma or equivalent
		Business or trade school
		Some college
		Associate or two-year degree
		Bachelor's or four-year degree
		Some graduate or professional school
		Graduate or professional degree

SCHOOL USE ONLY

Section Number 1 2 3 4 5 6 7 8 9

Fee Reduction Granted 1 Option 1 2 Option 2

ETS USE ONLY

Exam

Exam

762000

00657-88488 • UNLPDF212

Q3428/1-4

R. SURVEY QUESTIONS — Answer the survey questions in the Student Pack. Do not put responses to exam questions in this section.

1 (A)(B)(C)(D)(E)(F)(G)(H)(I)	4 (A)(B)(C)(D)(E)(F)(G)(H)(I)	7 (A)(B)(C)(D)(E)(F)(G)(H)(I)
2 (A)(B)(C)(D)(E)(F)(G)(H)(I)	5 (A)(B)(C)(D)(E)(F)(G)(H)(I)	8 (A)(B)(C)(D)(E)(F)(G)(H)(I)
3 (A)(B)(C)(D)(E)(F)(G)(H) I	6 (A)(B)(C)(D)(E)(F)(G)(H) I	9 (A)(B)(C)(D)(E)(F)(G)(H) I

S. LANGUAGE — Do not complete this section unless instructed to do so.

If this answer sheet is for the French Language and Culture, German Language and Culture, Italian Language and Culture, Spanish Language, or Spanish Literature Exam, please answer the following questions. Your responses will not affect your score.

1. Have you lived or studied for one month or more in a country where the language of the exam you are now taking is spoken?

◯ Yes ◯ No

2. Do you regularly speak or hear the language at home?

◯ Yes ◯ No

Indicate your answers to the exam questions in this section. If a question has only four answer options, do not mark option E. Your answer sheet will be scored by machine. Use only No. 2 pencils to mark your answers on pages 2 and 3 (one response per question). After you have determined your response, be sure to completely fill in the corresponding circle next to the number of the question you are answering. Stray marks and smudges could be read as answers, so erase carefully and completely. Any improper gridding may affect your score. Answers written in the multiple-choice booklet will not be scored.

1 (A)(B)(C)(D)(E)	26 (A)(B)(C)(D)(E)	51 (A)(B)(C)(D)(E)
2 (A)(B)(C)(D)(E)	27 (A)(B)(C)(D)(E)	52 (A)(B)(C)(D)(E)
3 (A)(B)(C)(D)(E)	28 (A)(B)(C)(D)(E)	53 (A)(B)(C)(D)(E)
4 (A)(B)(C)(D)(E)	29 (A)(B)(C)(D)(E)	54 (A)(B)(C)(D)(E)
5 (A)(B)(C)(D)(E)	30 (A)(B)(C)(D)(E)	55 (A)(B)(C)(D)(E)
6 A B C D E	31 A B C D E	56 A B C D E
7 A B C D E	32 A B C D E	57 A B C D E
8 A B C D E	33 A B C D E	58 A B C D E
9 A B C D E	34 A B C D E	59 A B C D E
10 A B C D E	35 A B C D E	60 A B C D E
11 (A)(B)(C)(D)(E)	36 (A)(B)(C)(D)(E)	61 (A)(B)(C)(D)(E)
12 (A)(B)(C)(D)(E)	37 (A)(B)(C)(D)(E)	62 (A)(B)(C)(D)(E)
13 (A)(B)(C)(D)(E)	38 (A)(B)(C)(D)(E)	63 (A)(B)(C)(D)(E)
14 (A)(B)(C)(D)(E)	39 (A)(B)(C)(D)(E)	64 (A)(B)(C)(D)(E)
15 (A)(B)(C)(D)(E)	40 (A)(B)(C)(D)(E)	65 (A)(B)(C)(D)(E)
16 A B C D E	41 A B C D E	66 A B C D E
17 A B C D E	42 A B C D E	67 A B C D E
18 A B C D E	43 A B C D E	68 A B C D E
19 A B C D E	44 A B C D E	69 A B C D E
20 A B C D E	45 A B C D E	70 A B C D E
21 (A)(B)(C)(D)(E)	46 (A)(B)(C)(D)(E)	71 (A)(B)(C)(D)(E)
22 (A)(B)(C)(D)(E)	47 (A)(B)(C)(D)(E)	72 (A)(B)(C)(D)(E)
23 (A)(B)(C)(D)(E)	48 (A)(B)(C)(D)(E)	73 (A)(B)(C)(D)(E)
24 (A)(B)(C)(D)(E)	49 (A)(B)(C)(D)(E)	74 (A)(B)(C)(D)(E)
25 (A)(B)(C)(D)(E)	50 (A)(B)(C)(D)(E)	75 (A)(B)(C)(D)(E)

ETS USE ONLY	48, 55, 62, 75, 87		R	W	O	OTHER		R	W	O
		PT02					TOTAL			
		PT03								
		PT04								

DO NOT WRITE IN THIS AREA

QUESTIONS 76–120

Be sure each mark is dark and completely fills the circle. If a question has only four answer options, do not mark option E.

