Ichiro Fukumori is a principal scientist in the Earth science section at the Jet Propulsion Laboratory, California Institute of Technology, in Pasadena.

Kamifusen, the self-inflating Japanese paper balloon

Ichiro Fukumori

Unlike a rubber balloon, a kamifusen has a hole left open to the surrounding air. So why doesn't it collapse when you bat it around?

Kamifusen (紙風船), meaning paper (*kami*) balloon (*fusen*), is a traditional Japanese toy. The balloon is constructed from semitransparent glassine segments put together in a manner similar to the way plastic segments make a beach ball. Typically 10–20 cm in diameter, the kamifusen is inflated through a small hole 8 mm or so wide and gently bounced on the palm of the hand, as illustrated in figure 1. Because it is made of paper, the kamifusen is light enough for indoor play yet heavy enough that keeping it aloft is a challenge.

FIGURE 1. BOUNCING A KAMIFUSEN. The balloon's hole is visible in the silver patch where the tapered ends of the different-colored wedge-shaped paper converge.

Kamifusen became popular in the early 1890s, but their origin is not clear. They used to be widely available at neighborhood snack shops called *dagashiya* (駄菓子屋) that sold inexpensive treats and toys for children. Nowadays such stores have become few and far between, but kamifusen can still be found as folk toys at souvenir shops and other specialty stores in Japan and elsewhere. Modern kamifusen also come in fruit or animal shapes or with printed patterns; some are more for display than for play. With its graceful bounce and pleasant sound of crumpling paper, the kamifusen continues to be a cherished and timeless toy. It is also an enigma.

The conundrum

Despite its hole being open to air, a kamifusen remains inflated. One might expect that bouncing the kamifusen would force air out of its hole and cause the balloon to deflate. Instead, the batting action actually increases the kamifusen's degree of inflation. In fact, repeated bouncing can make a nearly deflated kamifusen swell to its fully inflated condition. Part of the kamifusen's charm is its ability to be pumped up in that way—and the activity itself can be a lot of fun.

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The counterintuitive behavior of the kamifusen's inflation has previously been attributed by some physicists to viscoelasticity, the property that causes a crumpled sheet of paper to slowly unfold. Viscoelasticity can indeed expand a scrunched paper balloon. However, it does not fully explain the kamifusen's inflation, since viscoelastic unfolding does not completely smooth out plain crumpled paper even if the paper is bounced like a kamifusen. Other physicists have suggested that the bouncing causes pressure changes inside the balloon that alternately push out and pull in air. That's true, but it is not obvious how the pressure changes and why more air comes in than goes out—a requirement for the balloon to inflate. In this Quick Study, I explain the self-inflation of the kamifusen by taking a closer look at the pressure variations that occur as the balloon is batted about. I also touch on the material properties of the paper from which the balloons are made.

Pressure variation

The puzzle of the kamifusen's inflation is about airflow between the balloon and its surroundings. Air moves from whichever region—balloon or atmosphere—has higher pressure to the lower-pressure region, so I first focus on pressure.

Before being bounced, the kamifusen is in equilibrium with its surroundings and its pressure equals the pressure, p_0, of the ambient atmosphere. But when batted by hand, the balloon deforms, which changes its pressure. The question is, how and in what way does that pressure change happen?

Because the kamifusen's hole is small, the amount of air that can flow through it is limited. Thus, to first approximation, the total amount of air in the balloon is constant in time. When the balloon is struck, it suffers some plastic deformation (it does not fully return to its original shape after force is removed), but it also contracts and expands elastically, as illustrated in figure 2a; during that process pressure deviates from the ambient value. The elastic oscillation propagates to other regions of the balloon as sound waves analogous to the seismic waves that communicate an earthquake to the rest of the globe. As the waves propagate, pressure fluctuations force a small amount of air through the hole. When the balloon's pressure at the hole

