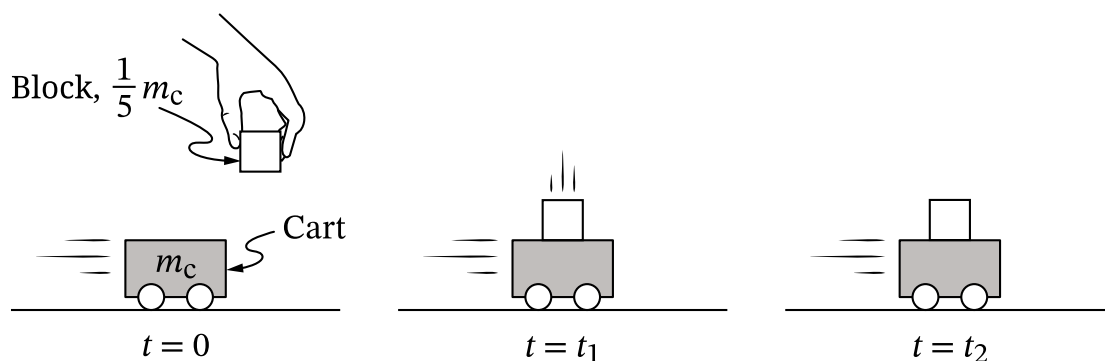


**Question 1: Version J**

1. A student has a cart of mass  $m_c$  and a block of mass  $\frac{1}{5}m_c$ , as shown in Figure 1.

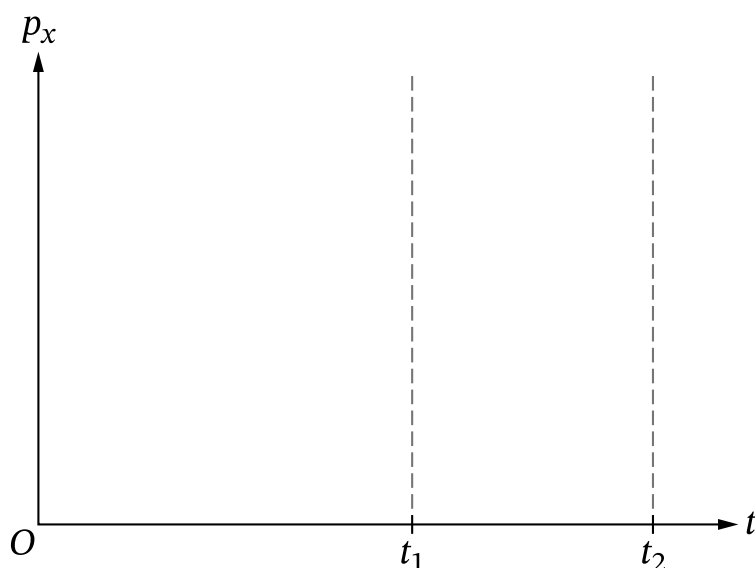
- At time  $t = 0$ , the cart is moving to the right across a horizontal surface with constant speed  $v_c$ , and the student releases the block from rest.
- At  $t = t_1$ , the block collides with and sticks to the top of the cart. The block does not slide on the cart.
- At  $t = t_2$ , the block-cart system continues to move to the right with constant speed  $v_f$ .

**Figure 1**



**A.**

- i. On the axes shown in Figure 2, **sketch** a graph of the magnitude  $p_x$  of the  $x$ -component of the momentum of the block-cart system as a function of time  $t$  from  $t = 0$  until  $t > t_2$ .



**Figure 2**

- ii. **Derive** an expression for the speed  $v_f$  of the block-cart system after time  $t = t_2$  in terms of  $m_c$ ,  $v_c$ , and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.
- iii. **Derive** an expression for the change in the kinetic energy  $\Delta K$  in the block-cart system from  $t = 0$  to  $t = t_2$  in terms of  $m_c$ ,  $v_c$ , and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.
- B.** Consider the case where a new block is dropped and collides with the top of the cart. The new block slides along the cart during the collision but does not slide off the cart. The time interval from when the new block collides with the cart and moves together with the cart is  $\Delta t$ . During  $\Delta t$  there is a frictional force between the new block and the cart.
- Indicate** whether the  $x$ -component of the momentum of the new block-cart system increases, decreases, or remains constant during  $\Delta t$ .

