Science
Lab

Flipping the Bottle

Flipping an object is a common human behavior. If someone gave you a stick of wood to play with, sooner or later you would probably try to flip it end over end and catch it. Once you did that successfully, you would probably try other variations, such as catching it after more rotations or flipping it faster or slower. Flipping can be fun!

Sometimes objects do not flip exactly as we expect. This activity is designed to help you explore one such object.




Tools and Materials

- A small empty plastic bottle with top, for example a 500-ml (17-oz) water or soft drink bottle
- Water
- Optional: different small particles, such as sand, gravel, or marbles, to fill the bottle to the halfway mark

What to Do

1. Rinse out the bottle with clean water and then empty it. Shake out all excess water. Replace the cap.

2. Hold the cap of the empty bottle in your hand so that the bottle hangs down vertically. Flip the bottle so that it turns one and one-quarter times in the air and then catch it with the same hand. The bottle will be horizontal when you catch it. Practice doing this until you can flip and catch the bottle consistently. You do not have to toss the bottle high in the air. Rather, begin the toss and then give the end a little extra push to flip it around.

3. Next, fill the bottle with water and fasten the top on securely. As in the step above, practice flipping the bottle so that you can catch it easily and consistently after one and one-quarter rotation. Observe any differences between this and what you experienced when flipping the empty bottle in Step 2.

Be careful—even such a small amount of water is somewhat heavy. Stay focused while flipping the full bottle of water so that you keep it under control.

4. Open the bottle and pour out about half of the water. Then fasten the top on tightly once more. Flip the bottle as you have done before, attempting to catch it after one and one-quarter rotations. Observe any differences between flipping a half-full bottle, an empty bottle, and a full bottle.

5. Do you notice any difference in the way the bottle behaves when it is half full of water compared with when it is empty or completely full of water? If so, what explanation can you suggest for this? Discuss this with your friends and work together on a satisfactory.

Hints and Tips
Below are some additional things to try as you develop your explanation.

One idea might focus on the behavior of the water. For example, freeze the half-full bottle of water. Once the water inside the bottle is frozen, try flipping it. Record your observations and compare them with those from the exercise involving flipping the half-full bottle of liquid water. Do the same thing for a bottle completely full of water. What differences, if any, do you see?

You might also explore the effect of varying amounts of water in the bottle. What happens when you flip a bottle with only a little water in it? What happens if the bottle is nearly but not completely full? Do you see any patterns?

What about the material in the bottle? Perhaps replace the water with something that behaves similar to water but in a way that will give you additional clues. For example, fill the bottle full of small particles, such as marbles or gravel, and flip it. Then flip the bottle when it is only half full. Watch the particles closely as the bottle is flipping, especially those in the top layers.

Does the same thing happen when you try to flip a bottle half-filled with sand?

Develop an explanation for what you are observing. Then figure out how you might test this explanation further. Good luck!

Check out our results below.

Our Results

We tried flipping the bottle when it was filled with different substances. We also asked some scientists for their explanations. What a great discussion we had! Even they did not agree on a single explanation. Each had a different perspective. Take a look. Do you get any ideas from what the scientists are saying?

Gerard Daccord, engineer:
I believe the explanation could simply be related to the amount of rotational inertia you are communicating to your bottle/water system.

1. Empty bottle, bottle half-filled with water frozen to ice, bottle completely full of water: The object is more or less behaving as a solid body.

2. Bottle half-filled with liquid water: Part of the water is not rotating when you flip the bottle, because it has a free boundary, that is, a surface not in contact with the bottle.

   In other words, you should be intuitively adapting the initial torque according to the weight of the object.

Our Response:
Thanks. Great comment! The three flipping actions for the bottle acting as a solid body are very similar. But what about a reaction to the weight? This is why we included in the activity the half-filled bottle with water frozen to ice. There is little difference between the weight of a bottle half-filled with liquid water and a bottle half-filled with ice. So as far as a physiological reaction goes, both bottles would feel essentially the same and would behave the same until the moment of release. At that point the liquid water no longer has to take the shape of its container. As you mention, the free boundary of the liquid is important.

