

# PHYSICS 1

## SECTION I

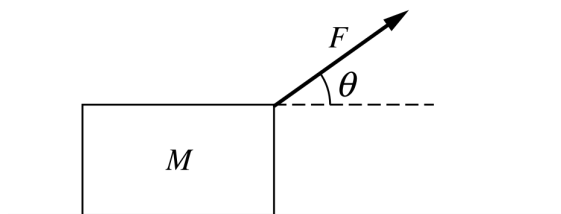
Time—1 hour and 30 minutes

50 Questions

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

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

1. Two identical cars, Car 1 and Car 2, are both moving along a straight, level road. At time  $t = 0$ , both cars have a velocity of  $+10 \text{ m/s}$ .  
  
Car 1 continues to move at a constant velocity, while Car 2 has a constant acceleration of  $-1 \text{ m/s}^2$ . What is the speed of the center of mass of the two-car system at  $t = 10 \text{ s}$ ?  
  
(A)  $15 \text{ m/s}$   
(B)  $10 \text{ m/s}$   
(C)  $5 \text{ m/s}$   
(D)  $0 \text{ m/s}$
2. Two identical elevators are lifted at constant speeds. Work is done on the first elevator at a rate  $P_1$  as it is lifted a distance  $h_0$  in time  $\Delta t$ . Work is done on the second elevator at a rate  $P_2$  as it is lifted a distance  $2h_0$  in time  $4\Delta t$ . How does  $P_2$  compare to  $P_1$ ?  
  
(A)  $P_2 = 4P_1$   
(B)  $P_2 = 2P_1$   
(C)  $P_2 = \frac{1}{2}P_1$   
(D)  $P_2 = \frac{1}{4}P_1$
3. A cart of mass  $m$  is traveling at velocity  $v$  to the right when it has a perfectly elastic collision with a cart of mass  $3m$  that is at rest. Immediately after the collision, the cart of mass  $3m$  moves with a velocity  $\frac{v}{2}$  to the right. What is the velocity of the cart of mass  $m$  immediately after the collision?  
  
(A) Zero  
(B)  $v$  to the right  
(C)  $\frac{v}{2}$  to the left  
(D)  $3v$  to the left



4. A block of mass  $M$ , initially at rest, is pulled along a horizontal frictionless surface by a force of magnitude  $F$  applied at an angle  $\theta$  to the horizontal, as shown above. The force is exerted on the block for a distance of  $d$ , accelerating the block to speed  $v_f$ . Which of the following expressions is equal to the work done by the applied force?

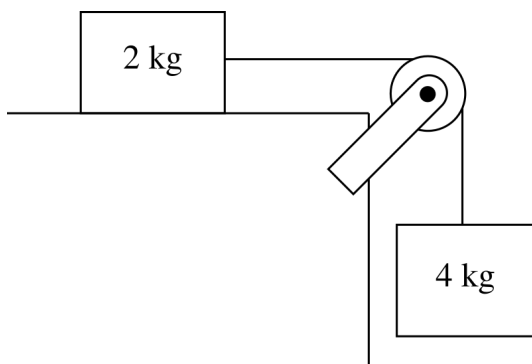
- (A)  $Fd$
- (B)  $Fd \sin \theta$
- (C)  $mgd \cos \theta$
- (D)  $\frac{1}{2}Mv_f^2$

5. Block 1 slides to the right at 2 m/s on a frictionless, horizontal surface toward Block 2, which is initially at rest. After the collision, Block 1 moves to the right at 1 m/s and Block 2 moves to the right at 3 m/s. Are the data provided sufficient to determine whether the collision is elastic? Why or why not?

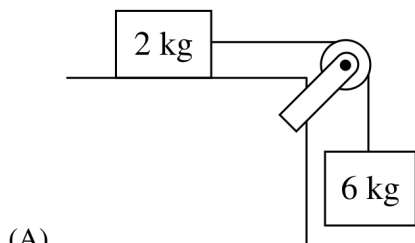
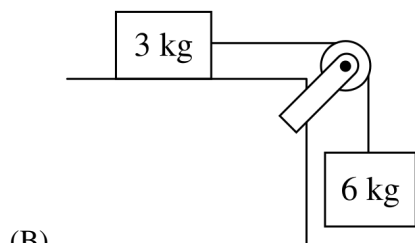
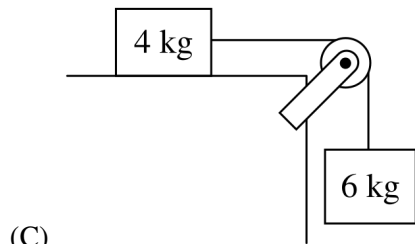
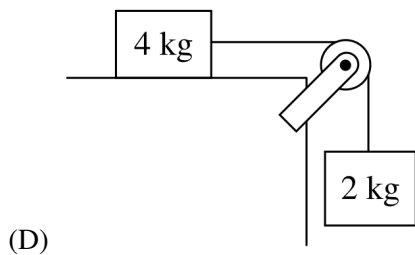
- (A) Yes, because the ratio of the blocks' masses can be determined.
- (B) Yes, because the total momentum can be calculated before and after the collision.
- (C) No, because the blocks' masses are unknown.
- (D) No, because it is not stated whether the blocks are permanently deformed during the collision.

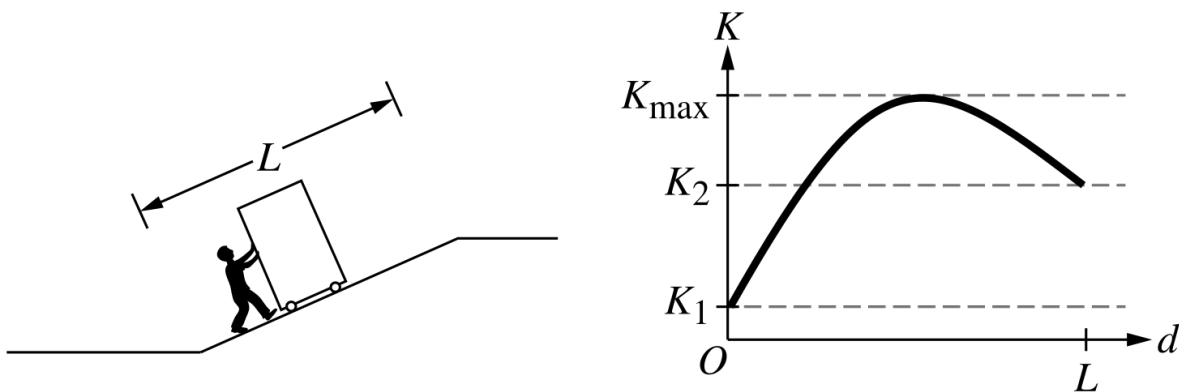
6. A 1000 kg spacecraft is traveling through deep space at a speed of 500 m/s when its thrusters turn on and exert a force opposite its original direction of motion. When the thrusters turn off, the spacecraft is traveling opposite the original direction at 500 m/s. What is the average force the thrusters exert on the spacecraft?

- (A) 0 N
- (B)  $5 \times 10^4$  N
- (C)  $1 \times 10^6$  N
- (D) It cannot be determined without knowing how long the thrusters were on.

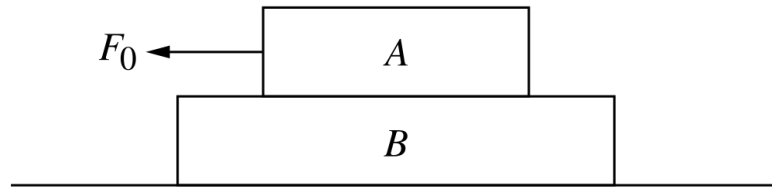


7. Two blocks with different masses are attached by a string, as shown above. One block hangs vertically, and the other block rests on a frictionless surface. The blocks are released from rest. The procedure is repeated with blocks of different mass in each position. For which of the following systems will the blocks have the same acceleration as the original system?





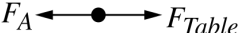
8. A person pushes a box up a ramp of length  $L$ , as shown. The graph above shows the kinetic energy  $K$  of the box as a function of its position  $d$  along the ramp. The net work done on the box while it is on the ramp equals
- (A)  $K_{\max}$
  - (B)  $K_2$
  - (C)  $K_{\max} - K_1$
  - (D)  $K_2 - K_1$
9. A simple pendulum consisting of a massive bob attached to a lightweight wire oscillates at small angles to the vertical. Which of the following changes will result in a significantly higher oscillation frequency for the pendulum?
- (A) Shortening the wire
  - (B) Using a bob with twice as much mass
  - (C) Doubling the amplitude of oscillation
  - (D) Taking the pendulum to a planet where the gravitational acceleration is less than  $g$



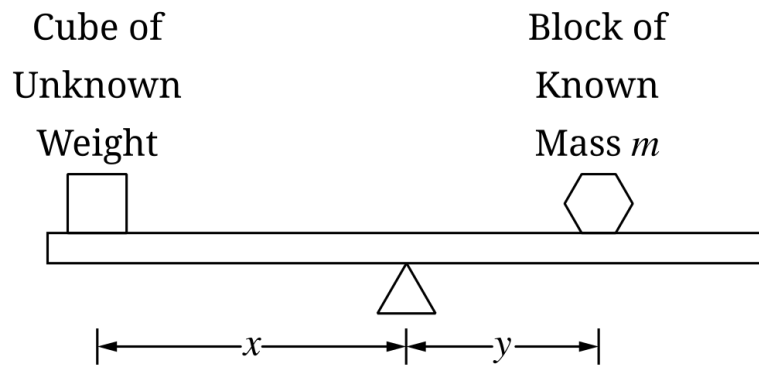
10. Books A and B are stacked on top of one another on a table, as shown in the figure. A force  $F_0$  is exerted to the left on Book A, and the books move together to the left at a constant speed. Which of the following best represents the directions of the horizontal forces, if any, exerted on Book B?

(A) 

(B) 

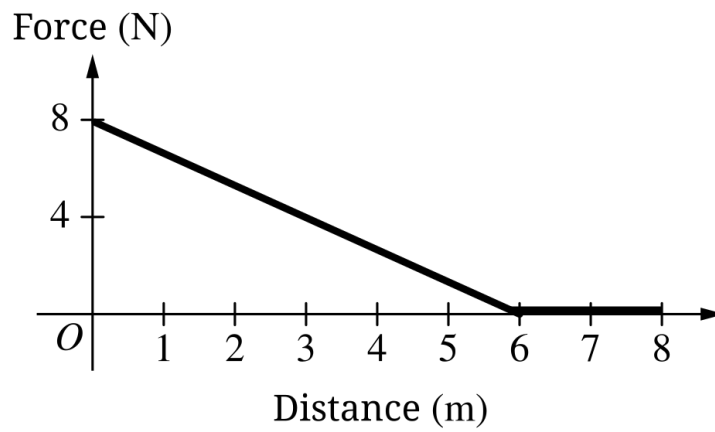
(C) 

(D) There are no horizontal forces exerted on Book B.

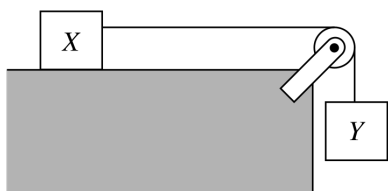
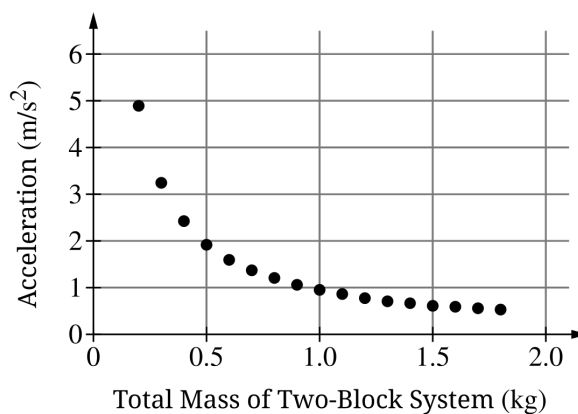


11. A student who does not have access to a scale wishes to determine the weight of a cube using the setup shown. A fulcrum is placed beneath the midpoint of a meterstick and the cube is placed on the meterstick a distance  $x$  from the fulcrum. A small block of known mass  $m$  is placed on the meterstick on the other side of the fulcrum at a distance  $y < x$ , such that the meterstick is balanced and horizontal. Which of the following expressions is equal to the weight of the cube?

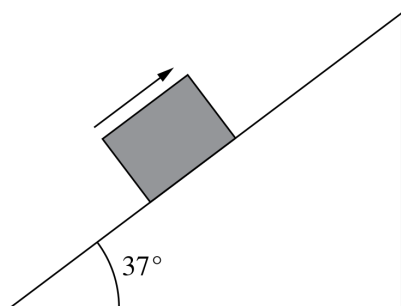
- (A)  $\frac{mgx}{y}$   
 (B)  $\frac{mgy}{x}$   
 (C)  $\frac{mgx}{x+y}$   
 (D)  $\frac{mgy}{x+y}$



12. The graph shows the net horizontal force exerted on a 3 kg box as a function of the distance the box has moved along a horizontal track. If the box started at rest, the speed of the box when it has moved 8 m is
- (A) 64 m/s
  - (B) 24 m/s
  - (C) 8 m/s
  - (D) 4 m/s

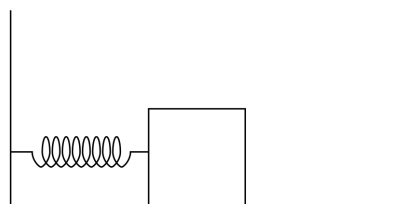


13. Block X rests on a frictionless, horizontal surface and is connected to Block Y by a light string that passes over a frictionless pulley of negligible mass, as shown. A student releases the blocks from rest and measures the acceleration of Block Y. The student then performs several more trials, adding mass to the two-block system in each trial. The graph above shows the acceleration of Block Y as a function of the total mass of the two-block system. Which of the following best describes how the mass was added to the two-block system?
- (A) In each trial, mass was only added to Block X.
  - (B) In each trial, mass was only added to Block Y.
  - (C) In each trial, mass was added equally to Block X and Block Y.
  - (D) In each trial, mass could have been added to either Block X, Block Y, or both.

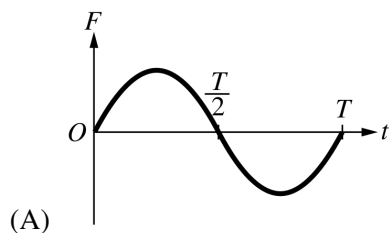
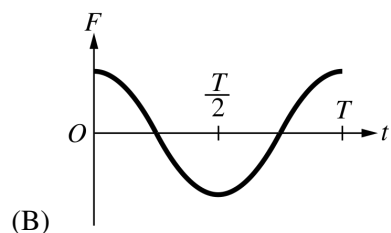
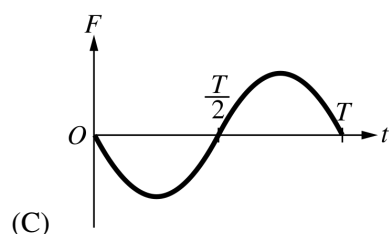
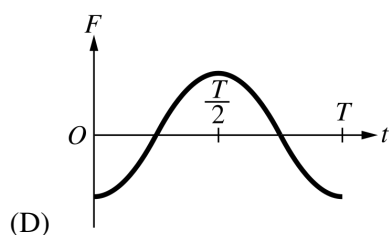


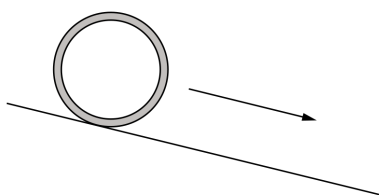
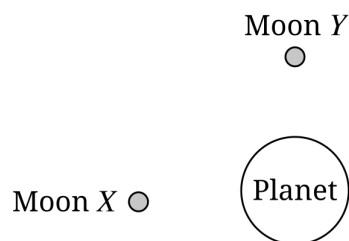
14. After receiving a brief push, a box slides up a ramp that is at an angle of  $37^\circ$  with the horizontal, as shown. The gravitational force on the box is 40 N, and the kinetic frictional force is 9 N directed down the ramp. What is the net force on the box as it slides up the ramp?

(A) 49 N up the ramp  
 (B) 15 N up the ramp  
 (C) 9 N down the ramp  
 (D) 33 N down the ramp

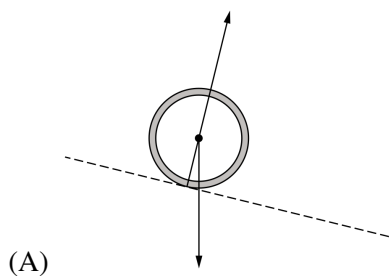
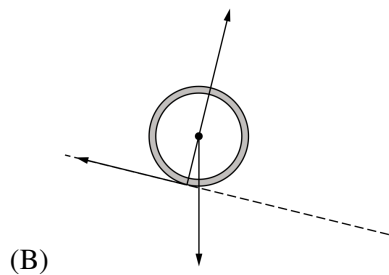
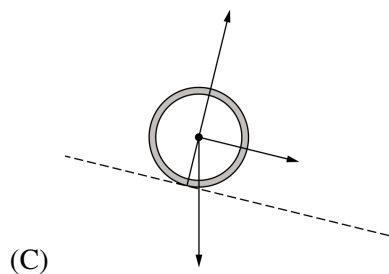
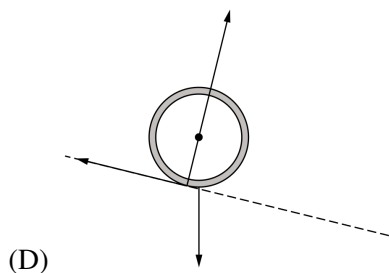


15. A block is attached to a spring, the other end of which is attached to a wall, as shown above. The block is pushed toward the wall from its equilibrium position, compressing the spring, and then is released from rest at time  $t = 0$ . There is no friction between the block and the horizontal surface. Assuming right to be the positive direction, which of the following graphs could represent the restoring force  $F$  versus time  $t$  for one period  $T$  of the oscillation of the block?



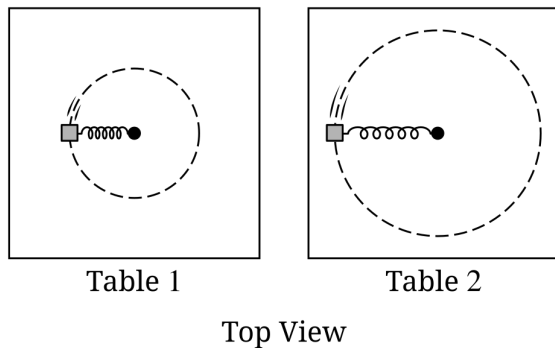


16. The figure shows a ring rolling down an inclined plane without slipping. Which of the following diagrams, once properly labeled, represents the forces acting on the ring, with the tail of each vector starting at the point of application of the force? (The dot represents the center of the ring.)



17. The figure above shows a planet with two moons, X and Y. The net gravitational force exerted on the planet by the two moons has magnitude  $F$ . If the mass of each moon is doubled, the net gravitational force exerted on the planet would have magnitude

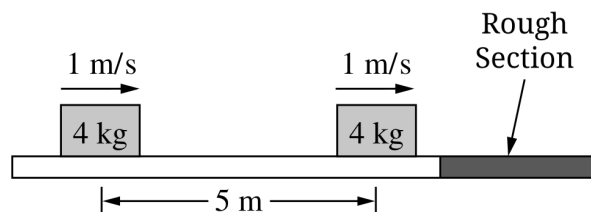
- (A)  $2F$   
 (B)  $2\sqrt{2}F$   
 (C)  $4F$   
 (D)  $4\sqrt{2}F$



18. Two identical blocks are each attached to an end of identical ideal springs, with the other end of each spring fixed in place on a level table, as shown. The blocks move with negligible friction in circular paths with different constant speeds. The block on Table 2 moves with a greater speed in a circle of larger radius than the block on Table 1. Which of the following relations correctly describes the work  $W$  done by the spring on the block during one full rotation for the two blocks?

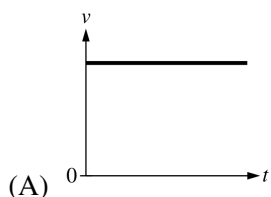
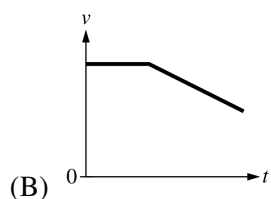
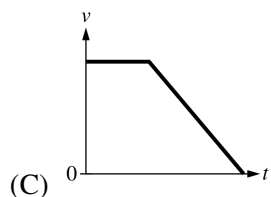
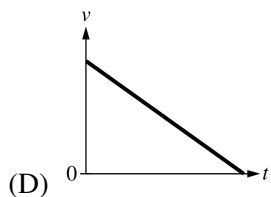
- (A)  $W_2 > W_1$
- (B)  $W_1 > W_2$
- (C)  $(W_1 = W_2) > 0$
- (D)  $W_1 = W_2 = 0$

## Questions 19-20

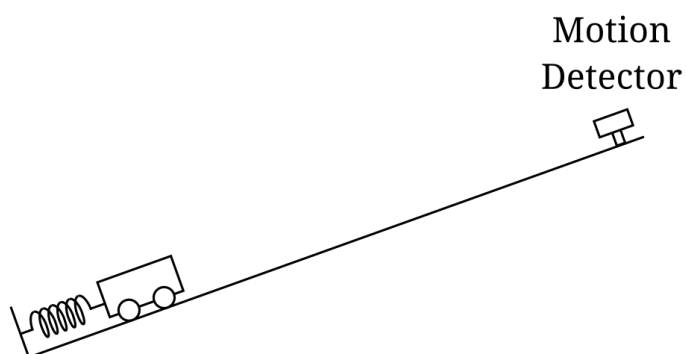


Two identical blocks of mass 4 kg each travel to the right with speed 1 m/s on a frictionless section of a horizontal surface, as shown in the figure above. The centers of the blocks are initially separated by 5 m. The first block then encounters a rough section, with a coefficient of kinetic friction of 0.025 between the block and the rough section. The first block comes to rest after traveling 2 m on the rough section. At this instant, the second block has not yet reached the rough section.

