Net Force and the Acceleration of Spacecraft

Purpose

This lesson introduces acceleration of an object (a gram scale spacecraft!) by a constant unbalanced (net external) force. Students should be thinking about how speed changes with time and that a moving object will not come to rest when no force acts upon it. The Bite describes how astronomers plan to use microscale spacecraft to study exoplanets by accelerating the spacecraft with a laser array.

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:

- determine acceleration using Newton's second law.
- apply an understanding of acceleration to describe the motion of an object through motion graphs, free body diagrams, and calculations.
- apply one dimensional kinematics concepts to determine applied forces.
- explain how scientists will send sensors to nearby stars to study exoplanets.

Key Words

exoplanet, light sail, light year, nanocraft, net force, Proxima Centauri

Big Question

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

Standard Alignments

- **Science and Engineering Practices**

  SP 5. Using mathematics and computational thinking

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

  HS-PS2-10(MA). Use free-body force diagrams, algebraic expressions, and Newton's laws of motion to predict changes to velocity and acceleration for an object moving in one dimension in various situations.

- **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.9–10.10. By the end of grade 10, read and comprehend science/technical texts in the grades 9-10 text complexity band independently and proficiently.

Misconceptions Addressed

- This lesson addresses some common misconceptions about forces, including that objects come to rest in the absence of applied force. (Questions 4 and 5)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite** "Shooting for the Stars" *based on*:

  - Brashears, Travis, Philip Lubin, Gary B. Hughes, Kyle Mcdonough, Sebastian Arias, Alex Lang, Caio Motta, Peter Meinhold, Payton Batliner, Janelle Griswold, Qicheng Zhang, Yusuf Alnawakhtha, Kenyon Prater, Jonathan Madajian, Olivia Sturman, Jana Gergieva, Aidan Gilkes, and Bret Silverstein. 2015. "Directed Energy Interstellar Propulsion of Wafersats." Nanophotonics and Macrophotonics for Space Environments IX. doi:10.1117/12.2189005.
  - Anglada-Escudé, Guillem, Pedro J. Amado, John Barnes, Zaira M. Berdiñas, R. Paul Butler, Gavin A. L. Coleman, Ignacio de la Cueva, Stefan Dreizler, Michael Endl, Benjamin Giesers, Sandra V. Jeffers, James S. Jenkins, Hugh R. A. Jones, Marcin Kiraga, Martin Kürster, María J. López-González, Christopher J. Marvin, Nicolás Morales, Julien Morin, Richard P. Nelson, José L. Ortiz, Aviv Ofir, Sijme-Jan Paardekooper, Ansgar Reiners, Eloy Rodríguez, Cristina Rodríguez-López, Luis F. Sarmiento, John P. Strachan, Yiannis Tsapras, Mikko Tuomi & Mathias Zechmeister. 2016. "A terrestrial planet candidate in a temperate orbit around Proxima Centauri." *Nature* 536:437–440. doi:10.1038/nature19106.
  - Dickinson, David. "Breakthrough Starshot Takes to Space." Sky & Telescope. Accessed April 28, 2018. http://www.skyandtelescope.com/astronomy-news/breakthrough-starshot-takes-to-space
  - Davis, Nicola. "Breakthrough Starshot Successfully Launch World's Smallest Spacecraft." *The Guardian.* July 28, 2017. Accessed April 28, 2018. https://www.theguardian.com/science/2017/jul/28/breakthrough-starshot-successfully-launch-worlds-smallest-spacecraft.

- **Misconceptions**

  Hestenes, David, Malcolm Wells, and Gregg Swackhamer. 1992. "Force Concept Inventory." *The Physics Teacher* 30(3): 141-58. doi:10.1119/1.2343497.

Materials

- Copies of the student handout and Science Bite for each student
- Way to show students the animation of Starshot concept: https://www.youtube.com/watch?v=xRFXV4Z6x8s
- Calculators, 1 per student
- Rulers for graphs, 1 per student

Time

This lesson should take approximately one 50-minute class period. Additional time may be necessary if students don't have much experience with graphing.

