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Is it simple to explain simple experiments? The 'heavy newspaper' stick break

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Abstract

In this paper we consider the well-known experiment with the 'heavy' newspaper that breaks a stick that it is laid on. Using several appropriate control experiments we show that the currently invoked explanation using atmospheric pressure cannot be correct. We perform a theoretical analysis and propose a new explanation based on the rotational motion of the stick.

1. Introduction

There is a well-known experiment performed with a newspaper and a wooden stick or ruler [1–6]. A stick of about 60–70 cm or more is placed on top of the table so that about 15–20 cm of it is sticking out. The longer part of the stick that is lying on the table is covered with a newspaper so that the paper is pressed against the table (figure 1). At first we slowly push on the overhanging part of the stick. It rotates around the edge of the table and easily lifts the newspaper up. Then we perform the attractive part of the experiment. Using a stronger stick (it can even be metal) we deliver a sharp blow to the overhanging part of the stick. It breaks off but the newspaper covered part remains in place, moving very little (figure 1). The optimal stick for use in this experiment has a fine-grained structure like particle board (without surface laminate). The long-fibre structure of regular wood requires a very strong hit, making the experiment harder to do and even unsafe.

The commonly accepted explanation of this demonstration is well-known [1–6]. Since the newspaper is flush to the table, air cannot get underneath. Because of this the air over the paper is applying significant pressure on the paper and the covered part of the stick. A small-sized newspaper is about 30 cm by 40 cm spread out. This provides an area of 2400 cm^2. Given that atmospheric pressure on 1 cm^2 is roughly equivalent to the weight of a 1 kg load, the total area of the paper experiences the equivalent of the weight of 2 tonnes. Thus a huge force acts on the newspaper. This force also acts on the covered part of the stick. Upon a sharp strike on the free end of the stick air cannot go under the paper quickly enough to compensate the atmospheric pressure on top. This is why the stick breaks. Upon a slower push on the free end, air can get under the newspaper and so the stick rotates without breaking. Obviously this experiment demonstrates the action of atmospheric pressure on the upper surface of the paper and stick. All these considerations are valid if air cannot get under the newspaper. But is this so?

What facts can be gleaned upon a more careful and unbiased observation of this experiment. When the stick is struck the covered part of it and the newspaper can lift up quite a bit. How do we explain that a rather thin newspaper can withstand

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the powerful action of the stick without tearing while the relatively stronger stick breaks? If we just place the newspaper appropriately and strike it with the stick directly it tears up easily. It is also quite easy to observe that however much we try to spread the newspaper out, there is always air underneath it, along practically its entire surface. We should look for some other explanation of the experiment, i.e. a different reason for the stick breaking.

2. Control experiments

Let us perform a control experiment without the newspaper (figure 2). We use a stick made of the same material, of the same size, place in the same way on the table. We again deliver a sharp strike on the overhanging end of the stick. The result is quite surprising—the stick breaks easily without a newspaper on top of it, as in the first case!

To avoid doubts about the strength of the strike we conducted a control experiment using the method of direct comparison with a single difference (figure 3). We used two identical sticks of the same material. We first place one of them on the table and cover it with the newspaper as in the first experiment. The second stick is then placed parallel to the first one, close to it on top off the paper. We deliver the strike as usual to the two sticks simultaneously. Both sticks break simultaneously in the same way. We changed the strength of the strike but the result was the same every time.

In this way we provide for an equivalent strike to both sticks without having to construct a more complicated experiment that would deliver a consistent, controlled strike on the sticks every time. This experiment reliably leads to an important conclusion—the placing of the newspaper on the stick does not play a significant role in its breaking. In other words, the atmospheric pressure that is normally used to explain this attractive demonstration in reality is not decisive for the main result—the breaking of the stick.

But what if the air pressure is acting on the stick itself? If the portion on the table is 50 cm long and 5 cm wide, this is still and area of 250 cm^2. If there is no air under the stick, the atmospheric pressure on top is still equivalent to a load of about 250 kg. This is a massive load that the stick could not move from. Even if the load is, say, 50 times smaller (‘just’ 5 kg) it would still be sufficient to break the stick. In order to make sure that this is not the case, we performed the experiment by lifting the stick over the table with two small supports (figure 4). This way the air can freely move underneath it. Upon a sharp strike the stick still breaks. Atmospheric pressure cannot be the reason for the stick breaking.

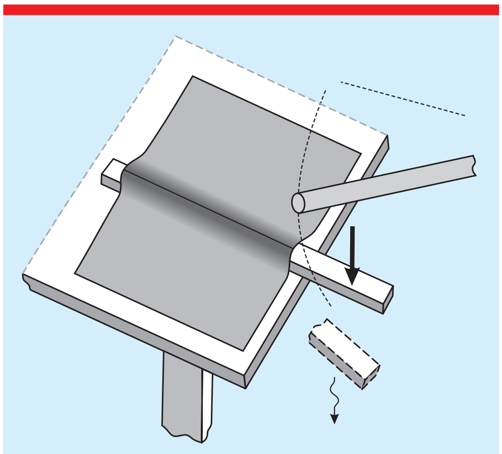

Figure 1. The ‘classic’ experiment.