76	A B C D E	91	A B C D E	106	A B C D E
77	A B C D E	92	A B C D E	107	A B C D E
78	A B C D E	93	A B C D E	108	A B C D E
79	A B C D E	94	A B C D E	109	A B C D E
80	A B C D E	95	A B C D E	110	A B C D E
81	A B C D E	96	A B C D E	111	A B C D E
82	A B C D E	97	A B C D E	112	A B C D E
83	A B C D E	98	A B C D E	113	A B C D E
84	A B C D E	99	A B C D E	114	A B C D E
85	A B C D E	100	A B C D E	115	A B C D E
86	A B C D E	101	A B C D E	116	A B C D E
87	A B C D E	102	A B C D E	117	A B C D E
88	A B C D E	103	A B C D E	118	A B C D E
89	A B C D E	104	A B C D E	119	A B C D E
90	A B C D E	105	A B C D E	120	A B C D E

DO NOT WRITE IN THIS AREA

HOME ADDRESS AND SCHOOL AREA — COMPLETE THIS AREA ONLY ONCE.

T. YOUR MAILING ADDRESS

Use the address abbreviations from your AP Student Pack. Fill in only one circle per column. Indicate a space in your address by leaving a blank box; do not grid that column.

STREET ADDRESS (include street number, street name, apartment number, etc.)

CITY

ZIP OR POSTAL CODE

COUNTRY CODE

STATE

AK	HI	MI	NV	UT
AL	IA	MN	NY	VA
AR	ID	MO	OH	VT
AZ	IL	MS	OK	WA
CA	IN	MT	OR	WI
CO	KS	NC	PA	WV
CT	KY	ND	RI	WY
DC	LA	NE	SC	Puerto Rico
DE	MA	NH	SD	
FL	MD	NJ	TN	Other
GA	ME	NM	TX	

U. AREA CODE AND NUMBER

INTERNATIONAL PHONE

V. SCHOOL YOU ATTEND

SCHOOL CODE

School Name

City

State

Country

W. COLLEGE TO RECEIVE YOUR AP SCORE REPORT

COLLEGE CODE

Using the college code listed in the AP Student Pack, indicate the **ONE** college that you want to receive your AP score report.

College Name

City

State

Country

X. FOR STUDENTS OUTSIDE THE UNITED STATES ONLY

If the address gridded above is not complete enough for delivery of your score report, please fill in this circle and print your complete address below. ◯

Address | City | State or Province | Country | ZIP or Postal Code

Y. EMAIL ADDRESS

By providing your email address, you are granting the College Board permission to use your email in accordance with the policies in the *2011-12 Bulletin for AP Students and Parents*.

Section I: Multiple-Choice Questions

PLACE SEAL HERE

Physics C: Mechanics Exam

SECTION I: Multiple Choice

2019

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
None 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 that may be helpful is in the booklet. 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.

PLACE SEAL HERE

Minimum 20% post-consumer waste

Form I
Form Code 4IBP4-S

PLACE SEAL HERE
DO NOT seal answer sheet inside

TABLE OF INFORMATION DEVELOPED FOR 2019

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 = 1.60×10^{-19} J
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Speed of light, $c = 3.00 \times 10^{8}$ m s^{-1}
Avogadro's number, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}
Universal gas constant, $R = 8.31$ J (mol K)$^{-1}$	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}	
1 unified atomic mass unit, 1 u = 1.66×10^{-27} kg = 931 MeV c^{-2}	
Planck's constant, $h = 6.63 \times 10^{-34}$ J s = 4.14×10^{-15} eV s	
$hc = 1.99 \times 10^{-25}$ J m = 1.24×10^{3} eV nm	
Vacuum permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2}	
Coulomb's law constant, $k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}$ N m^2 C^{-2}	
Vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}$ (T m) A^{-1}	
Magnetic constant, $k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T m) A^{-1}	
1 atmosphere pressure, 1 atm = 1.0×10^{5} N m^{-2} = 1.0×10^{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
	centi	c
	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 conventions are used in this exam.

I. Unless otherwise stated, the frame of reference of any problem is assumed to be inertial.

II. The direction of any electric current is the direction of flow of positive charge (conventional current).

III. For any isolated electric charge, the electric potential is defined as zero at an infinite distance from the charge.

IV. For mechanics and thermodynamics equations, W represents the work done <u>on</u> a system.

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

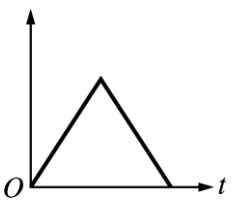
Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

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

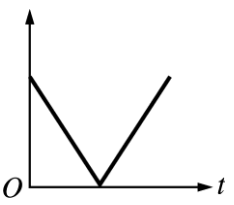
Questions 1-2

A ball is struck at time $t = 0$ and follows the parabolic path shown in the diagram above. The following graphs show quantities possibly associated with the motion as a function of time t. Assume that air resistance is negligible and that the positive directions are upward and to the right.

