Unit 1: Fossils

Biology in a Box

A science education outreach program brought to you by a partnership between The University of Tennessee and the National Institute for Mathematical and Biological Synthesis

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Unit 1: Fossils
Materials List

- 2 clear plastic boxes labeled “Exercise 1: Fossils T/F” containing
  - 22 specimens (numbered 1-22)
- Magnifying glass
- Plastic deli cup labeled “Exercise 3c: Half-life Experiment” containing:
  - 32 light-colored poker chips (with a colored dot on one side of each)
  - 32 dark-colored poker chips
- Round plastic container holding
  - modern shark jaw
- Plastic bag labeled “Exercise 4: Fossil Lineages” containing
  - Bag labeled “Exercise 4.1: Determining a Fossil Lineage” containing
    - 5 fossil shark teeth, each labeled and marked with a red dot:
      - *Cretolamna appendiculata*
      - *Carcharocles auriculatus*
      - *Carcharocles chubutensis* (or *C. angustidens*)
      - *Carcharocles megalodon*
      - *Otodus obliquus*
  - Bag labeled “Exercise 4.2: Comparing lineages” containing
    - A single fossil shark tooth - Crow shark (*Squalicorax pristodontus*)

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Unit 1: Fossils

Introduction

Fossils are the remains of organisms (biota) that have been dead a long, long time (typically in excess of 10,000 years). These organisms have failed to decay because they have been preserved in some form of bacteria-free environment (e.g. in ice, in pine sap, in a bog, or under layers of sediment). In this series of exercises, students will gain an understanding of what constitutes a fossil, as well as the various mechanisms of fossil preservation (**Exercise 1: Fossils: T/F?**). They will become familiar with the concept of geological time, and what really big numbers of years mean (**Exercise 2: Geological Time Scale**). They will learn about how dates are assigned to fossils (**Exercise 3: Dating Fossils**), and they will learn how fossils are utilized to examine the historical relationships among organisms (**Exercise 4: Fossil Lineages**).

Exercise 1: Fossils: T/F?

Fossils are the remains or evidence of animals or plants that have been preserved naturally. A deceased organism or evidence of it (e.g., footprints, burrows, excrement) becomes fossilized when it encounters an environment where it is protected from oxygen and bacteria that play major roles in the process of natural decay. The general fossilization process varies greatly depending on the exact situation. There are four basic kinds of fossils: 1) The hard parts of the organism remain intact (e.g., tooth enamel, the shell of a mollusc). 2) Minerals have replaced the original animal or plant material. This is termed mineral replacement, and can be full or partial. 3) The animal or plant with tissue matter largely intact has been preserved in peat (acidic bogs), tar (tar pits), ice, or amber (the fossilized sap of pine trees). 4) The impression an organism made in a soft substrate has been preserved, while the organism itself is gone (trace fossil). You may hear the term "living fossils" used to describe particular organisms. These are organisms that are relics of a group that once was prominent but that is now largely extinct. However, living fossils are not fossils in the true sense of the word, as they do not fit the definition of natural preservation. You may encounter a living fossil in your set of items.

- Find the #1 boxes containing items in bubble wrap. Carefully remove all of the items in this box, and place these on a table in front of you.
- Make a chart that has 4 columns and 22 rows, as shown on the following page.
- Fill in your chart by doing the following:
    - Examine each object and determine whether it is a fossil or not. If not, it may be a dead organism that has not been dead long enough to be considered a fossil (again, around 10,000 years), or it might be something abiotic (lacking the characteristics of life).
    - Read the number on the backside of the fossil, and record your decision as to whether you think it is a fossil (Y), or is not a fossil (N) in the row with the corresponding number on your chart.
    - Next, for each object that you think is a fossil, indicate what type of fossil (in terms of the method of preservation) you feel it is.
    - Finally, make a guess as to what each object is (e.g. coral, leaf, piece of coal, rock, etc.).

- Check your answers on the Key to Exercise 1 provided at the end of this book.
- Fill in additional information about your fossils for use in later exercises.

Item #	Fossil? Y/N	Fossil Type	Fossil Identity	Additional Information
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				

Example of table used to complete Exercise 1.

Exercise 2: Geologic Time Scale

Introduction

What is geology? Geology is the study of the Earth, what it is made from, the organisms living on Earth, and how Earth has changed over time. Do you ever dig in your yard or in the ground? All the soil and rocks and things that you find when you dig in the earth are studied in geology. Have you ever noticed that as you dig deeper into the earth that things change? Sometimes the color of the earth changes as you dig deeper, and sometimes the texture of the earth changes as you dig deeper. Changes occur over many years that create those changes. Very hot, dry weather periods affect the earth and how it looks and feels, and very cold and snowy weather periods also affect the earth and how it looks and feels. Scientists called geologists like to study all those materials you find when you dig in the earth.

What is a geologist? A geologist works to understand the history of Earth, the materials that make up Earth, and the processes that occur over time to affect Earth. They study why the earth changes as you dig deeper into the earth and how changes in the weather affect how the earth looks and feels. Geologists study the soil, rocks, fossils, mountains, earthquakes, and anything else that occurs on earth to help them better understand the earth.

Over 300 years ago, scientists started piecing together information about the earth's geological history. They did so by comparing the patterns and ages of rock layers all over the world. Using this information, geologists now have constructed a calendar called the **geologic timescale** or **planetary calendar** to help us better understand the history of earth and how changes over time have affected earth and the organisms that live on earth. Usually when we think of calendars, we think of months, weeks, and days, but the geologic timescale consists of sections called eras and periods which are very long periods of time compared to the months, weeks, and days we typically talk about. Eras and periods are made up of millions, and even billions of years. Our whole lifetime would only be a very tiny little speck on the geologic timescale because our whole lifetime is so small compared to how long an era or period is on the geologic timescale. A million years is an incredible length of time, one that is difficult to imagine, and a billion years is a thousand million! Wow!

Exercise 2a: Toilet Paper Geological Timeline (*Grades K-12*)

This exercise was adapted from the following source, with an introduction and guiding questions provided by Lu Howard:

Wenner, J.M. 2010. "Toilet Paper Analogy for Geologic Time". The Science Education Resource Center at Carleton College. Carleton College. Accessed 02 July 2010. <http://serc.carleton.edu/quantskills/activities/TPGeoTime.html>

NOTE TO TEACHERS: Concept of a Million

As an introduction, and as a means of introducing young students to the concept of a million, a suggested activity is to read How Much is a Million *by David Schwartz. The concept of a million is challenging for very young students so this book helps define the magnitude of the number prior to beginning their investigation of age of fossils and the geologic time scale.*

An alternative to reading How Much is a Million *is using familiar objects and ideas to help students understand the concept of a million. Show students an inch on a ruler and tell them that one million inches is about 16 miles, or one million inches is about the length of four trips from home to school (adjust as appropriate for specific student groups and distances they may travel to and from school). One million hours ago would be before K – 4 students' great, great grandparents were born. One million seconds is about 11.5 days.*

Materials

- 1 roll of toilet paper, long sheet of adding tape/butcher paper (Optional)
- A long hallway in or a sidewalk outside your school
- Clear tape
- Masking tape and/or markers

Instructions for teachers:

- Prior to this exercise, you should obtain measurements of each student's foot (in cm), and from this information, obtain the average foot size of the students in your class. Do not tell students why you are taking this measurement. This will help build excitement for the exercise at a later date!
- In addition to the above measurements, you should take approximately 30 minutes to an hour to prepare for this exercise before presenting it to your class.

- Open the file titled "Toilet Paper Timeline of Earth's History" in the Unit 1 folder on the Biology in a Box Teacher CD.
- If you will be using a roll of toilet paper, gently unroll the entire roll, counting the number of sheets on the roll. If the toilet paper tears, clear tape will come in handy!
- Enter this number in the appropriate cell on the spreadsheet.
- Also measure the width of each sheet as accurately (in cm) as possible. Most rulers with cm markings are also subdivided into millimeters, each of which, of course, is equal to 0.1 cm.
- Enter the width of each sheet in the appropriate cell on the spreadsheet.
- You will notice that the lengths from the end of the roll (in both cm and number of sheets) denoting important events in Earth's history are calculated for you.
- Mark these points with a marker at the appropriate spots on the toilet paper.
- Gently roll the toilet paper back onto the roll.
- If you are using adding tape or butcher paper in a single strip, you can simply enter "1" for the number of sheets, and the total length (in cm) for the value of “cm per sheet”. As above, the distances from the start point representing various events will then be calculated for you.
- If you do not wish to use paper of any sort, this exercise can be performed on a stretch of one or more hallways, or outside, with tape markers being placed at the appropriate points on the floor/sidewalk (again using “1” for the number of sheets, and the total length of the hall/sidewalk as the length of one “sheet” in the spreadsheet). A distance of at least around 100 feet (3048 cm) is recommended, if possible.
- At some point, after the # of sheets and # cm per sheet has been entered, also enter the average foot length of students in your class in the appropriate cell on the spreadsheet.
- You will notice, after entering this value, that the spreadsheet will tell you the span of time represented by the average foot length of a student in your class.

- When you are ready to present this exercise to class, randomly assign a number (from 1 to 22) to each student in your class. This is probably most easily done by putting slips of paper with each number from 1 to 22 on slips of paper in a hat, and letting students draw them from the hat. If you have more than 22 students, some may need to work in pairs, or if you have less than 22 students, some students may receive more than one number.
- It will be useful for you to have a copy of the list of events to help you keep track of them in order as this exercise progresses.
- Each of the numbers can be used to correspond to one of the major events in Earth's history that is listed on the spreadsheet.
- If students are not readers, explain to them what their designated events are.
- Have students draw pictures that correspond to their Earth history events. For non-readers, you may wish to also prepare labels for their pictures for later use.
- When you are ready to begin, go outside or into the hall, and have the student designated as the present time hold the end of the toilet paper (or adding tape/butcher paper). If you are only using a hall or a sidewalk with no paper to illustrate this, you will need to mark the beginning and end points of the total distance with tape, as well as the distances representing the various Earth history events ahead of time.
- Begin to unroll the toilet paper (or other paper), having the "present" student stay in place. When you reach an important event that you have marked on the paper, have the student representing that event stand at that mark.
- Continue unrolling the paper, again instructing students representing events stand in place at their marks as those marks become visible.
- Continue until the end of the roll is reached.
- Look at both ends of the time line your class has made.
- Have the students consider the following:
    - Look at how far apart some of you are. Are you close enough to others to see everyone else's pictures?
    - Considering this is a time line, what does that mean?

- Have the students take a minute to look at their feet.
- Let the students know how much time, on average, that the length of one of their feet represents. Then have them think about the following questions:
  - Now look toward the area on the time line that represents when humans first lived on earth, then look at the end of the time line that represents the beginning of earth. Are they close together, or are they far apart?
  - How would you describe how their locations on the time line compare to each other?
- If you had your students do this exercise in a hallway, have them hang their pictures on the wall alongside their marks on the timeline.
- Invite other classes on a field trip to come and see.
- These students can then walk from the “beginning of the earth” to “present time” and look at the drawings of the organisms to see how our planet, and the life on it, has changed over time.
- Your class can even offer a ‘field trip’ to other classes. As you lead them from the beginning of earth to the present, you can explain what you have learned about history of the earth! You can teach other students about the *geologic time scale*.

Exercise 2b: Geologic Time Scale (*Version for Grades 4-6*)

Exercise 2b.1: Construction of a Planetary Calendar

These instructions will help you construct a planetary calendar, or timeline, that is scaled to a single page. Eras of geological time will be represented by segments of the timeline. Points on the timeline represent events. By looking at a timeline you can tell the order in which events occur. Events on the timeline are ordered from left to right or from bottom to top. For example, the point that marks the extinction of the dinosaurs should be to the below the point that marks the first appearance of humans on your timeline.

A timeline contains much more information than an ordered list of events, because a time line allows you to visualize the length of time between events. In order for this timeline to give an accurate representation of the past, longer line segments should represent longer lasting eras, and shorter line segments should represent shorter lasting eras. For example if Era 1 lasted twice as long as Era 2 then the line segment spanning Era 1 should be twice as long as the line segment spanning Era 2.

- Make a 20.5 cm line down the length of a sheet of paper. Let the upper end be current time.
- Make a mark at 0.3 cm down from the top of the line.
- Make another mark at 1.1cm down from the top of the line
- Make a third mark at 2.5 cm from the top of the line
- You have demarcated the eras of the geological time scale.
- Your timeline represents a period of 4,500,000,000 years (4.5 billion years, the age of the Earth).
- Using your pencil, label each section of the line with its official geologic name. The long lower section below the 2.5 cm mark is referred to as the Precambrian Era. It is clear that the Precambrian Era takes up the majority of the time on our time line. In fact, the Precambrian Era makes up about 88% of the total time - almost all of it! The section between the 2.5 and 1.1 cm marks the Paleozoic Era. The Mesozoic Era is located between the 1.1 and 0.3 cm marks. The Cenozoic Era is the one we currently are in, and it is located above the 0.3 cm mark. Now answer the following questions:

  - **2b.1 Q1.** Which era was the longest: the Paleozoic Era or the Cenozoic Era?
  - **2b.1 Q2.** Which occurred first, the beginning of the Mesozoic Era, or the beginning of the Cenozoic Era?

Precambrian time lasted for almost 4 billion years. During most of this time, the Earth was gradually cooling and chemical compounds containing carbon were building up in the seas. Carbon is the basic building block of living organisms and compounds that contain carbon are referred to as organic compounds. Representatives of the first living organisms, prokaryotes that had DNA loose in the cell first appeared in the fossil record at about 3.5 billion years ago. The stromatolites (2 bya, or 2000 mya) from Exercise 1 are an example of fossilized colonies of cyanobacteria (the first photosynthetic organisms and descendants of earlier prokaryotes.)

- Mark this point on your calendar with the label “1st Life - Prokaryotes”.

All of the major body plans or phyla of animals appeared at the very beginning of the Paleozoic Era, during the first period called the Cambrian. This period ended 488 mya.

- Make a mark 2.2 cm from the top of your timeline to denote the end of the Cambrian Period. Label this point “End of Cambrian Period”.
- The Paleozoic Era as a whole is known as the “Age of Invertebrates,” as invertebrate organisms dominated during this time, or the “Age of Trilobites,” because invertebrates called trilobites were common and diverse during this era. Reptiles dominated the Mesozoic, which is termed the “Age of Reptiles,” or the “Age of Dinosaurs,” and the Cenozoic is referred to as the “Age of Mammals”. Human history in geologic time isn’t big enough to be seen at the end of the calendar.
- Add the following time information to your timeline:
  - Formation of the earth = 4,500 mya (million years ago)
    (This point is represented by the lower end of your line.)
  - Start of Paleozoic Era = 542 mya
    (This point is represented by the mark 2.5 cm from the top of your line.)
  - End of Cambrian Period within Paleozoic Era = 488 mya
    (This point is represented by the mark 2.2 cm from the top of your line.)
  - Start of Mesozoic Era = 251 mya
    (This point is represented by the mark 1.1 cm from the top of your line.)
  - Start of Cenozoic Era = 65.5 mya
    (This point is represented by the mark 0.3 cm from the top of your line.)
- Now that your geologic time line has been constructed, use the information you wrote on your chart in Exercise 1 to find the approximate place of the fossils from Exercise 1 along this time-line. Note that the Paleozoic Era involved diversification of life only in the seas. Major land building activity by volcanoes and earthquakes in the later eras led to the diversification of vertebrates, insects, spiders and their relatives on land. Plants and fungi also originated in the new terrestrial environments created in the Mesozoic and Cenozoic eras.

Exercise 2b.2: A Closer Look at Biodiversity in Geological Time

You probably have noticed that all of your organisms have been crowded into a very small part of the geological time line.

- Make a new scale on another sheet of paper to expand the time period during which life has diversified. Draw a line 20.5 cm down the length of the paper. Let the upper end be the current time and the lower end be the start of the Cambrian period of the Paleozoic Era at 542 mya (million years ago).
- Measure out and mark off the following lengths from the top of the line, 18.5 cm, 16.8 cm, 15.7 cm, 13.6 cm, 11.3 cm, 9.5 cm, 7.6 cm, 5.5 cm, 2.5 cm, 0.1 cm. These marks denote the beginnings and ends of the geological periods that you will explore further.
- Use the information on pages 17-22 (Life since the Cambrian) to label the segments of the expanded time line with period names.
- Find and mark the approximate position of each fossil sample from Exercise 1on this new time line.
- Which fossil(s) were you unable to place on the abbreviated time-line?
- Why were you unable to place them on this abbreviated time line?

