2019

AP® CollegeBoard

AP® Physics C: Mechanics

Sample Student Responses and Scoring Commentary Set 2

Inside:

Free Response Question 1

☑ Scoring Guideline

☑ Student Samples

☑ Scoring Commentary

General Notes About 2019 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.

2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf.

3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections — Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.

5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.

6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

Question 1

15 points

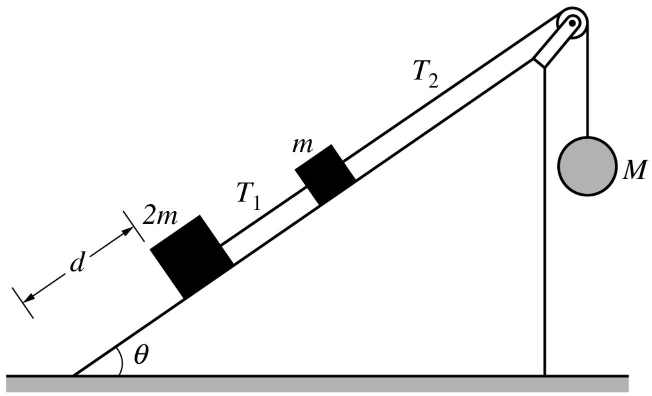
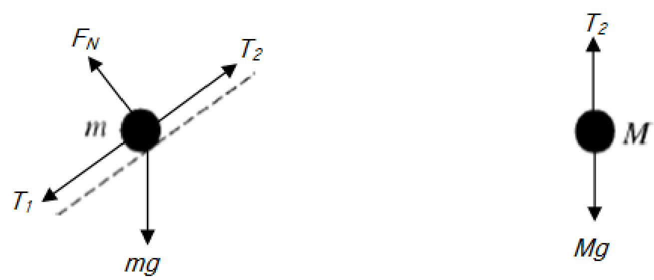


Figure 1

Blocks of mass m and $2m$ are connected by a light string and placed on a frictionless inclined plane that makes an angle θ with the horizontal, as shown in Figure 1 above. Another light string connecting the block of mass m to a hanging sphere of mass M passes over a pulley of negligible mass and negligible friction. The entire system is initially at rest and in equilibrium.

(a) LO INT-1.A, SP 3.D
3 points

On the dots below that represent the block of mass m and the sphere of mass M, draw and label the forces (not components) that act on each of the objects shown. Each force must be represented by a distinct arrow starting on and pointing away from the dot.



For correctly drawing and labeling vectors representing the normal force and the gravitational force on the block of mass m		1 point
For correctly drawing and labeling vectors representing the forces of tension on the block of mass m		1 point
For correctly drawing and labeling vectors representing the tension force and the gravitational force on the sphere of mass M		1 point
Note: A maximum of two points can be earned if there are any extraneous vectors.		

Question 1 (continued)

(b)

Derive expressions for the magnitude of each of the following. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figures in part (a).

i. LO INT-1.C.e, SP 1.D, 5.E
2 points

The force T_2 exerted on the block of mass m by the string. Express your answers in terms of m, θ, and physical constants, as appropriate.

For using an attempt at a correct statement of Newton's second law for the two blocks		1 point
$F_{net} = (m + 2m)a = 0 \therefore T_2 - (m + 2m)g\sin\theta = 0$		
For a correct answer with supporting work		1 point
$T_2 = 3mg\sin\theta$		

ii. LO INT-1.D, SP 5.E
1 point

The mass M for which the system can remain in equilibrium. Express your answers in terms of m, θ, and physical constants, as appropriate.

For using a correct statement of Newton's second law for the whole system to derive an expression for M		1 point
$F_{net} = m_{tot}a \therefore Mg - 2mg\sin\theta - mg\sin\theta = 0$		
$M = 3m\sin\theta$		
Alternate Solution		*Alternate Points*
For a correct statement of Newton's second law for the sphere and an answer consistent with part (b)(i)		1 point
$T_2 - Mg = 0 \therefore Mg = T_2 \therefore M = T_2/g$		
$M = 3m\sin\theta$		

Question 1 (continued)

(c)

Now suppose that mass M is large enough to descend and that the sphere reaches the floor before the blocks reach the pulley. Answer the following for the moment immediately after the sphere reaches the floor.

i. LO INT-1.D, SP 7.A
1 point

Does the tension T_1 increase, decrease to a nonzero value, decrease to zero, or stay the same?

