

Newton's Second Law: Force, Velocity and Acceleration

Duration:
2-3 class periods

Essential Question:

What are the relationships between force, mass, and acceleration?

Objectives: Students will...

- see that an unbalanced force acting on a mass will accelerate it.
- relate the motion and velocity of an object to its acceleration.
- interpret graphs of simple motions (optional).

Science Concept:

Newton's Second Law tells us that a net force acting on an object will change its velocity by changing either its speed or its direction or both.

About this Poster

The Swift Gamma-Ray Burst Explorer is a NASA mission which is observing the highest energy explosions in the Universe—gamma-ray bursts (GRBs). Launched in November, 2004, Swift is detecting and observing hundreds of these explosions, vastly increasing scientists' knowledge of these enigmatic events. Education and public outreach (E/PO) is one of the goals of the mission. The NASA E/PO Group at Sonoma State University develops classroom activities inspired by the science and technology of the Swift mission, which are aligned with the national standards. The front of the poster illustrates Newton's Second Law, demonstrating how a mass is accelerated when a force is applied to it. Descriptions of the drawings can be found on the next page. This poster and activity are part of a set of four educational wallsheets which are aimed at grades 6-9, and which can be displayed as a set or separately in the classroom.

The activity provides several simple illustrations of Newton's Second Law. The activity is complete and ready to use in your classroom with only paper and pencils. The activity is designed and laid out so that you can easily make copies of the student worksheet and the other handouts.

The NASA E/PO Group at Sonoma State University:

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The Swift Education and Public Outreach website is:

<http://swift.sonoma.edu>

This poster and other Swift educational materials can be found at:

<http://swift.sonoma.edu/education/>

National Science Education Standards and Mathematics Standards for the set of four Newton's Law wallsheets can be found at:

<http://swift.sonoma.edu/education/newton/standards.html>

Description of the Front of the Poster:

Waterfall: As the water flows over the edge of the rocks, gravity, which exerts a downward force on it, causes it to accelerate downward: the water moves faster the longer it falls.

Girl throwing a ball: When the girl throws the ball, she is applying a force to it and accelerating it. As soon as she lets go, gravity, which also applies a force, accelerates the ball downward.

Cube being pulled to the upper right: A heavy cube sits on a surface. If someone applies a force to it that is stronger than the effect of gravity and the frictional forces on it, then the object will accelerate.

Girl on a swing: When a girl swings, gravity accelerates her downward from the top of her arc. Her inertia keeps her moving at the bottom, and the force of the tension in the ropes makes her move in an arc upwards. Gravity then pulls her down, decelerating her until she stops, and the motion repeats. Note: We generally use the word deceleration to mean that something slows down, while acceleration means that something speeds up. In Newton's laws, any change in velocity is called an acceleration, so a deceleration is really a type of

acceleration. This can be a little confusing at first, so just remember that any change in speed or direction is referred to as an acceleration for the purposes of Newton's laws.

Swivel chair: The velocity of an object includes its speed and its direction. Acceleration is the change in velocity, so changing the speed and/or the direction of an object is an acceleration. In a swivel chair, the woman feels an acceleration because her direction is constantly changing as she spins.

Baseball player: A baseball player applies a large force to a baseball, accelerating it to high velocity. If the ball had more mass, that same force would not accelerate the ball to such a high velocity.

Cars: When a driver hits the gas, the wheels apply a force on the ground due to friction. This force accelerates the car forward. The brakes apply a force to the wheels, which in turn apply a frictional force to the ground, decelerating the car. So the gas pedal and the brakes are both accelerators, since they change the speed of the car. Because velocity is the combination of speed and direction, the steering wheel is an accelerator too! It changes the direction, and therefore the velocity of the car.

Background Information for Teachers:

Newton's Second Law takes up where the First Law ends. The First Law describes inertia: A body will not change its existing state of motion unless an unbalanced force acts on that body. In other words, without an unbalanced force, a body will remain still if still, or, if moving, keep moving in the same direction at a constant speed.

