



HOW DID DINOSAURS REGULATE THEIR BODY TEMPERATURES?

INTRODUCTION: THERMOREGULATION IN LIVING ANIMALS

This activity explores thermoregulation in living and extinct animals, including dinosaurs. The activity is divided into four parts. Read through this introduction and answer the questions included to become familiar with the topic.

1. Look at the images of the four animals in Figure 1. Imagine that you measured the temperature inside each animal and also the temperature in the environment where the animals live. Would you expect any differences between the animals and the environment? Would the pattern be the same for all the animals? Why or why not?

Most animals have the ability to regulate their body temperatures in some way. Adjusting temperature allows them to survive changes in temperature in the environment. You may have heard about animals being either “warm blooded” or “cold blooded.” The main difference between these groups of animals is their source of body heat. Cold-blooded animals are more accurately called **ectotherms**, whereas warm-blooded animals are **endotherms**. The prefix *ecto-* comes from the Greek word for “outside,” and *endo-* from “inside.”

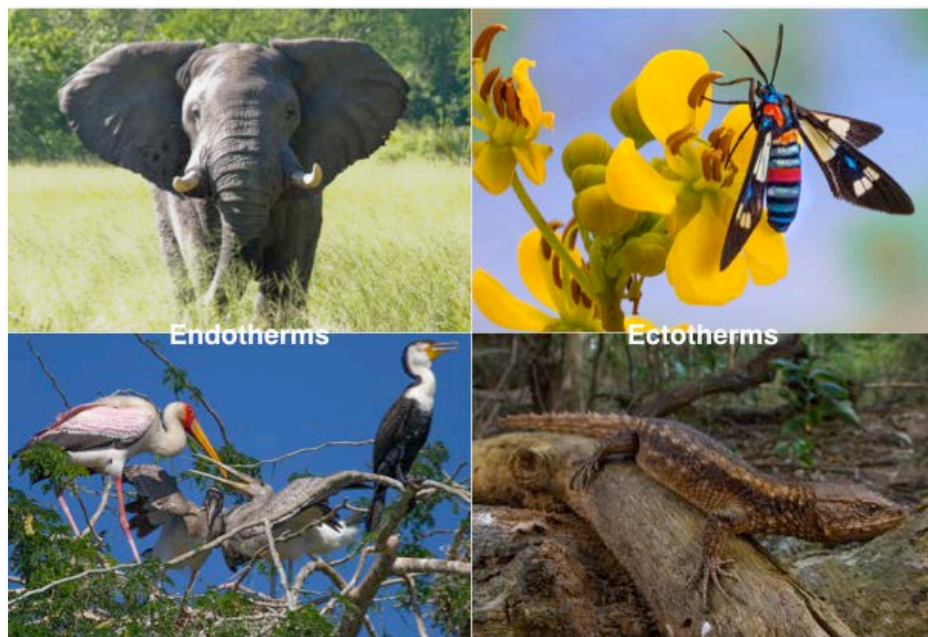


Figure 1. Examples of endothermic and ectothermic animals.(Credit: Photographs by Piotr Naskrecki, Museum of Comparative Zoology, Harvard University, Cambridge, MA.)



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The body temperatures of ectothermic animals are mostly determined by the outside environment, whereas endotherms rely on heat generated inside their bodies to regulate temperature. Most ectotherms do regulate their body temperatures to some extent. For example, an ectothermic animal, such as a lizard, may move to a sunny spot to warm up or to a shady spot to cool down. Endotherms can maintain a stable internal body temperature even as outside conditions vary. Arctic foxes and polar bears, for example, maintain their body temperatures at about 38°C even as the air temperature dips down to -40°C. Ectotherms, on the other hand, cannot maintain stable internal body temperatures and generally cannot remain active across a wide range of external conditions. They are, however, better able to withstand wider *internal* fluctuations than endotherms. A freshwater bass fish, which is an ectotherm, can survive internal temperatures ranging from near 0°C to 35°C. An endothermic human could die if the person's internal temperature rises or drops outside a 5°C range (from about 35°C to 40°C).

2. Write definitions for “**endothermic**” and “**ectothermic**” using your own words. List four examples of animals that would fit into each category.

How do endotherms maintain a relatively constant body temperature in different environments?

They use the energy produced by breaking down food. Food is broken down by cellular respiration to produce energy in the form of ATP that is then used for all types of biological work, such as growing new tissues, locomotion, and reproduction. In the process of doing work, some of the chemical energy in food is converted into heat. Endotherms can also contract muscle fibers rapidly when shivering to generate extra heat when they are cold. Making a lot of heat, plus insulating fur and feathers (or clothes), allow endotherms to keep warm in cold environments.

