

II. Newton's Laws of Motion

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CONCEPT REVIEW

Dynamics is the study of why things move. This particular set of exercises will only consider the basic concepts of motion embodied in Newton's Three Laws of Motion. A later chapter will explore particular applications of force concepts. Understanding the following definitions and principles will be both helpful and necessary for successfully answering the exercises in this section. However, this concept review is not meant to replace the full explanation of a textbook or lecture. If any of these principles are unfamiliar or confusing, please consult with an instructor or textbook.

1. Forces cause accelerations. The acceleration of an object is proportional to the 'net' applied force acting on it. The net force is the vector sum of all the forces acting on the object.
2. Constant velocity motion, also called uniform motion, is considered 'natural' and does not need to be explained. ('Rest' is the special case of zero magnitude velocity.) In other words, forces are not needed to explain velocities; constant velocity is not caused by a net force. Instead, for an object to move with constant velocity, the net force on the object must be zero. This is the essence of Newton's First Law of Motion.
3. Mass is the property of matter that resists the action of a force. Another word used to describe this property of an object is inertia. The acceleration of an object is inversely proportional to the mass for a constant force and is proportional to the magnitude of the applied force. This is Newton's Second Law of Motion, and may be expressed by the equation

$$F = ma$$

where F is the net force, m is the mass of the object, and a is the acceleration of the object. The direction of the acceleration must be in the direction of the net force.

4. Forces always come in pairs. The application of the force caused by one body on a second is equal in magnitude and opposite in direction to the force caused by the second body on the first. This is Newton's Third Law of Motion.
5. Newton's Second Law of Motion applies to all the forces acting on a single object. Newton's Third Law of Motion applies to the interacting forces between two objects.
6. Forces exist independently of the accelerations that they cause; in other words, force is not defined as the product of mass and acceleration. Forces can be acting in situations where there are no accelerations, but if an object is accelerating, then there must be at least one external force acting on it.

WARM-UP EXERCISES

1. Why is it harder to push a shopping cart when it is full of groceries compared to when it is empty?

2. A 3 kg mass is accelerated by a 6 Newton force. Both the mass and force are increased by 3 units (i.e., a 6 kg mass experiences a force of 9 Newtons). The experiment is repeated and the acceleration of the mass is calculated.
 - a. Is the calculated acceleration in the second case different from the first case? If it is different, is the new acceleration larger or smaller than the previous one?
 - b. If the accelerations are different, explain why increasing both the mass and force by the same amount did not result in the same acceleration. If the accelerations are the same, use equations to show why they must be the same.
 - c. If the accelerations are different, explain how one should increase both the mass and force so that the new acceleration would be the same as the original one.
3. If you push against an immovable brick wall, is the wall pushing back on you with the same force? When a wrecking ball pushes against the same brick wall and knocks it over, is the brick wall pushing back with the same force on the wrecking ball while it is in contact with the ball and falling down? (Assume the wall is pushed over as a single piece).
4. Suppose you stop a metal ball rolling toward you with your foot.

How much force would be required to stop the ball in the same length of time compared to this first case if it is moving twice as fast?

How much force would be required to stop the ball in the same length of time compared to the first case if it had twice the original mass?

How much force would be required to stop the ball in the same length of time compared to the first case if it had twice the original mass but was moving only half as fast?

All of these questions specified that the stopping time was going to be the same as the first case. Does that really make a difference? In other words, would a different stopping time change any of your answers to these questions?

CONFLICTING CONTENTIONS

1. Circular Motion Release

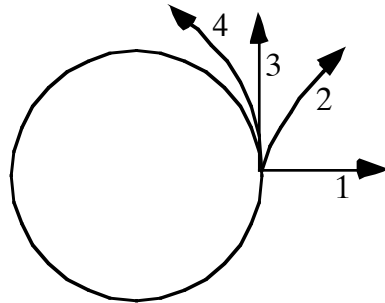
The Situation

Mr. Nicholls has another demonstration for the class. He has placed a hula hoop on the flat table top and set a marble against the inside edge. With a simple spinning motion, he gets the marble traveling at a constant speed around the inner edge of the hoop.

He then says the class, “In a moment I am going to lift the hoop off the table and we are going to observe the motion of the marble afterward. But before I do that, I want to consider the possibilities of what might happen to the motion of the marble when I suddenly lift the hoop off the table. I will show you a diagram of four possible paths the marble might take when I lift the hoop. I want you to write down a reasonable argument to support each case.

“Of course, only one of the answers will be correct, so not only will you have to give me a possible explanation for each case, you will also have to be able to tell me afterward what is the mistake in reasoning for each of the wrong explanations after we see what actually does happen.”

