How heavy is your pet dinosaur?

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Abstract How heavy is your pet *Tyrannosaurus rex*? Accurately ascertaining the mass of a large carnivorous dinosaur is a challenging task for most students. Here, a simple method using model dinosaurs and some straightforward mathematics is provided. This is considerably more practical and safer than weighing the living dinosaur itself.

Ascertaining the mass of a living pet *Tyrannosaurus rex* presents a number of logistical and feasibility problems, foremost among which is the current paucity of tyrannosaurs. Even assuming you have a live dinosaur to hand, the actual weighing poses technical challenges. Most bathroom scales will probably prove inadequate for the task. Such devices are designed with human usage in mind; in the majority of cases, dinosaurs weigh more than humans. Furthermore, the weighing of large carnivorous animals by students poses self-evident health and safety issues. An ingenious method relying on mathematical acumen is needed instead.

Here, a simple method to calculate dinosaur mass using models is presented. Students make scientific measurements, use mathematical concepts such as density and scale, and follow simple steps and procedures. As students (and many adults) find dinosaurs inherently interesting, this is an ideal way to integrate maths into biology lessons. This is an established method of ascertaining dinosaur mass: Colbert (1962), McNeill Alexander (1989), and Culp and Wolf (1995) used similar methods.

Using models to learn about the real world

Start the lesson by explaining why models are used in science. Models provide a realistic representation of something from the real world, but in a smaller more manageable format. Models allow an object's physical properties to be studied, without any of the inherent difficulties involved with handling the actual real-sized object. Before building bridges, civil engineers first make models to predict the strength and durability of the future structures. Aircraft engineers test the aerodynamics of model aircraft in wind tunnels, to learn about the flight capabilities of real-sized aircraft. Similarly, palaeontologists can use model dinosaurs as a safer and easier substitute for the real living and breathing animals.

An obvious biological parameter that budding amateur dinosaur biologists would like to know is dinosaur mass. Colloquially, we often confuse the terms 'weight' and 'mass'. However, 'mass' refers to the amount of matter an object contains, while 'weight' refers to the gravitational forces acting on a mass. Figures for dinosaur mass can be found in books. Often, however, especially if the book is non-scientific, the authors have simply guessed what a dinosaur's mass would have been based on its size and through comparing with large living animals around today. Can we work out dinosaur mass ourselves in a more scientific manner using models?

Task and concept

The task is to estimate the mass of a full-sized dinosaur using a smaller replica model. A model dinosaur submerged under water will displace its own volume in water. The volume of a real-sized dinosaur can then be worked out by multiplying the volume of the model by its scale. Living tissue will have a particular density, i.e. its mass per unit volume. An estimate of the mass of a full-sized dinosaur can be found by multiplying its volume by this density.

There are essentially five steps:

1. working out the volume of a model dinosaur;
2. ascertaining the scale of the model;
3. calculating the volume of the full-sized dinosaur using the scale;
4. multiplying dinosaur volume with the density of living tissue;
5. converting into tonnes.

Here, two examples are provided, with the mass of 'Sue' the tyrannosaur and 'Sophie' the stegosaur being estimated. Sue is the most complete known skeleton of a tyrannosaur. She is housed in the Field Museum of Natural History in Chicago (Field Museum of Natural History, 2018). She was discovered in 1990 by the palaeontologist Sue Hendrickson, after whom she is named. Sophie is an almost complete skeleton of a stegosaur, housed in the Natural History Museum in London (Brassey and Hendry, 2014).

Equipment

Students need a small model dinosaur, ideally made from plastic. The ready availability of such models is clear evidence of the enduring popularity of these gigantic reptiles. Models can be purchased for a relatively low price. Ideally, they should state the scale. If not, this can be easily calculated. Also needed is a large bowl or plastic container in which to immerse the models. A measuring cylinder is needed to measure the volume of water displaced by models.

Classroom procedure

Step 1: Working out model dinosaur volume

1.1 Setting up

Instruct the students to fill a large container with water until it is half full (Figure 1). Wait for the water to settle. Using a water-resistant fine felt-tip pen, they should mark the level of the water, using the bottom of the meniscus throughout (Figure 2).