The process by which cells use energy to do biological work is 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. To keep a constant body temperature, endotherms generally have higher metabolic rates than ectotherms. At similar masses, the metabolic rates of endotherms at rest (their “**resting metabolic rates**”) tend to be 5–20 times higher than those of ectotherms.

3. A major scientific principle is that energy is neither created nor destroyed, but it can be transferred or transformed. Summarize some of the transformations of energy described in the two paragraphs above.



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Endotherms tend to have higher metabolic rates than ectotherms, which allow them to stay warm and also to be more active, grow faster, and reproduce faster at a range of temperatures. Higher metabolic rates offer the benefits of a faster pace of life, but this comes at a cost. Endotherms must eat much more often than ectotherms. As a result, they are more at risk for running out of food. For instance, a lizard could go without food for several weeks, but a similarly sized shrew (a small mouse or mole-like mammal) would starve to death in a day without food.

Amphibians and most reptiles, fish, and invertebrates are ectotherms, whereas mammals and birds are endotherms. What about dinosaurs? In the film *Great Transitions: The Origin of Birds*, you learned that scientists used to think that dinosaurs were slow moving and probably ectothermic like most reptiles. However, when Dr. John Ostrom discovered the claw of *Deinonychus*, scientists started to think about dinosaurs differently. The slashing claw indicated that it hunted for prey. Could it be that dinosaurs were fast moving and more active than previously thought? Was it possible that they were endothermic like birds?

In this activity, you will use data from a study published in the journal *Science* to investigate whether dinosaurs regulated their temperatures more like birds (endotherms) or reptiles (ectotherms) do. You will learn one method by which scientists determine whether living animals are ectothermic or endothermic and how similar tests can be applied to animals that are now extinct.

4. Make a prediction of whether you think dinosaurs were more like endotherms or ectotherms. Include the reasons for your prediction.

PART 1: METABOLISM AND MASS OF LIVING ANIMALS

Evolutionary biologist Dr. John Grady and coworkers at the University of New Mexico in Albuquerque compiled data from many earlier studies that measured metabolic rates and metabolic masses for a wide variety of animals living today. A subset of the data they compiled is shown in Table 1. **Metabolic rates** are typically measured based on how much oxygen animals consume while at rest at a particular temperature. The **metabolic mass** is the mass of the animal when the metabolic rate measurement was taken. In some cases, the measurement was taken on a juvenile instead of a fully-grown animal. For example, you can tell that the mass of the alligator in Table 1 is that of a juvenile because its mass is similar to that of a raven, which is much smaller than an adult alligator. The Nile crocodile is also a juvenile.



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Table 1. Metabolic Mass and Resting Metabolic Rate of a Sample of Vertebrates

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



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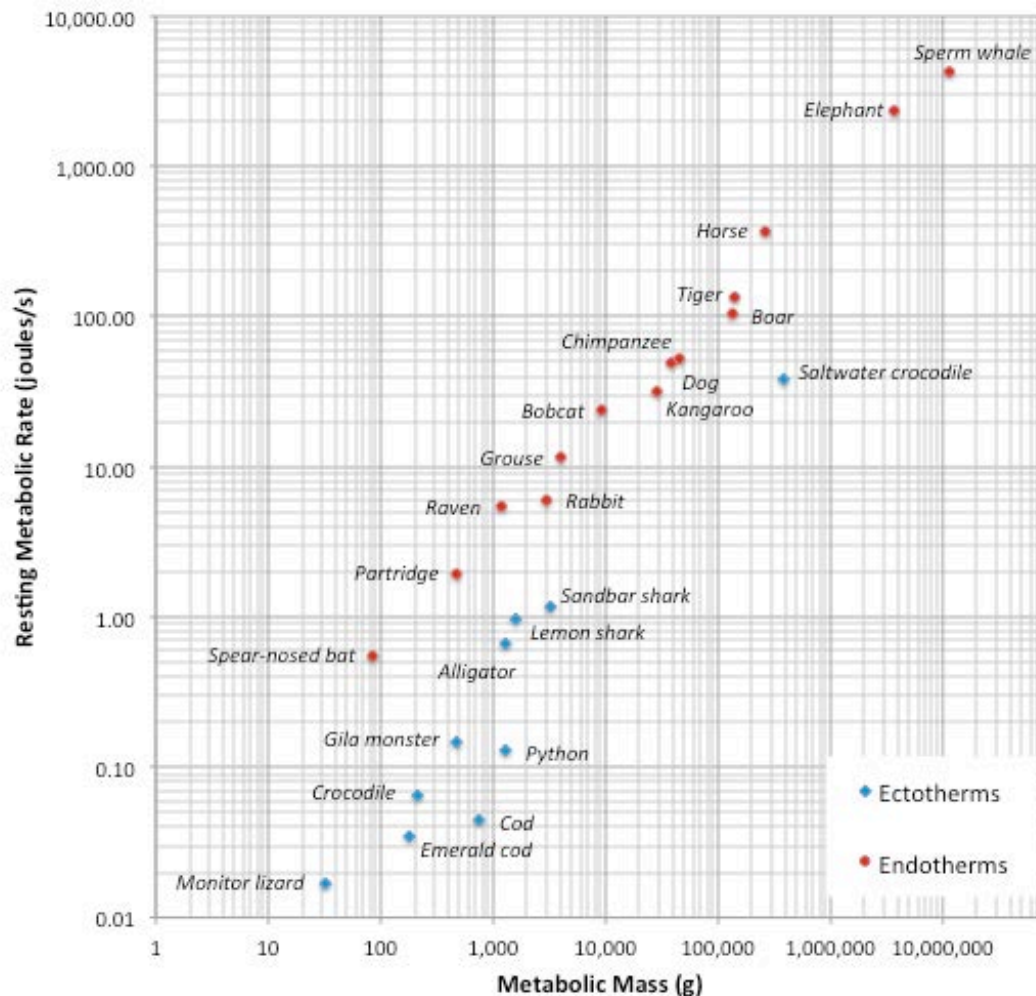


