<u>Coding Scheme</u>

Evidence of mechanistic reasoning (MR):

1. *Objects*: Identifying the central entities that interact to form the physical phenomena in a single hierarchical level. These objects have properties, spatial layout, and movement relevant to the solution process. Both directions of possible object ←→ object interaction are relevant to the phenomena.

   Word Examples: “car”, “box”, “ball”, “people”, “particles”.

   Problem 4 Example: “If 3 people were pushing the <u>box</u> but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the velocity was going upwards, the box might move at a slant.”

2. Influences: Identifying the non-central environmental entities that interact with objects. Only the influence → object interaction is relevant to the phenomena.

   Phrase Examples: “Earth’s gravitational field”, “human hand”, “electro-magnetic field”.

   Problem 4 Example: “If <u>3 people</u> were pushing the box but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the velocity was going upwards, the box might move at a slant.”

3. *Properties:* Identifying the relevant qualities that are confined to the physical boundary of an object.

   Word Examples: “mass”, “temperature”, “volume”.

   Problem 4 Example: “Force is responsible for the change in the velocity of the <u>mass, in this case the box</u>, and change in velocity is just acceleration.”

4. *Spatial Organization:* Identifying the spatial states or orientations of an object.

   Word Examples: “downwards”, “upwards”, “left”, “right”, “x-direction”, “y-direction”.

   Problem 4 Example: “If 3 people were pushing the box but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the <u>velocity was going upwards</u>, the box might move at a slant."

5. *Movement Activities*: Identifying the motion states of an object.

   Phrase Examples: "initial velocity", "slowing", "speeding", "experience acceleration"

   Problem 4 Example: "If 3 people were pushing the box but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the velocity was going upwards, the box might move at a slant."

6. *Interactions*: Identifying the physical exchanges between all object ←→ object and influence → object pairs.

   Phrase Examples: "gravitational force", "human pushing", "electromagnetic force".

   Problem 4 Example: "If 3 people were pushing the box but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the velocity was going upwards, the box might move at a slant."

   Problem 4 Non-Examples: "Affected by a constant acceleration (g)", "related to acceleration due to gravity"

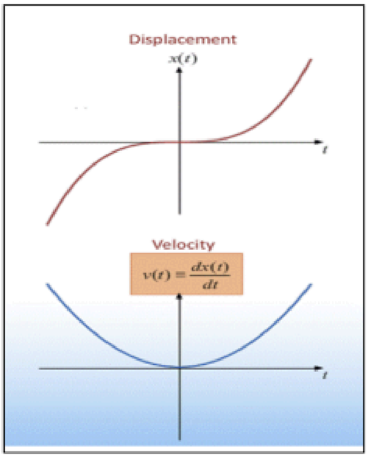
7. Chaining. Identifying the characteristic (a property, spatial organization, or activity) changes that result from specific object ←→ object interactions and influence → object interactions.

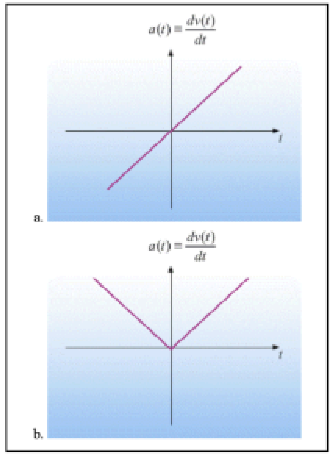
   Phrase Examples: "constant acceleration of a ball caused by Earth's gravitational field exerting a downward net force"; "acceleration of a book initially at rest caused by a human push".

   Problem 4 Example: "If 3 people were pushing the box but one person was pushing harder than the rest, the box would accelerate in the same direction as the greater force. However, with velocity, the final velocity has to take into account the initial velocity. Though the acceleration might go to the right, if the velocity was going upwards, the box might move at a slant."

Physics Problems:

Problem 1





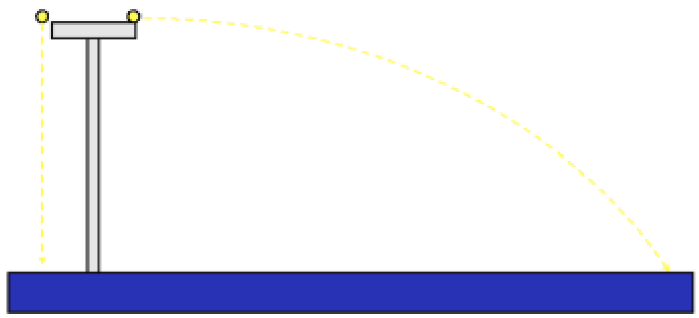
1. Which plot best represents the acceleration curve associated with the displacement and velocity curves shown here?

2. Briefly explain your answer to the previous question.

Annotation Procedure 1

(1) Does the student identify the object (object, car, etc.)?
(2) Does the student identify the object orientation (e.g. left or right)?
(3) Does the student identify movement 1 of the object(e.g. slow down)?
(4) Does the student identify movement 2 of the object (e.g. zero)?
(5) Does the student identify movement 3 of the object (e.g. speed up)?
(6) Does the student connect the formal language 1 to the concepts in the mechanism (e.g position of an entity changing is a pos/neg velocity)?
(7) Does the student connect the formal language 2 to the concepts in the mechanism (e.g velocity changes is a pos/neg acceleration)?