Another possible explanation could be that upon beginning to rotate, the long portion of the stick experiences air resistance and that can increase the load upon it. However, observing the experiment carefully and slow-motion video recordings of it show that the stick barely moves off the table. Air resistance cannot be the cause of the breaking, either.

In some cases, the experiment is performed with a thin ruler from the school supplies, covered with several layers of newspaper. We performed the experiment successfully with a ruler without covering it with the newspaper. The newspaper in this case essentially acts as an extra weight, comparable to the weight of the ruler itself.

The conclusion of all the control experiments is that air permeates quite easily under the newspaper and the stick. The way the experiment is normally demonstrated, air pressure cannot be the principal cause for the breaking of the stick. If air is to be properly prevented from moving under the stick and newspaper, the experiment would have to be carried out in a much more complicated way which defeats its purpose. But if air pressure cannot be the sole cause of the stick breaking, the demonstration still requires an explanation. What causes the stick to break?

3. Theoretical analysis

Let us consider what is happening with the stick from the point of view of the dynamics of rotational motion. The situation is presented in figure 5. Relative to the rotational axis we consider two portions of the stick—an outer one with mass m_1 and length l_1, whose moment of inertia is $I_1 = \frac{1}{3}m_1 l_1^2$ and one on the table with mass m_2, length l_2 and moment of inertia $I_2 = \frac{1}{3}m_2 l_2^2$ respectively. We strike with a force F at distance l_3 from the axis. Anything holding the part on the table is represented with as a net force H acting at distance l_4. The exact nature of this holding factor will be discussed in more detail bellow.

If we assume the stick to be relatively homogenous along its length we can define 'linear density' $\lambda = \frac{m}{l} = \frac{m_1+m_2}{l_1+l_2}$. Then $m_1 = \lambda l_1$ and $m_2 = \lambda l_2$. For the moments of inertia we get respectively $I_1 = \frac{1}{3}\lambda l_1^3$ and $I_2 = \frac{1}{3}\lambda l_2^3$. When we strike, inside the stick arise internal forces which create a torque τ relative to the axis of rotation. This torque acts on the right side of the stick (from figure 5) counterclockwise and the left part of the stick clockwise. If this internal torque exceeds a certain value the stick will break. Let us write down the dynamic equations for the two parts of the stick, assuming they move with the same angular acceleration α and taking into account the torques caused by the weight of each part of the stick:

$$m_1 g \frac{l_1}{2} + F l_3 - \tau = I_1 \alpha$$

$$\tau - m_2 g \frac{l_2}{2} - H l_4 = I_2 \alpha.$$

After the necessary transformations we can obtain

$$\tau = \frac{l_2^3}{l_2^3 + l_1^3} F l_3 + \frac{l_1^3}{l_2^3 + l_1^3} H l_4 + \frac{m g l_1^2 l_2^2}{2\left(l_1^3 + l_2^3\right)}.$$

The third term is largest for $l_1 = l_2 = \frac{1}{2}l$ and its maximum value is $\frac{mgl}{8}$. It is quite small

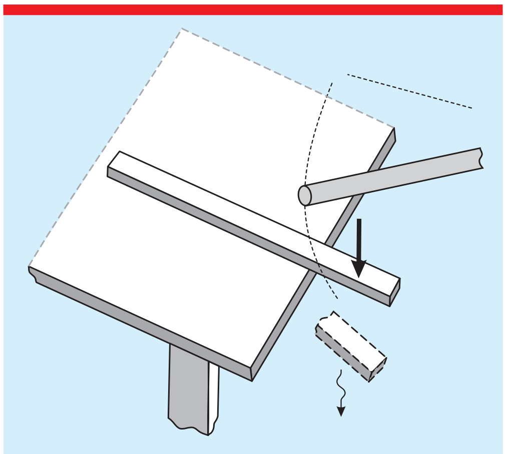

Figure 2. The experiment without the newspaper.

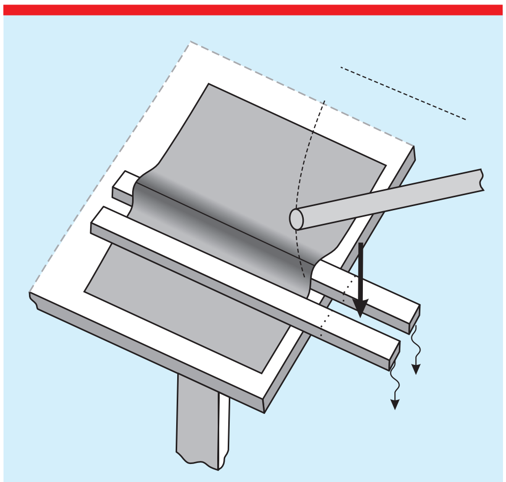

Figure 3. The control experiment.