But what happens when an unbalanced force acts on an object? The Second Law tells us that this type of force will change the velocity of an object by changing either its speed or its direction or both. Such changes in velocity are called acceleration. So, we can say that any unbalanced force acting on an object produces acceleration.

The Second Law goes on to mathematically define the exact relationship between force and acceleration: The acceleration of an object is directly proportional to the sum of all the forces acting on it and is inversely proportional to its mass. Mass is simply the measure of the quantity of matter that makes up an object. The more mass an object has, the more difficult it is to change its state of motion, whether it is at rest or moving in a straight line at a constant speed. Think of it this way: An elephant has more mass than a mouse. It is much harder to push an elephant across a floor than it is a mouse, and much harder to stop the elephant once it is moving. We can also say that the elephant has much more inertia than does a mouse – inertia and mass are just different ways of expressing the same concept.

Also, the direction of the acceleration is in the direction of the unbalanced (net) force acting on the object. More simply, and as Newton put it: $\mathbf{F} = m\mathbf{a}$, where “ \mathbf{F} ” (force) and “ \mathbf{a} ” (acceleration) are both vector quantities, meaning they have a magnitude and a direction (we use boldface type to remind us of this), and “ m ” is the object's mass. Note that the “ \mathbf{F} ” in this equation is the net force, that is, the vector sum of all the forces acting on the object.

Pre-Activity Reading:

Newton's Second Law and the Swift Satellite

Swift has a mass of about 1470 kilograms, which is about the same total mass as 20 people! In order to get the Swift satellite into orbit, it was launched from a Boeing Delta rocket which had a mass of about 231,800 kg. With Swift inside the rocket, the combined mass of the two, $m = 233,270$ kg! According to Newton's First Law, on the launch pad, both Swift and its rocket remain at rest until the rocket boosters begin to fire. At this moment, the Earth's gravity pulls the rocket (with Swift inside) down with a force of about 2,286,000 newtons. We can calculate this using Newton's Second Law, $F_{\text{gravity}} = ma = mg$, where on the Earth's surface the gravitational acceleration $g = -9.8$ m/s² in a direction pointing down towards the Earth. But by burning fuel, the rocket's boosters can exert an upward force of about $F_{\text{booster}} = 2,722,000$ newtons. As the rocket lifts off, its booster rockets exert an unbalanced upward force of $F_{\text{total}} = F_{\text{booster}} - F_{\text{gravity}} = 2,722,000$ newtons - 2,286,000 newtons = 436,000 newtons. With a total mass of 233,270 kg, the rocket accelerated upward at a rate of 1.8 meters per second per second ($a = F_{\text{total}}/m$). In other words, for every second of travel time the rocket will increase its velocity by almost 2 meters per second (See Fig.1.)

Additional information for advanced students (optional):

The motion of Swift and its rocket is really a bit more complicated - they do not travel in a straight line vertically up from the Earth's surface. To understand what really happens, we need to remember Newton's First Law: an object traveling in a straight line will continue its motion in a straight line, unless acted on by an unbalanced force. And we need to remember that the Earth is spinning! So Swift and its rocket are also moving in the direction of the Earth's spin at the time that they leave the Earth's surface.

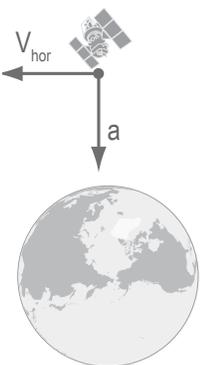


Fig. 2

Figure 2: Swift orbiting the Earth: Swift has horizontal velocity V_{hor} from a combination of the Earth's spin and repeated firings of the rocket's second stage. Swift is also constantly accelerating towards the Earth due to the force of gravity

Vectors are not part of the 6-9 grade standards, and so they will not be mentioned again on these posters. This introduction to them was added for the benefit of the instructor. In SI units, mass is measured in kilograms, acceleration is in meters per second per second, and the unit of force is the newton (N). One newton is the force required to impart an acceleration of 1 m/sec² to a mass of 1 kg (1N = 1 kg m/sec²). By the way, the newton unit of measurement was named in honor of Sir Isaac himself.

