INTRODUCTION

This activity explores how animals can regulate, or control, their body temperatures to survive in their environments. You will learn one method to determine how living animals regulate their body temperatures, then see how similar tests can be applied to extinct animals. You will also use real scientific data to investigate how dinosaurs regulated their body temperatures.

PROCEDURE

The activity is divided into five parts. Begin with Part 1 to become more familiar with the topic. Answer the questions in the spaces provided.

PART 1: Thermoregulation in Living Animals

Figure 1 shows four different animals. Think about the temperature inside the body of each animal compared to the temperature of the environment where that animal lives.

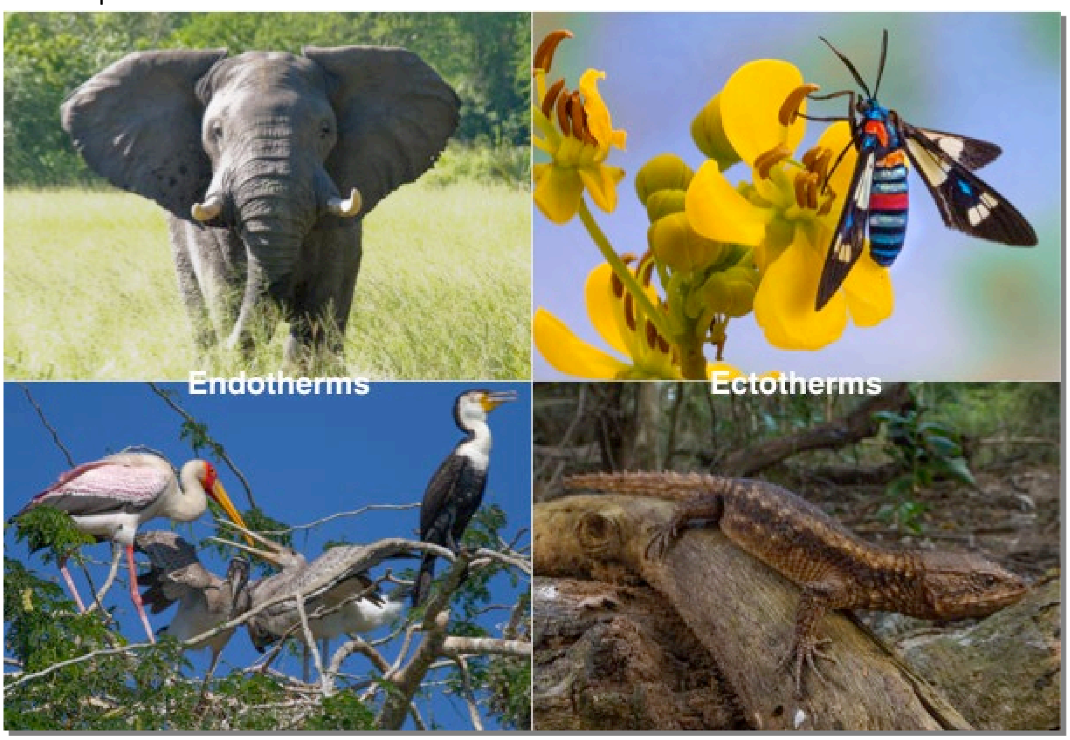

Figure 1. Examples of different animals.

1. Would you expect any differences between the body temperatures of these animals and the temperatures of their environments? Is your answer the same for all the animals? Why or why not?

To survive, most animals regulate their body temperatures to keep them within a certain range. The process of regulating body temperature is called **thermoregulation**. Based on how they regulate their body temperatures, most animals fit into two main categories: ectotherms or endotherms.

Ectotherms, sometimes called “cold-blooded,” regulate their body temperatures using heat from the *outside* environment. (The prefix *ecto-* comes from the Greek word for “outside.”) As a result, the body temperature of an ectotherm depends on the temperature of its environment. The ectotherm can adjust its body temperature by moving to different locations. For example, a lizard may move to a sunny spot to warm up or to a shady spot to cool down.