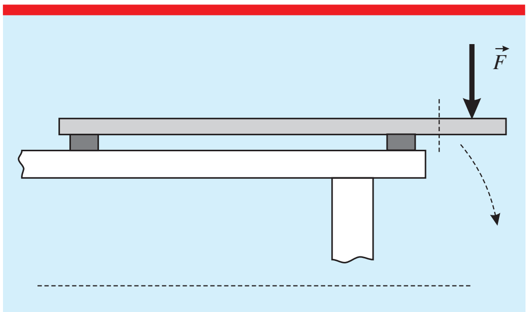

Figure 4. The experiment performed lifted over the table.

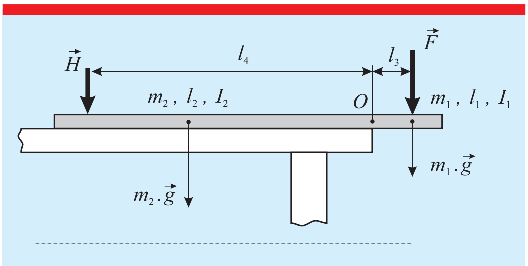

Figure 5. A diagram of the experiment.

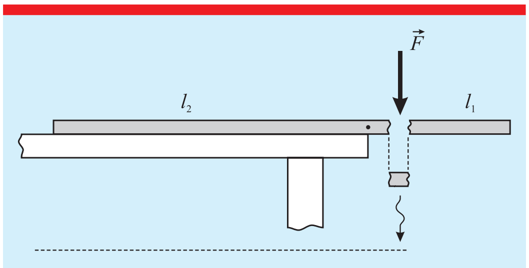

Figure 6. Under appropriate conditions we can break off a piece in the middle of the stick.

and obviously does not contribute significantly to the breaking, especially for the more realistic case of l_1 being about 4–5–6 times shorter than l_2 when it is even smaller. The second term is proportional to the 'holding' torque but the coefficient is small (for the typical case of $l_1 \approx 5l_2$ $\frac{l_1^3}{l_2^3+l_1^3} \approx 0.008$). The first term is proportional to the applied 'striking' torque with a coefficient that is almost one for the typical performance of the experiment (when $l_1 \approx 5l_2$ $\frac{l_2^3}{l_2^3+l_1^3} \approx 0.992$). This significant discrepancy in the coefficients is due to the moments of inertia of the two parts of the stick being proportional to the third power of their respective lengths (two from the formula for moment of inertia and one more from the mass being proportional to the length too). Thus the main cause of the stick breaking is the fact that the overhanging part of the stick has significantly less rotational inertia than the part that's lying on the table combined with the very hard strike that is normally delivered by the experimenter. The addition of a holding factor can make the breaking easier but does not ultimately cause it. The breaking is mainly due to the force of the strike.

A holding factor can be the weight of the newspaper—some of the clips on Internet show the experiment performed with a very thin stick covered with a whole newspaper with many sheets, whose weight can be higher than the weight of the stick itself. A holding factor can be the air resistance on the newspaper—some of the videos show that the part of the stick on the table initially rises quite a lot quite quickly, the newspaper on top undoubtedly experiences some air drag. A holding factor could be the action of the atmospheric pressure but in order to confirm this, the experiment would have to be performed in a much more precise way. With fine control of the striking force we could determine the force necessary to break the un-covered stick, then the force necessary to break the stick loaded with a weight equal to the newspaper (maybe the newspaper itself folded up) and only then we determine the force to break the newspaper-covered stick. Such an experiment would be quite complicated and defeats the purpose of a quick, visual qualitative demonstration. Actually measuring the striking force would be difficult so instead it can be controlled by dropping a selection of weight from a selection of heights but translating this into an actual striking force would still be difficult. In any case, when the demonstration is normally performed, the stick is first pressed relatively gently, without breaking, which obviously means that the holding factor is small enough so as to not cause the break by itself.

4. Conclusion

If we hit the stick hard enough it will break, even without anything else holding it down. Exactly how hard is 'hard enough' depends on the actual stick being used but the experiment normally uses a relatively flimsy piece of wood. When the experiment is performed in the classical way the demonstrator hits the stick as hard as they can. In this case the stick can break without the newspaper, from its own inertia alone. But then how do we explain some demonstration where the stick is first hit un-covered and does not break? A careful examination of the videos published on the Internet (the ones that we could find) shows that when the stick is hit without the newspaper the strike is delivered quite weakly, just so the stick would flip. After the newspaper is placed on top of it, the strike is delivered with the maximum strength of the person delivering it. This makes the comparison unfair. The fair comparison is the one we presented on figure 3.

There is an interesting situation that can arise when the experiment is performed (figure 6). Let us leave the portion l_1 hanging beyond the table fairly long (20–30 cm). Then it will be more inert and slower to rotate. If we then deliver the strike close to the edge of the table it may not rotate down quickly enough and only a small piece directly under the strike gets broken off. We confirmed this possibility experimentally.

The full theoretical explanation of this experiment would be very difficult, including internal forces, the speed of propagation of internal stress, the shape and material properties of the stick, etc. For the purposes of attractive demonstrations to large audiences this is not necessary. Revealing the principal fundament of the experiment is sufficient.

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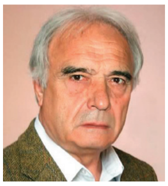

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