Fig 1:
The forces acting on the rocket: F_{booster} is the force from the rocket boosters, and it pushes the rocket away from the Earth. F_{gravity} is the force on the rocket from the Earth's gravity, which pulls it back towards the Earth. Note that F_{booster} is greater than F_{gravity} , as shown by comparing the size of the arrows.

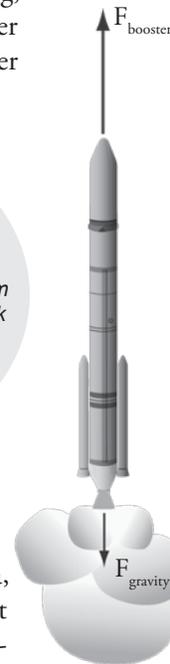


Fig. 1

The eastward velocity of the spinning Earth at Cape Canaveral, Florida, which is at a latitude of about 28.5 degrees north of the Equator, is about 400 m/s. This gives Swift a horizontal motion or velocity that will continue unchecked, since there are no horizontal forces to counteract this motion. In addition, Swift's rocket's second stage was fired at three different times during its first orbit around the Earth to add additional acceleration that increased Swift's horizontal velocity. (Swift was launched at 12:16 PM on November 20, 2004. The second stage fired from 12:20 – 12:26 PM, from 12:42 to 12:44 PM and again, very briefly, at 1:27 PM.)

By the time the rocket boosters have burned all their fuel and have released Swift into orbit around the Earth, the only force acting on Swift is that of the Earth's gravity, but Swift still maintains its horizontal velocity that arose from the Earth's spin and the sum of the horizontal velocities gained due to the three periods of time when the second stage rocket fired. It is the balance between this horizontal velocity and the downward acceleration due to gravity that keeps Swift orbiting the Earth for many years. (Eventually the small amount of air pushing on Swift in the Earth's atmosphere at the height of Swift's 600 km orbit will slow down its horizontal motion, gravity will prevail and Swift will return to Earth. But this is not expected to happen for many years.)

Pre-Activity Discussion:

The goal of this pre-activity discussion is to relate the motion and velocity of the objects to the forces acting on them and to their acceleration for several familiar situations.

It may be helpful to point to the poster and to write the questions below on the board. Alternatively, you may wish to have some students drop or throw a ball as described, and have others predict the motion. Discussions of velocity, acceleration and forces can then follow the demonstrations and predictions.

For each of the following events:

- 1) A ball dropped straight down to the ground
- 2) The ball thrown straight up into the air
- 3) The ball thrown horizontally with respect to the ground (see poster).
- 4) *Optional for advanced students:* A ball thrown at a target on the ground from a person sitting on a spinning chair (see poster).

Answers to Pre-Activity Discussion:

- 1 A. The path is shown in cartoon 1, in the in-class activity below.
B. The velocity of the ball is zero before it is dropped.
C. The direction of the velocity is straight down.
D. The only force that acts on the ball is the force of gravity.
E. The acceleration of the ball is due to the force of gravity and is towards the Earth (or $g = -9.8 \text{ m/sec}^2$).
- 2 A. The path is shown by cartoon 2 in the in-class activity below.
B. The velocity of the ball is zero before it is thrown.
C. The direction of the velocity is straight up until the ball reaches the peak of its trajectory. Afterwards, it is straight down. (In cartoon 2, we have the ball caught by a hand at the peak of its trajectory. However, the path down looks identical to the path up.)
D. The only force that acts on the ball is the force of gravity.
E. The acceleration of the ball is due to the force of gravity and is towards the Earth (or $g = -9.8 \text{ m/sec}^2$).
- 3 A. The path of the ball is shown by cartoon 3 in the in-class activity below.
B. The velocity of the ball is zero before it is thrown.
C. The direction of the velocity is initially all horizontal, however, as gravity acts on the ball, a vertical component of the velocity is created, causing a trajectory that is curved towards the ground. At the time that the ball hits the ground, it has both horizontal and vertical components.