Endotherms, sometimes called “warm-blooded,” regulate their body temperatures using heat generated *inside* their bodies. (The prefix *endo-* comes from the Greek word for “inside.”) An endotherm uses its internal heat to keep its body temperature stable, even when temperatures in its environment are changing. Arctic foxes and polar bears, for example, can keep their internal body temperatures at about 38°C, even when the air temperature dips down to −40°C.

2. Define “ectotherm” and “endotherm” in your own words. List four examples of animals that would fit into each category.

Both ectotherms and endotherms generate some heat by breaking down food. Food is broken down by cellular respiration to produce cellular energy in the form of ATP. ATP is used for all types of biological “work,” such as growth, movement, and reproduction. During cellular respiration, some of the chemical energy from food is also converted into heat.

The chemical reactions that occur in cells, including breaking down food molecules and generating ATP, are called metabolism. The rate at which animals transform chemical energy in food and release heat is the **metabolic rate**, which is measured in joules (or calories) per second.

Because endotherms use the heat generated by metabolism to regulate their body temperatures, they must generate much more heat than ectotherms do. As a result, endotherms generally have higher metabolic rates. The metabolic rate of an endotherm at rest, called the **resting metabolic rate**, tends to be 5–20 times higher than that of an ectotherm with a similar mass.

Endotherms can also generate heat by shivering. Shivering rapidly contracts the muscle fibers to use energy and produce heat. Making a lot of heat — plus having insulating fur, feathers, or clothes — keeps endotherms warm in cold environments.

3. According to a major scientific principle called the law of conservation of energy (or the second law of thermodynamics), energy cannot be created or destroyed. However, energy *can* be transformed. Summarize some of the energy transformations described in the paragraphs above.

Since endotherms tend to have higher metabolic rates than ectotherms, they are generally more active, grow and reproduce faster, and thrive over a wide range of temperatures. However, endotherms must also eat much more often and are more likely to run out of food. A shrew (a small endotherm similar to a mouse) may starve to death in a day without food. A similarly sized lizard (an ectotherm), on the other hand, could go without food for several weeks.

Amphibians and most reptiles, fish, and invertebrates are ectotherms. Mammals and birds are endotherms. What about dinosaurs?

4. Predict whether dinosaurs were more like endotherms or ectotherms. Support your prediction with evidence from the paragraphs above and your own knowledge.

PART 2: Metabolism and Mass of Living Animals

One way to determine whether animals are ectotherms or endotherms is to look at their metabolic rates. Scientists often measure **resting metabolic rate**, which is based on how much oxygen the animal uses while at rest at a particular temperature. This rate can be compared to the **metabolic mass**, the animal's mass when its metabolic rate was measured. Table 1 shows resting metabolic rates and metabolic masses for a variety of animals living today. These data were compiled from many previous studies by evolutionary biologist John Grady and his colleagues.

Table 1. Metabolic masses and resting metabolic rates for sample vertebrates. In some cases, the measurement was taken from a juvenile instead of a fully grown animal (for example, the alligator and Nile crocodile). Data from Grady et al. (2014).

Animal	Type of Animal	Metabolic Mass (g)	Metabolic Rate (joules/s)
Alligator	Reptile	1,287	0.67
Boar	Mammal	135,000	104.2
Bobcat	Mammal	9,400	23.54
Chimpanzee	Mammal	45,000	52.32
Cod	Fish	761.1	0.045
Dog	Mammal	38,900	49.02
Elephant	Mammal	3,672,000	2336.0
Emerald rock cod	Fish	178.1	0.035
Gila monster	Reptile	463.9	0.148
Grouse	Bird	4,010	11.63
Horse	Mammal	260,000	362.9
Kangaroo	Mammal	28,500	31.35
Lemon shark	Fish	1,600	0.959
Monitor lizard	Reptile	32.5	0.017
Nile crocodile	Reptile	215.3	0.064
Partridge	Bird	475	1.961
Python	Reptile	1,307	0.13
Rabbit	Mammal	3,004	6.063
Raven	Bird	1,203	5.534
Saltwater crocodile	Reptile	389,000	38.52
Sandbar shark	Fish	3,279	1.153
Spear-nosed bat	Mammal	84.2	0.559
Sperm whale	Mammal	11,380,000	4325.0
Tiger	Mammal	137,900	133.9

Figure 2 is a graph of the data in Table 1. It uses **logarithmic scales** on both axes to show data points over a large range. On a graph with regular linear scales, it would be hard to show all these data points together, since some of the animals and their metabolic rates are tiny, while others are huge.

