4.1: Relationship Between Distance, Speed, and Time

Learning Objectives

- You will be able to distinguish among distance, speed, and time
- You will be able to convert between various units of time
- You will be able to convert between various units of speed
- You will be able to perform calculations using the relationship between distance, speed, and time
- You will know what a light-year means and how it is related to a year
- You will be able to determine the lookback time to various astronomical events, including ones occurring at different distances and times

What Do You Think: How Long to Get There

4.1.1: Distance, Speed, and Time

Before we can apply the concepts of distance, speed, and time to the Universe, we must understand the specific meaning of each and examine how they are related.

Distance can be defined as how far apart two objects are in space. For example, the distance between Chicago and San Francisco is about 2,100 miles (about 3,400 km). As we discussed in Chapter 1, the distances involved in astronomy are so large that special distance units are often used for convenience. For example, Earth is about 150 million km from the Sun (93 million miles). This distance is called 1 astronomical unit (AU), a unit of measure invented specifically for astronomy.

Other units used specifically by astronomers to measure distance include light-years (ly), light-hours, light-minutes, and light-seconds. The light-minute is how far light travels in 1 minute. For example, Earth is about 8 light-minutes from the Sun (it takes 8 minutes for the light to travel from the Sun to Earth), so an astronomical unit is also 8 light-minutes. We often find it convenient to measure distances in the Solar System in terms of light-minutes, or even light-hours, the distance light travels in 1 hour.

A light-year is the distance light travels in a vacuum (empty space) in 1 year. In SI units, a light year is 9.5×10^{15} m. The light-year is used to measure large distances, those beyond our Solar System. We generally use light-years to measure distances to other stars in our Galaxy, or even to galaxies beyond our own. For example, the distance across the disk of the Milky Way Galaxy is about 100,000 light-years, and the nearest major galaxy to ours (Andromeda, or M31) is 2.5 million light-years away.

Another unit that astronomers use is the parsec (pc). A parsec is equal to 3.26 light-years, and so it is also used to describe large distances. Parsec is usually accompanied by Greek prefixes, such as kilo (10^3) and Mega (10^6), to mean a thousand parsecs or a million parsecs. When abbreviated, these units are written as kpc and Mpc, just as km is a thousand meters and MW is a million watts. Therefore, the distance across the disk of the Milky Way can be described as 100,000 light-years or as 30 kpc (30,000 parsecs).

Time is a measure of how long it takes for an event to occur, or its duration. It is an observed phenomenon that we use to describe past, present, and future events. Intervals of time are usually measured in units that are convenient to the events in our daily lives. These are the familiar measurements of years, months, weeks, days, hours, minutes, and seconds. For shorter times, we can again use Greek prefixes, so that a millisecond (ms) is one thousandth of a second. For longer times, we use the year: it takes 1 year—about 365 days—for Earth to travel around the Sun one time. Humans use the year to measure the age of people and things—including the Universe itself. We can also add the Greek prefixes to the year; for example, a Gyr (Gigayear) is 1 billion years.

Speed is defined as the rate that an object travels through space; it is the distance traveled in a certain amount of time. A familiar example from our daily lives can be seen when we drive to work or school. Our speed is measured by how fast or slowly we drive. Our car is said to have a speed of 60 miles per hour (mph) if it will travel a distance of 60 miles in exactly 1 hour.

Velocity is another term that you will see in the activities below. Velocity can be simply defined as speed in a particular direction. In the above example for speed, we said that a car travels at a speed of 60 mph. If we add a direction, say the car is traveling north at 60 mph, we then have the car's velocity: A car traveling 60 mph north is different from a car traveling 60 mph west. Both travel the same distance, 60 miles, in 1 hour, but if they start at the same spot, they will certainly arrive at different destinations! It is this difference that velocity takes into account.

Mathematically, velocity is often represented by the letter v as seen in the equation:

$$\vec{v} = \frac{\vec{d}}{t}$$

which means that velocity equals displacement (change of position) divided by time. Here, the *v* and *d* have arrows above them to remind us that they include the direction traveled.