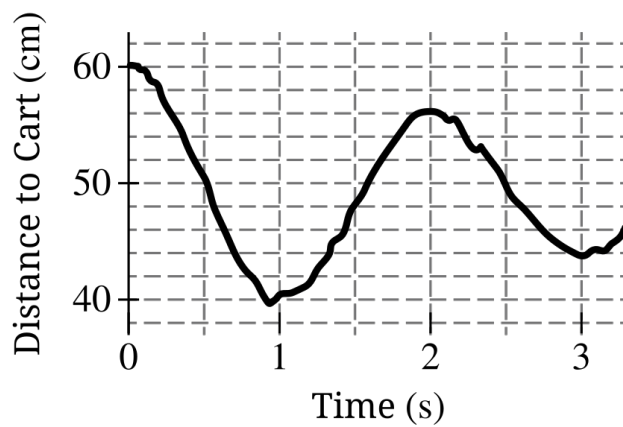
19. Which of the following graphs best represents the speed  $v$  of the center of mass of the two-block system as a function of time  $t$  from before the first block enters the rough section until the instant the first block comes to rest?
20. What is the change in the mechanical energy of the two-block system from when the two blocks are initially moving to the moment when the first block has come to rest?
- (A) 0 J  
(B)  $-0.25$  J  
(C)  $-2.0$  J  
(D)  $-4.0$  J



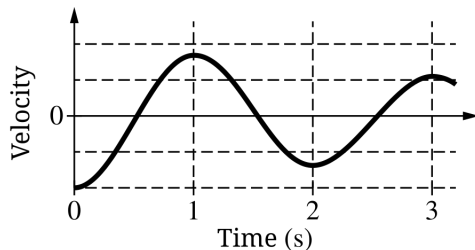
### Questions 21-23



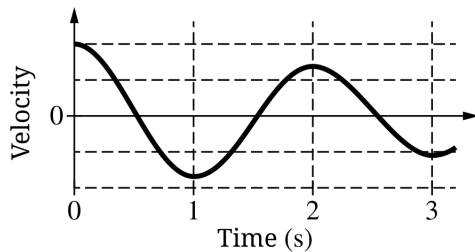
A cart on an inclined track is connected to a spring that is fixed at the other end, as shown above. The spring is compressed by pushing the cart against it, and then the cart is released from rest. A motion detector at the other end of the track records the distance between the cart and the detector as a function of time, as shown in the graph below.



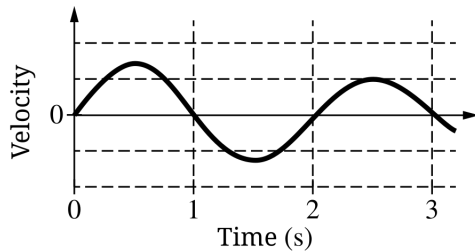
21. On the graph, the peak value occurring at  $t = 2\text{s}$  is lower than the value at  $t = 0\text{s}$ . Which of the following is most likely a contributing explanation?
- (A) Mechanical energy is dissipated by friction between the cart and the track.
  - (B) The spring is nonideal and exerts a nonlinear restoring force on the cart.
  - (C) The mechanical energy of the cart-spring-Earth system includes both the elastic potential energy of the spring and gravitational potential energy.
  - (D) The kinetic energy of the cart includes both the rotational kinetic energy of the cart's wheels and the translational kinetic energy of the cart.
22. Which of the following graphs best represents the velocity of the cart as a function of time, where a positive velocity corresponds to motion away from the detector?



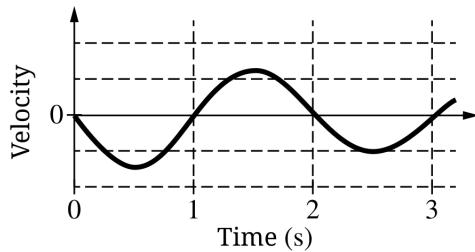
(A)



(B)

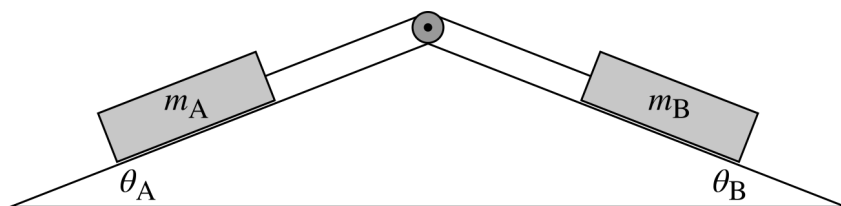


(C)



(D)

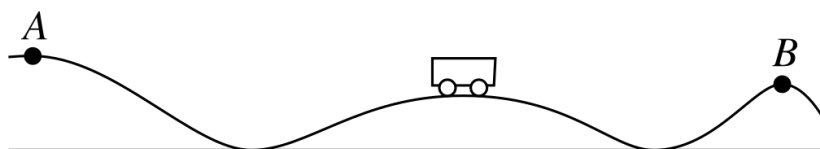
23. What is the cart's maximum displacement from its starting position?
- (A) 4 cm
  - (B) 20 cm
  - (C) 40 cm
  - (D) 60 cm



Note: Figure not drawn to scale.

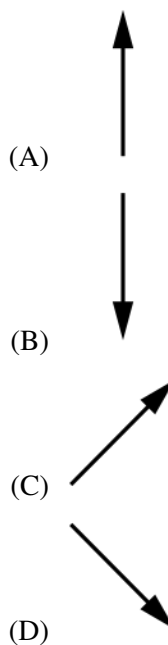
24. Two blocks with mass  $m_A$  and  $m_B$  are connected by a lightweight string that passes over a pulley with negligible mass and friction, as shown above. The blocks are free to move along frictionless inclined surfaces with angles  $\theta_A$  and  $\theta_B$ , respectively. For which of the following relationships between the masses and angles will the blocks always be in equilibrium?
- (A)  $m_A = m_B$  and any angles
  - (B)  $\sin \theta_A = \sin \theta_B$  and any masses
  - (C)  $m_A \sin \theta_A = m_B \sin \theta_B$
  - (D)  $m_A \sin \theta_B = m_B \sin \theta_A$

Questions 25-26

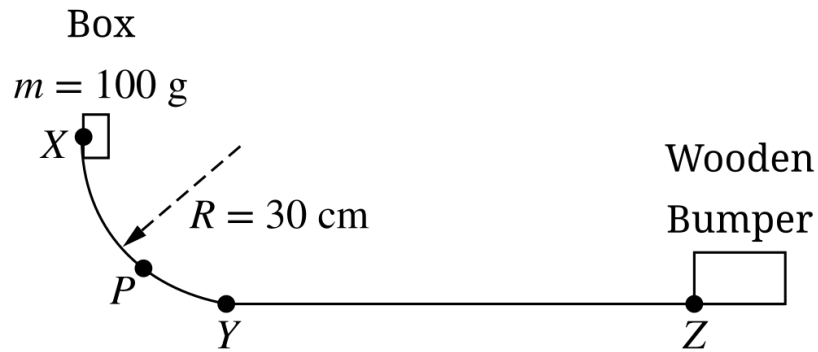


A cart of known mass is free to move on the frictionless track shown. The cart is released from rest at Point A and rolls freely toward Point B, without losing contact with the track. The heights of points A and B are known.

25. Which of the following is equal to the kinetic energy of the cart when it is at Point B?
- (A) The gravitational potential energy of the Earth-cart system when the cart is at Point A
  - (B) The gravitational potential energy of the Earth-cart system when the cart is at Point B
  - (C) The difference between the gravitational potential energy of the Earth-cart system when the cart is at Point A and when it is at Point B
  - (D) The sum of the gravitational potential energy of the Earth-cart system when the cart is at Point A and when it is at Point B
26. Which of the following best represents the direction of the net force exerted on the cart when it is at Point B?



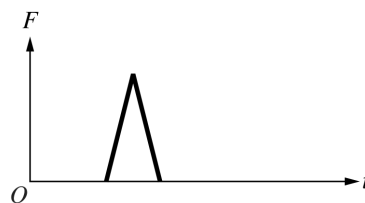
Questions 27-28



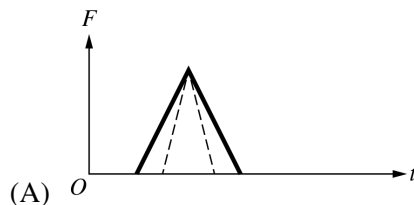
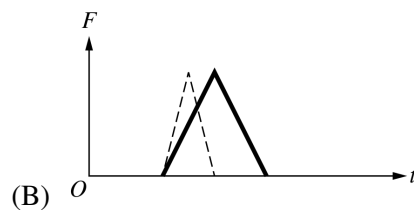
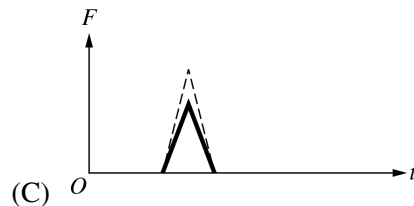
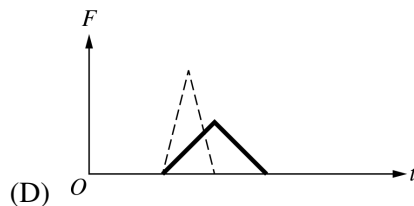
A 100 g box initially at rest slides down a rough circular ramp and makes a smooth transition onto a level horizontal track of negligible friction, as shown above. At Point Z, the box collides with a fixed wooden bumper that brings the box to rest. The radius of the circular ramp is 30 cm.

27. Take the gravitational potential energy of the box-Earth system to be zero when the box is at Point Y. One-third of the initial mechanical energy of the box-Earth system is dissipated as the box moves from Point X to Point Y. The speed of the box just before it hits the bumper is most nearly

(A) 1.4 m/s  
 (B) 2.0 m/s  
 (C) 4.0 m/s  
 (D) 20 m/s



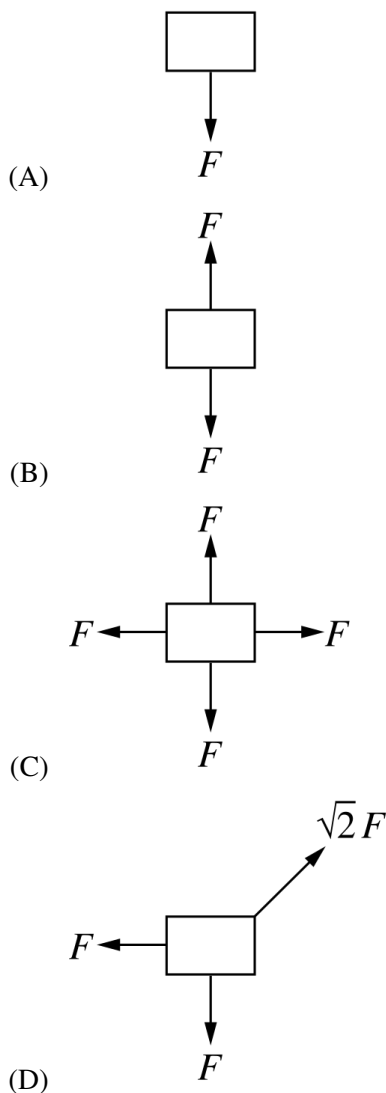
28. The graph above shows the magnitude  $F$  of the force the wooden bumper exerts on the box as a function of time  $t$  as the bumper brings the box to rest. If the wooden bumper is replaced by a bumper of the same size but made of a softer material, which of the following graphs could represent the magnitude of the force it exerts on the box? (An outline of the graph for the wooden bumper is shown as a dashed line for reference.)



29. Two balls of mass  $M$  and  $2M$  are released from rest at the same time from the same height and fall straight down with negligible air resistance. Just before hitting the ground, the ball of mass  $M$  has kinetic energy  $K$ . What is the kinetic energy of the ball of mass  $2M$  just before hitting the ground?

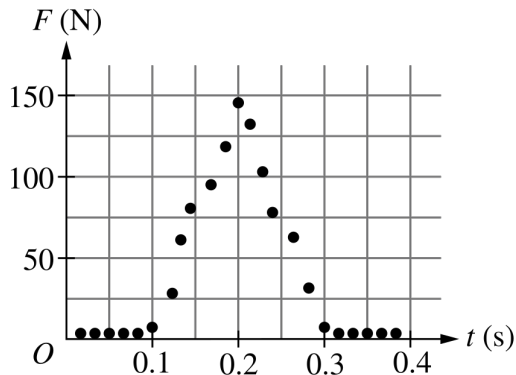
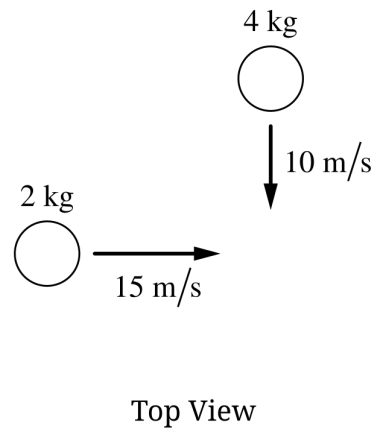
- (A)  $K$
- (B)  $\sqrt{2}K$
- (C)  $2K$
- (D)  $4K$

30. Four blocks of equal mass are moving at the same speed when different sets of forces are exerted on the blocks, as shown below, with the lengths of the arrows proportional to the magnitudes of the forces. Which of the following blocks could be losing kinetic energy?

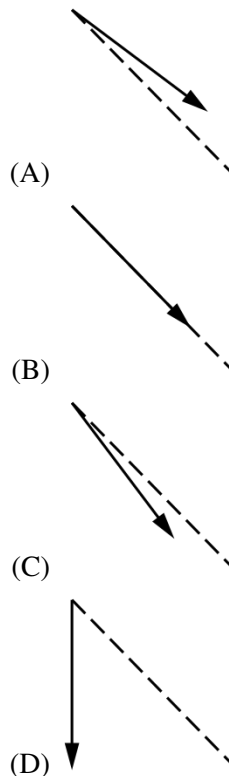


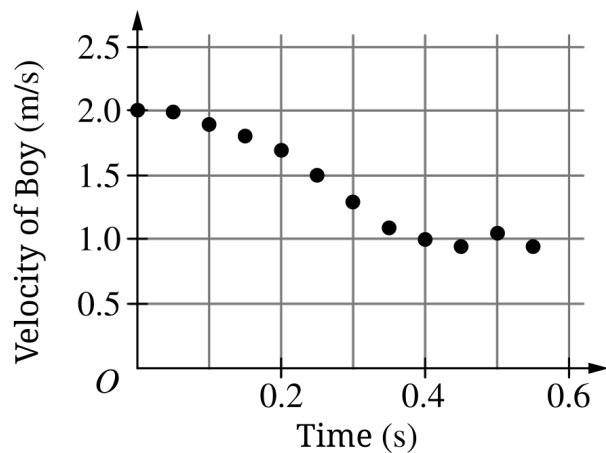
31. In an experiment on a horizontal track with low but nonzero friction, a student sets a block into motion at  $t = 0$  s. At  $t = 3$  s, the block collides with and sticks to another identical block. A motion detector records the velocity of each block from  $t = 0$  s to  $t = 6$  s. Which velocity measurements should the student use to determine whether the linear momentum of the two-block system changes during the collision?

- (A) The velocity of each block immediately before and immediately after  $t = 3$  s
- (B) The average velocity of each block between  $t = 0$  s and  $t = 3$  s and the average velocity of each block between  $t = 3$  s and  $t = 6$  s
- (C) The velocity of each block immediately before  $t = 3$  s and the average velocity of each block between  $t = 3$  s and  $t = 6$  s
- (D) The average velocity of each block between  $t = 0$  s and  $t = 3$  s and the velocity of each block immediately after  $t = 3$  s



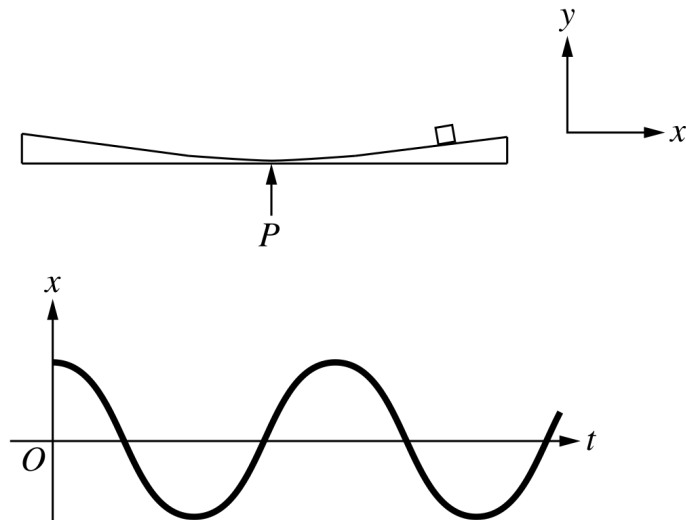
32. Cart A of mass 2.0 kg is initially traveling south at a speed of 5.0 m/s toward Cart B, which is traveling north. The two carts collide. The graph shows the magnitude  $F$  of the force exerted on Cart A by Cart B as a function of time  $t$ , as measured by a force sensor. If the ground is level and all other horizontal forces are negligible, what is the approximate velocity of Cart A at  $t = 0.4$  s?
- (A) 2.5 m/s south  
 (B) 2.5 m/s north  
 (C) 12.5 m/s south  
 (D) 12.5 m/s north
33. The figure above shows a top view of two objects sliding on a horizontal, frictionless surface, with masses and velocities indicated. The objects collide and stick together. Which of the following arrows best indicates the direction of motion of the center of mass of the two-object system after the collision? (The dashed line in each figure is  $45^\circ$  from the direction of motion of the 2 kg object.)





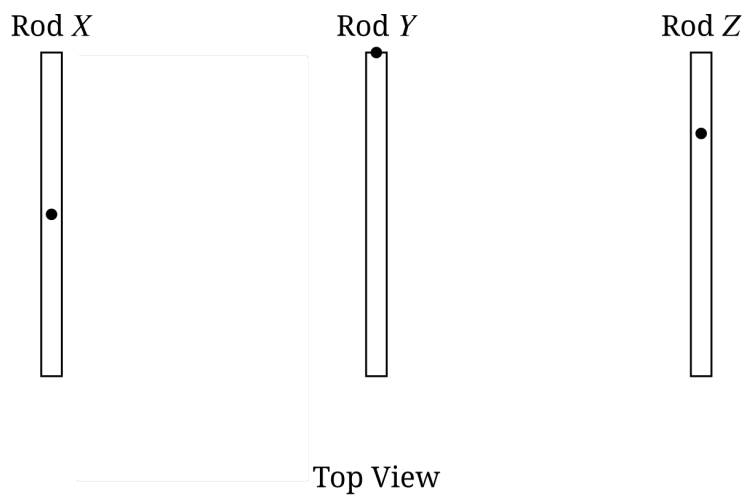
34. A 60 kg girl is standing at rest on an ice rink when an 80kg boy skating toward her gives her a push forward. The two skaters then keep sliding forward at different speeds, with negligible friction. The boy's velocity as a function of time, measured while the boy and girl are in contact, is shown above. What is the magnitude of the change in linear momentum  $|\Delta p_{\text{boy}}|$  of the boy, and how do the magnitudes of the average forces exerted on the skaters compare?

|     | $ \Delta p_{\text{boy}} $ | Magnitudes of Average Forces                                                |
|-----|---------------------------|-----------------------------------------------------------------------------|
| (A) | 80 kg·m/s                 | The magnitudes of the forces are the same.                                  |
| (B) | 80 kg·m/s                 | The force exerted on the girl is greater than the force exerted on the boy. |
| (C) | 160 kg·m/s                | The magnitudes of the forces are the same.                                  |
| (D) | 160 kg·m/s                | The force exerted on the girl is greater than the force exerted on the boy. |



35. The figure shows a block at rest near the top of a track with two sections that are each inclined at the same small angle from the horizontal. The bottom of the track is at Point P. The block is released at time  $t = 0$  and slides along the track with negligible friction. A student predicts that the  $x$ -position of the block as a function of time  $t$  is given by the curve in the graph above. Is the student's graph physically plausible? Why or why not?
- (A) Yes, because the net force on the block is always directed along the ramp toward Point P.
  - (B) Yes, because the net force gets bigger as the block moves through the center.
  - (C) No, because the gravitational force does not change direction.
  - (D) No, because the magnitude of the net force on the block is constant.