Exercise 2c: Geologic Time Scale (*Version for Grades 7 & up*)

Over 300 years ago, scientists started piecing together information about the earth's geological history. They did so by comparing the patterns and ages of rock layers all over the world. Using this information, geologists have constructed a calendar called the geologic timescale, or planetary calendar. While the calendars most of us use are subdivided into months and weeks, this planetary calendar consists of sections called eras and periods. Weeks and months are made up of days, while eras and periods are made up of millions of years, some near a billion years in length. This is an incredible length of time, one that is difficult to visualize and laborious to write down. It takes six zeros to write out one million (1,000,000), and nine zeros to write out one billion (1,000,000,000). To save time, scientists express large numbers like these in exponent form. This is called scientific notation:

$$\mathbf{1,000,000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^6}$$

$$\mathbf{1,000,000,000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^9}$$

Note that the exponent, the small number to the upper right of 10, tells us how many zeros follow the one. But what if we have a big number that doesn't begin with a one, like 4,500 million? Let's start by using scientific notation to write down 4,500,

$$\mathbf{4,500 = 4.5 \times 1,000 = 4.5 \times 10^3}$$

And so,

$$\mathbf{4,500\ \mathit{million} = 4,500 \times 1,000,000 = 4.5 \times 10^3 \times 10^6 = 4.5 \times 10^9}.$$

Laws of Exponents

$\boldsymbol{a^x a^y = a^{x+y}}$
$\boldsymbol{a^0 = 1}$
$\boldsymbol{a^{-x} = \frac{1}{a^x}}$
$\boldsymbol{a^x a^{-y} = a^{x-y}}$
$\boldsymbol{(a^x)^y = a^{xy}}$

We used the laws of exponents above to obtain $\mathbf{10^3 \times 10^6 = 10^{3+6} = 10^9}$ in converting 4,500 million years into 4.5×10^9 years (4.5 billion years, which is the age of the Earth).

In Exercise 2, you will construct your own version of the geologic time scale, and then use the charts you make to understand the age relationships among the fossils you have identified under Exercise 1, and will be working with in Exercise 4.

Exercise 2c.1: Construction of a Planetary Calendar (*Grades 7-12*)

These instructions will help you construct a planetary calendar, or timeline, that is scaled to a single page. Eras of geological time will be represented by segments of the timeline. A timeline contains much more information than an ordered list of events, because a time line allows you to visualize the length of time between events. In order for this timeline to give an accurate representation of the past, longer line segments should represent longer lasting eras, and shorter line segments should represent shorter lasting eras. For example, if Era 1 lasted twice as long as Era 2, then the line segment spanning Era 1 should be twice as long as the line segment spanning Era 2. This means that the ratio of the length of a line segment to the length of the total line should be equal to the ratio of the time spanned by the line segment to the total time as follows:

$$\frac{\textit{length of line segment}}{\textit{length of total line}} = \frac{\textit{time spanned by line segment}}{\textit{total time}}$$

- Make a 20.5 cm line down the length of a sheet of paper. Let the upper end be current time.
- Make a mark at 0.3 cm down from the top of the line.
- Make another mark at 1.1cm down from the top of the line
- Make a third mark at 2.5 cm from the top of the line
- You have demarcated the eras of the geological time scale.
- Your timeline represents a period of 4,500,000,000 years (4.5 billion years, the age of the Earth).
- Using your pen or pencil, label each section of the line with its official geologic name. The long lower section below the 2.5 cm mark is referred to as Precambrian Time. It is clear that the Precambrian takes up the majority of the time on your time line. (We will make this statement more precise in the next exercise.) The section between the 2.5 and 1.1 cm marks the Paleozoic Era. The Mesozoic Era is located between the 1.1 and 0.3 cm marks. The Cenozoic Era, located above the 0.3 cm mark, is the current geological era.
- Now determine the percentage of Earth's history that each of the geological eras takes up. To get you started, let's find the percentage of time that the Precambrian takes up together.
    - The length of the section prescribing the Precambrian is equal to 20.5 cm - 2.5 cm, for a total of 18 cm.
    - Since the total line length is 20.5 cm long, we find that the ratio of this section's length to the entire line's length is $\frac{18}{20.5} \approx 0.88$.
    - That means that this section's length is approximately 100 × 0.88 = 88% of the length of the entire line. **Thus, Precambrian time makes up about 88% of Earth's history - almost all of it!**

Using the same technique, answer the following questions:

- **2c.1 Q1.** What percent of the total time does the Paleozoic Era take up?
- **2c.1 Q2.** What percent of the total time does the Mesozoic Era take up?
- **2c.1 Q3.** What percent of the total time does the Cenozoic Era take up?

Check your answers under Exercise 2c.1 at the end of this book.

Precambrian time lasted for almost 4 billion years. During most of this time, the Earth was gradually cooling and chemical compounds containing carbon were building up in the seas. Carbon is the basic building block of living organisms and compounds that contain carbon are referred to as organic compounds. Representatives of the first living organisms, prokaryotes that had DNA loose in the cell first appeared in the fossil record at about 3.5 bya (billion years ago). The stromatolites (2bya) from Exercise 1 are an example of fossilized cyanobacteria colonies that were the first photosynthetic organisms and descendants of the earlier prokaryotes (organisms that lack double membrane organelles that permit greater specialization of function in the higher organisms).

- **Question:**
  Where on our time line is the point denoting the appearance of the first living organisms?

- **Answer:**
  - Because this event occurred 3.5 billion, or 3500 million years ago, we find that the ratio of the time since this event occurred and the total time is $\frac{\mathbf{3500}}{\mathbf{4500}} \approx \mathbf{0.78}$.
  - This means that the ratio of the length of the line segment spanning this time and the length of the entire timeline is also 0.78.
  - That is, $\frac{\boldsymbol{length\ of\ segment}}{\boldsymbol{length\ of\ total\ line}} = \frac{\boldsymbol{length\ of\ segment}}{\mathbf{20.5}} = \mathbf{0.78}$.
  - So that *length of segment* = $\mathbf{0.78} \times \mathbf{20.5} \approx \mathbf{16.0}$.
  - Therefore the point denoting the appearance of the first living organisms is 16.0 cm down from the top of the line.

- Mark this point on your calendar with the label “1st Life - Prokaryotes” (organisms lacking a nucleus).

Most of the major body plans or phyla of animals appeared at the very beginning of the Paleozoic Era, during the first period called the Cambrian. This period ended 488 million years ago (mya).

- Use the process we just used to find the point that denotes the appearance of the first living organisms to find the point that denotes the end of the Cambrian Period. Label this point End of Cambrian Period.

The Paleozoic Era as a whole is known as the "Age of Invertebrates," as invertebrate organisms dominated during this time, or the "Age of Trilobites," because invertebrates called trilobites were common and diverse during this era. Reptiles dominated the Mesozoic, which is termed the "Age of Reptiles," or the "Age of Dinosaurs," and the Cenozoic is referred to as the "Age of Mammals". Human history in geologic time isn't big enough to be seen at the end of the calendar.

- Write the age names in after the era name on your timeline.
- Add the following dates to your line, recording each time in scientific notation:
  - Lower end = 4,500 mya (million years ago)
  - Start of Paleozoic Era = 542 mya
  - End of Cambrian Period within Paleozoic Era = 488 mya
  - Start of Mesozoic Era = 251 mya
  - Start of Cenozoic Era = 65 mya
- Now that your geologic timeline has been constructed, use the information you wrote on your chart in Exercise 1 to place your fossils along this timeline. Note that the Paleozoic Era involved diversification of life only in the seas. Major land building activity by volcanoes and earthquakes in the later eras led to the diversification of vertebrates, insects, spiders, and their relatives on land. Plants and fungi also originated in the new terrestrial environments created in the Mesozoic and Cenozoic eras.

Exercise 2c.2: A Closer Look at Biodiversity in Geological Time
You probably have noticed that all of your organisms have been crowded into a very small part of the geological time line.

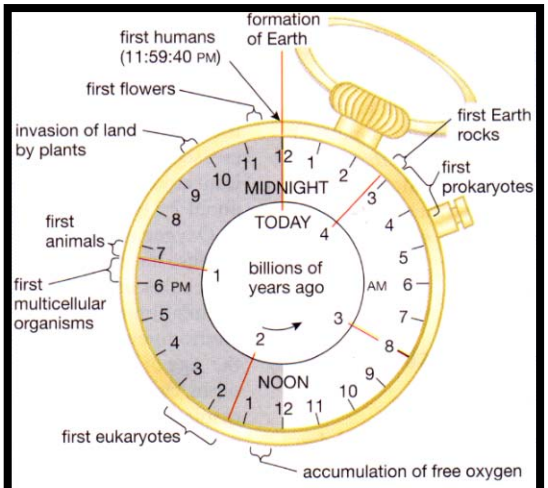
- Make a new scale on another sheet of paper to expand the time period during which multicellular life has diversified (the Cambrian through the present). Draw a line 20.5 cm down the length of the paper. Let the upper end be the current time and the lower end be the start of the Cambrian period of the Paleozoic Era at 542 mya.

Use the information provided on pages 17-22 (Life since the Cambrian) to separate the expanded upper end of the time line into periods within eras from 542 mya to present. Use the mathematical technique described in Exercise 2a to find the points on the line that correspond to the beginning of each period.

- Find and mark the position of each of your fossil samples from Exercise 1 on this new time line, using the same mathematical technique.
- Which fossil(s) were you unable to place on the abbreviated time-line?

Exercise 2c.3: Comparing Time Frames (*Open-ended Exploration*)

- Form teams, if you have not already done so.
- Each team should compare the geological timeline you made to the one projected below on a 24-hour clock.
- Add the events listed on this 24-hour clock to your time line.
  - o Begin by finding the length of a single "hour" on your timeline. Hint: There should be 24 hours total on your timeline, and each hour should be of the same length.
- Discuss how this comparison contributes to your understanding of geological time.
- Which exercise was more meaningful to you, the drawing of geological time to scale, or the placement of our 24-hour clock on a geological time line? Explain your answer.



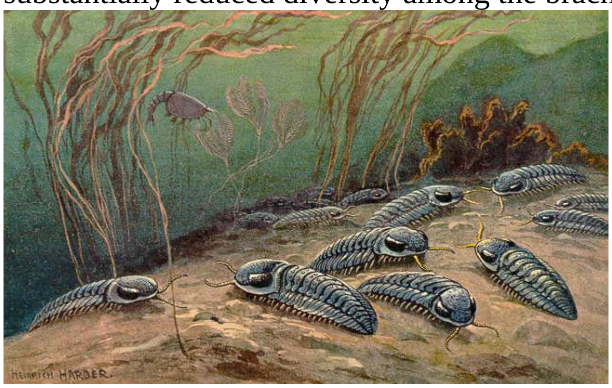
Earth's history projected on a 24-hour day

GEOLOGIC TIMELINE OF EARTH: LIFE SINCE THE CAMBRIAN

PALEOZOIC ERA – "The Age of Invertebrates"

CAMBRIAN PERIOD: 542-488 million years ago

The algae and invertebrates similar to jellyfish and worms are abundant. The first shelled animals (brachiopods) begin to appear, and early arthropod predators, the trilobites (now extinct) appeared, as well. Most of the currently existing major body plans of animals appear, as well as many bizarre organisms that are dissimilar to any major animal group today. The appearance of a great diversity of life forms over such a relatively short time period is often referred to as the "Cambrian Explosion". The Burgess Shale Formation in Canada is one of the most famous locations from where many fossils from this period have been found. At the end of this period, however, a major extinction event substantially reduced diversity among the brachiopods and trilobites.



Cambrian sea floor, with numerous trilobites, a single *Canadaspis* (an early arthropod similar to modern crustaceans), and three crinoid echinoderms ("sea lilies") in the background.

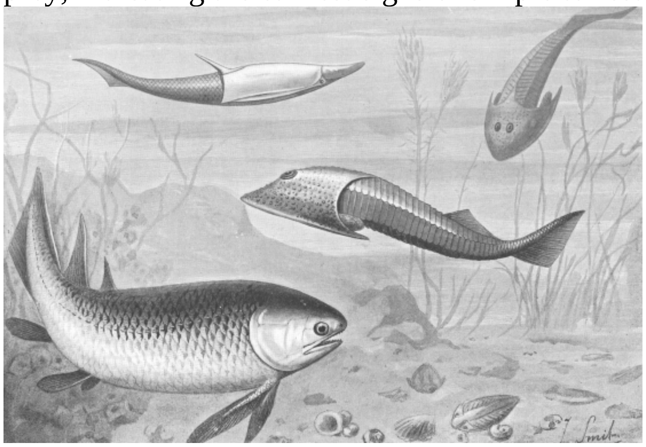
ORDOVICIAN PERIOD: 488-444million years ago

Though hit hard by the earlier extinction event, trilobites were still diverse. Blastoids and crinoids (ancient relatives of our modern echinoderms like starfish), bryozoans ("moss animals"), corals, sponges, and mollusks like snails, clams, and cephalopods (relatives of octopus, squid, etc.) were abundant, and eurypterids ("sea scorpions," ancient relatives of horseshoe crabs and arachnids), crawled the sea floors. Jawless, armored fish known as ostracoderms, the first vertebrates, appear. Evidence suggests the possible appearance of simple, non-vascular plants (without specialized tissues for transporting water and nutrients) on land. Near the end of this period, a major extinction event, possibly caused by a major glaciation, wiped out over a hundred families of marine organisms, making this the second largest extinction of marine life in Earth's history.

An Ordovician cephalopod feasting on a trilobite

SILURIAN PERIOD: 444-416 million years ago

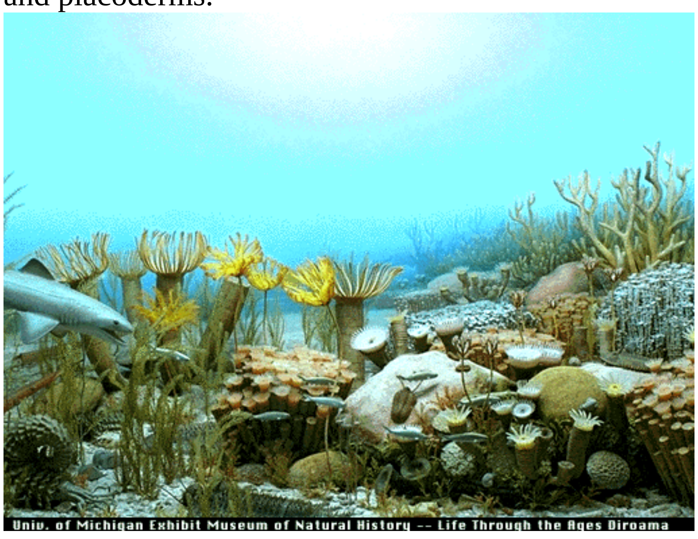
Jawless fish diversified widely and rapidly, and the first freshwater and jawed fishes (the acanthodians) appeared. The first vascular land plants appear, and forests of non-vascular mosses lined streams and lakes. Evidence suggests the appearance of the first terrestrial fungi during this time. Remains of the first arachnids and centipedes, both of which are predatory, suggest the presence of other arthropods that would have been their prey, indicating the earliest signs of simple terrestrial food webs.



Three ostracoderms (background), and an early jawed fish of the Silurian.

DEVONIAN PERIOD: 416-359 million years ago

During the early Devonian, massive reefs of corals and red algae expanded. Brachiopods were the dominant aquatic life forms, but bivalves, echinoderms (the crinoids and blastoids), and trilobites were still present, though most trilobites were gone by this period's end. Ammonoids, ancient cephalopods with coiled shells, also appeared. This period is often referred to as the "Age of Fishes," due to great diversification in fish. Jawed fishes (including the highly armored placoderms), early sharks, and lobe-finned fishes (sarcopterygians, eventually give rise to the earliest amphibians. The anphibians become abundant during the late Devonian. Life on land consisted of giant representatives of modern mosses and ferns. The earliest seed-producing plants also appeared during this period along with the first wingless insects. A major extinction event in the late Devonian wiped out about 70% of marine invertebrates, all jawless fish, and placoderms.



Devonian sea floor. An early shark is at left, and several small fish are also visible.

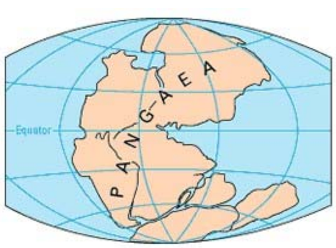
CARBONIFEROUS PERIOD: 359-299 million years ago

Trilobites became increasingly rare. Bony fish and sharks similar to modern groups further diversified, and freshwater clams first appeared. Terrestrial environments were humid and tropical, with no well-defined seasons. Swampy forests of ferns and their relatives were common, and ancestors of cone-bearing trees appeared. Winged insects such as cockroaches, mayflies, and dragonflies appeared, and without plentiful predators, attained huge sizes. Amphibians, some species over 18 feet in length, were numerous and diverse. The development of an amniote egg (possessing a membrane, called the amnion, which protects the embryo from drying out) was a key adaptation for life on land in the first lizardlike reptiles. These reptiles evolved from amphibian ancestors.

Carboniferous forest with dragonfly, which may have had a wingspan of up to 2.5 feet!