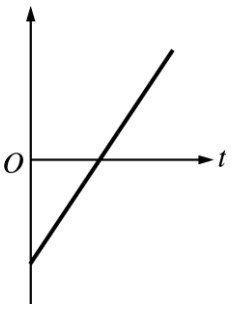
(A)



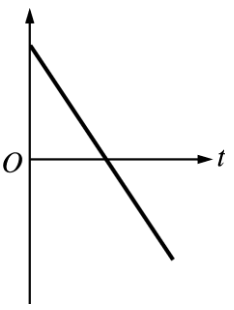
(B)



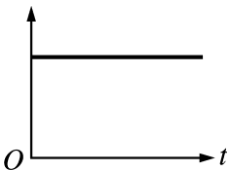
(C)



(D)

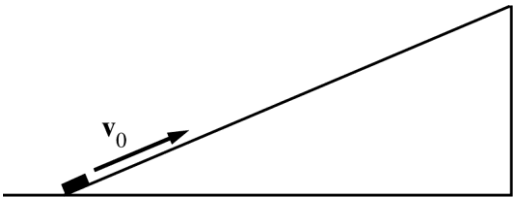


(E)



1. Which graph represents the horizontal component of the velocity of the ball?

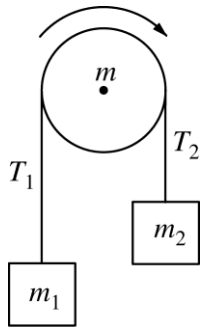
2. Which graph represents the vertical component of the velocity of the ball?



3. An object with initial velocity $\mathbf{v}_0$, as shown above, slides up and then down a long, frictionless, inclined plane. Which of the following is true of the object as it moves?

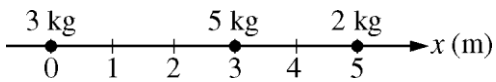
(A) It has a constant acceleration while moving up the plane and a greater acceleration when moving down the plane.
(B) It has a constant acceleration while moving up the plane and a smaller acceleration when moving down the plane.
(C) It moves with a constant velocity both up and down the plane.
(D) It has the same acceleration as it moves up and down the plane.
(E) It has a continually varying acceleration as it moves up and down the plane.

GO ON TO THE NEXT PAGE.



4. Two blocks of masses m_1 and m_2 are connected by a massless string that passes over a wheel of mass m, as shown above. The string does not slip on the wheel and exerts forces T_1 and T_2 on the blocks. When the wheel is released from rest in the position shown, it undergoes an angular acceleration and rotates clockwise. Which of the following statements about T_1 and T_2 is correct?

   (A) $T_1 = T_2$ because the wheel has mass.
   (B) $T_1 = T_2$ because both blocks have the same acceleration.
   (C) $T_1 > T_2$ because m_1 is farther from the wheel than m_2.
   (D) $T_1 > T_2$ because m_1 accelerates upward.
   (E) $T_2 > T_1$ because an unbalanced clockwise torque is needed to accelerate the wheel clockwise.



5. Three objects are located along the x-axis as shown above. The center of mass of the objects is at x =

   (A) 1.0 m
   (B) 1.5 m
   (C) 2.0 m
   (D) 2.5 m
   (E) 3.0 m

6. Which of the following is equivalent to a unit of momentum?

   (A) Joule
   (B) Newton
   (C) Joule · second
   (D) Newton · second
   (E) Newton · meter

7. Two objects are dropped from rest from the same height. Object A falls through a distance d_A during a time t, and object B falls through a distance d_B during a time $2t$. If air resistance is negligible, what is the relationship between d_A and d_B?

   (A) $d_A = \frac{1}{4} d_B$
   (B) $d_A = \frac{1}{2} d_B$
   (C) $d_A = 2 d_B$
   (D) $d_A = 4 d_B$
   (E) It cannot be determined from the information given.

GO ON TO THE NEXT PAGE.

8. The maximum mass that can be hung vertically from a string without breaking the string is 10 kg. A length of this string that is 2 m long is used to rotate a 0.5 kg object in a circle on a frictionless table with the string horizontal. The maximum speed that the mass can attain under these conditions without the string breaking is most nearly

(A) 5 m/s
(B) 10 m/s
(C) 14 m/s
(D) 20 m/s
(E) 100 m/s

9. An object moving on a horizontal, frictionless surface makes a glancing collision with another object initially at rest on the surface. In this case which of the following is true about momentum and kinetic energy?

(A) Momentum is always conserved, and kinetic energy may be conserved.
(B) Kinetic energy is always conserved, and momentum may be conserved.
(C) Momentum is always conserved, and kinetic energy is never conserved.
(D) Both momentum and kinetic energy are always conserved.
(E) Neither momentum nor kinetic energy is conserved.

10. A particle of mass m starts from rest at position $x = 0$ and time $t = 0$. It moves along the positive x-axis under the influence of a single force $F_x = bt$, where b is a constant. The velocity u of the particle is given by

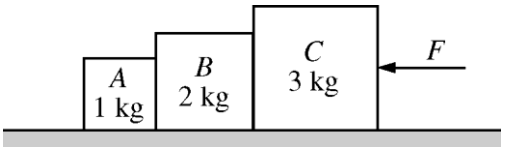
(A) $\frac{bt}{m}$

(B) $\frac{bt^2}{2m}$

(C) $\frac{bt^2}{m}$

(D) $\frac{b\sqrt{t}}{m}$

(E) $\frac{b}{mt}$

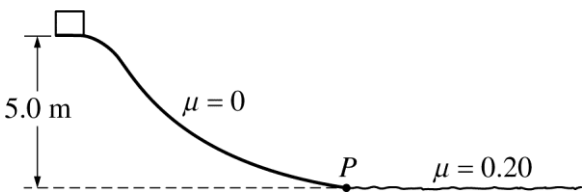


11. Three blocks, A, B, and C, of masses 1, 2, and 3 kg, respectively, are initially at rest on a frictionless surface as indicated in the figure above. What force F has to be applied on block C to accelerate the three blocks at 2 m/s^2 ?