Student Prior Knowledge

Students should have working knowledge of the relationship between position, velocity, acceleration, and time. Students will need a basic understanding of linear relationships.

Instructions and Teacher Tips

- **General Procedure**
  - Show the video animation of the Breakthrough Starshot project, either at the start of the lesson or before students read the Bite.
  - Provide students with the student handout. Have them complete Question 1, discuss as a class, and then have them read the Science Bite.
  - After reading the Science Bite, students should answer Questions 2–11. It is recommended that you check student answers to the graphing questions (Question 2) before allowing them to continue.
  - When students have completed the work in the student handout it is important that they review their answers especially for Question 3. Some options include:
    - Ask students to stand on the left side of the room if they answered yes and on the right if they answered no to Question 4b. Ask representatives from each side to make their case citing evidence from the Bite and Student handout.
    - Place students in small groups to review and discuss their answers and make corrections. Students should be instructed to make their arguments based on the Bite and Student handout.
- **Tips, Extensions, and Variations**
  - You may wish to introduce the lesson with a general discussion on observation. At this point in the year, many classes will have used multiple methods for measuring position, velocity, and acceleration (meter sticks and stopwatches, motion sensors, video analysis, etc.). An opening discussion on choosing the best tool for the job at hand will help students connect to the Big Question at the end of the lesson.

- Preview vocabulary as needed. It is expected that students are comfortable with velocity and acceleration. This lesson can be their first exposure to Newton's Second Law, but is not designed to be their first exposure to the concept of force.
- You could have students create a quantitatively accurate position *vs*. time graph in Question 2.
- The decimal points in the Force column are given in Table 1 in order to show that there are three significant figures for each force. You may choose to remind students of significant figures in their calculations.

Background Information and Research Details

- Light sails move because of the collision of photons with the sail. They work in a manner very similar to traditional sails, but iInstead of harnessing the energy in wind as the wind reflects off of a cloth sail, light sails harness the energy in a laser beam as the laser beam reflects off of the light sail.
- Because the spacecraft described in this lesson are very small (~ 1 g), they rapidly accelerate to speeds approaching the speed of light. The gram scale spacecraft could carry cameras to our nearest neighbor star, Proxima Centauri, where small cameras will take pictures and send them to Earth while moving through the system.
- The exoplanet orbiting Proxima Centauri was discovered by the European Southern Observatory in 2016. Scientists believe that the temperature on the exoplanet could allow for liquid water; however as a flare star, Proxima Centauri has random increases in its brightness which may make it difficult for the planet to support life. Additionally, Proxima Centauri is a red dwarf star, which is one of the coldest types of stars. Because it is a cool star, less light is emitted and the light that is emitted has lower wavelengths which could also make it challenging for an orbiting planet to support life.
- Solar sailing has already been used by organizations to help propel spacecraft. In 2010, the Japanese Aerospace Exploration Agency launched the IKAROS solar sail. Pictures of the sail were taken by tiny cameras that were ejected from the sail. You can see these images and learn more here. The first functioning solar sail launched by a non-government agency belongs to The Planetary Society and was deployed in 2019. Data collected by The Planetary Society demonstrates that the sail works effectively to change the orbit of the satellite the sail is attached to. More information about this mission can be found here.

Big Question Discussion

This lesson should get students thinking about the Big Question "*What does it mean to observe?*" In particular, about the limitations of taking images in space. If the Breakthrough Starshot project is successful, we will obtain images taken of an exoplanet at very close range; however those images will be taken at very high velocity. Students will discuss the benefits and drawbacks of this method. They will also discuss if they think these images are worth the time, effort, and cost. If you choose to delve into the Big Question, consider the following ideas:

- A prompt for an opening discussion could be, “Have you ever tried to take a picture while on a roller coaster or in a fast moving car? Did it turn out well? Why?”
- In the wrap-up ask students, “Which is a better picture, one taken from close up while in a moving vehicle or one taken from miles away?”