____ Increase ____ Decrease to a nonzero value

____ Decrease to zero ____ Stay the same

For correctly stating that the magnitude of T_1 drops to zero		1 point

ii. LO INT-1.D, SP 7.A
1 point

Is the velocity of the block of mass m up the ramp, down the ramp, or zero?

_____ Up the ramp _____ Down the ramp _____ Zero

For selecting "Up the ramp"		1 point

iii. LO INT-1.D, SP 7.A
1 point

Is the acceleration of the block of mass m up the ramp, down the ramp, or zero?

_____ Up the ramp _____ Down the ramp _____ Zero

For selecting "Down the ramp"		1 point

(d) LO INT-1.D, SP 5.A, 5.E
3 points

Consider the initial setup in Figure 1. Now suppose the surface of the incline is rough and the coefficient of static friction between the blocks and the inclined plane is μ_s. Derive an expression for the minimum possible value of M that will keep the blocks from moving down the incline. Express your answer in terms of m, μ_s, θ, and fundamental constants, as appropriate.

For an attempt at a correct statement of Newton's second law for the system		1 point
$F_{net} = m_{tot}a \therefore 2mg\sin\theta - f_{s2} + mg\sin\theta - f_{s1} - Mg = 0$		
For attempting to substitute in for the force of friction		1 point
$3mg\sin\theta - \mu_s F_{N2} - \mu_s F_{N1} = Mg$		
$3mg\sin\theta - \mu_s(2mg\cos\theta) - \mu_s(mg\cos\theta) = Mg$		
For a correct answer with supporting work		1 point
$M = 3m(\sin\theta - \mu_s\cos\theta)$		

Question 1 (continued)

(e) LO INT-1.D, CHA-1.A.b, SP 5.A, 5.E
3 points

The string connecting block m and the sphere of mass M then breaks, and the blocks begin to move from rest down the incline. The lower block starts a distance d from the bottom of the incline, as shown in Figure 1. The coefficient of kinetic friction between the blocks and the inclined plane is μ_k. Derive an expression for the speed of the blocks when the lower block reaches the bottom of the incline. Express your answer in terms of m, d, μ_k, θ, and fundamental constants, as appropriate.

For an attempt at a correct statement of Newton's second law for the two blocks		1 point
$F_{\text{net}} = m_{tot}a \therefore 2mg\sin\theta - f_{k2} + mg\sin\theta - f_{k1} = 3ma$		
Solve for the acceleration		
$3mg\sin\theta - \mu_k(2mg\cos\theta) - \mu_k mg\cos\theta = 3ma$		
$a = g(\sin\theta - \mu_k\cos\theta)$		
For using a correct kinematics equation to solve for the final velocity		1 point
$v_2^2 = v_1^2 + 2ad$		
$v_2^2 = 0^2 + 2g(\sin\theta - \mu_k\cos\theta)d$		
For a correct answer with supporting work		1 point
$v = \sqrt{2gd(\sin\theta - \mu_k\cos\theta)}$		
Alternate Solution		*Alternate Points*
For an attempt at a correct statement of conservation of energy for the two blocks		*1 point*
$U_1 + K_1 = U_2 + K_2 + E_{\text{lost}}$		
$2mgh + mgh + 0 = 0 + \frac{1}{2}(2m)v^2 + \frac{1}{2}mv^2 + fd$		
For correct substitutions of height and friction		*1 point*
$3mgd\sin\theta = \frac{1}{2}(3m)v^2 + \mu_k(2mg\cos\theta)d + \mu_k(mg\cos\theta)d$		
$3gd\sin\theta - 3\mu_k gd\cos\theta = \frac{3}{2}v^2$		
For a correct answer with supporting work		*1 point*
$v = \sqrt{2gd(\sin\theta - \mu_k\cos\theta)}$		

Question 1 (continued)

Learning Objectives

CHA-1.A.b: Calculate unknown variables of motion such as acceleration, velocity, or positions for an object undergoing uniformly accelerated motion in one dimension.
INT-1.A: Describe an object (either in a state of equilibrium or acceleration) in different types of physical situations such as inclines, falling through air resistance, Atwood machines, or circular tracks).
INT-1.C.e: Derive a complete Newton's second law statement (in the appropriate direction) for an object in various physical dynamic situations (e.g., mass on incline, mass in elevator, strings/pulleys, or Atwood machines).
INT-1.D: Calculate a value for an unknown force acting on an object accelerating in a dynamic situation (e.g., inclines, Atwood Machines, falling with air resistance, pulley systems, mass in elevator, etc.)