Problem 2



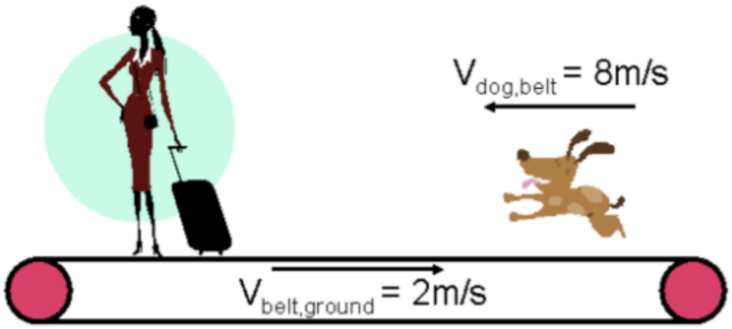
A physics demo launches a ball horizontally while dropping a second ball vertically at exactly the same time.
1. Which ball hits the ground first?
(a) Dropped ball
(b) Launched (horizontally) ball
(c) Both hit at the same time

2. Briefly explain your answer to the previous question.

Annotation Procedure 2

(1) Does the student identify object 1 (e.g. ball 1)?
(2) Does the student identify object 2 (e.g. ball 2)?
(3) Does the student identify the possible environmental influences on object 1 (e.g. gravity)?
(4) Does the student identify the possible environmental influences on object 2 (e.g. gravity)?
(5) Does the student identify object 1 spatial organization (e.g. down)?
(6) Does the student identify object 2 spatial organization (e.g. horizontal up)?
(7) Does the student identify object 1 motion post the drop (e.g. speeding up)?
(8) Does the student identify object 2 motion post the drop (e.g. speeding up)?
(9) Does the student identify the interaction between object 1 and gravity (e.g. gravitational force)?
(10) Does the student identify the interaction between object 2 and gravity (e.g. gravitational force)?
(11) Does the student identify the mechanistic relationship between gravity and a change in motion (e.g. Earth's gravitational force is a mechanism that causes the object to move down at a constantly increasing speed)?

Problem 3



A girls stands on a moving sidewalk (conveyor belt) that is moving to the right at a speed of 2 m/s relative to the ground. A dog runs on the belt toward the girl at a speed of 8 m/s/ relative to the belt.

1. What is the speed of the dog relative to the girl?
(a) 10 m/s
(b) 6 m/s
(c) 8 m/s

Annotation Procedure 3

(1) Does the student identify object 1 (e.g. girl)?
(2) Does the student identify object 2 (e.g. dog)?
(3) Does the student identify object 3 (e.g. moving sidewalk, conveyor belt)?
(4) Does the student identify the spatial organization of the dog (e.g. left)?
(5) Does the student identify the spatial organization of the belt (e.g. right)?
(6) Does the student identify the movement of the girl (e.g. at rest)?
(7) Does the student identify the movement of the dog (e.g. 8m/s constant speed)?
(8) Does the student identify the movement of the belt (e.g. 2 m/s constant speed)?
(9) Does the student identify the interaction between the girl and the belt (e.g. moving her to the right)?
(10) Does the student identify the interaction between the dog and the belt (e.g moving the dog to the right)?
(11) Does the student identify the mechanistic relationship between motion of the observer and motion of the observed? (e.g. the observer moving relative to the object impacts the observed motion of the object)

Problem 4

1. The net force on a box is in the positive x direction. Which of the following statements best describes the motion of the box?
(a) Its acceleration is parallel to the x axis.
(b) Its velocity is parallel to the x axis.
(c) Both its velocity and acceleration are parallel to the x axis.
(d) Neither its velocity not its acceleration need to be parallel to the x axis.

Annotation Procedure 4

(1) Does the student identify the object (e.g. object, box, etc.)?
(2) Does the student identify the possible environmental influence acting on the object (e.g. applied net force)?
(3) Does the student identify the object properties (e.g. mass)?
(4) Does the student identify the object spatial organization before applied force (e.g. upwards)?
(5) Does the student identify the object spatial organization after applied force (e.g. horizontal)?
(6) Does the student identify the object movement prior to the applied force (e.g. constant velocity)?
(7) Does the student identify the object movement after the applied force (e.g. final velocity)?
(8) Does the student identify the interaction between the object and the net applied force (e.g. change in direction)?
(9) Does the student identify the mechanistic relationship between an applied net force and a change in motion? (e.g. a net force applied in the x direction will be a mechanism that causes a change in motion/acceleration in the x direction)

<u>Specific rules that emerged from all IRR discussions:</u>

Rule for domain 1: The student must describe an object prior to using pronouns rather than only using a pronoun term such as "they". If the problem contains more than one object and the student refers to only one object rather than two, this object is taken to be object 1. If they only mention pronouns, it's a 0 for all potential objects.

Rule for domains 2-6: The student has to explicitly relate all object influences, properties, activities, and spatial organizations to the object. This means that the student MUST mention an object for there to be evidence of the other domains.

Rule for domain 4: The student must describe *specific* orientations of objects.

Phrase Examples: "Upward", "downward", "the vertical direction towards the ground", "the ball dropped vertically, "the ball launched horizontally", etc.

Rule for domains 3 and 5: The student can be less specific with their descriptions of object's properties and motion.

Phrase Examples: "The object has mass" or "The ball has a constant velocity".

Rule for domain 6: The student can describe the influences/objects touching and can be less specific as to *how* they are touching.

Phrase Examples: "The girl is on the belt" or "The hand is pushing the box".

Rule for all domains: Students can make analogies and do not have to refer to the object in question.

Problem 2 Example: "Honestly I thought of the example of the <u>bullet</u> leaving the gun in the pre-lecture video. Even though one of the bullets was <u>being shot out of a gun</u> and the other it was <u>being dropped straight down</u>, they're being dropped at the same height."

*We note that these were specific decisions made by the first author in the original coding. All rules can (and should be) re-evaluated for utility in future iterations of this coding scheme.