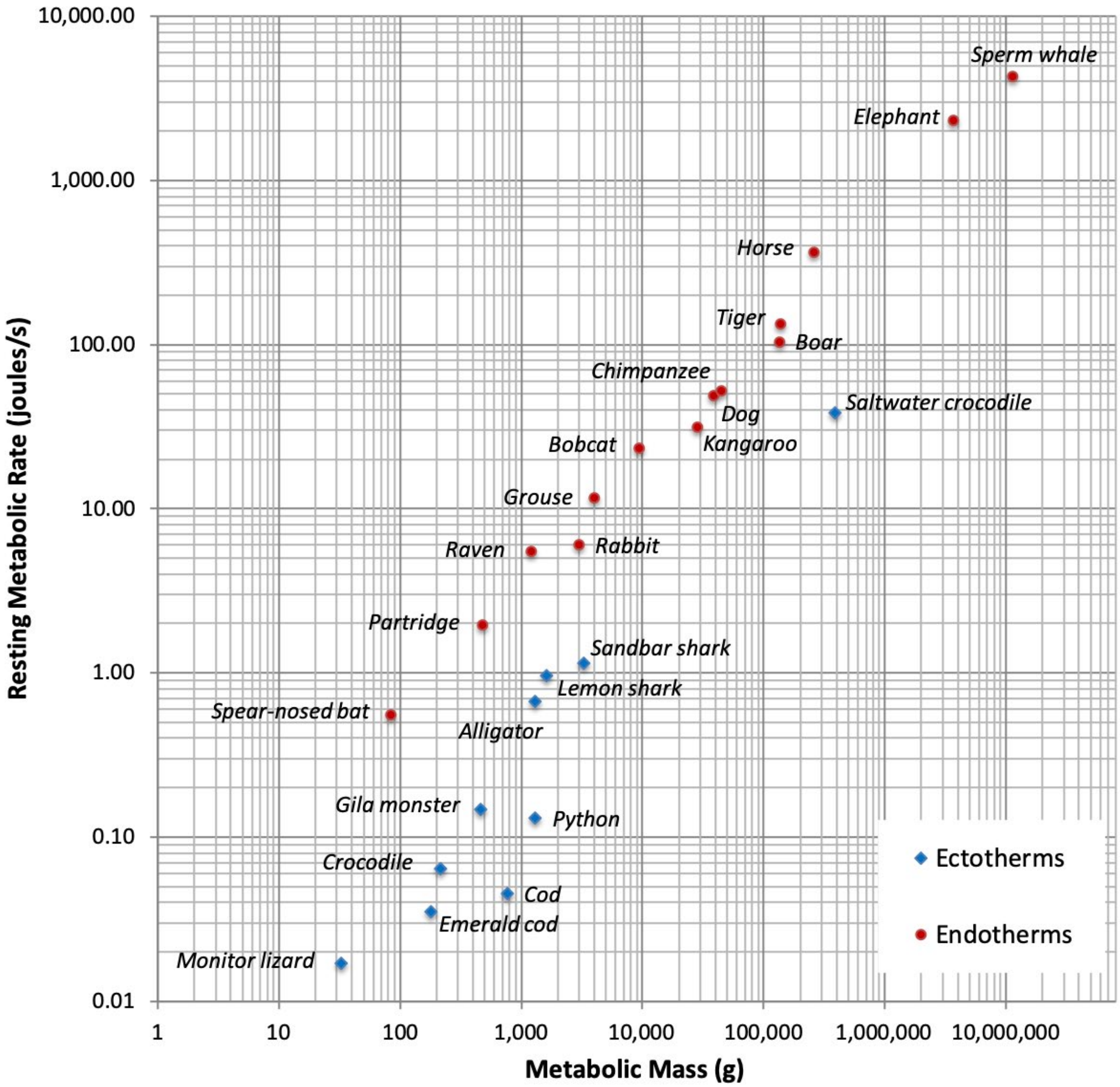

Figure 2. Metabolic rate versus metabolic mass of the vertebrates in Table 1. The filled blue diamonds represent ectotherms. The filled red circles represent endotherms. Figure adapted from Grady et al. (2014).

Use Figure 2 to answer the following questions.

1. Based on the general trends in Figure 2:
    a. How do the metabolic rates of ectotherms compare with those of endotherms of similar mass?

    b. How do the metabolic rates of both ectotherms and endotherms vary with mass?

2. An average adult cheetah has a metabolic mass of 44,010 grams and a resting metabolic rate of 61.77 joules per second. Use this information to add a data point for the cheetah to Figure 2. Based on these data, would you characterize the cheetah as an ectotherm or endotherm? Support your answer with evidence from the graph.

3. Briefly describe other data you could collect to provide additional evidence for whether the cheetah is an ectotherm or an endotherm.

4. As the masses of the animals increase, how do their metabolic rates tend to change? Answer this question for both ectotherms and endotherms.

5. Make a claim about how the metabolic rates of endotherms compare with those of ectotherms of similar mass. Support your claim with at least three pairs of data points from Figure 2.

We can't measure metabolic rates and masses of dinosaurs directly, like we do with living animals. We also can't directly analyze the dinosaurs' body temperatures, soft tissues, or DNA. Instead, we have to study dinosaurs through fossils.

6. What kinds of evidence from fossils might help determine whether dinosaurs were ectotherms or endotherms?

PART 3: Estimating Dinosaur Mass and Metabolism

Part 2 showed how mass and metabolism can be used to distinguish ectotherms from endotherms. These properties could also be used to determine whether dinosaurs were more like ectotherms or endotherms. But since dinosaurs have been extinct for millions of years, we can't measure their masses or metabolisms directly. Instead, we estimate these properties using fossilized bones.