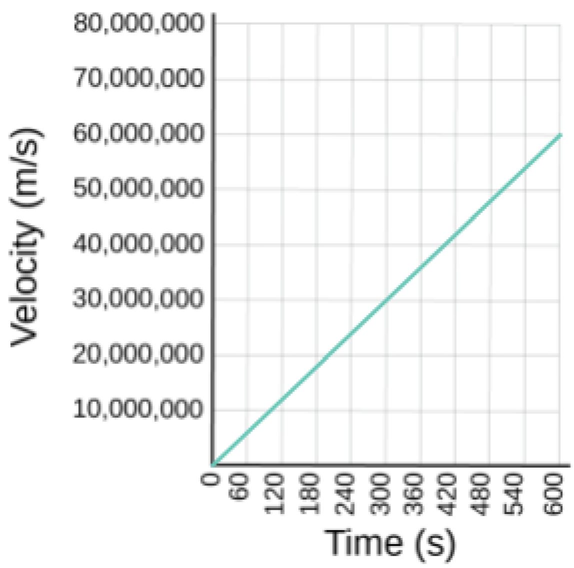
Answers

1. To study far away objects, researchers are considering ways to quickly accelerate a very tiny spacecraft. Why is it advantageous for scientists to use a very tiny spacecraft? Use Newton’s Second Law to justify your answer.

With a very tiny space craft, you would need a relatively small force to accelerate it to a high speed, since acceleration is inversely proportional to mass and directly proportional to net force.

2. The Bite describes the predicted acceleration of the nanocraft. Consider the different ways we can represent this acceleration:

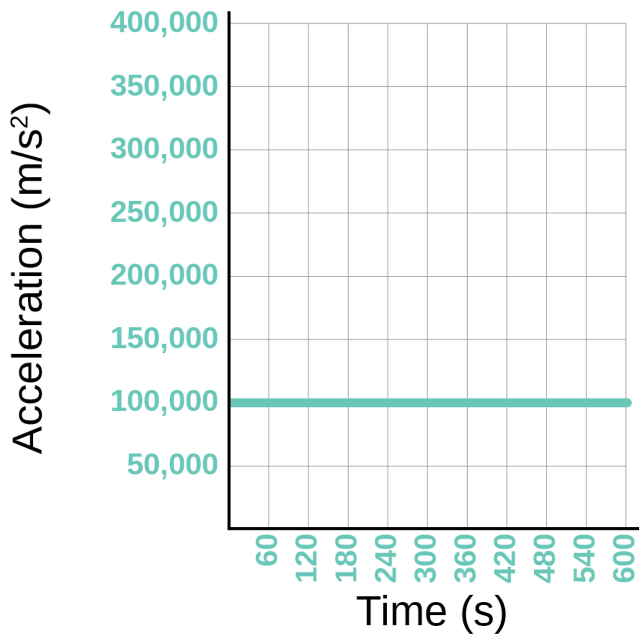
   a. Sketch a graph of velocity vs. time of the nanocraft. Recall that the nanocraft’s velocity is predicted to increase from 0 to 60,000,000 m/s in ten minutes (600 seconds). Assume the acceleration is constant.



   b. Calculate the acceleration of the nanocraft. Show your work.

$$a = \frac{\Delta v}{\Delta t} = \frac{60{,}000{,}000\,\frac{m}{s} - 0\,\frac{m}{s}}{600\,s - 0\,s} = 100,000\,\frac{m}{s^2}$$

c. Add values to the x- and y-axes to the graph below and draw an accurate acceleration vs. time graph of the nanocraft from 0–600 seconds.

