Unit 2: Of Skulls & Teeth

Biology in a Box

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Unit 2: Of Skulls & Teeth
Materials List

- Sealed plastic container labeled "Tooth Types", containing mounted teeth
  - Fox/coyote canine
  - Beaver incisor
  - Deer molar
- Various numbered plastic containers holding skulls from 11 animals, numbered from 1-11
- Graduated cylinder (50 or 100 mL)
- Container with BBs and small plastic cup inside
- Funnel
- Plastic dishpan (to minimize BB spills)
- Rulers (6)
- Protractors (6)
- Vernier calipers (6)

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Introduction

Skulls can tell you a great deal about their owners. Through the skull, the vertebrate feeds, senses its environment, communicates with other organisms, and even defends itself against enemies. Thus, we can learn much about an animal from examining the structure of its skull and the teeth in it. In the following exercises, you will learn how to read these structures to gain an understanding of how an animal lives. **Exercise 1: Tooth Types and Diet Types** is meant for all, and should be completed before moving on to **Exercise 2: Dental Formulas**, and **Exercise 3: Morphometrics**. These later exercises provide experience with the basic tools that scientists use when studying skulls.

Exercise 1: Tooth Types & Diet Types

Picture by University of Michigan Museum of Zoology

Teeth stab, tear, slice, grind, crush, and chop food in hundreds of different ways, and more can be revealed about animals' lifestyles by examining their teeth than by any other single physical characteristic. This is because tooth size, shape, and arrangement in the mouth are important determinants of the type of food an animal can obtain and consume. Its diet and method of feeding are, in fact, closely related to its dentition (as in number, kinds, and arrangement of teeth). In fact, dentition can be used to tell what type of animal you are looking at.

Exercise 1a: Tooth Types

In your box, you should find a container labeled "Tooth Types" displaying several mounted teeth from various organisms. Each of the tooth types represented in this box (canine, incisor, and molar) are possessed by most mammals. Though these tooth types may differ in terms of shape and size among different species, they still provide valuable information on the lifestyle of the animals from which they came. Examine each of these teeth, paying close attention to the shapes of the roots and crowns of the teeth, as well as overall size. Think about the organisms from which these teeth came, and how these particular types of teeth help those animals obtain the food that they eat. After you have taken some time to examine and think about these teeth and their functions, move to the next page for more detailed descriptions of the four major tooth types mammals possess.

Mammalian Tooth Types

1. **Incisors** are the flat, chisel-shaped teeth at the front of the mouth (behind the lips) that are used in biting, cutting, nibbling, and stripping.
2. **Canines** are behind the incisors, and are located on the cheek-side of the mouth. They are cone-shaped, and may even be dagger-like. They are used for seizing, piercing and tearing.
3. **Premolars** are transitional teeth located between the canines and the molars at the rear. They have 1 or more cusps (points) and are generally used for grinding and crushing, but they may also be used in slicing food.
4. **Molars** have many major cusps (e.g., 3-5), and are located in the back of the mouth on the cheek side. Molars function in grinding and crushing.

Examine Figure 1.1, which displays the locations of each of these types of teeth in a mammal's skull. What you are looking at in this image is the upper jaw from a skull. "**Ventral** view" means that you are looking at the underside of the jaw (you are looking at the jaw where the roof of the mouth is facing you). The term "**anterior**" refers to the front end of a structure (face of the mammal), and "**posterior**" refers to the back end of the structure (back of the head in the mammal). Familiarize yourself with the locations of the four tooth types by examining Figure 1.1 below.

Figure 1.1. Ventral view of skull showing location and structure of teeth.

Incisors (I)   **Canines (C)**   **Premolars**   **Molars**

Picture by University of Michigan Museum of Zoology

Exercise 1b: Diet Types

Animals can generally be assigned to one of four major groups with respect to diet: 1) carnivore (meat eater), herbivore (plant eater), insectivore (insect eater) and omnivore (an animal that eats a variety of foods including meat and plants). Read the more detailed descriptions of these diet types, as well as descriptions about how particular types of teeth might differ between animals of different diet types below. Refer back to Figure 1.1 if necessary to help you envision how these teeth might look in animals of a particular diet type.

1. **Carnivores** share special adaptations for life as predators. Most notably, they have large slicing canines and long roots on all of their teeth. The fourth upper premolar and first lower molar carnivores are called **carnassial teeth**. These are the longest and sharpest teeth in the carnivore's mouth, and are specialized for cutting flesh. The cusps on a carnivore's molars are also high and pointed. Even these teeth in the back of the mouth are used in tearing flesh. Carnivores also have front facing eyes, heavy skulls, and jaws that are strong but that can only open and shut, not move side to side. Below are some examples of the typical appearance of carnivore teeth:
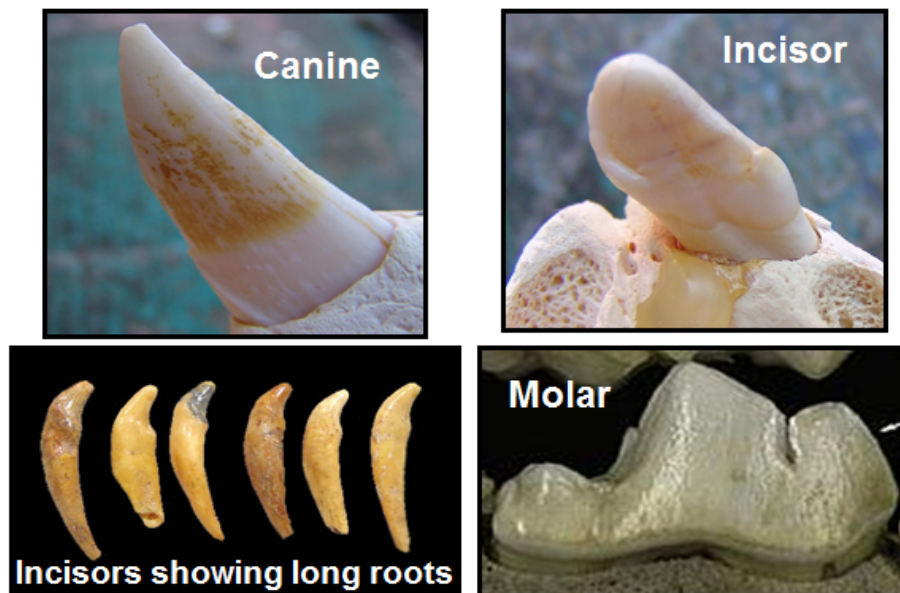
2. **Herbivores** have tall molar teeth that are very broad. These molars have flat upper surfaces sometimes with ridges on them to help grind plant material. Associated with the grinding tooth structure, many herbivores are able to move their jaws from side to side. This increases the ability of the herbivore to grind plant material between the surfaces of the molars.

Many herbivores lack canines entirely because the canines are specially adapted to tearing flesh and herbivores feed on plants. There are, however, numerous exceptions, with some herbivores (such as gorillas, hippopotami, pandas, and male deer and horses) possessing canine teeth, which are usually used in self-defense, or in fighting over territory or mates. The incisor in the herbivore is not dagger-like, but rather may be clipper-like, for use in cutting off plant stems. In many herbivores, the incisors grow continuously. Cutting hard plant material wears an herbivore's incisors down, so continuous tooth growth keeps them at an optimal length for this work. See the images of typical herbivore teeth below:
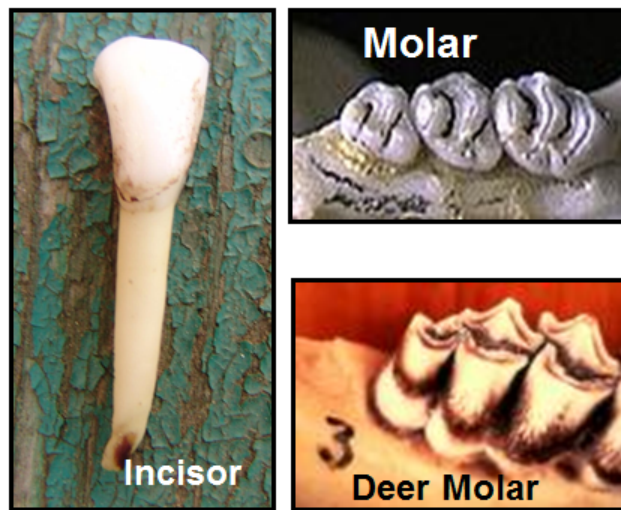
3. Insectivores have a mouthful of sharp little teeth that are similar in size and shape. These are used in seizing and crushing hard-shelled insects and other small animals like worms. Below is an image of a tarsier, a small, primarily insectivorous primate, as well as an illustration of typical insectivore teeth.
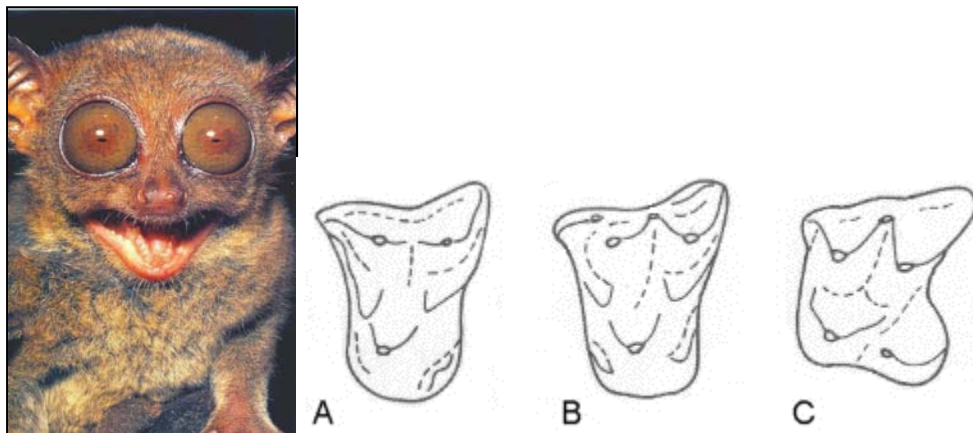
4. Omnivores have sharp, long canines for puncturing and grabbing onto animal prey. Wide molar teeth with low bumpy crowns are often present to handle both the chewing of meat and grinding of plant material. Greater variability in the shape of different teeth is the key to this type of animal, which has a broad diet. In other words, omnivores' teeth typically consist of teeth that show characteristics of the teeth of both carnivores and herbivores. Omnivore incisors, for example, are typically intermediate in shape between those of carnivores and herbivores, usually being more shovel-shaped than pointed. Long, sharp canines are used for puncturing and grabbing onto animal prey, but these may be less pronouncedly pointy than those of carnivores. Wide molar and premolar teeth with low, bumpy crowns handle both the chewing of meat and the grinding of plant material. Below are some examples of an omnivore's teeth, as illustrated by a chimpanzee.
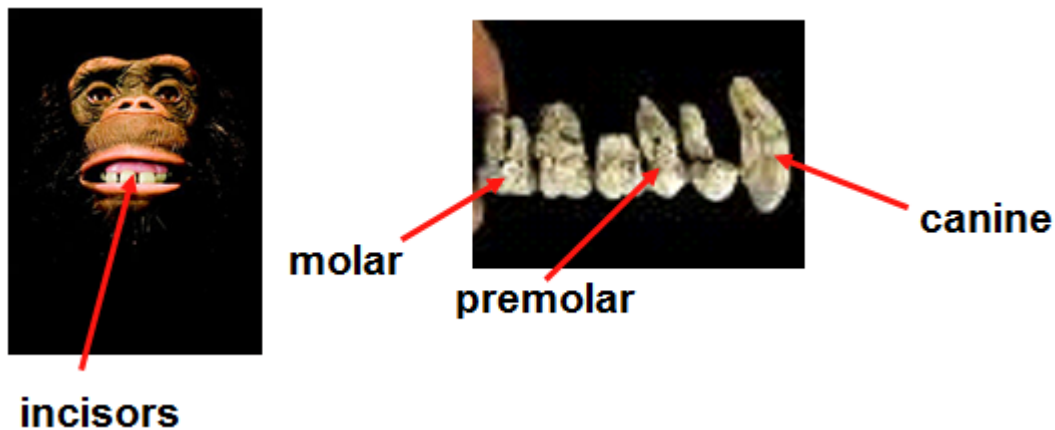
- Based the information presented above, what diet type do you think is represented by the animal in Figure 1.1?