Will you accept Mr. Nicholls challenge? Can you give a reason for each prediction?



The Predictions

Here is the list of possibilities developed by the class (see the diagram):

For Path 1: A force supplied by the hoop is pushing the marble around its edge. When the hoop is lifted, that force is gone, so the marble could move opposite to the direction of the push, which is directly away from the center of the circle. (Everyone agrees that this possibility is very unlikely, since no one has ever seen an object released from a circular path behave that way.)

Path 2: It is true that the hoop is pushing on the marble, but it also has a velocity. So when the hoop is lifted, the marble should move away from the center of the circle but in a wide gentle arc until it finally travels in a straight line.

Besides, that is the type of observation you would make if you were flinging a ball on a string in a circle over your head and suddenly let go of the string.

Path 3: When the hoop is lifted, the marble moves in a straight line and tangent to the release point. That is what Newton’s First Law predicts.

Path 4: Path 3 doesn’t take into account the forces acting on the ball after release. Although the push inward is gone, there is still a sideways push that kept it moving along the path, so the ball should travel in an arc but past the tangent line instead of before it, as with path 2. That path would also coincide with the arc that you would see if you let go of the ball on a string.

Which prediction do you believe is the correct one? Or do you have a different prediction or reason?

The Answer

Satisfied with their predictions and reasons, the class watches as Mr. Nicholls starts the motion and lifts the hoop. The ball travels in a straight line path, tangent to the circle at the last point of contact, which is Path 3.

Now, can you explain what is wrong with the reasoning behind each of the other predictions?

Also, can you explain why the ball on the string appears from the point of view of the spinner to be traveling in an arc, when in fact it is traveling in a straight line?

2. The Horse and Sled

This is a very old physics brain-teaser. See if you can figure out where and how the reasoning made in the question becomes illogical.

A horse is pulling a wooden sled across the ground. According to Newton's third law of motion, the force of the horse acting on the sled pulling it forward must be equal and opposite to the force of the sled pulling backward on the horse.

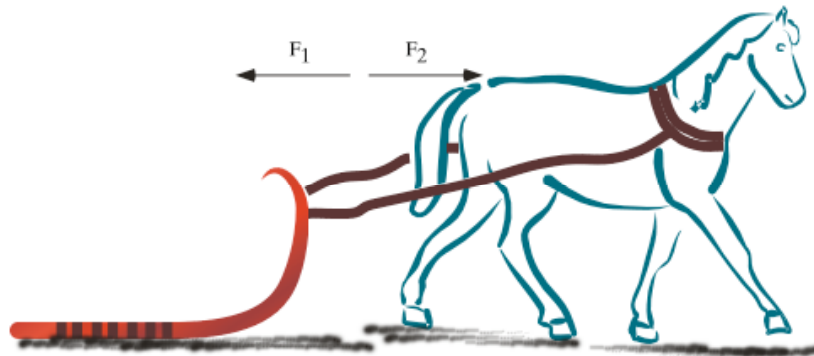
According to Newton's second law of motion, only net forces cause accelerations. Since the two forces must add to zero by the third law, the acceleration of the horse and sled must also be zero. So how can the sled ever move, much less accelerate?

Can you explain this?

Hint: The brain-teaser refers to both the second and third laws of motion, and the statements made about the two laws of motion are perfectly correct. But under what conditions do each of the laws apply?

Follow-up question: It is true that an acceleration must be caused by a net force acting on an object. Can you identify the force or forces causing the acceleration of the horse and sled?

Hint: Under what conditions could the horse not cause the sled to move?



3. Push Off

The Situation

Mr. Nicholls has asked for two volunteers from the class to help with a demonstration. He has Frank and Beth sit opposite each other on two chairs with wheels. Beth takes off her shoes and puts her feet against Frank's knees. Beth pushes off, and the two chairs move in opposite directions. Beth is quite a bit smaller than Frank, so her chair moves noticeably faster than his.

“Which student, Frank or Beth, experiences the greater force?”, Mr. Nicholls asked.

Do you have an answer to Mr. Nicholls' question?

The Predictions

Here were the class's responses.

Mary: “Beth did the pushing and Frank was just sitting there, so Beth must have been pushing harder than Frank because she was causing the acceleration.”

Cathy: “I agree with Mary. Besides, she was moving faster than Frank. Her acceleration was larger, so she must have experienced the greater force.”

Daniel: “I disagree. Frank didn't accelerate as much as Beth because he has a greater mass. A greater mass requires a greater force, so Frank must have experienced a greater force than Beth.”