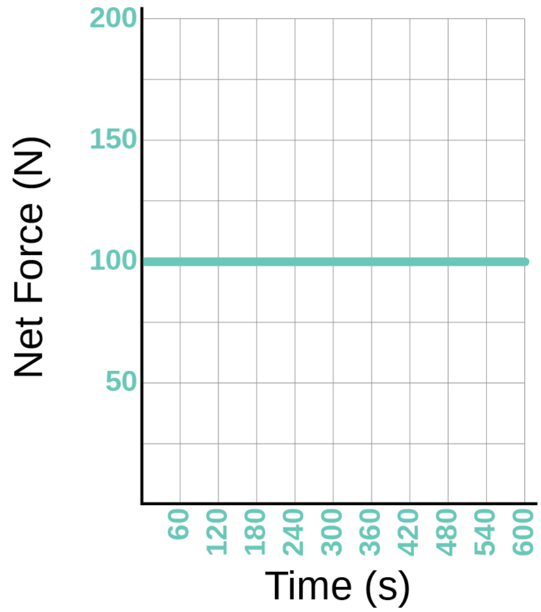


Students may choose different values for their axes, but their answer is correct as long as they have time going to 600 seconds, have 100,000 m/s^2 on the y-axis, and each line on the x- or y-axis represents the number of seconds or m/s^2, respectively.

d. What is the net force acting on the 1 gram nanocraft from 0–600 seconds? Show your work.

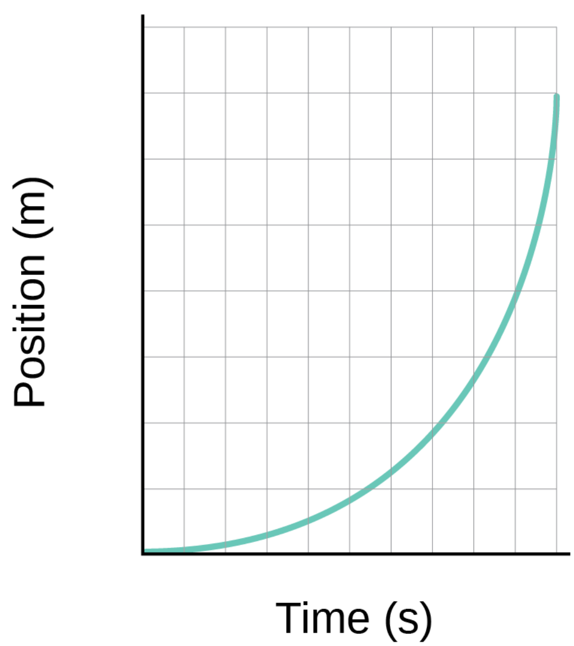
$F_{net}=ma=(0.001\ kg)(100{,}000\ m/s^2) = 100\ N$

e. Add values to the x- and y-axes to the graph below and draw an accurate Fnet vs. time graph from 0–600 seconds for the nanocraft.



Students may choose different values for their axes, but their answer is correct as long as they have time going to 600 seconds, have 100 N on the y-axis, and each line on the x- or y-axis represents the number of seconds or N, respectively.

f. Sketch the shape of the position vs. time graph for the nanocraft.

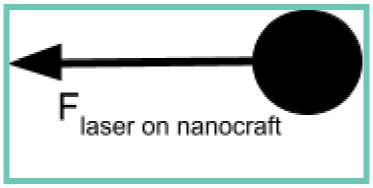


g. Calculate how far the nanocraft would travel in 600 seconds.

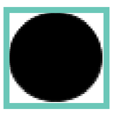
$$\Delta x = v_i \Delta t + \frac{1}{2} a \Delta t^2 = (0 \frac{m}{s})(600\, s) + \frac{1}{2}(100,000 \frac{m}{s^2})(600\, s)^2 = 18,000,000,000\, m$$

3. Based on the descriptions in Bite, draw free body diagrams for the nanocraft in each of the following situations (Assume the force of gravity from the Earth and other objects in space is negligible):

a. When the laser beams are hitting the nanocraft.



b. After the laser beams have stopped hitting the nanocraft, it is traveling away from Earth towards Proxima Centauri.