If your answer to the previous question was "carnivore," you are right!

In this exercise, you will examine skulls of several animals, and see what kind of information you can obtain about the animals from which they came, based on what you've learned about teeth so far.

- In your box, you should now locate a series of skulls (numbered 1-11) that have different dentitions (numbers and shapes of each tooth type).
- Your job is to determine the diet of each of the animals represented by the skulls in the trunk.

- Each skull with most of its teeth intact is numbered so that you can look up the correct answer (diet) on the answer sheet at the end of this book.
- Try to make your determinations before looking up the answer, and see if you can guess the type of animal that each skull belonged to, as well.
- Construct a table like the one below, with numbers 1-11. Fill in your guesses for the diet type of each numbered skull, as well as your guess for what type of animal each skull represents.
- After you have made your guesses, check the answers at the end of the book, and fill in the rest of the table with the correct answers for each skull.

Skull Number	Your Guesses		Correct Answers	
	Diet Type	**Animal ID**	**Diet Type**	**Animal ID**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				

Exercise 2: Dental Formulas

Exercise 2a: Dental Formulas (*Version for grades 1-3*)

Materials:
- o Provided carnivore skulls (#3, #4, & #9)
- o Provided herbivore skulls (#2, #5, #6, & #11)
- o Provided omnivore skulls (#7, #8, & #10)
- o Plain paper, graph paper, rulers, & pencils

NOTE TO TEACHERS: We have not provided counters (cm cubes, plastic disks, buttons, beads, etc.). If you have them in your classroom, these will be useful in providing your students a more concrete graphing experience in this exercise!

All mammals have teeth, with the exception of mammals that lay eggs (i.e., the duck-billed platypus), anteaters, and some whales. You learned in Exercise 1 that mammals have a variety of tooth types that include *incisors* for cutting, biting, nibbling and stripping, *canines* for grabbing, piercing, and tearing, *premolars* for grinding, crushing, and slicing, and *molars* for grinding and crushing. Mammalian species typically have a unique number of each of these tooth types, though in a few species, these numbers differ with the sex of the individual or age. (Think about human teeth.)

You are going to look at the dentition of different adult animals in this exercise and will count and compare the numbers of the different types of teeth present in each species. The information you gather will allow you to answer questions like: Do flesh-eating mammals (carnivores) have more or less incisors than other types of mammals? Do vegetation-eating mammals (herbivores) have more or less canines than other types of mammals?

Before you begin your investigation, you need to know something about creating a **frequency table**. A frequency table is a type of chart that helps you keep up with your counts of the types of teeth each species has. This table keeps all of your information in a single place and in a form that makes it is easy to read and understand. The information you collect in this frequency table can be used in creating a visual display of your tooth counts as well. **Graphs** are visual displays of information. Instead of writing about how many of a certain type of

teeth you find in words and sentences, a graph provides a picture of your information that is all in one place and easy to read.

- Look at the frequency table below.

Individual	Number of cat's- eye marbles
Bob	2
Susan	16
Meg	32
John	20

Each person listed in the table was given a bag of marbles. Each of the four people had some cat's-eye marbles in his or her bag, but not everyone had the same number of cat's-eye marbles in their bags. The frequency table was created to show how many cat's-eye marbles each person had in his or her bag. The number of cat's-eye marbles each person had is indicated by the number in the table. If you put all the cat's-eye marbles together in one group, the total number of cat's-eye marbles is 70.

- If you have counters available to you, count out 70 counters and divide them into piles that show the number of cat's-eye marbles Bob, Susan, Meg and John had.

You know that Bob only has 2 cat's-eye marbles in his bag, so we can say he has 2 out of 70 (which we can also represent as 2:70, or 2/70), because he has 2 cat's-eye marbles, and there are 70 cat's-eye marbles total. You also know that Meg has 32 cat's-eye marbles in her bag, which is a lot more than Bob had in his bag. We can say that Meg has 32 out of 70 cat's-eye marbles (which we can also represent as 32:70, or 32/70), because 32 of the total 70 cat's- eye marbles were in Meg's bag. Bob has a very small number of the total group, while Meg has a much larger number of the total number of cat's-eye marbles. Or we can say that Bob has a small **proportion** of the total number, and Meg has a much larger **proportion** of the total number.

- Now answer the following questions:
  - How many more cat's-eye marbles does Meg have than Bob?
  - How many fewer does Susan have than John?
  - How many fewer marbles does Bob have than Susan?

You are now going to create two types of similar graphs of the information in the frequency table using a plain sheet of paper, some graph paper, and a ruler.

- Using a ruler, draw a straight line along one side of a plain sheet of paper.
- Write the names of the four people listed in the frequency table below the line (see the example below).
- Following the example below, draw a column of circles (each representing a marble) above each person's name, until you have drawn, for each person, a number of circles equal to the number of cat's-eye marbles, that they have in their bag.
- **Note that the graph below has only been started for you as an example, so your completed graph will have more circles on it!**

| Bob | Susan | Meg | John |
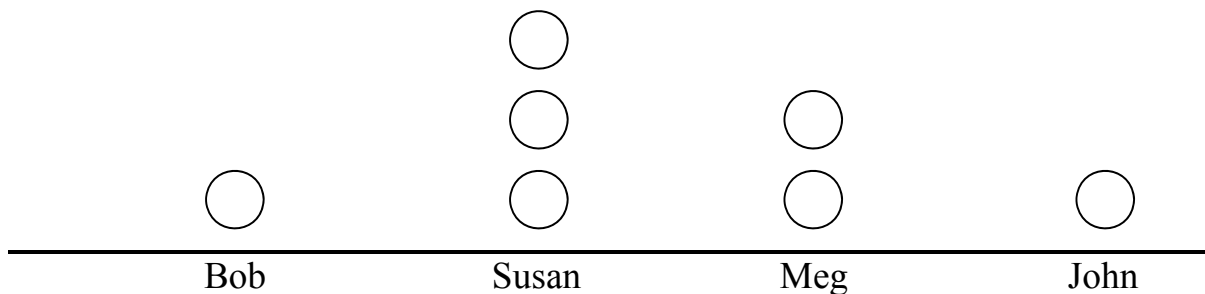
You have just created a graph of the information given to you in the frequency table showing the number of cat's-eye marbles each person has. The table provides the information for us, while the graph gives you a *picture* of the information rather than explaining the information to you in words and sentences. We sometimes call the type of graph you created a **pictograph**, because we are using circular drawings or pictures to represent each cat's-eye marble.

Instead of drawing circles (or using counters), we could also show the same information using a **bar graph**, which gets its name from rectangular bars drawn above a category (in this case, each person's name). In a bar graph, the length of a bar represents the number of something belonging to a particular category: in our case, the number of cat's-eve marbles in a particular person's

bag. An example of a bar graph (showing how much each person has saved to buy more marbles) is pictured below.

Dollars saved to buy more marbles

A bar graph titled "Dollars saved to buy more marbles" with a y-axis labeled from 0 to 33 in increments of 3. Bob is 12, Susan is 18, Meg is 30, and John is 9.
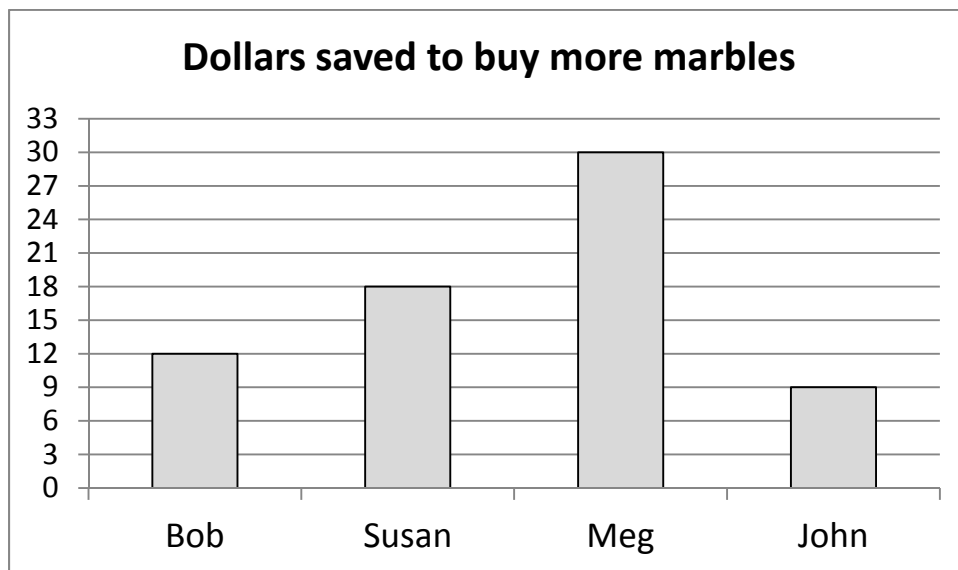
Let's also construct a bar graph representing the number of cat's-eye marbles owned by each person, using the following instructions:

- On a sheet of graph paper, write the names of each of the marble owners in a horizontal line near the bottom of the sheet.
- Above each person's name, draw (using the grid of the graph paper as a guide) rectangles to represent the number of cat's-eye marbles that each person has in his or her bag.
- If your graph paper does not have enough gridlines to represent the appropriate number of marbles owned by the person with the largest number of cat's-eye marbles, you could let each gridline represent a larger number of marbles. For example, you might use 2 marbles for every gridline of height. ***Just make sure if you do this, that you use this same relationship for constructing each of your bars! For example, in the bar graph above, each gridline of height of the bars represents $3.00.***
- Label your bar graph with an appropriate title.

Before we move on to counting teeth in skulls, answer this question: Could you make your pictograph of circles into a bar graph? If so how would you do it?

Counting teeth in a skull

In Exercise 1, you learned that mammals with different diets have different shaped teeth and that you could tell what an animal eats by examining these teeth for their shapes. Some animals eat only meat, and they are called **carnivores**. Some animals eat only plants, and they are called **herbivores**. Animals that eat only insects are called **insectivores**, and animals that eat a variety of foods, including meats and plants, are called **omnivores**.

In addition to have canines, incisors and molars that look different, animals that have different diets may have more of one tooth type than another. To look for these types of differences you are going to find out how many of each type of tooth is in each of several skulls given to you. Use the descriptions of the different teeth types on page 3, as well as the "Tooth Types" container from the box to help you decide the types of teeth in each skull. Pay close attention to the shapes of the roots (the part that fits into the jaw) and crowns, or tops, of the teeth, as well as the sizes of the teeth. As you learn about the different types of teeth, think about the following questions:

- o What kind of animal did the teeth come from?
- o How would the types of teeth it has help that animal process the food it eats?
- o How are the types of teeth in the skull related to the food that particular animal eats?

If you could draw a line through the middle of each skull from front to back, both sides of each skull would be very similar to each other. Each of the two sides will contain the same number of each different type of tooth. That is because the animal skulls are **symmetrical**. If an object or figure is symmetrical, or has **symmetry**, that means an imaginary line could be drawn down the middle of the object or figure so that if you could fold one side onto the other side they would match exactly with no gaps or overlaps. All the edges would meet together exactly.

- Find a picture of something that is symmetrical and see if you can fold so that all the edges would meet together exactly (e.g., a kite).