Ask the students:

- A. What kind of path will the ball take? What shape will that path be?
- B. What is the velocity of the ball before it is thrown or dropped?
- C. What is the direction of the velocity of the ball after it is thrown or dropped?
- D. What forces act on the ball after it is thrown or dropped?
- E. What is the acceleration of the ball after it is thrown or dropped?

- D. The only force that acts on the ball is the force of gravity.
- E. The acceleration of the ball is due to the force of gravity and is towards the Earth (or $g = -9.8 \text{ m/sec}^2$).

4 Optional

- A. See fig.3.
- B. The velocity of the ball is due to the velocity of the spinning chair.
- C. The ball has a velocity component due to motion of the spinning chair, and another velocity component due to being thrown, which may be part horizontal and part vertical, or perhaps just purely horizontal (This latter case is what is shown in the figure). Another component of the velocity is created by the acceleration due to gravity. The sum of all three velocities: the initial velocity from the spinning chair, the velocity that the ball is thrown, and the velocity due to gravity, must add up correctly in order to produce a trajectory that will hit the target.
- D. The only force that acts on the ball is the force of gravity.
- E. The acceleration of the ball is due to the force of gravity and is $g = -9.8 \text{ m/sec}^2$

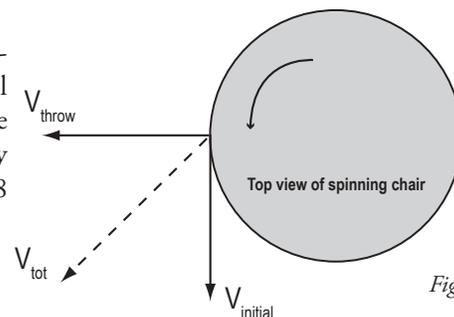


Fig. 3

Procedure for In-class Activity: Force, Velocity and Acceleration

The student handout includes cartoon drawings of six different scenarios. Most students will analyze the cartoons and answer simple questions about motions, velocities, acceleration and forces. Alternatively, more advanced students can use the optional procedure to match these cartoons to sets of graphs on an optional worksheet, and can answer more detailed questions about the relationships between motion, velocity, acceleration and forces.

Materials:

A pencil and paper for each student, plus a copy of the drawings and plots.

Answers to In-Class Activity Questions:

Most students should be able to describe the motions that are depicted in the cartoons. It is harder to correctly describe the motions and accelerations. The most difficult concept is to relate the accelerations to the forces, especially in the case of the girl throwing the ball. A common misconception is that the girl will continue to exert force on the ball, even after it leaves her hand. Many students believe that an object needs a force acting on it in order to continue its motion in a straight line. Answers for Cartoon 1 are given on the student handout.

Cartoon 2

- A) Girl is throwing the ball up into the air (and another hand is catching it)
- B) Velocity decreases
- C) Ball is decelerating
- D) Gravity is acting on the ball to slow down its rise

Cartoon 3

- A) Girl is throwing the ball sideways
- B) Velocity increases
- C) Ball is accelerating
- D) Gravity is acting on the ball to change its path and speed up its fall

Answers to Extension

Activity Questions:

Matching cartoons and graphs:

1 = F 2 = D 3 = A 4 = C 5 = E 6 = B

A. Explain:

- 1 – Girl is dropping the ball
- 2 – Girl is throwing the ball up into the air (and another hand is catching it)
- 3 – Girl is throwing the ball sideways
- 4 – Car is speeding up (accelerating)
- 5 – Car is moving at a steady speed (constant velocity)
- 6 – Car is slowing down (decelerating)

Cartoon 4

- A) Car is speeding up
- B) Velocity increases
- C) Car is accelerating
- D) The car's engine is providing the force to speed it up

Cartoon 5

- A) Car is moving at a steady speed
- B) Velocity stays the same
- C) Car has zero acceleration
- D) The car's engine is maintaining a constant speed (to overcome friction between the wheels and the road.)