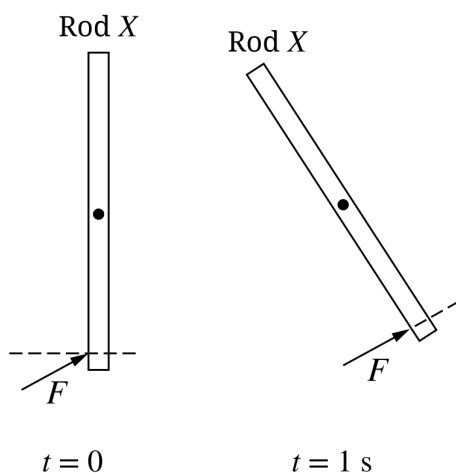
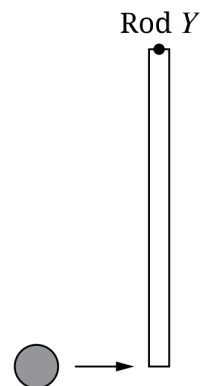
### Questions 36-38



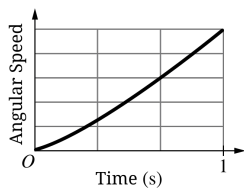
Identical uniform rods X, Y, and Z are free to rotate on a horizontal surface about vertical axles indicated by the dots in the diagram above. Frictional forces are negligible.

36. All three rods rotate with the same angular speed. How does the angular momentum  $L$  of each rod about its axle compare?

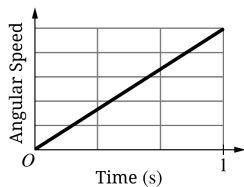
- (A)  $L_X = L_Y = L_Z$
- (B)  $L_Y > L_X > L_Z$
- (C)  $L_Y > L_Z > L_X$
- (D)  $L_Z > L_Y > L_X$



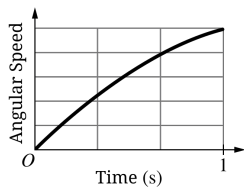
37. Rod X is free to rotate on a horizontal surface with negligible friction about a pivot through its center. At time  $t = 0$  the rod is at rest and a force of magnitude  $F$  is exerted near the end of the rod at an angle, as shown in the figure on the left. As the rod rotates, the force remains constant in magnitude and direction until the rod is perpendicular to the force at time  $t = 1 \text{ s}$ , as shown in the figure on the right. Which of the following graphs could show the rod's angular speed as a function of time between 0 and 1 s?



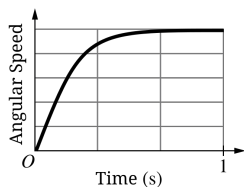
(A)



(B)



(C)



(D)

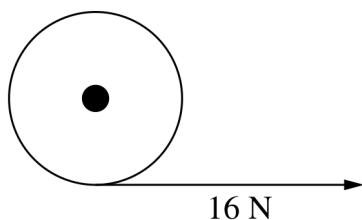
38. A lump of clay moves toward Rod Y, which is at rest, as shown. The rotational inertia of the clay with respect to the rod's axle is twice that of the rod. The clay collides with and sticks to the end of the rod, and during the collision the rod gains angular momentum  $L$  with respect to the axle. The change in angular momentum of the clay with respect to the axle during the collision is

(A)  $-2L$

(B)  $-L$

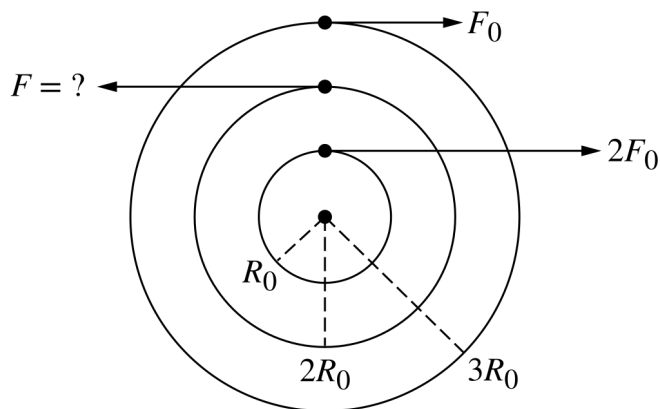
(C)  $-\frac{L}{2}$

(D)  $0$



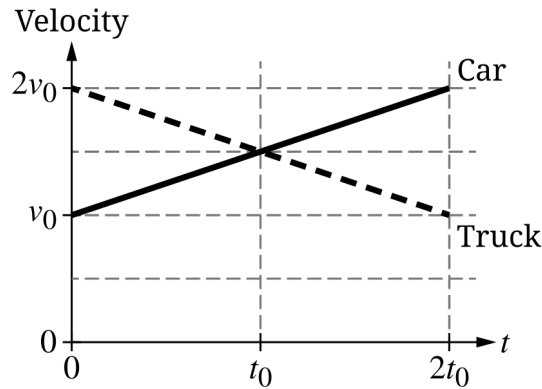
39. A wheel is initially at rest and is free to rotate on an axle through its center. The wheel has a radius of 0.5 m and a rotational inertia of  $4 \text{ kg}\cdot\text{m}^2$ . A constant force of 16 N is exerted tangent to the edge of the wheel, as shown, for 10 s. What is the final angular speed of the wheel?

(A) 2 rad/s  
 (B) 20 rad/s  
 (C) 40 rad/s  
 (D) 80 rad/s



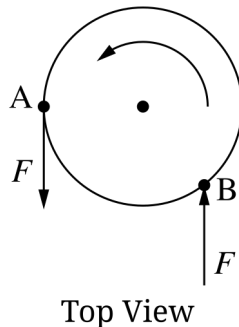
40. Three forces are exerted on a disk that is free to rotate with negligible friction around a pivot at the disk's center. The three forces are exerted at different locations on the disk, as shown by the arrows in the figure. What should the magnitude of the force exerted at a distance of  $2R_0$  from the center be so that the net torque about the center is zero?

(A)  $1.5F_0$   
 (B)  $2.5F_0$   
 (C)  $3F_0$   
 (D)  $5F_0$



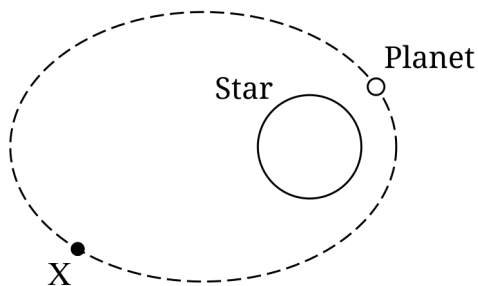
41. The graph represents the velocity as a function of time  $t$  of a car and a truck that travel along a straight road. Compare the distances traveled by the car and truck for two time intervals: from  $0$  to  $t_0$  and from  $0$  to  $2t_0$ .

|     | <u><math>0</math> to <math>t_0</math></u> | <u><math>0</math> to <math>2t_0</math></u> |
|-----|-------------------------------------------|--------------------------------------------|
| (A) | Greater for the truck                     | Greater for the car                        |
| (B) | Greater for the truck                     | The same for both objects                  |
| (C) | The same for both objects                 | Greater for the car                        |
| (D) | The same for both objects                 | The same for both objects                  |



42. A uniform disk is initially spinning in a counterclockwise direction about an axis through its center. Two forces of equal magnitude  $F$  are then exerted at points A and B on the disk, as shown in the figure above. Which of the following correctly describes the effects of the two forces on the rotation at the instant shown?

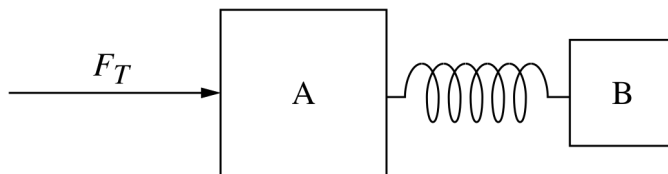
- (A) Both forces have the effect of slowing down the rotation by the same amount.
- (B) Both forces have the effect of speeding up the rotation by the same amount.
- (C) Both forces have the effect of speeding up the rotation, but the force at Point A has a greater effect than does the force at Point B.
- (D) The force at Point A has the effect of speeding up the rotation, while the force at Point B has the effect of slowing down the rotation.



Note: Figure not drawn to scale.

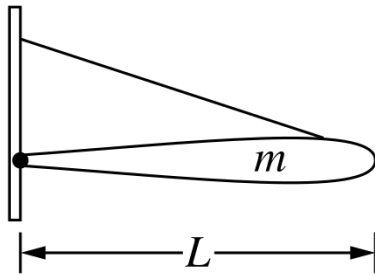
43. A planet of mass  $M$  is in orbit around a star, as shown. Which of the following best describes the change in the planet's rotational inertia about the center of the star and its angular momentum about the star as the planet travels from the position shown in the figure to the position marked with an X?

|     | <u>Rotational inertia</u> | <u>Angular momentum</u> |
|-----|---------------------------|-------------------------|
| (A) | Increases                 | Greater for the car     |
| (B) | Increases                 | Stays the same          |
| (C) | Stays the same            | Greater for the car     |
| (D) | Stays the same            | Stays the same          |

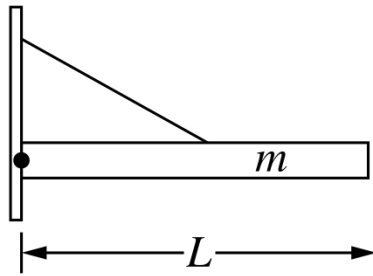


44. A system consists of two blocks of different masses connected by a spring of negligible mass. A force of magnitude  $F_T$  is exerted on the system, as shown above, giving it an acceleration to the right. The spring is uniformly compressed and is not oscillating. The spring exerts a force of magnitude  $F_A$  on Block A and a force of magnitude  $F_B$  on Block B. Which of the following is a correct relationship among the magnitudes of the three forces?

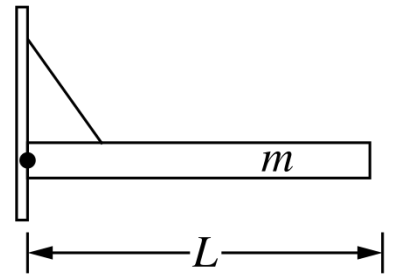
- (A)  $F_T = F_A = F_B$   
 (B)  $(F_T = F_A) > F_B$   
 (C)  $F_T > (F_A = F_B)$   
 (D)  $F_T > F_A > F_B$



I



II



III

45. The three uniform solid objects shown above have the same mass  $m$  and length  $L$ . Each object is held at rest by a hinge and a cord attached to a rigid wall. Which of the following correctly ranks the magnitude of the torque  $\tau$  exerted by gravity with respect to the hinge on each object?

- (A)  $\tau_I = \tau_{II} = \tau_{III}$
- (B)  $\tau_I > (\tau_{II} = \tau_{III})$
- (C)  $\tau_I > \tau_{II} > \tau_{III}$
- (D)  $(\tau_{II} = \tau_{III}) > \tau_I$

**Directions:** For each of the questions or incomplete statements below, two of the suggested answers will be correct. For each of these questions, you must select both correct choices to earn credit. No partial credit will be earned if only one correct choice is selected. Select the two that are best in each case and then fill in the corresponding circles that begin with number 131 on the answer sheet.

131. A ball falls onto a horizontal surface and then bounces back into the air. At time  $t_1$ , the ball is at height  $h_1$  above the surface and has a downward vertical speed  $v_1$ . At a later time  $t_2$ , the ball has bounced back up and is at height  $h_2$  above the surface with an upward vertical speed  $v_2$ . Which of the following could be correct about  $h_2$  and  $v_2$ ? Select two answers.
- (A)  $h_2 = h_1, v_2 > v_1$
  - (B)  $h_2 > h_1, v_2 < v_1$
  - (C)  $h_2 > h_1, v_2 > v_1$
  - (D)  $h_2 < h_1, v_2 = v_1$
132. Identical disks X and Y are on a horizontal, frictionless surface. Disk X slides with velocity  $\vec{v}_0$  and collides elastically with Disk Y, which is initially at rest. The disks then move away from the collision point at different angles. Which of the following must be true after the collision? Select two answers.
- (A) Disk X has the same kinetic energy as Disk Y.
  - (B) Disk X has the same momentum as Disk Y.
  - (C) The speed of Disk X is less than  $v_0$ .
  - (D) The velocity of the center of mass of the two-disk system is in the direction of The velocity of the center of mass of the two-disk system is in the direction of  $\vec{v}_0$ .
133. A machine exerts a force on an object of known rotational inertia. An engineer wants to know the change in angular momentum of the object for a given time interval. Which of the following can be measured as a function of time to provide the desired information? Select two answers.
- (A) The instantaneous angular velocity of the object
  - (B) The instantaneous linear velocity of the object
  - (C) The instantaneous value of the force exerted on the object
  - (D) The instantaneous value of the torque exerted on the object
134. Two identical spheres, X and Y, are connected by a light string. A person holds Sphere X and lets Sphere Y hang straight down, then releases them from rest. Which of the following is true of the speed of the center of mass of the two-sphere system at time  $t$  while both spheres are falling? Select two answers.
- (A) It is zero relative to Sphere X.
  - (B) It is zero relative to the ground.
  - (C) It is equal to  $gt$  relative to Sphere X.
  - (D) It is equal to  $gt$  relative to the ground.

| Cart | Mass   | Initial Velocity (m/s) | Velocity at Closest Approach (m/s) | Final Velocity (m/s) |
|------|--------|------------------------|------------------------------------|----------------------|
| X    | 3.0 kg | 3.0 to the right       | 2.0 to the right                   | 1.0 to the right     |
| Y    | ?      | 1.0 to the left        | 2.0 to the right                   | 5.0 to the right     |

135. Carts X and Y move toward each other on a level, frictionless track. The carts have magnets in their bumpers and begin to repel each other as they get closer. They reach a common velocity for an instant and then separate. Which of the following questions can be answered using only the data in the table? Select two answers.

- (A) What is the mass of Cart Y?
- (B) Which cart has a stronger magnet?
- (C) Is mechanical energy dissipated during the collision?
- (D) What maximum force is exerted on Cart X at the closest approach?

**STOP**  
**END OF SECTION I**

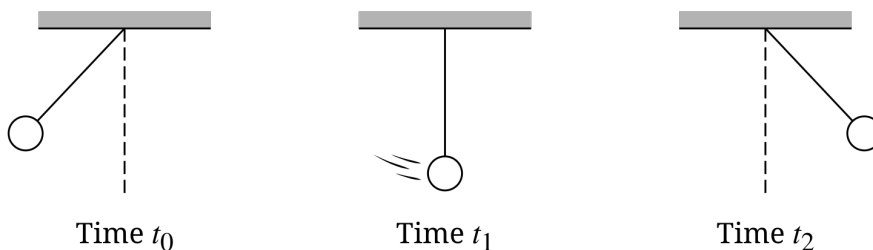
# PHYSICS 1

## SECTION II

Time—1 hour and 30 minutes

5 Questions

**Directions:** Questions 1, 4, and 5 are short free-response questions that require about 13 minutes each to answer and are worth 7 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.



1. (7 points, suggested time 13 minutes)

A sphere attached to the end of a light string that makes an angle with the vertical is released from rest at time  $t_0$  as shown above. At time  $t_1$  the sphere is at the lowest point in its path, and at time  $t_2$  it is momentarily at rest at its maximum height.

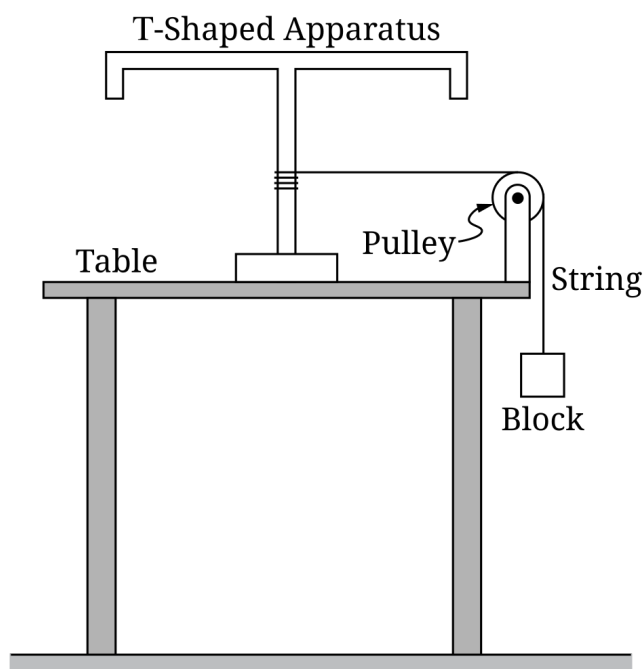
- (a) The dots below represent the sphere at times  $t_1$  and  $t_2$ . On each dot, draw and label the forces (not components) exerted on the sphere at the corresponding time. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



- (b) The magnitude of the tension force in the string at time  $t_1$  is  $F_1$ , and at time  $t_2$  is  $F_2$ . The gravitational force exerted on the sphere has a magnitude  $F_g$ . Rank  $F_1$ ,  $F_2$ , and  $F_g$  from greatest to least in the spaces indicated below. Use 1 for the greatest magnitude, 2 for the next greatest, and so on. If any two or all three magnitudes are the same, use the same number for their ranking.

\_\_\_\_\_  $F_1$       \_\_\_\_\_  $F_2$       \_\_\_\_\_  $F_g$

In a clear, coherent paragraph-length response that may also contain figures and/or equations, justify your ranking.



2. (12 points, suggested time 25 minutes)

A light string is attached to a block, passes over a pulley, and is wrapped around a T-shaped apparatus, as shown above. The pulley has negligible rotational inertia and negligible friction, and the T-shaped apparatus rotates with negligible friction. The system is released from rest. As the block accelerates downward, it pulls the string, which causes the apparatus to start rotating.

Students in a physics lab first wish to determine the value of the block's constant downward acceleration once it is released from rest by observing it fall.

- (a) Derive an equation for the acceleration of the block in terms of quantities that can be obtained from measurements made using only a meterstick and a stopwatch.

- (b) Design an experimental procedure the students could use to collect the data needed to determine the block's linear acceleration  $a$ .

In the table at left below, list the quantities that would be measured in your experiment using the meterstick and the stopwatch. Define a symbol to represent each quantity.

In the space to the right of and below the table, describe the overall procedure. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table.

If needed, you may include a simple diagram of the setup with your procedure.

| Quantity to be Measured | Symbol for Quantity | Equipment for Measurement | Procedure (and diagram, if needed) |
|-------------------------|---------------------|---------------------------|------------------------------------|
|                         |                     | Meterstick                |                                    |
|                         |                     | Stopwatch                 |                                    |
|                         |                     |                           |                                    |

- (c) Explain how the students should analyze the data from part (b) to determine the value of the block's constant linear acceleration  $a$ .

(d) The students produce the data table shown below for five blocks with different masses.

| Mass of Block (kg) | Linear Acceleration of Block ( $\text{m/s}^2$ ) | Angular Acceleration of T-shaped Apparatus ( $\text{rad/s}^2$ ) | Tension in String (N) | Torque Exerted on T-shaped Apparatus by String ( $\text{N}\cdot\text{m}$ ) |
|--------------------|-------------------------------------------------|-----------------------------------------------------------------|-----------------------|----------------------------------------------------------------------------|
| 0.200              | 0.34                                            | 27                                                              | 1.87                  | 0.0237                                                                     |
| 0.400              | 0.92                                            | 72                                                              | 3.56                  | 0.0453                                                                     |
| 0.600              | 1.37                                            | 108                                                             | 5.11                  | 0.0649                                                                     |
| 0.800              | 1.58                                            | 124                                                             | 6.53                  | 0.0830                                                                     |
| 1.000              | 1.93                                            | 152                                                             | 7.84                  | 0.0996                                                                     |

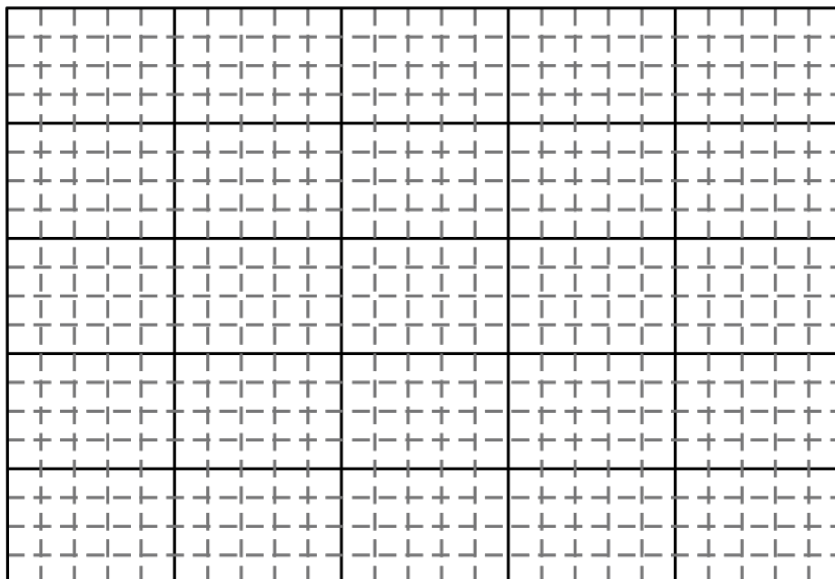
The students now want to determine the rotational inertia of the T-shaped apparatus.

- i. Indicate below which quantities could be graphed to yield a straight line whose slope could be used to calculate a numerical value for the rotational inertia of the T-shaped apparatus.