Look at the two figures below, one rectangle and one triangle. The dashed lines indicate lines of symmetry for each figure, because if the figures were folded

along the dashed lines, one side would fit right onto the other side without any gaps or overlaps.

- Select one of the carnivore skulls. Make a table similar to the one below so you will have a place to write down your data as you count types of teeth in the skulls.

Species			
Diet Type			
Incisors (upper jaw)			
Incisors (lower jaw)			
Canines (upper jaw)			
Canines (lower jaw)			
Premolars (upper jaw)			
Premolars (lower jaw)			
Molars (upper jaw)			
Molars (lower jaw)			
Sum			
2×Sum =Total			

- Create an imaginary line down the middle of each skull from front to back, which would be a line of symmetry for each skull. Count the number of incisor teeth on one side (one side of the imaginary center line) of the skull's upper jaw and write down the number in your table. If a tooth is missing from one side of a skull, look at the tooth in the same position on the other side of the jaw so you know what kind of tooth would have been in that position.
- Using that same imaginary center line, count the number of incisor teeth on one side of the skull's lower jaw and write down the number in your table.
- Repeat the previous two steps for canine, premolar, and molar teeth (first counting one side of upper jaw, then counting one side of lower jaw).

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- Count the total number of teeth on one side of the skull (including both upper and lower jaws) and record the number in the row labeled "sum" in your table. Alternatively, you can add up all of the numbers of the different types of teeth in both the lower and upper jaws that you already counted and recorded in your table.
- Repeat all of the above steps for an herbivore skull and an omnivore skull.

You will notice that the bottom row of your table says **2 x Sum = Total**. Since you only counted the teeth on one side of the skull, you are now going to take your counts and double them for a total number of teeth in the skull (since there are an equal number of teeth on the other side of the skull due to the animals' symmetry).

- Place those totals in the bottom row of the table. Now you have the total number of teeth for each skull, and you know which animal each skull belonged to.
- Using your table, answer the following questions:
  o For each animal, which type of tooth was the most numerous (had the largest number)?
  o Which type of tooth was the least numerous (had the smallest number) for each animal?
  o Why do you think the different types of animals had the numbers of each tooth types they had?
- Now compare the *total number of teeth* in each skull.
  o Which animal had the highest total number of teeth?
  o Which animal had the lowest total number of teeth?
  o Think about what kinds of food the animals eat and the number of teeth they have. Do you think the number of teeth they have is related to the kind of foods they eat?
- Look at the skull of at least one other carnivore, and collect the same information as listed above, and add this information to your table. You also may wish to examine all of the carnivore skulls in your box.
- Now answer the following question:
  o How do the numbers of different types of teeth compare to the numbers of different types of teeth in the first carnivore skull you looked at?

- Do the same with at least one other herbivore skull & one other omnivore skull.
- Now pick a particular tooth type.
- Make a bar graph showing the numbers of that particular tooth type found in each animal's skull. To make it easier for you to compare different diet types, you might wish to group all of the animals of each diet type together on the graph.
- Make separate bar graphs of the other tooth types, making sure to label each bar graph with an appropriate title.
- Use your table & bar graphs to help you think about the following questions:
  - Are there more of a certain type of tooth in the carnivore skulls than in the herbivore skulls?
  - Are there more of a certain type tooth in the herbivore skulls than in the omnivore skulls?
  - Do you see similarities of numbers of certain tooth types for one type of animal? For instance, do you see similarities in the number of molars for carnivores as compared to molars for herbivores?

Exercise 2b: Dental Formulas (*Version for grades 4 & up*)

Materials:
- Provided carnivore skulls (#3, #4, & #9)
- Provided herbivore skulls (#2, #5, #6, & #11)
- Provided omnivore skulls (#7, #8, & #10)
- Graph paper or plain paper

All mammals have teeth, with the exception of monotremes (egg-laying mammals such as the duck-billed platypus), anteaters, and certain whales. As you have already learned in the previous exercise, mammals have a variety of tooth types. These include incisors (I), canines (C), premolars (P), and molars (M). Refer back to the information on each tooth type, as well as Figure 1.1 on page 3 to refresh your memory to assist you with this exercise, if necessary.

A mammal's dental formula designates the number of each type of tooth found in its dentition. It provides one kind of **quantitative** (**Pronunciation:** 'kwän-t&-"tA-tiv) measure of the differences between individual animals, different

age or sex classes of the same species, different species, and animals having different feeding strategies or diets. In the Tooth Type exercise, you used your observational skills to assign a skull (representing an animal) to a feeding category. This is what is considered a **qualitative** (**Pronunciation:** 'kwä-l&-"tA-tiv) measure or approximation. Quantification, on the other hand, involves actual measurement, and provides for numerical and graphical comparison of two or more samples. We will use dental formulas in this exercise to quantitatively compare skulls that we have identified in Exercise 1 as having different diets.

Your specific goal in this exercise is to quantitatively compare the dental formulas for a flesh-eating mammal (carnivore), an insect-eating mammal (insectivore), a vegetation-eating mammal (herbivore) and a mammal that feeds both on plants and animals.

Before we do this, however, it is important to learn about frequency tables and graphs. A frequency table or chart presents the distribution of some item (e.g., cat's-eye marbles) according to some type of category (e.g., marble owners). The data presented in the table below were collected from four individuals, each of whom had a bag of marbles. If we count the cat's-eye marbles each person has, we can visualize the distribution of this type of marble among the four individuals by placing the marble counts/frequencies in tabular form.   As you can see in the table, Bob has very few cat's-eye marbles in his bag, and Meg has the most.

Individual	Number of cat's- eye marbles
Bob	2
Susan	16
Meg	32
John	20

It is easier to visualize relationships between frequencies or counts if these are relativized to some standard such as 1. A **proportion** is a number between zero and one that compares the size/weight/number etc. of things relative to the cumulative whole. In our marble example, the whole is the sum of all the cat's-eye marbles the four individuals have (70).   To be precise, the proportion of the whole that is the part is equal to the fraction

$$\frac{number\ within\ category}{number\ of\ the\ whole}.$$

Thus Bob has one of the 70 cat's-eye marbles, or 2/70 ≈ 0.03. Note that proportions are usually given in decimal form.

The new chart below displays the frequency data and this same information expressed as proportion of total cat's-eye marbles that belong to the individuals sampled. From this new column, we can easily see that Meg has almost half of the total cat's-eye marbles (½ = 0.50).

Individual	Number of cat's-eye marbles	Proportion of Cat's-eye marbles
Bob	2	0.03
Susan	16	0.23
Meg	32	0.46
John	20	0.28

It is easier to compare counts that are presented as proportions. It is even easier to compare values such as counts if these are presented graphically, in visual form.

- Examine the bar graph below that provides a visual representation of the proportion data from our table.

Distribution of cat's-eye marbles among individuals
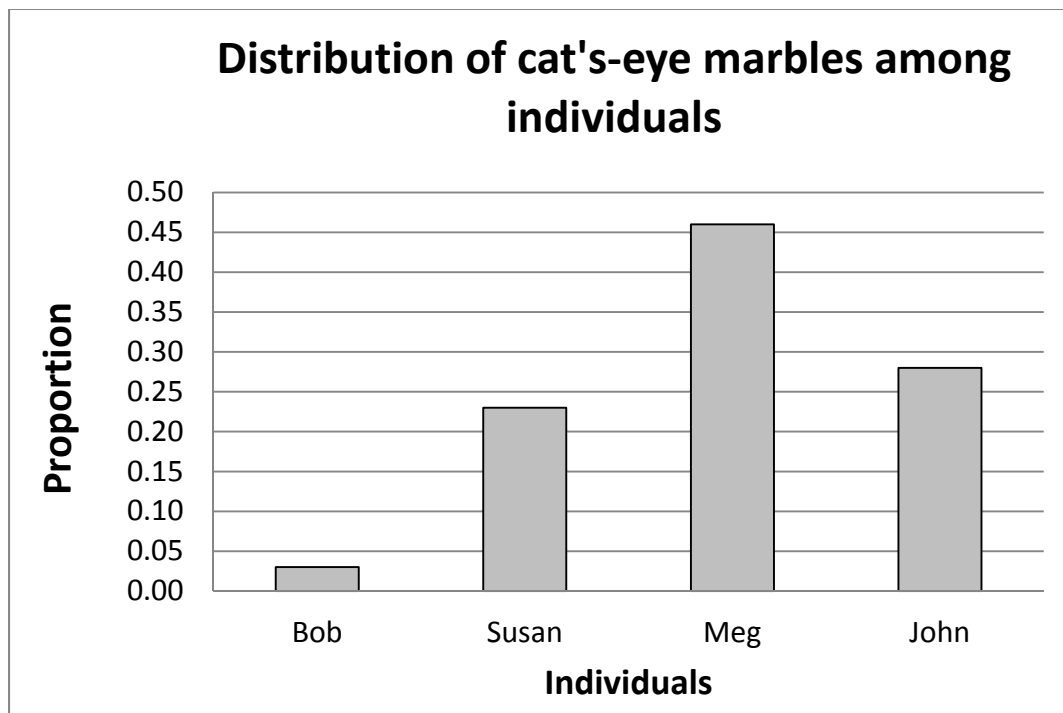
A bar graph consists of the following parts:

1. A **title** tells the viewer what the bar graph is comparing. At the top of every bar graph there should be a title.
2. The **y-axis** is the vertical axis. It measures the value of the quantitative variable. The y-axis should be labeled with the name of the quantitative variable.
3. The **x-axis** is the horizontal axis. It charts the value of the qualitative variable. The x-axis should be labeled with the name of the qualitative variable.
4. Each value that the qualitative variable may take has its own bar. Along the x-axis, each bar should be labeled with the value of the qualitative variable to which it belongs.
5. The height of each bar tells us the value that the quantitative variable takes when the qualitative variable takes the value associated with the bar. To find this value, draw a horizontal line from the top of the bar to the y-axis. The number on the y-axis that this line hits is the value of the quantitative variable. Note that if this line falls between two tick marks on the y-axis, then you will need to estimate the value of the quantitative variable.
6. The example marble graph is a special type of bar graph called a relative frequency bar graph. A relative frequency bar graph displays proportions rather than absolute numbers.

- **Answer the following questions about the bar graph on the previous page:**

    Q1. What is the title of the marble example bar graph?

    Q2. How is the y-axis labeled in the figure?

    Q3. How is the x-axis labeled in the figure?

    Q4. List all the values that the qualitative variable (category) takes in the marble figure.

    Q5. Use the table to determine which two individuals have the closest to equal proportions of cat's-eye marbles.

Now you are ready to turn your attention to quantifying the differences among skulls of each of the three feeding strategies (carnivore, herbivore, and omnivore) that we are interested in comparing.

- Select a skull of each diet type (carnivore, herbivore, and omnivore).

To find the dental formula for a skull, you must first count how many teeth of each type are in the skull. Because both sides of the skull should contain the same number of each tooth type, you will only need to count the teeth in one side of the skull.

Note that some teeth may be missing in your skulls. You can determine what type of tooth once filled the hole by looking at the tooth in the same position on the other side of the jaw. Right and left sides should be symmetrical, or mirror images of each other. This is because all higher animals (except the echinoderms) are bilaterally symmetrical. That is, the body can be divided into two identical halves along a central longitudinal axis (Figure 2).

Figure 2. Bilateral symmetry is characteristic of the higher animals. The midline drawn on this face from top to bottom produces two identical halves (two lateral sections).

<u>How to find the dental formula for a skull:</u>

- Select one skull from a carnivore, one skull of an herbivore, and one skull of an omnivore.
- Make a table similar to the one below, and fill it in with the data you collect on each skull examined.

Step 1: Pick one of the skulls that you have selected, and count the number of incisors on one side of the skull's upper jaw, and record the result in your table.

Step 2: Count the number of incisor teeth on one side of the skull's lower jaw, and record the result in your table.

Step 3: Repeat steps 1 and 2 for canine, premolar, and molar teeth.