Cartoon 6

- A) Car is slowing down
- B) Velocity decreases
- C) Car is decelerating
- D) The car's brakes are providing a force to slow it down (and so is friction)

B. For 1, 2 and 3, the acceleration is in the (negative) y-direction at -9.8 m/sec^2 due to gravity. So you need more information in order to figure out the matches for graphs A, D and F. For graph A, both the x and y positions change, so this matches cartoon 3. For graph D, the y-position starts at zero, and goes up, so this matches cartoon 2. For Graph F, the y-position starts at a positive value, and goes down to zero, so this matches cartoon 1.

For 4, the car is accelerating, so the acceleration in the x-direction is positive, which only matches graph C. For 5, the car is moving at a steady speed so the acceleration in the x-direction is zero, which only matches graph E. For 6, the car is slowing down, so the acceleration in the x-direction is negative, which only matches graph B.

- C. For cartoons 4, 5 and 6, the acceleration graphs were the most important.
For cartoon 1, both the x- and y-position graphs were important. However, the x-velocity graph is unique, as it is the only one in which there a positive value.
- D. All the graphs contribute interesting information, but some are more helpful than others. All the ball graphs have the same y-acceleration, so they are not that helpful in distinguishing the cartoons.
For graphs D and F, the x-position stays at zero throughout, and do not help to distinguish between dropping down and throwing up the ball.
- E. The objects accelerated in all the examples except for the one in which the car moves at a steady rate. You can tell because the acceleration value is non-zero on the graph, and the cartoons show the effects of acceleration (or deceleration.)
- F. No. There was no example in which acceleration occurred in more than one direction. There was one example (ball thrown sideways) in which motion occurred in more than one direction, but the only acceleration that occurred was due to gravity (negative y-direction.)

Answers to Post-Activity Discussion:

Both the ball and the rocket are acted on by the force of gravity pulling them down towards the Earth. The rocket carrying Swift has engines which provide an extra force that pushes it up and overcomes gravity. However, there is no force on the ball once it leaves the girl's hand, and so it eventually falls back down to the ground.

Again, both the ball and the rocket are acted on by the force of gravity pulling them down towards the Earth. The ball has a horizontal velocity that was provided by the girl, but is also acted on by air resistance. Swift was given extra horizontal velocity from the second stage booster rockets once it got up high enough to overcome air resistance. This extra horizontal velocity was needed to create a circular orbit around the Earth. If the girl could throw the ball hard enough (and was up higher so that there was little air resistance), the ball could begin to orbit the Earth. However, without the extra horizontal push of the booster rockets, the orbit would not be circular, and the ball would eventually hit the Earth at a point on the other side.

Assessment:

Points	Action Force	Action Force (Extension)
4	A) Student is able to correctly describe the motions portrayed in both sets of cartoons. B) Student is able to correctly determine the trends in velocities in both sets of cartoons. C) Student is able to correctly determine the accelerations in both sets of cartoons. D) Student is able to relate the accelerations to the forces in both sets of cartoons.	A) Student is able to correctly describe the motions portrayed in both sets of cartoons. B) Student is able to correctly match all the graphs to the cartoons. C) Student is able to explain the reasoning behind the matching process. D) Student is able to explain how the motion, the velocity and the acceleration are related.
3	Student achieves A) and B) and can correctly answer C) and D) for one set of cartoons.	Student achieves A) and B) and has thoughtful but not entirely clear answers to C) and D).
2	Student achieves A) and B) but does not correctly answer C) and/or D).	Student achieves A) and has at least 4 out of 6 graphs correctly matched but does not clearly answer C) and/or D).
1	Student achieves A) but does not correctly answer B), C) or D).	Student achieves A) but does not correctly answer B), C) or D).
0	Student achieves none of the four objectives above.	Student achieves none of the four objectives above.

Student Handout: *Newton's Second Law: Force, Velocity and Acceleration*

The goals of this activity are to understand how the motion shown in the drawings relates to velocity, whether or not the velocity is changing (acceleration) and what forces are causing the acceleration.

