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The Atwood machine revisited using smartphones

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The Atwood machine is a simple device used for centuries to demonstrate Newton's second law. It consists of two supports containing different masses joined by a string. Here we propose an experiment in which a smartphone is fixed to one support. With the aid of the built-in accelerometer of the smartphone, the vertical acceleration is registered. By redistributing the masses of the supports, a linear relationship between the mass difference and the vertical acceleration is obtained. In this experiment, the use of a smartphone contributes to enhance a classical demonstration.

Theory

The Atwood machine is a simple device invented in 1784 by the English mathematician George Atwood.[1-3] It consists of two objects of mass m_A and m_B, connected by an inextensible massless string over an ideal massless pulley.[1] Applying Newton's second law to each mass we obtain

$$m_A g - T = m_A a \qquad T - m_B g = m_B a, \tag{1}$$

where g is the gravitational acceleration, T is the tension force, and a is the vertical acceleration. Eliminating the tension between these equations, we obtain

$$a = \frac{m_A - m_B}{m_A + m_B} g \tag{2}$$

or, in terms of the mass difference Δm and the total mass M,

$$a = \frac{\Delta m}{M} g. \tag{3}$$

As mentioned in the original Atwood's book, many possible experiments can be implemented using his machine.[1] One of the simplest possibilities, adopted here, is, keeping the total mass constant, to vary Δm by redistributing a set of weights. In this case, a linear relationship between the vertical acceleration and the mass difference is obtained.

The experiment

In our experimental setup, shown in Fig. 1, an Atwood machine was built using two pulleys. A smartphone is fixed on the right support (A), while on the left support (B), up to five weights can be placed. The smartphone, an LG G2, is kept fixed to the string as indicated in Fig. 2 using a clamp similar to those provided with tripods or monopods. In this experience, the smartphone is located in such a way that the only relevant axis is the x-axis, which coincides with the vertical direction.

Initially, the support A contains only the smartphone[the mass of the smartphone and support is m_A = 191.2 (2 g)] while the support B holds five different weights [the mass of the support and the weights is m_B = 190.8(2) g]. The total

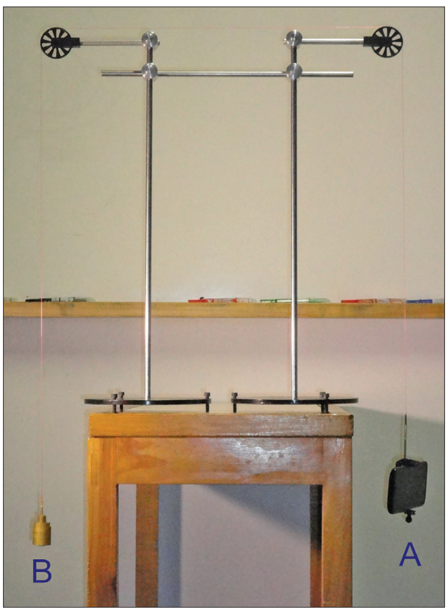

Fig. 1. Experimental setup consisting of two supports (A) and (B), connected by a string and supported on two pulleys.

Fig. 2. Details of the support and the clamp.

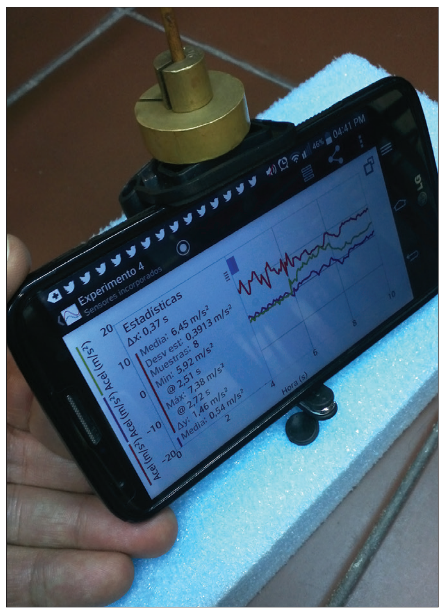

Fig. 3. Smartphone mounted on the support showing the Vernier app on the screen.