Step 4: Complete the calculations indicated in the last two rows of the table to determine the total number of teeth each skull has.

Step 5: Repeat steps 1-4 for the other two skulls of the other diet types.

Species			
Diet Type			
Incisors (upper jaw)			
Incisors (lower jaw)			
Canines (upper jaw)			
Canines (lower jaw)			
Premolars (upper jaw)			
Premolars (lower jaw)			
Molars (upper jaw)			
Molars (lower jaw)			
Sum			
2×Sum =Total			

The number you arrive at for each skull in the bottom row of the table is equal to the total number of teeth it has.
- Record your formulas, along with the identity of each mammal you in your table, and then check your formulas against those provided in the accompanying answer key under **Exercise 2: Dental Formulas.**
- Compare the differences in the total number of teeth in each skull. Which one has the highest number? Which one the lowest number? Is the difference in total tooth number related to the difference in diets?
- For each of the diet types, determine which type of tooth was the most common. How could you use these materials to better delimit (determine) whether the differences in most common tooth type reflect dietary adaptations or some other causation (e.g. differences in animal size)?
- If you guessed counting the teeth of additional representatives of each diet type, you are a scholar.
- Count the teeth of additional skulls of each diet type, recording the dental formula for each of them as you did above. Check your results on the table in the answer section of the book when you are finished.

- Investigate the relationship between an animal's diet and the types of teeth the animal has by making a bar graph or series of bar graphs similar to the marble distribution example. Be sure to make a frequency table first for each question you wish to explore.

Q7. Why is it more meaningful to compare the proportion of teeth of a species that are molars than it is to compare the absolute number of molars within a skull if our goal is to understand the relationship between an animal's diet and its teeth?

You might wish to present more than one quantitative variable or trait on a graph. It would resemble the graph shown on the following page, which displays the values of two quantitative variables measured in the same scale. Note that if you add a second qualitative variable to your graph you will also need to include a **legend**, which illustrates how the data representing each quantitative variable is portrayed on the graph. The legend is circled on the graph below to give you an example of how to construct a legend for your graph.

Example of a bar graph incorporating more than one quantitative variable.
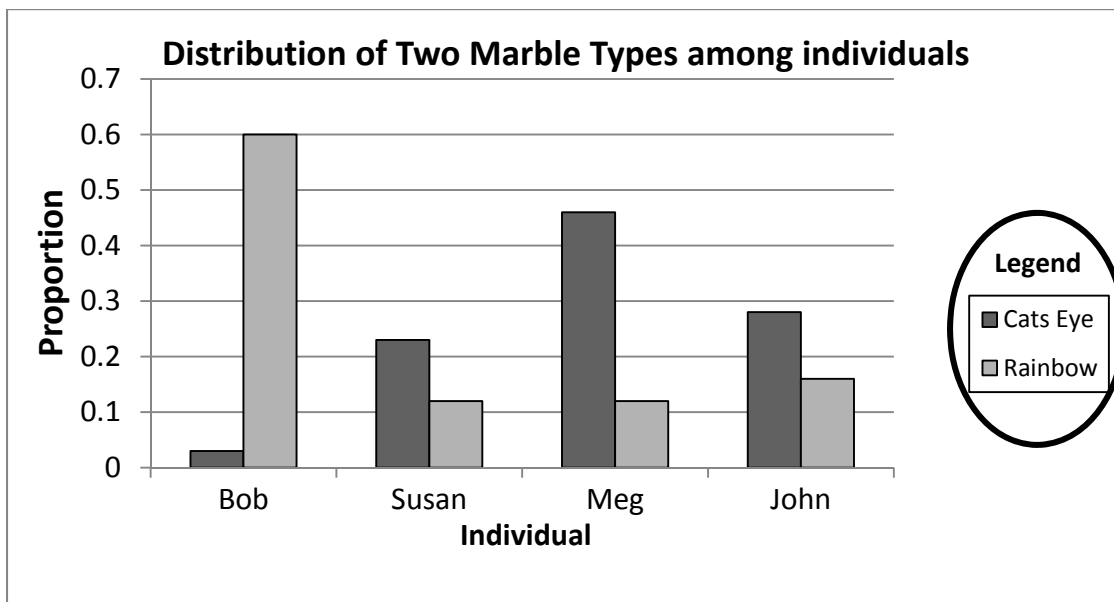
Exercise 3: Morphometrics: Shape has Meaning

Exercise 3a: Morphometrics: Shape has Meaning (*Version for grades 1-4*)

Materials:
- o Provided carnivore skulls (#3, #4, & #9)
- o Provided herbivore skulls (#2, #5, & #6)
- o Several strips of plain or construction paper, cut lengthwise, all approximately the same width (24 strips per student or group)

Morphometrics is the study of the shape of organisms. Morphometrics is used to describe species and their relationships to other species, as well as to understand how an individual species can vary in the shapes and sizes of its members.

In this exercise, you are going to look at the skulls in the box and think about how the size and shape of each skull is related to that animal's feeding role. The skull is only one part of the whole animal skeleton, and the skull's purpose is to protect the brain. Thus, before you examine the skulls provided in your box, you should take some time to think about the rest of the skeletal system present in many animals. If you look at the diagram of the skeleton on page 25, you see that there are many parts of a skeleton. Each part of the skeleton has a purpose.

- Look at the skeleton diagram and think about what each part does for the animal, and answer the following questions:
    - o What do you think is the reason for having ribs?
    - o What do you think is the purpose for the tibia and the femur?
    - o What about the other labeled parts of the skeleton?
- Talk with others and see if you agree on the functions of different skeletal parts. Did any of you have different ideas on how particular parts of the skeletal system might be useful?

Now you are going to take a closer look at the animals' skulls and see if the size and shape of the skulls are related to the feeding role of the different animals. For this activity, you are only going to look at the carnivore (meat-eater) skulls and the herbivore (plant-eater) skulls since there are several of each type of skull in the box.

- Pull out all the carnivore and herbivore skulls, putting all carnivore skulls together and all herbivore skulls together.
- Now examine one of the carnivore skulls, and describe its shape. To help you with this, consider the following questions:
    o Is it rounded like a baseball, or oblong like a football?
    o Are the jaws big compared to the rest of the skull, or are the jaws small compared to the rest of the skull?
    o Is the braincase (the part that actually holds the brain) small compared to the whole skull or large compared to the whole skull?
- Now look at another carnivore skull and answer the same questions about the second skull, and answer the following questions:
    o Are the two carnivore skulls similar in any way?
    o How are they different?
- Continue to compare all the carnivore skulls to see if you can find characteristics that are similar for all the carnivore skulls.

Now you are going to take a few measurements that you can use to describe the skulls **quantitatively** (with numbers).

- Lay a skull on a strip of paper so that one end of the paper is at the outermost edge of the front of the skull.
- Make a mark on the paper to indicate the outermost edge of the back of the skull. Cut the paper strip at the mark.
- Label the strip with the animal name and write "skull length" on it as well
- Do the same with another strip of paper to measure the skull from side to side by the **brain case** (cranium), putting the end of the paper strip is at the outermost edge of one side of the skull, and make a mark to indicate the outermost edge of the other side of the skull.
- Cut the paper strip at the mark.
- Label the strip with the animal name and label it also as "skull width."
- Put the two strips side-by-side and set aside.
- Do this same exercise with each skull, being sure to label them correctly with the animal name and indicating "length" or "width" on each strip.

- When you have completed measuring all carnivore skulls, lay out the pairs of strips for the skulls so that each animal's skull width and length are side-by-side.

Now that you have examined the overall sizes of the carnivore skulls in terms of length and width, you should examine the teeth on each skull. You will also take some measurements of each skull's teeth, which you will use to later compare (along with skull length and width) to the skulls of animals with a different diet (herbivores). More specifically, you will measure the tooth row lengths of these skulls, on both their lower and upper jaws.

- Put the end of the paper at the back edge of the tooth farthest back in the row of teeth in the lower jaw and measure the length to the front of the tooth row (front of the mouth).
- Make a mark on the paper to show the front end of the tooth row and cut the paper at the mark.
- Label the strip of paper with the animal name and "lower tooth row."
- Using another strip of paper, do the same thing for the upper jaw tooth row and label it with the animal name and "upper tooth row."
- **Now complete the same activity for all the herbivore skulls, being sure to label each strip with the animal name and the part of the skull the strip represents.**
- When you have completed measuring all herbivore skulls, lay out the pairs of strips for the skulls so that each animal's skull width, length, and tooth row strips are all side-by-side, and keeping the group of carnivore strips and the group of herbivore strips separate.
- First, look at the strips for the carnivores. Do you notice anything about the way the skull widths and lengths compare?
- Also compare the lengths of the upper and lower tooth rows of each skull to the lengths and widths of the skulls on which they were measured. Do you notice any trends here?
- To assist you with these questions, think about how you initially described the shapes of each of the skulls with words, and compare these descriptions to your actual measurements depicted by your strips.

- Now look at the strips representing your measurements for the herbivore skulls, and answer the same questions you answered above for the carnivores.
- Now that you have described the shapes of your carnivore and herbivore skulls both qualitatively (with words) and quantitatively, compare your overall descriptions of the skulls of one diet type to the skulls of the other diet type, and try to answer the following questions:
    - Do you notice any similarities in skull shapes between diet types?
    - What about differences? Are there aspects of skull shape that appear to differ in carnivores and herbivores?
    - How do you think these differences might relate to the diet type and lifestyles of these animals?
    - Why might a particular shape be important to an animal of a particular diet type?

**Exercise 3b: Morphometrics: Shape has Meaning** (*For grades 5 & up*)

Materials:
o Carnivore skulls (#3, #4, & #9)	o Vernier calipers
o Herbivore skulls (#2, #5, & #6)	o Container with BBs
o Rulers & protractors	o Graduated cylinder

Morphometrics is the quantitative analysis of the shape of organisms. It thus is an integral component of many evolutionary, ecological, and developmental studies in biology. Morphometrics is important to taxonomists and systematists, who use the physical characteristics of individuals to describe species and their relationships to other species. These techniques are also applied to the patterns of shape variation within and among samples (life stages, populations, species, ecological equivalents, etc.). This permits the development and testing of hypotheses as to the origin of noted patterns of variation. For example, quantifying skull morphological variation might help us to understand the function of various traits with respect to the ecological role of the species being examined.

Here we are interested in the feeding role of the animals represented by the skulls available to us. Remember that the skull is part of the skeleton of a mammal and is designed to protect the brain.

- Examine Figure 3.1 below, identifying the parts of a skeleton. See if you can come up with the functions of these various parts.
- Share your ideas with others and see if there is general agreement about the functions you have assigned to different parts of the mammalian skeleton.

Figure 3.1. A generalized mammal skeleton.
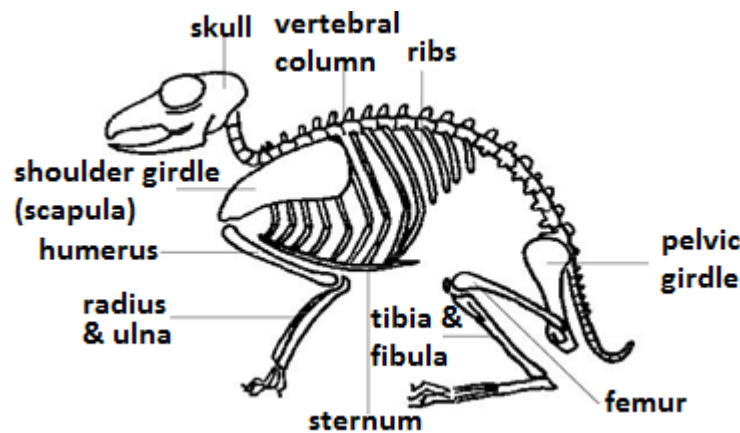
Your task in this exercise is to determine whether tooth shape or the skull characteristics you choose to examine reflect an animal's feeding role, merely reflect its size, or have no significance at all. Specifically, we will compare carnivores to herbivores, the two skull types for which we have multiple representatives.

