

APPARATUS NOTES

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Measuring momentum without the use of $p=mv$ in a demonstration experiment

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Classical demonstration experiments related to momentum, like collision experiments on the air track¹ or the measurement of momentum with a ballistic pendulum,² are all based upon the relation

$$p = mv. \quad (1)$$

Here, p is the momentum of a body, m is its mass, and v is its velocity.

This way of operating with momentum strongly suggests that momentum is always proportional to velocity and that it is a "derived" quantity, as is even stated explicitly in older textbooks.

Since the advent of the theory of relativity and of quantum mechanics, we consider momentum as a quantity in its own right. Therefore, in order to introduce momentum we propose to carry out an experiment that allows for a measurement of momentum without having recourse to Eq. (1).

The principle of the experiment can be seen in Fig. 1. The momentum to be measured is that of body B which is moving from left to right. A series of bodies U_i is moving from right to left. The bodies U_i are all identical among themselves and, moreover, all of them have the same velocity. To state this in another way: All the variables on which momentum presumably depends have the same values for these bodies. We now define that every body U_i carries one unit of momentum. Notice that for this definition we do not need Eq. (1). All the bodies are prepared in such a way that

every collision that will take place is an inelastic collision: First, body U_1 will collide with body B , and will stick to B ; then, U_2 collides with the compound body consisting of B and U_1 , and will stick to this compound body, etc.

To measure the momentum that B had initially, we simply let unit bodies collide with B (and the bodies already attached to B) until B has come to rest. Let n be this number of unit bodies. We now know that B had, before the first collision had taken place, a momentum of n units. Notice that with this procedure one cannot determine momentum changes of B before B has come to rest: As long as B is still in motion, the unit bodies attached to B are also in motion and this means that they have not transmitted one unit each to B yet.

By the way, it is instructive to discuss an analog procedure for measuring electric charges. (Transfer negative unit charges to the body whose charge is to be measured.)

Figure 2 shows a general view of the apparatus. Body B , whose momentum is to be measured, is a glider on an air track. The unit bodies are spherical air-gun pellets that are shot at the glider by means of compressed air with a pressure of approximately 2 bars. The glider carries a device for catching the bullets.

The tube for accelerating the bullets is an air-gun barrel with an inner diameter of 4.45 mm (corresponding to the bullets). We took the air from the compressed air pipe of the lecture room; however, a compressed gas from a bottle is just as good.

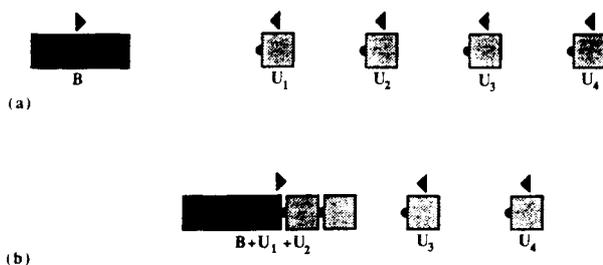


Fig. 1. The momentum of body B is to be measured. Each of the bodies U_i carries one unit of momentum. (a) Situation before the measuring process; (b) two unit bodies have collided with B .

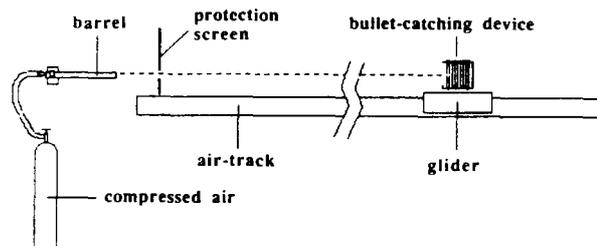


Fig. 2. General view of the experiment. Bullets are shot on the glider by means of compressed air until the glider has come to a halt.