Figure 2. Metabolic Rate versus Metabolic Mass of Vertebrates. Each data point represents an animal listed in Table 1. The filled red circles are endotherms, whereas the filled blue diamonds are ectotherms. Source: Adapted from Grady, John M., Brian J. Enquist, Eva Dettweiler-Robinson, Natalie A. Wright, and Felisa A. Smith. 2014. "Evidence for Mesothermy in Dinosaurs." Supplementary Materials. *Science*, 344, no. 6189 (2014): 1268–1272.

Note that the graph uses **logarithmic scales** on each axis to display data points that span over many orders of magnitude. Why do you think the data were plotted on a log-log graph (i.e., both axes have a logarithmic scale)?

If the data were plotted as a regular linear graph, it would be hard to show all the data, because some animals and their metabolic rates are tiny and some huge. Straight lines on a log-log graph become curved lines if plotted on an ordinary linear scale.

Answer Questions 1–4 relating to the graph in Figure 2.



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1. Look first at the general trends on the graph. How do the metabolic rates of endotherms compare with those of ectotherms?

2. An average adult cheetah has a mass of 44,010 grams and a metabolic rate of 61.77 joules per second. Use these data to place the cheetah on the graph. Based on these data, would you characterize the cheetah as an endotherm or ectotherm? How do you know?

3. Briefly describe data you could collect that would provide additional evidence to directly support the placement of the cheetah as an ectotherm or an endotherm.

4. As the masses of the animals increase, how do their metabolic rates change?

Ectotherms _____

Endotherms _____

5. Use the data in Figure 2 to make a claim about how the metabolic rates of endotherms compare with those of ectotherms for animals of similar mass. Support your claim with at least three pieces of evidence.

6. Fossils are our only link to dinosaurs—we cannot observe their internal temperatures directly, nor can we analyze their soft tissues or DNA. What ideas do you have for the kinds of evidence you could collect from fossils that might allow you to make a claim about whether dinosaurs were ectothermic or endothermic?



PART 2: ESTIMATING DINOSAUR GROWTH AND METABOLISM

Read the questions at the end of Part 2 to prepare for the reading below. As you find information to help you answer the questions, stop and complete the questions.



You learned in Part 1 that mass and metabolic rate can be used to distinguish ectotherms and endotherms. So knowing the masses and metabolic rates of dinosaurs could help settle the question of whether they regulated their temperatures more like birds (endothermic) or like reptiles (ectothermic). But how can we tell how heavy dinosaurs were or how fast their metabolisms were when they haven't been around for millions of years? Fossilized bones can help.

Bone size usually correlates with the mass of an animal. A mouse has narrow, light bones compared to an elephant. We can estimate the mass of an extinct animal by measuring its fossilized bones and comparing these measurements to those of living animals' bones.

Just as bones can be an indicator of mass, bones can also tell you something about an animal's metabolism. The bones of many animals have growth rings similar to the growth rings in trees. The number of bone rings tells you how old the animal is (one ring = a year), and the width can tell you how fast it grows. A fast-growing animal, like a mouse, has wide rings in its bones, while a more slowly growing animal, like a lizard, has narrower bone rings. Scientists can use growth rings to estimate resting metabolic rates. Estimates of metabolic rates calculated this way are in close agreement with metabolic rates measured directly by looking at oxygen consumption. In fact, if you were to draw a graph of *growth rates* versus mass it would look quite similar to the graph in Figure 2 that plots *metabolic rates* versus mass.