Science Practices

1.D: Select relevant features of a representation to answer a question or solve a problem.
3.C: Sketch a graph that shows a functional relationship between two quantities.
3.D: Create appropriate diagrams to represent physical situations.
5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
7.A: Make a scientific claim.

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

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

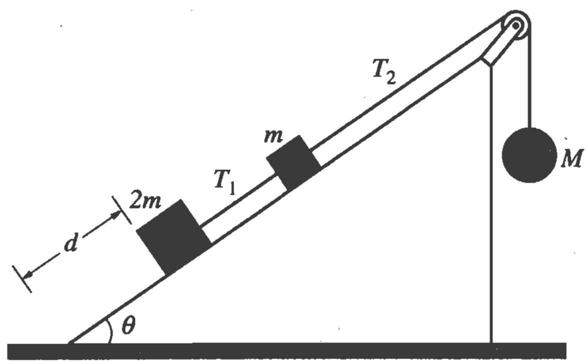


Figure 1

1. Blocks of mass m and $2m$ are connected by a light string and placed on a frictionless inclined plane that makes an angle θ with the horizontal, as shown in Figure 1 above. Another light string connecting the block of mass m to a hanging sphere of mass M passes over a pulley of negligible mass and negligible friction. The entire system is initially at rest and in equilibrium.

(a) On the dots below that represent the block of mass *m* and the sphere of mass *M*, draw and label the forces (not components) that act on each of the objects shown. Each force must be represented by a distinct arrow starting on and pointing away from the dot.

(b) Derive expressions for the magnitude of each of the following. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figures in part (a).

i. The force T_2 exerted on the block of mass *m* by the string. Express your answers in terms of *m*, θ, and physical constants, as appropriate.

$T_1 + F_g = T_2$

$2mg\sin\theta + mg\sin\theta = T_2$

$\boxed{3mg\sin\theta = T_2}$

ii. The mass *M* for which the system can remain in equilibrium. Express your answers in terms of *m*, θ, and physical constants, as appropriate.

$Mg = T_2$

$\frac{Mg}{g} = \frac{3mg\sin\theta}{g}$

$\boxed{M = 3m\sin\theta}$

Question 1 continues on the next page.

GO ON TO THE NEXT PAGE.

(c) Now suppose that mass M is large enough to descend and that the sphere reaches the floor before the blocks reach the pulley. Answer the following for the moment immediately after the sphere reaches the floor.

i. Does the tension T_1 increase, decrease to a nonzero value, decrease to zero, or stay the same?

____ Increase ____ Decrease to a nonzero value

X Decrease to zero ____ Stay the same

ii. Is the velocity of the block of mass m up the ramp, down the ramp, or zero?

X Up the ramp _____ Down the ramp _____ Zero

iii. Is the acceleration of the block of mass m up the ramp, down the ramp, or zero?

_____ Up the ramp X Down the ramp _____ Zero

(d) Consider the initial setup in Figure 1. Now suppose the surface of the incline is rough and the coefficient of static friction between the blocks and the inclined plane is μ_s. Derive an expression for the minimum possible value of M that will keep the blocks from moving down the incline. Express your answer in terms of m, μ_s, θ, and fundamental constants, as appropriate.

$$\frac{Mg}{g} = \frac{2mg\sin\theta + mg\sin\theta - 2mg\cos\theta\, \mu_s - mg\cos\theta\, \mu_s}{g}$$

$$\boxed{M = 3m\sin\theta - 3m\cos\theta\,\mu_s}$$

(e) The string connecting block m and the sphere of mass M then breaks, and the blocks begin to move from rest down the incline. The lower block starts a distance d from the bottom of the incline, as shown in Figure 1. The coefficient of kinetic friction between the blocks and the inclined plane is μ_k. Derive an expression for the speed of the blocks when the lower block reaches the bottom of the incline. Express your answer in terms of m, d, μ_k, θ, and fundamental constants, as appropriate.

$$\Sigma F = m \cdot a$$

$$\frac{3mg\sin\theta - 3mg\cos\theta\,\mu_k = 3m\cdot a}{3}$$

$$\frac{mg\sin\theta - mg\cos\theta\,\mu_k = ma}{m}$$

$g\sin\theta - g\cos\theta\,\mu_k = a$

$V_0 = 0$

$V =$

$a = g\sin\theta - g\cos\theta\,\mu_k$

$d = d$

$t =$

$\sqrt{V^2} = \sqrt{2(a)(d)}$

$$\boxed{V = \sqrt{(2)(g\sin\theta - g\cos\theta\,\mu_k)(d)}}$$

GO ON TO THE NEXT PAGE.

