7.2 Half-Life

A half-life can be used to compare the rate of radioactive decay for an isotope. The shorter the half-life, the faster the decay rate. All radioactive decay rates follow a similar pattern called a decay curve. The difference between different isotopes is the length of their half-lives. The Common Isotope Pairs Chart identifies the parent isotope (which decays) and the daughter isotope (one of the decay products). The chart also shows the half-life of the parent and the dating range the isotope can be used for in radioisotope dating. A decay curve can be used to estimate the amount of parent isotope remaining or the amount of daughter isotope produced at any time after the radioactive sample first formed or, in the case of carbon dating, after the organism died.

Words to Know

daughter isotope
decay curve
half-life
parent isotope
radiocarbon dating

The oldest living organism on Earth is a bristlecone pine tree growing in the California White Mountains (Figure 7.14A). This tree is more than 4780 years old. How can you determine the age of a tree? One method is to extract a sample of wood and count the thin bands (annual rings)—one ring for each year of life (Figure 7.14B). Suppose you wanted to determine the age of something that was no longer alive, such as a bone or an ancient wooden tool. How would you establish its age?

Did You Know?

The ages of the oldest rocks on Earth were established by American chemist Clair Patterson (1922–1995) in 1953. The rock meteorites Patterson analyzed contain uranium that is slowly turning into lead through radioactive decay. He was able to infer from the amount of each element present that the rocks were 4.55 billion years old.

Figure 7.14 An ancient bristlecone pine (A). Annual rings (B)

Anchor Activity

7-2A Modelling Rates of Radioactive Decay

Find Out ACTIVITY

Radioactive elements contain at least one unstable isotope. Each radioisotope decays at a unique rate. However, graphs showing the rate at which isotopes decay show striking similarities. The rate at which a sample of a radioisotope decays can be modelled by tossing pennies and letting them land randomly. In this activity, you will use coin tosses to generate data for a graph.

Safety

- Wash your hands after completing this activity.

Materials

- 100 pennies or other two-sided objects
- container for shaking the pennies
- graph paper

What to Do

1. Create a data table like the following. Give your data table a title.

Number of Tosses Completed	Number of Pennies Remaining	Total Number of Pennies Removed Since the Start
0	100	0
1		
2		
etc.		
Last toss (record the number)	0	100

2. Working in pairs or small groups, count out 100 pennies.
3. Shake the pennies in the container and let them fall on a surface where they can be examined. Count all pennies that landed "heads" up and put them back into the shaker. You will shake them again because they represent atoms that did not yet decay. Record this number of pennies in the column "Number of Pennies Remaining."
4. Count the number of pennies that landed "tails" up. These represent atoms that decayed, so you will not shake them again. Add this number of pennies to the previous total number of pennies removed so you have a running total of all the pennies removed. Record this number of pennies in the third column.
5. Repeat steps 3 and 4 until there are no pennies left.
6. You will plot two smooth curves on the same piece of graph paper.
   - The first curve will show the number of pennies remaining after each toss. This will represent the number of nuclei of the parent isotope remaining in the sample after each decay.
   - The second curve will show the number of pennies removed since the start. This will represent the number of daughter isotopes produced during the decay.

   Your graph should have the following features.
   - Give your graph a title.
   - The *x*-axis (horizontal) will be the number of tosses. The *x*-axis should increase left to right from 0 tosses to how many you needed in the activity.
   - The *y*-axis will plot the number of pennies. The *y*-axis should extend from 0 to 100.
   - Join the dots on each curve with a smooth line.
   - Label the falling curve as parent isotopes and the rising curve as daughter isotopes.

What Did You Find Out?

1. (a) Could you use your graph to estimate how many pennies would be present after four tosses if you had already done three tosses but not the fourth? Explain.
   (b) Does your data suggest you could predict exactly how many pennies would be present after four tosses if you had already done three tosses but not the fourth? Explain why or why not.
   (c) Does your data permit you to predict which particular pennies will land heads up? Explain.
   (d) Obviously there is no such thing as "half a toss" of the pennies. However, does your data suggest that you could estimate the number of pennies remaining after $2\frac{1}{2}$ tosses? Explain.

