Evolving_for_Survival_-_Learning_About_Fluid_Dynamics_through_the_Urinary_System_of_Mammals

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DAVID HU: We're at the Franklin Park Zoo in Boston, Massachusetts. And I'm David Hu, an associate professor of mechanical engineering and biology at the Georgia Institute of Technology. My laboratory is interested in the motion of animals, both on the outside and on the inside. You might remember my BLOSSOMS lesson on mosquitoes back in 2013.

Today, we'll consider how an animal pumps fluid out of its body. In particular, we'll consider the urinary system, which works just as well for a small mouse as well as it does for the big giraffe right behind me. Our bodies are mostly fluid. For proper functioning of the body, fluid must be taken in and it also must be excreted. These systems work so well that they are in fact underappreciated. In reality, they are the result of fine tuning of millions of years of evolution.

Your urinary system too is an evolved system. Years of evolution have resulted in a urinary system that works so well that it goes unnoticed. We don't notice how well these systems work until they break down. Medical problems with the urinary system include kidney stones, urinary tract infections, and prostate cancer. Many of these problems are hard to diagnose, because the urinary system is hidden inside your body.

Today, we'll introduce a simple way to characterize the health of your urinary system. We also look into how evolution has helped animals solve an interesting variety of problems. The marvelous thing about evolution is the wide range of body sizes that have emerged. It involves a mass range of 1,000, from a puppy that weighs just a few pounds to an elephant that weighs several thousand pounds.

The urinary system that works well for the puppy must also work for the elephant. Imagine designing both a squirt gun and a fire hydrant using the same set of genes. This is the task the nature has at hand when evolving systems for a wide variety of animals.

Today, we'll study the urinary system. It allows animals as big as this lion to release gallons and gallons of fluid at huge flow rates. It allows these animals to do so quickly, to avoid predation and being eaten by larger prey. Now let me introduce my assistant, Patricia Yang, who will start us off with our first experiment.

PATRICIA YANG: We're going to empty out a plastic bottle. How much time does it take? What are the forces involved in emptying a bottle?

DAVID HU: Thank you for measuring the time to empty out the plastic bottle. We saw that the plastic bottle empties because of the force of gravity. And it takes about six seconds. We know that gravity acts on solid objects such as these keys. My hand makes it go up. Gravity makes it fall back down.

PATRICIA YANG: Gravity is the force that pulls down the fluid particles to the lowest point on the ground.

DAVID HU: Now imagine the liquid in this plastic bottle consists of many small balls called fluid particles. Gravity is acting on each fluid particle and wants it to reach its lowest point, which is in a puddle on the ground. Now, the interesting thing about fluids is that they can transmit forces in surprising ways. We saw that the plastic bottle emptied out even faster if held vertically.

I've taken these two plastic bottles and I've drilled holes, both on the side and on the bottom. Now, take the bottles and measure the time to empty them when they're held both horizontally and vertically. In which orientation does the bottle empty faster? Why?

Thanks for measuring the time to empty out these bottles. Remember, they both have the same volume. But the bottle that was held vertically emptied out the fastest. To measure how quickly fluid leaves the bottle, we first use flow rate, also known as volumetric flow rate Q. Q has units of volume per time, for example, liters per second. The higher the volumetric flow rate, the more volume comes out of the bottle per second.

For example, your shower head has a flow rate of one fifth of a liter per second. The volumetric flow rate is related to the volume of the container and the time to empty it according to the equation Q equals volume divided by time, where Q is flow rate, V is the volume of the container, and T is the time to empty it. Q is the average flow rate over the duration that the container is emptied. Now that we have Q, the volumetric flow rate, we can estimate the fluid speed U.

This is the speed of individual fluid particles. Consider the cross-sectional area of your pipe is a highway and the fluid particles are flowing down the highway and out the pipe. The relationship between Q, the flow rate, and U, the flow speed, is Q equals U times A, where the area A is pi R squared, or the cross-sectional area of a circular tube of radius R.

Now that you have calculated the fluid speed, please consider the relationships between fluid speed and the height of your container. You'll find that the speed increases with the height of the container, but very slowly. This equation is called Torricelli's law. And it was discovered in 1643 by the Italian physicist Evangelista Torricelli.

Torricelli also invented the barometer, which is used in atmospheric pressure measurement. This law states that the relationship between speed of fluid and the height of the container from which the fluid is emptied is U is equal to the square root of the quantity 2 times gravity times L, where U is a fluid speed exiting the container, G is the acceleration of gravity, and L is the height of the fluid in the container.

The reason for this phenomenon relates to the pressure at the bottom of the bottle. The pressure is higher for bottles held vertically, because the weight of the fluid pressing down. The higher the pressure, the higher the flow speed coming out. Now, using the equations you've learned, derive the time to empty the bottle as a function of its shape, its volume, its height, and the area of the hole underneath and the acceleration of gravity G. In our next lesson, we'll use the relationship between body mass and bladder shape to predict the time for all sorts of animals to empty their bladders.