Having made the distinction between speed and velocity, we must warn you that people often say velocity when they really mean speed. For instance, when discussing planets orbiting the Sun, or the flight path of rockets and other spacecraft, we might refer to their velocity when we really have no interest in the direction of travel. Fortunately, it is generally easy to tell from the context if the direction as well as speed is important.

In physics and astronomy, the speed of light plays an important role in understanding how our Universe works. Light-speed is the rate that light travels through empty space (a vacuum), which is about 3.0×10^8 m/s or 3.0×10^5 km/s. It is represented by the symbol *c*, and measurements show it to be constant—it does not change, regardless of the state of motion of either its source or the one measuring it.

Using the mathematical relationship between velocity, distance, and time is how we find the equivalent distances of light-minutes and light-years in SI units. Using the previous equation, and ignoring the arrows in this example because we are not concerned about direction, we can determine how far the light year and light minute are in meters:

$$v = \frac{d}{t}$$

Rearranging,

$$d = v \times t$$

Plugging in values,

$$\begin{aligned} 1 \text{ light-minute } &= (3 \times 10^8 meters/ \cancel{second}) \times (60 \ \ \cancel{seconds}) \\ &= 1.8 \times 10^{10} \, meters. \end{aligned}$$

and

$$\begin{aligned} 1 \text{ light-year } &= (3 \times 10^8 meters/ \cancel{second}) \times (1 \ \cancel{year} \times 3.15 \times 10^7 \ \cancel{second}/ \ \cancel{year}) \\ &= 9.5 \times 10^{15} \, meters \end{aligned}$$

Play Animation **Play Animation**

Keep the definitions of time, distance, and speed, and of the relationships between them, in mind as you work through the activities that are presented in the following sections.

> **Powers of Ten: Timescales**
>
> In this activity, you must drag and drop the tiles from the right-hand side of the screen into the correct open space in the table.
>
> The first column gives a physical description of a time span, the second is the measurement of that time span in convenient units, and the third represents the time span expressed in seconds using scientific notation.
>
> You will know you have dragged the tiles into the correct space when you see a green check mark.
>
> Play Activity

The previous activity gave you a chance to think about some different timescales you might encounter in your daily life or as part of this class. It asked you to compare them and rank them. This is a useful skill to have when you are trying to understand how one process or event might relate to another. However, in the previous activity, you were given all of the times in a common unit, seconds. Normally, things are not so convenient. You will generally have to convert to a common unit before you can make a comparison. The next set of activities gives you additional practice with this useful skill

> **Unit Conversions: Time**

In the next set of activities, you will work with the relationship between distance, speed, and time. These quantities can be described in various ways. For instance, speed can be miles per hour (mi/hr or mph) or kilometers per second (km/s), or even furlongs per fortnight! The important thing is that speed is always the ratio of a distance traveled to the time needed to travel that distance: distance/time. While the units we use to describe a speed are arbitrary, we generally use whatever is most convenient. The next several activities are intended to give you a better understanding of speed and its relation to distance and time.

DISTANCE, TIME, AND SPEED IN EVERYDAY LIFE

A. Speed

Worked Example:

1. If you have been driving on the highway for 1 hour and have traveled 30 miles, what is your average speed?

- Find: v
- Given: t = 1 hour, d = 30 miles
- Concept(s): $v = d/t$
- Solution: v = 30 miles/1 hour = 30 miles/hour

Question:

B. Distance

Worked Example:

1. If you have been driving on the highway at 60 miles/hour for 2 hours, how far have you traveled?

- Find: d
- Given: t = 2 hours, v = 60 miles/hour
- Concept(s): $v = d/t \rightarrow d = vt$
- Solution: d = (60 miles/~~hour~~)(2 ~~hours~~) = 120 miles

Question:

C. Travel Time

Worked Example:

1. If you have been driving on the highway at 20 miles/hour and have traveled a total of 80 miles, how much time have you been traveling?