(A) 0.33 N
(B) 1.5 N
(C) 3.0 N
(D) 6.0 N
(E) 12 N

12. An electrical motor provides 0.50 W of mechanical power. How much time will it take the motor to lift a 0.1 kg mass at constant speed from the floor to a shelf 2.0 m above the floor?

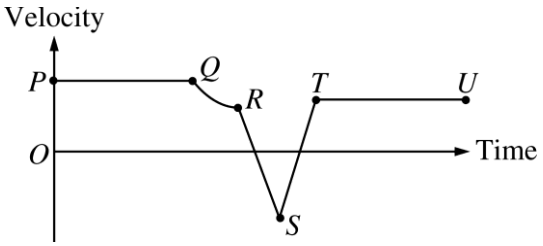
(A) 0.25 s
(B) 0.40 s
(C) 1.0 s
(D) 2.0 s
(E) 4.0 s



13. A block slides from rest with negligible friction down the track above, descending a vertical height of 5.0 m to point P at the bottom. It then slides on the horizontal surface. The coefficient of friction between the block and the horizontal surface is 0.20. How far does the block slide on the horizontal surface before it comes to rest?

(A) 0.40 m
(B) 1.0 m
(C) 2.5 m
(D) 10 m
(E) 25 m

GO ON TO THE NEXT PAGE.



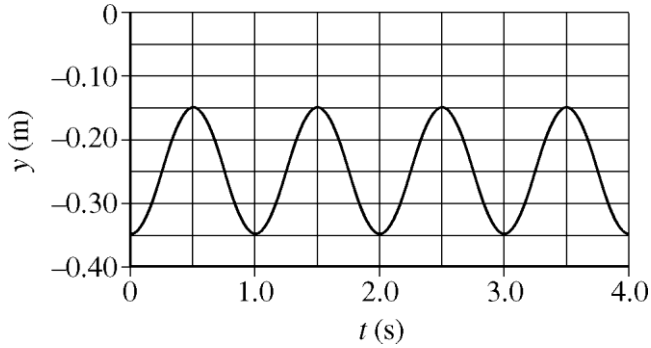
14. The graph above shows velocity as a function of time for an object moving along a straight line. For which of the following sections of the graph is the acceleration constant and nonzero?

(A) *QR* only
(B) *ST* only
(C) *PQ* and *TU* only
(D) *RS* and *ST* only
(E) PQ, *RS*, *ST*, and *TU*

15. The velocity of a particle moving along the *x*-axis is given as a function of time by the expression $u(t) = 3.0t^2 - 2.0t + 4.0$, where u is in meters per second and t is in seconds. What is the acceleration of the particle at $t = 2.0$ s?

(A) 4.0 m/s^2
(B) 6.0 m/s^2
(C) 8.0 m/s^2
(D) 10.0 m/s^2
(E) 12.0 m/s^2

Questions 16-17



An unstretched ideal spring hangs vertically from a fixed support. A 0.4 kg object is then attached to the lower end of the spring. The object is pulled down to a distance of 0.35 m below the unstretched position and released from rest at time $t = 0$. A graph of the subsequent vertical position y of the lower end of the spring as a function of t is given above, where $y = 0$ when the spring was initially unstretched.

16. At which of the following times is the upward velocity of the object the greatest?

(A) 0.00 s
(B) 0.25 s
(C) 0.50 s
(D) 0.75 s
(E) 1.00 s

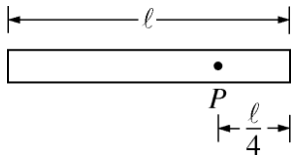
17. What is the spring constant of the spring?

(A) 16 N/m
(B) 20 N/m
(C) 32 N/m
(D) 40 N/m
(E) 64 N/m

GO ON TO THE NEXT PAGE.

18. Identical net forces act for the same length of time on two different spherical masses. Which of the following describes the change in linear momentum of the smaller mass compared to that of the larger mass?

(A) It is smaller than the change in linear momentum of the larger mass but not zero.
(B) It is larger than the change in linear momentum of the larger mass.
(C) It is equal to the change in linear momentum of the larger mass.
(D) It is zero.
(E) It depends on the relative diameters of the two masses.



19. The uniform thin rod shown above has mass m and length A. The moment of inertia of the rod about an axis through its center and perpendicular to the rod is $(1/12)mA^2$. What is the moment of inertia of the rod about an axis perpendicular to the rod and passing through point P, which is halfway between the center and the end of the rod?

(A) $\frac{1}{3}mA^2$
(B) $\frac{1}{6}mA^2$
(C) $\frac{1}{12}mA^2$
(D) $\frac{1}{48}mA^2$
(E) $\frac{7}{48}mA^2$

20. A certain one-dimensional conservative force is given as a function of x by the expression $F = -kx^3$, where F is in newtons and x is in meters. A possible potential energy function U for this force is

(A) $U = -\frac{1}{2}kx^2$
(B) $U = \frac{1}{2}kx^2$
(C) $U = -\frac{1}{4}kx^4$
(D) $U = \frac{1}{4}kx^4$
(E) $U = -3kx^2$

21. Which of the following is a differential equation that correctly describes Newton's second law for a simple harmonic oscillator of mass m and restoring force constant k?