PERMIAN PERIOD: 299-251 million years ago

During the early and middle Permian, marine invertebrate life was still somewhat similar to that in the previous period, the Carboniferous. However, towards the end of the period, the largest extinction event in Earth's history occurred with about 96% of all marine life forms, including the trilobites, going extinct. By the middle of this period, all of Earth's landmasses had drifted together to form the supercontinent Pangaea. Although life on land was also affected heavily by extinctions, terrestrial life suffered far less than marine life. A spreading warm dry zone in the middle of Pangaea allowed for further diversification of terrestrial fungi, arthropods, and plants. Many of the swampy forests of ferns and their relatives gave way to early relatives of conifers (similar to modern pines), and the extensive radiation (diversification) of the reptiles set the stage for the beginning of the Mesozoic Era, the "Age of Dinosaurs."



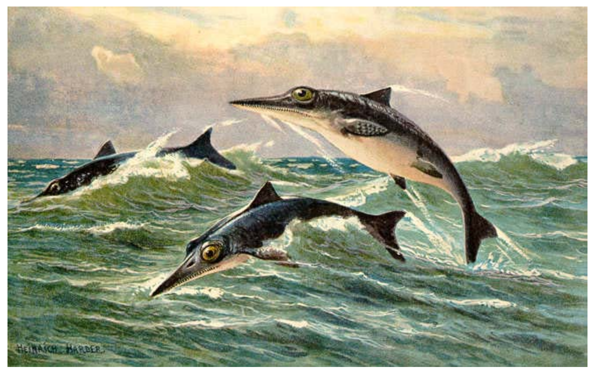
PERMIAN
225 million years ago

Pelycosaurs (late Permian reptiles) basking beneath horsetail "trees"

MESOZOIC ERA – “The Age of Reptiles” / “The Age of Dinosaurs”

TRIASSIC PERIOD: 251-201.6 million years ago

In the seas, life began to recover, although slowly. New types of corals began again forming reefs. Many other groups, including the bivalves, brachiopods, and ammonoid cephalopods, also made a slow comeback. Though heavily affected by the Permian mass extinction, echinoderms persisted. The blastoids disappeared though. On land, seed-bearing plants and insects diversified even further. There were many new types of reptiles showing up in this period, including plant-eaters, meat-eaters (crocodilians), flying reptiles (pterosaurs) and giant aquatic reptiles such as the ichthyosaurs, plesiosaurs, pliosaurs, and sea turtles. By the end of the Triassic, representatives of all modern tetrapods: the salamanders, frogs, turtles, lizards, crocodilians, birds (represented by their dinosaur ancestors), and even mammals (most of which were small, shrew-like creatures) had evolved.



Left: Two *Yaleosaurus* eye a *Plateosaurus*. Right: Ichthyosaurs leap from a Triassic sea.

JURASSIC PERIOD: 201.6-145.5 million years ago

Giant herbivorous (plant-eating) dinosaurs, such as long-necked sauropods and stegosaurs roamed the earth. Predatory dinosaurs were also present, but many were substantially smaller than herbivores during the time, suggesting that early predatory dinosaurs may have preyed mostly on smaller herbivores, hunted in packs, and/or scavenged carcasses of large herbivores. Large flying reptiles, the pterosaurs, dominated the skies, but the first bird, *Archaeopteryx*, also appeared. Large marine reptiles such as ichthyosaurs, plesiosaurs, and giant marine crocodiles reached numerical prominence. Sharks and rays similar to modern forms cruised the Jurassic seas, which were also filled with corals, cephalopods (including the ammonoids, and belemnites, which were similar to modern squid, but with bullet-shaped shells that were both partially internal and external), bivalves, and snails. Although early decapod crustaceans (ancestors of modern shrimp and lobsters) appeared way back in the Devonian, they diversified immensely during this time. Terrestrial mammals also diversified. Most were previously thought to have been relatively small burrow-dwellers whose nocturnal habits may have protected them from dinosaur predators. However, more recent evidence reveals that some of the early mammals were larger, and capable of preying on baby dinosaurs. The earliest known aquatic mammal, *Castorocauda*, similar to a beaver or otter, also dates from this period.

Left: A mid-19th century depiction of Jurassic reptile diversity. Right: *Archaeopteryx*, the first bird.

CRETACEOUS PERIOD: 145.5-65.5 million years ago

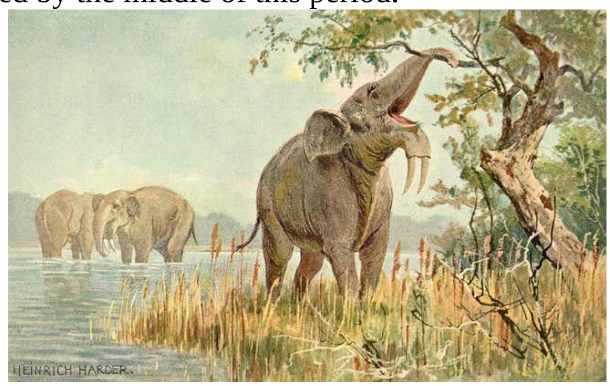
The earliest deciduous trees and flowering plants appear, accompanied by a burst of insect diversity, including the earliest known ants and butterflies. Dinosaurs and other large reptiles flourished throughout much of the early and middle Cretaceous, with the famed *Tyrannosaurus rex* and mosasaurs appearing. Though mammals were still a relatively minor component of biodiversity, the first marsupials (mammals that carry their young in a pouch on the mother's body) appeared. Pterosaurs were still common, but experienced growing competition from birds. At the end of the Cretaceous, the most famous extinction event occurred, wiping out all dinosaurs except for birds, as well as large marine reptiles, pterosaurs, and several groups of marine invertebrates, though many other groups of organisms were relatively unaffected. Large concentrations of an element called iridium (which is rare on Earth, but found in much higher concentrations in meteors), at the boundary of Cretaceous and Tertiary rock layers, coupled with several large craters dated to this time suggest that one or more meteor impacts could have played a major part in this large extinction, although scenarios also involving increased volcanic activity, as well as falling sea levels have been hypothesized.

Left: A mosasaur and two ichthyosaurs. Right: *T. rex*, one of the most well-known Cretaceous dinosaurs. All of these organisms went extinct at the end of the Cretaceous.

CENOZOIC ERA – "The Age of Mammals"

TERTIARY PERIOD: 65.5-2.6 million years ago

With the risk of predation from dinosaurs now removed, mammals diversified rapidly, quickly claiming the role of dominant vertebrates from the reptiles. Monotremes (egg-laying mammals such as the echidna and platypus) appeared, followed by a major radiation of odd-toed ungulates (relatives of horses, deer, and rhinos) and even-toed ungulates (represented by our modern sheep, goats, camels, etc.). The first elephants with trunks and early horses appeared. Towards the end of this period, climates became cooler and drier, and ice sheets began to accumulate at the poles. Many areas of closed forests began to give way to more open areas, such as grasslands, deserts, and tundras, perhaps due to the global cooling of this time. Nearly all modern families of angiosperms (flower and seed-producing plants) appeared by the middle of this period.



The echidna, an egg-laying mammal (left) and *Dinotherium*, an ancient elephant, are only two of numerous diverse mammals that appeared during the Tertiary.

QUATERNARY PERIOD: 2.6 million years ago to present

For most of the Quaternary, the climate of Earth was marked by periods of repeated glaciations (ice ages), with an estimate of as much as a third of Earth's surface being covered by ice at the largest glacial maximum (though the climate of Earth that we know now has been about the same since the retreat of major ice sheets approximately 10,000 years ago). Many more mammals appeared, including many now-extinct megafauna (large animals), including saber-toothed tigers, wooly mammoths and mastodons, glyptodonts (giant relatives of armadillos), and giant ground sloths. A much more familiar mammal, modern man, appeared during this time, as well!

Left: *Megatherium*, a giant ground sloth. Right: Early humans hunting a glyptodont.

Exercise 3: Dating Fossils

Exercise 3a: Dating Fossils (*Version for grades 3-6*)

Photo by Tony Armor, *landandseaimages.com*

Biologists can determine the approximate age of fossils by their locations within the layers of sediment. Look at the picture above, and you will notice how the sediment has formed layers in the rock. Unless large chunks of rock have been overturned, the fossils in the lower layers are older than the fossils that are in the layers near the top. This is because the sediment in the bottom was deposited first, with additional layers being stacked on top of lower layers.

Scientists have developed ways of determining the age of each layer and the fossils found in each layer. They have developed a way of finding the age of fossils by using what is called **radiometric dating** to determine an **absolute time scale**. This can be done because scientists know that some minerals contain radioactive isotopes that change over time into other minerals through a process called **radioactive decay**.

Isotopes are forms of chemical elements, like carbon or uranium, that have one primary difference from the normal form, and that is the number of neutrons in the nucleus. If an atom does not maintain the same number of neutrons and protons in its nucleus, it becomes unstable and will drop some of its particles until the nucleus reaches a stable state. The decay process continues over time because isotopes become unstable and will then shed particles to return to a stable state.

It is not known when a given unstable, radioactive atom, or **parent isotope**, will shed particles to become a stable, non-radioactive atom, or **daughter isotope**, but it is possible to determine how long a big group of atoms will take to decay. The amount of time it takes for half of the parent atoms in a sample to turn into daughter isotopes is called its **half-life**. The ratio of parent atoms to daughter atoms can help scientists know the age of a sample. If there are many more parent atoms that daughter atoms, the sample is younger than if the difference between parent atoms to daughter atoms were smaller.

Half-Life Graphing Activity

<u>Materials:</u>

- o Graph paper
- o 2 strips of construction paper of equal width (narrower widths around 0.5", or the width of the squares on the graph paper used would probably work well)
- o Scissors
- o Glue or tape
- o Pencil, pen, or marker

- Draw a horizontal and a vertical axis on your graph paper.
- Label the vertical axis “Amount of Radioactive Parent Isotope Remaining,” and label the horizontal axis “Number of Half-lives Elapsed.”
- Lay one strip of paper vertically along the y-axis with one end at the origin. The gridlines on your graph paper should help you line the strip up to make sure that it is properly vertically aligned.
- Tape or glue this strip to the graph paper.
- Now take the other strip of paper, and fold it in half as precisely as possible.
- Unfold this strip, and cut the strip into two equal pieces along the crease that marks the halfway point. Set one half of this strip aside.

- Take the half strip currently in your hand, and place it vertically on your graph paper, parallel to the first strip, with the bottom of the strip touching the horizontal axis, a small distance to the right of the first strip (or with their edges touching).
- Glue or tape this strip in place, just as with the first strip.
- Using the remaining half strip, repeat the previous three steps, placing the new strip on the graph to the right of the previous strip (at a distance equal to the distance between the first two strips).
- Continue following this procedure, adding new cut pieces of your strips until the pieces become too small to comfortably manage (probably 5-6 cuts, depending on the initial length of the strips).
- Now label, on your x-axis, each of your strips, with your first strip having the number "0", and your last strip having a number equal to one less than the total number of strips on your graph.
- Using a pencil or marker, make a mark at the midpoint at the distance across the top of each strip on your graph.
- Now try to join all of these points with a smooth curve (do not just simply connect them with straight lines!).

This graph shows the decay of a radioactive element. The first strip on your graph represents an initial amount (at a given point in time) of a radioactive element. Each new strip that you added represents the amount of the radioactive parent isotope remaining after an amount of time equal to one half-life of the parent isotope has elapsed.

Note that each strip represents a particular quantity of atoms of the parent isotope present. Atoms are very, very small; too small for us to see, so even a very small sample of a radioactive element may be made up of very many atoms! Even though you may only have been able to add just a few strips of paper to your graph, there would still be some parent isotope remaining after the point in time represented by your last strip, for perhaps many more half-lives, until only one single atom of the parent isotope remained, and it finally decayed to its stable state. Just remember, after each half-life, the amount of the parent isotope remaining is equal to half of the amount present at the time before that half-life elapsed!

Exercise 3b: Dating Fossils (*Version for grades 7 & up*)

Biologists obtain an estimate of the **relative** age of fossils by their locations within strata, or layers of sediment that the fossils are buried in at a particular locality. Unless large chunks of rock have been somehow overturned, fossils that are located in the lower strata are older than those that are near the top. This should make sense, if you think about how sedimentary rock is formed, as sediment near the bottom would have been deposited first, and sediment in upper layers was deposited on top of lower layers at a later time. There is a tool called radiometric dating, however, which geologists and biologists use to obtain an **absolute** time scale. Using radiometric dating, we can assign an age to a particular stratum and the fossils found in it. This method is based on the fact that some minerals have radioactive isotopes that change through time into other minerals through a process called radioactive decay. The amount of time it takes for half of a parent (radioactive) isotope to turn into its non-radioactive daughter isotope is called its **half-life**.

In order for you to best understand the process of radioactive decay, it is necessary that you understand the mathematical tool called a function. Complete Exercise 3b.1 on mathematical functions before going on to the radioactive decay exercises 3b.2 and 3b.3.

Exercise 3b.1: Functions

Functions are useful mathematical tools. You can think of a function as a factory that takes elements from one set called the domain and produces elements belonging to another set called the range. The picture below illustrates this idea. Logs go into a paper factory and paper comes out.

Now let's examine a biological example: a poison dart frog. Think of a function as a rule that takes elements from a set of inputs, the domain, and returns elements belonging to a set of outputs, the range. The picture below illustrates the idea with a function (rule) we call the toxicity function. This function takes organisms as its input and returns the toxicity of the organism as an output.

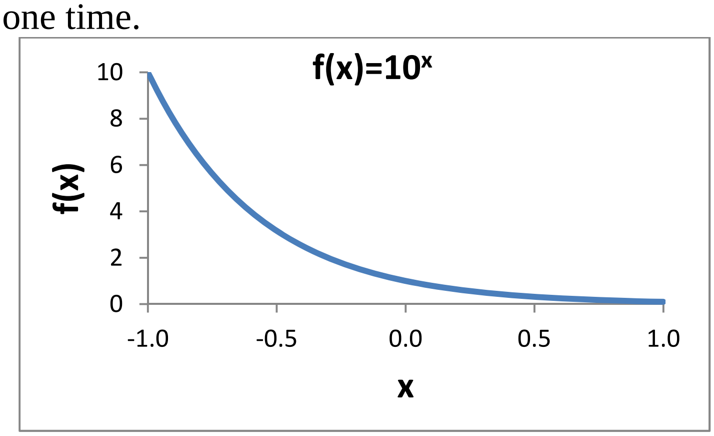
A **function** is a rule that takes elements from a set of inputs (the **domain**) and returns elements from a set of outputs (the **range**). Functions take *one* element from the domain to *exactly one* element in the range.

Domain (organisms) | **Function** | **Range (toxic or nontoxic)**

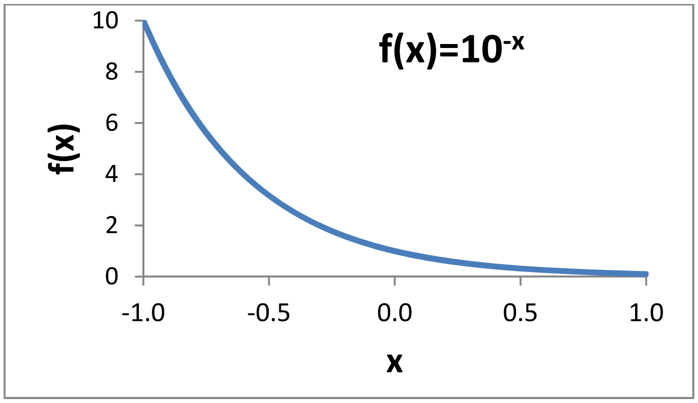
It is important to know that a function takes *one* element from the domain to *exactly one* element in the range. Graphically this means that any vertical line intersects the graph of a function just one time. In the example above, an organism is defined as toxic OR nontoxic. It is impossible to be both.

A simple example of a function is $\boldsymbol{g(x) = x^2}$. The domain of this function is the set of all real numbers. *Recall that the real numbers represent all of the points on a real number line, where 0 marks the middle of the line. Unlike the natural numbers that only consist of the numbers used for counting {1,2,3,4....}, the real numbers may be fractions like ½, or even numbers with infinite decimal expansions like π.* The range of the function $\boldsymbol{g(x) = x^2}$ is the set of all nonnegative real numbers.

One very important function is that describing exponential growth, which can be described mathematically as $\boldsymbol{f(x) = 10^x}$. The domain of this function is the set of all real numbers and the range is the set of all positive numbers. Below is a graph of the exponential function for $\boldsymbol{-1 \leq x \leq 1}$. Note that any vertical line that could be drawn on the graph intersects the graph at most one time.



In the following exercises we will use another important function called the exponential decay function, $\boldsymbol{f(x) = 10^{-x}}$. The domain of this function is also the set of all real numbers, and the range is also the set of all positive numbers. Its graph is pictured below for $\boldsymbol{-1 \le x \le 1}$.