- Sort your mammalian skulls and pull out all of the the carnivores and herbivores.
- What we need to do is complete the same measurements on all skulls of each category, so that we have sufficient data to detect a pattern as to whether particular traits differ between the two feeding strategies: carnivory and herbivory.
- You will use the Vernier caliper in taking most of your measurements. (A ruler may be needed to measure skull length in the case of some of the larger skulls). Learn how to use a Vernier caliper using the information and Figures 3.2 and 3.3 below before starting this exercise.

The Vernier caliper is a measuring device that can be used to measure an object's outer diameter, inner diameter, and length, as well as the depth of a hole.   It gives an additional decimal of precision over the standard ruler. The Vernier caliper consists of the following parts:

- The large lower jaws, used to measure the outer diameter or length of an object.
- The small upper jaws, used to measure the inner diameter of an object.
- The sliding metal bar, which is used to measure the depth of a hole.
- The stationary scale.
- The Vernier or moveable scale.

Figure 3.2. Parts of a Vernier caliper.
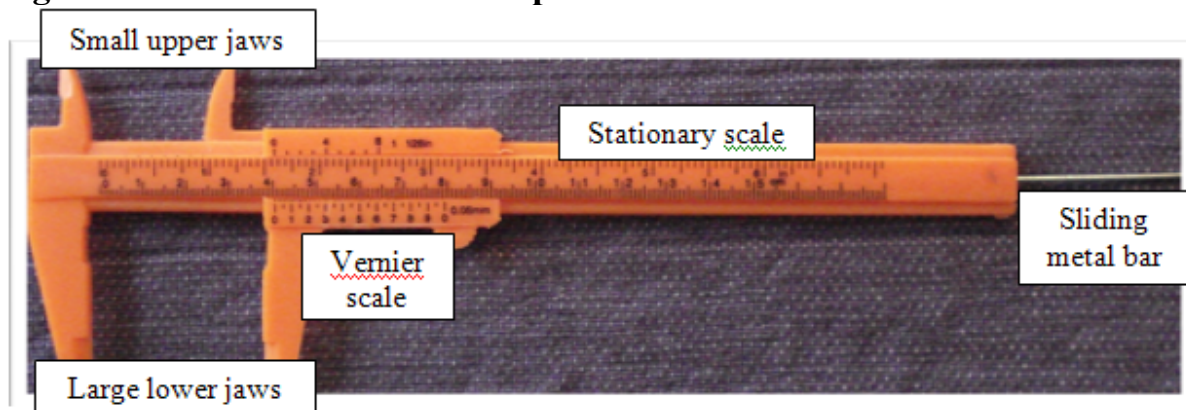
How to measure the length of an object with the Vernier caliper:

1. Fit the object to be measured securely between the lower jaws of the caliper.
2. The zero mark of the Vernier scale marks the length of the object on the stationary scale to the nearest tenth of a centimeter (mm). This value is between 4.0 cm and 4.1 cm in the picture, so the first decimal place is a 0, because it does not quite meet the 4.1 cm mark.
3. Now find the first line of the Vernier scale that exactly corresponds to a line of the stationary scale. The number of this line gives the second decimal of the object's length. In the figure below, the first line that exactly matches is the line labeled 5, so the length of the object is 4.05 cm.

Figure 3.3. Measuring an object using a Vernier caliper.

- Scientists use the metric system in making measurements, so record all of your measures in centimeters (10 mm = 1 cm) with one significant digit (e.g., the length of the rock in the picture is 4.1 cm with one significant digit).
- In order to account somewhat for inter-observer differences, scientists have more than one person measure each character for each specimen. You should have at least three individuals make each measurement you decide to complete.
- Compute the mean value of the measurements of each character and use that value in subsequent analyses. The mean value refers to central tendency. The formula for calculating the mean for total skull length is:

$$\text{TL}_{\text{mean}} = \Sigma X / n$$

where Σ (the Greek letter sigma) means the sum, X = each of the three values (X_1, X_2, X_3), and n = the total number of measurements of this trait (3 in this case). If the three measurements of skull length were 19.5, 19.8 and 20.1, $\text{TL}_{\text{mean}} = (19.5 + 19.8 + 20.1)/3$ or $\text{TL}_{\text{mean}} = 19.8$ for the particular skull.

A series of measurements that you might make on the skulls (List A) and teeth (List B) can be found on the following pages. You may choose other measures not on either of these lists if you would like . Consult the drawings presented in Figure 3.5 to locate particular measurements.

- Choose some subset of the measurements to complete. **You must, however, include total skull length (Figures 3.5c and 3.5d) in the measurements**

you make on the skulls. This is because we will use total skull length as a measure of overall size. General body size tends to confound patterns we wish to examine in other traits: larger animals would tend to have larger values for all traits you might wish to measure. Thus, although a larger bird may have a longer beak than a smaller bird, the smaller bird may actually have a relatively greater beak length if its beak makes up a greater proportion of overall skull length. We will factor out the effects of overall size by expressing the value of each trait as proportional to overall body size (measured as total skull length in this case). Thus, we will compute the ratio: trait value/total skull length. This technique is called **ratio standardization**.

- As you take these measurements, construct a table on a sheet of paper. Across the top (columns of the table), list the traits (e.g., total length, snout length snout width, total tooth row length). Down the side (rows of the table), list the skulls grouped by type as in carnivore species (e.g., bobcat, skunk, coyote) followed by herbivore species (e.g., deer, rabbit, beaver). Insert your measurements in the respective cells as you complete them. An example of such a table (Table 3.1) follows Lists A and B. Note that you will need to add additional rows for characters that require calculation using the measurements you have taken (e.g., for the area of the foramen magnum for which diameter would be measured and recorded. Area determination requires applying the formula for a circle, πr^2, where $\pi =$ pi (**pronounced pie**) ≈ 3.14 and the radius r = diameter/2.

<p style="text-align: center;">**List A: Skull Measurements**</p>

*Must Do: **Total (greatest) skull length** (Figures 3.5c & 3.5d).

- Select additional measures from following and/or add your own:

1. Palate length: distance from G to a point equidistant from (midway between) A and E in Figure 3.5a.
2. Maximum palate width: distance between C & D (Figure 3.5a)
3. Minimum palate width: distance between A & E (Figure 3.5a)
   The above measurements on the palate might be combined in calculating palate area as a trapezoid, triangle etc.
4. Foramen magnum diameter: distance between B & F (Figure 3.5a)
   This measure could be used in calculating the area (size) of the spinal cord.
5. Snout (nasal) width: (Figure 3.5c)
6. Snout (nasalia) length: (Figure 3.5d)
   Multiply nasal width by length to get another estimate of snout or rostrum size.
7. Interorbital breadth (Figure 3.5c) can be used as an estimate of the degree to which the eyes face forward versus to the side.
8. Biorbital breadth (Figure 3.5c)
   Subtract interobital breadth from biorbital breadth and divide by 2 to obtain an estimate of eye size.
9. Measure the volume (height x length x width) of the tympanic bulbs (H in Figure 3.5a).
10. Measure the height of the sagittal crest (ridge for muscle attachment) at the midline of the top of the skull (Figure 3.5c).
    May be absent in some and recorded as 0 mm
11. Measure the length, width and height of the cranium (Figures 3.5c & 3.5d).
    L X W X H will provide a rough estimate of brain size (volume).
12. For a more accurate measure of brain size, fill the chamber with BBs using a funnel extended into the foramen magnum (opening) at the base of the skull (between B and F on Figure 3.5a). **(You will need to plug nerve holes with cotton before pouring the BBs in, and be sure to place the skull in the plastic tub while making this measurement to avoid BB spills.)**
    - Pour these BBs that filled the cranium into the graduated cylinder and record the volume in milliliters (mL) that these take up. Note that you

may have to fill the cylinder more than one time to obtain the volume estimate for the larger brains.
- • Be sure to return all of the BBs to the storage container when you are finished making this estimate.

List B: Suggested Tooth Measurements. Consult Figures 3.5 & 3.6.

1. Total tooth row length for mandible (lower jaw): (Figure 3.5b)
2. Molar tooth row length for mandible (lower jaw): (Figure 3.5b)
3. Total tooth row length for maxilla (upper jaw): distance between E & I (Figures 3.5a & 3.6)
4. Molar tooth row length for maxilla (upper jaw): distance between I & J (Figures 3.5c & 3.6)
5. Record the geometric shape of the surface of a representative tooth of each of the four types of teeth (e.g. triangle, rectangle, square) present in the upper versus lower jaws of each skull. Measure the appropriate dimensions while looking down on this surface, and calculate the area.
6. Using the protractor provided, measure the angle from the cusp (tip) (highest cusp in case of molars) to base of the tooth for the teeth measured under #5.
7. Measure the parameters needed to complete the volume estimates shown below for a representative tooth of each of the four tooth types that might be present (incisor, canine, premolar, molar) from #5.
8. Number of cusps (points or ridges) on top surface of representative tooth of each of the tooth types on maxilla (upper jaw)
9. Number of cusps (points or ridges) on top surface of representative tooth of each of the tooth types on mandible (lower jaw)

Figure 3.4. Calculating volumes of various shapes.
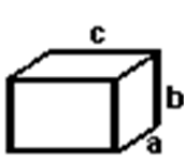
'molar'   'incisor'   'canine'

$V_{rectangular}$ **prism = a×b×c** V_{cone} **= 1/3 $\pi r^2 h$,** where π (pi) = 3.14

Table 3.1. Example table of measurements.

Measurement	Carnivores			Herbivores		
	bobcat	coyote	mink	beaver	deer	porcupine
Total skull length						
Foramen magnum diameter						
Foramen magnum area						
Nasalia length						
Nasal width						
Snout size						
Mandibular Tooth row length						
Mandibular Molar tooth row length						
Representation of molars in mandible *(MTL/tot TL)*						
etc.						