(There are no forces acting on the nanocraft after the laser beams have stopped hitting it.)

4. Below are velocity vs. time graphs modeling the nanocraft's motion from 0–600 seconds and from 600 seconds to 10 years.

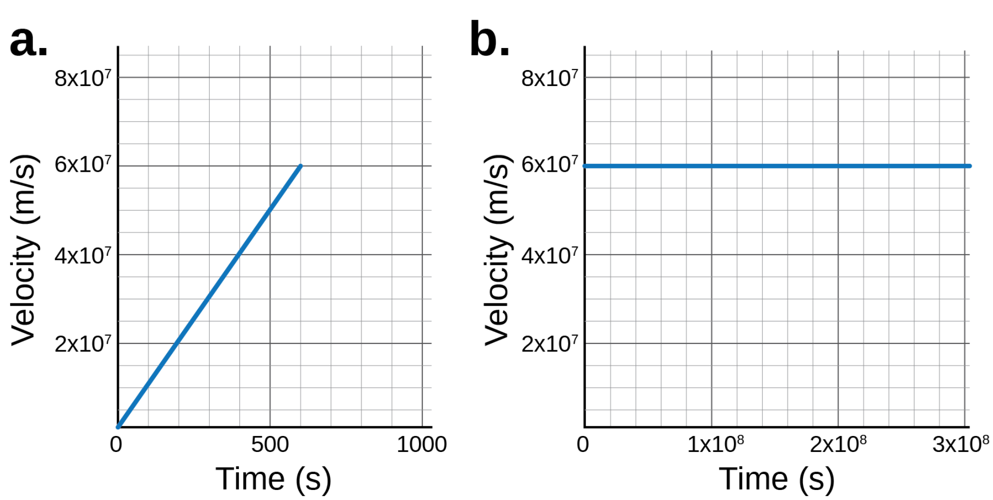


Figure 2. Modeling Nanocraft Motion. Velocity *vs.* time graphs for **a)** the first 600 seconds of the nanocraft's motion; and **b)** the nanocraft's motion from 600 seconds to 10 years.

a. When is there no net force acting on the nanocraft? Explain how you know.

There is no net force acting on the nanocraft from 600 seconds to 10 years. I know because the velocity is constant. If there is a net force acting on an object the velocity changes.

b. Does the nanocraft come to rest when there is no net force on it? Explain how you know.

No, the velocity is a constant 60,000,000 m/s. It is still traveling very fast.

5. Two students are discussing the relationship between the net force acting on the nanocraft and the nanocraft's velocity. Each student's claim is below.

Claim 1: Because the nanocraft is traveling at 60,000,000 m/s it must have a net force acting on it.

Claim 2: Because the nanocraft is traveling at a constant velocity there is no net force acting on the nanocraft.

Which claim (if either) do you agree with? Explain your reasoning.

I agree with Claim 2. An object will stay in motion until it is acted upon by a net external force. The nanocraft is traveling at a constant velocity, therefore there is no net external force acting on the nanocraft.

6. After the 600 second period of acceleration, how long will it take the spacecraft to reach Proxima Centauri, 4 light years away? Show your calculations or explain your answer. (1 light year = 1 x 10^{16} meters)

$\Delta t = \frac{\Delta x}{\Delta v} = \frac{4\times10^{16} m}{60{,}000{,}000 \frac{m}{s}} = 6.7 \times 10^{8} s$ or approximately 21 years

7. Traditional spacecraft are very massive. Would a traditional spacecraft accelerate more or less than the nanocraft if the same force was applied by the lasers? Explain your answer.

Traditional spacecraft would accelerate less because for a fixed force (from the lasers) as the mass increases the acceleration increases.