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

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

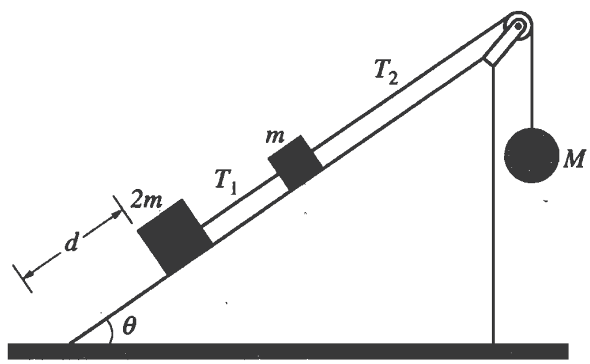
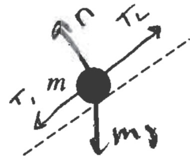


Figure 1

1. Blocks of mass m and $2m$ are connected by a light string and placed on a frictionless inclined plane that makes an angle θ with the horizontal, as shown in Figure 1 above. Another light string connecting the block of mass m to a hanging sphere of mass M passes over a pulley of negligible mass and negligible friction. The entire system is initially at rest and in equilibrium.

(a) On the dots below that represent the block of mass *m* and the sphere of mass *M*, draw and label the forces (not components) that act on each of the objects shown. Each force must be represented by a distinct arrow starting on and pointing away from the dot.



(b) Derive expressions for the magnitude of each of the following. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figures in part (a).

i. The force T_2 exerted on the block of mass *m* by the string. Express your answers in terms of *m*, θ, and physical constants, as appropriate.

$\Sigma F_y = 0$ $\Sigma F_x = 0$

$T_2 = mg\cos\theta + T_1$ $T_1 = 2mg\cos\theta$

$T_2 = mg\cos\theta + 2mg\cos\theta$

$T_2 = 3mg\cos\theta$

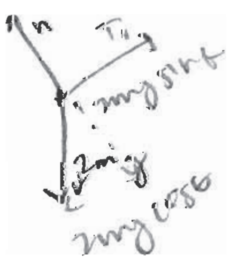
ii. The mass *M* for which the system can remain in equilibrium. Express your answers in terms of *m*, θ, and physical constants, as appropriate.

$\Sigma F_y = 0$

$Mg = T_2$

$Mg = 3mg\cos\theta$

$M = 3m\cos\theta$



Question 1 continues on the next page.

(c) Now suppose that mass M is large enough to descend and that the sphere reaches the floor before the blocks reach the pulley. Answer the following for the moment immediately after the sphere reaches the floor.

i. Does the tension T_1 increase, decrease to a nonzero value, decrease to zero, or stay the same?

____ Increase ____ Decrease to a nonzero value

____ Decrease to zero ____ Stay the same

ii. Is the velocity of the block of mass m up the ramp, down the ramp, or zero?

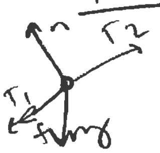
_____ Up the ramp _____ Down the ramp _____ Zero

iii. Is the acceleration of the block of mass m up the ramp, down the ramp, or zero?

_____ Up the ramp _____ Down the ramp _____ Zero

(d) Consider the initial setup in Figure 1. Now suppose the surface of the incline is rough and the coefficient of static friction between the blocks and the inclined plane is μ_s. Derive an expression for the minimum possible value of M that will keep the blocks from moving down the incline. Express your answer in terms of m, μ_s, θ, and fundamental constants, as appropriate.