Carbon Dating

We can measure how the radioactivity in plant or animal remains has changed over time and calculate the age of the remains. All organisms on Earth contain carbon. Plants use carbon dioxide to make their food. Animals take in the carbon when they eat plants. Carbon's isotopes include carbon-12 and carbon-14. When an organism is alive, the ratio of the number of carbon-14 atoms to the number of carbon-12 atoms in the organism remains nearly constant. But when an organism dies, its carbon-14 atoms decay without being replaced. The ratio of carbon-14 to carbon-12 then decreases with time. By measuring this ratio, the age of an organism's remains can be estimated. **Radiocarbon dating** is the process of determining the age of an object by measuring the amount of carbon-14 remaining in that object. Only material from plants and animals that lived within the past 50 000 years contains enough carbon-14 to be measured using radiocarbon dating.

Connection

Section 2.2 has information about the carbon cycle.

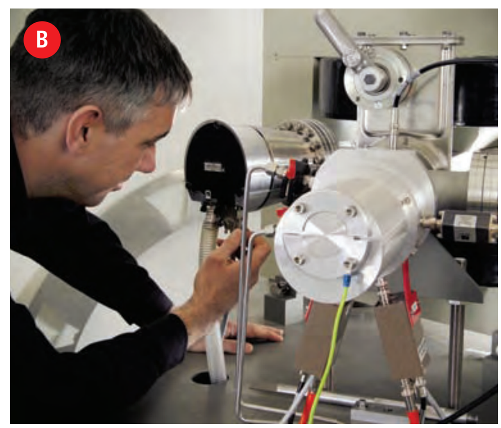


Figure 7.15A A sample is removed from bone for carbon dating. The bone is a human femur that is more than 500 years old.

Figure 7.15B A machine called an accelerator mass spectrometer is used for carbon dating. The machine converts atoms from a sample into a beam of ions. The mass of the ions is then measured using electric and magnetic filters.

The Rate of Radioactive Decay

The rate of radioactive decay can be compared using a quantity called half-life. A **half-life** is a constant for any radioactive isotope and is equal to the time required for half the nuclei in a sample to decay. For example, the half-life of the radioisotope strontium-90 is 29 years (Table 7.5). If you have 10.0 g of strontium-90 today, 29 years from now you will have 5.0 g left.

Table 7.5 Half-Life of Strontium-90

Number of Half-Lives	Elapsed Time (y)	Percentage of Strontium-90 Present	Amount of Strontium-90
0	0	100%	10.0 g
1	29	50%	$10.0\text{ g} \times \frac{1}{2} = 5.00\text{ g}$
2	58	25%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} = 2.50\text{ g}$
3	87	12.5%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 1.25\text{ g}$
4	116	6.25%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 0.625\text{ g}$

Using a Decay Curve

When the information in Table 7.5 is graphed, a type of line called a decay curve is produced. A **decay curve** is a curved line on a graph that shows the rate at which radioisotopes decay. If you graph the rate of decay of any radioisotope, it will look the same as the decay graph in Figure 7.16. The only difference will be the length of the half-life. Each type of radioisotope decays at a different rate. For example, radon-222 has a fairly short half-life of 3.8 days. Carbon-14 has a longer half-life of 5730 years. Uranium-238 has an extremely long half-life of 4.5 billion years.

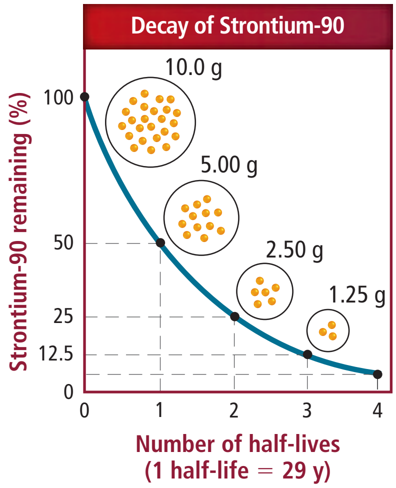


Figure 7.16 The graph shows how the amount of strontium-90 in a sample changes over time.

You can use the information represented in a decay curve to infer additional data.