Bone rings have been preserved in the fossilized bones of some dinosaurs. This gives researchers a way to estimate the metabolic rates of these long-extinct animals. Grady and colleagues compiled a database of the estimated metabolic rates of 21 dinosaurs. Table 2 lists five of them.

Table 2. Masses and Estimated Resting Metabolic Rates of Five Dinosaurs

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

(Dinosaur images courtesy of Nobu Tamura and Jim Robins through Wikimedia Commons.)



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Plot the data from Table 2 in the graph in Figure 2 and then answer the questions below.

7. From the reading, summarize the evidence that scientists use to estimate the mass and the metabolic rate of dinosaurs.

8. Explain why a mouse has wider rings in its bones than a lizard.

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

10. Draw a **line of best fit** through the endotherms, through the ectotherms, and through the dinosaurs in Figure 2. Make a claim about whether the relationship between mass and metabolic rate in dinosaurs follows a pattern more similar to ectotherms or endotherms. Support your answer with evidence.

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



PART 3: THE ENERGETICS OF DINOSAURS

In Part 2, you learned that metabolic rate can be inferred from growth rate. You also discovered that animals with greater mass have higher metabolic and growth rates. For example, both an alligator and a dog have higher metabolic rates than small birds called warblers because they are bigger in size, regardless of whether they are ectotherms or endotherms. So what happens if you take mass out of the equation? In the graph in Figure 3, which is from the original *Science* paper, Grady and colleagues plotted growth rates and metabolic rates for various animals, including dinosaurs, in a way that controls for mass. In other words, if the alligator and the warbler were the same size, what would their metabolic and growth rates be? The growth rates and metabolic rates of dinosaurs were calculated from fossilized bone rings.