Procedure: Action Force

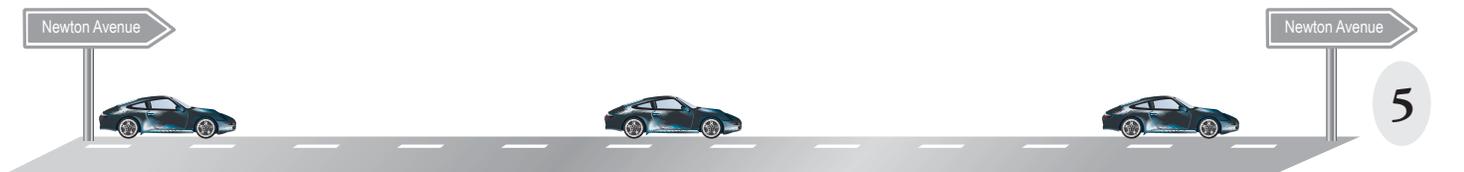
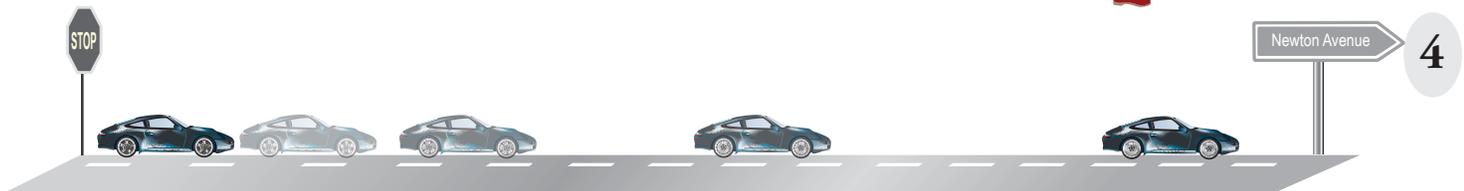
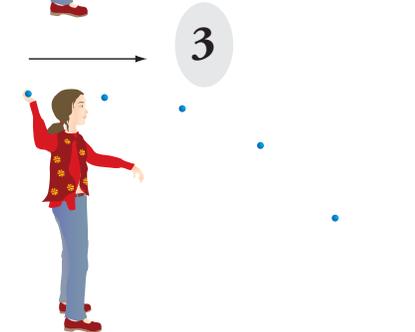
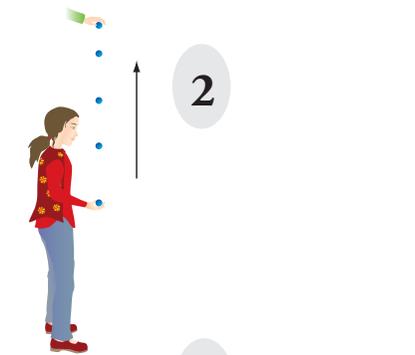
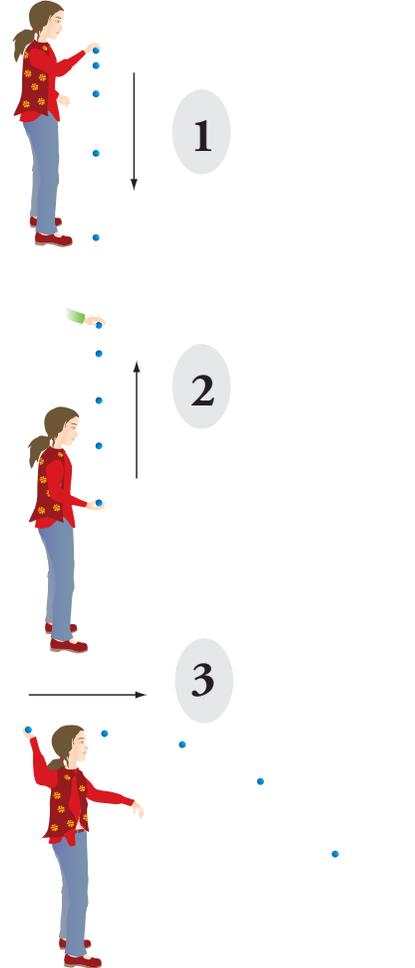
Look at the six cartoons on this page. There are three cartoons that show different ways that a girl can throw a ball, and three cartoons that show different motions of a car. For each cartoon, answer the following on a separate sheet of paper:

- A) What type of motion does each cartoon represent?
- B) As time passes, does the velocity increase, decrease or stay the same in each cartoon?
- C) As time passes, is the ball or car accelerating, decelerating or is the acceleration equal to zero?
- D) What forces are acting in each cartoon and what is the effect of these forces?