Lawrence Lee, engineer:
I believe this goes back to Newton's first law, which states that an object will remain at rest or in uniform motion in a straight line unless acted upon by an external force. Putting it in another way, momentum is conserved.

In an "empty bottle," the bottle is filled with air; however, the total mass of the air is significantly less than that of the bottle. Thus, once we imparted rotation to the bottle, the momentum of the bottle was sufficient to carry the air within it around as it rotated. In other words, if you would have tossed the bottle high up, it would have made multiple turns before falling back into your hand.

In a "water-filled" bottle, the water was behaving much like a solid body. There is probably some internal movement, but it is limited. As a solid body, the bottle will continue to flip much like a truly empty bottle. The internal flow of the fluid inside will eventually consume sufficient rotational energy and the bottle will quit flipping.

In a half-filled bottle, the water is free to flow from one end of the bottle to the other end. When we flip the bottle, we "poured" the water from one end to the other. Unless we continue flipping the bottle, there is insufficient force to move the water from that end of the bottle back to the initial end. However, if the mass of the bottle is sufficiently high relative to that of the water within, then perhaps it could develop a force that would carry the water around. In other words, the rotational momentum of the bottle would dominate.

I see that you also tried dry sand. Didn't that produce results similar to those of water?

Our Response:
Your comment about "pouring" the water in the half-filled case might be just what is needed to start thinking about a satisfactory explanation. But what about the trajectory of the center of mass of the water in the half-filled bottle? Why is this a different trajectory from that of the ice in the half-filled bottle? For example, at the moment of release, does the water stop contributing to the rotational momentum of the bottle? In particular, at that moment does the water drop out of the mass that contributes to the moment of inertia of the bottle and water system?

Tony Veneruso, engineer:
I would emphasize that this experiment demonstrates that a fluid with a low viscosity, such as water, will not react to a shear or sliding force acting on its surface. However, the same fluid will react to a uniform perpendicular force on its surface. A simple way we express this is "pressure."

The rotation of the half-empty bottle is not transmitted to the water by the sides of the bottle. The water tends to stay put. It has not accelerated and it acts as a drag on the rotating bottle. When the full bottle is rotated, the water has no place to go if any force is applied on the surface of the bottle. The water will certainly try to remain in place, but the forces from rotating the bottle are transmitted as pressure to accelerate the water into rotation. When the water in the half-empty bottle is frozen, it behaves about the same as the empty and filled bottles. Forces are transmitted easily.

I learned a trick based on this same principles to tell the difference between a hard-boiled and a fresh egg without breaking them. You simply spin the egg. The hard-boiled egg spins easily like a top, but the fresh egg is sluggish. It stops rotating quicker than the boiled one.

This phenomenon is similar to that for the rotating bottles. The fluid in the fresh egg is viscous. It tends to stay put. There are two key factors. First, when the fresh egg is rotated by hand, the rotational force is not transmitted to the whole mass of the egg, because the fluid yields under shear force. Once you let go, the fluid in the egg acts as a drag on the rotating part of the egg.

This opens up the area of exploring different fluid viscosities.

Our Response:
This is generating a fascinating discussion! Yes, the idea of shear forces within a liquid certainly comes into play. Maybe that would be a good way to approach the explanation.

Jose Navarro, physicist:
Great experiment! I like to think of the half-full experiment as trying to spin the bottle around the water, whereas in the other experiments the bottle and the contents rotate together.

Our Response:
Yes, this would probably be an excellent approach for the explanation—because in the half-full bottle, the water has some space. Nothing is holding it to the shape of its container once the bottle is released.

What Do You Think?
Did the discussion of the scientists create additional questions for you? Try to find answers to your questions by experimenting in different ways. Keep thinking about a satisfactory explanation that makes sense to you.