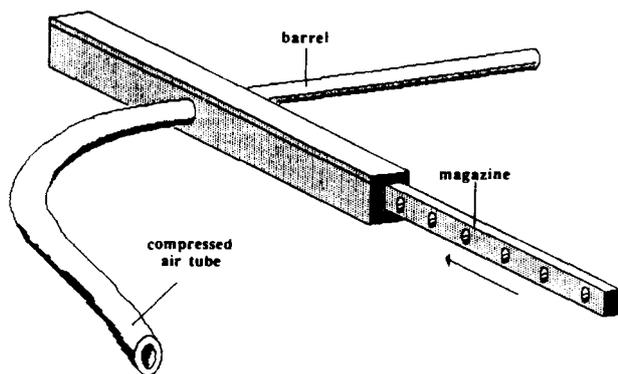


Fig. 3. Shooting device. The inner bar, which is pierced by ten holes, serves as the magazine. If it is displaced in the direction of the arrow, one bullet after the other gets in front of the entry of the barrel.

To allow for a quick shooting sequence, we constructed the setup of Fig. 3. A bar of rectangular profile is pierced with 10 holes to receive the bullets. For the measurement, this magazine is displaced in the direction of its length so that one bullet after the other is positioned in a way that the entrance opening of the barrel is in front of it and the compressed air inlet is on the back side. To carry out the experiment one simply pushes the magazine until the glider has come to rest.

The construction of the bullet-catching device presented a particular problem. One might think that it is sufficient to mount a plate of a material in which an incoming bullet would stick on top of the glider, for instance, styrofoam. However, occasionally it occurs that one bullet hits the target at the same position as a previous one. It would then be thrown back by this previous bullet and not transfer the desired amount of momentum to B . No bullet can escape from the catching device of Fig. 4. It consists essentially of a series of pieces of cardboard 10×10 cm in size. One bullet perforates about three cards and then falls to the bottom of the catcher. If now another bullet hits the catcher at the same location, it passes the first three cards unhindered but is stopped by cards 4 to 6.

After each shot an air current comes out of the barrel which disperses after a distance of about 1 m. If the glider

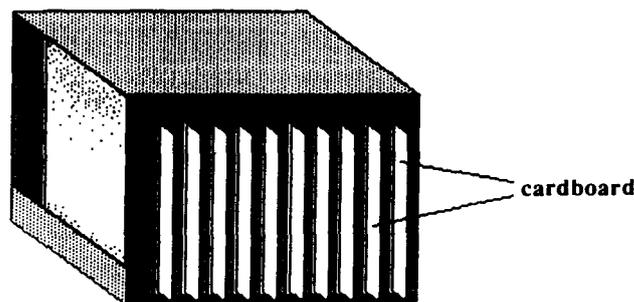


Fig. 4. Bullet catcher. Each bullet perforates about three cards and then falls to the bottom of the catcher.

comes too near to the gun, this air current will transfer an unknown amount of momentum to it. To avoid this effect, it suffices to put a screen in front of the barrel, 0.2 m away from it, with one hole of 1-cm-diam to allow for the passage of the bullets.

In typical experiments the number n of bullets necessary to stop the glider is about 5 to 8. For this reason, the precision of the momentum measurements cannot be better than about 10%. However, our intention is not to make precision measurements but to demonstrate an operational definition of momentum.

In order to test the reliability of the apparatus, we compared the results of our new method with those of a calculation of the momentum of the glider by means of Eq. (1). For that purpose, we had to determine mass and velocity of the glider and mass and velocity of the bullets. The agreement was better than the 10% uncertainty due to the coarseness of our momentum units. The reproducibility of the bullet velocity (56 m/s when the pressure was 2 bars) was better than 5%. The main error source was the air friction of the glider.

¹ *Physics Demonstration Experiments*, edited by Harry F. Meiners (Ronald, New York, 1970), Vol. I, p. 258.

² F. W. Sears, M. W. Zemansky, and H. D. Young, *University Physics* (Addison-Wesley, Reading, MA, 1987), p. 191.