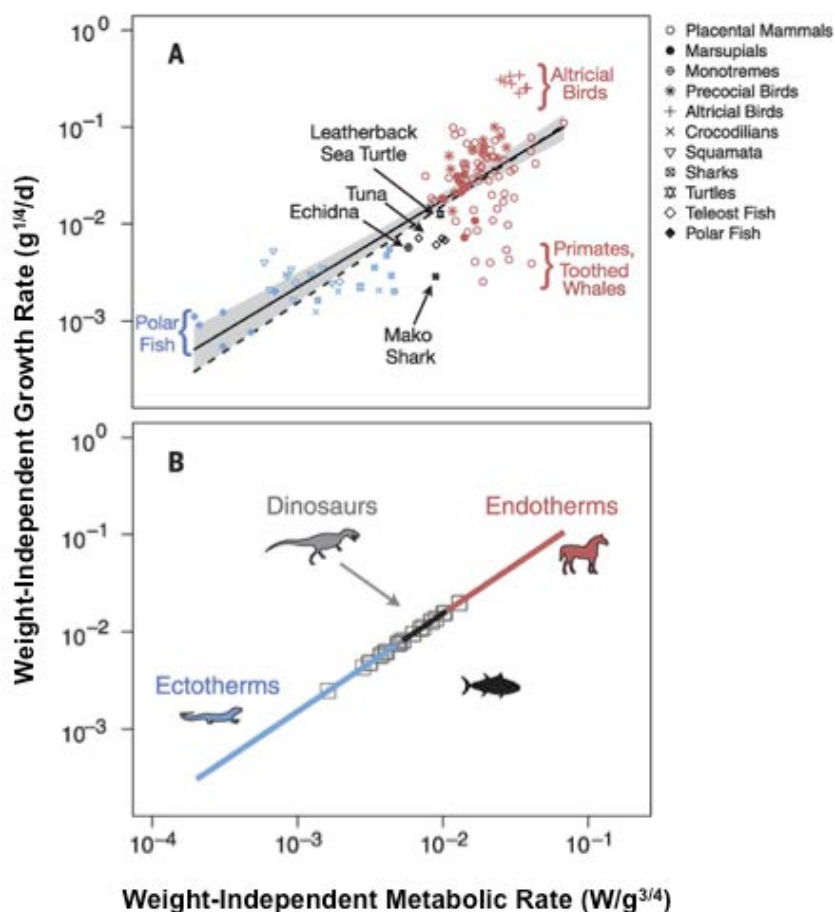


Figure 3. Mass-Independent Growth Rate versus Resting Metabolic Rate. This graph uses logarithmic scales on each axis to display data points that span over many orders of magnitude. Note that the metabolic rate unit watts (W) is equal to joules per second. (A) Mass-adjusted rates of living vertebrates. The shaded area represents 95% confidence intervals. (B) Estimated rates for dinosaurs. The line represents predicted rate ranges for living ectotherms (blue, lower left), endotherms (red, upper right), and animals in between the two (black, middle). Estimated dinosaur rates are shown as open squares. Source: Grady, John M., Brian J. Enquist, Eva Dettweiler-Robinson, Natalie A. Wright, and Felisa A. Smith. 2014. "Evidence for Mesothermy in Dinosaurs." *Science*, 344, no. 6189 (2014): 1268–1272.



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12. In the graph in Figure 3, which types of animals have the highest weight-independent growth rate? Which have the lowest?

Highest _____

Lowest _____

13. In the graph, which types of animals have the highest weight-independent resting metabolic rate? Which have the lowest?

Highest _____

Lowest _____

14. As the resting metabolic rate increases, how does the growth rate change?

15. In their paper, Grady and colleagues conclude that dinosaurs were **mesotherms** (*meso-* means “middle”). Compare the growth rates of dinosaurs with the growth rates of living ectotherms and endotherms. Why do you think these scientists describe dinosaurs this way, and do you agree with their conclusion? Refer to specific data points to support your answer.

16. Grady and colleagues made their data available to all other scientists. One scientist reanalyzed their data using some different assumptions and came to an alternative conclusion. This scientist also carefully described the methods he used for his calculations. Grady and colleagues reviewed the work of the other scientist and replied with an argument about why their method of calculating metabolic rates was correct. Describe how these events exemplify how science works.



PART 4: THERMOREGULATION IN DINOSAURS

The data in Figure 3 suggest that dinosaurs fall somewhere in the middle on the continuum between ectotherms and endotherms in terms of their metabolic and growth rates. Because dinosaurs are in between ectotherms and endotherms, Grady and colleagues classified them as mesotherms—a term used for animals who have features of both these categories of animals.

Dinosaurs are not the only mesotherms. Great white sharks, tuna, and leatherback turtles are examples of living mesotherms (Figure 4). These animals use their metabolisms to maintain temperatures higher than the environment around them, but they do not regulate their temperatures as closely around a fixed point as most mammals and birds do.



Figure 4. Examples of mesotherms. Leather back turtles, great white sharks, bluefin tuna are living mesotherms. (Photos courtesy of U.S. Fish and Wildlife Service Headquarters and Elias Levy through Wikimedia Commons.)

How Can Being a Mesotherm Be an Advantage?

There are both costs and benefits associated with being endothermic or ectothermic. Consider the following information about endotherms:

- To maintain their body temperatures, endotherms need to take in much more energy than ectotherms—as much as 5–10 times the number of joules at any given body mass.
- Endotherms can maintain a stable internal temperature even when outside temperatures rise far above or far below their body temperatures.
- Ectotherms can tolerate more variable internal conditions than endotherms can.
- Endotherms can have higher levels of activity than ectotherms because of efficient respiratory and circulatory systems, and because they are optimized to use more energy. Ectotherms can have high levels of activity in warm conditions, but they tend to become very sluggish when their bodies are cold.
- Although large reptiles exist, they are mainly limited to areas that lack endothermic predators of similar size. For instance, crocodiles hunt in rivers where few mammals go. Large Komodo dragons and tortoises live on islands lacking mammalian predators. The reason there are few large reptiles in our present time is that, due to their relatively slow growth, reproduction, and overall activity rates, large ectotherms would be likely outcompeted (or eaten) by large endotherms. Only in the ocean, where air-breathing endotherms (such as dolphins) are less dominant, do large ectothermic sharks and fish coexist with endothermic mammals.



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- 17.** From an evolutionary point of view, how could being mesothermic have been an advantage for dinosaurs as compared to being ectothermic or endothermic?

- 18.** In the previous answer, you described how being mesothermic can be an advantage. Why do you think that more animals are not mesotherms at this point in time?

- 19.** The HHMI film presented research findings that support the idea that birds evolved from theropod dinosaurs. Much of the information in the film focuses on structures in the body that were either more reptile-like or more bird-like. How do the data in this activity add to your understanding of the relationship between dinosaurs and birds?

REFERENCE

Grady, John M., Brian J. Enquist, Eva Dettweiler-Robinson, Natalie A. Wright, and Felisa A. Smith. "Evidence for Mesothermy in Dinosaurs." *Science*, 344, no. 6189 (2014): 1268–1272.