Figure 3.5. Views of skulls showing location of measurements suggested in List A and some from List B.
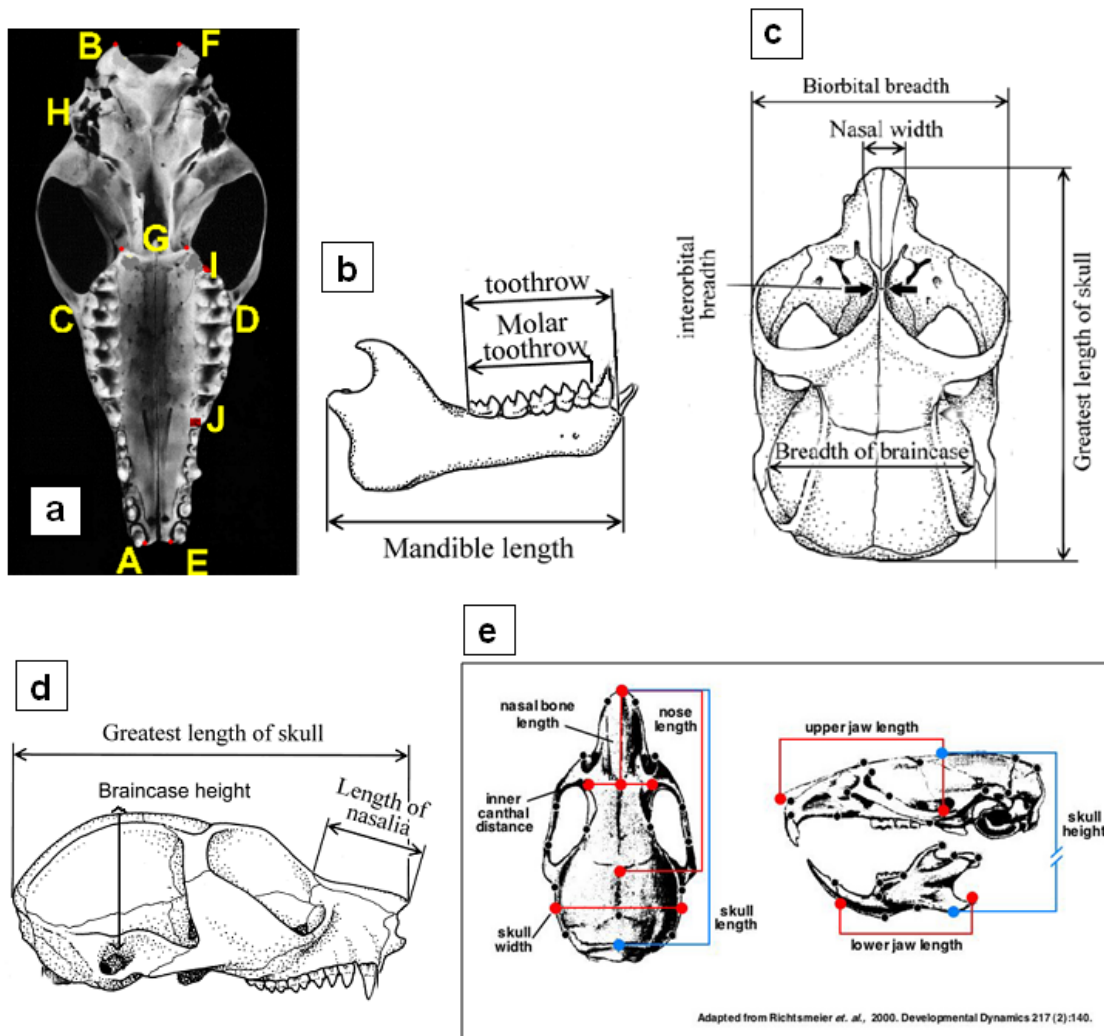
Figure 3.6. Ventral view of skull showing positions and shapes of tooth types.

■ Incisors (I) ■ Canines (C) ■ Premolars ■ Molars
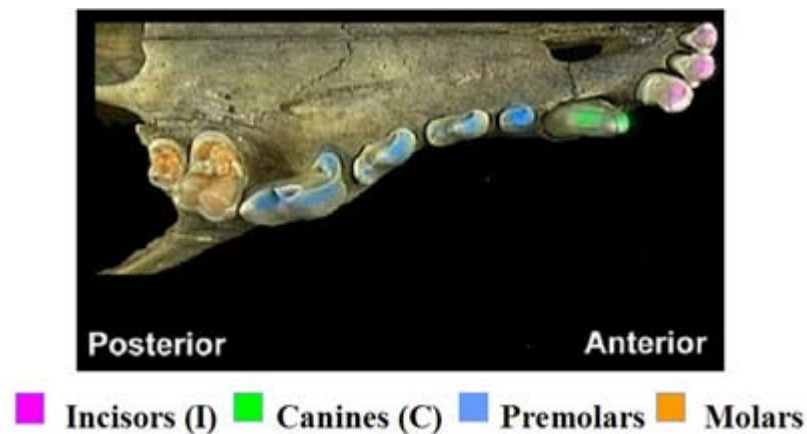
Analyses

- Now that you have collected a number of measurements on the two categories of skulls, you need to summarize your data in some way. It is very difficult to identify patterns without organizing and reducing your data.
- We will use linear functions to help us organize this data. A few facts about linear functions are summarized below. If you are already familiar with linear functions, then you may skip the next section.

Linear Functions:

A linear function is a function of the form $y = mx + b$. Where m and b are real numbers. The number m is called the slope of the line. The number b is called the y-intercept of the line. The graph of a linear function is a line. We say that a point (x_1, y_1) is on the line if $mx_1 + b = y_1$.

Q1. Check to see if the following points are on the line $y = 3x + 4$
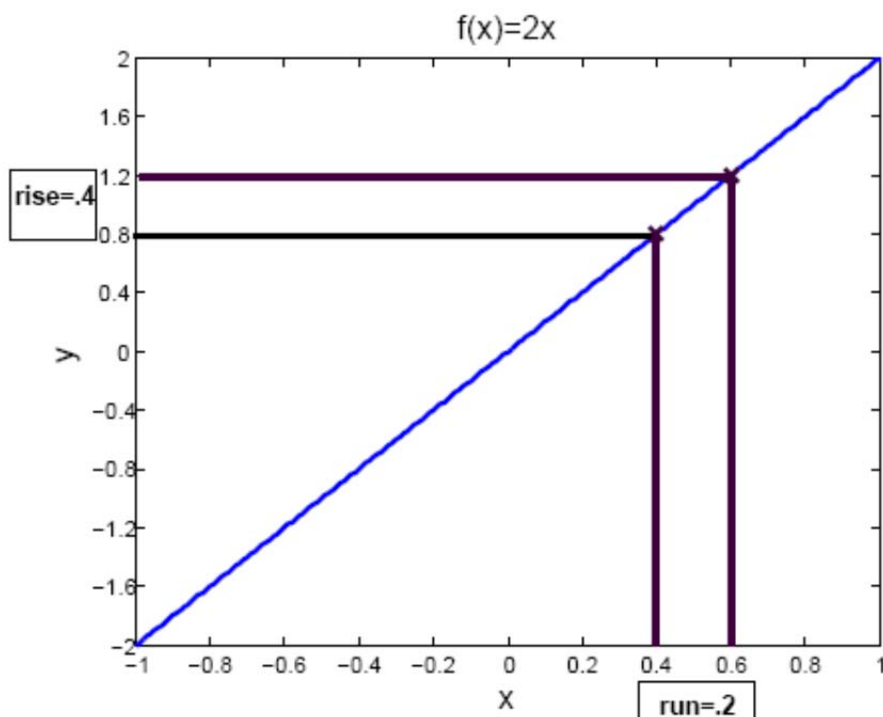- $(1, 8)$
- $(2, 10)$

The slope m tells us how the value of y changes with the value of x. The slope is equal to the change in y divided by the change in x, that is the rise over the run.

$$m = \frac{\text{rise}}{\text{run}}$$

This definition is illustrated in Figure 3.7 on the next page.

Figure 3.7. Illustration of the slope of a line.

f(x)=2x

Q2. Find the slope of the line in the figure.

If (x_1, y_1) and (x_2, y_2) are any two points on the line then the slope of the line is:

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

If m is positive, then as x gets bigger so does y. If m is negative, then as x gets bigger y gets smaller.

Because the slope is the quotient of the change in y divided by the change in x, it is measured in $\frac{y \text{ units}}{x \text{ units}}$. For example, if the y-axis of a plot is measured in miles and the x-axis of the plot is measured in minutes, then the slope of a line on the plot is measured in $\frac{\text{miles}}{\text{min}}$.

The y-intercept b is the value that y takes when x is zero. This means that the point $(0, b)$ is on the line.

Q3. What is the y-intercept of the line $y = 3x + 4$?

The formula $y = mx + b$ is called the **slope-intercept** formula for the line. If (x_1, y_1) is any fixed point on the line $y = mx + b$, then given any other point (x, y) on the line we have that

$$m = \frac{y_1 - y}{x_1 - x}$$

This is called the **point-slope** formula for the line.

Q4. Suppose that a line has slope $m = 2$ and that the point $(2, 7)$ is on the line. Write down the point-slope formula for the line.

Super Solver Question

Q5. Find the slope-intercept formula for the line in **Q4**.

Analyses (continued)

The graphs below are examples of scatter plots. Scatter plots are used to explore possible relationships between two variables (traits in our case) that both relate to the same phenomenon (skull length/brain volume in mammals). By convention, the independent variable (if one is identified as such) is positioned on the x-axis, and the dependent variable (the trait you are questioning) is placed on the y-axis. You should place skull length on the x-axis, because of the fact that you will use it to standardize (normalize) the other traits measured for size.
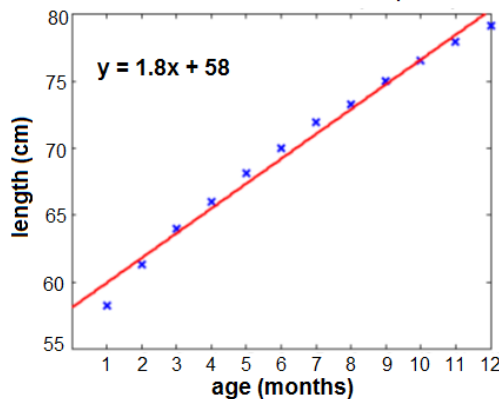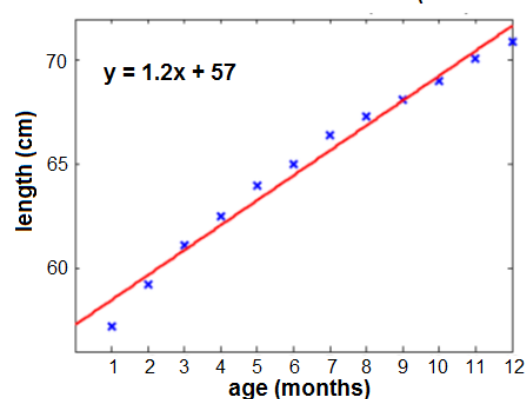
In each figure above, body length is plotted against infant age. We used Matlab to draw the 'best fit' line through the scatter plots. The equation of the best fit

line is also displayed on each plot. The closer the points are to this line, the better the fit, and the stronger the relationship between the two variables. For example, in the scatter plots on the previous page, it looks like the relationship between body length and age is very strong in both Chinese and American infants. If many of the points lie very far from the line there is probably no correlation (relationship) between the traits. If the data points in the figure cluster in a band from upper left down to lower right, then the two traits are **negatively correlated** (i.e., as age increases, length decreases). In this case the slope of the best fit line is negative.   If the points cluster in a band running from lower left to upper right as seen in our figures, the two traits are **positively correlated**, and the slope of the best fit line is positive. Thus older female infants tend to have longer body lengths than younger female infants.

What else can we see from the figures? Body length in both American and Chinese female infants is correlated with age. However, the data points for American females tend to lie above those for Chinese females. This is reflected in the fact that the best fit line for the American data lies above that for the Chinese data. This suggests that American female infants are, in general, longer than Chinese female infants. Why might this be the case?

Q6. Record the slope of the best fit line for both the American and Chinese infant growth data. Which best fit line has the largest slope? How would you interpret this fact?

Q7. Record the y-intercept of the best fit line for the Chinese and American infant growth data. Which data set has the smallest y-intercept?   How would you interpret this fact?

- For each trait that you have measured, make two scatter plots, one for herbivores and one for carnivores, plotting the trait's value versus the skull length.   Label the x-axis skull length and the y-axis according to the trait that you are plotting.
- Draw a line through your data points so that as many points as possible are as close to your line as possible. (There is a statistical procedure to find the actual 'best fit' line for your data, but for our purposes your best guess will suffice.) The line you have drawn is described by a linear equation of the form

$$y = mx + b$$

In the equation on the previous page, the slope of the line is represented by m, and the y-intercept of the line is represented by b.

- Find two points on your line, (x_1, y_1) and (x_2, y_2). These points need not be data points. They just need to fall on your line.
- Calculate the slope, m, of your line using the formula $m = \frac{y_2 - y_1}{x_2 - x_1}$.

Example: If the points (2,4) and (4,9) both fall on the line then the slope of the line is

$$m = \frac{9-4}{4-2} = \frac{5}{2} = 2.5.$$

- Use the point slope formula, $m = \frac{y_1 - y}{x_1 - x}$, where (x_1, y_1) is one of the points on your line to determine the value of b.