\_\_\_\_\_ Increases

\_\_\_\_\_ Decreases

\_\_\_\_\_ Remains constant

**Justify** your response.

Begin your response to **QUESTION 5** on this page.

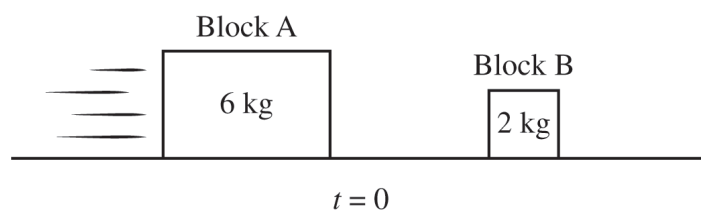


Figure 1

5. (7 points, suggested time 13 minutes)

At time  $t = 0$ , Block A slides along a horizontal surface toward Block B, which is initially at rest, as shown in Figure 1. The masses of blocks A and B are 6 kg and 2 kg, respectively. The blocks collide elastically at  $t = 1.0$  s, and as a result, the magnitude of the change in kinetic energy of Block B is 9 J. All frictional forces are negligible.

(a) **Determine** the speed of Block B immediately after the collision.

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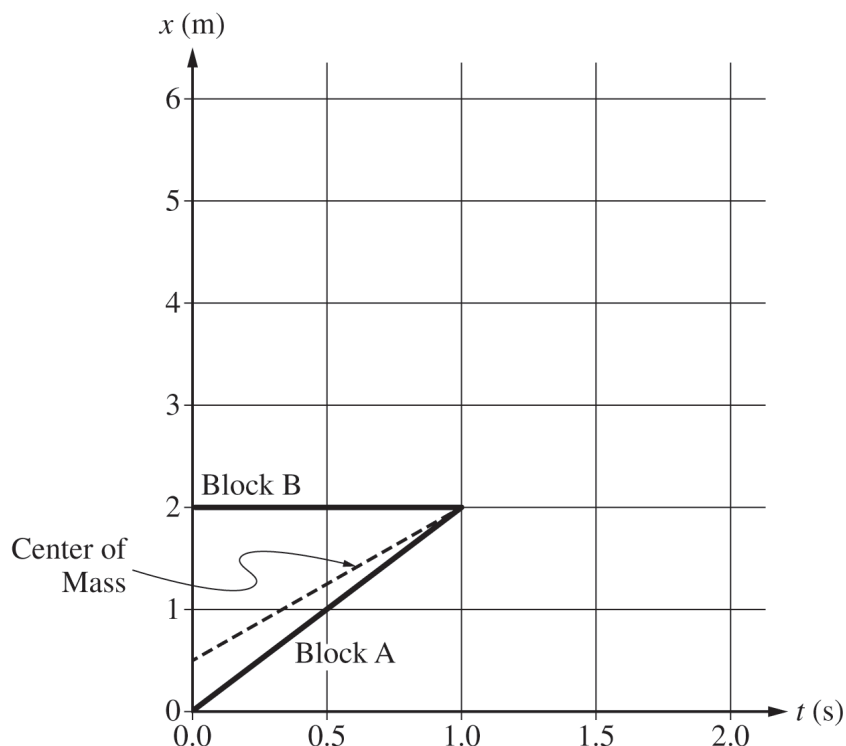
Continue your response to **QUESTION 5** on this page.

Figure 2

The graph shown in Figure 2 represents the positions  $x$  of Block A, Block B, and the center of mass of the two-block system as functions of  $t$  between  $t = 0$  and  $t = 1.0$  s.

- (b) On the graph in Figure 2, **draw** and **label** three lines to represent the positions of Block A, Block B, and the center of mass of the two-block system as functions of  $t$  between  $t = 1.0$  s and  $t = 2.0$  s. Each line should be distinctly labeled.
- (c) Consider if in the original scenario, instead of colliding elastically, the blocks collided and stuck together. **Describe** how the line drawn for the center of mass in part (b) would change, if at all. Briefly **justify** your response.