Example answers for Cartoon 1:

- A) Girl is dropping a ball straight down.
- B) Velocity is increasing
- C) Ball is accelerating
- D) Gravity is acting on the ball to speed up its fall.

Cartoons



Student Handout: *Newton's Second Law: Force, Velocity and Acceleration-Extension Activity*

Procedure: Action Force (Extension)

Examine the six cartoon drawings, and the six different sets of graphs on the attached page. There are three cartoons that show different possible motions of a ball, and three cartoons that show different motions of a car. Each set of graphs contains the following: x-position vs. time, y-position vs. time, x-velocity vs. time, y-velocity vs. time, and acceleration (in either the x or y direction.)

The goal is to match the cartoon drawings with the correct set of graphs that represent the motion shown in the cartoon.

Explain:

- A) What type of motion does each cartoon represent?
- B) How did you decide what matches to make?
- C) For each cartoon, which graph was the most important in helping you to decide the match?
- D) Were there some graphs that did not help you very much? Which ones were they?
- E) In which of the above examples did the objects accelerate? How could you tell?
- F) Did any of the above examples accelerate in more than one direction?

Post-activity Discussion:

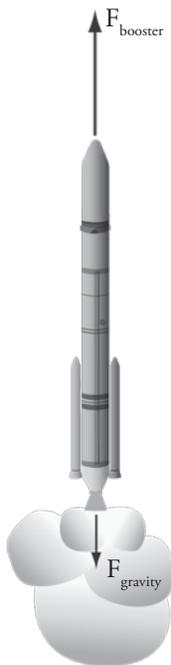


Fig.1

Compare and contrast cartoon 2 (girl throwing the ball up into the air) to Fig. 1 that shows the forces at the launch of the Swift satellite.



Girl 2

Compare and contrast cartoon 3 (girl throwing the ball sideways) to Fig. 2 that shows the velocity and acceleration of Swift as it goes into orbit.

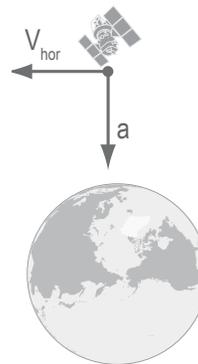
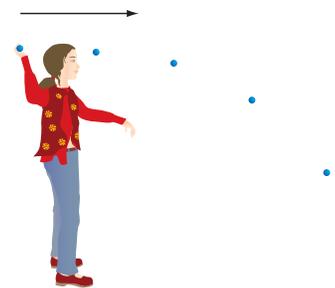


Fig.2



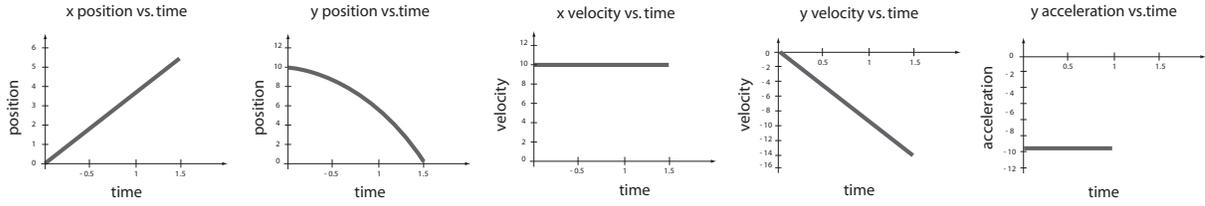
Girl 3



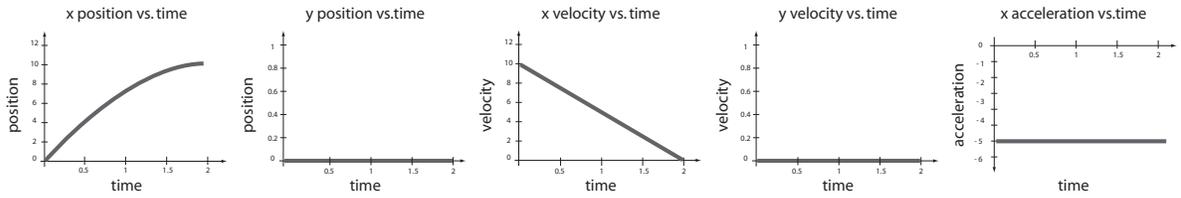
Write your answer in the gray box below with the cartoon number that corresponds to the correct set of graphs. [Note: you may want to place the two pages together to help you do the comparison.]