- Find: t
- Given: d = 80 miles, v = 20 miles/hour
- Concept(s): v = d/t → t = d/v
- Solution: d = (80 ~~miles~~)/(20 ~~miles~~/hour) = 4 hours

Question:

HOW MUCH TIME TO GET THERE

Now the goal is to determine how much time it would take you to get to various places in the Universe, if you were traveling on foot (if it were possible!), in our current fastest spaceship, at the speed of light, or at half of the speed of light.

Assume the following speeds:

- Speed of a person walking: about 3 miles/hour = 5 km/hour
- Speed of our fastest spaceship: 10 miles/second = 16 km/second = 57,600 km/hour
- Speed of light: 186,000 miles/second = 300,000 km/second
- Half of the speed of light: 93,000 miles/second = 150,000 km/second

Drag and drop the travel time tiles for the following places you might like to visit. Their distances are:

- Moon : 240,000 miles
- Nearest star (Proxima Centauri): 4 light-years
- Across the Galactic Disk : 100,000 light-years across
- Nearest galaxy : 2.5 million light-years

There are several worked examples below to get you started. All of the times can be calculated based on the concept that speed = distance

time ($v = d/t$), or equivalently, that time = distance/speed ($t = d/v$).

Worked Examples:

1. How much time would it take to walk to the Moon, if you could?

- Find: t
- Given: Use the facts that the distance d to the Moon is about 240,000 miles, and the typical person can walk at a speed, v, of about 3 miles/hour (without breaks).
- Concept(s): Use the concept that v = d/t → t = d/v.
- Solution: Put in the known numbers: t = d/v = (240,000 ~~miles~~) / (3 ~~miles~~/hour).
- Cancel miles, and use calculator: t = 80,000 hours.
- Convert hours to years: t = 80,000 ~~hours~~ × (1 ~~day~~/24 ~~hours~~) × (1 year/365 ~~days)~~ = 9 years.

2. How much time would it take to get to the nearest star (4 light-years away) traveling at light-speed?

- Find: t
- Given: d = 4 light-years, v = speed of light
- Concept(s): t = d/v

- Solution: (4 light-years) / (1 light-year/year) = 4 years.

3. How much time would it take to get to the nearest star (4 light-years away) traveling at half light-speed?

- If you are going at half of the speed of light, that means you are going slower by a factor of 2. That means it will take you 2 times longer than if you were traveling at light-speed.
- 4 years × 2 = 8 years.

Now you are ready to fill in the chart.

Play Activity

4.1.2: Lookback Time - Looking Far Away is Looking Back in Time

What Do You Think: Light-years

The Stargazers Club is discussing a galaxy that is far, far away. Keisha has pulled up an image of it on her phone and tells the group that it is 10 billion light-years away.

- **Indira:** “That means we’re seeing the galaxy as it looked 10 billion years ago, when it was very young. It probably looks a lot different now.”
- **Jason:** “Light-years is the amount of time it takes the light to get to us, right?”
- **Keisha:** “If the galaxy is 10 billion light-years away, then it must be 10 billion years old.”

The distances to stars and galaxies are so large that even light, traveling almost 300,000 km every second, still requires *years* to travel to them. That means when we look at a star, Alpha Centauri for example, we are not seeing it as it is. We are seeing it as it was *4 years ago*. The same is true for the Sun, of course. We do not see it as it is, we see it as it was 8 minutes ago. That has certain implications for our observations of the Universe; if the Sun were to shut off at this moment, we would not know it for 8 minutes. That is because any photons that just left the Sun would not arrive for 8 minutes, and until they got here we would have no way to know that the Sun had gone out.

This concept is so important in astronomy that it is given a special name: lookback time. We would say that the lookback time to the Sun is 8 minutes. To Alpha Centauri, the lookback time is about 4 years. But what about other parts of the Milky Way Galaxy, or other galaxies? Well, the typical lookback time to objects inside our Galaxy is several tens of thousands of years. That is because our Galaxy is about 100,000 light-years across. As a result, light requires up to about 100,000 years to reach one part of the Galaxy from another part. For external galaxies, the lookback times are even bigger.