Example 1: Iodine-131 is an isotope used in the treatment of thyroid cancer. Iodine-131 has a half-life of eight days. This length of half-life is very useful. It is long enough to allow the radiation treatment to work but short enough that the radiation from it drops to very low levels after a few weeks. Fresh iodine-131 must be prepared near or in the hospital before each use, because it decays quickly.

If a sample of iodine-131 weighs 20 g, what mass of iodine would remain after 16 days?

16 days is twice as long as 8 days, so it represents 2 half-lives.

$$\text{mass remaining} = 20 \text{ g} \times \frac{1}{2} \times \frac{1}{2} = 5 \text{ g}$$

Example 2: A sample of rock contains 64 g of a radioisotope. How much of the radioisotope will remain after three half-lives?

Three half-lives mean that the original mass of isotope will be reduced by half three times.

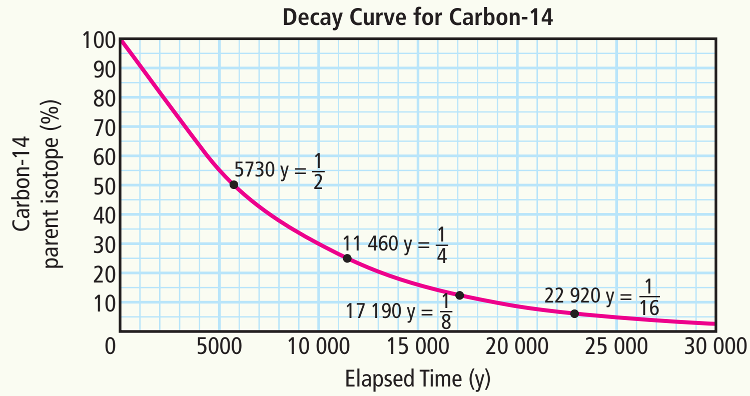
$$\text{mass remaining} = 64 \text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 8 \text{ g}$$

Did You Know?

To a very small extent, even you are radioactive, due to the carbon-14 and other radioisotopes found naturally in the molecules of your body.

Practice Problems

Try the following half-life problems yourself. Use the decay curve shown below for carbon-14.



The Decay of Carbon-14		
Number of Half-Lives	Elapsed Time (y)	Percentage of Carbon-14 Present
0	0	100%
1	5730	$50\% = 100 \times \frac{1}{2}$
2	11 460	$25\% = 100 \times \frac{1}{2} \times \frac{1}{2}$
3	17 190	$12.5\% = 100 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$
4	22 920	$6.25\% = 100 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$

1. What is the length of one half-life of carbon-14?

2. How many half-lives have passed when there is $\frac{1}{4}$ of the original amount of carbon-14 remaining?

3. Estimate the percentage of carbon-14 remaining after:
(a) 5000 years
(b) 10 000 years
(c) 20 000 years

4. Estimate the time elapsed when the amount of carbon-14 remaining is:
(a) 70 percent
(b) 40 percent
(c) 5 percent

Answers provided on page 592

Common Isotope Pairs

There are many different isotopes that can be used for dating fossils, including those shown in Table 7.6. The isotope that undergoes radioactive decay is called the **parent isotope**. The stable product of radioactive decay is called the **daughter isotope**. The production of a daughter isotope can be a direct reaction or the result of a series of decays. Notice in Table 7.6 that each parent isotope is paired with a daughter isotope. Each isotope can be used for radioisotope dating, but the dating range is different for each depending on the half-life of the parent isotope. The longest half-life shown is 47 billion years.

Table 7.6 Common Isotope Pairs Chart

Isotope		Half-Life of Parent (y)	Effective Dating Range (y)
Parent	Daughter		
carbon-14	nitrogen-14	5730	up to 50 000
uranium-235	lead-207	710 million	> 10 million
potassium-40	argon-40	1.3 billion	10 000 to 3 billion
uranium-238	lead-206	4.5 billion	> 10 million
thorium-235	lead-208	14 billion	> 10 million
rubidium-87	strontium-87	47 billion	> 10 million

The Potassium-40 Clock

A clock does not have to look like a digital display or a dial with two hands on it. Any method for determining the passing of time or the age of something can be considered a kind of clock. Ernest Rutherford created a practical application for half-life of radioisotopes when he used the constant rate of decay as a clock to help determine the age of Earth. His technique has been applied many times since its discovery.