Which student do you agree with? Or do you have a different answer or explanation?

The Answer

“Wait a minute,” says John, “I think this is one of Nicholls' trick questions. The first law says forces cause accelerations, which we saw for ourselves. And the second law says force, mass and acceleration are all related, which is what we have been talking about. But what about the third law?”

“John is right,” says Mr. Nicholls. “All of your arguments make a lot of sense, but in fact the two forces are equal in magnitude and opposite in direction because of Newton's Third Law of Motion.”

So then what is wrong with each of the explanations given by Mary, Cathy, and Daniel? How can we reconcile their observations with Newton's Third Law of Motion?”

QUALITATIVE REASONING

General Hint: For both the Qualitative Reasoning questions and Can You Explain This? exercises, first consider which of Newton's three laws should be applied to explain each particular situation before determining the correct answer to the problem.

1. Car Push

A truck has broken down on the side of the road and the owner of a small compact car is willing to help out. He nudges up to the truck's bumper and begins pushing the truck down the highway.

How does the force of the car acting on the truck compare to the force of the truck acting on the car:

- a. When the car and the truck are accelerating?
- b. When the car and the truck are traveling at a constant velocity?

2. Moving Elevator

Consider an elevator first accelerating upward from rest, then traveling at a constant velocity, and finally slowing down to a stop at one of the upper floors of a building. There are two forces acting on the elevator: the weight of the elevator and the tension in the cable attached to it.

How do the magnitudes of these two forces compare:

- a. When the elevator is accelerating upward,
- b. When the elevator is moving at a constant velocity,
- c. And when the elevator is slowing down to a stop?

Now suppose the elevator makes the return trip to where it started from. How would the tension and weight magnitudes compare for each leg of the journey downward?

3. Second and Third Law Pairs

A book is resting on a table. There are two forces acting on the book: the weight of the book pointing downward, and a 'normal force' caused by the table top, pointing upward. These two forces are equal in magnitude and opposite in direction, but this is not an example of Newton's Third Law of Motion. These forces are equal and opposite because the book is not accelerating: it is at rest. This is an application of Newton's *Second* Law of Motion!

- a. What is the correct 'third law pair' reaction force for the normal force pushing up on the book?

- b. What is the correct ‘third law pair’ reaction force for the weight of the book?
- c. How could you demonstrate that the normal force and the weight cannot be a third law pair?

HINT: To identify the pair of forces resulting from Newton’s third law complete the sentence:

“The force of *A* acting on *B* is equal and opposite to the force of *B* acting on *A*.”

But replace ‘A’ and ‘B’ with two different words.

For example, if I stretch a rubber band between my two fingers,

“The force of the *rubber band* acting on *my finger* is equal and opposite to the force of *my finger* acting on *the rubber band*.”

What two nouns do you need for each case in this problem?

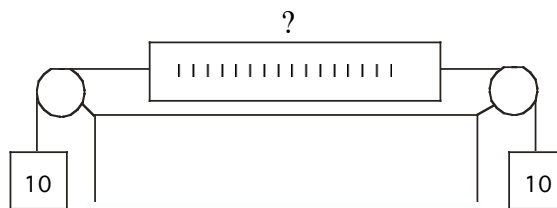
4. Applied Forces

A constant net force of 2 Newtons pushes a bowling ball from rest until it reaches a final speed of 2 m/s after 10 seconds.

- a. How much more time would it take with the constant force acting to increase the speed of the ball from 2 m/s to 4 m/s?
- b. How much more time would it take with the constant force acting to increase the speed of the ball from 4 m/s to 8 m/s?
- c. How much time would it take to reach the final speed of 2 m/s, compared to the first case, if the applied force was only 1 Newton?
- d. How much time would it take to increase the speed of the ball by a total of 2 m/s, compared to the first case, if the ball did not start from rest but had an initial speed of 1 m/s (in other words, achieving a final speed of 3 m/s)?

5. Rope Tension

This is another classic concept question, but very difficult to answer correctly. Two 10 Newton masses are hanging from two pulleys with a force spring scale between them, as shown in the picture.

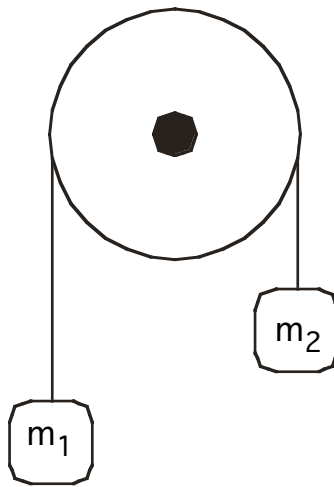


Would the spring scale read 0, 10, or 20 Newtons, or something else?

