Newton's Second Law and Acceleration:
Finding Planets Using Physics

Purpose

This lesson conceptually explores Newton's second law; specifically, the idea that acceleration is any change in velocity, not just speeding up or slowing down.

Audience

This lesson was designed to be used in an introductory high school physics course.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- explain the difference between speed and velocity.
- explain that an object in a circular or elliptical orbit is always accelerating due to the change in the direction of its motion.
- describe how a change in force can lead to a change in acceleration.

Key Words

acceleration, eccentricity, orbit, velocity

Big Question

This lesson addresses the Big Question "*What does it mean to observe?*"

Standard Alignments

- **Science and Engineering Practices**

  SP6. Constructing explanations (for science) and designing solutions (for engineering)

- **MA Science and Technology/Engineering Standards (2016)**

  HS-PS2-1. Analyze data to support the claim that Newton's second law of motion is a mathematical model describing change in motion (the acceleration) of objects when acted on by a net force.

- **NGSS Standards (2013)**

  HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

- **Common Core Math/Language Arts Standards**

  CCSS.ELA-LITERACY.RST.9-10.1. Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

Misconceptions Addressed

- This lesson addresses many common misconceptions about acceleration, velocity, and force. Including the ideas that:
  - velocity and speed are the same (i.e., non-vectorial). (Questions 1, 3, 7)
  - acceleration implies increasing force. (Question 2c)
  - motion implies active force. (Question 2d)
  - greater mass implies greater forces. (Question 8b)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite "**Is There a Planet Nine in Our Solar System?" *based on:*

  Batygin, Konstantin, and Michael E. Brown. 2016. "Evidence for a distant giant planet in the solar system." *The Astronomical Journal* 151(2):22.

- **Related write-ups of research paper**
  - Burdick, Alan. "Discovering Planet Nine." *The New Yorker*. Conde Nast, January 20, 2016.
  - Chang, Kenneth. "Ninth Planet May Exist Beyond Pluto, Scientists Report." *New York Times*, January 20, 2016.
  - Hand, Eric. "Astronomers say a Neptune-sized planet lurks beyond Pluto." *Science* 20 (2016).
  - Parks, Jake. "In Pursuit of Planet Nine." *Astronomy*, January 3, 2020.

- **Misconceptions**

  Hestenes, David, Malcolm Wells, and Gregg Swackhamer. 1992. "Force concept inventory." *The Physics Teacher* 30(3): 141–58.

Materials

Copies of the Student Handout and Science Bite for each student

Time

This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

Students should already be familiar with velocity, speed, and acceleration. This lesson will review these concepts at the beginning, but students should have already explored these topics. It would also be helpful if students were familiar with Newton's 2nd law of motion; however this could be used as a conceptual introduction to Newton's 2nd law of motion. Students need to be familiar with Newton's 3rd law of motion in order to answer questions 8b and 8c. If students have not discussed Newton's 3rd law of motion at this point, those questions can be removed.

Instructions and Teacher Tips

- **General Procedure**
  - Instruct students to read the Introduction on the Student handout and answer the first three analysis questions.
  - Distribute the Bite and tell students to read and annotate it. One option for annotating is to have students star the main ideas, underline new vocabulary, and put a question mark next to phrases they find confusing. This will help students remember key information and ask questions.
  - Have students answer the remaining analysis questions.
  - Discuss the answers to the questions and the research discussed in the Bite as a class.
- **Tips, Extensions, and Variations**
  - Cool resources for 3D solar system visualization (such as https://nineplanets.org/tour/) exist and may help your students build an intuition for the structure of our solar system, either to start the discussion or to use as a follow-up.
  - If you haven't covered Newton's 3rd Law or are short on time, skip Questions 8b and 8c.
  - Question 8 could also be a starting point for further discussion on gravity and/or Newton's 3rd Law. Consider asking students, What is the force that is causing accelerations on the planets?
  - You could extend this lesson to a discussion of centripetal force/acceleration and circular motion. Students may be curious about what exactly is causing the change in velocity of a planet like Earth / how planets stay in a circular orbit.

Background Information and Research Details

- What is the Kuiper Belt? The Kuiper Belt is a region full of small, icy objects beyond Neptune. The objects within it are known as Kuiper Belt Objects, or Trans-Neptunian Objects. Most of the known dwarf planets are in the Kuiper Belt, too, such as Pluto, Sedna, Makemake, Eris, and Haumea. NASA's New Horizons mission (in 2015) provided the first close-up of a KBO when it did a flyby of the Pluto system.
- Why is the Kuiper Belt important? It's one of the places where comets come from, and can also tell us a lot about the solar system's history, since the icy objects out there are remnants of the formation of the solar system.

- Until recently (in the 2000s), scientists had not observed many Kuiper Belt Objects. Due to their extreme distances from the Sun (e.g. not as much light gets to them, so there's less to reflect off their surfaces) and very small sizes, they are very faint and therefore hard to detect. As they discovered more KBOs, this led to the demotion of Pluto (since there are many other Pluto-like objects, now known as dwarf planets) and eventually to the Planet 9 hypothesis.
- The Earth is about 90,000,000 miles away from the sun, so objects in the Kuiper Belt are often hundreds of times further from the sun than the Earth.
- Batygin and Brown created computer models of orbits to test their Planet 9 hypothesis, and thoroughly ruled out other hypotheses to explain the clustering of the KBOs.
- The original paper was published in 2016, and since then, they have done follow up studies that suggest there's only a 1 in 500 chance that the clustering is a result of observational bias. Although the big question probes the debate around Planet 9, further research and observations of more KBOs now show even stronger evidence for the existence of Planet 9.
- It seems strange for a planet to be so far away from the sun, so how did it get there? There are currently three ideas: First, it may have formed closer in and then been kicked out when it got close to the other giant planets, particularly Jupiter and Saturn; Second, it could be an object captured from another solar system; or, Third, another star may have passed close to the solar system, moving things around and kicking Planet 9 out to its current orbit.
- Scientists are still actively looking for Planet 9, using large research telescopes to search parts of the sky where their models suggest it might be (based on where it would need to be to affect the clustered KBO orbits in the way we observe).
- Why haven't they found it yet? Something as far away as Planet 9 would appear VERY faint, meaning we'd need to stare at a given patch of sky for a long time to gather enough light from it to see it. Also, it's really small, and scientists have only been able to narrow down their search region to a patch of sky that's still pretty large. So, it just requires many hours of observations and data analysis!