Example: Assuming that the points (2,4) and (4,9) fall on the line we found that $m = 2.5$, and so the point slope formula becomes

$$2.5 = \frac{y - 4}{x - 2} \rightarrow$$

$$2.5(x - 2) = y - 4 \rightarrow$$

$$2.5y - 5 = y - 4 \rightarrow$$

$$2.5x - 1 = y$$

So for this example, we see that $b = -1$

- Examine the cluster of points along the lines and the slopes of the lines to determine if there is a potential positive or negative relationship between the two variables.
- Examine the points for the herbivores versus those for the carnivores. If one group tends to have higher or lower data values than the other then that feeding type tends to have a smaller value for that trait relative to body size than the other feeding type.
- Compare the measures you have taken on the carnivore skulls relative to those recorded for the herbivore skulls.
- For those measures that appear to show a negative or positive correlation with total skull length (our measure of animal size), you will need to express

your values in the form of a proportion using the ratio: trait value of interest/total skull length. This corrects for animal size as already discussed.
- Compare the two categories (corrected for skull length) using scatter plots similar to the one shown above. In this case, however, there will not be an independent variable axis (total skull length) but merely comparison of two traits of equal interest. For example, compare the rough estimate of brain size to the volumetric measure obtained by filling the skull with BBs, or compare molar tooth row lengths of mandibles to the estimates of eye diameter. You are looking for correlations among a suite of traits that might be associated with a feeding strategy, carnivore or herbivore.

Note that with larger sample sizes (more skulls to measure), you could actually quantitatively determine whether the associations or correlations you found are significant ones. The exercise you have completed here is exploratory in that it can only provide clues as to such relationships.

Data Extrapolation and Interpolation
- Choose one of your scatter plots for which there appears to be a strong correlation between the trait of interest and skull length.
- Use the line that you fit to this plot to estimate the value of the trait of interest in an animal with a skull length that lies outside your data's range.

Example: If the largest skull that you measured was 22 cm long, and the smallest skull that you measured was 2 cm long, then your data's range is 2-22 cm. Since 30 cm is larger than the largest skull that you measured, it lies outside your data's range. (Similarly 1 cm lies outside your data's range.) So, you might choose to estimate the value of the trait of interest in an animal with a skull length of 30 cm. If the equation of the line you fit to this data was $y = 2.5x - 1$, then you would estimate the value of the trait of interest to be $2.5(30) - 1 = 74$ cm. You have **extrapolated** a value that lies outside of your data range!
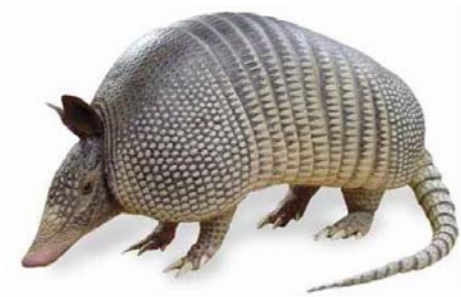
- Use the line that you fit to this plot to estimate the value of the trait in an animal with a skull length that lies *within* your data's range. This is known as **interpolation**.

Q8. Which type of estimation do you think is more reliable, extrapolation or interpolation? Why?

ANSWERS

ANSWERS FOR EXERCISE 1: TOOTH TYPES & DIET TYPES

#1. Armadillo (*Dasypus novemcinctus*) - insectivore. This animal eats insects and worms. The armadillo is a member of the mammal order Edentata. Edentata means "toothless". Sloths and anteaters are other members of this order. Only the anteater is actually toothless. Armadillos do not have incisors or canines. Their teeth have no roots and no enamel. These teeth grow continuously.

#2a. Prairie Dog (*Cynomys ludovicianus*) – herbivore. This animal eats grass and herbs/forbs. The black-tailed prairie dog is a burrowing member of the order Rodentia, the largest group of mammals in the world. This species occupies prairies in the western US, and lives in large colonies covering 1-1000 acres. The dogs maintain an extensive underground burrow system. Note the large eye sockets on the prairie dog skull. Prairie dogs sit on the mound opening of a burrow and visually search for predators. Grasses are the preferred food of the prairie dog, and generally make up about three quarters of its diet. In the fall, herbs become more important, as green grass is less available. In winter, any available green vegetation is consumed. In the spring and summer, each prairie dog consumes up to two pounds of vegetation per week. In addition to the vegetation it eats, the prairie dog also uses its teeth to cut down the vegetation within its colony. This is probably done to keep the vegetation clipped short to provide an unobstructed view of approaching predators.

#2b. Rabbit (*Sylvilagus sp.* or *Oryctolagus cuniculus*) - herbivore. There are approximately 21 species of rabbits in 8 genera worldwide. The rabbit skull in your box probably came from either a cottontail species (genus *Sylvilagus*), or a domestic

rabbit (*Oryctolagus cuniculus*). Along with the hares, rabbits are members of the family Leporidae, which is almost exclusively herbivorous, feeding primarily on grasses and herbs, but also leaves, fruits, and seeds. The diet of rabbits, by nature, is very high in cellulose, which is a tough structural component of plant cell walls. The high amount of cellulose in rabbits' diets makes it very difficult for rabbits to digest their food and get sufficient nutrition from it. Due to this, rabbits (as well as hares and pikas, another group of lagomorphs) pass food through their digestive systems twice. The first digestion results in soft green feces (poop), known as cecotropes, which lagomorphs then re-ingest. After being passed through the digestive tract again, the food is expelled as hard, dark pellets. Though this might seem a bit gross, this behavior is necessary for rabbits to obtain adequate nutrition (primarily vitamin B12) from their food. Though their dentition (number of various types of teeth) is quite similar to that of rodents, rabbits have more cheek teeth than rodents do.

#2c. Rat (*Rattus sp.*) - omnivore.
Worldwide, there are approximately 64 species of "true" rats, which are classified into the genus *Rattus*. This genus of rats is also often called "Old World" rats, as they are only native to the Old World (the continents of Europe, Asia, and Africa). *Rattus* species, however, have been introduced all over the world, usually as stowaways in the ships of traders and settlers. Two species of rats, the Norway rat (*Rattus norvegicus*) and the black rat, also known as the house rat (*Rattus rattus*) are found in North America. Though rats have a reputation as notorious pests of stored grains such as corn and wheat (as well as other crops), and their teeth are most similar to the teeth of herbivores, they are actually quite opportunistic omnivores, consuming a wide variety of seeds, fruits, vegetables, fungi, invertebrates, small vertebrates, and carrion (dead animals).

#3. Coyote (*Canis latrans*) - carnivore. This relative of the domestic dog eats rabbits, mice and other small rodents. Canine teeth, often known as fangs, are used to hold prey and in tearing flesh while eating. The family Canidae is comprised of the thirty-three species of wild dogs found throughout the world, as well as domestic dogs, which represent numerous breeds of one species

(*Canis familiaris*). They range from small foxes, coyotes, and jackals to large wolves and wild dogs, such as the dingo of Australia. Species may inhabit all terrains, from hot deserts to arctic ice fields. Many run in packs which may number up to thirty members, while others are solitary or hunt in pairs. Canids are cunning, skillful hunters with good hearing and acute senses of smell. They utilize these skills to hunt and consume a variety of herbivorous animals.

#4. Mink (*Mustela vison*) carnivore. The mink preys chiefly on muskrats but also eats mice, rabbits, chipmunks, fish, snakes, frogs, and birds. Minks are also known to raid poultry houses. A mink is a weasel-like carnivore of the family Mustelidae. It is about the size of a house cat and has a general color of dark chocolate brown. Mink den near water in burrows abandoned by other animals. Foxes, bobcats, and great horned owls are known predators of mink. The pelts of mink are highly valued, so they are now commercially raised on mink ranches.

#5. White-Tailed Deer (*Odocoileus virginianus*) - herbivore. Herbivores like deer that feed on bushes, the lower branches of trees, and on bark, are referred to as browsers. (In contrast, other herbivores that feed primarily on grass, like sheep, called grazers.) Deer belong to the mammalian order Artiodactyla, or even-toed animals. The family Cervidae is comprised of 45 species of deer. Generally they are slender, graceful herbivores whose diets consist of grass, bark, and twigs. In most species, only the male has antlers. These bony protrusions are shed yearly, and are used to combat other males during breeding.

#6. Beaver (*Castor canadensis*) - herbivore. Beavers eat plants and use their single pair of long front incisors to gnaw on trees and branches. These incisors grow continuously throughout their lives, as do their molars. Rodentia is the largest order of living mammals, containing approximately 1500 species. Beavers are the largest rodents in North America and Eurasia. They are heavy aquatic rodents perhaps best

known for making dam homes that may lead to the production of large ponds and even lakes.

#7. Snapping Turtle (*Chelydra serpentina*) – **omnivore**. This reptile that lacks teeth, and swallows its food (which includes invertebrates, fish and other vertebrates, and aquatic plants) whole or tears it into manageable chunks with its large, sharp beak. The class Reptilia is divided into three major living orders. It includes the primitive order Chelonia, represented by about 250 species of toothless turtles. Members of the more recently derived orders have teeth, including many lizards and snakes (order Squamata) and all crocodilians (order Crocodylia), as well as a fourth reptile order (Sphenodontia), which is represented by only two species of tuataras (similar to lizards). One characteristic identifying a reptilian skull is the presence of a single ball-and-socket connection (condyle) at the head-neck joint, instead of the two found in mammals. Another defining characteristic is that the roof of the mouth (palate) is divided into two sections. This partitioning separates the food and air passageways in the turtle so that breathing can continue while the food is being chewed.

#8. Human (*Homo sapiens*) **- omnivore**. Eats both plants and animals. The human skull has an enormous cranial vault that protects a large brain for our complex thought processes. Note the large eye sockets as well, suggesting the importance of vision to the survival of early man. Humans are the ultimate omnivores. We have the greatest variety of teeth of any animal, reflecting our broad diets.

#9. Bobcat (*Felis rufus*) – **carnivore**. This American cat species eats small mammals. The family Felidae of the order Carnivora is comprised of cats entirely. There are thirty-seven species that are found throughout the world. All cats share many tendencies. All have large eyes and good vision. Most have very sharp retractable claws and long

slender canine teeth. The bobcat was originally assigned the name *Lynx rufus*. The word *lynx* means lamp in Greek, and refers to the fact that the bobcat's eyes shine in the headlights of vehicles. *Rufus* refers to the red color of the bobcat's fur. Some authors place the bobcat in the genus *Felis*, reflecting the fact that this species is closely related to domestic cats. *Felis* is Greek for cat.

#10. Skunk (*Mephitis mephitis*) – omnivore. The striped skunk belongs to the family Mephitidae (which includes four species of North American skunks, as well as Asian stink badgers), although skunks were formally classified in the same family as weasels (Mustelidae). Skunks are one of the most omnivorous members of the Carnivora, and use their keen sense of smell to locate and capture prey, such as rodents, insects, frogs, bird eggs, and baby birds, but their diets also include berries, fruit, and other plant material. Though they are quite omnivorous, they share several traits with other members of the mammalian order Carnivora, such as front-facing eyes and large slicing canines. Their roles as predators of small herbivores make them an essential part of the balance of nature, as they keep populations of many potentially destructive herbivores (particularly rodents) at moderate levels. Of course, skunks are most known for their defensive smell, which is very offensive!

#11. Porcupine (*Erethizon dorsatum*) – Herbivore. Eats bark. This heavy-bodied rodent weighs around 20 pounds. It has powerful legs and long curved claws for climbing trees. The porcupine forages on bark, twigs and leaves and comes down to the ground only to move from tree to tree. Its rump and tail are covered in over 30,000 barbed quills, which protect the slow moving porcupine from its main predators, the mountain lion, fisher, bobcat, and coyote.