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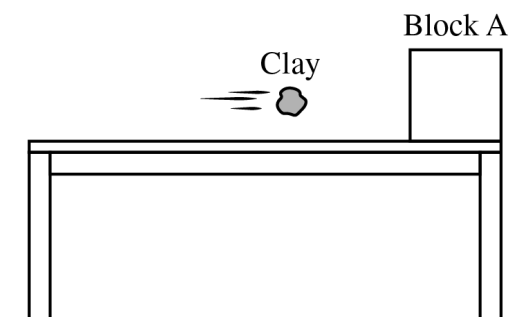
**STOP**

**END OF EXAM**

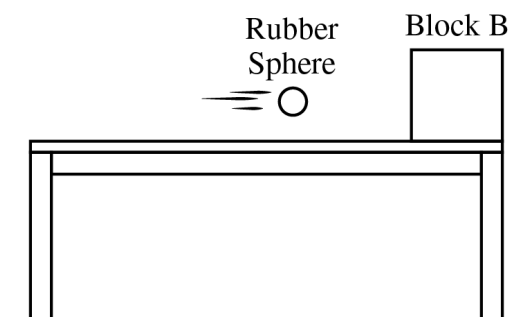
(7 points, suggested time 13 minutes)

A student has a piece of clay and a rubber sphere, both of the same mass. Both objects are thrown horizontally at the same speed at identical blocks that are at rest at the edge of identical tables, as shown, where friction between the blocks and the table is negligible. After the collisions, both blocks fall to the floor.

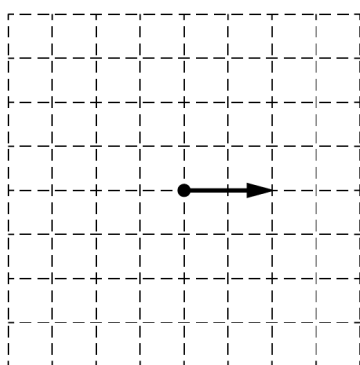
In Case A, the clay sticks to Block A after the collision. In Case B, the rubber sphere bounces off of Block B after the collision.



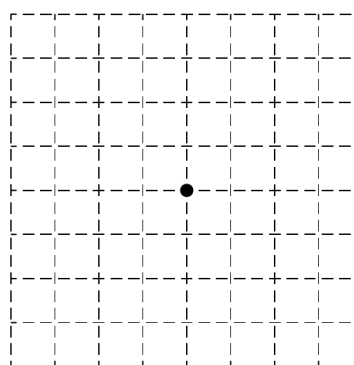
Case A: Clay and Block A  
Before Collision



Case B: Rubber Sphere and Block B  
Before Collision



Case A: Momentum of  
Clay-Block System  
Immediately After Collision



Case B: Momentum of  
Sphere-Block System  
Immediately After Collision

- (a) In the figure at left above, the arrow represents the momentum immediately after the collision for the clay-block system in Case A. In the figure at right above, draw an arrow starting on the dot to represent the momentum of the sphere-block system immediately after the collision in Case B. If the momentum is zero, write “zero” next to the dot. The momentum, if it is not zero, must be represented by an arrow starting on, and pointing away from, the dot. The length of the vector, if not zero, should reflect the magnitude of the momentum relative to Case A.

**GO ON TO THE NEXT PAGE.**

Continue your response to **QUESTION 4** on this page.

- (b) After the clay and Block A collide, Block A lands a horizontal distance  $d_A$  from the edge of the table. Does Block B land on the floor at a horizontal distance from the edge of the table that is greater than, less than, or equal to  $d_A$  ? In a clear, coherent, paragraph-length response that may also contain equations and/or drawings, explain your reasoning. Neglect any frictional effects due to the table or air resistance.

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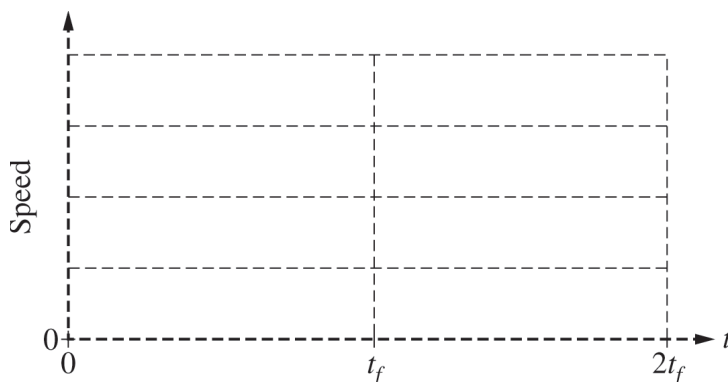
3. (12 points, suggested time 25 minutes)

(a) A student of mass  $M_S$ , standing on a smooth surface, uses a stick to push a disk of mass  $M_D$ . The student exerts a constant horizontal force of magnitude  $F_H$  over the time interval from time  $t = 0$  to  $t = t_f$  while pushing the disk. Assume there is negligible friction between the disk and the surface.

i. Assuming the disk begins at rest, determine an expression for the final speed  $v_D$  of the disk relative to the surface. Express your answer in terms of  $F_H$ ,  $t_f$ ,  $M_S$ ,  $M_D$ , and physical constants, as appropriate.