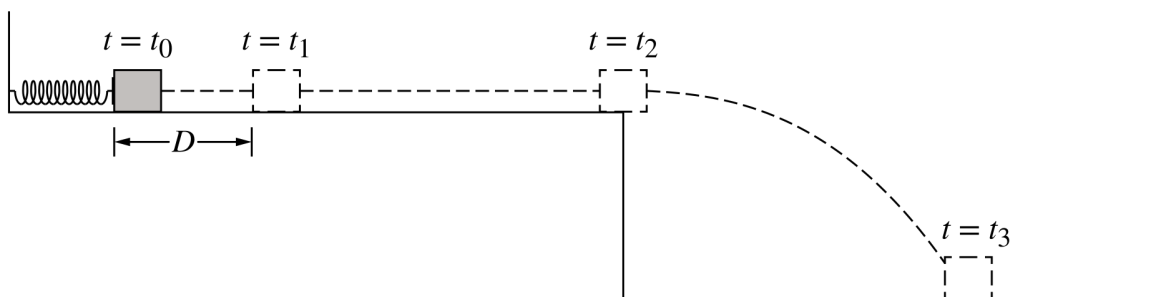
Vertical axis \_\_\_\_\_

Horizontal axis \_\_\_\_\_

- ii. Use the grid below to plot the data points for the quantities indicated in part (d)(i). Clearly scale and label all axes, including units as appropriate. Draw a straight line that best represents the data.



- iii. Using the straight line from part (d)(ii), calculate a value for the rotational inertia of the T-shaped apparatus.



3. (12 points, suggested time 25 minutes)

A block is launched from a table by a compressed spring that is attached to a wall. The spring is initially compressed a distance  $D$  before the block is launched, as shown above. There is negligible friction between the block and the table.

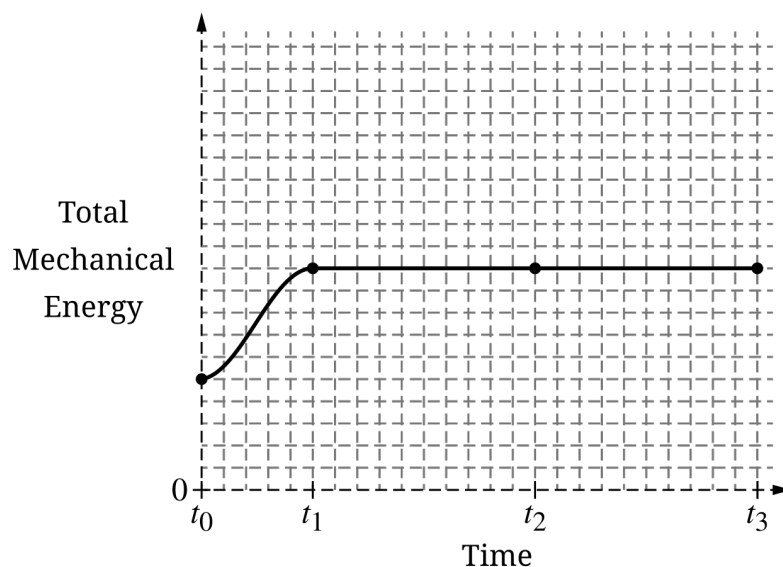
At time  $t = t_0$  the block is released from rest.

At  $t = t_1$  the block loses contact with the spring.

At  $t = t_2$  the block leaves the edge of the table.

At  $t = t_3$  the block lands on the floor.

The graph below shows the total mechanical energy of the system containing the block and Earth from  $t = t_0$  to immediately before  $t = t_3$ . The gravitational potential energy is defined to be zero when the block is on the floor.



Note: Time axis not drawn to scale.

(a) On the same axes, sketch a graph of the total mechanical energy of just the block from time  $t_0$  to time  $t_3$ .

The procedure is repeated with a second block, Block 2, which is more massive than the original block, Block 1. Block 2 is placed on the table, and the spring is compressed the same distance  $D$  as before.

- (b) For Block 2, is the horizontal distance traveled from the edge of the table to where it hits the ground greater than, less than, or equal to the corresponding distance for Block 1?

\_\_\_\_\_ Greater than      \_\_\_\_\_ Less than      \_\_\_\_\_ Equal to

Justify your answer.

- (c) Derive a general expression for  $X$ , the horizontal distance traveled by a block of mass  $m_B$ , from the edge of the table to where it hits the floor. Let  $k_0$  represent the spring constant and  $h_0$  represent the height of the tabletop above the floor. Express your answer in terms of  $D$ ,  $m_B$ ,  $k_0$ ,  $h_0$ , and physical constants, as appropriate.

- (d) Does your expression derived in part (c) support your reasoning in part (b)?

\_\_\_\_\_ Yes      \_\_\_\_\_ No

Justify your answer.

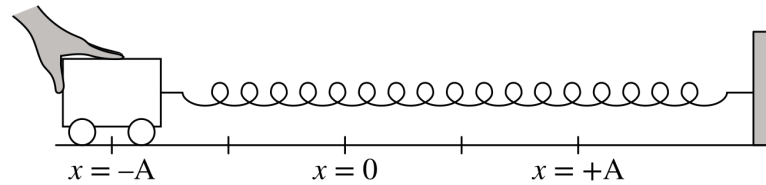
- (e) Is the kinetic energy of Block 2 immediately after it leaves the spring the same as or different than the kinetic energy of Block 1 immediately after it leaves the spring?

\_\_\_\_\_ Same      \_\_\_\_\_ Different

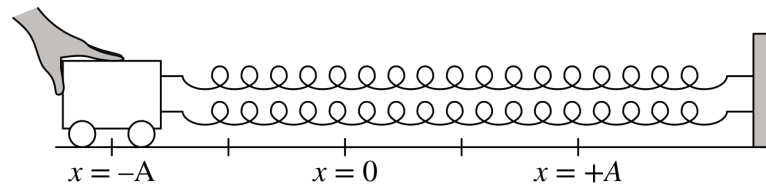
Justify your answer.

4. (7 points, suggested time 13 minutes)

The following two scenarios describe a cart attached to either one or two identical springs which are at their relaxed length when the cart is at position  $x = 0$ . In each scenario, the cart is pulled to position  $x = -A$ , is released from rest, and oscillates with negligible friction between  $x = +A$  and  $x = -A$ .



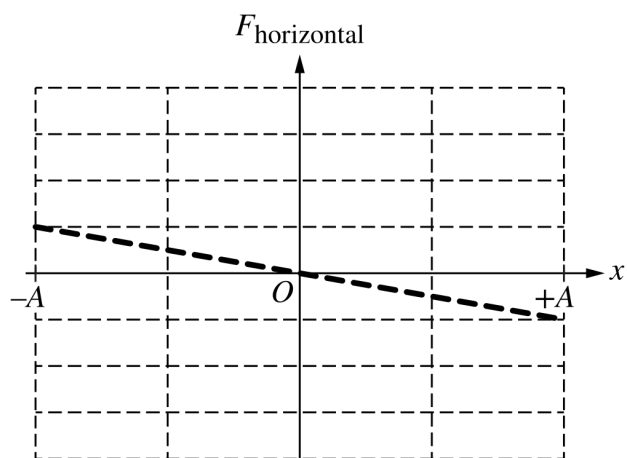
Scenario 1



Scenario 2

In Scenario 1, the cart is attached to the wall with one spring as shown. The total mechanical energy of the cart-spring system in Scenario 1 is  $E_1$ .

- For Scenario 1, derive an expression for the kinetic energy of the cart in terms of  $E_1$  when the cart is at position  $x = +\frac{A}{2}$ .
- As shown in the figure for Scenario 2, a second identical spring is attached between the same cart and the wall before the cart is pulled to position  $x = -A$ .
  - Determine the total mechanical energy of the cart-springs system in Scenario 2 in terms of  $E_1$ .
  - The maximum speed of the cart in Scenario 1 is  $v_1$  and the maximum speed of the cart in Scenario 2 is  $v_2$ . Calculate the numerical value of the ratio  $\frac{v_2}{v_1}$ .



A student correctly sketches a graph of the horizontal component of the net force exerted on the cart by the spring in Scenario 1 as a function of position, as shown above with a dashed line.

- (c) On the same graph above, using a solid line, sketch the horizontal component of the net force exerted on the cart in Scenario 2 with two springs attached.



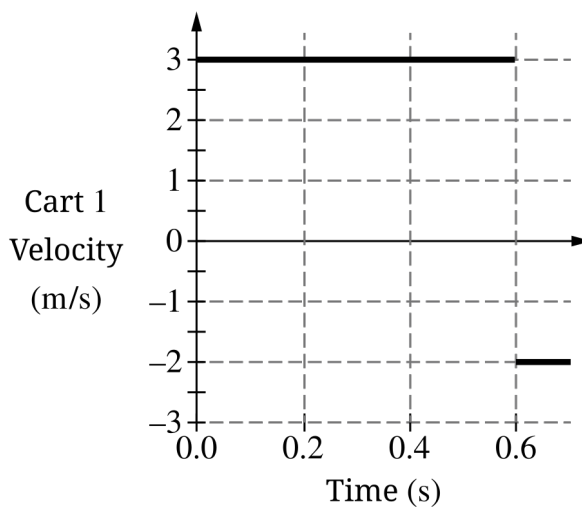
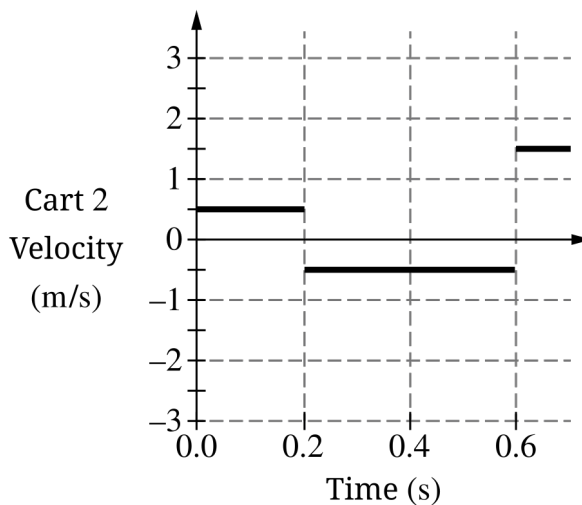
Note: Figure not drawn to scale.

5. (7 points, suggested time 13 minutes)

Two carts are moving to the right on a straight, level track with negligible friction. At time  $t = 0$ , the carts are at the positions shown above. Cart 2 collides with and bounces off a wall at the right end of the track, after which the two carts collide.

Cart 1 has a mass of 0.20 kg and an initial velocity of 3.0 m/s to the right. Cart 2 has a mass of 0.5 kg and an initial velocity of 0.50 m/s to the right.

The graphs below show the velocity of each cart from  $t = 0$  to sometime after the carts collide.



(a) Consider the system consisting of just Cart 2 when it bounces off the wall.

i. Is the momentum of Cart 2 the same before and after bouncing off the wall?

\_\_\_\_\_ Yes          \_\_\_\_\_ No

Briefly justify your answer.

ii. Is the mechanical energy of Cart 2 the same before and after bouncing off the wall?

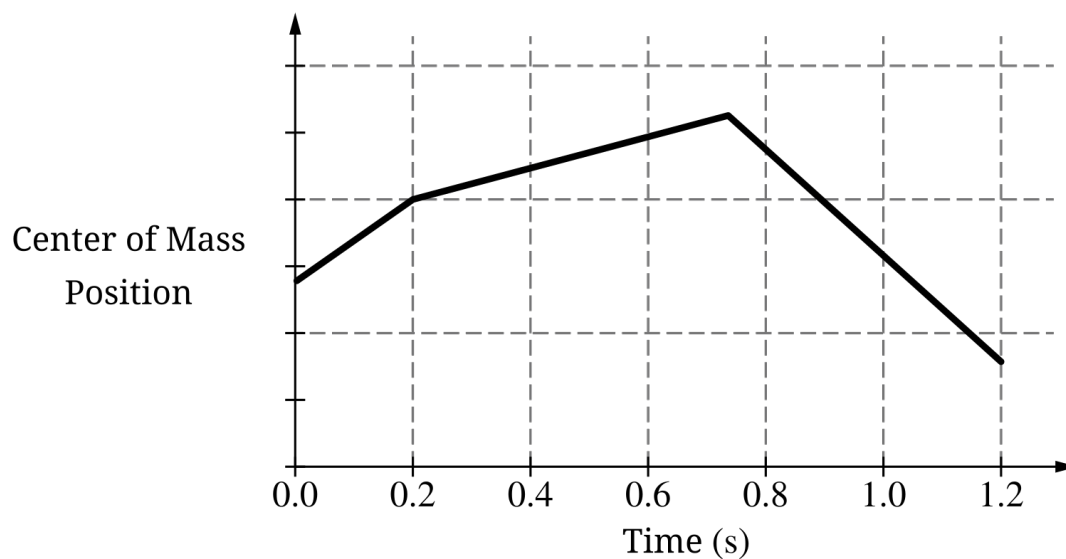
\_\_\_\_\_ Yes          \_\_\_\_\_ No

Briefly justify your answer.

(b) Is the momentum of the two-cart system the same before and after the collision that occurs at  $t = 0.6\text{s}$ ?

\_\_\_\_\_ Yes          \_\_\_\_\_ No

Using calculations based on the information shown in the graphs, justify your answer.



- (c) The graph above shows the position of the center of mass of the two-cart system for a longer time interval  $0 < t < 1.2$  s. The slope of the graph changes at time  $t = 0.2$  s and also at time  $t = 0.73$  s, which are the two times at which Cart 2 bounces off the wall. However, the slope does not change at time  $t = 0.6$  s, when the two carts collide.
- Use physics principles to explain why the slope of the graph changes at  $t = 0.2$  s and  $t = 0.73$  s.
  - Use physics principles to explain why the slope of the graph does not change at  $t = 0.6$  s.

**STOP**  
**END OF EXAM**

# **AP Physics 1**

**2022**

## **APPENDIX - ANSWERS**

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

### 3 Answers

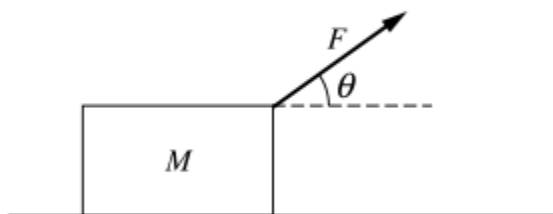
| Question | Answer | Question | Answer |
|----------|--------|----------|--------|
| 1        | C      | 26       | B      |
| 2        | C      | 27       | B      |
| 3        | C      | 28       | D      |
| 4        | D      | 29       | C      |
| 5        | A      | 30       | A      |
| 6        | D      | 31       | A      |
| 7        | B      | 32       | B      |
| 8        | D      | 33       | C      |
| 9        | A      | 34       | A      |
| 10       | C      | 35       | A      |
| 11       | B      | 36       | C      |
| 12       | D      | 37       | A      |
| 13       | A      | 38       | B      |
| 14       | D      | 39       | B      |
| 15       | B      | 40       | B      |
| 16       | B      | 41       | B      |
| 17       | A      | 42       | C      |
| 18       | D      | 43       | B      |
| 19       | B      | 44       | C      |
| 20       | C      | 45       | B      |
| 21       | A      | 131      | BD     |
| 22       | D      | 132      | CD     |
| 23       | B      | 133      | AD     |
| 24       | C      | 134      | AD     |
| 25       | C      | 135      | AC     |

## 2022 Form I

1. Two identical cars, Car 1 and Car 2, are both moving along a straight, level road. At time  $t = 0$ , both cars have a velocity of  $+10 \text{ m/s}$ .  
Car 1 continues to move at a constant velocity, while Car 2 has a constant acceleration of  $-1 \text{ m/s}^2$ . What is the speed of the center of mass of the two-car system at  $t = 10 \text{ s}$ ?
- (A)  $15 \text{ m/s}$   
(B)  $10 \text{ m/s}$   
(C)  $5 \text{ m/s}$  ✓  
(D)  $0 \text{ m/s}$
2. Two identical elevators are lifted at constant speeds. Work is done on the first elevator at a rate  $P_1$  as it is lifted a distance  $h_0$  in time  $\Delta t$ . Work is done on the second elevator at a rate  $P_2$  as it is lifted a distance  $2h_0$  in time  $4\Delta t$ . How does  $P_2$  compare to  $P_1$ ?
- (A)  $P_2 = 4P_1$   
(B)  $P_2 = 2P_1$   
(C)  $P_2 = \frac{1}{2}P_1$  ✓  
(D)  $P_2 = \frac{1}{4}P_1$
3. A cart of mass  $m$  is traveling at velocity  $v$  to the right when it has a perfectly elastic collision with a cart of mass  $3m$  that is at rest. Immediately after the collision, the cart of mass  $3m$  moves with a velocity  $v/2$  to the right. What is the velocity of the cart of mass  $m$  immediately after the collision?
- (A) Zero  
(B)  $v$  to the right  
(C)  $v/2$  to the left ✓  
(D)  $3v$  to the left

## 2022 Form I

4.



A block of mass  $M$ , initially at rest, is pulled along a horizontal frictionless surface by a force of magnitude  $F$  applied at an angle  $\theta$  to the horizontal, as shown above. The force is exerted on the block for a distance of  $d$ , accelerating the block to speed  $v_f$ . Which of the following expressions is equal to the work done by the applied force?

- (A)  $Fd$
- (B)  $Fd \sin \theta$
- (C)  $mgd \cos \theta$

(D)  $\frac{1}{2} Mv_f^2$



5. Block 1 slides to the right at 2 m/s on a frictionless, horizontal surface toward Block 2, which is initially at rest. After the collision, Block 1 moves to the right at 1 m/s and Block 2 moves to the right at 3 m/s. Are the data provided sufficient to determine whether the collision is elastic? Why or why not?

(A) Yes, because the ratio of the blocks' masses can be determined.



- (B) Yes, because the total momentum can be calculated before and after the collision.
- (C) No, because the blocks' masses are unknown.
- (D) No, because it is not stated whether the blocks are permanently deformed during the collision.

6. A 1000 kg spacecraft is traveling through deep space at a speed of 500 m/s when its thrusters turn on and exert a force opposite its original direction of motion. When the thrusters turn off, the spacecraft is traveling opposite the original direction at 500 m/s. What is the average force the thrusters exert on the spacecraft?

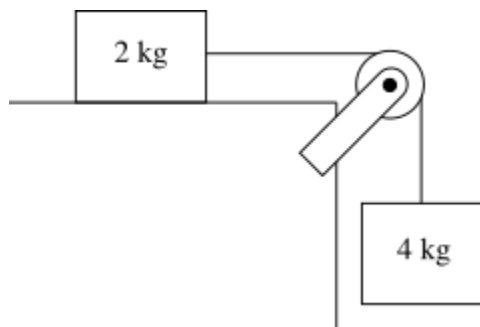
- (A) 0 N
- (B)  $5 \times 10^4$  N
- (C)  $1 \times 10^6$  N

(D) It cannot be determined without knowing how long the thrusters were on.

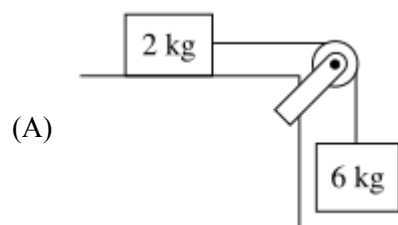
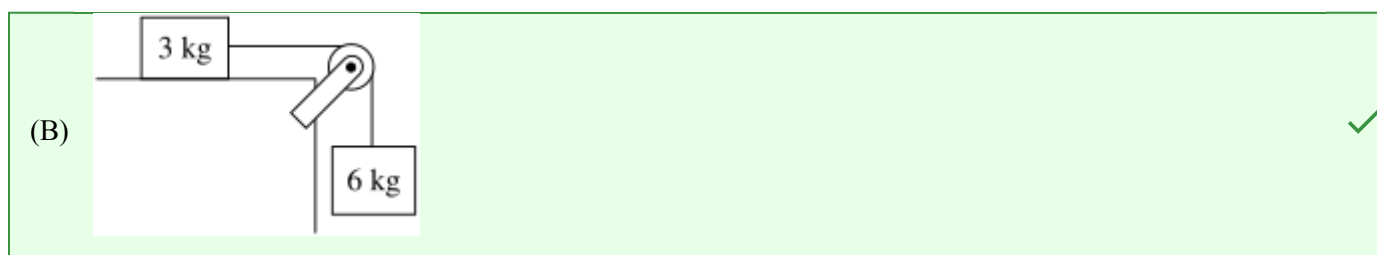
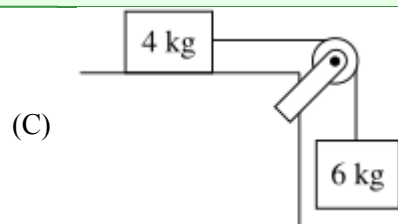
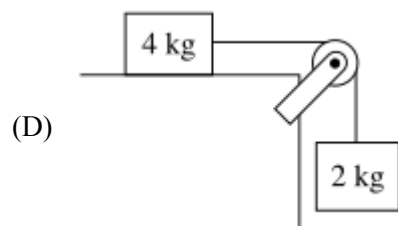


2022 Form I

7.

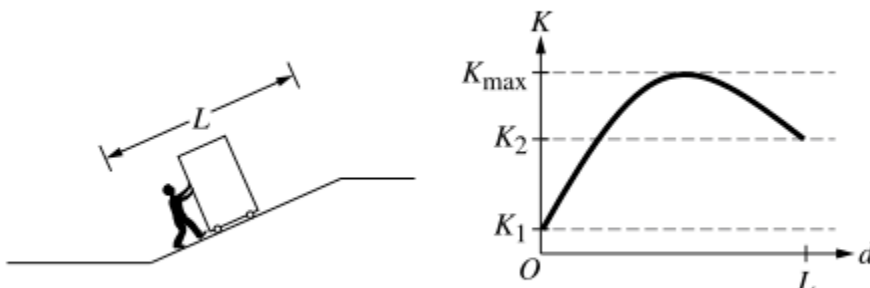


Two blocks with different masses are attached by a string, as shown above. One block hangs vertically, and the other block rests on a frictionless surface. The blocks are released from rest. The procedure is repeated with blocks of different mass in each position. For which of the following systems will the blocks have the same acceleration as the original system?