ANSWERS FOR EXERCISE 2: DENTAL FORMULAS

Q1. What is the title of the marble example bar graph?
    Distribution of cat's-eye marbles among individuals

Q2. How is the y-axis labeled in the figure?
    Proportion

Q3. How is the x-axis labeled in the figure?
    Individuals

Q4. List all the values that the qualitative variable (category) takes in the marble figure.
    Bob Susan Meg John

Q5. Use the table to determine which two individuals have the closest to equal proportions of cat's-eye marbles.
    Susan and John

Q7. Why is it more meaningful to compare the proportion of teeth that are molars than it is to compare the number of teeth that are molars if our goal is to understand the relationship between an animal's diet and its teeth?
    If we are investigating the effect of diet on tooth composition, it is more
    meaningful to compare the proportion of teeth that are molars than it is to
    compare the number of teeth that are molars because the number of teeth
    that are molars is partially determined by the total number of teeth in the
    animal's skull, while the proportion of teeth that are molars is
    independent of the number of teeth in the animal's skull.

Dental Formulas

Teeth Types and Counts	Skull Number & Animal ID												
	1	2a	2b	2c	3	4	5	6	7	8	9	10	11
	Armadillo	Prairie Dog	Rabbit	Rat	Coyote	Mink	Deer	Beaver	Turtle	Human	Bobcat	Skunk	Porcupine
Incisors (Upper Jaw)	0	1	1	2	3	3	0	1	0	2	3	3	1
Incisors (Lower Jaw)	0	1	1	1	3	3	3	1	0	2	3	3	1
Canines (Upper Jaw)	0	0	0	0	1	1	0	0	0	1	1	1	0
Canines (Lower Jaw)	0	0	0	0	1	1	1	0	0	1	1	1	0
Premolars (Upper Jaw)	7	2	0	3	4	3	3	1	0	2	2	3	1
Premolars (Lower Jaw)	7	1	0	2	4	3	3	1	0	2	2	3	1
Molars (Upper Jaw)	0	3	3	3	2	1	3	3	0	3	1	1	3
Molars (Lower Jaw)	0	3	3	3	3	2	3	3	0	3	1	2	3
Sum	14	11	8	14	21	17	16	10	0	16	14	17	10
Total Teeth (= Sum × 2)	28	22	16	28	42	34	32	20	0	32	28	34	20

ANSWERS FOR EXERCISE 3: MORPHOMETRICS

Q1. Check to see if the following points are on the line $y = 3x + 4$
- $(1, 8)$ $3(1) + 4 = 7 \neq 8$ NO
- $(2, 10)$ $3(2) + 4 = 6 + 4 = 10$ YES

Q2. Find the slope of the line in the figure.
$$m = 2$$

Q3. What is the y-intercept of the line $y = 3x + 4$?
$$b = 4$$

Q4. Suppose that a line has slope $m = 2$ and that the point $(2, 7)$ is on the line. Write down the point-slope formula for the line.
$$2 = \frac{7 - y}{2 - x}$$

Q5. Find the slope-intercept formula for the line in **Q4**.
$$2 = \frac{7 - y}{2 - x} \rightarrow$$

$$2(2 - x) = 7 - y \rightarrow$$

$$4 - 2x = 7 - y \rightarrow$$

$$y = 2x + 3$$

Q6. Record the slope of the best fit line for both the American and Chinese infant growth data. Which best fit line has the largest slope? How would you interpret this fact?

    Chinese female infants: $m = 1.2 \; \frac{cm}{month}$

    American female infants: $m = 1.8 \; \frac{cm}{month}$

This means that American female infants grow faster than Chinese female infants.

Q7. Record the y-intercept of the best fit line for the Chinese infant growth data and American growth data. Which data set has the smallest y-intercept? How would you interpret this fact?

Chinese female infants: $b = 57$ cm
American female infants: $b = 58$ cm

This means that Chinese females are shorter at birth than American females.

Q8. Which type of estimation do you think is more reliable, extrapolation or interpolation? Why?

Interpolation is more reliable than extrapolation. Outside of your data's range other factors might influence the relationship between the two variables of interest so that the linear equation you fit to your data is no longer valid.

SUGGESTED READING

Grades K-3
Dem Bones - Bob Barner
You Can't See Your Bones with Binoculars - Harriet Ziefert & Amanda Haley (Illustrator)
Bones - Stephen Krensky
A Book About Your Skeleton - Ruth Belov Gross & Steve Bjorkman (Illustrator)
The Search for the Missing Bones (The Magic School Bus Chapter Book, No. 2) - Eva Moore
    & Ted Enik (Illustrator)
Skeletons (The Magic School Bus, A Science Fact Finder) - Jackie Glassman, Carolyn
    Bracken (Illustrator), Lynda Nyse (Illustrator)
A Magic Skeleton Book: Safari Animal Adventure - Shaheen Bilgrami, Chantal Kees
    (Illustrator), & Chris Shields (Illustrator)
The Skull Alphabet Book - Jerry Pallotta and Ralph Masiello (Illustrator) (Beautiful
    illustrations, fascinating for ALL ages!)

Grades 4-7
Bones: Our Skeletal System - Seymour Simon
Skeleton - Steve Parker
*The Bone Detectives: How Forensic Anthropologists Solve Crimes and Uncover Mysteries of
    the Dead* - Donna M. Jackson & Charlie Fellenbaum (Photographer)
Make This Life-Size Model Skeleton - Iain Ashman, Susanna Addario (Illustrator), Claudia
    Saraceni (Illustrator), Thomas Trojer (Illustrator)
The Skeletal System - Eduard Arnau & Antonio Munoz Tenllado (Illustrator)

Grades 7+
*Death's Acre: Inside the Legendary Forensic Lab the Body Farm Where the Dead Do Tell
    Tales* - William Bass & Jon Jefferson
*Skulls and Bones: A Guide to the Skeletal Structures and Behavior of North American
    Mammals* - Glenn Searfoss
The Archaeology of Animals - Simon J. M. Davis
The Skull, Volume 2: Patterns of Structural and Systematic Diversity - James Hanken

Scientific Journal Articles (PDFs included on Teacher CD!)
Dayan, T., D. Wool, and D. Simberloff. 2002. Variation and covariation of skulls and teeth:
    modern carnivores and the interpretation of fossil mammals. *Paleobiology* 28(4):508-
    526.
Mattson, D.J. 1995. Diet and morphology of extant and recently extinct northern bears. *Ursus*
    10:479-496.
Patterson, B.D., E.J. Neiburger, and S.M. Kasiki. 2003. Tooth breakage and dental disease as
    causes of carnivore -- human conflicts. *Journal of Mammalogy* 84(1):190-196.
Perez-Barbería, F.J. and I.J. Gordon. 2001. Relationships between oral morphology and
    feeding style in the Ungulata: A phylogenetically controlled evaluation. *Proceedings:
    Biological Sciences* 268(1471):1023-1032.

Wroe, S., C. McHenry, and J. Thomason. 2005. Bite club: Comparative bite force in big biting mammals and the prediction of predatory behaviour in fossil taxa. *Proceedings of the Royal Society B* 272:619-625.

Zuccarelli, M.D. 2004. Comparative morphometric analysis of captive vs. wild African Lion (*Panthera leo*) skulls. *Bios* 75(4):131-138.

LINKS

Biology4Kids.com: Vertebrates – Good information about vertebrates!
http://www.biology4kids.com/files/vert_main.html

The Truth About Teeth – Good introductory info for younger students about types of teeth and tooth anatomy from KidsHealth.org.
http://kidshealth.org/kid/htbw/teeth.html

Super Teeth – Part of the American Natural History Museum's Ology site with an activity for younger students in which they match teeth to their animal owners.
http://www.amnh.org/ology/features/stufftodo_zoology/superteeth_activities.php

Primate Teeth – An image comparing the upper teeth of several families of primates, hosted by the University of Michigan Museum of Zoology's Animal Diversity Web, which is a great site to explore!
http://animaldiversity.ummz.umich.edu/site/resources/anatomical_images/family_pages/primates/primate_teeth.jpg/view.html
http://animaldiversity.ummz.umich.edu/site/index.html

Primate Dentition – An exercise from the Jane Goodall Institute using dental formulas to compare several groups of primates (prosimians, Old and New World Monkeys, apes, and humans).
http://www.chimpanzoo.org/dental_analysis.html

Dinosaur Paleoecology – Exercise for older students by David J. Davies (Centenary College of Louisiana) on functional morphology of dinosaur teeth
http://www.beloit.edu/sepm/Fossil_Explorations/Dinosaur_Paleoecology.html

Tooth Detectives – Exercise by James W. Westgate (Lamar University); good source material for Exercise 1 with information on tooth types.
http://www.beloit.edu/sepm/Fossil_Explorations/Tooth_Detectives.html

Rat Teeth – Good information on rodent dentition, as well as mammal teeth in general.
http://www.ratbehavior.org/Teeth.htm

Skulls Unlimited International – Supplier of a huge range of skulls for educational purposes, which has an EXCELLENT Educational Resources section. Also check out the website of their Museum of Osteology!
http://www.skullsunlimited.com/
http://www.skullsunlimited.com/educational-resources.html
http://www.museumofosteology.org/

Dental Formulae of Mammals of North America – Ever wondered how many teeth a particular kind of mammal has? Get the answer here!
http://wildwoodtracking.com/skulls/dentalformulae.html

Using Dentition to Age Cattle – Good information on herbivore teeth from the USDA, including dental formulas and information on tooth development in cows.
http://www.fsis.usda.gov/ofo/tsc/bse_information.htm

Skull and Dentition Measuring Standards – Excellent images illustrating cranial anatomy and common skull measurements using the skulls of lorises and pottos.
http://www.loris-conservation.org/database/population_database/Standards_for_Measurement/10a-figures_skull_toothrow_measurements.html

Researchers put 'teeth' into dinosaur classification scheme – Interesting article on identification of dinosaur species from teeth.
http://record.wustl.edu/news/page/normal/6132.html

www.skullsite.co.uk – Great site with images and information on numerous animal skulls, including dental formulas (check out his Species List), an excellent Glossary of skull terminology, and a section on Skull Preparation.
http://www.skullsite.co.uk/
http://www.skullsite.co.uk/lists.htm
http://www.skullsite.co.uk/glossary.htm
http://www.skullsite.co.uk/preparation.htm

Standard Protocols and Procedures – Source of Figure 3.53 for Exercise 3. The homepage of the Jackson Laboratory, which uses mouse models to study inherited craniofacial dysmorphologies in humans may be of interest to teachers at the high school level. A link to an online publication from the Jackson Laboratory is also listed.
http://craniofacial.jax.org/standard_protocols.html
http://craniofacial.jax.org/index.html
http://www.hopkinsmedicine.org/craniofacial/Research/MouseArt3-JB.cfm

Vertebrate Skeleton and Vertebrate Skull – These sites, from a course by Sandra Millen at the University of British Columbia offer images, information, and questions that might be good for high school biology courses.
http://www.zoology.ubc.ca/courses/bio204/lab7_frameset.htm
http://www.zoology.ubc.ca/courses/bio204/lab6_frameset.htm

Key to Skulls of North Dakota Mammals – Though the mammal skulls in your box may not be in the linked key (if they're not found in ND), the link itself first goes to a key to mammalian orders. All mammal skulls in the box could easily be keyed to at least the level of order by most middle to high school students with maybe some assistance from skullsite.co.uk Glossary linked above! (From Wiehe, J. M. 1978. Key to the skulls of North Dakota mammals. Prairie Naturalist 10(1):1 -16. Jamestown, ND: Northern Prairie Wildlife Research Center Online.)
http://www.npwrc.usgs.gov/resource/mammals/skulls/key.htm

Digimorph.org – AMAZING site with digitized 3-D images (using X-ray CT technology) of skeletal and cranial structures of over 750 specimens of numerous species of all vertebrate groups (and some invertebrates). Students can view movies displaying rotation of skulls and skeletons along all three body planes, as well as movies of slices through each, allowing visualization of internal features of the skull. SUPER COOL!
http://www.digimorph.org/navcommon.phtml