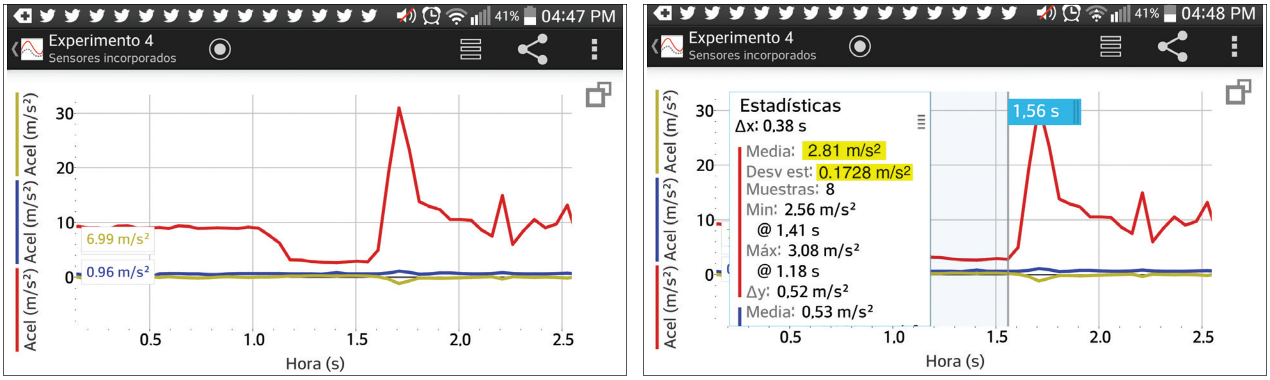

Fig. 4. Snapshots of the Vernier app showing the values registered by the acceleration sensor as a function of time. The only relevant component here is the *x*, which corresponds to the vertical acceleration. On the left panel, the plateau of constant acceleration can be appreciated. The statistical values (mean and standard deviation) calculated for this interval are highlighted in the right panel above.

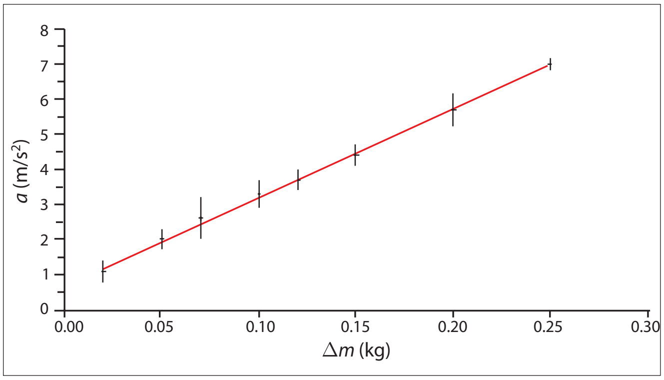

Fig. 5. Acceleration as a function of the mass difference: experimental points with error bars (black) and a linear regression (red line). Note that the yellow highlighted results from Fig. 4 are included here as the right-most data point after subtracting the acceleration due to gravity (9.8 m/s^2 – 2.81 m/s^2 ≈ 7.0 m/s^2).

mass, $M = 382.0(4)$ g, is kept constant along the experiment. The system is released and the app Vernier Graphical Analysis,[4] shown in Fig. 3, is used to record the acceleration values during the interval in which the support A is going downward and the support B upward. Of course, care should be taken to avoid hitting the smartphone against the floor.

Once the smartphone is stopped, the app is paused and a plot of the acceleration as a function of time exhibiting a region of constant acceleration or *plateau* is displayed on the screen (see the left panel of Fig. 4). The vertical acceleration and its error are obtained from the mean value and the standard deviation provided by the app (Fig. 4). The acceleration measured includes the gravitational contribution, so it is necessary to subtract it to obtain the real acceleration.[5–7] Subsequently, each of the weights is removed from the support B and placed on the support A. In this way, the mass of the system remains constant, and only the mass difference $\Delta m = m_A - m_B$ is varied. For each configuration the vertical acceleration is measured. Then, in Fig. 5, plotting the acceleration as a function of the mass difference, we obtain a straight line whose slope corresponds to g/M as indicated in Eq. (3).

Analysis and conclusion

From the slope fitted in the linear regression, we obtain a value for the total mass of the system

$$M_{\text{exp}} = \frac{g}{\text{slope}},$$

which results in $M_{\text{exp}} = (387 \pm 20)$ g. This value is in considerable agreement with the value obtained by direct weighting, $M = (382.0 \pm 0.4)$ g. We conclude that, thanks to the aid of the accelerometer of a smartphone, it is possible to foster this demonstration and obtain a precise verification of Newton's second law.

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