Easily digestible Aerospace Principles revealed for K-12 Students and Educators. These lessons will be sent on a bi-weekly basis and allow grade-level focused learning. - AIAA STEM K-12 Committee.

POPPING A WATER BALLOON IN SPACE

What happens when you pop a water balloon? Water goes everywhere and everybody in the area gets wet. But what happens when you pop a water balloon in space? This lesson explores this question, as well as delving more deeply into the question of popping a water balloon here on the Earth.

Next Generation Science Standards (NGSS):

- Discipline: Motion and Stability: Forces and Interactions
- Crosscutting Concept: Cause and Effect
- Science & Engineering Practice: Planning and Carrying Out Investigations

GRADES K-2

K-PS2-1. Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.

Water is a liquid. What makes a liquid a liquid and not a solid or a gas? It keeps a constant volume and takes the shape of whatever container it is placed in. So water balloons are squishy, wobbly fun—until they burst. (Then they are wet, messy fun.) If you throw a water balloon very gently or drop it only a short distance, it may bounce when it lands and the water will slosh around inside of it from the force of the collision. But if the balloon hits a surface hard enough, or is pierced by something sharp, then "Bye-bye, balloon," and the water sprays everywhere. Why is that?

Several factors are at work here on Earth when we throw or pop a water balloon. There is the elastic nature of the balloon material, which shifts and molds itself to whatever surface it encounters (hands, face, ground). Because it is not a rigid container, it changes shape and redistributes the force of the impact, sometimes allowing the balloon to remain intact. There is also the liquid state of the water inside the balloon, which shifts with the changing shape of the balloon. (If you put a water balloon in the freezer until it becomes an ice balloon, you can see the difference.)

The pressure from the water pushing outward against the inside of the balloon causes the material of the balloon to stretch. When the water does not make the balloon stretch too

GRADES K-2 (CONTINUED)

far, the balloon remains intact. (If you have ever overfilled a water balloon, you know what happens when the pressure from the water exceeds the tolerance of the balloon's skin.) After a balloon is tossed and hits another surface, or if it is punctured by something sharp, the part of the balloon's skin at the impact point or at the sharp object is stretched too far and it breaks, letting the water escape. The water's pressure against the balloon skin causes a little bit of the water to spray outward from where it has been pressed against the balloon; if the water balloon was thrown, the water also continues along the path it was traveling while inside the balloon. And then there is gravity, which pulls the balloon and water downward. Here is a video demonstrating what happens to water balloons when they pop; you may want to try these links (please be cautioned that the video in the Mental Floss article showing the six-foot water balloon contains a mild expletive) and find one to share with your class. If you have the chance to do some of the activities below, afterward you can show one of these videos about water balloons in space and compare what is shown with your own experiences.

Suggested activities: Fill water balloons with your class and then take them outside for some hands-on experiments. Drop the balloons from different heights and onto different surfaces to see how they hold up to impact, or not. Try underfilling and overfilling a few balloons to see how they perform—whether it is easier or more difficult to pop them—with more or less water inside. If it is a nice sunny day, let your students have a balloon toss at greater and greater distances until the balloons pop (pass out safety glasses for this activity). To add some math into the mix, measure the heights from which the balloons were dropped, the distance between students in the longest toss, or the splatter radius of some of the balloons.

GRADES 3-5

3-PS2-1. Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

As the lesson above discusses, there are several factors that affect the way water balloons act when they are popped here on Earth. Even if the balloon is held still while it is popped, the water will disperse in response to forces like gravity or the wind (if it is blowing strongly). But what if there were no gravity to pull on the water? Then another factor would have a much greater influence on the behavior of the water: surface tension. We

GRADES 3-5 (CONTINUED)

can see in the slow motion videos that water maintains the roughly spherical shape of the balloon, very briefly, after the balloon no longer surrounds it. But the surface tension is quickly overcome by the other forces at work.

Surface tension, as its name sounds, is a force on a liquid-to-gas or liquid-to-liquid surface that makes the surface tend to shrink to the smallest area possible. It is caused by the molecules of the liquid attracting each other and tending to stay together. The amount of force for any given area depends strongly on what is in the liquid; for example, soapy water has much less surface tension than clean water. For a given volume of water, the shape that has the smallest surface area is a sphere; thus without any other forces at work, the surface tension will pull a glob of water into a spherical shape.

Popping Water Balloons in Slow Motion shows at increasing rates of slow motion how the water inside the balloon reacts when the balloon is popped. You can see that for a brief instant the shape of the balloon lingers before the water sprays outward and is pulled downward by gravity. Since this balloon was not in motion when it was popped, it does not have the additional momentum that a balloon that was dropped or thrown would have. Notice how the "strings" of water spray break up into droplets; this is the effect of the surface tension making the surface area as small as possible. You can also see the indentation in the water caused by the hand and the dart that popped the balloon.

GRADES 6-8

MS-PS2-2. Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.