How can we use radioisotopes, such as potassium-40 and argon-40, as a clock? Potassium-40 has a half-life of 1.3 billion years. Its daughter isotope is argon-40. When rock is produced from lava, all the gases in the molten rock, including argon-40, have been driven out. This process sets the potassium radioisotope clock to zero, because there is potassium-40 (the parent) present in the molten rock but no argon-40 (the daughter) present.

Suppose that a very long time goes by. As the molten rock cools, it traps any gases that form inside it as a result of nuclear decay of atoms within the rock. A geologist finds this rock and takes it back to the laboratory for analysis. The analysis shows that both potassium-40 and argon-40 are now present in the rock. The argon gas is present in microscopic gas pockets, trapped inside the rock.

Connection

Chapter 12 has more information about the age of rocks.

Did You Know?

Radioisotopes are atoms whose nuclei are unstable and will eventually disintegrate, even if it takes billions of years. Stable isotopes exist indefinitely and have no known half-life.

Using data from a potassium-40 clock

Table 7.7 shows that, as the mass of the parent isotope drops, the mass of the daughter isotope increases. This should make sense because the potassium-40 is turning into argon-40. If analysis showed that there were equal masses of potassium-40 and argon-40 in a rock, how old is the rock? If you said 1.3 billion years old, you are correct. After one half-life, the parent isotope has decayed by half and is now present in an amount equal to the daughter isotope.

Table 7.7 The Decay of Potassium-40

Number of Half-Lives	Elapsed Time (billion y)	Amount of Potassium-40 Present	Amount of Argon-40 Present	Ratio of Argon-40 to Potassium-40
0	0	1000 g	0	0:1
1	1.3	500 g	500 g	1:1
2	2.6	250 g	750 g	3:1
3	3.9	125 g	875 g	7:1
4	5.2	62.5 g	937.5 g	15:1

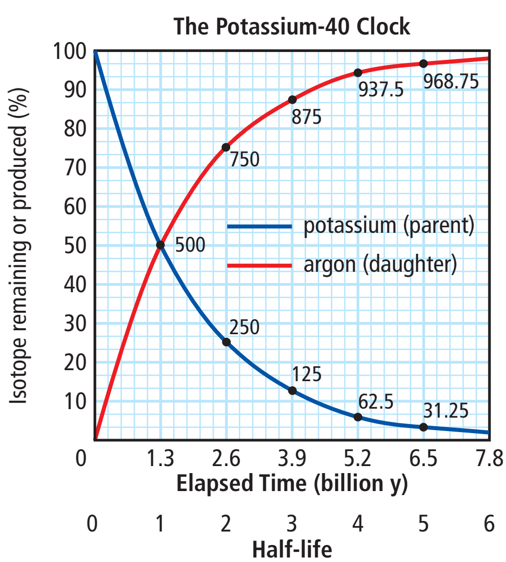


Figure 7.17 The blue line shows that the parent isotope is decaying. The red line shows that the daughter isotope is being produced.

When the trends shown in Table 7.7 are plotted on the same graph (Figure 7.17), a remarkable pattern becomes apparent. Notice in Figure 7.17 that at every age of the rock a different amount of parent is present with the daughter. For example, after one half-life, there are equal amounts of parent isotopes and daughter isotopes. This is shown on the graph at the place where the lines intersect. The red and blue lines intersect at one half-life, which for potassium-40 and argon-40 is 1.3 billion years.

What if there is more of the argon-40 daughter isotope present than there is of the potassium-40 parent isotope? It means that the rock is older than one half-life, or in this case, older than 1.3 billion years. Wherever the red (daughter) curve is above the blue (parent) curve, the age of the rock is greater than one half-life.

Why is this helpful for radioisotope dating of the rock? Because it means that all you have to do to date a rock is compare the amount of daughter isotope to the amount of parent isotope. Then, you can use this chart to find the age.

Suggested Activity

Think About It 7-2B on page 309

Practice Problems

Try the following radioisotope dating problems yourself. You may wish to use Table 7.7 and Figure 7.17 on page 308.