1.2 Submerging the dinosaur

Next, students should immerse the dinosaur fully in the water (Figure 3). The orientation of the dinosaur does not matter as long as it is fully covered with water. They will see that the level of water rises as the dinosaur is immersed. Keeping the dinosaur immersed, they should mark the level the water now reaches (Figure 4). There are now two marks: one recording the original level of the water, and a second higher mark recording the level when the dinosaur was submerged.

1.3 Measuring the volume

When the dinosaur is removed, the water level will fall back to where the original first lower mark was made (Figure 5). Using a measuring cylinder, students should add measured amounts of water into the container, recording as they go. I used 5 cm^3 of water at a time, but different set amounts can be used depending on the model size – students can experiment to find what volume works best. The water level will rise as the students add measured amounts of water, until it reaches the upper mark corresponding to the level when

Figure 1 The model dinosaur and the container

Figure 2 The container half-filled with water; making the first mark

Figure 3 Immersion of the model dinosaur

Figure 4 A second mark is made, higher than the first, when the dinosaur is fully immersed

Figure 5 Once the dinosaur is removed, add measured amounts of water to the container until the water rises again to the second mark. How much water was added?

the dinosaur was immersed. How much water did they need to add? This is the volume of the model. Alternatively, students can add water until the upper mark is reached and then pour out the water contained between the two marks into a measuring cylinder.

The teacher should practise beforehand to ensure that the equipment used is suitable. Students can also practise and make trial runs. This is just like real-life science: experiments rarely function correctly the first time. Using a bowl or container that is fairly narrow in diameter makes the experiment easier as the differences in water level are greater and thus easier to measure. Students might attempt to immerse dinosaurs in an upright orientation; however, the models should be immersed in whatever orientation is most practical. The dinosaur will not complain if it immersed upside down. Students could try different sized and shaped containers to find the most suitable. They need to be fairly exact; care needs to be taken in making the pen marks and in measuring. I repeated measurements three times and then worked out the average: for Sue this was 72.7 cm^3 and for Sophie it was 73.3 cm^3 (Table 1). These were then rounded to 73 cm^3 for both models. The manufacturer probably made both models using the same standard volume of material.

Table 1 The volumes of water displaced when immersing the dinosaur models

Volume of water displaced / cm^3	
Sue the tyrannosaur	**Sophie the stegosaur**
74	74
72	73
72	73
Average: 72.7	Average 73.3

Step 2: Calculating the model's scale

Students then need to determine the scale of the model dinosaurs. By how much do we have to multiply the size of the model to obtain the size of the actual dinosaur? Sometimes the models will tell you this. It can also be easily worked out. Students need to find the body length of the 'real-life' dinosaur by referring to books or the internet. Sue the tyrannosaur had an actual body length of 12.3 m, with the model length being 180 mm. Sophie the stegosaur had an actual body length of 5.6 m, with the model length being 152 mm.

Dividing the actual body length by the measured length of the model provides the scale.

$$\text{scale} = \frac{\text{actual length (mm)}}{\text{model length (mm)}}$$

Note that the units used must be the same, for example mm. Thus:

Sue the tyrannosaur: 12300/180 = 68.33
Sophie the stegosaur: 5600/152 = 36.84

For simplicity, we can round these scales to 1 : 68 and 1 : 37. If we multiply the length of the models by these scale factors, we obtain the actual length of the 'real-life' dinosaurs.

Step 3: Working out the actual dinosaur volume

Students now know both the volume of the model and its scale. What is the corresponding volume of a real-sized dinosaur? We use multiplication to find out. Volume is a measurement of three dimensions: length, height and depth.

$$\text{volume} = \text{length} \times \text{height} \times \text{depth}$$

We must multiply the volume of the model (cm^3) by the scale cubed:

$$\text{volume of actual dinosaur} = (\text{volume of model}) \times (\text{scale})^3$$

The rounded volume of both models was 73 cm^3. Sue's scale was 1 : 68 and Sophie's scale was 1 : 37. Therefore:

volume of Sue the tyrannosaur:

$$\begin{aligned} 73 \times 68^3 &= 73 \times (68 \times 68 \times 68) \\ &= 73 \times 314432 \\ &= 22953536 \\ &\approx 23000000 \text{ cm}^3 \end{aligned}$$

and

volume of Sophie the stegosaur:

$$\begin{aligned} 73 \times 37^3 &= 73 \times (37 \times 37 \times 37) \\ &= 73 \times 50653 \\ &= 3697669 \\ &\approx 3700000 \text{ cm}^3 \end{aligned}$$