The nearest large galaxy to the Milky Way is M31, the Andromeda Galaxy. This galaxy is about the same size as ours, but it lies about 2.5 million light-years away. So, if you go out tonight and find M31 (it can be seen from the northern hemisphere in the late summer or fall if you know where to look), the glow you see will have begun its journey 2.5 million years ago. Think about that for a moment. When that light started out, human beings (*Homo sapiens*) did not yet exist as a species. Parts of the Coast Range of California were still pushing upward from the sea, the current volcanoes of the Andes mountains and the Cascades had not yet grown, and the island of Hawaii was still hidden below the Pacific waves.

Still, if we could somehow violate the laws of physics and see M31 as it is right now, we would see very few differences between now and 2.5 million years ago. Galaxies do not change very much over such a time period, unlike Earth and its living creatures. However, if we look at even more distant objects, and that includes all galaxies, then the lookback time is greater. Nearby galaxies are tens of millions of light-years away, and the most distant galaxies are *billions* of light-years distant. We are seeing those galaxies, the nearest of them, as they were tens of millions of years ago. For the most distant galaxies, we see them as they were *billions* of years ago. Even for a galaxy, a billion years is a long time. In fact, the lookback time for the most distant galaxies goes back to nearly the beginning of the Universe. (Did you know that the Universe had a beginning?) In a sense, the finite speed of light turns the entire Universe into a time machine, allowing us to see its history.

Lookback Time and Units

In this activity, we will review measures of distance and time that are typically used by astronomers.

A. Basic definitions

B. Observing an astronomical event

In 1994, scientists were amazed and thrilled to watch pieces of Comet Shoemaker-Levy 9 hit the planet Jupiter. Tremendous explosions resulted, creating plumes many thousands of kilometers high, hot “bubbles” of gas in the atmosphere, and large dark “scars” on the atmosphere that lasted for weeks. At the time, NASA’s Galileo satellite was about 1.6 AU from Jupiter, and the Voyager 2 satellite was at a distance of 42 AU from Jupiter (on its way out of the Solar System).

Hints: Recall that 1 AU = 8.3 light-minutes. Also, when speed is the speed of light, if the distance is in light-minutes, the time is in minutes. (The same is true for light-years and years.)

C. Communicating with satellites

In 2003, NASA sent missions to Mars that placed the rovers Spirit and Opportunity on the surface of the planet.

Hints: Recall that 1 AU = 8.3 light-minutes = 150 million km.

1. The closest distance from Earth to Mars is about 55 million km. At this distance, how much time does it take for radio control signals from Earth to reach Spirit? Round to the nearest minute.

✓ LOOKBACK TIME

In this activity, you should see a star field. In the center is the Observer star. Around the Observer star are various other stars that may go supernova (explode). In fact, three of them are going to go supernova, and you need to figure out the order that the Observer star will see them.

When you select the “next” button in the bottom right, the “event order” field at the top will be filled out. The “event order” displays the three stars in the star field that will go supernova. Also displayed is the timeline for when the stars explode. The first star explodes at time zero and starts the clock running.

Find the stars that will go supernova in the star field and hover your cursor over them. This displays the distance to the star from the Observer star in light-years. This distance corresponds to its lookback time in years. For example, Star D is 1.75 light-years from the Observer star, which means that if it were to go supernova, 1.75 years would pass before the Observer would see it. The lookback time is 1.75 years for that star.

Determine the order in which the Observer will see the three supernovae based on the time between each supernova and the distance from the Observer star.

Once you have made your selections in the “observation order” drop-down boxes, click the “next” button again and watch the supernovae.

As each supernova is seen by the Observer star, their order will be indicated at the bottom, over your selections. Once all three supernovae have been observed by the Observer star, the application will let you know if you were correct or not.

Click the “next” button to start another round.

Play Activity