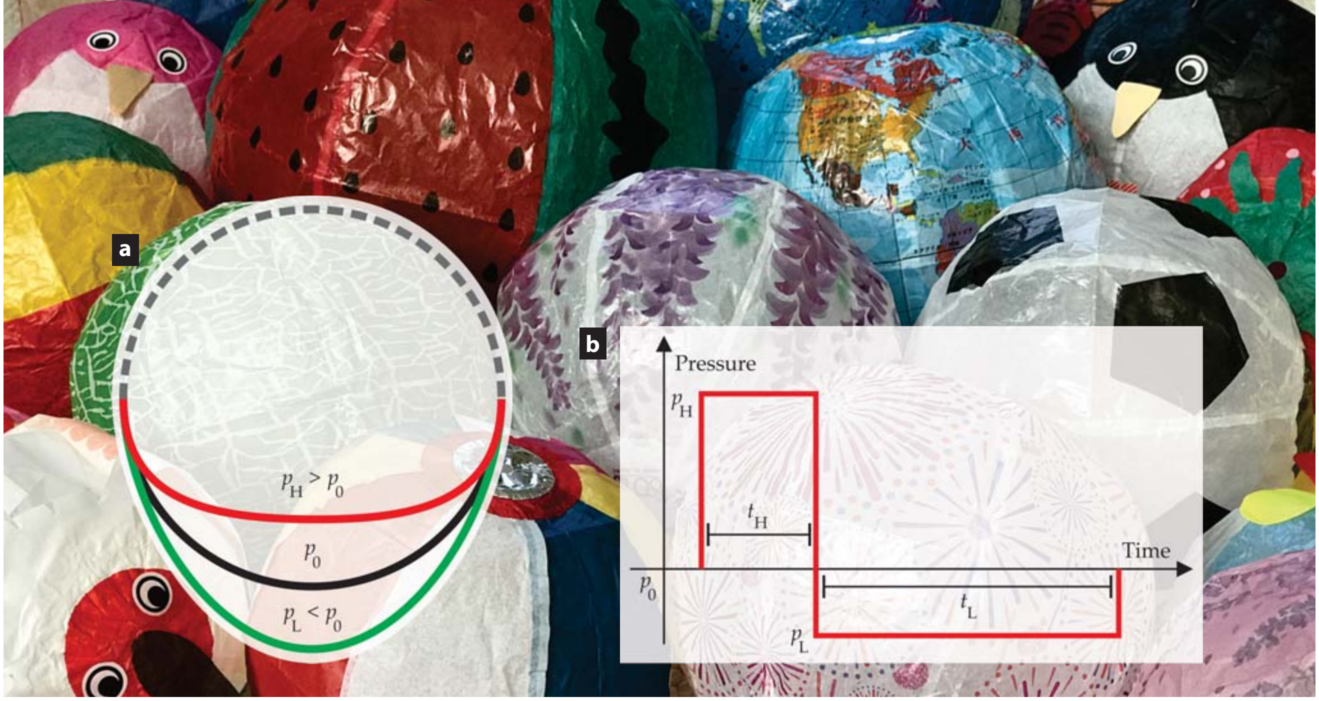

FIGURE 2. AN OSCILLATING KAMIFUSEN. When bounced, **(a)** a kamifusen oscillates between states that are contracted (red) and expanded (green) relative to the balloon's equilibrium volume (black). Pressure changes accompany the oscillation. When the balloon is contracted, the inside pressure is higher than atmospheric pressure p_0; when expanded, it is lower than p_0. The pressure difference between balloon and atmosphere works to restore the balloon to its equilibrium position. As described in the text, the fluctuations propagate as sound waves. **(b)** Compared here are the average duration t and average pressure of the waves' high-pressure (H) and low-pressure (L) phases at an arbitrary location in the balloon. As explained in the text, t_H is shorter than t_L, but $p_H - p_0$ is greater than $p_0 - p_L$. Indeed, $(p_H - p_0)t_H = (p_0 - p_L)t_L$; in other words, the rectangles of width t_H and t_L have the same area.

is higher than atmospheric pressure, air is forced out; when it is lower, air is sucked in.

If that pressure variation were symmetric between its highs and lows, the amounts of air flowing in and out of the kamifusen would be equal and the balloon's volume would not change. Such, however, is not the case. When the balloon is struck, pressure increases simultaneously across the region where the hand impacts the kamifusen. But subsequent waves reflect and scatter off different parts of the balloon's surface, which leads to a spread in the duration and amplitude of the pressure variation. The result, as illustrated in figure 2b, is an asymmetry between the high- and low-pressure states.

Specifically, at any given location inside the balloon, the average duration t_H of the high-pressure state is shorter than the average duration t_L of the low-pressure state. On the other hand, the average high pressure p_H deviates more from atmospheric pressure than does the average low pressure p_L. In fact, pressure difference and duration are inversely proportional to each other and satisfy $(p_H - p_0)t_H = (p_0 - p_L)t_L$. The inverse relation is a statement of energy conservation; it equates the energy transported by the sound waves' high- and low-pressure phases. The difference between kamifusen pressure and p_0 is proportional to the power carried by the wave. And that power, multiplied by time, gives the energy transported.

Now that I've described how pressure changes, I turn to how the pressure variations affect airflow. The amount of air moving through the balloon's hole depends on the speed and duration of the flow. Bernoulli's principle, which relates fluid motion and pressure, tells us that the speed is proportional to the square root of the pressure difference. So the ratio of the flow speeds in the high- and low-pressure phases in figure 2b is not as great as the ratio of their pressure differences. But I've just shown that the duration of the two phases is inversely related to those pressure differences. So, for example, if $p_H - p_0 = 4(p_0 - p_L)$, the expelled flow has twice the speed but only ¼ the duration of the incoming flow. As a result, the amount of air flowing into the balloon is greater than the amount flowing out, and the kamifusen inflates.

Material considerations

Part of the kamifusen's genius is the paper from which it is made. The paper is not only lightweight and relatively impermeable to air, but it also has a degree of plasticity that allows it to deform easily and retain its resulting shape. Because of those properties, the kamifusen inflates to a volume commensurate with its air content and maintains that volume until additional air is added. As a result, a squashed kamifusen can accumulate air and eventually inflate to its full size from repeated bouncing, even though the net pumping from a single bounce may be small. A balloon made of plastic, rubber, or any other material that does not share the key properties of kamifusen paper would not inflate as the Japanese balloon does.

Elastic waves, fluid motion, and the paper's plasticity work together in the self-inflation of the kamifusen. The balloon's deceptively simple design conceals an intricate process at work and attests to the ingenuity of the artisans who devised this elegant, intriguing toy.

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Additional resources (in Japanese)

▶ Logergist, "Kamifusen no nazo wo toku," in *Shin butsuri no sanpomichi*, vol. 1, Chikuma Shobo (2009), p. 210.
▶ Logergist, "Mimi ga itaku naru hanashi," in *Dai-san butsuri no sanpomichi*, Iwanami Shoten (1966), p. 119. PT