## 2022 Form I

8.



A person pushes a box up a ramp of length  $L$ , as shown. The graph above shows the kinetic energy  $K$  of the box as a function of its position  $d$  along the ramp. The net work done on the box while it is on the ramp equals

- (A)  $K_{\max}$
- (B)  $K_2$
- (C)  $K_{\max} - K_1$
- (D)  $K_2 - K_1$



9. A simple pendulum consisting of a massive bob attached to a lightweight wire oscillates at small angles to the vertical. Which of the following changes will result in a significantly higher oscillation frequency for the pendulum?

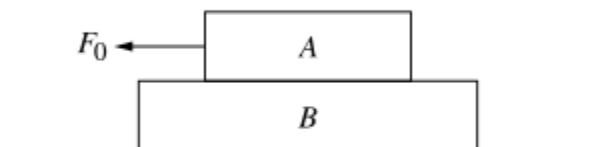
(A) Shortening the wire



- (B) Using a bob with twice as much mass
- (C) Doubling the amplitude of oscillation
- (D) Taking the pendulum to a planet where the gravitational acceleration is less than  $g$

## 2022 Form I

10.



Books A and B are stacked on top of one another on a table, as shown in the figure. A force  $F_0$  is exerted to the left on Book A, and the books move together to the left at a constant speed. Which of the following best represents the directions of the horizontal forces, if any, exerted on Book B?

(A)  $F_{Table}$

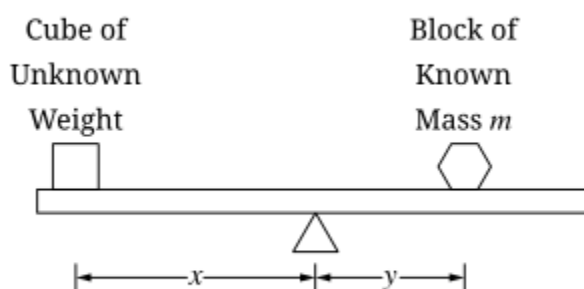
(B)  $F_A$

(C)  $F_A$   $F_{Table}$



(D) There are no horizontal forces exerted on Book B.

11.



A student who does not have access to a scale wishes to determine the weight of a cube using the setup shown. A fulcrum is placed beneath the midpoint of a meterstick and the cube is placed on the meterstick a distance  $x$  from the fulcrum. A small block of known mass  $m$  is placed on the meterstick on the other side of the fulcrum at a distance  $y < x$ , such that the meterstick is balanced and horizontal. Which of the following expressions is equal to the weight of the cube?

## 2022 Form I

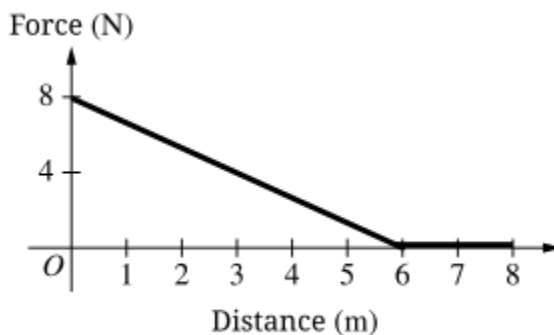
(A)  $mgx/y$

(B)  $mgy/x$  ✓

(C)  $mgx/(x+y)$

(D)  $mgy/(x+y)$

12.



The graph shows the net horizontal force exerted on a 3 kg box as a function of the distance the box has moved along a horizontal track. If the box started at rest, the speed of the box when it has moved 8 m is

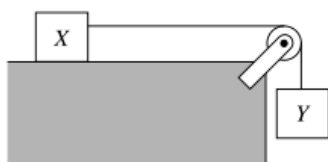
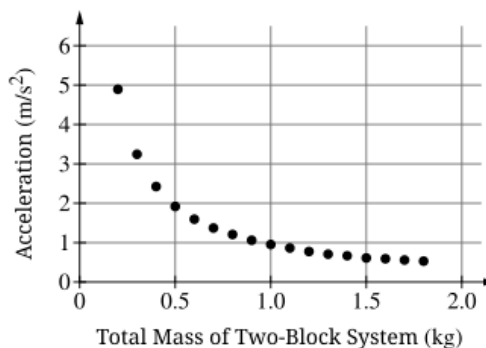
(A) 64 m/s

(B) 24 m/s

(C) 8 m/s

(D) 4 m/s ✓

13.

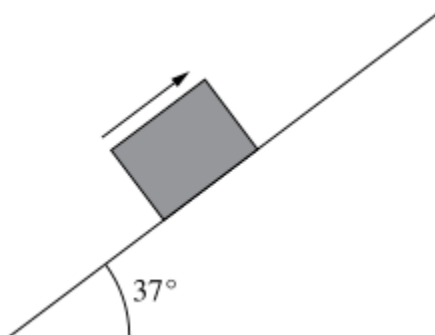


Block X rests on a frictionless, horizontal surface and is connected to Block Y by a light string that passes over a frictionless pulley of negligible mass, as shown. A student releases the blocks from rest and measures the acceleration of Block Y. The student then performs several more trials, adding mass to the two-block system in each trial. The graph above shows the acceleration of Block Y as a function of the total mass of the two-block system. Which of the following best describes how the mass was added to the two-block system?

## 2022 Form I

- (A) In each trial, mass was only added to Block X. ✓
- (B) In each trial, mass was only added to Block Y.
- (C) In each trial, mass was added equally to Block X and Block Y.
- (D) In each trial, mass could have been added to either Block X, Block Y, or both.

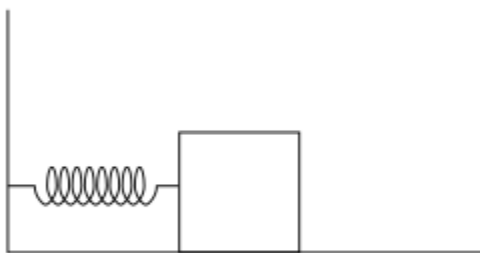
14.



After receiving a brief push, a box slides up a ramp that is at an angle of  $37^\circ$  with the horizontal, as shown. The gravitational force on the box is 40 N, and the kinetic frictional force is 9 N directed down the ramp. What is the net force on the box as it slides up the ramp?

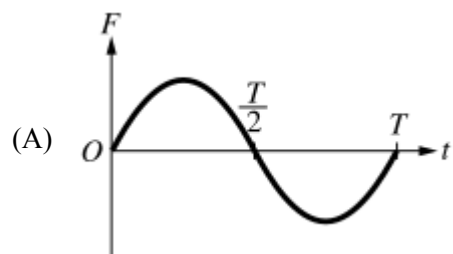
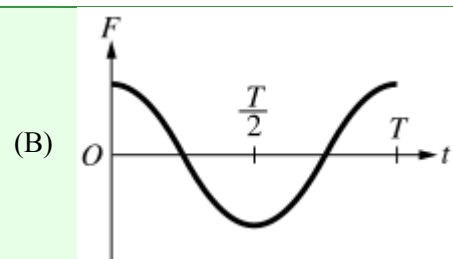
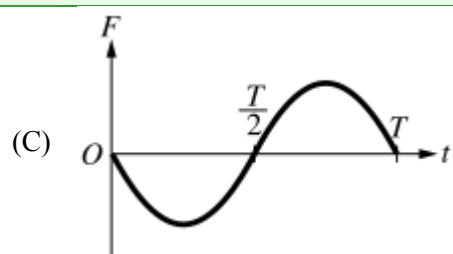
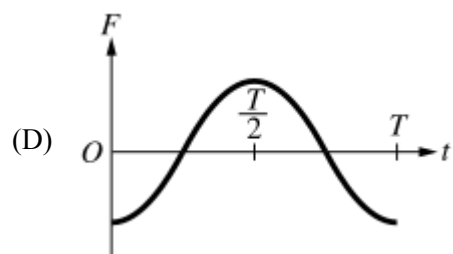
- (A) 49 N up the ramp
- (B) 15 N up the ramp
- (C) 9 N down the ramp
- (D) 33 N down the ramp ✓

15.



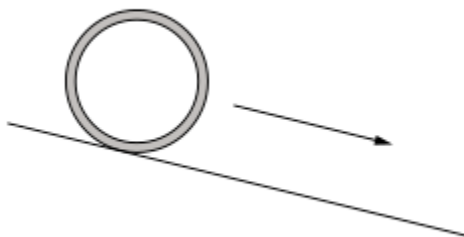
A block is attached to a spring, the other end of which is attached to a wall, as shown above. The block is pushed toward the wall from its equilibrium position, compressing the spring, and then is released from rest at time  $t = 0$ . There is no friction between the block and the horizontal surface. Assuming right to be the positive direction, which of the following graphs could represent the restoring force  $F$  versus time  $t$  for one period  $T$  of the oscillation of the block?

2022 Form I



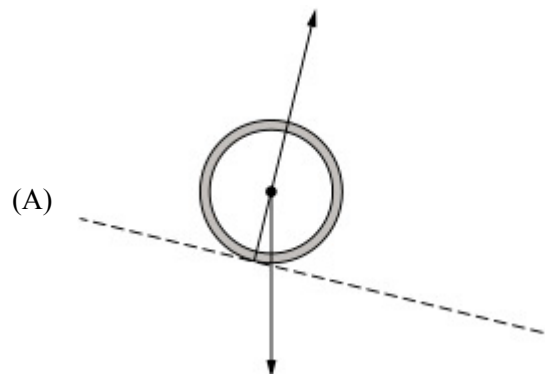
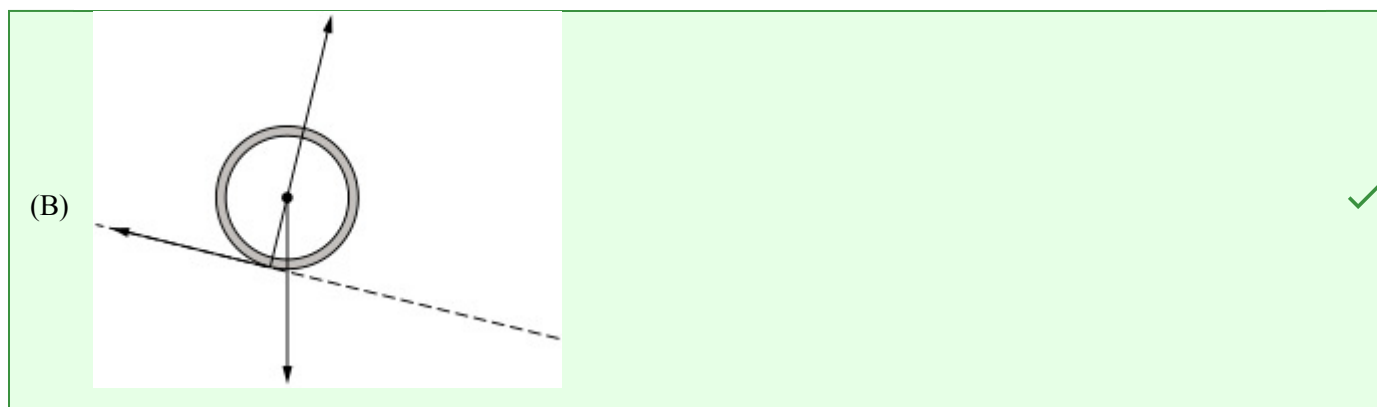
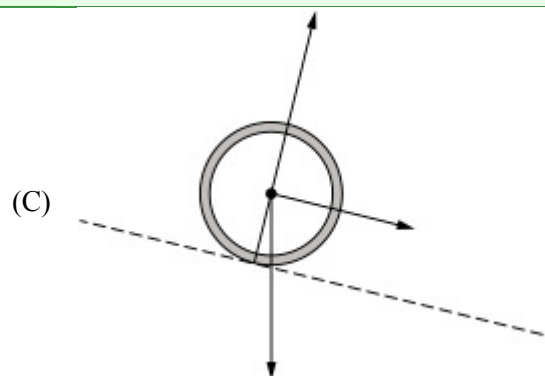
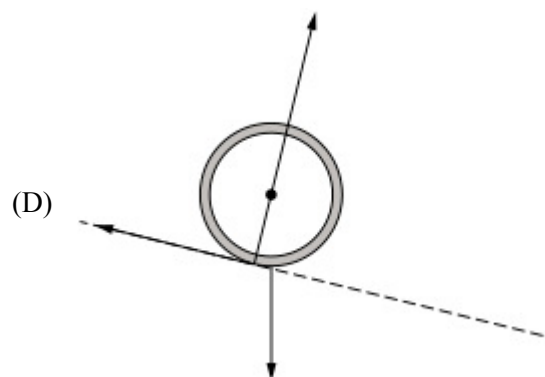
## 2022 Form I

16.



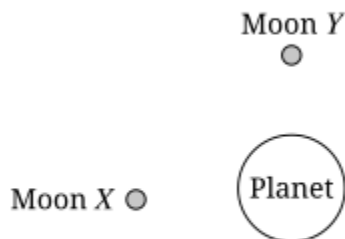
The figure shows a ring rolling down an inclined plane without slipping. Which of the following diagrams, once properly labeled, represents the forces acting on the ring, with the tail of each vector starting at the point of application of the force? (The dot represents the center of the ring.)

2022 Form I



## 2022 Form I

17.



The figure above shows a planet with two moons, X and Y. The net gravitational force exerted on the planet by the two moons has magnitude  $F$ . If the mass of each moon is doubled, the net gravitational force exerted on the planet would have magnitude

(A)  $2F$

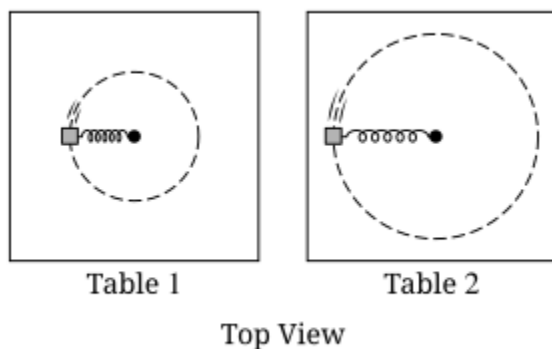


(B)  $2\sqrt{2}F$

(C)  $4F$

(D)  $4\sqrt{2}F$

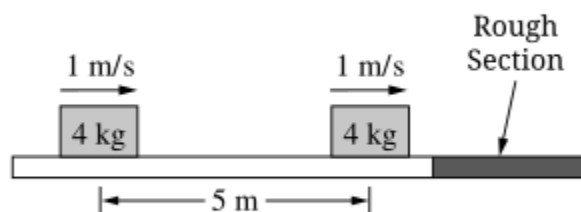
18.



Two identical blocks are each attached to an end of identical ideal springs, with the other end of each spring fixed in place on a level table, as shown. The blocks move with negligible friction in circular paths with different constant speeds. The block on Table 2 moves with a greater speed in a circle of larger radius than the block on Table 1. Which of the following relations correctly describes the work  $W$  done by the spring on the block during one full rotation for the two blocks?

## 2022 Form I

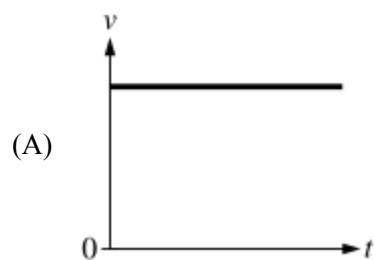
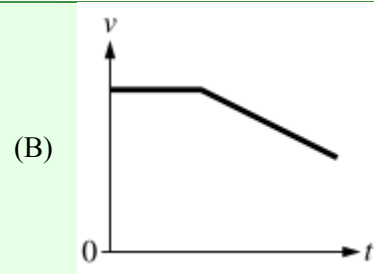
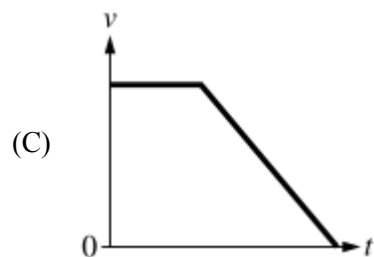
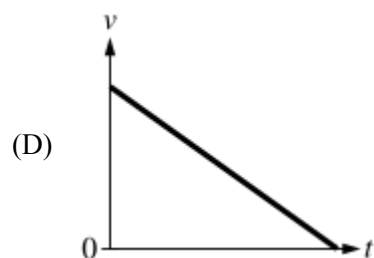
- (A)  $W_2 > W_1$   
(B)  $W_1 > W_2$   
(C)  $(W_1 = W_2) > 0$   
(D)  $W_1 = W_2 = 0$



Two identical blocks of mass 4 kg each travel to the right with speed 1 m/s on a frictionless section of a horizontal surface, as shown in the figure above. The centers of the blocks are initially separated by 5 m. The first block then encounters a rough section, with a coefficient of kinetic friction of 0.025 between the block and the rough section. The first block comes to rest after traveling 2 m on the rough section. At this instant, the second block has not yet reached the rough section.

19. Which of the following graphs best represents the speed  $v$  of the center of mass of the two-block system as a function of time  $t$  from before the first block enters the rough section until the instant the first block comes to rest?

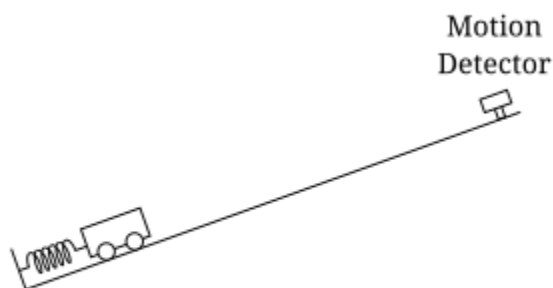
## 2022 Form I



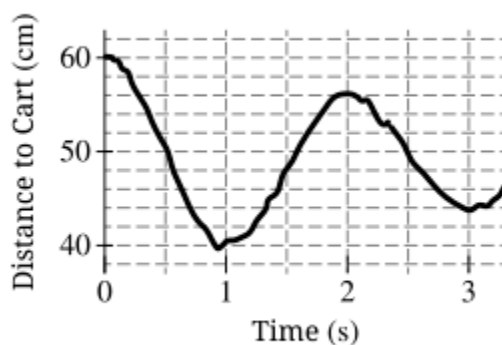
20. What is the change in the mechanical energy of the two-block system from when the two blocks are initially moving to the moment when the first block has come to rest?

- (A) 0 J  
(B)  $-0.25$  J  
(C)  $-2.0$  J  
(D)  $-4.0$  J

## 2022 Form I



A cart on an inclined track is connected to a spring that is fixed at the other end, as shown. The spring is compressed by pushing the cart against it, and then the cart is released from rest. A motion detector at the other end of the track records the distance between the cart and the detector as a function of time, as shown in the graph below.



21. On the graph, the peak value occurring at  $t = 2$  s is lower than the value at  $t = 0$  s. Which of the following is most likely a contributing explanation?

(A) Mechanical energy is dissipated by friction between the cart and the track. ✓

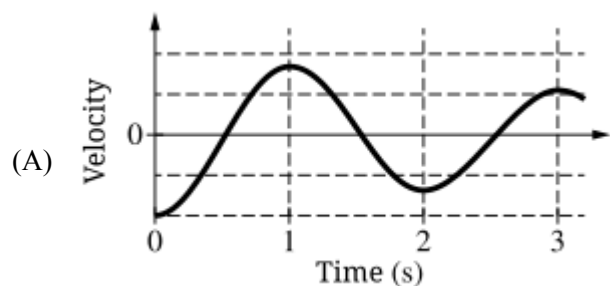
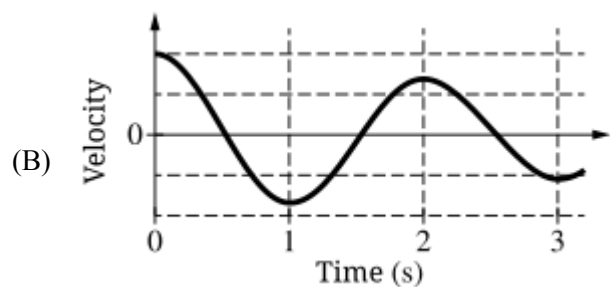
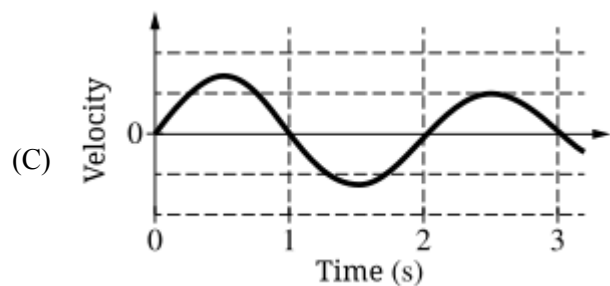
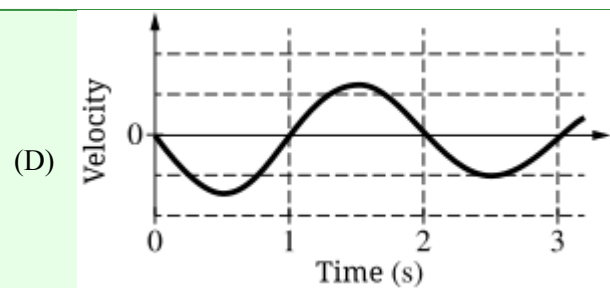
(B) The spring is nonideal and exerts a nonlinear restoring force on the cart.