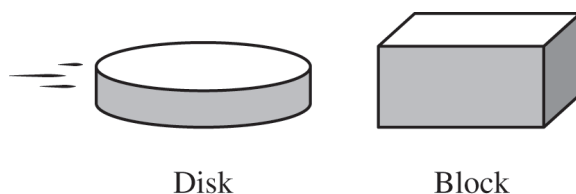
ii. Assume there is negligible friction between the student's shoes and the surface. After time  $t_f$ , the student slides with speed  $v_S$ . Derive an equation for the ratio  $v_D / v_S$ . Express your answer in terms of  $M_S$ ,  $M_D$ , and physical constants, as appropriate.

(b) Assume that the student's mass is greater than that of the disk ( $M_S > M_D$ ). On the grid below, sketch graphs of the speeds of both the student and the disk as functions of time  $t$  between  $t = 0$  and  $t = 2t_f$ . Assume that neither the disk nor the student collides with anything after  $t = t_f$ . On the vertical axis, label  $v_D$  and  $v_S$ . Label the graphs "S" and "D" for the student and the disk, respectively.

**GO ON TO THE NEXT PAGE.**

Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.





Disk

Block

(c) The disk is now moving at a constant speed  $v_1$  on the surface toward a block of mass  $M_B$ , which is at rest on the surface, as shown above. The disk and block collide head-on and stick together, and the center of mass of the disk-block system moves with speed  $v_{\text{cm}}$ .

- i. Suppose the mass of the disk is much greater than the mass of the block. Estimate the velocity of the center of mass of the disk-block system. Explain how you arrived at your prediction without deriving it mathematically.
- ii. Suppose the mass of the disk is much less than the mass of the block. Estimate the velocity of the center of mass of the disk-block system. Explain how you arrived at your prediction without deriving it mathematically.
- iii. Now suppose that neither object's mass is much greater than the other but that they are not necessarily equal. Derive an equation for  $v_{\text{cm}}$ . Express your answer in terms of  $v_1$ ,  $M_D$ ,  $M_B$ , and physical constants, as appropriate.
- iv. Consider the scenario from part (c)(i), where the mass of the disk was much greater than the mass of the block. Does your equation for  $v_{\text{cm}}$  from part (c)(iii) agree with your reasoning from part (c)(i) ?  
\_\_\_\_ Yes      \_\_\_\_ No  
Explain your reasoning by addressing why, according to your equation,  $v_{\text{cm}}$  becomes (or approaches) a certain value when  $M_D$  is much greater than  $M_B$ .

**GO ON TO THE NEXT PAGE.**

Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

## 2. (12 points, suggested time 25 minutes)

A new kind of toy ball is advertised to “bounce perfectly elastically” off hard surfaces. A student suspects, however, that no collision can be perfectly elastic. The student hypothesizes that the collisions are very close to being perfectly elastic for low-speed collisions but that they deviate more and more from being perfectly elastic as the collision speed increases.

- (a) Design an experiment to test the student’s hypothesis about collisions of the ball with a hard surface. The student has equipment that would usually be found in a school physics laboratory.
- What quantities would be measured?
  - What equipment would be used for the measurements, and how would that equipment be used?
  - Describe the procedure to be used to test the student’s hypothesis. Give enough detail so that another student could replicate the experiment.
- (b) Describe how you would represent the data in a graph or table. Explain how that representation would be used to determine whether the data are consistent with the student’s hypothesis.
- (c) A student carries out the experiment and analysis described in parts (a) and (b). The student immediately concludes that something went wrong in the experiment because the graph or table shows behavior that is elastic for low-speed collisions but appears to violate a basic physics principle for high-speed collisions.
- Give an example of a graph or table that indicates nearly elastic behavior for low-speed collisions but appears to violate a basic physics principle for high-speed collisions.
  - State one physics principle that appears to be violated in the graph or table given in part (c)i. Several physics principles might appear to be violated, but you only need to identify one.

Briefly explain what aspect of the graph or table indicates that the physics principle is violated, and why.