In our last lesson, we learned that the time to empty a container was related to both its volume and the speed of the flow. The speed of the flow is related in turn to the height of the container through a relationship that we saw earlier was called Torricelli's law. This is an important result, and we'll use it throughout this lesson. You probably didn't think there was so much physics going on in just emptying a container. But just because a phenomenon is familiar, doesn't mean it's well-understood.

From the previous activity, you learned how to calculate the time it takes to empty a container. This time was a function of the shape of the container, specifically, its height and the area of the hole. Thus, a container shape can affect how quickly it's emptied. How does this physics affect the emptying of fluid-filled vessels in nature?

In fact, there are many fluid-filled vessels in the body, including the cardiovascular system, the lymphatic system, the digestive system, and the urinary system. In this last example, the fluid is urine, which has properties, such as density and viscosity, that are quite similar to water. This feature makes the urinary system the most amenable to the modeling methods that we have covered.

In nature, there's quite a large range of bladder sizes. They range from the size of a kitchen cup to a garbage can, which contains almost 20 liters. That's a volume range of over 100 times. In your experiments, you only varied the volume of your containers by a factor of five. Because the volume range is so large, it's best to use theory to predict the emptying rates of these containers.

But in using theory, we must decide on a single variable to compare how quickly an animal empties its bladder. We saw previously that we had two such variables, the emptying time and the flow rate. Let's use time, because it's easier to measure. We've recorded the time to empty bladders in nature, from a dog all the way up to an elephant.

That data is shown here. The dashed line indicates the best fit for all these measured urination times. You'll see there's a narrow range of time, between five and 30 seconds, that encapsulates all this data. That's a small range, considering the factor of 100 range in bladder sizes. The relationship between the time and body mass is time is equal to k times M to the 0.13 power.

We call this the law of urination, or the golden rule. The small magnitude of the exponent means that urination time changes very slowly with body mass. We provide the bladder volumes, urethra diameters, and urethra lengths for three animals in the table here. For each animal, please estimate the fluid speed, flow rate, and time to empty their bladders.

You've just calculated the bladder emptying times for three animals of vastly differing size-- a dog, a cow, and an elephant. You found that these emptying times were quite similar, all about 20 seconds, despite the huge variance in the volume of the bladder, which is a factor of over 100. It's quite an unexpected result, isn't it? You'd expect bigger bladders would require more time to empty. But that would also mean that bigger animals would be in greater danger of predation.

In fact, our experiment showed that roughly all mammals take the same time to urinate. Why do animals of such vastly different bladder volumes have the same urination duration? There are two answers. Let's use the elephant urethra as an example. The elephant's urethra has dimensions almost the same size as your arm. Its width is about 10 times wider than a dog's urethra.

This is like a highway. The wider the highway, the more lanes it has. The more lanes, the more cars can flow through. So every single second, there are more cars flowing down the urethra. This is one way the elephant increases its flow rate. The second reason is more subtle. As I said, the elephant's urethra is about this long.

The higher the urethra, the greater the gravitational force and the greater the pressure that drives the flow. The greater the pressure, the faster the cars move. So not only are there more lanes, but each car is driving faster. This combination of a wide, cross-sectional area and a very tall height allows the urethra of the elephant to eject 20 liters in just 20 seconds.

That is a flow rate of five shower heads. We have also discovered the purpose of the urethra. It's a biological valve. Its geometry varies the speed at which flow leaves the bladder. Specifically for the elephant, the elephant urethra's length of one meter amplifies the force of gravity, an increase of the speed at which urine is ejected from the elephant.

This method is not restricted only to animals. It can also be applied to engineered systems. In our next activity, we'll show that you can build a water tower of arbitrary volume that can be emptied in a very short period of time.

Up to now, the largest container we considered was only 20 liters. Our last activity of the day will be to consider how long it takes to empty a water tower. Consider water towers of volume 100, 1,000, and 10,000 liters. What shape of pipe would you put underneath this water tower to make sure that all of the fluid leaves in 20 seconds?

There are many applications for getting fluid out quickly. For example, often in apartment buildings, water use all occurs all at the same time, for example when people need to take a shower. So we need a fast way to release this water. You can also imagine a water irrigation system that uses the same technique.

We can use these principles to design new pumps that eject fluid as fast as we want. We can control the speed without having valves. We call this concept a scalable hydrodynamic system. This concept of a scalable hydrodynamic system may be used in the design of portable reservoirs, such as water towers, storage tanks, and hydration packs.

We hope you enjoyed this BLOSSOMS lesson, evolving for survival. Animals like this can be inspirational for engineering all sorts of new devices. If you just keep alert, you might be inspired too next time you take a trip to the zoo.

Thank you for considering this BLOSSOMS lesson for your classroom. In terms of prerequisites, the students should have had some familiarity with basic physics. So they should know what a speed is, in particular, its units of distance per time. That's important, because throughout this lesson, to get the time to empty a bladder, you've got to calculate the speed at which fluid flows.

They should also be able to use a calculator. In this lesson, we provide different biological values for this geometry of this urinary system, the bladder volume, the urethra length, the urethra width. And they'll need to be able to input these numbers either into a calculator or maybe better yet, an Excel spreadsheet and figure out this urination time through the equations we provided. So some basic ability to manipulate several numbers, different numbers together to make a calculation is needed.