1. What is the ratio of argon-40 to potassium-40 two half-lives after the rock has formed?
2. What ratio of argon-40 to potassium-40 remains 3.9 billion years after the rock formed?
3. (a) When there is more parent isotope present in a sample than there is daughter isotope, what does this tell you about the age of the sample in terms of half-lives?
   (b) For how many years after the start of the potassium-40 clock is there more parent material than daughter material?

Answers provided on page 592

Explore More

The Bluefish Caves in the Yukon contain what may be the oldest evidence of human presence in Canada. Radiocarbon dating of this site indicates that the tools there were used by hunting parties between 12 000 and 25 000 years ago. To find out more about this important site and what tools were found there, visit **www.bcscience10.ca**.

7-2B Uses for Radioisotopes

Think About It

There are many different radioisotopes and many uses for them. In this activity, you will research one particular radioisotope or parent/daughter pair and report on what it is as well as some applications for it.

What to Do

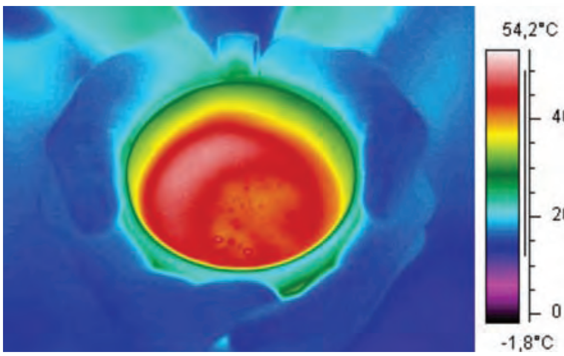
1. Select a radioisotope from a list that your teacher will provide or select your own radioisotope. You may wish to explore an application, such as one of the following, and then find out what radioisotope is used for that application.
   - research, diagnose, and treat disease
   - sterilize medical equipment
   - trace processes in living organisms
   - preserve food
   - detect smoke
   - analyze pollutants
   - detect weakness in metal structures
   - analyze minerals and fuels
   - study the movement of water
   - measure ages of rocks and remains of plants and animals
2. Consult with your teacher about your selection to make sure it is appropriate.
3. Find the name and nuclear symbol for your radioisotope or radioisotope pair, its sources, method of decay (alpha, beta, gamma, or other), half-life, and application.
4. In consultation with your teacher, choose a format for reporting on your investigation. Here are some suggestions.
   - Design an information poster including your own drawing or photographs with captions.
   - Design an informational brochure.
   - Write a 250-word summary in your own words.
   - Give a short oral presentation to the class, explaining what you have found.
   - Create a five-segment slide show presentation.

What Did You Find Out?

1. Post or present your information to the class.

Science Math connect

Exponential Decay



A thermogram shows the various temperatures of hands holding a hot drink. The heat radiation is detected electronically and displayed with different colors representing different temperatures.

How fast will a warm cup of tea cool down? How long will a medicine remain active in your body? How quickly does the air pressure drop as you travel up through the atmosphere? As different as all of these questions may seem, there is a mathematical relationship called the exponential decay equation that can help connect them all. This is the same equation that governs how fast a radioisotope will decay and the concept of a half-life. The equation for the remaining amount of a radioactive element is:

$$N = N_0(\tfrac{1}{2})^{t/T}$$

N is the amount remaining. N_0 is the initial amount. t is the elapsed time. T is the length of the half-life. The $(\frac{1}{2})$ that appears in the formula is the mathematical expression of the concept of half-life. For example, the half-life of carbon-14 is 5730 years. What mass of a 50 g sample of carbon-14 remains after 1000 years?

$$N_0 = 50 \text{ g}$$

$$t = 1000 \text{ y}$$

$$T = 5730 \text{ y}$$

$$N = N_0(\tfrac{1}{2})^{t/T} = 50(\tfrac{1}{2})^{\frac{1000}{5730}} = 50(\tfrac{1}{2})^{0.1745}$$
$$= 50 \times 0.8861 = 44 \text{ g}$$

After 1000 y, a 50 g sample of carbon-14 will have 44 g remaining.

How can this mathematical relationship be applied to the cooling of a cup of tea, the rate of removal of a medicine from the body, or a drop in pressure? Consider the following question: Suppose two cups of tea are made and that they are identical in every way, except that one starts out at 80°C while the other starts out at 100°C. Which will be the first to cool by 10 degrees? The answer is the one beginning at 100°C. This is because the total temperature drop is dependent on the starting temperature of the tea. The higher the temperature, the faster the rate at which the temperature drops. The exponential decay equation can even be used to calculate the temperature at any time after cooling has started.