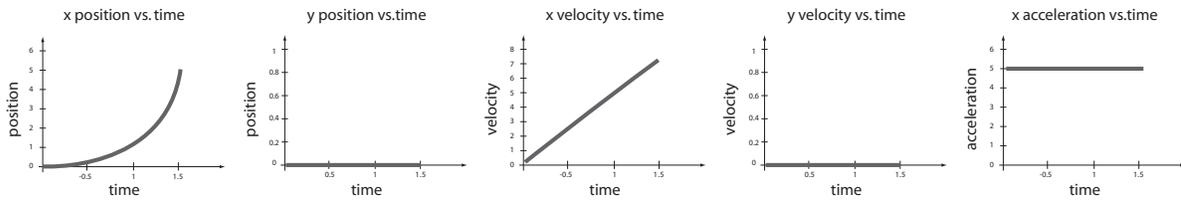
A



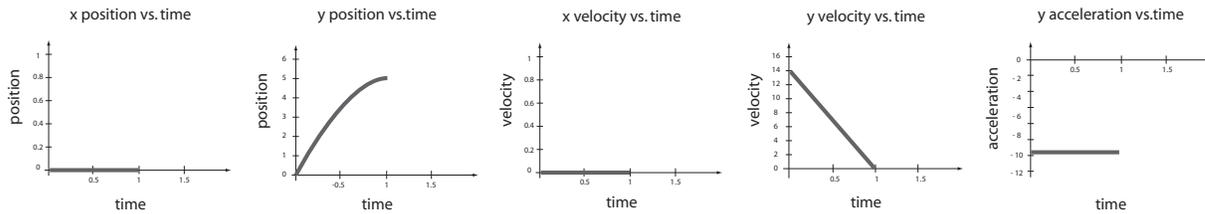
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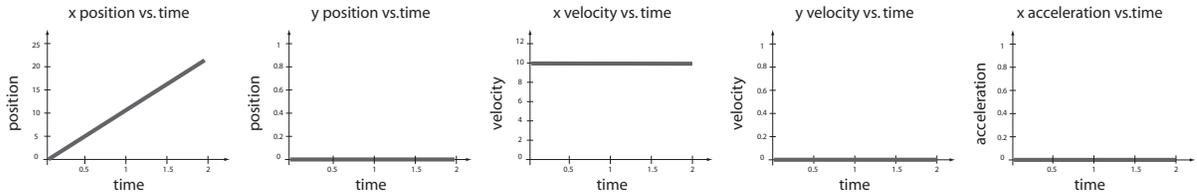
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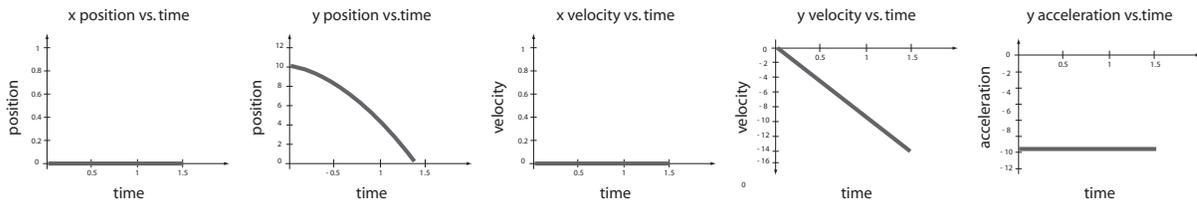
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E



F



Name: _____

Date: _____

Period: _____