(C) The mechanical energy of the cart-spring-Earth system includes both the elastic potential energy of the spring and gravitational potential energy.

(D) The kinetic energy of the cart includes both the rotational kinetic energy of the cart's wheels and the translational kinetic energy of the cart.

22. Which of the following graphs best represents the velocity of the cart as a function of time, where a positive velocity corresponds to motion away from the detector?

## 2022 Form I



23. What is the cart's maximum displacement from its starting position?

(A) 4 cm

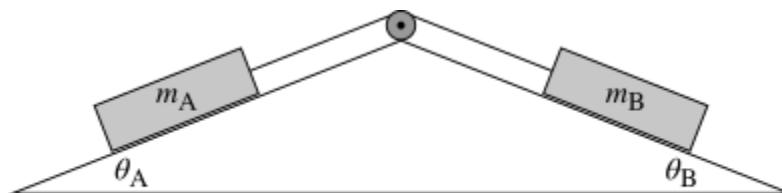
(B) 20 cm

(C) 40 cm

(D) 60 cm

## 2022 Form I

24.



Note: Figure not drawn to scale.

Two blocks with mass  $m_A$  and  $m_B$  are connected by a lightweight string that passes over a pulley with negligible mass and friction, as shown above. The blocks are free to move along frictionless inclined surfaces with angles  $\theta_A$  and  $\theta_B$ , respectively. For which of the following relationships between the masses and angles will the blocks always be in equilibrium?

- (A)  $m_A = m_B$  and any angles
- (B)  $\sin \theta_A = \sin \theta_B$  and any masses
- (C)  $m_A \sin \theta_A = m_B \sin \theta_B$
- (D)  $m_A \sin \theta_B = m_B \sin \theta_A$



A cart of known mass is free to move on the frictionless track shown. The cart is released from rest at Point A and rolls freely toward Point B, without losing contact with the track. The heights of points A and B are known.

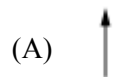
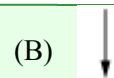
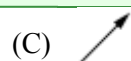
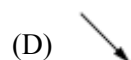
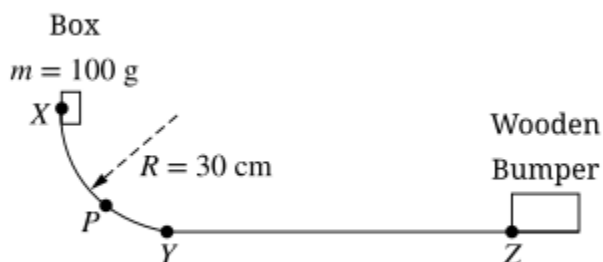
25. Which of the following is equal to the kinetic energy of the cart when it is at Point B ?

- (A) The gravitational potential energy of the Earth-cart system when the cart is at Point A
- (B) The gravitational potential energy of the Earth-cart system when the cart is at Point B
- (C) The difference between the gravitational potential energy of the Earth-cart system when the cart is at Point A and when it is at Point B
- (D) The sum of the gravitational potential energy of the Earth-cart system when the cart is at Point A and when it is at Point B



## 2022 Form I

26. Which of the following best represents the direction of the net force exerted on the cart when it is at Point B?



A 100 g box initially at rest slides down a rough circular ramp and makes a smooth transition onto a level horizontal track of negligible friction, as shown above. At Point Z, the box collides with a fixed wooden bumper that brings the box to rest. The radius of the circular ramp is 30 cm.

27. Take the gravitational potential energy of the box-Earth system to be zero when the box is at Point Y. One-third of the initial mechanical energy of the box-Earth system is dissipated as the box moves from Point X to Point Y. The speed of the box just before it hits the bumper is most nearly

(A) 1.4 m/s

(B) 2.0 m/s

(C) 4.0 m/s

(D) 20 m/s

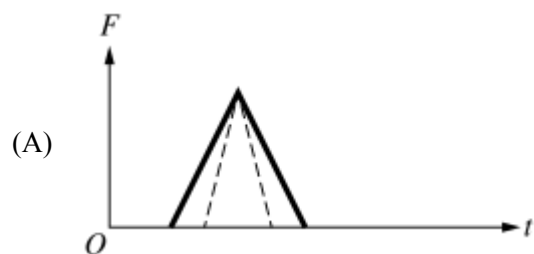
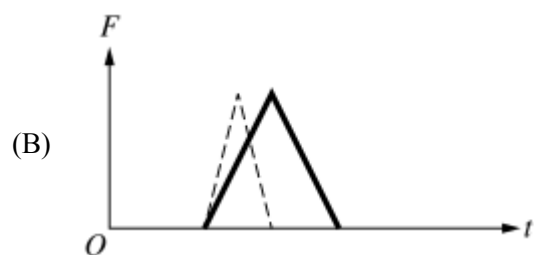
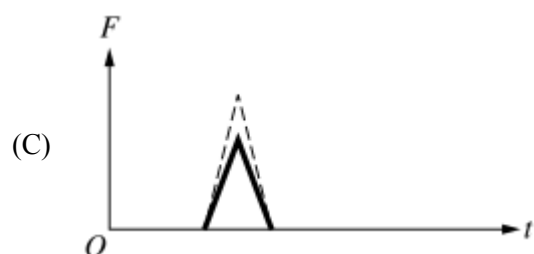
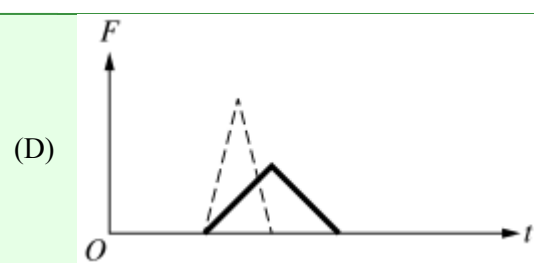
## 2022 Form I

28.



The graph above shows the magnitude  $F$  of the force the wooden bumper exerts on the box as a function of time  $t$  as the bumper brings the box to rest. If the wooden bumper is replaced by a bumper of the same size but made of a softer material, which of the following graphs could represent the magnitude of the force it exerts on the box? (An outline of the graph for the wooden bumper is shown as a dashed line for reference.)

## 2022 Form I



29. Two balls of mass  $M$  and  $2M$  are released from rest at the same time from the same height and fall straight down with negligible air resistance. Just before hitting the ground, the ball of mass  $M$  has kinetic energy  $K$ . What is the kinetic energy of the ball of mass  $2M$  just before hitting the ground?

- (A)  $K$   
 (B)  $\sqrt{2}K$

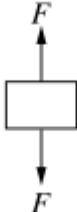
(C)  $2K$

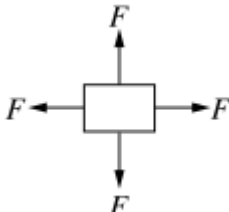
(D)  $4K$

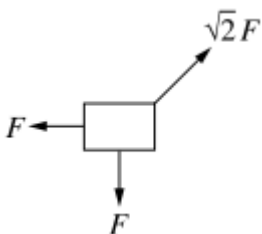
30. Four blocks of equal mass are moving at the same speed when different sets of forces are exerted on the blocks, as shown below, with the lengths of the arrows proportional to the magnitudes of the forces. Which of the following blocks could be losing kinetic energy?

## 2022 Form I

(A) 

(B) 

(C) 

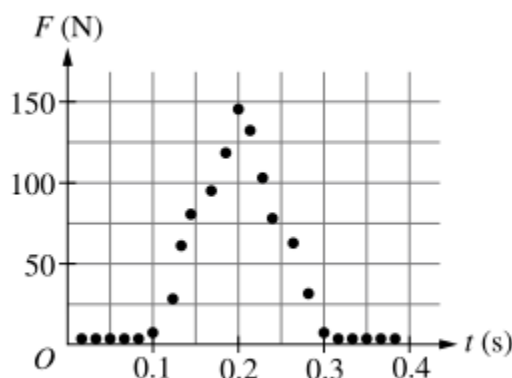
(D) 

31. In an experiment on a horizontal track with low but nonzero friction, a student sets a block into motion at  $t = 0$  s. At  $t = 3$  s, the block collides with and sticks to another identical block. A motion detector records the velocity of each block from  $t = 0$  s to  $t = 6$  s. Which velocity measurements should the student use to determine whether the linear momentum of the two-block system changes during the collision?

- (A) The velocity of each block immediately before and immediately after  $t = 3$  s
- (B) The average velocity of each block between  $t = 0$  s and  $t = 3$  s and the average velocity of each block between  $t = 3$  s and  $t = 6$  s
- (C) The velocity of each block immediately before  $t = 3$  s and the average velocity of each block between  $t = 3$  s and  $t = 6$  s
- (D) The average velocity of each block between  $t = 0$  s and  $t = 3$  s and the velocity of each block immediately after  $t = 3$  s

## 2022 Form I

32.



Cart A of mass  $2.0 \text{ kg}$  is initially traveling south at a speed of  $5.0 \text{ m/s}$  toward Cart B, which is traveling north. The two carts collide. The graph shows the magnitude  $F$  of the force exerted on Cart A by Cart B as a function of time  $t$ , as measured by a force sensor. If the ground is level and all other horizontal forces are negligible, what is the approximate velocity of Cart A at  $t = 0.4 \text{ s}$ ?

(A)  $2.5 \text{ m/s}$  south

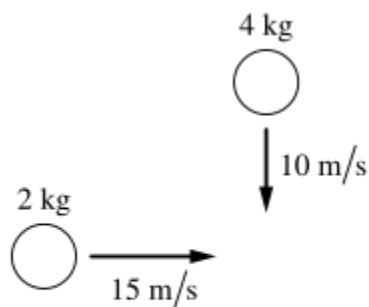
(B)  $2.5 \text{ m/s}$  north

(C)  $12.5 \text{ m/s}$  south

(D)  $12.5 \text{ m/s}$  north



33.



Top View

The figure above shows a top view of two objects sliding on a horizontal, frictionless surface, with masses and velocities indicated. The objects collide and stick together. Which of the following arrows best indicates the direction of motion of the center of mass of the two-object system after the collision? (The dashed line in each figure is  $45^\circ$  from the direction of motion of the  $2 \text{ kg}$  object.)

2022 Form I

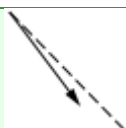
(A)



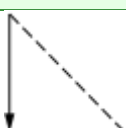
(B)



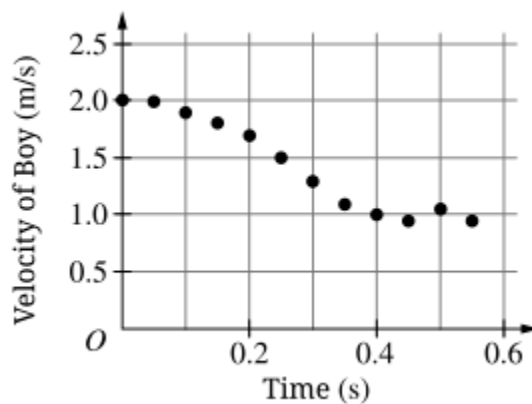
(C)



(D)



34.



A 60 kg girl is standing at rest on an ice rink when an 80 kg boy skating toward her gives her a push forward. The two skaters then keep sliding forward at different speeds, with negligible friction. The boy's velocity as a function of time, measured while the boy and girl are in contact, is shown above. What is the magnitude of the change in linear momentum  $|\Delta p_{\text{boy}}|$  of the boy, and how do the magnitudes of the average forces exerted on the skaters compare?

|   | $ \Delta p_{\text{boy}} $ | Magnitudes of Average Forces                                                |
|---|---------------------------|-----------------------------------------------------------------------------|
| A | 80 kg·m/s                 | The magnitudes of the forces are the same.                                  |
| B | 80 kg·m/s                 | The force exerted on the girl is greater than the force exerted on the boy. |
| C | 160 kg·m/s                | The magnitudes of the forces are the same.                                  |
| D | 160 kg·m/s                | The force exerted on the girl is greater than the force exerted on the boy. |

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(A) A

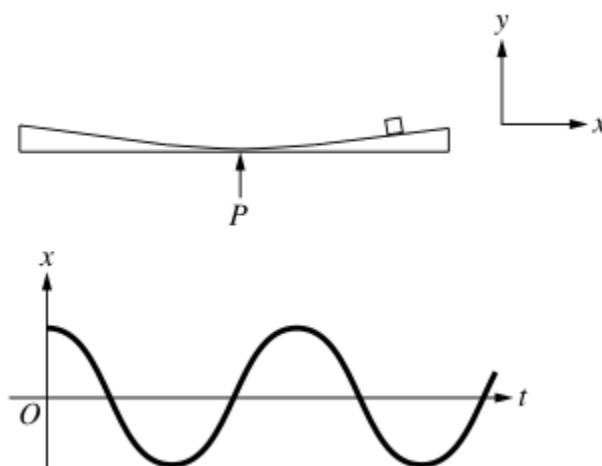


(B) B

(C) C

(D) D

35.



The figure shows a block at rest near the top of a track with two sections that are each inclined at the same small angle from the horizontal. The bottom of the track is at Point P. The block is released at time  $t = 0$  and slides along the track with negligible friction. A student predicts that the  $x$ -position of the block as a function of time  $t$  is given by the curve in the graph above. Is the student's graph physically plausible? Why or why not?

(A) Yes, because the net force on the block is always directed along the ramp toward Point P.

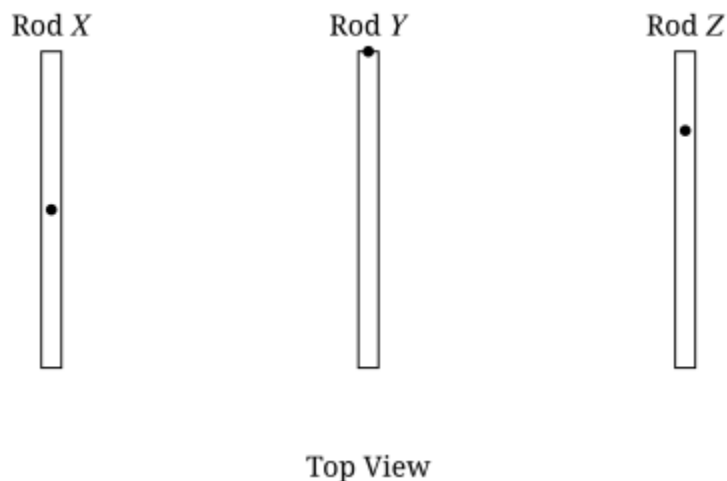


(B) Yes, because the net force gets bigger as the block moves through the center.

(C) No, because the gravitational force does not change direction.

(D) No, because the magnitude of the net force on the block is constant.

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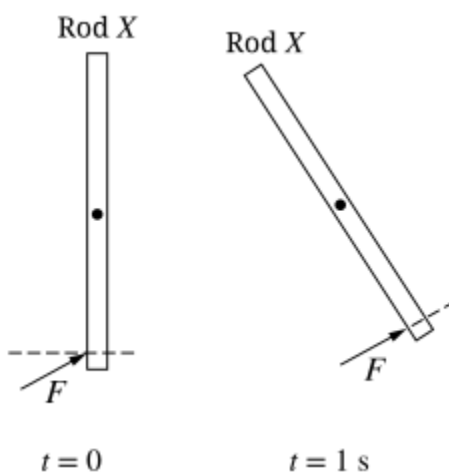
Identical uniform rods **X**, **Y**, and **Z** are free to rotate on a horizontal surface about vertical axes indicated by the dots in the diagram above. Frictional forces are negligible.

36. All three rods rotate with the same angular speed. How does the angular momentum  $L$  of each rod about its axle compare?

- (A)  $L_X = L_Y = L_Z$   
 (B)  $L_Y > L_X > L_Z$   
 (C)  $L_Y > L_Z > L_X$   
 (D)  $L_Z > L_Y > L_X$



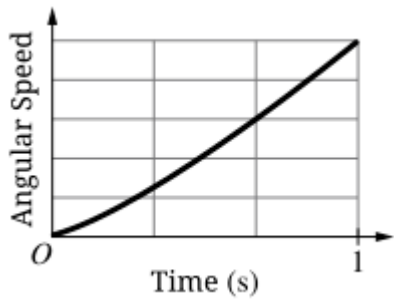
37.



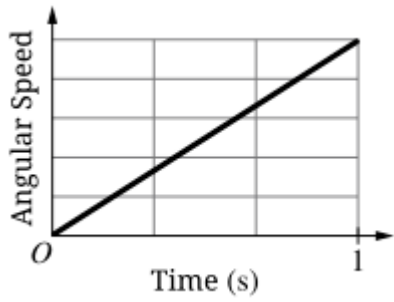
Rod **X** is free to rotate on a horizontal surface with negligible friction about a pivot through its center. At time  $t = 0$  the rod is at rest and a force of magnitude  $F$  is exerted near the end of the rod at an angle, as shown in the figure on the left. As the rod rotates, the force remains constant in magnitude and direction until the rod is perpendicular to the force at time  $t = 1$  s, as shown in the figure on the right. Which of the following graphs could show the rod's angular speed as a function of time between 0 and 1 s?

2022 Form I

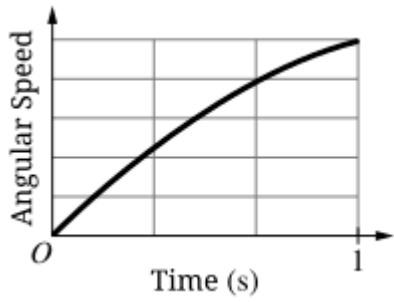
(A)



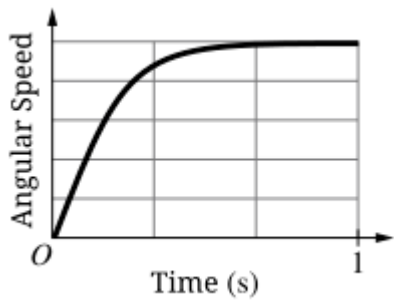
(B)



(C)



(D)



## 2022 Form I

38.



A lump of clay moves toward Rod Y, which is at rest, as shown. The rotational inertia of the clay with respect to the rod's axle is twice that of the rod. The clay collides with and sticks to the end of the rod, and during the collision the rod gains angular momentum  $L$  with respect to the axle. The change in angular momentum of the clay with respect to the axle during the collision is

(A)  $-2L$

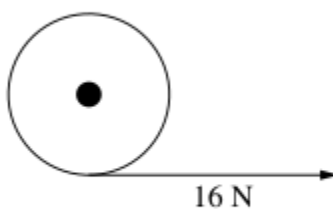
(B)  $-L$

(C)  $-L/2$

(D)  $0$



39.



A wheel is initially at rest and is free to rotate on an axle through its center. The wheel has a radius of  $0.5 \text{ m}$  and a rotational inertia of  $4 \text{ kg} \cdot \text{m}^2$ . A constant force of  $16 \text{ N}$  is exerted tangent to the edge of the wheel, as shown, for  $10 \text{ s}$ . What is the final angular speed of the wheel?

## 2022 Form I

(A) 2 rad/s

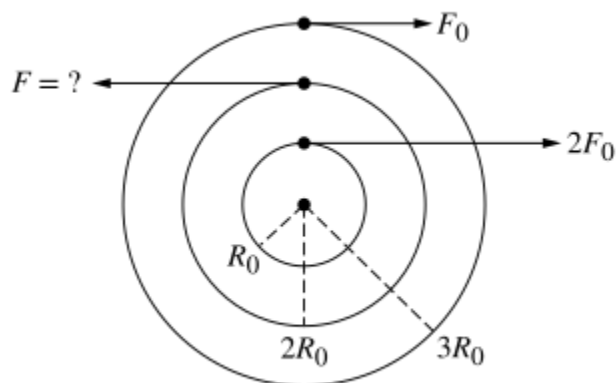
(B) 20 rad/s

(C) 40 rad/s

(D) 80 rad/s



40.

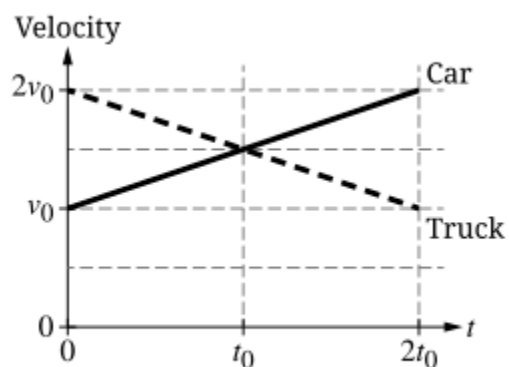


Three forces are exerted on a disk that is free to rotate with negligible friction around a pivot at the disk's center. The three forces are exerted at different locations on the disk, as shown by the arrows in the figure. What should the magnitude of the force exerted at a distance of  $2R_0$  from the center be so that the net torque about the center is zero?

(A)  $1.5F_0$ (B)  $2.5F_0$ (C)  $3F_0$ (D)  $5F_0$ 

## 2022 Form I

41.



The graph represents the velocity as a function of time  $t$  of a car and a truck that travel along a straight road. Compare the distances traveled by the car and truck for two time intervals: from  $0$  to  $t_0$  and from  $0$  to  $2t_0$ .

|   | $0$ to $t_0$              | $0$ to $2t_0$             |
|---|---------------------------|---------------------------|
| A | Greater for the truck     | Greater for the car       |
| B | Greater for the truck     | The same for both objects |
| C | The same for both objects | Greater for the car       |
| D | The same for both objects | The same for both objects |

(A) A

(B) B

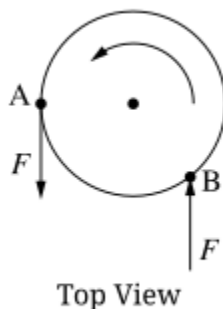
(C) C

(D) D



## 2022 Form I

42.