A dinosaur's *mass* can be estimated from its *bone size*. An animal's mass generally increases with the size of its bones. (So a small animal, such as a mouse, usually has lighter, narrower bones than a large animal, such as an elephant, has.) We can measure the size of a dinosaur's bones, then compare these measurements to those of living animals, to estimate how large the dinosaur was.

A dinosaur's *metabolism* can be estimated based on its *bone rings*, which are similar to the growth rings in tree trunks. The widths of the bone rings can be used to estimate an animal's **growth rate**, which is how much the animal grows per unit of time. (Each year, for example, a bone may grow a new ring. Fast-growing animals grew more during that year, so their bone ring will be bigger and wider than it would be for slow-growing animals.) Growth rate is related to metabolic rate, so we can use the growth rates estimated from bone rings to estimate an animal's metabolic rate. These estimated metabolic rates are similar to those measured directly from oxygen use.

Use the information in this reading to answer the questions below.

1. Summarize the evidence used to estimate the masses and the metabolic rates of dinosaurs.

2. Explain why a mouse (an endotherm) would probably have wider bone rings than a similarly sized lizard (an ectotherm).

Using the methods described above, Grady and colleagues estimated the masses and metabolic rates of 21 dinosaurs. Their estimates for five of these dinosaurs are shown in Table 2.

Table 2. Estimated masses and resting metabolic rates of five dinosaurs. Data from Grady et al. (2014).

Dinosaur	Mass (kg)	Metabolic Rate (joules/s)
Allosaurus	1,862	205.85
Apatosaurus	19,170	2,999.04
Coelophysis	33	7.405
Tyrannosaurus	5,654	853.38
Troodon	52	10.956

Plot the Table 2 data on Figure 2 (from Part 1 of the activity), then answer the questions below.

3. As the masses of the dinosaurs increase, how do their metabolic rates change? How does this compare to the living animals?