Step 4: Calculating the mass of a full-sized dinosaur

Depending on its density, a particular volume of a material will have a certain mass. For example, a single 1 cm^3 of water will have a mass of 1 g because the density of water is 1 g cm^{-3}. While the various component tissues of an organism, such as bone, muscle and fat, will each have different densities, the average density is sufficient for our purposes. Imagine liquidising a dinosaur so that the mixture would have uniform density throughout!

If the mass of 1 cm^3 of this mixture, i.e. the density, is multiplied by the volume of the real-sized dinosaur, we will have an estimate of its mass.

What is the density of 'living material'? Colbert (1962) used figures from living reptiles: an average 1 cm^3 of alligator has a mass of 0.89 g. In his calculations, he used a figure of 0.9 g cm^{-3}. McNeill Alexander (1989) and Henderson (1999) used a rounded figure of 1 g cm^{-3} for simplicity. For these calculations, I decided to say that 1 cm^3 had a mass of 0.9 g.

volume (cm^3) × density (g cm^{-3}) = mass (g)

Sue the tyrannosaur: 23000000 × 0.9 = 21000000 g
Sophie the stegosaur: 3700000 × 0.9 = 3300000 g

Step 5: Convert to kilograms and tonnes

Using grams is cumbersome for such large masses; kilograms or tonnes would be easier to comprehend. A tonne (or 'metric ton' in the USA) is 1000 kg, and, similarly, to convert grams to kilograms we have to divide by 1000 (there are 1000 grams in a kilogram).

Sue the tyrannosaur: 21000000/1000
= 21000 kg = 21 tonnes
Sophie the stegosaur: 3300000/1000
= 3300 kg = 3.3 tonnes

Scientific estimates

Sue is the largest tyrannosaur ever to be found. Estimates for her mass vary widely: Henderson (1999) used a method of slicing dinosaurs using computer images and estimated 6.8 tonnes. A more recent estimate using more advanced computer technology estimated a mass of 18.5 tonnes (Hutchinson *et al.*, 2011). Recent analysis at the Natural History Museum using 3D computer modelling suggests that Sophie the stegosaur had a mass of 1.6 tonnes (Brassey, Maidment and Barrett, 2014; Amos, 2015). Our estimates are larger than these. Can students think of reasons why? There remains no consensus over dinosaur mass; research continues to refine estimates.

Problems

This method provides only an approximate estimate of dinosaur mass. Slight variations in the scale and volume of model will greatly influence the final figures obtained. Although apparently easy, obtaining an accurate measurement of scale is deceptively difficult. As dinosaurs are extinct, knowing their exact volume is not possible (Henderson, 1999). The models may not be an entirely accurate representation, as making dinosaur models is a matter of interpretation. Additionally, the figure used for the average density of reptile tissue is not exact. Henderson (1999) tried to deal with this by reducing the density estimate by 10% to account for lung volume and by treating some dinosaur slices differently.

The concepts involved can be challenging for some students. It is easy for them to fall into the trap of thinking they are finding the mass of a life-sized dinosaur made of the same material as the model. Emphasise that this is not so with targeted questioning: Why do we need to know the mass a particular volume of living material has?

Suggestions

- Consider doing the calculations together as a class with results being pooled; they can be confusing for some.
- It is best to concentrate on only one or two models, rather than many. Although this might mean much sharing, this is better than having to work out the calculations for many models.
- The teacher should practise with the models to be used beforehand to check that the method works effectively. Have figures at hand for your models should problems arise.

Extensions

- Can students suggest problems with the method? Why might it not be accurate? Why do the estimates obtained vary from those in books and the internet? How could the experiment be made better?
- What are the advantages and disadvantages of your method and others using computer technology?
- What if dinosaurs were fatter or more muscular than modern reptiles? How would this affect the accuracy of estimates?
- Most people understand how much a kilogram of flour is, but large masses have little everyday relevance to most. What else compares to a dinosaur weighing over a tonne? Are dinosaurs heavier than a car, a lorry, a bus? Find out!

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