But there'll be no calculus in this lesson, so all we're doing is algebra, some multiplication, and division. And I think that's all they'll need. They don't need any biology experience, really. We'll provide all the biological variables, but they do need some familiarity with using numbers.

This BLOSSOMS lesson has several learning objectives. The first is to learn to use a wide variety of units and numbers. To calculate the speed of urination, they've got to manipulate a couple different variables-- lengths, speeds, times, acceleration of gravity. And they've got to be able to keep these units straight. So learning to do this will teach them how to manipulate variables of different kinds of units.

Another objective is to be able to compare their calculations to real life. And this is very important. This is what a lot of scientists do. And the nice thing about this lesson is that we have experiments that can be very easily done. So the students will actually be able to do the experiment themself, measure the time to empty these pretend bladders. And then they'll be able to calculate what that time should be.

So being able to compare real-life data to calculations-- that's another important learning objective of this lesson. Now let me give you a few suggestions for how to coordinate the lesson. What I like about this lesson is the ease of the experiments. These experiments couldn't get any easier. We just get a few containers and we use them to conduct these experiments.

Now, I suggest that you run through this on your own first, because the experiments are easy, but they can get wet. I mean, there's going to be water everywhere. So make sure all the plugs and things are put away when these experiments are being done. But I think the students will also enjoy that part of the lesson.

I suggest that students work in teams of at least two, because the process of doing these experiments requires one person, really, to hold the container, to open the plug. And it requires another student to do the stopwatch part, basically-- maybe taking their cellphone and timing the amount of time this fluid leaves and writing it down. It really requires two sets of hands. The nice thing about this lesson is that the students can actually do the experiments themselves, and there's a minimum of equipment.

So these experiments are actually quite surprising in the sense that the different containers, a lot of different behaviors of how they release fluids. So let me show you a little bit about how-- so a student built these containers for me. But I think you could probably easily do them yourself or recruit someone to help you. So the ones we used in the very beginning of the lesson were simply these models. We prefer to use transparent bottles, because you can actually see more easily when the fluid is finished emptying.

So when you make these, what we do is take off the labels, and then you simply take a drill and drill. For example, this one, if you remember, it was the fluid that was being emptied out horizontally. We drilled two holes, one to drain the fluid and the other to allow air to come in. And that's basically a rule we use for all the bottles we make. You have to have this entry hole for the air. Otherwise, you get suction that builds up, generates problems with the flow. And it's because the real bladders in nature actually are collapsible, whereas all the things here are rigid.

So this one has two holes all the way through. The one in the vertical bottle has just simply a hole in the bottom, so we could just hold them just like this and the students can do the timing. You got to remember, make sure the students are holding them straight. If the students are holding them at an angle, it'll affect the time. So make sure they're held simply horizontally and vertically.

Another striking thing about this lesson is that the methods that we use work for any size of container, all the way from these small plastic bottles we had earlier to very large ones. This is a gallon jug that we used. Again you have the entry hole for air in the back. And when you're not-- when basically you're filling up the bottle, you want to plug it up with some kind of rubber stopper.

And then we take the cap and we can basically use the cap to make an airtight seal to place the urethra. So the cap can be screwed on like this after you've placed the water and then you can conduct your experiment. The hardest part about making these bottles is the seals. So we have just this hot glue gun that we use to glue this plastic tube, which can be purchased on McMaster-Carr website and make a watertight seal.

But in my experience, I've found that students really like it when there's varying amounts of fluid. And it also adds the drama of the thing, because this is going to get really heavy when you hold it. And you can imagine how difficult it is when the elephant is doing this thing, because the elephants actually carrying five of these around in its bladder.

Now, there's a portion of the segment that the students calculate Torricelli's law. This is where they prove Torricelli's law of themselves, and to do that, they need to use-- so Torricelli's law, if you remember, relates the speed at which fluid leaves a container to the height of the container.

And the easiest way to do that is to make containers using replaceable urethras. So for example, this is simply a plastic bottle that you can find in a store. We drill through the bottom, and then we hot glue a larger tube, making it so that we can basically insert other tubes into it.

And then you can imagine inserting a tube of this length, this length or shorter. And if you have enough tubes, the student can use all these to get data, which they can write down. And I think this is a nice exercise. It allows them to prove Torricelli's law for themselves. When you these different experimental apparatuses, make sure that you buy a lot of extra stoppers.

They're always being lost. But I think you'll find that the time to make these experimental equipment is quite worth it. The students will really enjoy doing experiments. And it's one of the few experiments you can do that involve fluids that you can really get some pretty accurate numbers compared to what you find in nature.

So thanks again for watching this teacher segment and for considering this lesson. If you have further questions, please consult the website where this BLOSSOMS lesson is. We have links to the original paper which was published in Proceedings of National Academy of Sciences. And there's a few other educational videos. There's an NPR segment that also shows lots of videos of animals urinating. Thanks again. See you next time.

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