(A) $kx = m\frac{d^2x}{dt^2}$
(B) $-kx = m\frac{d^2x}{dt^2}$
(C) $-ku = m\frac{du}{dt}$
(D) $kx = m\frac{dx}{dt}$
(E) $mg - ku = m\frac{du}{dt}$

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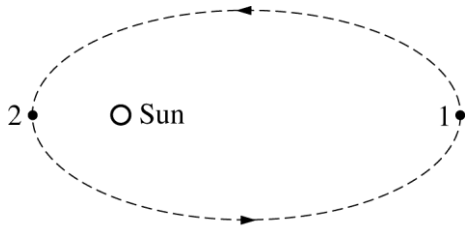
Questions 22-24



Note: Figure not drawn to scale.

The elliptical orbit of a comet is shown above. Positions 1 and 2 are, respectively, the farthest and nearest positions to the Sun, and at position 1 the distance from the comet to the Sun is 10 times that at position 2.

22. At position 2, the comet's kinetic energy is

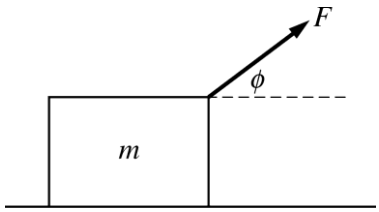
(A) the same as at position 1
(B) less than at position 1
(C) at its maximum value for the orbit
(D) at its minimum value for the orbit, but greater than zero
(E) equal to zero

23. What is the ratio u_1 / u_2 of the speed of the comet at position 1 to the speed at position 2 ?

(A) 1/100
(B) 1/10
(C) 1
(D) 10
(E) 100

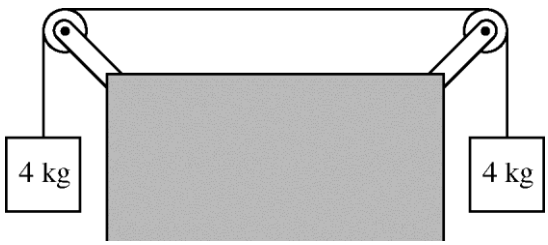
24. What is the ratio F_1 / F_2 of the force on the comet at position 1 to the force on the comet at position 2 ?

(A) 1/100
(B) 1/10
(C) 1
(D) 10
(E) 100



25. A block of mass m is pulled across a rough surface, as shown above. The coefficient of friction between the block and the surface is m_k. The force F that pulls the block is exerted at the angle ϕ shown. Which of the following is an expression for the magnitude of the frictional force on the block if it is moving at constant speed?

(A) $m_k mg$
(B) $m_k F \cos \phi$
(C) $m_k (F \sin \phi + mg)$
(D) $m_k (F \sin \phi - mg)$
(E) $m_k (mg - F \sin \phi)$



26. Two 4 kg blocks hang from a rope that passes over two frictionless pulleys, as shown in the figure above. What is the tension in the horizontal portion of the rope if the blocks are not moving and the rope and the two pulleys have negligible mass?

(A) 4 N
(B) 8 N
(C) 20 N
(D) 40 N
(E) 80 N

GO ON TO THE NEXT PAGE.

27. A person throws a ball of mass 0.20 kg. The ball starts from rest, accelerates horizontally and uniformly through a distance of 0.90 m, and leaves the person's hand at 30 m/s. The average horizontal force applied to the ball by the person's hand is

(A) 3.3 N
(B) 16.7 N
(C) 81 N
(D) 100 N
(E) 200 N

28. A railroad car of mass 1500 kg rolls to the right at 4 m/s and collides with another railroad car of mass 3000 kg that is rolling to the left at 3 m/s. The cars stick together. Their speed immediately after the collision is

(A) $\frac{2}{3}$ m/s

(B) 1 m/s

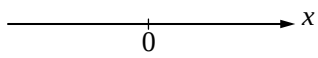
(C) $\frac{5}{3}$ m/s

(D) $\frac{10}{3}$ m/s

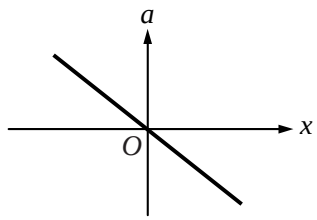
(E) 7 m/s

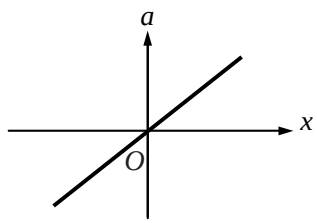
29. A meterstick of negligible mass is placed on a fulcrum at the 0.4 m mark, with a 1 kg mass hung at the zero mark and a 0.5 kg mass hung at the 1.0 m mark. The meterstick is held horizontal and released. Immediately after release, the magnitude of the net torque on the meterstick about the fulcrum is most nearly

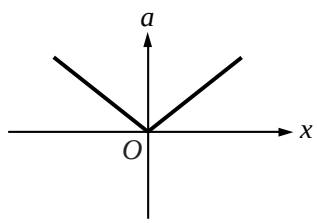
(A) 1 N·m
(B) 2 N·m
(C) 2.5 N·m
(D) 7 N·m
(E) 7.5 N·m

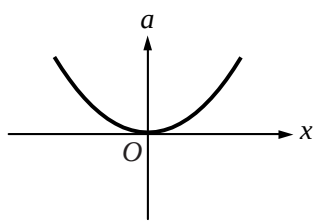


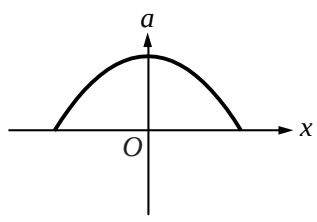
30. An object undergoes simple harmonic motion along the x-axis shown above, where $x = 0$ is the object's equilibrium position. Which of the following graphs best shows the relationship between the object's acceleration a and its displacement x from equilibrium? (Assume positive a to be acceleration directed to the right.)