Certain functions are *one-to-one*. A function is one-to-one if it takes distinct values in the domain to distinct values in the range. The toxicity function is not one-to-one, because it takes many different types of organisms to the output "toxic". For example, poison dart frogs and black widow spiders are unrelated organisms, and their toxins are packaged in different ways, exuded on the skin in the case of the poison dart frog, and delivered through the cheliceral fangs in the case of the black widow spider. Nevertheless, the toxicity function takes both of these organisms to the value "toxic". The function $\boldsymbol{g(x) = x^2}$ is also not one-to-one because $\boldsymbol{g(-2) = (-2)^2 = 4 = 2^2 = g(2)}$. That is, $\boldsymbol{g(x)}$ takes both the elements $\boldsymbol{2}$ and $\boldsymbol{-2}$ in the domain to the same number, $\boldsymbol{4}$, in the range. Graphically, a function is one-to-one if every *horizontal* line intersects the graph of the function just one time. You can see by the picture above that $\boldsymbol{f(x) = 10^{x}}$ is one-to-one.

If $\boldsymbol{f(x)}$ is one-to-one, then it has an inverse function $\boldsymbol{f^{-1}(x)}$ that undoes what $\boldsymbol{f(x)}$ does. If $\boldsymbol{f(x)}$ is a very simple function, it is easy to find $\boldsymbol{f^{-1}(x)}$. For example, to undo division by 3 we should multiply by 3. That is if $\boldsymbol{f(x) = \frac{x}{3}}$, then $\boldsymbol{f^{-1}(x) = 3x}$. Likewise, to undo subtraction of 2, we should add 2. That is, if $\boldsymbol{f(x) = x - 2}$, then $\boldsymbol{f^{-1}(x) = x + 2}$. Combining these ideas, we can find the inverse of a slightly more complicated function, $\boldsymbol{f(x) = \frac{x+2}{3}}$. Since $\boldsymbol{f(x)}$ takes $\boldsymbol{x}$, adds $\boldsymbol{2}$ and divides by $\boldsymbol{3}$, $\boldsymbol{f^{-1}(x)}$ does the reverse: it takes $\boldsymbol{x}$, multiplies by three and subtracts $\boldsymbol{2}$. That is, $\boldsymbol{f^{-1}(x) = 3x - 2}$.

To find the inverse of a function such as the example of $\boldsymbol{f(x) = \frac{x+2}{3}}$, you can imagine $\boldsymbol{f(x)}$ as being represented by $\boldsymbol{y}$, so that $\boldsymbol{y = \frac{x+2}{3}}$ (when you see an equation with $\boldsymbol{y}$ expressed in terms of $\boldsymbol{x}$, $\boldsymbol{y}$ is indeed a function of $\boldsymbol{x}$!) Solve the equation for $\boldsymbol{x}$ in terms of $\boldsymbol{y}$. In this example, then, $\boldsymbol{x = 3y - 2}$. If you now switch the variables $\boldsymbol{x}$ and $\boldsymbol{y}$ in the newly-obtained equation, resulting in $\boldsymbol{y = 3x - 2}$, you have now found the inverse of the original function! So, if $\boldsymbol{f(x) = \frac{x+2}{3}}$, then the inverse of the function is $\boldsymbol{f^{-1}(x) = 3x - 2}$. **Remember, though, that in order for a function to have an inverse, it must be one-to-one!** Again, this means that in a graph of the function, no horizontal line can be drawn that passes through more than one point on the plot of the function. In other words, each value of $\boldsymbol{f(x)}$ can ONLY be obtained from ONE value of $\boldsymbol{x}$!

- **Solve the following question.**

Q1. Find the inverse of the following function:

$$\boldsymbol{f(x) = \frac{x}{7} + 1}$$

- Check your answer on the answer sheet under Exercise 3b.1.

The inverse of the exponential function $\boldsymbol{f(x) = 10^x}$ is called the logarithmic (log) function $\boldsymbol{f^{-1}(x) = \log x}$. Thus, $\boldsymbol{\log x}$ gives the exponent to which 10 must be raised to in order to get $\boldsymbol{x}$.

Examples:

$$\boldsymbol{\log 10^3 = 3}$$

$$\boldsymbol{\log 10^{-2} = -2}$$

And since $\boldsymbol{100 = 10^2}$,

$$\boldsymbol{\log 100 = \log 10^2 = 2}$$

If we don't know the exponent to which 10 must be raised to make $\boldsymbol{x}$, then we must use a calculator to evaluate $\boldsymbol{\log x}$. For example, consider $\boldsymbol{\log 27}$. Since we don't know the exponent $\boldsymbol{x}$ so that $\boldsymbol{10^x = 27}$, we can plug $\boldsymbol{\log 27}$ into a calculator to find $\boldsymbol{\log 27 \approx 1.4314}$.

- **Now evaluate the following expressions:**

  Q2. $\log 10^{-5} =$

  Q3. $\log\left(\frac{1}{10}\right) =$

  Q4. $\log 1000 =$

- Find the answers to questions 2-4 under **Exercise 3b.1** in the answers section of this book.

Inverse functions are useful, because they can help us solve for variables. We will use this method to solve equations of the form $\mathbf{10^{x} = y}$ for $\boldsymbol{x}$.

Using the fact that $\mathbf{\log 10^{a} = a}$, we see that

$$\mathbf{10^{x} = y \Rightarrow \log 10^{x} = \log y \Rightarrow x = \log y}.$$

- Solve the following equation for $\boldsymbol{x}$.

Q5. $\mathbf{10^{x} = 17}$

- Find the answer to this problem under the answers for Exercise 3b.1.

Exercise 3b.2: Determining the Age of a Fossil

Now that you have reviewed the subject of mathematical functions, you will be able to see how the decay function given below, can be used to determine the age of a fossil, This equation calculates the fraction of the parent radioactive material remaining $\boldsymbol{t}$ years after the radioactive material was produced, and the decay process initiated.

$$\boldsymbol{F(t) = 10^{-\lambda t}}$$

Note that $\boldsymbol{F(0) = 10^{-\lambda 0} = 10^{0} = 1}$. That is, at the time of conception of the radioactive material (zero years have elapsed), 100% of the atoms present are atoms of the parent isotope.

Here $\boldsymbol{\lambda}$ (read as "lambda") is a positive constant called the decay constant that depends of the radioactive isotope we are measuring. The rate of decay represents the number of atoms that decay in an infinitesimal length of time. Another important characterization of a radioactive isotope is its half-life, $\hat{t}$. The half-life of a radioactive isotope is the time it takes for half of the original atoms of parent isotope to decay to the daughter isotope. Scientists have determined the decay constant λ, and the half-life $\hat{t}$ for many different radioactive isotopes. Some of them are listed in the table on the following page. Different radiometric dating methods may be more appropriate than others when determining the age of a given fossil or other geological object. It is important when attempting to radiometrically date an object that the appropriate method is used. Selection of the best method is dependent on the approximate age of the object in question, as well as other factors, such as the type and concentration of elements present in the object, etc. The important fact to remember, however, is that there must be some radioactive parent material remaining in the sample and some daughter project accumulated to obtain an age estimate.

Isotope		Decay Constant (λ)	Half-Life ($\hat{t}$) (in years)
Parent	Daughter		
Carbon-14	Nitrogen-14	5.25358×10^{-5}	5,730
Uranium-235	Lead-207	4.30043×10^{-10}	700,000,000
Rubidium-87	Strontium-87	6.14347×10^{-12}	49,000,000,000
Samarium-147	Neodymium-143	2.83991×10^{-12}	106,000,000,000

Which of the above radioactive isotopes would you use to date the following fossils? (Though not universally true, as a general rule of thumb for making your selections for the following situations, consider a radiometric dating method to be appropriate if at least 0.01 half-lives, but no more than 10 half-lives of the radioisotope have elapsed. If a very small portion of a half-life of an isotope has elapsed, there will be very little of the daughter isotope present. On the other hand, if a large number of half-lives have elapsed, then there will be very little parent isotope remaining. Both of these scenarios present situations in which very accurate determination of the concentration of either parent or daughter isotope might be difficult.)

Q1. Stromatolites (photosynthetic bacterial colonies) dating 1.5 billion years old
Q2. Wooly mammoth fur dating 10,000-14,000 years old
Q3. Tree fern leaves 300 million years old
Q4. Sea urchin dating 36-42 million years old

Q5. Which of the above radioactive isotopes might geologists use to date the age of the universe (13.5-14 billion years old) from meteorites attributed to different stars?

- Find the answers to questions 1-5 under Exercise 3b.2 in the answers section of this book.

To find the time $\boldsymbol{t_1}$ since an organism died, we start by measuring the proportion (fraction) of radioactive parent isotope, $\boldsymbol{F(t_1)}$, that remains in the fossil or a rock found associated with it. This measurement is accomplished as follows. First we measure the amount of parent isotope that remains in the fossil. Let's call this number **P**. Then we measure the amount of daughter isotope in the fossil. Let's call this number **D**. Now since every atom of daughter isotope was once an atom of parent isotope, we know that at the time of death there was **D+P** parent isotope in the fossil. That means that the fraction of parent isotope remaining is **P/(D+P)**. That is, $\boldsymbol{F(t_1) = \frac{P}{D+P}}$. Combining this information with the fact that the parent isotope decays exponentially, we find that $\boldsymbol{10^{-\lambda t_1} = F(t_1) = \frac{P}{D+P}}$. That is, $\boldsymbol{10^{-\lambda t_1} = \frac{P}{D+P}}$. Now we can solve for $\boldsymbol{t_1}$ (which represents the age of the fossil!) by taking the log of each side of the previous equation.

$$\boldsymbol{\frac{P}{D+P} = 10^{-\lambda t_1} \Rightarrow \log\frac{P}{D+P} = -\lambda t_1 \Rightarrow -\frac{1}{\lambda}\log\frac{P}{D+P} = t_1}$$

- Answer the following questions:

Q6. Suppose that the fraction of Uranium-235 remaining in fossil number 10 is 0.71. Use this information to find the age of the fossil.

Q7. Assume there is small error in our measurement, and in fact the fraction of Uranium-235 remaining is 0.714. How does this affect the answer in the previous question?

- Check your answers for these questions in the answer section at the end of this workbook.

In the table of radioactive isotopes on page 32, the half-life of each isotope is listed along with its rate of radioactive decay. The half-life, $\hat{\boldsymbol{t}}$, of an isotope is the time it takes for half of the original concentration to decay. That is,

$$\frac{\mathbf{1}}{\mathbf{2}} = \boldsymbol{F}(\hat{\boldsymbol{t}}) = \mathbf{10}^{-\lambda\hat{t}}$$

OR

$$\frac{\mathbf{1}}{\mathbf{2}} = \mathbf{10}^{-\lambda\hat{t}}$$

- **Answer the following two questions**

Q8. Solve the equation above for the half-life $\hat{\boldsymbol{t}}$ in terms of **λ**.

Q9. Given that the decay rate of Radium-226 is $\mathbf{.814 \times 10^{-5}}$, find the half-life of Radium-226.

- Check your answers under Exercise 3b.2 answers at the end of this book.

Exercise 3b.3: Half-life Experiment

The half-life ($\hat{\boldsymbol{t}}$) of a particular radioactive mineral is based on the mean, or average, time it takes half of the parent material to decay into the daughter material. Individual atoms, however, may show considerable variation in their lifetimes. This variation is random, or due to chance, such as in obtaining a particular number when rolling dice, or obtaining heads or tails when flipping a coin. The following experiment demonstrates how radioactive decay occurs due to the chance change of individual radioactive atoms into their non-radioactive daughter atoms.

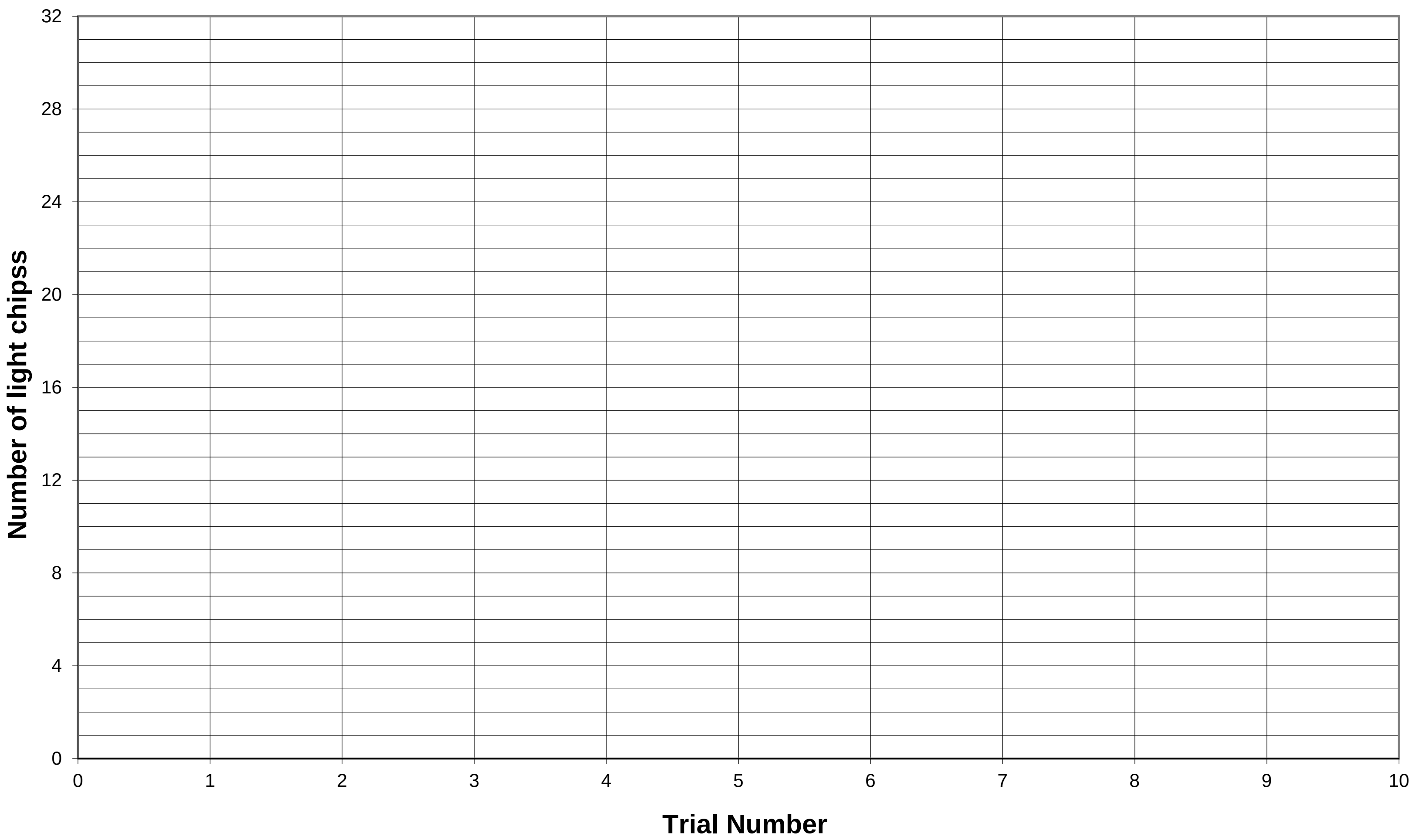
- Locate the box containing plastic chips (Box #3). Pour the chips out of the box and sort them into two clusters, light and dark chips. Assume that the box is a fossil, of which you want to determine the age. The chips represent the concentrations of the radioactive parent material (light-colored chips) and its decay product/daughter material (dark colored chips) at any time interval, which in this experiment is defined as trial number. You should have 32 light-colored chips in one cluster, which you should put back into the box. The concentration of the radioactive parent atoms at death of the box = 100% or 1. Put the second pile of 32 dark colored chips aside for the moment. These represent daughter atoms which have a concentration of 0 in the fossil (box) initially, representing the moment of the death of the organism

- Flip each light-colored chip (parent radioactive material atom) onto the table or some other flat surface.
- Replace each light chip that has landed with the colored center-side up with a dark chip (representing the transformation of those atoms of the parent isotope into daughter atoms or decay product).
- Make a table that resembles the one shown on the next page.
- Now record the number of light chips remaining in the pool under parent atom and number of dark chips present under daughter atom under trial 1 in your table.
- Repeat the process until all of the light chips have been removed from your sample pile, or until you have completed trial 10.
- Calculate the fraction of parent material remaining at the end of each trial. Record this in the appropriate column in your table.
- Plot your results on two graphs, one depicting the decay of the parent material (light chips, graph A) and the other depicting the accumulation of the daughter material (dark chips, graph B; see graph formats following the table template). Alternatively, you could plot these results on the same graph, but you should make sure to use different colors and/or styles of lines for the graphs of decay of parent material and accumulation of daughter product, as well as include a legend to indicate which line is which!