Draw three lines of best fit ("trend lines") in Figure 2: one for the endotherms, one for the ectotherms, and one for the dinosaurs.

4. Make a claim about whether the relationship between mass and metabolic rate in dinosaurs follows a pattern more similar to that of ectotherms or endotherms. Support your answer with evidence from the graph.

5. Based on the graph, which animal would you expect to have wider rings in its bones: a mountain lion or the dinosaur called a *Troodon*? (*Troodon*s were about the same mass as mountain lions and looked like feathered velociraptors.) Explain your answer.

PART 4: The Energetics of Dinosaurs

Part 3 mentioned that an animal's metabolic rate is related to its growth rate. Animals of greater mass tend to have higher metabolic and growth rates, regardless of whether they are ectotherms or endotherms. (For example, both an alligator and a dog have higher metabolic rates than small birds, such as warblers, have.) What happens if you take mass out of the equation? (In other words, if the alligator and the warbler were the same mass, how would their metabolic and growth rates compare?)

Figure 3 shows the growth and metabolic rates of various animals, including dinosaurs, in a way that controls for mass. Like Figure 2, Figure 3 uses logarithmic scales on both axes to show data points over a large range.

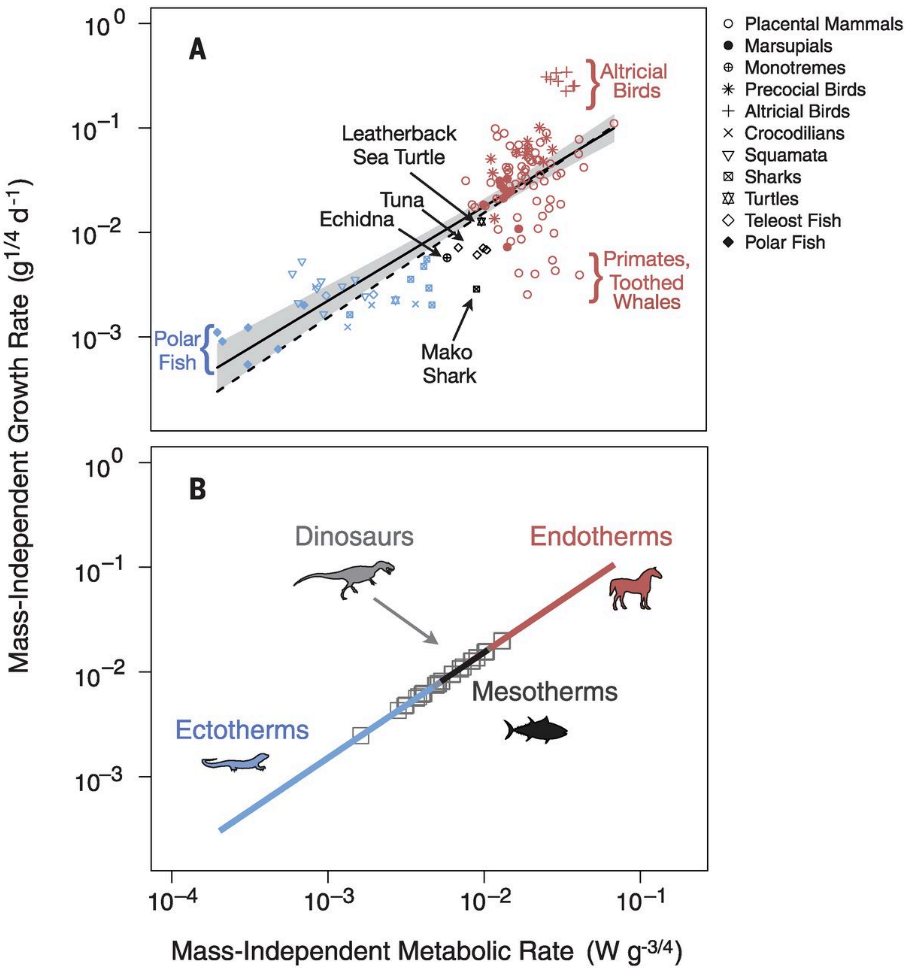

Figure 3. Mass-independent growth rate versus mass-independent metabolic rate of sample vertebrates. The unit watts (W) is equivalent to joules per second. **A)** Rates for living vertebrates, shown with different symbols. The shaded area represents 95% confidence intervals. **B)** Estimated rates for dinosaurs, shown as open squares. The line represents predicted rate ranges for living ectotherms (blue, lower left), endotherms (red, upper right), and animals between the two (black, middle). Figure from Grady et al. (2014).