(A)


(B)


(C)


(D)


(E)


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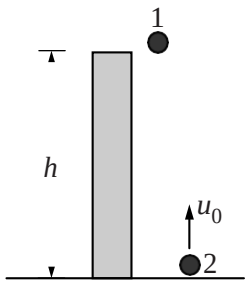


31. Ball 1 is dropped from rest at time $t = 0$ from a tower of height h, as shown above. At the same instant, ball 2 is launched upward from the ground with initial speed u_0. If air resistance is negligible, at what time t will the two balls pass each other?

(A) $\frac{1}{4}\frac{h}{u_0}$

(B) $\frac{1}{2}\frac{h}{u_0}$

(C) $\frac{h}{u_0}$

(D) $2\frac{h}{u_0}$

(E) $4\frac{h}{u_0}$

32. Suppose that the potential energy of a particle constrained to move along the x-axis can be described by the function $U(x) = \frac{1}{2}kx^2 - ax$, where both k and a are positive constants. Stable equilibrium points, about which the particle oscillates, are located at

(A) $x = 0$ only

(B) $x = \frac{a}{k}$ only

(C) $x = \frac{2a}{k}$ only

(D) $x = 0$ and $\frac{a}{k}$

(E) $x = 0$ and $\frac{2a}{k}$

33. A ball of mass m falls vertically, hits the floor with a speed u_i, and rebounds with a speed u_f. What is the magnitude of the impulse exerted on the ball by the floor?

(A) $2m(u_f - u_i)$

(B) $m(u_f - u_i)$

(C) $m(u_f + u_i)$

(D) mu_i

(E) mu_f

GO ON TO THE NEXT PAGE.

Questions 34-35

A particle moves in a circle in such a way that the x- and y-coordinates of its motion, given in meters as functions of time t in seconds, are:

$$x = 5\cos(3t)$$
$$y = 5\sin(3t).$$

34. What is the radius of the circle?

(A) $\frac{5}{3}$ m

(B) $\frac{5}{2}$ m

(C) 5 m

(D) 10 m

(E) 15 m

35. Which of the following is true of the speed of the particle?

(A) It is always equal to 5 m/s.
(B) It is always equal to 15 m/s.
(C) It oscillates with a range of 0 to 5 m/s.
(D) It oscillates with a range of 0 to 15 m/s.
(E) It oscillates with a range of 5 to 15 m/s.

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.

Section II: Free-Response Questions

This is the free-response section of the 2019 IPho exam. It includes cover material and other administrative instructions to help familiarize students with the mechanics of the exam. (Note that future exams may differ in look from the following content.

IPho® Physics C: Mechanics Exam

SECTION II: Free Response

2019

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.

TABLE OF INFORMATION DEVELOPED FOR 2019

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^{-1}
Avogadro's number, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}
Universal gas constant, $R = 8.31$ J (mol K)$^{-1}$	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}	
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,	$\epsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2}
Coulomb's law constant,	$k = 1/4\pi\epsilon_0 = 9.0 \times 10^{9}$ N m^2 C^{-2}
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}$ (T m) A^{-1}
Magnetic constant,	$k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T m) A^{-1}
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 conventions are used in this exam.

I. Unless otherwise stated, the frame of reference of any problem is assumed to be inertial.

II. The direction of any electric current is the direction of flow of positive charge (conventional current).

III. For any isolated electric charge, the electric potential is defined as zero at an infinite distance from the charge.

ADVANCED PLACEMENT PHYSICS C EQUATIONS DEVELOPED FOR 2019

MECHANICS

$u = u_0 + at$

$x = x_0 + u_0 t + \frac{1}{2}at^2$

$u^2 = u_0^2 + 2a(x - x_0)$

$\Sigma \mathbf{F} = \mathbf{F}_{net} = m\mathbf{a}$

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

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

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

$F_{fric} \le \mu N$

$W = \int \mathbf{F} \cdot d\mathbf{r}$

$K = \frac{1}{2}mu^2$

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

$P = \mathbf{F} \cdot \mathbf{v}$

$\Delta U_g = mgh$

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

$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$

$\Sigma \boldsymbol{\tau} = \boldsymbol{\tau}_{net} = I\boldsymbol{\alpha}$

$I = \int r^2 dm = \Sigma mr^2$

$\mathbf{r}_{cm} = \Sigma m\mathbf{r} / \Sigma m$

$u = r\omega$

$\mathbf{L} = \mathbf{r} \times \mathbf{p} = I\boldsymbol{\omega}$

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

$\omega = \omega_0 + \alpha t$

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

a = acceleration
F = force
f = frequency
h = height
I = rotational inertia
J = impulse
K = kinetic energy
k = spring constant
ℓ = length
L = angular momentum
m = mass
N = normal force
P = power
p = momentum
r = radius or distance
$\mathbf{r}$ = position vector
T = period
t = time
U = potential energy
u = 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