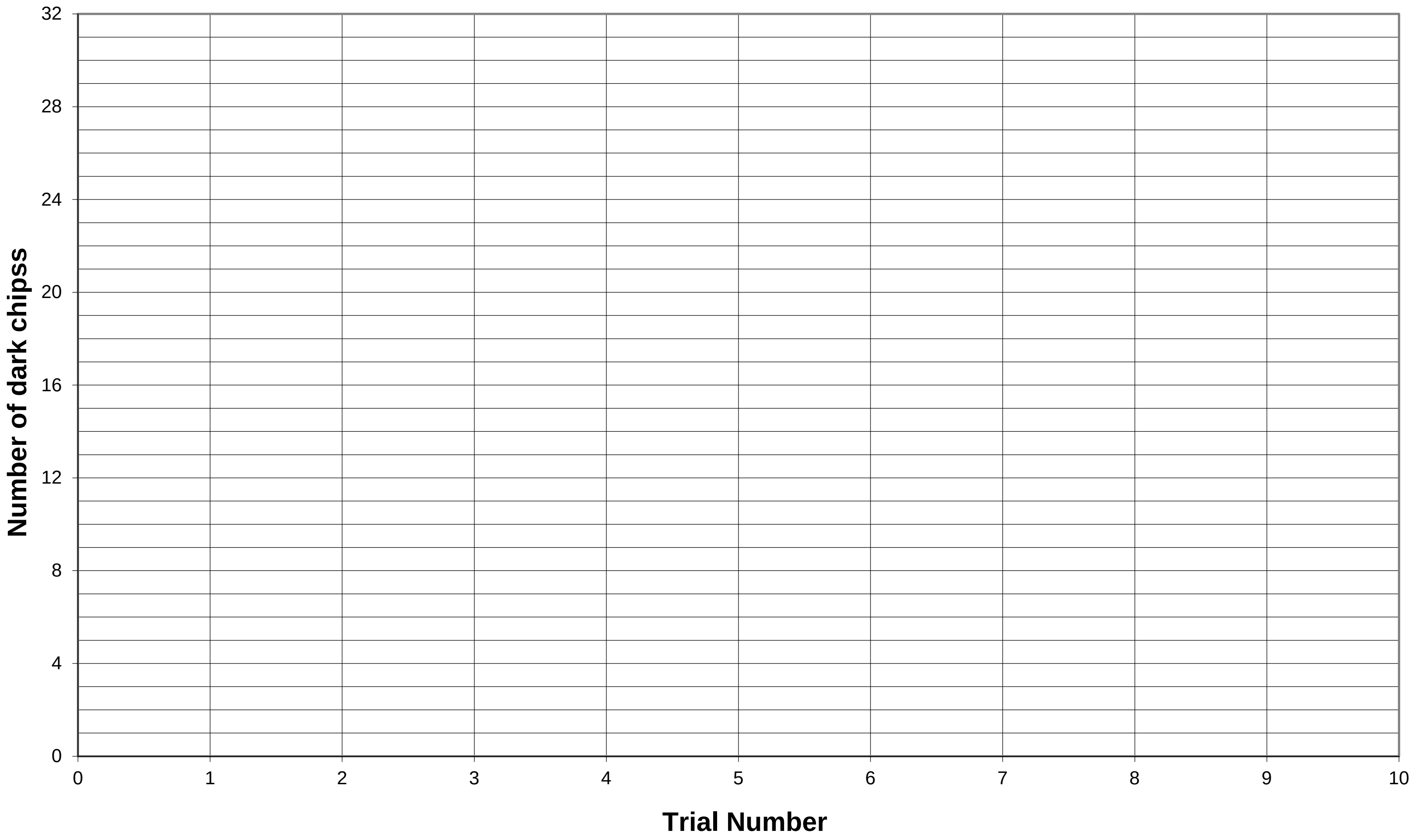
Table of Experimental Results

Trial Interval #	**# of Light Chips (Parent Radioactive Material)**	**# of Dark Chips (Daughter Decay Product)**	**Fraction of Parent Atoms Remaining (Light Chips)**
0 (# of atoms at start)	**32**	**0**	**1**
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

A. Graph of decay of parent material



B. Graph of accumulation of daughter product



- **Answer the following questions after you have completed your experiment:**

Q1. What kind of curve does the decay of the parent material resemble? (See curve figures on the following pages for comparison). Note the mathematical formula that underlies the shape of the curve representing chip numbers decaying through time.

Q2. What kind of curve does the accumulation of the daughter product resemble? (See the plots on the following page for comparison). Note the mathematical formula that underlies the shape of the curve representing chip numbers decaying through time.

Q3. What is the half-life (in number of trials) for the white chips in this experiment? **Hint: You can determine this by examining your fraction column!**

Q4. If you found a box with only 4 light-colored chips in it and 28 dark-colored chips, how 'old' would you estimate the box to be in trial number time? Use your graphs to answer this question!

In the following questions, you are presented with a total number of "atoms" different than the total number with which you started!

Q5. What would be a way to estimate the "age" of a box containing a different total number of "atoms" than 32 by using a graph produced using only your data? Think about this for a moment, and produce these graphs to help you answer the next two questions.

Q6. If you found a box with only 12 light-colored chips in it and 24 dark-colored chips, how 'old' would you estimate the box to be in trial number time?

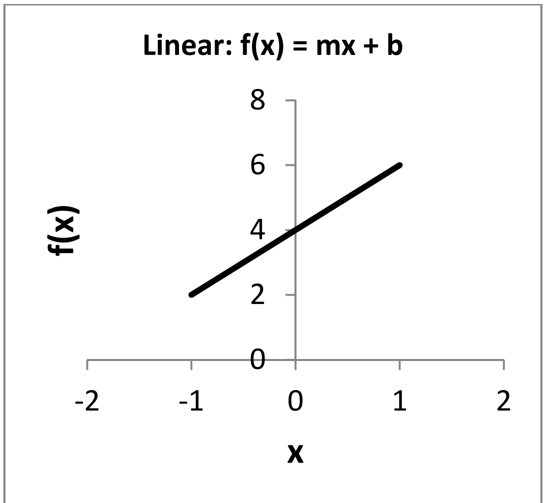
Q7. If you found a box with 38 light-colored chips and only 4 dark-colored chips, how 'old' would you estimate the box to be in trial number time?

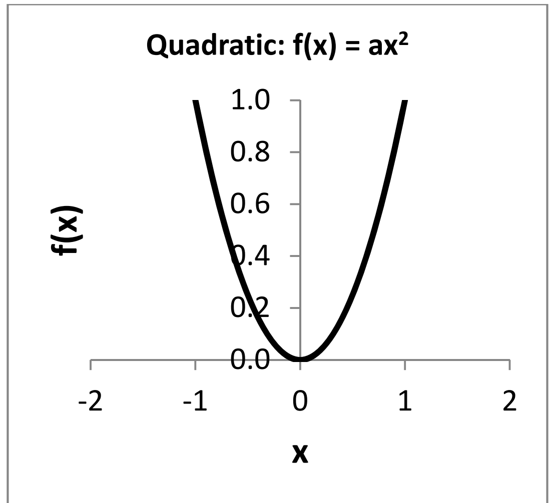
Q8. What is another way of estimating the "ages" of boxes containing the numbers of chips specified in questions 4, 6, and 7? Use this method to also estimate the "ages" of the boxes in questions 4, 6, & 7. **HINT: A calculator might come in handy!**

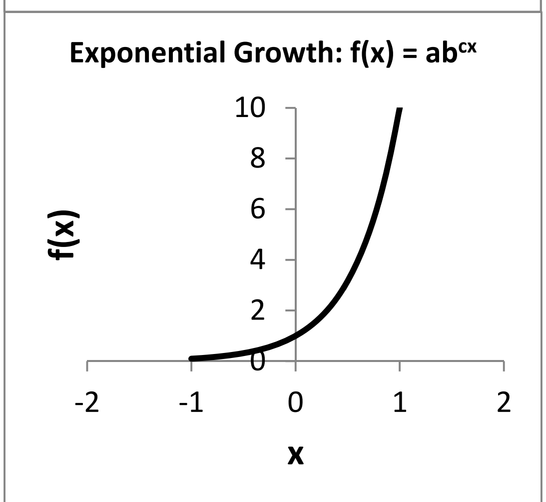
Q9. What is your conclusion about what determines age estimates of fossils, based on your answers to questions 4 - 8?

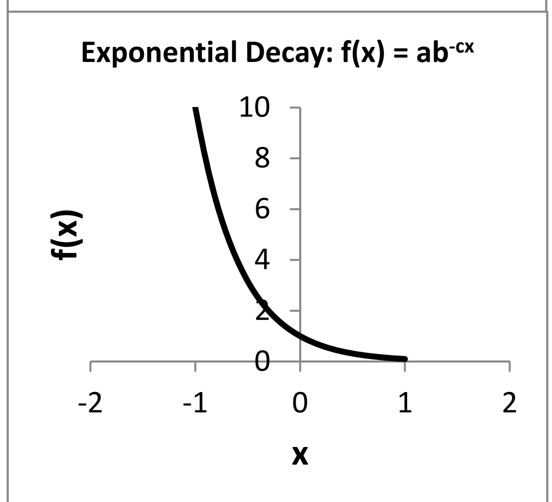
Check your answers to these questions in the answer section of this book for Exercise 3b.3!

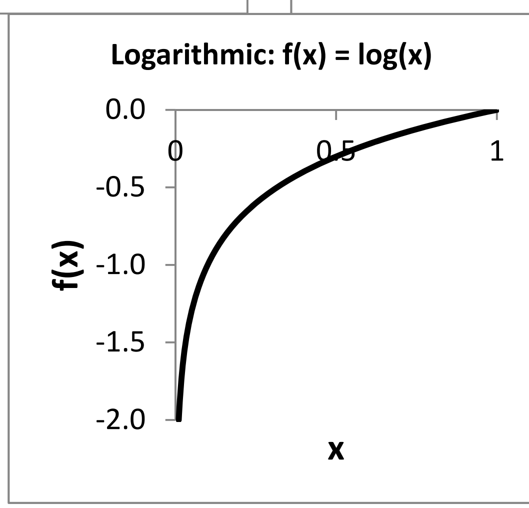
Plots of various mathematical functions











Note, in all equations, any letters other than *x* represent constants that do not change the overall shape of each graph. Also note that the logarithmic function is only valid for positive, non-zero values of *x*.

Exercise 4: Fossil Lineages

Evolution refers to a change in the average values of traits in populations of organisms over time. These may be morphological (e.g., body length), physiological (e.g., resting metabolic rate), or behavioral traits (e.g., temperament) that are passed from parents to their offspring through their genetic material (DNA). Evolution can often result in changes within a single species population that are visible on the scale of a few generations. Over longer ecological, historical, and geological scales, sufficient changes may accumulate to result in speciation events, some of these leading to the formation of new branches in a lineage. In previous exercises, you have learned about the mechanisms of fossil preservation and how we can obtain an estimate of when these organisms lived. Examining fossil lineages is important to our understanding of how evolutionary change in organisms is related to environmental change, chance events, and gradual modification to better adapt organisms to their roles in the ecosystem.

The information we can obtain on adaptation from fossils is limited to morphological traits, and often only those aspects of morphology that are associated with the hard parts that are more likely to be preserved, such as teeth, bones, or shells. Though we are unable to observe extinct organisms eating, reproducing, or moving, we can infer some aspects of their behavior by comparing the shapes and structures of fossilized parts to those of living organisms, in which we **can** observe behavior. This is an indirect approach for sure, but fossils are valuable to the biologist because they can provide an ordered record of the timing of appearance and/or loss of traits as organisms are replaced by descendants over millions of years of geologic time. In Exercises 4a and 4b, you will learn how decisions are made about the historical relationships among organisms through examination of fossil tooth morphology in sharks.

Exercise 4a.1: Fossil Lineages (*Version for Grades K-3*)

Suggested reading: *Shark Tooth Tale* by Abby Klein

NOTE TO TEACHERS: To help young students understand classification of organisms, put together a collection of different but related items (different colors and shapes of blocks, for example). Sort the items according to a particular characteristic (or several), but do not specifically say to students what characteristic(s) you used to sort them.

We put different things into groups, or classifications, to sort them according to their similarities and differences. For example, we sort the foods we eat into groups, like vegetables, fruits, breads, meats, etc. and within each of those groups are different groups. If we sort vegetables into sub-groups, we might sort according to colors of green or yellow, or we might sort according to their shape. Vegetables can be round like a beet, oblong like a zucchini, or can be leafy like spinach. Even though we can divide vegetables into these smaller subgroups, they are all still part of the food group of vegetables, which is itself a sub-group of foods.

- Look at the collection of items your teacher has provided for you.
- Try to answer the following questions:
    - Why are the items sorted this way?
    - How are items in the same group similar?
- Think of another way to sort these same items that will give you different groups. What other characteristics could you use to sort the items a different way?

Sometimes one group of items can be sorted in several different ways depending on the characteristics they have in common. We might sort one group of items according to color, or we may choose to sort them according to shape, or even weight. We sort, or classify, items in order to find out which items share similar characteristics.

The same is true for living organisms. Living organisms have been classified according to characteristics they have in common. The more characteristics, or traits, they share, the more closely related they are to each other. Think about dogs and cats. What characteristics do dogs and cats have in common? How are they different? We can look at how organisms have changed over time by examining changes in their traits. Scientists organize life in a classification system with the seven categories listed below:

KINGDOM
PHYLUM
CLASS
ORDER
FAMILY
GENUS
SPECIES

As organisms are found to have more characteristics in common, they may be placed in sub-groups further down the list together. This means that two organisms in the same *genus* are more closely related than two organisms in the same *order*. If two organisms are in a subgroup together that is lower down the list, that means that they also are in the same sub-groups higher on the list. One way to help you understand this is to think back to our vegetable analogy. We might consider a carrot and a zucchini to be in the same sub-group of elongated vegetables, which means that they are also in the same higher subgroups (vegetables, and foods). However, they are not necessarily in the same lower sub-groups (for example, orange elongated vegetables versus green elongated vegetables). In terms of classifying organisms, for example, two kinds of frogs in the same family are also in the same order (Anura, which are the frogs and toads), as well as in the same Class, Phylum, and Kingdom. However, those two kinds of frogs are not necessarily in the same genus or species.

We are now going to look at five teeth. All of these teeth are from the fossil shark lineage (sort of like a family tree!) of the family Otodontidae, mackerel sharks that include the giant Megalodon shark. The Megalodon shark was a giant shark that we know existed in ancient times because their fossilized teeth have been found deep in the earth. Shark skeletons are composed of cartilage instead of bones, and cartilage does not fossilize so the only remaining traces of ancient sharks are their teeth. Your nose and ears are made of cartilage and that is why they can bend and seem somewhat flexible, unlike bones that are firm and do not bend without breaking. Information about the Megalodon has been gathered from studying only their teeth since their full skeletons were made of cartilage and did not fossilize. All of these shark teeth are fossils, which mean these sharks lived on earth many millions of years ago and none of these types of sharks are living today.

- Look closely at the shark teeth.
- Think about the size of your own teeth compared to the size of your whole body.
    - How do you think that relates to the size of the shark teeth and the size their bodies probably were?
- Now examine the shark teeth more closely. What particular characteristics do you notice about these shark teeth?
- See how many similarities and differences you can notice on each of these teeth.

- Your teacher may make a list of your suggestions on the board for discussion a little later.
- All of these teeth come from extinct sharks that were closely related, but some of them are much older than others.
- See if you can guess which tooth is the oldest, and which is the youngest (that existed most recently). You may wish to look at the modern shark jaw provide in your box to help make your decision on which shark tooth is the most recent, based on similarities to a modern shark's teeth.
- See if you can place the other teeth in order between the teeth that you said were the oldest and the youngest, and try to answer the following questions:
    - Why do you believe they lived in the order you chose?
    - Why do you think the shark teeth changed over time?

NOTE TO TEACHERS: The explanations and diagrams on pages 50-51 give the correct order the sharks lived on earth. Using this information, show students the correct order and use student observations of the teeth to discuss what changes might have occurred over time to cause changes in the tooth structure.

Exercise 4a.2: Determining a Fossil Lineage (*Version for grades 4 & up*)

Teeth are well represented in the fossil record because tooth enamel is resistant to decay, particularly when it becomes buried in sediment or some other material where there is no oxygen to foster bacterial decomposition. Shark teeth are the most abundant teeth in fossil beds, because sharks produce so many teeth over their lifetimes. The shark's tooth is a modified fish scale, and each shark has numerous rows of teeth in its mouth.

- Examine the jaw of a modern shark found in Box 4, noting how the teeth are organized in the mouth, and how the general shape of the teeth differs based on the position of the teeth within the jaw.

Each tooth is only loosely attached at its base by connective tissues to the jaws, so these tend to break off during feeding, and in fights with other sharks over food, etc. Several rows of replacement teeth continually develop behind the outer rows of the functional teeth, and as the functional teeth fall out, replacement teeth take their place.