Big Question Discussion

This lesson should get students thinking about the Big Question "What does it mean to observe?" In particular, how do you know your evidence (what you "observe") is reliable? If you choose to delve into the Big Question, consider the following ideas:

- What kind of "observations" can students make if they look up at the night sky? (noticing things moving, seeing the shapes and brightnesses of things, etc.)
- Are there things you can't see? (Opportunity to draw the connection between our observations and scientific observations. Some things are just too faint for the equipment we have, whether it's our eyes or a telescope, but that doesn't mean they're not there.)
- Question 9 on the Student Handout provides context on the Planet 9 debate, and gives students an opportunity to discuss based on what they've learned from the Bite.

- How can we get a more complete picture of what's going on? (More observations, observations with another method/instrument, thinking about if our observations make sense in context)
- How are "scientific" observations different from other observations we could make? (Quantitative, tries to be objective, etc.)
- How can we be better observers in our daily life?

Answers

1. Speed only describes how fast something is going. How is that different from velocity?

Velocity describes how fast something is going and the direction it is going in, while speed only describes how fast it is going.

2. A person is pushing a box on a frictionless table.

   a. If the force on the box increases, what happens to its acceleration? Explain your answer.

The acceleration will increase. Newton's 2nd law states that acceleration is directly related to force - the more force, the more acceleration.

   b. What happens to the acceleration if the person decreases the force on the box? Explain your answer.

The acceleration will decrease. Newton's 2nd law states that acceleration is directly related to force - the less force, the less acceleration.

   c. If the force stays constant, is the box still accelerating? Explain your answer.

Yes, any time you have a net force acting on an object, the object will be accelerating.

The person stops pushing the box.

   d. What happens to the box's acceleration? Explain your answer.

The acceleration will become zero, because there is no longer a net force acting on the box.

   e. What happens to the box's velocity? Explain your answer.

The velocity will become constant, because the box is no longer accelerating.

3. You and your friend are watching a documentary about the Solar System. Your friend is watching the planet's orbit, and says that there is no way that Earth is accelerating—it looks like it's moving the same speed around the Sun during its whole orbit! Do you agree with their claim that the Earth is not accelerating? Explain why or why not.

I do not agree. Even if the Earth's speed isn't changing, its direction is changing, because it is moving in a circle. Velocity has both magnitude and direction, so if the direction of motion is changing, the velocity is changing. If velocity is changing, the object is accelerating.

STOP & read Science Bite:
[A Mysterious New Planet in the Solar System]

4. Where are Kuiper Belt Objects in our solar system and what are they made of?

Kuiper Belt Objects are located beyond Neptune and they are made of ice and rock.

5. Why do scientists think that there is a "Planet 9"? What evidence do they have? Cite specific evidence from the text.

Scientists think there is a Planet 9 because they noticed that KBOs at a particular distance away from the sun are clustered together when their orbits are nearest the sun, which is unusual. As the text notes, "We would expect that those points of closest approach to the Sun would be random." One explanation for why the orbits are clustered together is that a large planet is located far from the sun and its force of gravity pulls on the KBOs making them cluster together.

6. What can cause an object's orbit to change?

The force of gravity from another mass (like a planet) can cause an orbit to change.

7. Are the KBOs near "Planet 9" accelerating? Why or why not?

Yes, the direction of their motion is changing, therefore they must be accelerating.

8. Gravity is a force that pulls two objects together, based on their size and distance from each other. If the objects are closer, the force is stronger. As a KBO gets close to a planet the force of gravity between the two objects increases.

a. What would this change in force do to the acceleration of the KBO?

The acceleration would increase.

b. Is the force exerted on the planet by the KBO the same as the force exerted by the KBO on the planet? Why or why not?

Yes, Newton's third law of motion states that the force exerted on object A by object B must be equal in magnitude, but in the opposite direction as the force exerted by object B on the object A, therefore the force of the planet on a KBO must be equal and opposite to the force exerted by the KBO on the planet.

c. Would the acceleration of the KBO be more noticeable than the acceleration of the planet? Explain your reasoning. *Hint: Think about F=ma. What terms are different for the planet and the KBO? Which would be the same?*

The acceleration of the KBO would be much larger than that of the planet, because the KBO has a much smaller mass and the force on each from each other is equal.

9. **Connect to the Big Question**. Some other scientists claimed that Planet 9 actually doesn't exist. Their research showed that the observations of the "clustered" KBOs might be biased—that is, we observe only the clustered KBOs because they're easier for our telescopes to detect, but there may be more KBOs out there we just can't see yet. Are you convinced Planet 9 is out there? Why or why not? If not, would extra observations change your mind?

Sample answer: I am not yet convinced that there is a Planet 9 out in our solar system. If it is more likely that we find KBOs that are clustered together then there is not enough evidence for a Planet 9. Additionally, even if it is far away, I feel like we should have been able to make direct observations of it already. I would be more convinced if scientists were able to study a larger number of KBOs and find the same pattern or were able to observe Planet 9 directly.