$\mathbf{F}_s = -k\mathbf{x}$

$U_s = \frac{1}{2}kx^2$

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

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

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

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

$\mathbf{F}_G = -\frac{Gm_1m_2}{r^2}\hat{\mathbf{r}}$

$U_G = -\frac{Gm_1m_2}{r}$

ELECTRICITY AND MAGNETISM

$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$

$\mathbf{E} = \frac{\mathbf{F}}{q}$

$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\varepsilon_0}$

$E = -\frac{dV}{dr}$

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

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r}$

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

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

$C_p = \Sigma_i C_i$

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

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

$U_C = \frac{1}{2}QV = \frac{1}{2}CV^2$

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

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

$I = Ne u_d A$

$V = IR$

$R_s = \Sigma_i R_i$

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

$P = IV$

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

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

$\oint \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I$

$d\mathbf{B} = \frac{\mu_0}{4\pi}\frac{I\, d\boldsymbol{\ell} \times \mathbf{r}}{r^3}$

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

$B_s = \mu_0 nI$

$\Phi_m = \int \mathbf{B} \cdot d\mathbf{A}$

$\mathcal{E} = \oint \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d\Phi_m}{dt}$

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

$U_L = \frac{1}{2}LI^2$

ADVANCED PLACEMENT PHYSICS C EQUATIONS DEVELOPED FOR 2019

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

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

Circle

$A = \pi r^2$

$C = 2\pi r$

Rectangular Solid

$V = Awh$

Cylinder

$V = \pi r^2 A$

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

Sphere

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

$S = 4\pi r^2$

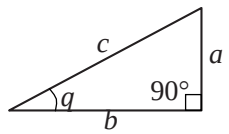
Right Triangle

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

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

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

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



A = area
C = circumference
V = volume
S = surface area
b = base
h = height
A = length
w = width
r = radius

CALCULUS

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

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

$$\frac{d}{dx}(e^x) = e^x$$

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

$$\frac{d}{dx}(\sin x) = \cos x$$

$$\frac{d}{dx}(\cos x) = -\sin x$$

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

$$\int e^x\,dx = e^x$$

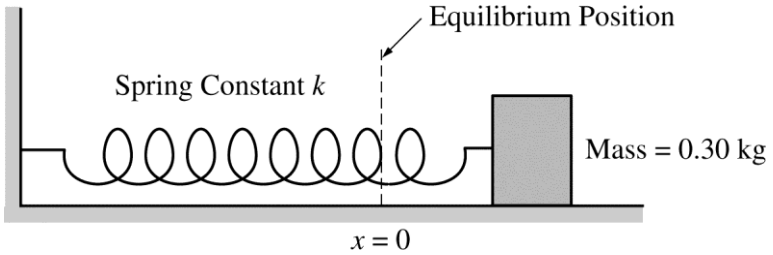
$$\int \frac{dx}{x} = \ln|x|$$

$$\int \cos x\,dx = \sin x$$

$$\int \sin x\,dx = -\cos x$$

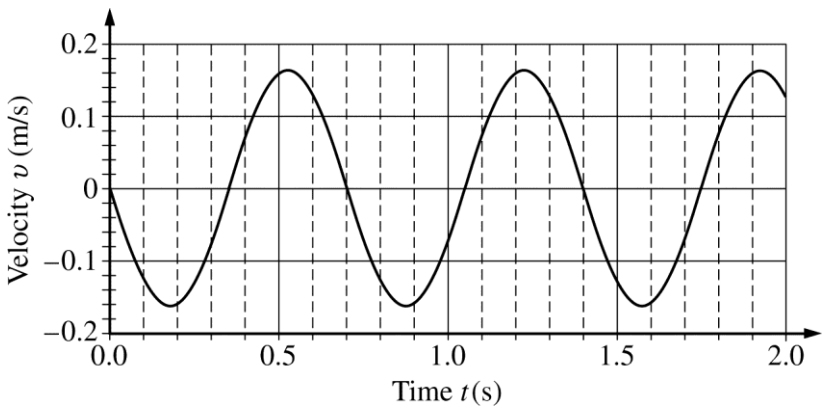
PHYSICS C: MECHANICS
SECTION II
Time—45 minutes
3 Questions

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.

Experiment 1. A block of mass 0.30 kg is placed on a frictionless table and is attached to one end of a horizontal spring of spring constant k, as shown above. The other end of the spring is attached to a fixed wall. The block is set into oscillatory motion by stretching the spring and releasing the block from rest at time $t = 0$. A motion detector is used to record the position of the block as it oscillates. The resulting graph of velocity v versus time t is shown below. The positive direction for all quantities is to the right.



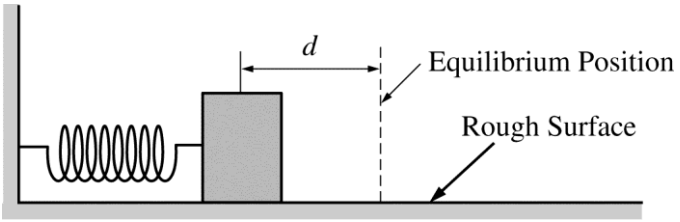
(a) Determine the equation for $v(t)$, including numerical values for all constants.