$\Sigma F_x = 0$ $f = \mu_s n$



$T_2 = T_1 + mg\cos\theta + f = T_1 + mg\cos\theta + mg\sin\theta\,\mu_s$

$T_2 = 3mg\cos\theta + 3mg\,\mu_s\sin\theta$

$\Sigma F_y = 0$

$Mg = T_2$

$Mg = 3mg\cos\theta + 3mg\,\mu_s\sin\theta$

$M = 3m\cos\theta + 3m\mu_s\sin\theta$

$\Sigma F_x = 0$

$T_1 = 2mg\cos\theta + f$ $f = \mu_s n$

$T_1 = 2mg\cos\theta + \mu_s n = 2mg\cos\theta + 2mg\sin\theta\,\mu_s$

(e) The string connecting block m and the sphere of mass M then breaks, and the blocks begin to move from rest down the incline. The lower block starts a distance d from the bottom of the incline, as shown in Figure 1. The coefficient of kinetic friction between the blocks and the inclined plane is μ_k. Derive an expression for the speed of the blocks when the lower block reaches the bottom of the incline. Express your answer in terms of m, d, μ_k, θ, and fundamental constants, as appropriate.

$\Sigma F = ma$

$f = \mu_k n$

$2mg\cos\theta - f - T_1 = 2ma$

GO ON TO THE NEXT PAGE.

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

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

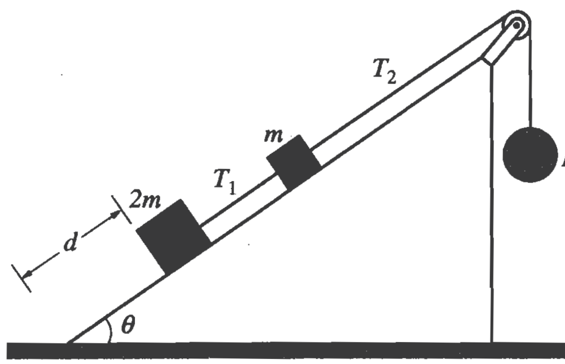
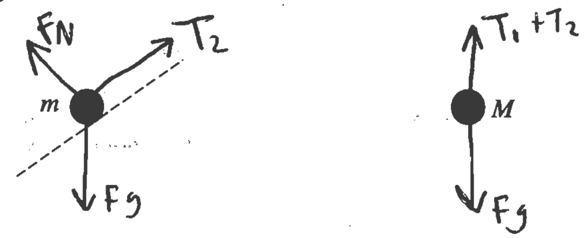


Figure 1

1. Blocks of mass *m* and 2*m* are connected by a light string and placed on a frictionless inclined plane that makes an angle θ with the horizontal, as shown in Figure 1 above. Another light string connecting the block of mass *m* to a hanging sphere of mass *M* passes over a pulley of negligible mass and negligible friction. The entire system is initially at rest and in equilibrium.

GO ON TO THE NEXT PAGE.

(a) On the dots below that represent the block of mass m and the sphere of mass M, draw and label the forces (not components) that act on each of the objects shown. Each force must be represented by a distinct arrow starting on and pointing away from the dot.



(b) Derive expressions for the magnitude of each of the following. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figures in part (a).

i. The force T_2 exerted on the block of mass m by the string. Express your answers in terms of m, θ, and physical constants, as appropriate.

$\Sigma F = 0$

$\Sigma F_x = ma_x$

$-F_N + T_2 = ma_x$

$T_2 = ma_x + F_N$

$\Sigma F_y = ma_y$

$T_2 + F_N - F_g = ma_y$

$T_2 = ma_s - F_N + F_g$

$T_2 = \frac{mg_y - F_N \sin\theta + F_g}{\cos\theta}$

$T_2 = \frac{\sin\theta}{\cos\theta}$

ii. The mass M for which the system can remain in equilibrium. Express your answers in terms of m, θ, and physical constants, as appropriate.

$\Sigma F = 0$

$\Sigma F_x = ma_x$

$0 = ma_x$

$0 = ma_x$

$\Sigma F_y = ma_y$

$T_1 + T_2 - F_g = ma_y$

$a_y = g$

$T_1 + T_2 - mg = mg$

$+mg \quad +mg$

$T_1 + T_2 = 2(mg)$

$\frac{T_1 + T_2}{2} = mg$

$\frac{T_1 + T_2}{2g} = m$

Question 1 continues on the next page.

GO ON TO THE NEXT PAGE.