The greatest difference between the environment inside a spacecraft and on the Earth is the absence of gravity. If you consider the forces on a water balloon containing a pint of water, you will find that gravity is the dominant force. A pint of water weighs a pound, meaning that the gravitational force on it is one pound of force (or just less than five Newtons in metric units). If you throw it at a speed of 30 feet per second (about 9 meters per second), the aerodynamic drag on it is about 0.14 pounds of force (about 0.62 Newtons). (You can calculate the aerodynamic drag from the formula

GRADES 6-8 (CONTINUED)

$$D = \frac{1}{2}\rho V^2 S C_D$$

where ρ is the density of the air, V is the speed the water balloon is flying through the air, S is the cross-section area of the water balloon, and C_D is the drag coefficient of a round object. In our case, ρ is 2.38×10^{-3} sl/ft^3 or 1.225 Kg/m^3, V is 30 ft/sec or 9 m/s, S is about 0.087 ft^2 or 0.0081 m^2, and C_D is about 1.5.)

Calculating the force from the surface tension is less intuitive. Without the balloon material holding the water together, only the surface tension would keep it in a spherical shape. The surface tension along a line on the water surface, meaning the force pulling the water together, is the product of the surface tension coefficient and the length of the line. If we take a "great circle" around the pint of water (which is about four inches, or ten centimeters, in diameter) and use the surface tension coefficient for water and air of 5×10^{-3} lbf/ft or 7×10^{-2} N/m, we get the surface tension force to be about 0.005 pounds of force or 0.022 Newtons.

Putting all of this together, let us compare the sizes of these forces:

- Gravity – about 1.0 pounds of force or 4.4 Newtons
- Aerodynamic Drag (for a thrown balloon) – about 0.14 pounds of force or 0.62 Newtons
- Surface Tension – about 0.005 pounds of force or 0.022 Newtons

We find that gravity dominates the aerodynamic drag by a factor of seven and the surface tension by a factor of 200. When you pop a water balloon on the surface of the Earth, the water falls down because of the gravity; everything else is secondary.

When you take gravity away, though, the smaller forces have a chance to show their effects. In the demonstrations of popping a water balloon in space, the astronauts are not throwing the water balloon, so there are no significant aerodynamic forces on the water. What remains is the surface tension.

The surface tension acts to minimize the surface area of the glob of water. Any parts of the glob that stick out are pulled in and any indentations in the glob are pushed out. But water

GRADES 6-8 (CONTINUED)

has mass and moving water has momentum, and once the water that was projecting from the glob has been pulled back into a spherical surface it will tend to keep moving because of its momentum. This will create an indentation in the glob of water where the projection was. In the same way, the water that has flowed into an indentation in the glob will tend to keep going and will create a projection sticking out of the glob. As you can see in videos of water balloons being popped in space, the result is an oscillation of the water glob where it changes shape back and forth.

GRADES 9-12

HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

When watching a slow-motion video of a water balloon popping, particularly at a very high frame rate, one can notice many details. (Note that the two views are of different events.) First, the material of the balloon itself splits and shrinks down to its unstretched size almost immediately, before the bulk of the water has a chance to start moving. The direction in which the balloon material splits, with an almost horizontal split causing the material to separate into an upper part and a lower part, is the direction in which the material is under the most tension.

The reason the balloon material splits so easily once it has a hole in it is because it is already stretched tightly. At any point on the balloon's surface, the load on the balloon's material—the stress causing it to deform—is partly taken up by the material on either side of it. Next to a hole, however, there is no material and the load on the balloon is larger. This is known as a "stress concentration" and is very well known in stress analysis. The increased stress is too much for the balloon's material and it splits, making the hole larger.

As the balloon material snaps back to its unstretched size, it moves quickly—very quickly—across the surface of the water. This motion kicks up a spray from the surface of the water which one can see readily in the high-speed video. One can also see the "seam" in the surface of the water where the balloon material has split away from.

GRADES 9-12 (CONTINUED)

Even before the balloon is popped, one can see the indentation caused by the pin that is popping it. This indentation is shaped like an expanding circle and pushes the water in the area right next to the pin toward the center of the balloon. This motion of the water toward the balloon's center continues after the balloon is popped, creating an indentation in the water surface. (The indentation is easier to see at lower frame rates after the spray has dissipated a little.)

You can use the question of what causes the water spray to illustrate the scientific method. One could hypothesize that the indentation from the pin causes some up-and-down waves in the balloon material that cause the water spray; this would make sense because it is an up-and-down motion. But this hypothesis would predict that the pattern of the spray would be circularly symmetric around the pin location. The presence of the "seam" in the surface of the water contradicts this hypothesis. That said, one can also see a little spray in a circular pattern around the cavity surrounding the pin's location; this is a result of the indentation. So the pin's indentation does cause some spray; it simply does not cause most of the spray.

Sixty Years Ago in the Space Race:

November 15: Scott Crossfield reaches Mach 2.97 in an X-15.