(b) Given that the equilibrium position is at $x = 0$, determine the equation for $x(t)$, including numerical values for all constants.

GO ON TO THE NEXT PAGE.

(c) Calculate the value of k.

Experiment 2. The block and spring arrangement is now placed on a rough surface, as shown below. The block is displaced so that the spring is compressed a distance d and released from rest.

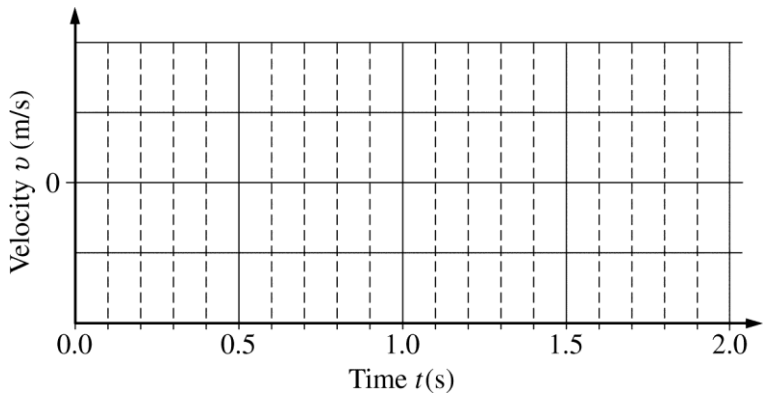


(d) On the dots below that represent the block, draw and label the forces (not components) that act on the block when the spring is compressed a distance $x = d/2$ and the block is moving in the direction indicated below each dot.

Toward
the equilibrium position

Away from
the equilibrium position

(e) Draw a sketch of v versus t in this case. Assume that there is a negligible change in the period and that the positive direction is still to the right.



Mech. 2.

You are to perform an experiment investigating the conservation of mechanical energy involving a transformation from initial gravitational potential energy to translational kinetic energy.

(a) You are given the equipment listed below, all the supports required to hold the equipment, and a lab table. On the list below, indicate each piece of equipment you would use by checking the line next to each item.

____ Track	____ Meterstick	____ Set of objects of different masses
____ Cart	____ Electronic balance	____ Lightweight low-friction pulley
____ String	____ Stopwatch	

(b) Outline a procedure for performing the experiment. Include a diagram of your experimental setup. Label the equipment in your diagram. Also include a description of the measurements you would make and a symbol for each measurement.

GO ON TO THE NEXT PAGE.

(c) Give a detailed account of the calculations of gravitational potential energy and translational kinetic energy both before and after the transformation, in terms of the quantities measured in part (b).

(d) After your first trial, your calculations show that the energy increased during the experiment. Assuming you made no mathematical errors, give a reasonable explanation for this result.

(e) On all other trials, your calculations show that the energy decreased during the experiment. Assuming you made no mathematical errors, give a reasonable physical explanation for the fact that the average energy you determined decreased. Include references to conservative and nonconservative forces, as appropriate.

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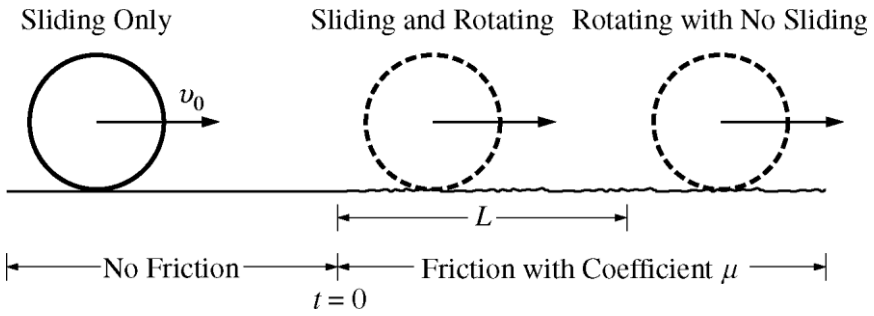

Mech. 3.

A ring of mass M, radius R, and rotational inertia MR^2 is initially sliding on a frictionless surface at constant velocity v_0 to the right, as shown above. At time $t = 0$ it encounters a surface with coefficient of friction m and begins sliding and rotating. After traveling a distance L, the ring begins rolling without sliding. Express all answers to the following in terms of M, R, v_0, m, and fundamental constants, as appropriate.

(a) Starting from Newton's second law in either translational or rotational form, as appropriate, derive a differential equation that can be used to solve for the magnitude of the following as the ring is sliding and rotating.

i. The linear velocity v of the ring as a function of time t

ii. The angular velocity w of the ring as a function of time t

(b) Derive an expression for the magnitude of the following as the ring is sliding and rotating.

i. The linear velocity v of the ring as a function of time t

ii. The angular velocity w of the ring as a function of time t

GO ON TO THE NEXT PAGE.

(c) Derive an expression for the time it takes the ring to travel the distance L.

(d) Derive an expression for the magnitude of the velocity of the ring immediately after it has traveled the distance L.

(e) Derive an expression for the distance L.

GO ON TO THE NEXT PAGE.

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(ES) ON THE COVER(S).**
- **MAKE SURE YOU HAVE USED THE SAME SET OF AP NUMBER LABELS ON ALL AP EXAMS YOU HAVE TAKEN THIS YEAR**

GO ON TO THE NEXT PAGE.