The pressure of the air in our atmosphere decreases the higher you get above sea level. In fact, the higher you get, the faster it decreases. The rate at which the atmospheric pressure decreases is given by the exponential decay equation. The rate at which medicines are removed from our blood by our kidneys can also be given by a form of the exponential decay equation. Part of the beauty of mathematics is discovering that a relationship like this is so deeply connected with our world that it shows up again and again in different places.

Questions

Use the exponential equation to answer the following questions.

1. What mass of a 200 g sample of carbon-14 remains after 25 000 y?
2. What was the original amount of carbon-14 if 10 g of it remains after a period of 2500 y?
3. Suppose that a cup of freshly steeped tea at 100°C is allowed to cool in a room whose air temperature is 0°C. Suppose that every 5 min the temperature of the tea drops half way from its current temperature to 0°C. What is its temperature after 13 min?

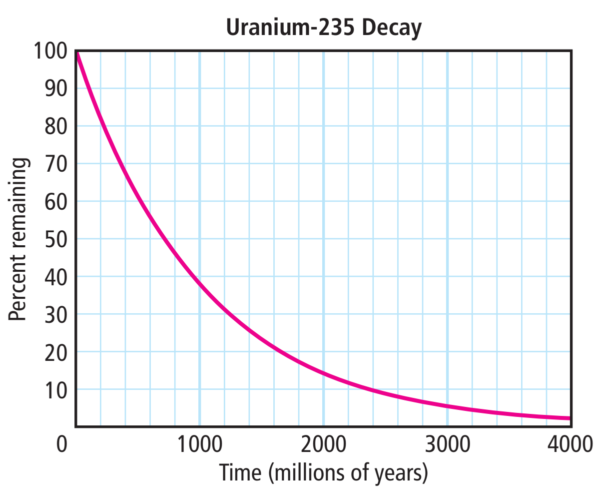
Check Your Understanding

Checking Concepts

1. Define half-life.
2. Distinguish between a parent isotope and a daughter isotope.
3. All isotopes decay in a similar pattern. What is the main difference between the rates of decay of different isotopes?
4. Explain the meaning of this statement: “A radioisotope can be used as a clock.”
5. How does the lava cooling to form rock set the potassium-40/argon-40 clock to zero?
6. Iodine-131 has a half-life of eight days. If a sample contained 512 g of iodine-131, what mass of iodine would remain after 32 days?
7. A sample of rock contains 800 g of a radioisotope. How much of the radioisotope will remain after three half-lives?
8. How are decay curves different for different isotopes?

Understanding Key Ideas

9. Consider the following graph showing the decay curve for uranium-235.



(a) What is the half-life of uranium-235?
(b) What percentage of uranium-235 remains after 1420 million years?
(c) The daughter product in this decay is lead-207. What percentage of the total possible amount of lead-207 has been produced after 1420 million years?
(d) What percentage of uranium-235 remains after three half-lives?
(e) If 80 g of uranium-235 decays for 355 million years, estimate the mass of uranium-235 that remains.
(f) How many years does it take for 60 percent of the original amount of uranium-235 to decay?

Use the following chart to answer questions 10 to 13.

Isotope		Half-Life of Parent (y)	Effective Dating Range (y)
Parent	Daughter		
uranium-235	lead-207	710 million	> 10 million
potassium-40	argon-40	1.3 billion	10 000 to 3 billion
carbon-14	nitrogen-14	5730	up to 50 000

10. Which parent isotope has the slowest rate of radioactive decay?
11. State which isotopes would be useful for dating a material that is:
    (a) 3000 years old
    (b) 30 000 years old
    (c) 60 000 years old
    (d) 60 million years old
12. If an original 10 g sample of carbon-14 decayed for 11 460 years, what mass of nitrogen-14 would have been produced?
13. Which of the three parent isotopes decays through beta decay?

Pause and Reflect

Why do you think it is important to date the age of the remains of living organisms? Why is it important to date the age of rocks and Earth? How might this information be useful to you in your life?