(c) Now suppose that mass M is large enough to descend and that the sphere reaches the floor before the blocks reach the pulley. Answer the following for the moment immediately after the sphere reaches the floor.

i. Does the tension T_1 increase, decrease to a nonzero value, decrease to zero, or stay the same?

____ Increase ____ Decrease to a nonzero value

____ Decrease to zero __X__ Stay the same

ii. Is the velocity of the block of mass m up the ramp, down the ramp, or zero?

__X__ Up the ramp _____ Down the ramp _____ Zero

iii. Is the acceleration of the block of mass m up the ramp, down the ramp, or zero?

_____ Up the ramp __X__ Down the ramp _____ Zero

(d) Consider the initial setup in Figure 1. Now suppose the surface of the incline is rough and the coefficient of static friction between the blocks and the inclined plane is μ_s. Derive an expression for the minimum possible value of M that will keep the blocks from moving down the incline. Express your answer in terms of m, μ_s, θ, and fundamental constants, as appropriate.

$f_s = F_N \cdot \mu_s$
$= mg \cdot \mu_s$

$M = \frac{T_1 + T_2}{2g} + F_N \cdot \mu_s$

$M = \frac{T_1 + T}{2g} - m g \cdot \mu_s$

(e) The string connecting block m and the sphere of mass M then breaks, and the blocks begin to move from rest down the incline. The lower block starts a distance d from the bottom of the incline, as shown in Figure 1. The coefficient of kinetic friction between the blocks and the inclined plane is μ_k. Derive an expression for the speed of the blocks when the lower block reaches the bottom of the incline. Express your answer in terms of m, d, μ_k, θ, and fundamental constants, as appropriate.

$v_f^2 = v_i^2 + 2a\Delta x$

Question 1

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses to this question were expected to demonstrate the following:

- Problem-solving strategies that would allow students to break down a complex problem into manageable pieces
- An understanding of Newton's laws and an ability to apply Newton's second law to form one or more algebraic expressions
- Apply Newton's third law to couple these algebraic expressions and simplify them
- Apply algebra and trigonometry to arrive at the correct answer

Sample: M Q1 A
Score: 15

This paper earned full credit. In part (a) 3 points were earned for correctly drawing and labeling the vectors representing tension force and weight for mass M, for correctly drawing and labeling vectors representing the normal force and weight for mass m, and for correctly drawing and labeling vectors representing the tension forces acting on mass m. In part (b)(i) 2 points were earned for correctly deriving an expression for T_2. In part (b)(ii) 1 point was earned for a correct statement of Newton's second law to derive an expression for M. In parts (c)(i), (c)(ii), and (c)(iii), 1 point each was earned for choosing "Decrease to zero," "Up the ramp," and "Down the ramp," respectively. Part (d) uses Newton's second law on the system, correctly substitutes the force of friction, and derives the correct expression for M, so 3 points were earned. In part (e) 3 points were earned for using Newton's second law and solving for acceleration, using an appropriate kinematics equation to solve for velocity, and deriving the correct expression for v.

Sample: M Q1 B
Score: 7

Parts (a) and (b)(ii) received full credit, 3 points and 1 point, respectively. In part (b)(i) use of Newton's second law on both blocks is shown, but the final derived expression is not consistent with required variables, so 1 point was earned. Parts (c)(i), (c)(ii), and (c)(iii) did not earn any points because no choices are indicated. Part (d) uses Newton's second law on the system and correctly substitutes the force of friction, but the final expression is incorrect, so 2 points were earned. In part (e) no points were earned because no attempt at solving for acceleration is shown.

Sample: M Q1 C
Score: 4

Part (a) correctly draws and labels vectors representing the normal force and weight for mass m, but the vector for the force of tension on M is incorrectly labeled and the vector representing T_1 is not shown, so 1 point was earned. In part (b)(i) no points were earned because an attempt at using Newton's second law is only shown for block m, the derived expression is incorrect and inconsistent with any prior results. In part (b)(ii) the expression derived for M is inconsistent with part (b)(i), so no points were earned. In part (c)(i) an incorrect choice is chosen, so no points were earned. In parts (c)(ii) and (c)(iii) 1 point each was earned for choosing "Up the ramp," and "Down the ramp," respectively. In part (d) there is an attempt to substitute the force of friction, but the expression derived for M is inconsistent with the question, so 1 point was earned. In part (e) no points were earned because no attempt at solving for acceleration is shown.