Use Figure 3 to answer the following questions.

1. Which types of animals have the highest mass-independent **growth** rates? Which have the lowest?

2. Which types of animals have the highest mass-independent **metabolic** rates? Which have the lowest?

3. In general, as metabolic rate increases, how does growth rate change?

Based on these and other data, Grady and colleagues concluded that dinosaurs were **mesotherms**. The prefix *meso-* means “middle.”

4. Compare the growth rates of dinosaurs to those of living ectotherms and endotherms. Why do you think the scientists described dinosaurs as “mesotherms,” and do you agree with their conclusion? Use evidence from Figure 3 to support your answer.

Grady and colleagues made their data available to other scientists. Another scientist, Michael D’Emic, reanalyzed the data using some different assumptions and came to a different conclusion. D’Emic carefully described the methods he used and also made them available to other scientists. After reviewing D’Emic’s work, Grady and colleagues replied with an argument about why they believed their original method was correct.

5. Describe how these events are a good example of how science works.

PART 5: Thermoregulation in Dinosaurs

Figure 3 suggests that dinosaurs fall between ectotherms and endotherms in terms of their metabolic and growth rates. Based on these results, Grady and colleagues classified dinosaurs as **mesotherms**, animals with features of both ectotherms and endotherms. Similar to endotherms, mesotherms generate heat through metabolism to regulate their body temperatures. However, mesotherms do not keep their temperatures as stable as most endotherms do.

Dinosaurs are not the only mesotherms. Figure 4 shows several examples of mesotherms living today.

Figure 4. Examples of living mesotherms. Left to right: leatherback turtle, great white shark, and bluefin tuna.

What is the advantage of being a mesotherm? To answer this question, consider the following comparisons of ectotherms and endotherms:

- **Energy Use:** To keep their body temperatures stable, endotherms need as much as 5–10 times more energy than ectotherms need.
- **Activity Level:** Endotherms usually have higher levels of activity, because they are optimized to use more energy and have more efficient respiratory and circulatory systems. Ectotherms may have high levels of activity when they are warm, but they tend to become slow and sluggish when they are cold.
- **Tolerance to External Change:** Endotherms can maintain a stable body temperature even when outside temperatures become much colder or hotter. This helps endotherms stay active over a wider range of environmental conditions.
- **Tolerance to Internal Change:** Ectotherms can handle larger changes in their internal body temperatures than endotherms can. For example, freshwater bass fish (ectotherms) can survive body temperatures from near 0°C to 35°C. Humans (endotherms), on the other hand, can die if their body temperature rises or drops outside a 5°C range (from about 35°C to 40°C).
- **Competition:** Due to their relatively slower growth, reproduction, and activity rates, ectotherms may be outcompeted by endotherms of similar size. As a result, for example, large ectotherms mainly live in places without large endotherms. Crocodiles hunt in rivers where they rarely compete with large predatory mammals. Large Komodo dragons and tortoises often live on islands lacking predatory mammals altogether. In parts of the ocean with fewer large endotherms, large ectotherms (such as sharks and fish) have been able to thrive.

1. How might being a mesotherm, rather than an ectotherm or endotherm, have been advantageous for dinosaurs?

2. Today, mesotherms are relatively rare. If being a mesotherm was advantageous for dinosaurs, why do you think there aren't more mesotherms now?

3. A lot of evidence suggests that birds evolved from theropod dinosaurs. How did the data in this activity add to your understanding of the relationship between dinosaurs and birds?