Suppose one side had a mass of 5 Newtons and the other side had a mass of 15 Newtons, so that the system was accelerating. Now what would be the scale reading (if you could read it while it accelerated past you)?

6. Atwood's Machine

Like Galileo, Atwood invented a 'gravity dilution device', as shown in the picture. Atwood's machine consists of two masses attached to each other on opposite sides of a pulley. The two masses are able to remain at rest if the two masses are equal ($m_1 = m_2$); if the two masses are not equal, then they will experience an acceleration, with the heavier mass falling and the lighter mass rising.



Suppose we construct an Atwood's machine by placing 5 masses with a weight of 0.1 Newton each on two identical 0.5 Newton weight hangers, resulting in a total weight of 1.0 Newton on each side of pulley.

- Suppose you tap one of the weight hangers under these conditions of equal weight, pushing it downward. What would you observe about the motion of the two masses?

One 0.1 Newton weight is now transferred from one weight hanger to the other, causing one side to have a weight of 1.1 N and the other to have a weight of 0.9 N. When the weight hangers are let go, the two masses accelerate due to the force difference of 0.2 N.

- If a second 0.1 N weight is transferred from the lighter side to the heavier side, how will the acceleration of the weight hangers compare to the previous situation?

Now suppose a force difference of 0.2 N is maintained, but an extra 0.5 N of weight is added to both of the weight hangers.

- How will the acceleration of the system change compared to the previous case, or will it stay the same as before?

CAN YOU EXPLAIN THIS?

1. Hand Slam

Why does it hurt more if you slam the back of your hand against the wall when you are holding a book compared to when your hand is empty? Which of Newton's laws is most useful for explaining this observation?

2. Coin Flick

Try this yourself. Set a 3x5 index card on top of a glass and place a coin on top of the card over the center of the glass. Flick the edge of the card quickly with your index finger and the coin falls into the glass. Can you explain the motions of both the coin and the card using Newton's laws of motion?

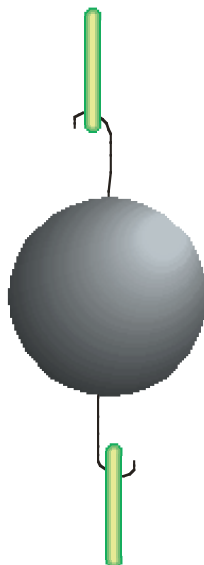
3. The Myth of 'Hang-Time'

Use Newton's laws to explain why it is impossible for a basketball player to have a 'hang time' when jumping into the air to make a shot.

4. String Pull

You can try this yourself if you can find an object with a mass around 1 kilogram that has two hooks or holes on opposite sides, so that you can tie two strings to it. If you do try this, it is important that the string is made of cotton: you will never be able to break a nylon string!

Tie a string to each side of the heavy object. Hold the object in the air with one string.



Pull the lower string quickly and the lower string breaks.

Pull the lower string slowly and the upper string breaks.

Warning: If you try this yourself, make sure the mass is not too heavy and move your hand out of the way so it doesn't get hit by the falling mass!

Can you explain these results using Newton's laws of motion?

Which of Newton's law(s) are most useful for explaining the observations made in each situation?

5. Air Bags and Seat Belts

Use Newton's laws of motion to explain how an air bag is able to save a person's life in a head-on car crash.

Why is an air bag dangerous to a small person, young child, or infant?

Use Newton's laws of motion to explain how seat belts are able to save a person's life in a car crash.

Why are seat belts a useful safety device no matter what the direction of impact, but air bags are most effective in head-on collisions?

6. Tug of War

The physics class is having an imaginary tug of war — the men against the women. For a long time the two teams are pulling with equal force and the knot in the center of the rope isn't going anywhere. But then Frank sneezes and stops pulling as hard for just a few seconds. Of course, he quickly recovers, and the two sides are pulling with equal strength once again.

"Is it possible", Mr. Nicholls asks, "to determine who wins the tug of war based on this information?"

"Of course not," Frank says, "The other team was pulling with greater force for a short time, but the two forces are equal again. So the knot in the middle moved a little bit towards the girls' side but then stopped. The tug of war isn't over yet."

"Wait a minute," Cathy says, "You have to listen carefully to the set-up. Mr Nicholls said that the girls were pulling harder for a short time, but then the boys recovered and began pulling with the same force as they were before. That means that our side won! Right Mr. Nicholls?"

Cathy is right: the women do win the tug of war. But can you apply Newton's laws correctly to explain why that is the case?