8. Suppose scientists have a laser that can provide a force of 100.0 N and a variety of spacecraft of different masses as shown in Table 1.

a. Calculate and record the accelerations of the spacecraft in the third column **Table 1**. Show your work below.

Force (N)	Mass (kg)	Acceleration (m/s^2)
100.	1.0	$\frac{100\ N}{1.0\ kg} = 100 \frac{m}{s^2}$
100.	0.50	$\frac{100\ N}{0.50\ kg} = 200 \frac{m}{s^2}$
100.	0.25	$\frac{100\ N}{0.25\ kg} = 400 \frac{m}{s^2}$

100.	0.10	$\frac{100\ N}{0.10\ kg} = 1,000\frac{m}{s^2}$
100.	0.010	$\frac{100\ N}{0.010\ kg} = 10,000\frac{m}{s^2}$
100.	0.0010	$\frac{100\ N}{0.0010\ kg} = 100,000\frac{m}{s^2}$

b. What trend do you see in the calculated accelerations? Why does that make sense?

As the mass is decreased the acceleration increases.

9. Suppose scientists want a spacecraft to accelerate at a rate of 100,000 m/s^2. They are considering spacecraft with a variety of masses as shown in **Table 2**.

a. Calculate and record the required forces from the lasers in the first column of Table 2. Show your work below.

Force (N)	Mass (kg)	Acceleration (m/s^2)
(2.0 kg)(100,000 m/s^2)=200,000 N	2.0	100,000.
(0.50 kg)(100,000 m/s^2)=50,000 N	0.50	100,000.
(0.10 kg)(100,000 m/s^2)=10,000 N	0.10	100,000.
(0.010 kg)(100,000 m/s^2)=1,000 N	0.010	100,000.
(0.0020 kg)(100,000 m/s^2)=200 N	0.0020	100,000.
(0.0010 kg)(100,000 m/s^2)=100 N	0.0010	100,000.

b. What trend do you see in the calculated forces? Why does that make sense?

For a given acceleration as the mass is decreased the force decreases.

10. Imagine you are pushing two boxes, one heavy and one light, with a constant force on a frictionless surface.

a. You want the two boxes to reach the same final velocity. Which will you need to push for a longer amount of time, the lighter box or the heavier one? Explain your answer.

The heavy mass would need to have the force applied for a longer period of time. It will have a smaller acceleration. Since acceleration is the rate of change of velocity with a smaller acceleration it will take longer to reach the final speed.

b. If the heavy box has twice the mass as the light box, how much time will the heavy box need to be pushed compared to the light box to reach the same final velocity?

The doubly heavy mass will need to be pushed for twice as long because it will have half the acceleration.

c. Why do you think scientists want to create the lightest spacecraft possible to travel to distant star systems? Provide evidence from the tables in your response.

The lightest spacecraft will need smaller forces applied to them in order to have large accelerations. For example, in Table 2, the mass of 0.0010 kg only needed a 100 N force to have an acceleration of 100,000 m/s^2, while a 2.0 kg object needed 200,000 N of force to reach the same acceleration. You can also see this relationship in Table 1 where the smaller mass objects have a larger acceleration with the same net force.

11. **Connect to the Big Question**. Currently, the most powerful telescopes cannot see exoplanets. Why will the pictures from Breakthrough Starshot be better than the pictures from telescopes we have on Earth? What limitations will the Breakthrough Starshot cameras have? Do you think the pictures will be worth the time, effort, and cost? Why or why not?

Many blurry pictures can be used to make a good picture, so using the Breakthrough Starshot pictures we will be able to get more detail than ever before on exoplanets. The cameras are small and might hit spacedust and not get there. They might not go to the right place because of bad aim. The cameras are moving fast and the pictures will be super blurry. It will take a long time for them to get there and then a long time for the pictures to come back. They only get one chance to take pictures. I do think the pictures will be worth the cost as we will learn new information about an exoplanet that we could not have learned otherwise. Additionally, we will have developed technology that could be used for many other things.