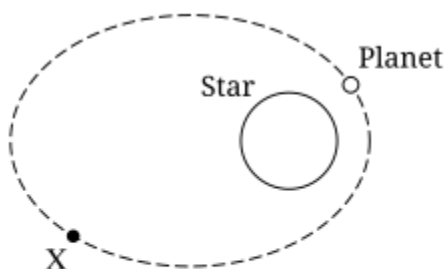


A uniform disk is initially spinning in a counterclockwise direction about an axis through its center. Two forces of equal magnitude  $F$  are then exerted at points A and B on the disk, as shown in the figure above. Which of the following correctly describes the effects of the two forces on the rotation at the instant shown?

- (A) Both forces have the effect of slowing down the rotation by the same amount.
- (B) Both forces have the effect of speeding up the rotation by the same amount.
- (C) Both forces have the effect of speeding up the rotation, but the force at Point A has a greater effect than does the force at Point B. ✓
- (D) The force at Point A has the effect of speeding up the rotation, while the force at Point B has the effect of slowing down the rotation.

## 2022 Form I

43.



Note: Figure not drawn to scale.

A planet of mass  $M$  is in orbit around a star, as shown. Which of the following best describes the change in the planet's rotational inertia about the center of the star and its angular momentum about the star as the planet travels from the position shown in the figure to the position marked with an X?

|   | Rotational inertia | Angular momentum |
|---|--------------------|------------------|
| A | Increases          | Decreases        |
| B | Increases          | Stays the same   |
| C | Stays the same     | Decreases        |
| D | Stays the same     | Stays the same   |

(A) A

(B) B

(C) C

(D) D



## 2022 Form I

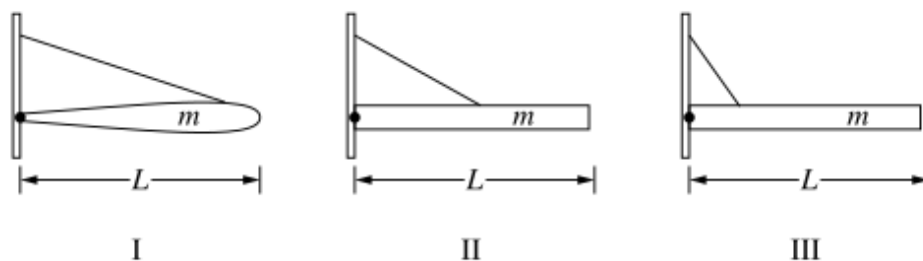
44.



A system consists of two blocks of different masses connected by a spring of negligible mass. A force of magnitude  $F_T$  is exerted on the system, as shown above, giving it an acceleration to the right. The spring is uniformly compressed and is not oscillating. The spring exerts a force of magnitude  $F_A$  on Block A and a force of magnitude  $F_B$  on Block B. Which of the following is a correct relationship among the magnitudes of the three forces?

- (A)  $F_T = F_A = F_B$   
(B)  $(F_T = F_A) > F_B$   
(C)  $F_T > (F_A = F_B)$  ✓  
(D)  $F_T > F_A > F_B$

45.



The three uniform solid objects shown above have the same mass  $m$  and length  $L$ . Each object is held at rest by a hinge and a cord attached to a rigid wall. Which of the following correctly ranks the magnitude of the torque  $\tau$  exerted by gravity with respect to the hinge on each object?

## 2022 Form I

(A)  $\tau_I = \tau_{II} = \tau_{III}$

(B)  $\tau_I > (\tau_{II} = \tau_{III})$  ✓

(C)  $\tau_I > \tau_{II} > \tau_{III}$

(D)  $(\tau_{II} = \tau_{III}) > \tau_I$

46. A ball falls onto a horizontal surface and then bounces back into the air. At time  $t_1$ , the ball is at height  $h_1$  above the surface and has a downward vertical speed  $v_1$ . At a later time  $t_2$ , the ball has bounced back up and is at height  $h_2$  above the surface with an upward vertical speed  $v_2$ . Which of the following could be correct about  $h_2$  and  $v_2$ ? Select two answers.

(A)  $h_2 = h_1, v_2 > v_1$

(B)  $h_2 > h_1, v_2 < v_1$  ✓

(C)  $h_2 > h_1, v_2 > v_1$

(D)  $h_2 < h_1, v_2 = v_1$  ✓

47. Identical disks X and Y are on a horizontal, frictionless surface. Disk X slides with velocity  $\vec{v}_0$  and collides elastically with Disk Y, which is initially at rest. The disks then move away from the collision point at different angles. Which of the following must be true after the collision? Select two answers.

(A) Disk X has the same kinetic energy as Disk Y.

(B) Disk X has the same momentum as Disk Y.

(C) The speed of Disk X is less than  $v_0$ . ✓(D) The velocity of the center of mass of the two-disk system is in the direction of  $\vec{v}_0$ . ✓

48. A machine exerts a force on an object of known rotational inertia. An engineer wants to know the change in angular momentum of the object for a given time interval. Which of the following can be measured as a function of time to provide the desired information? Select two answers.

(A) The instantaneous angular velocity of the object ✓

(B) The instantaneous linear velocity of the object

(C) The instantaneous value of the force exerted on the object

(D) The instantaneous value of the torque exerted on the object ✓

49. Two identical spheres, X and Y, are connected by a light string. A person holds Sphere X and lets Sphere Y hang straight down, then releases them from rest. Which of the following is true of the speed of the center of mass of the two-sphere system at time  $t$  while both spheres are falling? Select two answers.

(A) It is zero relative to Sphere X. ✓

(B) It is zero relative to the ground.

(C) It is equal to  $gt$  relative to Sphere X.(D) It is equal to  $gt$  relative to the ground. ✓

## 2022 Form I

50.

| Cart | Mass   | Initial Velocity (m/s) | Velocity at Closest Approach (m/s) | Final Velocity (m/s) |
|------|--------|------------------------|------------------------------------|----------------------|
| X    | 3.0 kg | 3.0 to the right       | 2.0 to the right                   | 1.0 to the right     |
| Y    | ?      | 1.0 to the left        | 2.0 to the right                   | 5.0 to the right     |

Carts X and Y move toward each other on a level, frictionless track. The carts have magnets in their bumpers and begin to repel each other as they get closer. They reach a common velocity for an instant and then separate. Which of the following questions can be answered using only the data in the table? Select two answers.

(A) What is the mass of Cart Y ?



(B) Which cart has a stronger magnet?

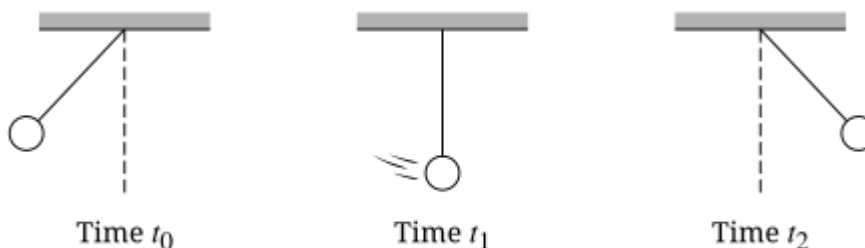
(C) Is mechanical energy dissipated during the collision?



(D) What maximum force is exerted on Cart X at the closest approach?

## 2022 Form I

51. This question is a short free-response question. Show your work for each part of the question.



(7 points, suggested time 13 minutes)

A sphere attached to the end of a light string that makes an angle with the vertical is released from rest at time  $t_0$  as shown above. At time  $t_1$  the sphere is at the lowest point in its path, and at time  $t_2$  it is momentarily at rest at its maximum height.

- (a) The dots below represent the sphere at times  $t_1$  and  $t_2$ . On each dot, draw and label the forces (not components) exerted on the sphere at the corresponding time. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



- (b) The magnitude of the tension force in the string at time  $t_1$  is  $F_1$ , and at time  $t_2$  is  $F_2$ . The gravitational force exerted on the sphere has a magnitude  $F_g$ . Rank  $F_1$ ,  $F_2$ , and  $F_g$  from greatest to least in the spaces indicated below. Use 1 for the greatest magnitude, 2 for the next greatest, and so on. If any two or all three magnitudes are

## 2022 Form I

the same, use the same number for their ranking.

\_\_\_  $F_1$      \_\_\_  $F_2$      \_\_\_  $F_g$

In a clear, coherent paragraph-length response that may also contain figures and/or equations, justify your ranking.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for a correctly labeled tension force pointing vertically upward, a correctly labeled weight arrow pointing down, **and** no extraneous forces at time  $t_1$
- ☐ 1 point is earned for a correctly labeled tension force pointing up and to the left **and** a correctly labeled weight arrow pointing down at time  $t_2$

**Scoring Note:** Appropriate labels for the force due to gravity include:  $F_G$ ,  $F_g$ ,  $F_{grav}$ ,  $W$ ,  $mg$ ,  $Mg$ ,  $F_{\text{Earth on Block}}$ ,  $F_{\text{on Block by Earth}}$ ,  $F_{\text{E,Block}}$ ,  $F_{\text{Block,E}}$ . The labels  $G$  or  $g$  are not appropriate labels for the force due to gravity. Appropriate labels for the tension force include:  $F$ ,  $T$ ,  $F_1$  or  $F_2$ ,  $T_1$  or  $T_2$ ,  $F_T$ ,  $F_{\text{tension}}$ ,  $F_{\text{rope}}$ , “Tension,” “Rope force.” It is okay to use the same label for the different tension forces since the differentiation between tensions is to be explained in the paragraph-length response.

## Example Response:



## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|

## 2022 Form I

The response accurately includes **all** of the following criteria.

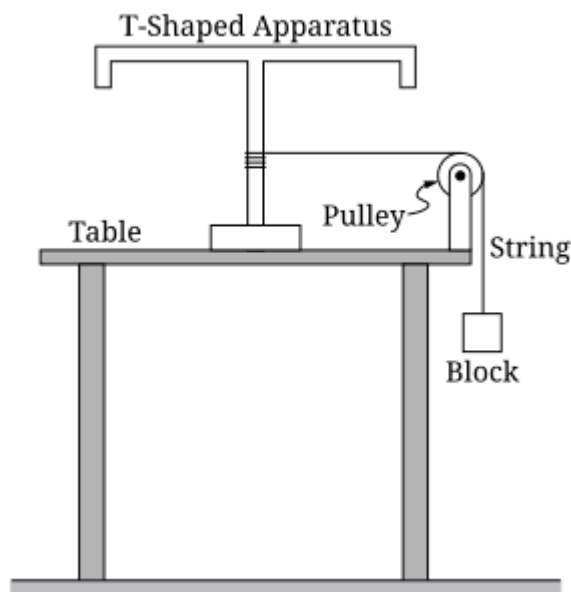
- ☐ 1 point is earned for **either** of the following:
  - relating net force and acceleration consistent with Newton’s second law
  - indicating that the net force is upward at  $t_1$  (or toward the center of the circle).
- ☐ 1 point is earned for indicating that the tension at  $t_1$  is greater than the weight because the string supports the entire weight and also provides the necessary centripetal force to move the bob in its circular path.  
**Scoring Note:** This point is earned for a response that identifies the correct relationship tension > weight.
- ☐ 1 point is earned for indicating that  $F_2 < F_g$  at time  $t_2$ , with an attempt at a justification.
- ☐ 1 point is earned for indicating that, the tension is equal to a component of the weight,  $F_2$
- ☐ 1 point is earned for a logical, relevant, and internally consistent argument that addresses the required argument or question asked, and follows the guidelines described in the published requirements for the paragraph-length response

**Example Response:**

*At time  $t_1$ , the sphere is accelerating upward, so the net force must be upward, so the  $F_1$  must be larger than the force of gravity exerted on the sphere. At time  $t_2$ , the object is accelerating down and to the left so  $F_2$  is equal to a component of the gravitational force, so  $F_2$  is less than  $F_g$ . Therefore,  $F_1 > F_g > F_2$ .*

## 2022 Form I

52. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

A light string is attached to a block, passes over a pulley, and is wrapped around a T-shaped apparatus, as shown above. The pulley has negligible rotational inertia and negligible friction, and the T-shaped apparatus rotates with negligible friction. The system is released from rest. As the block accelerates downward, it pulls the string, which causes the apparatus to start rotating.

Students in a physics lab first wish to determine the value of the block's constant downward acceleration once it is released from rest by observing it fall.

(a) Derive an equation for the acceleration of the block in terms of quantities that can be obtained from measurements made using only a meterstick and a stopwatch.

(b) Design an experimental procedure the students could use to collect the data needed to determine the block's linear acceleration  $a$ .

In the table at left below, list the quantities that would be measured in your experiment using the meterstick and the stopwatch. Define a symbol to represent each quantity.

In the space to the right of and below the table, describe the overall procedure. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table.

If needed, you may include a simple diagram of the setup with your procedure.

## 2022 Form I

| Quantity to be Measured | Symbol for Quantity | Equipment for Measurement | Procedure (and diagram, if needed) |
|-------------------------|---------------------|---------------------------|------------------------------------|
|                         |                     | Meterstick                |                                    |
|                         |                     | Stopwatch                 |                                    |
|                         |                     |                           |                                    |

(c) Explain how the students should analyze the data from part (b) to determine the value of the block's constant linear acceleration  $a$ .

(d) The students produce the data table shown below for five blocks with different masses.

## 2022 Form I

| Mass of Block (kg) | Linear Acceleration of Block ( $\text{m/s}^2$ ) | Angular Acceleration of T-shaped Apparatus ( $\text{rad/s}^2$ ) | Tension in String (N) | Torque Exerted on T-shaped Apparatus by String ( $\text{N} \cdot \text{m}$ ) |
|--------------------|-------------------------------------------------|-----------------------------------------------------------------|-----------------------|------------------------------------------------------------------------------|
| 0.200              | 0.34                                            | 27                                                              | 1.87                  | 0.0237                                                                       |
| 0.400              | 0.92                                            | 72                                                              | 3.56                  | 0.0453                                                                       |
| 0.600              | 1.37                                            | 108                                                             | 5.11                  | 0.0649                                                                       |
| 0.800              | 1.58                                            | 124                                                             | 6.53                  | 0.0830                                                                       |
| 1.000              | 1.93                                            | 152                                                             | 7.84                  | 0.0996                                                                       |

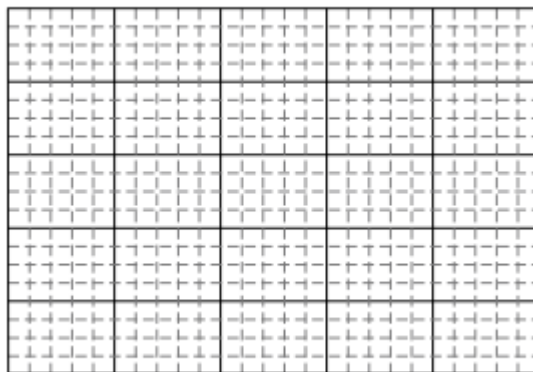
The students now want to determine the rotational inertia of the T-shaped apparatus.

- i. Indicate below which quantities could be graphed to yield a straight line whose slope could be used to calculate a numerical value for the rotational inertia of the T-shaped apparatus.

Vertical axis \_\_\_\_\_ Horizontal axis \_\_\_\_\_

- ii. Use the grid below to plot the data points for the quantities indicated in part (d)(i). Clearly scale and label all axes, including units as appropriate. Draw a straight line that best represents the data.

## 2022 Form I



- iii. Using the straight line from part (d)(ii), calculate a value for the rotational inertia of the T-shaped apparatus.

**Part A**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response accurately includes:

☐

1 point is earned for using a relevant kinematics equation and correctly solving the equation for the acceleration

**Example Response:**

$$\Delta y = v_0 t + \frac{1}{2} a t^2$$

$$v_0 = 0$$

$$a = \frac{2\Delta y}{t^2}$$

**Part B**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

## 2022 Form I



|   |   |   |   |   |
|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for relevant and consistent quantities, symbols, and equipment
- ☐ 1 point is earned for a plausible procedure (i.e., can be done in a typical physics lab)
- ☐ 1 point is earned for a procedure that could be used to determine the acceleration
- ☐ 1 point is earned for a procedure that reduces experimental uncertainty by including multiple heights or multiple trials

**Example Response:**

*Measure the height of the hanging block above the floor and release the hanging mass from rest. Measure the amount of time it takes the hanging mass to hit the floor. Repeat several times to reduce uncertainty. Repeat multiple times with different starting heights above the ground.*

**Part C**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response accurately includes:

- ☐ 1 point is earned for **either** of the following:
  - An analysis that is consistent with the equation in part (a)
  - Deriving a correct kinematic equation to analyze the data collected in part (b), and applying a consistent analysis

**Scoring Note:** If part (a) is incorrect, or not attempted, this point can still be earned if a relevant equation is derived in part (c).

**Example Response:**

*Students should graph the height  $h$  as a function of time squared. The slope would then be equal to half of the acceleration of the system*

**Part D**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

## 2022 Form I



|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for choosing two quantities that, when graphed together, can be used to determine the rotational inertia.

**Scoring Note:** Either variable may be on either the vertical or the horizontal axis.

**Example Response:**

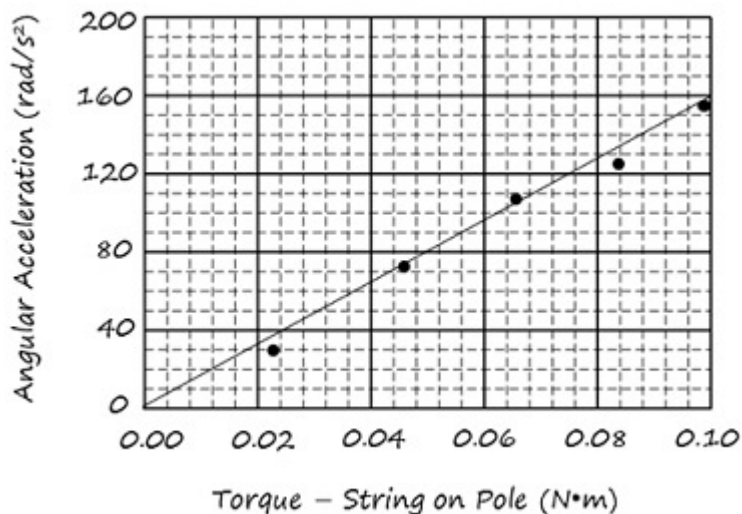
*Torque and angular acceleration (which may be on either axis)*

- ☐ 1 point is earned for axis labels consistent with the quantities indicated in (d)(i) and appropriate scales that are linear and use at least half of each graph axis.

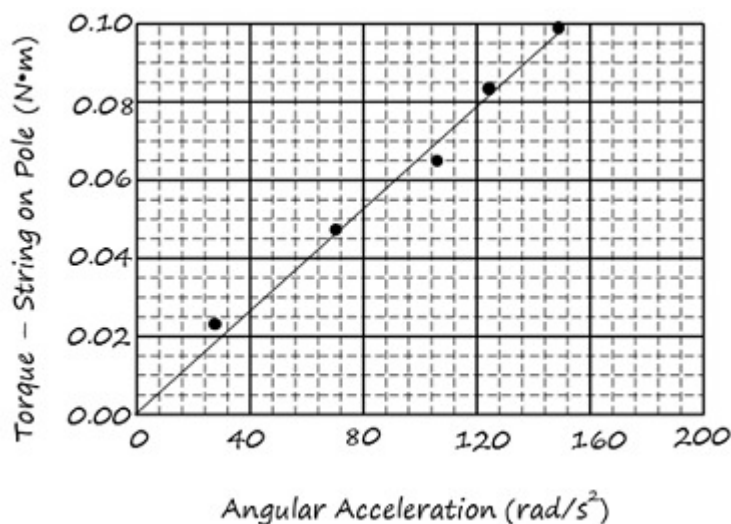
**Scoring Note:** Including units is not required to earn this point, since units are required in part (d)(iii)

- ☐ 1 point is earned for correctly plotting the data
- ☐ 1 point is earned for drawing a straight line that represents the data

**Example Responses:**



## 2022 Form I



- ☐ 1 point is earned for **one** of the following:
- correctly calculating the slope from the straight line, and not from the data points unless the points fall on the line
  - a statement of using a calculator to do a linear regression of the data to calculate the equation of the line
- ☐ 1 point is earned for determining the correct value with units for rotational inertia:  $0.00062 \text{ kg} \cdot \text{m}^2$

**Scoring Note:** [range of values:  $(4.00 - 8.00) \times 10^{-4} \text{ kg} \cdot \text{m}^2$ ]

**Example Response:**

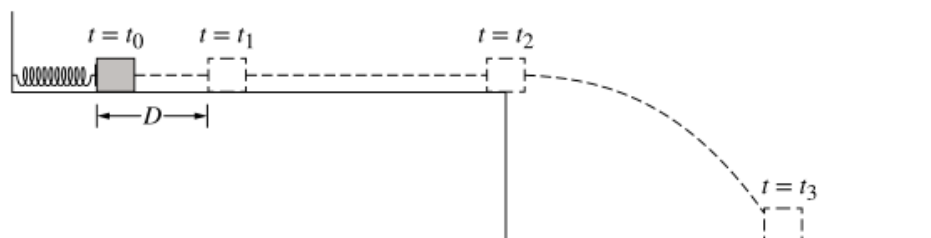
$$\text{slope} = \frac{97-65}{0.06-0.04} = 1600 \text{ (N} \cdot \text{m)}\text{s}^2$$

$$I = \frac{1}{\text{slope}} = 6.25 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

$$\text{slope} = I = \frac{0.065-0.04}{100-60} = 6.25 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

## 2022 Form I

53. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

A block is launched from a table by a compressed spring that is attached to a wall. The spring is initially compressed a distance  $D$  before the block is launched, as shown above. There is negligible friction between the block and the table.