The best way to examine historical relationships among organisms is to examine changes in traits (tooth structure in the case if this exercise) in lineages through time. Organisms that are more closely related share more traits in common. Based on this fact, biologists organize life in a hierarchical classification scheme that has seven categories listed here from most inclusive (e.g., includes all animals) to least inclusive (e.g., includes only animals that share sufficient numbers of genes in common to successfully interbreed):

KINGDOM
PHYLUM
CLASS
ORDER
FAMILY
GENUS
SPECIES

Individuals share more characteristics in common, and thus are more closely related to one another, the further one goes down in the hierarchy from kingdom to species. In other words, a pair of organisms that are within the same genus are more closely related than a pair of organisms that are in the same order. For example, all members of the animal kingdom (Kingdom Animalia) have their genetic material (DNA) enclosed in a double-membraned compartment, are multicellular, and feed on other organisms (are heterotrophic). In addition to the above traits, members of the phylum Chordata (of which sharks, humans, and all vertebrates are members), have a skeletal rod called a notochord, a dorsal hollow nerve cord, a post-anal tail, and have gill pouches at some stage in their life cycle.

The Mackerel shark family you will be examining in this exercise has the following classification:

Category	Name	Characteristics
Kingdom	Animalia	Multicellular organisms with DNA enclosed within double-membraned nucleus & that feed on other organisms (are heterotrophs)
Phylum	Chordata	notochord, dorsal hollow nerve cord, post anal tail, & gill pouches
Subphylum	Vertebrata	vertebral column/backbone
Class	Chondrichthyes	Jawed fish with paired fins & flexible cartilaginous internal skeleton
Order	Lamniformes (Mackerel sharks)	Upper teeth well differentiated along the jaws, forming the so-called "lamnoid dental pattern," which features enlarged anterior (front) teeth, slightly to much smaller intermediate teeth, large lateral (side) teeth, followed by much smaller posterior (back) teeth.
Family Otodontidae		Individual teeth have a convex lingual (facing lip) surface, elongated root branches forming V- or U-shape, and an extended neck zone of bone (collum) on the lingual surface.

- Examine the above table, noting the new characters added at each more specific level as the hierarchy descends from kingdom to species.
- Now find the plastic bag marked 4.1 in Box #4. This packet contains five teeth in the fossil shark lineage of the family Otodontidae, mackerel sharks that include the giant Megalodon shark, which was previously thought (erroneously) to be the ancestor of the Great White Shark of today.

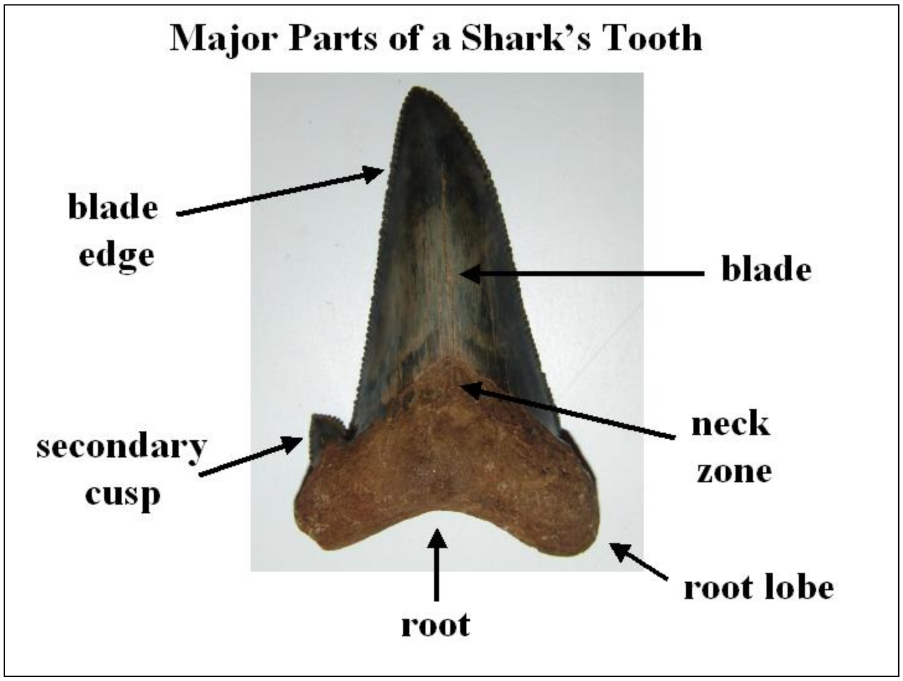
In alphabetical order, you should have one tooth of each of the following species on the table in front of you: *Carcharocles auriculatus, Carcharocles chubutensis, Carcharocles megalodon, Cretolamna appendiculata,* and *Otodus obliquus.* (**To aid in locating these teeth for return to the correct packet, each has a red dot on the enamel at the base of its blade/crown. See the tooth structure figure below to aid you in correctly describing the regions of the teeth using appropriate anatomical terminology.) This is indeed the giant Megalodon shark lineage that you will be examining!** None of these species is living today, though all were present in the fossil record for at least a few million years, and all were geographically widespread in the seas during their existence.

Your job is to examine these teeth and to attempt to arrange them in some form of hypothesized lineage that represents a trend in one or more aspects of tooth structure. In other words, think about how this lineage may have changed over time, considering selective pressures that may have been important in determining how teeth may have evolved in this group of sharks.

NOTE: Differences in the degree of curvature of the teeth may not be reflective of changes in the lineage over time, as the shapes of teeth within a single species vary with their placement in the mouth. Take another look at the modern shark jaw provided to get a sense of the general trend in tooth shape between anterior (front) and lateral teeth (teeth towards the sides of the mouth).

- First, make a table like the one on the next page to show your decision process.

Hypothesized Lineage (Most recent to oldest) 1st Try	Reasoning (1st Try)	Actual Lineage (Most recent to oldest)	Reasoning (2nd Try)	Actual Changes in Lineage



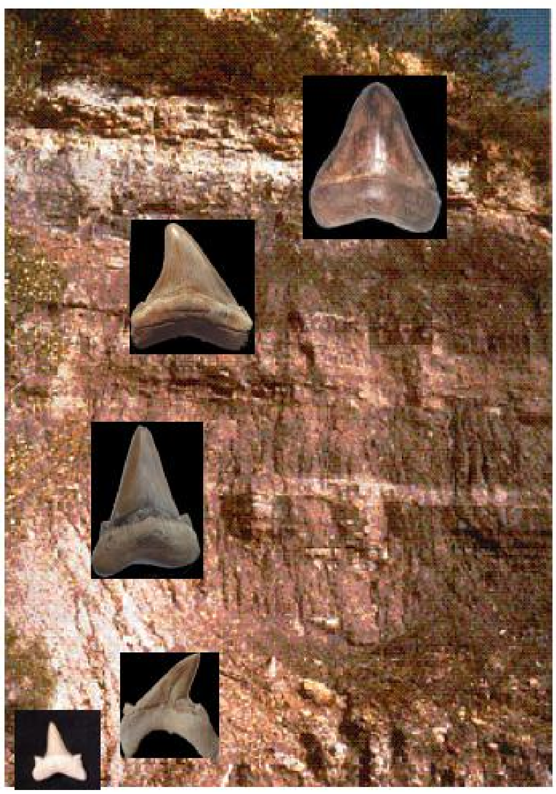
- Examine the figure above that shows major parts of a shark tooth.
- Move your teeth around attempting to place them in an order that shows some progression of one or more traits. In doing so, you have just made a hypothesized lineage for these species!
- Make a hypothesis as to which state of each trait you are interested in is ancestral or primitive, and which is derived (a more recent change). For example, you may wish to use, 'small' versus 'large' as states of the trait representing size, and/or 'pointed' versus 'blunt' as states for the tip of the blade portion of the tooth. You might hypothesize that a predator such as a shark would develop increasingly more pointed teeth over time. 'Blunt' would be the ancestral value of the trait in this case, and 'pointed' derived. According to such a hypothesis, species with the more blunt teeth would be older in the lineage, and you would put the tooth with the most blunt or squared tooth on the bottom row in the table, and the one with the sharpest tip on the top row of the table. (**You are arranging these with the hypothesized most recent species at the top and the oldest at the bottom to reflect how these teeth might have been found in rock layers. Remember, lower layers of sediment were deposited first, and are thus older than the layers deposited on top of them!**)
- In the "Reasoning (1st Try)" column following the ranking of your species from oldest to youngest, describe the trait trends you have observed, and below the table, speculate as to why these trends might

exist, as in the example for tooth tips. **Note that teeth take on the color of the minerals in the sediment in which they are fossilized, so color is not a good trait on which to base relationships!**

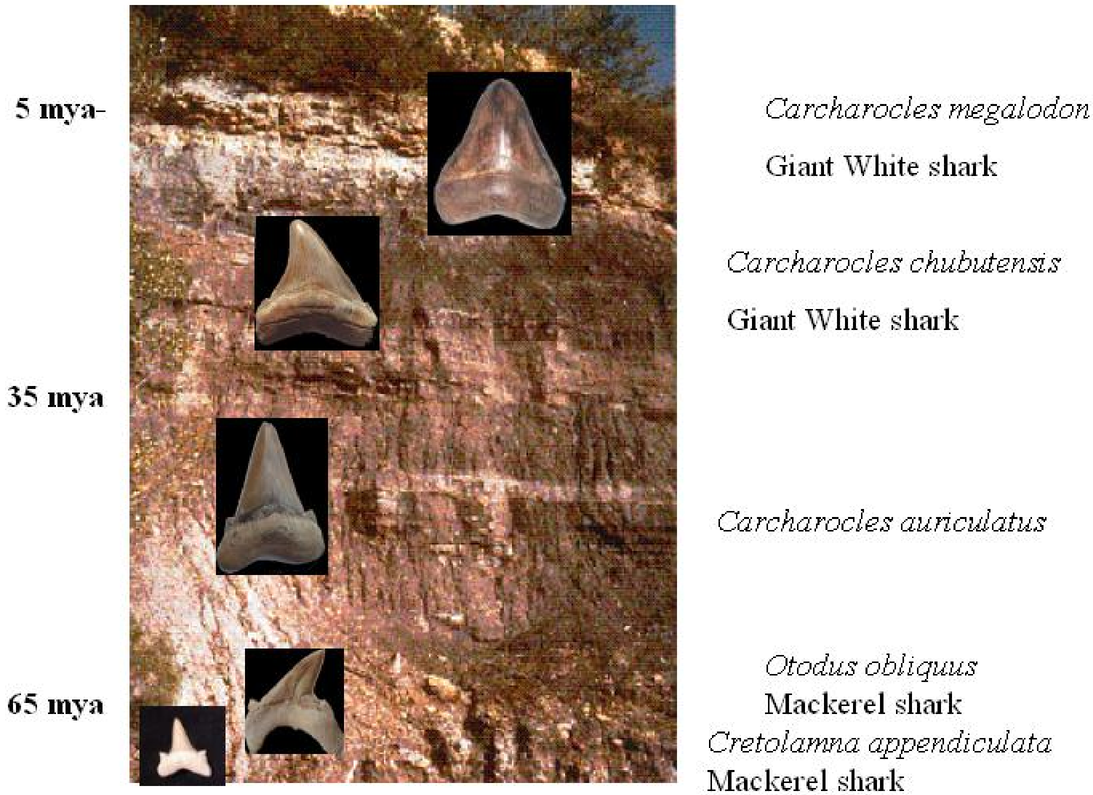
NO CHEATING! COMPLETE THESE STEPS BEFORE GOING ON TO THE NEXT PAGE!

The figure below is a cross section of sediment layers that often contain fossils.

- From the relative positions of species on this figure, rank your species on the "Actual Lineage" column on your table from oldest to youngest.
- Check the ranking you originally made in the first column of your table (based on your hypotheses) against the one suggested by the actual stratigraphy (order of specimens in the fossil record) of fossil specimens, which provides an estimate of relative age of the fossils.
- You should revisit your hypothesized trait progressions in light of this new information, and fill in the "Second Try" column with revised hypotheses of changes in various traits of the teeth in this lineage over time.



- Finally, examine the figure below, to which radiometric dates have been added to the stratigraphy.
- Add the Mackerel shark species to the the geological timeline that you completed under Exercise 2.



- Consult the answer sheet under Exercise 4a for a discussion of trait progression in this lineage, adding this information to your “Actual Changes in Lineage” column.

NOTE: Though all of the sharks whose teeth you examined in this exercise are given separate formal species names, many paleontologists agree that this collection of species (as well as others in this lineage) represent a **chronospecies**, or a single **biological species** that evolved substantial changes over millions of years. What defines a “species”? You may wish to do some library or online research on “species concepts” to learn more on this topic, which has been (and continues to be) a topic of much debate!

Exercise 4b: Comparing lineages (*Open-Ended Exploration, Grades 4+*)

In **Exercise 4a**, you examined changes in tooth structure that occurred over millions of generations in a single family or lineage (changes passed on to offspring). In this exercise, student teams are expected to consider the relationship between the extinct Megalodon/Giant White Shark, *Carcharocles megalodon*, examined in Exercise 4a, and today's giant shark in the seas, the Great White Shark, *Carcharodon carcharis*.

- Each student team should search the web, exploring what is known about the historical relationship between these two species and the families to which they belong. Do they share a common ancestor? If so, what is it?
- Learn about cladograms, trees that depict the evolutionary relationships between lineages. Then develop a tree (cladogram) that depicts the evolutionary relationship between the two lineages.
- Compare and contrast the tooth structure of the two lineages, listing the similarities and differences of the teeth. In determining whether traits are either ancestral or derived in a lineage (or multiple lineages), an outgroup is often used. An outgroup is an organism that is not a member of a lineage that is being considered (in other words, is not **closely** related to, but shares a distant common ancestor with the organisms in question). Comparing the teeth in the Giant White and Great White shark lineages to a very different shark species (an outgroup) will help in identifying the traits that are shared by the modern day great white shark and the ancient giant white shark, as well as comparing the changes between the two lineages. Find the bag with the crow shark (*Squalicorax pristodontus*) tooth in it. This is the outgroup species you can use for comparison. When a particular trait displays multiple states, when the value of a trait of a species is the same as that observed in the outgroup, that trait value is likely ancestral, while a trait value that differs between the organisms in question and the outgroup would represent a derived, or more modern character state, which has evolved since a shared common ancestor. (Note that a particular outgroup may not always necessarily display trait values that are *only* ancestral values of the trait. Because of this, most scientists usually use

multiple outgroups in comparing changes in lineages over time!)

- Check the Answer sheet for Exercise 4b for discussion of the relationship between the Mackerel and White shark lineages.

Exercise 4c: Size of the Megalodon (*Grades 4 and up*)

Materials

- o Megalodon tooth from Exercise 4.1
- o Other shark teeth from Exercise 4.1 (optional)
- o Graph paper

The Megalodon was the largest shark that ever lived on earth. We can use the teeth of the Megalodon to help us determine the relative size of this massive animal. Since scientists know the width of the teeth and body length of modern-day sharks are related, we can use this information to determine the approximate size of the ancient Megalodon. You are going to use modern-day shark information to determine the approximate length of the Megalodon shark.
The following table includes information gathered about the tooth width and body length of modern-day sharks.

Tooth Width (cm)	Body Length (cm)
0.5	66.0
1.3	137.2
2.0	254.0
2.5	322.6
3.6	457.2
5.1	635.0

- Graph the information in the chart, using *tooth width* as your horizontal, or *x* axis and *body length* your vertical, or *y* axis.

What scale will you use for the x- and y-axis on your graph? The 'tooth width' data begins with 0.5cm and ends with 5.1cm, and the 'body length' data begins with 66cm and ends with 635cm, but because you are going to include the size of the Megalodon tooth in your graph, you may need to extend your scales beyond the given data in the table. Remember that both your x-axis and y-axis scales must be divided into even intervals.

- Connect the points with a line and extend the line beyond the last point you plotted on the graph.
- Now measure the width of your Megalodon shark tooth by measuring it across the widest point of the root.
- Record the width, locating the width on the x-axis.
- Extend a line vertically from the width dimension and find the point of intersection with the line drawn connecting points from the data table.
- Using a ruler as a guide, draw a horizontal line back to the y-axis to locate the dimension that indicates the approximate length of the Megalodon shark.
- Now answer the following questions:
  - According to your graph, how long was the Megalodon shark from which your Megalodon tooth was obtained?
  - How does the length of the Megalodon shark compare to the different modern-day sharks listed in the table?
- Using a ruler or measuring tape, measure the lengths given in the data table above along a wall in your classroom or in a hallway.
- Mark one point on the wall or hallway with tape as your beginning point, and measure from that same point each time.
- Measure each length and mark its end with tape until you have measured each length in the chart. When you have finished each measure, each new length will be progressively farther from the beginning point than the previous measure.
- Using the length of the Megalodon from your graph, measure the length of the Megalodon on the wall or hallway as you did your other shark lengths, beginning at the same point of beginning for your other measurements.
- Compare the length of the Megalodon to the lengths of the modern-day sharks, and answer the following questions:
  - How do their lengths compare?
  - Are they close in length, or are there large differences in their lengths?
- **OPTIONAL:** Measure each of the other shark teeth provided in this unit, and use the same methods above to estimate the sizes of the

individuals of those shark species represented by the teeth that you were provided.