At time  $t = t_0$  the block is released from rest.

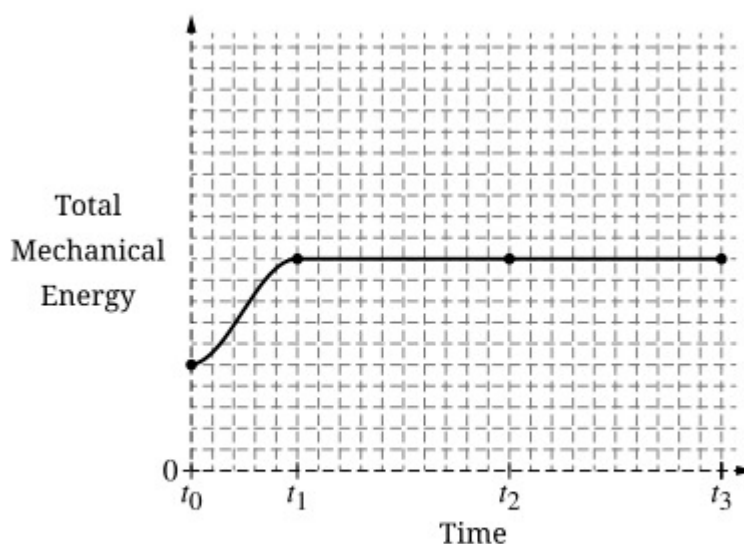
At  $t = t_1$  the block loses contact with the spring.

At  $t = t_2$  the block leaves the edge of the table.

At  $t = t_3$  the block lands on the floor.

The graph below shows the total mechanical energy of the system containing the block and Earth from  $t = t_0$  to immediately before  $t = t_3$ . The gravitational potential energy is defined to be zero when the block is on the floor.

## 2022 Form I



Note: Time axis not drawn to scale.

- (a) On the same axes, sketch a graph of the total mechanical energy of just the block from time  $t_0$  to time  $t_3$ .

The procedure is repeated with a second block, Block 2, which is more massive than the original block, Block 1. Block 2 is placed on the table, and the spring is compressed the same distance  $D$  as before.

- (b) For Block 2, is the horizontal distance traveled from the edge of the table to where it hits the ground greater than, less than, or equal to the corresponding distance for Block 1?

\_\_\_ Greater than      \_\_\_ Less than      \_\_\_ Equal to

Justify your answer.

- (c) Derive a general expression for  $X$ , the horizontal distance traveled by a block of mass  $m_B$ , from the edge of the table to where it hits the floor. Let  $k_0$  represent the spring constant and  $h_0$  represent the height of the tabletop above the floor. Express your answer in terms of  $D$ ,  $m_B$ ,  $k_0$ ,  $h_0$ , and physical constants, as appropriate.

- (d) Does your expression derived in part (c) support your reasoning in part (b)?

\_\_\_ Yes      \_\_\_ No

Justify your answer.

- (e) Is the kinetic energy of Block 2 immediately after it leaves the spring the same as or different than the kinetic energy of Block 1 immediately after it leaves the spring?

\_\_\_ Same      \_\_\_ Different

Briefly justify your answer.

## Part A

## 2022 Form I

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

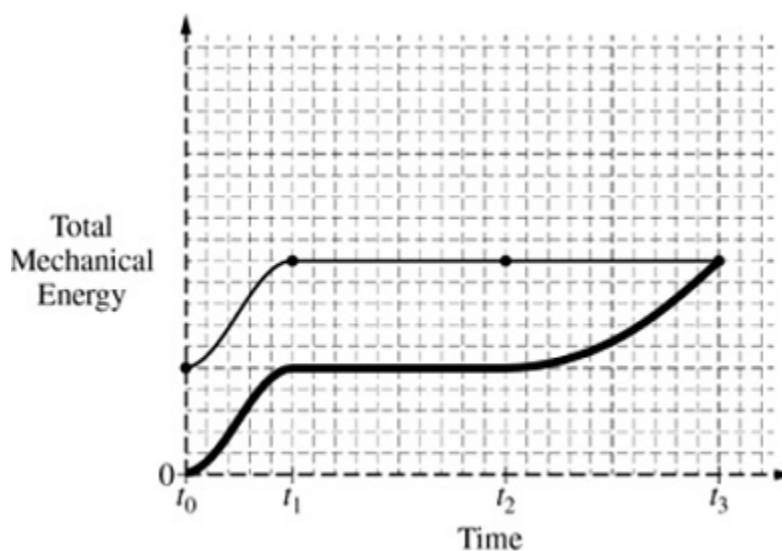


|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for curve that **both**:
  - starts at 0 at  $t_0$
  - is reasonably similar in shape to the original curve between  $t_0$  and  $t_1$
- ☐ 1 point is earned for **both** of the following:
  - a non-zero horizontal line from  $t_1 - t_2$
  - a curve or function that is continuous at  $t_1$
- ☐ 1 point is earned for **all** of the following:
  - a line or curve with a positive slope from  $t_2 - t_3$
  - a curve or function that is continuous at  $t_2$
  - the same energy as the original curve at  $t_3$

## Example Response:



Note: Time axis not drawn to scale.

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

## 2022 Form I

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for **both** of the following:
  - Selecting “Less”
  - An attempt at a relevant justification.
- ☐ 1 point is earned for indicating that Block 2 has a smaller horizontal speed
- ☐ 1 point is earned for indicating that the fall time is the same in both scenarios

**Example Response:**

*In both situations there is the same spring potential energy at the beginning which means both blocks are launched with the same kinetic energy. However, the more massive block will have a smaller launch speed. Because both blocks are launched from the same table height, they fall for the same amount of time. This means that the more massive block which is launched with a smaller speed travels a smaller horizontal distance before landing.*

**Part C**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for using conservation of energy to find the speed of a block after leaving the spring.
 
$$v = \sqrt{\frac{k_0 D^2}{m_B}}$$
- ☐ 1 point is earned for correctly finding the fall time to be  $\sqrt{\frac{2h_0}{g}}$
- ☐ 1 point is earned for multiplying the speed and fall time to find the horizontal distance in terms of the given variables and physical constants.

**Example Response:**

$$\frac{1}{2}k_0 D^2 = \frac{1}{2}m_B v_h^2$$

$$v_h^2 = k_0 D^2 / m_B \rightarrow v_h = D \sqrt{k_0 / m_B}$$

$$h_0 = \frac{1}{2}gt^2 \rightarrow t = \sqrt{2h_0/g}$$

$$X = v_h t = \left( D \sqrt{k_0 / m_B} \right) \left( \sqrt{2h_0 / g} \right)$$

$$X = D \sqrt{\frac{2k_0 h_0}{m_B g}}$$

## 2022 Form I

## Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for addressing the functional dependence between  $X$  and  $m_B$  in the equation derived in part (c)  
**Scoring Note:** It is not necessary to use the functional dependence correctly to earn this point.
- ☐ 1 point is earned for **both** of the following:
  - Correctly identifying the relationship between  $X$  and  $m_B$  for the expression derived in part (c)
  - Comparing the relationship to the reasoning in part (b)

## Example Response:

$m_B$  is in the denominator of the expression for  $X$ , so the larger mass of block 2 means that  $X$  is less for block 2, consistent with my answer in part b.

## Part E

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |
|---|---|
| 0 | 1 |
|---|---|

The response accurately includes:

- ☐ 1 point is earned for **both** of the following:
  - Selecting “Same”
  - Providing a valid justification

## Example Response:

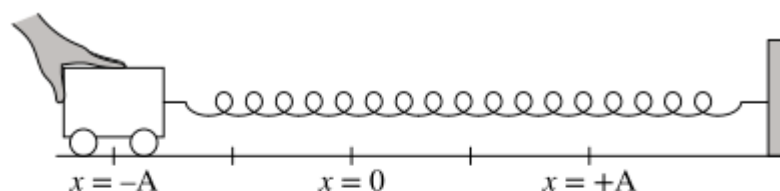
The spring stores the same amount of potential energy because it is compressed the same distance  $D$ . So the same amount of energy is transferred to kinetic energy of each block.

## 2022 Form I

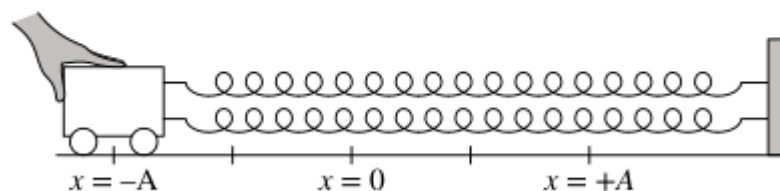
54. This question is a short free-response question. Show your work for each part of the question.

(7 points, suggested time 13 minutes)

The following two scenarios describe a cart attached to either one or two identical springs which are at their relaxed length when the cart is at position  $x = 0$ . In each scenario, the cart is pulled to position  $x = -A$ , is released from rest, and oscillates with negligible friction between  $x = +A$  and  $x = -A$ .



Scenario 1



Scenario 2

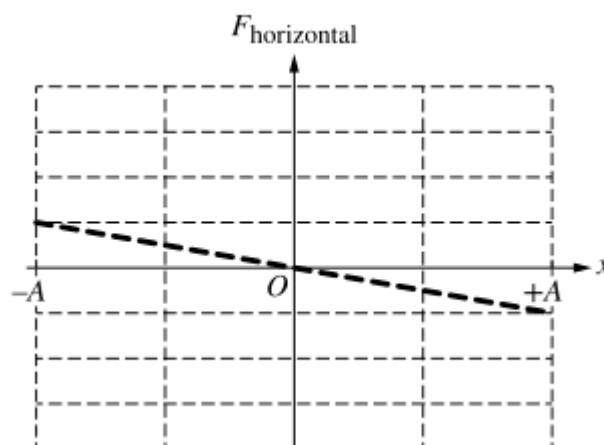
In Scenario 1, the cart is attached to the wall with one spring as shown. The total mechanical energy of the cart-spring system in Scenario 1 is  $E_1$ .

- (a) For Scenario 1, derive an expression for the kinetic energy of the cart in terms of  $E_1$  when the cart is at position  $x = +\frac{A}{2}$ .

(b) As shown in the figure for Scenario 2, a second identical spring is attached between the same cart and the wall before the cart is pulled to position  $x = -A$ .

- Determine the total mechanical energy of the cart-springs system in Scenario 2 in terms of  $E_1$ .
- The maximum speed of the cart in Scenario 1 is  $v_1$  and the maximum speed of the cart in Scenario 2 is  $v_2$ . Calculate the numerical value of the ratio  $\frac{v_2}{v_1}$ .

## 2022 Form I



A student correctly sketches a graph of the horizontal component of the net force exerted on the cart by the spring in Scenario 1 as a function of position, as shown above with a dashed line.

(c) On the same graph above, using a solid line, sketch the horizontal component of the net force exerted on the cart in Scenario 2 with two springs attached.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for an attempt at relating the mechanical energy of the system at  $x = \frac{1}{2}A$  and  $x = A$
- ☐ 1 point is earned for using  $E = K + U$  to determine the kinetic energy and writing the correct value of the kinetic energy in terms of  $E_1$ :  $K_{A/2} = \frac{3}{4}E_1$

## Example Response:

$$E_1 = U_A = \frac{1}{2}kA^2$$

$$U_{A/2} = \frac{1}{2}k\left(\frac{A}{2}\right)^2 = \left(\frac{1}{2}\right)^2 \left[\frac{1}{2}kA^2\right] = \left(\frac{1}{4}\right)U_A = \left(\frac{1}{4}\right)E_1$$

$$E = K + U, \text{ so } K = E - U$$

$$K_{A/2} = E - U_{A/2} = E_1 - \frac{1}{4}E_1 = \frac{3}{4}E_1$$

$$K_{A/2} = \frac{3}{4}E_1$$

## Part B

## 2022 Form I

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for writing  $2E_1$
- ☐ 1 point is earned for relating the maximum speed of the cart to the square root of the total energy of the cart-springs system
- ☐ 1 point is earned for a numerical value consistent with part (b)(i) OR (b)(ii)

**Example Response:**

$$E = K + U = K_{\max} + 0 = K_{\max} \quad (K = K_{\max} \text{ when } U = 0)$$

$$K = \frac{1}{2}mv^2, \text{ so } K \propto v^2 \text{ or } v_{\max} \propto \sqrt{K_{\max}} = \sqrt{E}$$

$$\frac{v_2}{v_1} = \sqrt{\frac{E_2}{E_1}} = \sqrt{\frac{2E_1}{E_1}} = \sqrt{2}$$

$$\frac{v_2}{v_1} = \sqrt{2}$$

**Part C**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



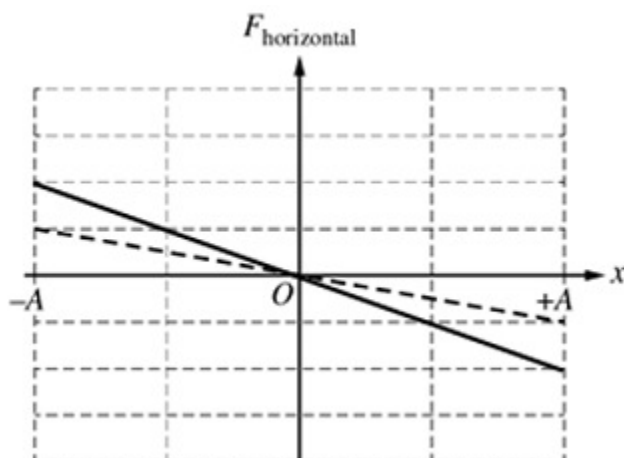
|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for a straight line that passes through the origin
- ☐ 1 point is earned for a line or curve that has double the values at  $-A$  and at  $+A$

**Example Response:**

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## 2022 Form I

55. This question is a short free-response question. Show your work for each part of the question.



Note: Figure not drawn to scale.

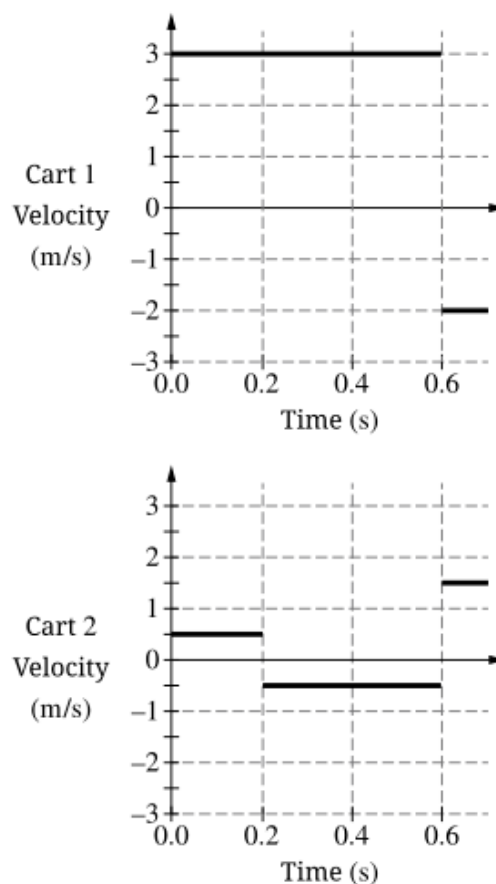
(7 points, suggested time 13 minutes)

Two carts are moving to the right on a straight, level track with negligible friction. At time  $t = 0$ , the carts are at the positions shown above. Cart 2 collides with and bounces off a wall at the right end of the track, after which the two carts collide.

Cart 1 has a mass of  $0.20 \text{ kg}$  and an initial velocity of  $3.0 \text{ m/s}$  to the right. Cart 2 has a mass of  $0.5 \text{ kg}$  and an initial velocity of  $0.50 \text{ m/s}$  to the right.

The graphs below show the velocity of each cart from  $t = 0$  to sometime after the carts collide.

## 2022 Form I



(a) Consider the system consisting of just Cart 2 when it bounces off the wall.

i. Is the momentum of Cart 2 the same before and after bouncing off the wall?

\_\_\_ Yes     \_\_\_ No

Briefly justify your answer.

ii. Is the mechanical energy of Cart 2 the same before and after bouncing off the wall?

\_\_\_ Yes     \_\_\_ No

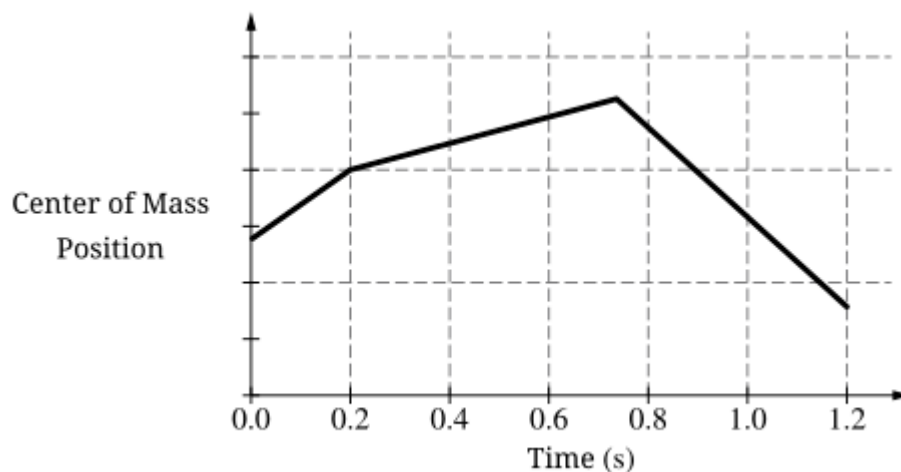
Briefly justify your answer.

(b) Is the momentum of the two-cart system the same before and after the collision that occurs at  $t = 0.6$  s?

\_\_\_ Yes     \_\_\_ No

Using calculations based on the information shown in the graphs, justify your answer.

## 2022 Form I



(c) The graph above shows the position of the center of mass of the two-cart system for a longer time interval  $0 < t < 1.2$  s. The slope of the graph changes at time  $t = 0.2$  s and also at time  $t = 0.73$  s, which are the two times at which Cart 2 bounces off the wall. However, the slope does not change at time  $t = 0.6$  s, when the two carts collide.

- Use physics principles to explain why the slope of the graph changes at  $t = 0.2$  s and  $t = 0.73$  s.
- Use physics principles to explain why the slope of the graph does not change at  $t = 0.6$  s.

## Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for using selecting “no” and a justification that indicates **one** of the following:
- the presence of a net force on the Cart 2 during the collision
  - the direction of either the momentum or the velocity changes for Cart 2

**Example Response:**

*Momentum is a vector, and since the direction of the velocity changes from before the collision to after the collision, the momentum also changes.*

- ☐ 1 point is earned for selecting “yes” and a justification that indicates **both** of the following:
- the presence of kinetic energy only (this can be implicit, by not mentioning other forms of energy)
  - that there is no change in the kinetic energy of the cart.

**Example Response:**

## 2022 Form I

*Mechanical energy of the cart is made up of only the kinetic energy of the cart which is a scalar. This has the same value before and after the collision because it doesn't depend on the direction of the speed.*

## Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
|---|---|---|---|

The response accurately includes **all** of the following criteria.

- ☐ 1 point is earned for using the correct 4 velocities from the graph (Cart 1 & 2, before & after collision) in a correct momentum calculation
- ☐ 1 point is earned for marking a response of “yes” or “no” consistent with calculations **and** calculating **one** of the following:
  - the change in momentum of each object and examining whether they are equal and opposite
  - the initial and final momenta of the two-cart system

## Example Response:

$$\Delta p_1 = p_{1f} - p_{1i} = (0.2 \text{ kg})(-2 \text{ m/s}) - (0.2 \text{ kg})(3 \text{ m/s}) = -1 \text{ kg m/s}$$

$$\Delta p_2 = p_{2f} - p_{2i} = (0.5 \text{ kg})(1.5 \text{ m/s}) - (0.5 \text{ kg})(-0.5 \text{ m/s}) = 1 \text{ kg m/s}$$

OR

$$\Delta p_{2\text{-cartsystem}} = (p_{2f} + p_{1f}) - (p_{2i} + p_{1i})$$

$$\Delta p_{2\text{-cartsystem}} = ((0.5 \text{ kg})(1.5 \text{ m/s})) + ((0.2 \text{ kg})(-2 \text{ m/s})) - ((0.5 \text{ kg})(-0.5 \text{ m/s}) + (0.2 \text{ kg})(3 \text{ m/s}))$$

$$\Delta p_{2\text{-cartsystem}} = 0$$

## Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



|   |   |   |
|---|---|---|
| 0 | 1 | 2 |
|---|---|---|

The response accurately includes **both** of the following criteria.

- ☐ 1 point is earned for indicating **one** of the following:
  - there is an external force that changes the momentum OR velocity of the system (center of mass)
  - there is an external force that changes the momentum OR velocity of Cart 2

## Example Response:

*There is a net force from the wall on cart 2 when cart 2 hits the wall. This external force changes the*

## 2022 Form I

*speed of the center of mass. The speed of the center of mass of the system is equal to the slope of the center of mass position as a function of time graph.*

☐

1 point is earned for indicating that there is no net external force on the two-cart system

**Example Response:**

*During the two cart collision, the center of mass speed remains the same (the slope of the center of mass position as a function of time) because there is no external force exerted on the system.*