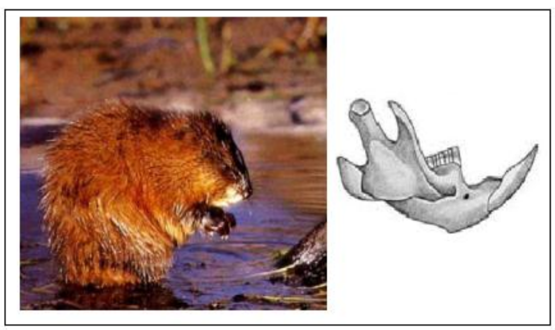
  - How do the sizes of these other extinct shark species compare to the size of the Megalodon?
  - If you have already completed the exercise on determining a fossil lineage, you know the approximate ages of each of these teeth, indicating the time periods when these species existed. How did this lineage change, in terms of overall body size over time?

- **OPTIONAL:** Make another plot, showing body size of these shark species, plotted against time.

ANSWERS FOR EXERCISE 1: FOSSILS: T/F?

 # 1. True. This is a piece of amber from South America that has a tiny insect(s) that lived 35 million years ago entombed in it. Like the fly in the picture below, your insect(s) became trapped in the sticky resin of a pine tree (*Pinus sp*) as it landed on its bark. The resin or amber itself became hardened with the insect trapped inside. Scientists have obtained the genetic material (DNA) from insects preserved in amber.

#2. False. This is the lower jaw of a muskrat, *Ondatra zibethicus*, that died just a few years ago in the northwestern US.



#3. True. These are impressions of tree fern (*Alethopteris pennsylvanicus*) leaves, which fell from trees about 213 million years ago in Pennsylvania. Ferns were our major trees back then, and these fern trees were 130 feet tall. (How many meters is this?)

#4. True. The specimen is a sand dollar (an echinoderm, related to starfish) that lived in the seas between 36 and 42 million years ago. The species, *Leodia sexiesperforata*, is common in fossil beds along the eastern coast of the United States and northern South America.

#5. False. This is the shell of a clam (Phylum Mollusca, Class Bivalvia/Pelecypoda) that was washed up on a beach in Florida. A clam's shell is secreted by its mantle. Your clam died within the last 10 years, and the materials composing its shell have not been replaced by minerals.

#6. False. This object was never living. It is an abiotic (not derived from a living organism) rock composed of a crystallized mineral called gypsum (calcium sulfate: $CaSO_4$). Gypsum is common to saline waters that have high levels of minerals dissolved in them. This piece was collected along the shore of a desert lake. Water rapidly evaporates from desert lakes, leaving minerals such as gypsum behind.

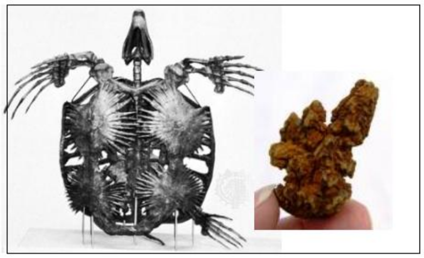
#7. True. This is called a trace fossil. It is hard to assign a species name to a trace fossil, as it is fossilized behavior, rather than an organism or its feces. Based on comparison with modern species and some animals preserved in these burrows found in fossil beds in North Carolina, your specimen was produced by a ghost shrimp (phylum Arthropoda, subphylum Crustacea, class Decapoda, probably *Calianassa sp.*). Here, *sp.* refers to the fact that the species designation cannot be made. A ghost shrimp dug this burrow and sheltered in it on the sea floor 10-20 million years ago. The burrow itself has become a cast.

#8. True. Not only organisms and their parts are fossilized, but the products they made when they were living can become fossilized, as well. Smell this piece of coprolite. Coprolite is animal feces (poop), which has been replaced by minerals. One of the types of coprolites described below is in your box.

> **#8a.** This particular piece of coprolite was produced by a mammal which lived about 4 million years ago. A reconstruction of what such an animal might look like is shown here. What modern organism(s) does it resemble?

> **#8b.** This piece of coprolite was produced by a shark or fish 13-15 million years ago. Look for the impression made by the intestines of the animal that produced this fecal pellet.

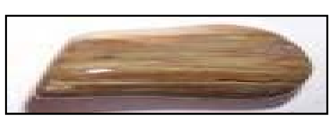
#8c. This coprolite was produced by a sea turtle that visited a beach in Madagascar about 30 million years ago. Sea turtles visit the same beach today, but their poop has not been replaced by the mineral iron. Iron is found in the gravel at this beach.



#8d. This dinosaur coprolite came from a Utah fossil dig that covers the period 65-159 my ago. Thus your fossil is no younger than 65 my, and no older than 150 my. The stone that replaced this dinosaur's poop is agate. Check to see if you can find any bone fragments in the coprolite. If you find them, what can you say about this dinosaur's diet?

#9. False. This is a tibia (leg bone) of a coyote (*Canis latrans*) that was recently killed on a road in the desert southwest USA.

#10.True. This is petrified wood from a tree that lived 340 million years ago. Can you see the growth rings that were added each year during the growing season? Some are wider than others. Why? Your specimens were replaced, molecule by molecule, with mineral rich silica (sand) in water, forming agate.



#11. False. This is a concretion called a pseudofossil. It is abiotic, or non-living and was never alive. It resembles a fossil, but consists of mineral matter that formed when minerals in water deposited around some particle. The particle might have been another mineral, or some piece of organic matter. Concretions are similar to concrete. Since this material is frequently harder than the surrounding mineral matter, that matrix tends to erode away, leaving the concretion exposed.

You might have a particular concretion called a Moki Ball. It is an iron concretion that was formed about 30 my ago around sand crystals. The round shape is thought to be produced from the rolling of the concretion down sandstone cliffs in Utah. The name comes from the Moki Indians that lived in the area and used the small metal balls to play games similar to our marbles. Medicine men also kept the balls in medicine bags, as they used them to help in healing their patients.

#12.True. This is a tooth from a dinosaur.

#12a. This is the tooth of a meat-eating dinosaur called a spinosaurus (*Spinosaurus marocanus*) that lived 98-105 million years ago. The tooth has had mineral replacement and was found in the Atlas Mountains of Morocco in Africa.

#12b. *Mosasaurus* was a predator that inspired legends of dragons. The name means "Meuse lizard", because it was first found in the Meuse River in the Netherlands. This animal lived in the seas during the Age of Dinosaurs (70 million years ago), and obtained lengths of 10 meters (30 feet). Its streamlined body, powerful, paddle-like limbs, and huge jaws with numerous razor-like teeth allowed this animal to catch and consume large fish, turtles, mollusks, and shellfish. Your tooth was collected in Morocco, Africa.

#13. False. This is a pottery sherd from a clay pot that was produced by Pueblo Indians in northern New Mexico about 400 years ago. These Indians always broke their pots when being attacked by Apaches, so that the Apaches could not have use of them. Former Pueblo Indian sites thus have huge mounds of pottery pieces called sherds.

#14. True. This is a trilobite. Your specimen might be *Elrathia kingi* or perhaps a *Phacops sp*. Approximately 10,000 species of trilobites lived in our seas over 500 million years ago. Before fish, the trilobites, squids, and octopi were the major predators in our oceans. All trilobites are now extinct (no species exist today). However, trilobites are ancient relatives of modern arthropods like insects and spiders. This specimen was collected in ancient sea beds from Morocco. Its exoskeleton has been replaced by a carbon film, much as in an imprint or an impression.

#15. True. This is a fossil tooth of either

#15a. An ancient shark. The enamel is still present in its original form, though the bone has been replaced by minerals. Sharks have been around for at least 420 million years (since the early Silurian; possibly longer, but the oldest undisputed shark scales have been dated at 420 MYA). If you have computer access, check out "A 'Quick & Dirty' Guide to Fossil Shark Teeth" at

http://www.elasmo-research.org/education/evolution/guide_f.htm

Does your fossil tooth look like it came from any species in the guide?

OR

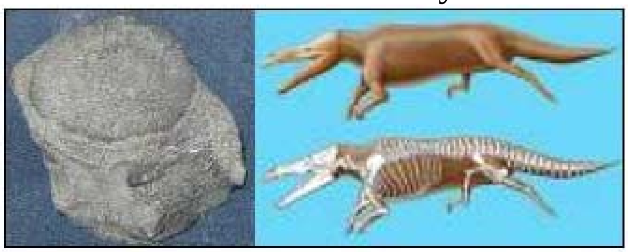
#15b. A bison. Bison dispersed into North America from Asia during the Middle Pleistocene Era, 300,000 years ago. While native species of horse, llama, and elephant went extinct at the end of the Pleistocene, bison survived. This tooth is 4,000 years old, and is at the stage of partial mineral replacement. It is of the living species *Bison bison*. Fossils do not have to be material from extinct species!

OR

#15c. *Mesohippus*. *Mesohippus bairdi* was one of the earliest horses. This specimen is from a *Mesohippus* that lived in the South Dakota Badlands 30 million years ago in the Oligocene. This was a small horse of about the size of a domestic dog. Its skeleton closely resembled that of modern horses, but it carried its weight on three toes per leg instead of on a single toe as horses do today. Its teeth also differ from those of a modern horse, which grazes on grasses. *Mesohippus* had low-crowned teeth, suggesting that it browsed on leaves of trees and shrubs.

#16.True. This is a fossilized vertebra:

#16a. You may have a mammalian vertebra from an early small whale (cow whale) that was similar to our modern porpoise. The mineralized vertebra is between 3 and 5 million years old.



OR

#16b. You might have the vertebra of an ancient shark of about the same age. Mineral replacement has also occurred in the shark vertebra.

#17. True and False. This is a piece of coal. Coal is a rock that consists of decomposed plants and animals that lived 299-359 million years ago. Because the organisms had decomposed into an organic soil called peat before heat and pressure formed the rock, coal is not a real fossil. It is referred to as a fossil fuel, though, and is burned today as a source of energy.

#18. True. This is a fossil fish. You may have a fossil fish from the genus *Lycoptera*, which is related to modern fish that produce electric fields. These fossils are from the Liaoning province of northeast China that dates at 120 million years old. This specimen was collected from a freshwater lake-bed adjacent to a site where feathered dinosaurs have been found.

Alternatively, you may have a fossil fish (likely from the genus *Knightia*, *Priscacara*, or *Diplomystus*) from the Green River Formation in Wyoming. Fish fossils from that site date to the Eocene epoch (54 mya to 37 mya) of the Cenozoic Era. In either case, the fish fossil in your box is an impression with mineral replacement (iron replacing the carbon material film that was left as the animal decayed).

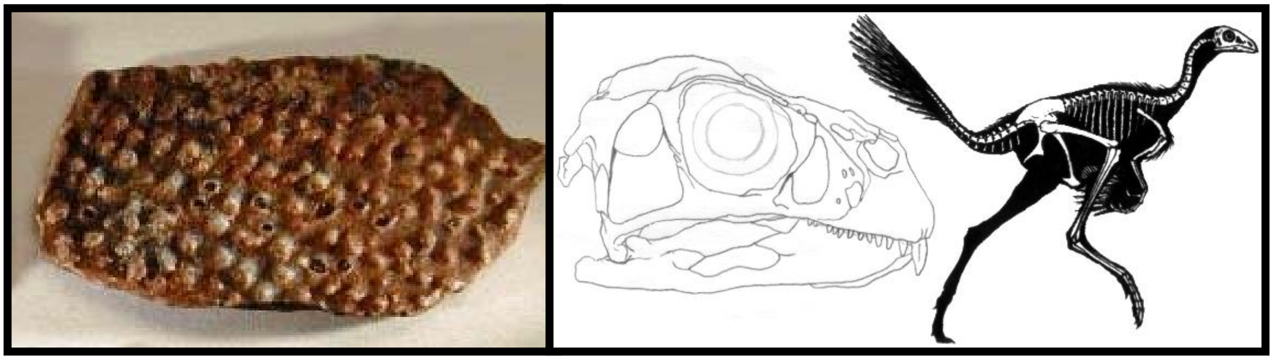
#19. True. This is an example of first numerous fossils to appear in the fossil record. This specimen is a stromatolite that is 1.5 billion years old that came from a stone quarry in Minnesota. Stromatolites are colonies of bacteria that are rock-like buildups of microbial mats that stick up out of the sea floor. Cyanobacteria that formed stromatolites were the first organisms to produce sugars through the process of photosynthesis (converting solar energy into organic compounds). They release oxygen as a byproduct of the photosynthetic process, and thus are responsible for producing the large quantities of oxygen that permitted the development of more complex organisms in the early seas. The oldest prokaryote fossils date at 3.5 billion years old. You are not seeing the individual cells on this fossil, but the layers of algal mat produced by the colony, in cross-section. One picture shows stromatolite colonies dispersed over the sea floor (they can get as large as apartment buildings!). The other is the cross section you will see on your fossil that has been cut and polished. Mineral rich silica dissolved in water replaced the algal mat.

#20. True. This sample of hair comes belongs to an extinct relative of the elephant, the wooly mammoth, *Mammuthus primigenius*. This hair was collected from an animal that was frozen in the permafrost in Siberia, Russia. The sample of hair is approximately 10,000 years old.

#21. False. This is not a true fossil, as this specimen was collected recently from a wet area on the grounds of the University of Tennessee campus. It is part of the stem of a horsetail (*Equisetum sp.*) that is only 1 m tall. The horsetails are referred to as living fossils, modern representatives of what was once a prominent group of trees in fossil history. During the Age of Reptiles, tree ferns and horsetails formed forests. They have since been replaced by deciduous (e.g. oaks and maples) and coniferous (pines, spruces, and firs) trees. Today the *Equisetum* resemble grasses.

#22. True: This is a piece of an egg shell produced by a bird-like theropod dinosaur that was flightless, but that had feathers, presumably for warmth. These oviraptors (Oviraptosauria) are abundant in the fossil beds in Mongolia, China, and date about 100 my in the late Cretaceous (Age of

Dinosaurs). Some workers feel that these are early birds that had lost the ability to fly, while most consider them dinosaurs.



ANSWERS FOR EXERCISE 2: GEOLOGICAL TIME SCALE

Exercise 2b.1. (*Version for grades 4-6*)

- **2b.1 Q1. Which era was the longest the Paleozoic Era or the Cenozoic Era?**
  The Paleozoic Era was the longest.
- **2b.1 Q2. Which occurred first, the beginning of the Mesozoic Era or the beginning of the Cenozoic Era?**
  The beginning of the Mesozoic Era occurred first.

Exercise 2c.1 (*Version for grades 7-12*)

- **2c.1 Q1. What percent of the total time does the Paleozoic Era take up?**
  About 7%
- **2c.1 Q2. What percent of the total time does the Mesozoic Era take up?**
  About 4%
- **2c.1 Q3. What percent of the total time does the Cenozoic Era take up?**
  About 1%

ANSWERS FOR EXERCISE 3: DATING FOSSILS

Answers for Exercise 3b.1:

Q1. Find the inverse of the following function:

$$f(x) = \frac{x}{7} + 1$$

Inverse =

$$f^{-1}(x) = 7(x-1)$$

Q2. $\log 10^{-5}$ **= -5**

Q3. $\log\left(\frac{1}{10}\right)$ **= -1**

Q4. $\log 1000 = 3$

Q5. Solve $10^x = 17$ for x.

$$10^x = 17 \Rightarrow \log 10^x = \log 17 \Rightarrow x = \log 17$$

Answers for Exercise 3b.2 :

Q1. Stromatolites -1.5 BY
Uranium-235: useful range 10 million - 4.6 by

Q2. Wooly mammoth fur- 10,000- 14,000 Y
Carbon-14: useful range = 100 - 30,000 years

Q3. Tree fern leaves - 300 MY
Uranium-235

Q4. Sea urchin - 36- 42 MY
Uranium-235

Q5. The age of stars dated from meteorites -15 BY
Either Rubidium-87 or Samarium-147 (both with useful ranges of billions of years) would be appropriate.

Q6. Suppose that the fraction of Uranium-235 remaining in fossil number 10 is 0.71. Use this information to find the age of the fossil.
3.4588×10^8, or $345,880,000$ years old.

Q7. Assume there is small error in our measurement and in fact the fraction of Uranium-235 remaining is 0.714. How does this affect the answer in the previous question?

$\mathbf{3.4020 \times 10^8}$, or $\mathbf{340,200,000}$ years old: a difference of $\mathbf{5,680,000}$ years from the previous estimate.

Q8. Solve the equation below for the half-life $\hat{t}$ in terms of λ.

$$\frac{1}{2} = 10^{-\lambda\hat{t}} \rightarrow \hat{t} = \frac{-\log(1/2)}{\lambda}$$

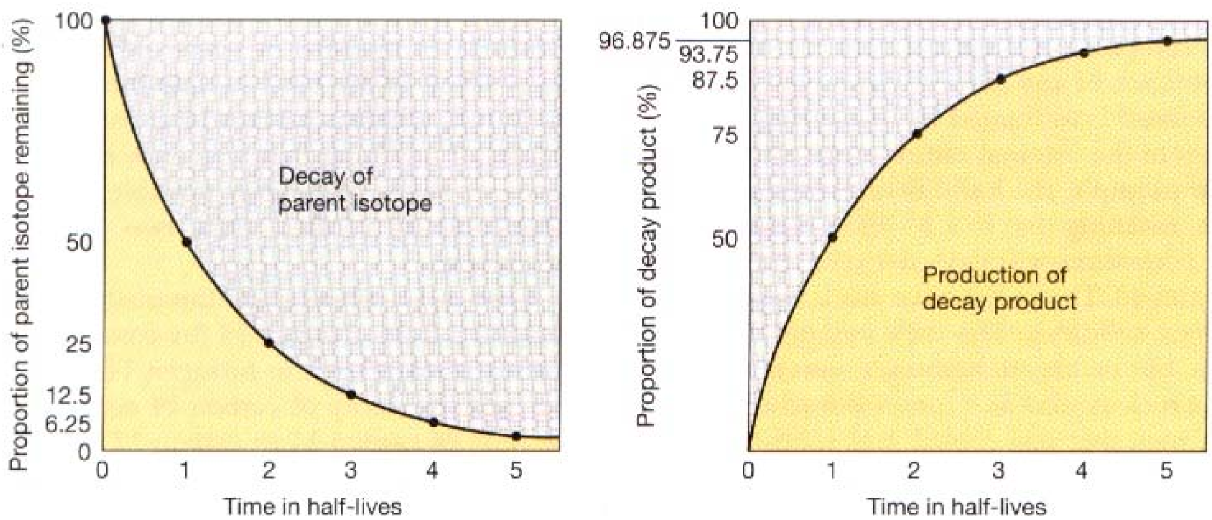
Q9. Given that the decay rate of Radium-226 is $.814 \times 10^{-5}$, find the half-life of Radium-226.

1,600 years

Answers for Exercise 3b.3:

Q1. What kind of curve does the decay of the parent material resemble?
After examining your graph, you should see that the decay of the parent isotope resembles the exponential decay curve.

Q2. What kind of curve does the accumulation of the daughter product resemble?
After examining your graph, you should see that the accumulation of the daughter isotope resembles the logarithmic curve.



Q3. What is the half-life (in number of trials) for the white chips in this experiment? Hint: You can determine this by examining your fraction column!

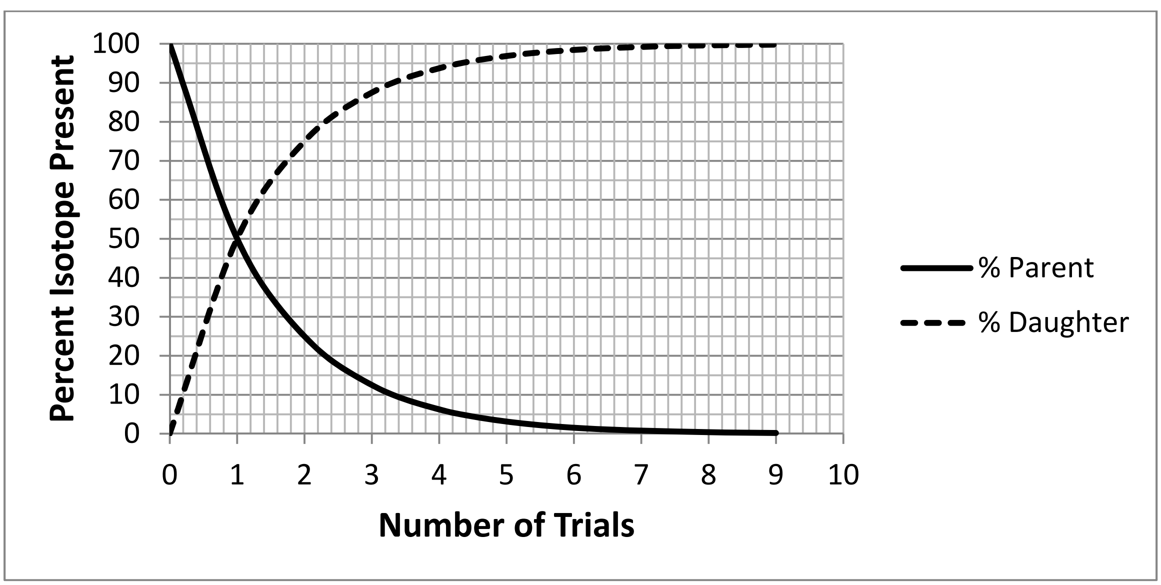
The half-life of the white chips in this experiment is equal to one trial. On average, you should see that the number of white chips remaining after each trial is approximately half the amount present compared to before the trial.

Q4. If you found a box with only 4 light-colored chips in it and 28 dark-colored chips, how 'old' would you estimate the box to be in trial number time?

This question should be easy to answer simply by looking at your graphs, since you are examining a total of 32 atoms, just as you did in your experiment. Your estimate of the age of the box in this case should be about 3 trials old.

Q5. What would be a way to estimate the "age" of a box containing a different total number of "atoms" than 32 by using a graph produced using only your data? Think about this for a moment, and produce these graphs to help you answer the next two questions.

If you were to convert the numbers of each color chip in your experiment to a percentage or proportion, this would allow you to easily estimate "ages" of boxes containing different numbers of chips by examining your graphs. If you were to do so, your graphs would look similar to the one below:



Q6. If you found a box with only 12 light-colored chips in it and 24 dark-colored chips, how 'old' would you estimate the box to be in trial number time?

In this box, the light "parent isotope" chips represent 12/36 total chips, or approximately 33.3% of the chips present. Using your graph, you should arrive at an age estimate of approximately 1.6 trials.

Q7. If you found a box with 38 light-colored chips and only 4 dark-colored chips, how 'old' would you estimate the box to be in trial number time?

In this box, the light "parent isotope" chips represent approximately 90.4% of the total chips. Using this information and your graph, you should arrive at an age estimate of approximately 0.2 trials.

Q8. What is another way of estimating the "ages" of boxes containing the numbers of chips specified in questions 4, 6, and 7? Use this method to also estimate the "ages" of the boxes in questions 4, 6, & 7. HINT: A calculator might come in handy!

Another way of estimating the "ages" of the boxes would be to simply use the formula presented earlier in the text. Remember, that formula is

$$\boldsymbol{t_1 = -\frac{1}{\lambda}\log\left(\frac{P}{D+P}\right)}$$

Also, remember that the decay constant ($\boldsymbol{\lambda}$) is related to the half-life ($\boldsymbol{\hat{t}}$), as follows:

$$\boldsymbol{\hat{t} = \frac{-\log\left(\frac{1}{2}\right)}{\lambda}}$$

Thus, we can solve for the decay constant like so:

$$\boldsymbol{\lambda = \frac{-\log\left(\frac{1}{2}\right)}{\hat{t}}}$$

Since we know that the half-life of the chips in this experiment is equal to one trial, the decay constant would be equal to

$$\frac{-\log\left(\frac{1}{2}\right)}{\hat{t}} = \frac{-(-0.301)}{1} = 0.301$$

We can now substitute that into our equation for estimating the "ages" of the "fossil" boxes in the previous questions:

$$t_1 = -\frac{1}{0.301}\log\left(\frac{P}{D+P}\right)$$

Now, all we have to do is just substitute the number of parent atoms for *P*, and the number of daughter atoms for *D* in this equation to find the ages of the boxes, which are as follows:

Q4: 3.00 trials; **Q6:** 1.58 trials; **Q7:** 0.14 trials

Q9. What is your conclusion about what determines age estimates of fossils, based on your answers to questions 4 - 8?

Your age estimates using your graphs from questions 4, 6, and 7 may have differed slightly from the age estimates obtained using the formula for radioactive decay. This is because the amount of parent isotope atoms in a radioactive element does not immediately instantly decrease by one half after each half-life elapses. However, statistically, they do decrease, on average, by very close to one half with each half-life. After a half-life elapses, the **chance** that any one parent atom will decay to form a stable daughter atom is equal to one half, which is illustrated quite well by your flipping of the poker chips. With each flip of a remaining "parent" chip, the chance that a chip will land with the dot side up is equal to one half. One never knows which particular parent atoms will decay at any moment, only the probability that one will do so. This element of **stochasticity**, or randomness, thus introduces some degree of uncertainty to estimates of ages based on the half-lives of radioactive elements. Thus, when scientists report age estimates of fossils, they typically express the estimate plus/minus a number of years, which expresses a level of confidence (usually 95% confidence) that the actual age of the fossil falls within that range. Though there is some degree of uncertainty, radioactive elements' tendencies to very closely approximate a decay rate equal to one half with every half-life elapsed, this margin of error is usually quite small.

ANSWERS FOR EXERCISE 4: FOSSIL LINEAGES

Exercise 4a:

From most recent to oldest species*:

Youngest/most recent	*Carcharocles megalodon*
	Carcharocles chubutensis/C. angustidens
	Carcharocles auriculatus
	Otodus obliquus
Oldest/ most ancient	*Cretolamna appendiculata*

*The reason for the above lineage is the presence of fossils of the sharks in the layers of sediment deposited over time (see figure in Exercise 4.) *Cretolamna* was found at the deepest layers and *Carcharocles megalodon* at the layers closest to the surface.

The general trend in the Megalodon lineage (Family Otodontidae) is an initial increase in tooth size and thickness with the loss of the secondary cusps due to the increase in thickness. There is also the acquisition of a serrated cutting edge on the tooth blade (crown).

Exercise 4b: Comparing Lineages

The tooth morphology between the Megalodon (Giant White) and Great White Shark lineages is very different. Characteristics that are common to all members of the family Otodontidae (Megalodon lineage) include the neck zone or collum, which is the large transitional area between crown and root on the lingual (facing towards the inside of the jaws) face of the tooth. The collum provides an additional area of collagenous tissue beside the root that helps to attach the tooth to the jaw. The V- or U-shaped roots also add greater attachment strength, and this V-shape is most noticeable in the front teeth. Because of the same reason, the root branches of the anterior (front) teeth are elongated to resemble a 'V' or 'U' (Fig.1). The Otodontid tooth has a convex face (resembles a D in cross-section) that provides greater stability to the tooth itself, making the blade less likely to break.

The Lamnidae, as represented by the Great White Shark, have teeth with almost no collum. The roots of the tooth also do not have well-branched root lobes, and thus the V- or U-shaped roots are not observed. The tooth crown, or blade, is flat in cross-section. Only the serrated edge is shared in common between the Great White and Giant Megalodon sharks, and even here there are significant differences. The serrations of the Megalodon are even and small. Those of the Great White are variable in size but generally larger.

These significant differences caused the paleoichthyologist Henri Cappetta (1987) to place the Megalodon Shark and the Great White Shark not only in separate genera, but in separate families.

SUGGESTED READING

Grades K-3

Encyclopedia Prehistorica Mega-Beasts Pop-Up - Robert Sabuda and Matthew Reinhart
Dinosaurs!: The Biggest Baddest Strangest Fastest - Howard Zimmerman
Mammoths on the Move - Lisa Wheeler and Kurt Cyrus (Illustrator)
Dinosaurs of Waterhouse Hawkins - Barbara Kerley
Boy, Were We Wrong About Dinosaurs! - Kathleen V. Kudlinski and S.D. Schindler (Illustrator)
Smithsonian Rock and Fossil Hunter - Ben Morgan & Douglas Palmer
Stone Girl, Bone Girl: The Story of Mary Anning - Laurence Anholt & Sheila Moxley (Illustrator)
How Much is a Million? – David Schwartz

Grades 4-7

Dinosaurs Walked Here and Other Stories Fossils Tell - Patricia Lauber
Geology Rocks! 50 Hands-On Activities to Explore the Earth - Cindy Blobaum & Michael Kline
Bodies from the Ice: Melting Glaciers and the Recovery of the Past – James M. Deem
Bones Rock!: Everything You Need to Know to Be a Paleontologist - Peter Larson & Kristin Donnan
Uncovering the Mysterious Wooly Mammoth - Michael Oard
Fossils - Trudi Strain Trueit
Dinosaurs!: Battle of the Bones - Sharon Siamon
Is There a Dinosaur in Your Backyard?: The World's Most Fascinating Fossils, Rocks, and Minerals - Spencer Christian & Antonia Felix

Grades 7+

Dinosaur Tracks and Other Fossil Footprints of the Western United States **-** Martin Lockley and Adrian P. Hunt
Reading Between the Bones: The Pioneers of Dinosaur Paleontology - Susan Clinton
Dinosaurs: The Most Complete, Up-to-Date Encyclopedia for Dinosaur Lovers of All Ages **-** Dr. Thomas R. Holtz Jr. & Luis V. Rey (Illustrator)
Fossil Legends of the First Americans **-** Adrienne Mayor
An Introduction to Fossils and Minerals: Seeking Clues to the Earth's Past **-** Jon Erickson

Scientific Journal Articles

Botella, H., J.I. Valenzuela-Rios, and C. Martinez-Perez. Tooth replacement in early chondrichthyans: a qualitative approach. *Lethaia* 42:365-376.
Hone, D.W.E. and O.W.M. Rauhut. Feeding behaviour and bone utilization by theropod dinosaurs. *Lethaia*. 10.1111/j.1502-3931.2009.00187.x
Sánchez et al. Cleptoparasitism and detritivory in dung beetle fossil brood balls from Patagonia, Argentina. *Palaeontology* 52(4): 837-848.

LINKS

General Information on Fossils and Earth's Geologic History

Paleontology News (Science Daily) – get the latest info on new fossil discoveries!
http://www.sciencedaily.com/news/fossils_ruins/paleontology/headlines/

PaleontOLogy: The Big Dig – The main page for the paleontology channel at the American Museum of Natural History's OLogy site. Lots of good stuff here for a broad age range!
http://www.amnh.org/ology/index.php?channel=paleontology

Fossils, Rocks, and Time – Good introductory information from USGS.
http://pubs.usgs.gov/gip/fossils/contents.html

Paleontology - Online Resources – This is a HUGE compilation of tons of informative links, organized by the United States Geological Survey. Excellent! (Note: This page was last updated in 1999, so not all links may work. It's well worth it for the ones that do, though!)
http://geology.er.usgs.gov/paleo/paleonet.shtml

Statefossils.com – Did you know that most states have an official state fossil? Well, now you do! This site provides a list of all state fossils, as well as information about each of those organisms!
http://www.statefossils.com/

UCMP - University of California Museum of Paleontology – Another great comprehensive paleo site! Make sure to check out The Paleontology Portal, too!
http://www.ucmp.berkeley.edu/

The Paleontology Portal: Exploring Time and Space – Even though TPP is mentioned above, this page deserves a mention of its own! Contains an interactive map of the US, allowing students to click on a state to see the (bio)geological history of that state, including interactive fossil galleries!
http://www.paleoportal.org/index.php?globalnav=time_space

Gray Fossil Museum – This museum in Washington County, Tennessee, is located near an impressive dig site, where lots of Miocene mammal fossils between 4.5-7 million years old have been recovered. Sounds like a great idea for a field trip!
http://www.grayfossilmuseum.com/

Frank H. McClung Museum – This museum, located on the University of Tennessee campus in Knoxville, has an excellent exhibit on the geology and fossil history of Tennessee, including many three-dimensional recreations of ancient Tennessee environments. Best of all, admission is free!
http://mcclungmuseum.utk.edu/

Fossils – Resources for teachers and students
http://www.teachers.ash.org.au/jmresources/fossils/links.html

Radioactive Decay and Radiometric Dating

Simulating Radioactive Decay - Exercise 3 is based on this simulation exercise developed by John DeLaughter.
http://www.earth.northwestern.edu/people/seth/202/DECAY/decay.pennies.slow.html

Applet: Decay – This is a Java applet that is a simulation of radioactive decay, in which students can change the half-life of a hypothetical radioisotope, and observe the process of decay to daughter material.
http://www.lon-capa.org/~mmp/applist/decay/decay.htm

Halflife – Website from the Physics department at the University of Colorado Boulder. Offers good basic information on radioactive decay, as well as another web-based applet that allows the students to select from several actual real-world radioisotopes and observe both the decay of parent isotope and formation of daughter isotope, with images of "atoms", as well as graphical output of the process.
http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html

Evolution and Shark Lineages

Understanding Evolution – great source for information on evolution from UC Berkeley
http://www.evolution.berkeley.edu/

A Golden Age of Sharks – Page about the evolution of sharks from the ReefQuest Centre for Shark Research. Lots of great information here for students interested in sharks!
http://www.elasmo-research.org/education/evolution/golden_age.htm

Megalodon Shark Evolution – An article by Lutz Andres describing the evolution of the Megalodon shark lineage, which students examine directly in Exercise 4.
http://www.fossilguy.com/topics/megshark/megshark.htm

A Key to the Common Genera of Neogene Shark Teeth – A taxonomic key by Robert Purdy, used for the identification of ancient shark species based on their teeth.
http://paleobiology.si.edu/pdfs/sharkkey.pdf