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2012 Phys. Educ. 47 21

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Speed, acceleration, chameleons and cherry pit projectiles

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Abstract
The paper describes the mechanics of cherry pit projectiles and ends with showing the similarity between cherry pit launching and chameleon tongue projecting mechanisms. The whole story is written as an investigation, following steps that resemble those typically taken by scientists and can therefore serve as an illustration of scientific reasoning and how scientific knowledge is built.

Introduction

It is often argued that science subjects today should prepare future generations to be able to make decisions in several situations that are related to science. In order to achieve this we should in addition to teaching facts and data create opportunities for students to learn how science knowledge is built, improved and applied but also what are its limitations. This paper describes a scientific explanation of a simple activity well known to most students that can serve for the purpose described above. The story is written as an investigation, following steps that resemble those typically done by the scientists. Such an investigative approach is found to also be successful as a basis for teaching strategies that engage students in learning that mirrors scientific practice, such as the Investigative Science Learning Environment (ISLE) [1][1].

The ability to shoot projectiles by our own force has been very important for human history. From throwing stones and spears people gradually improved shooting techniques by using slings, catapults, bows, crossbows and other tools that help them use their own power in a more optimal way. The goal was very pragmatic: to kill animals or enemies. Today some of these techniques are still present, luckily as sporting activities: shot put, discus, hammer, javelin and archery, to name only those that are recognized as Olympic sports. Yet there is another humble and totally harmless technique with as long a history as stone throwing that remains today: cherry pit shooting. In the present article we will describe the simple physics of cherry pit shooting supported by data obtained from a high-speed video camera. At the end we will explain what this technique has in common with the chameleon's mechanism for projecting its tongue.

You can shoot cherry pits in two ways: by spitting the pit from the mouth or by squeezing the pit between the fingers. Though both methods have interesting physical backgrounds, we will focus here on the latter one (note that in some places cherry pit spitting is known as an amateur sport). The principle is very simple: insert a fresh cherry in your mouth, eat all but the pit, spit the pit on your hand, hold the pit between your thumb and forefinger, squeeze the pit as hard as you can while slowly moving the point of compression towards the back of the pit—and the pit will shoot out at a high speed. A curious person will go beyond the 'sport level' of this activity. She will want to know how the cherry pit launching mechanism works.

[1] In ISLE, students construct new ideas themselves by first observing carefully selected phenomena, proposing multiple explanations for their observations and then designing experiments to rule out those explanations. Explanations that they fail to rule out are then used for further investigations and practical applications.

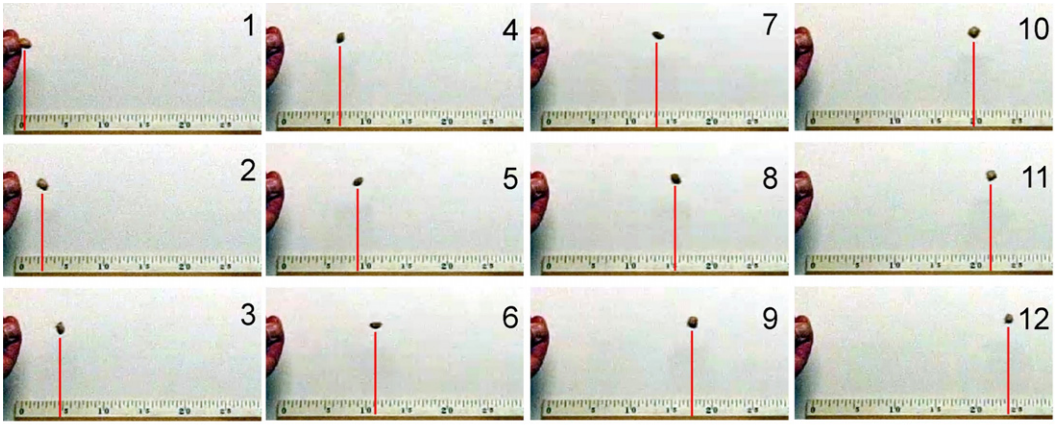
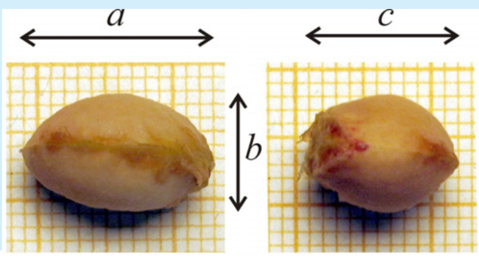


Figure 1. Sequence of 12 video frames showing the cherry pit after launching. Time interval between successive photos is 1/600 s. The scale on the ruler is in centimetres.

Box 1. Basic data for the cherry pit used in our experiments. The photograph below shows the pit on the millimetre mesh as seen from two perpendicular directions.

Mass of the cherry (without the stem): 6.65 g
Mass of the pit (as used in experiments):
$m_{\mathrm{p}} = 0.60$ g

Dimensions (see photograph on the right):
$a = 14$ mm
$b = 9$ mm
$c = 11$ mm (perpendicular to a and b).



Observations and measurements

Basic data for the cherry pit used in our experiments are summarized in box 1. Our measurements are based from the analysis of high-speed videos obtained with a Casio Exilim camera. We filmed videos at 600 frames s^{-1} and with shutter time 1/4000 s. The shutter time was chosen after the approximate speed of the pit (10 m s^{-1}) was determined. At shutter time 1/4000 s the smearing of the pit due to motion (in the direction of motion) is about 3 mm, which is acceptable concerning the dimensions of the pit. A short shutter time requires intense lighting, which was in our case obtained using a 1000 W studio lamp.

The speed of the cherry pit can be determined from pit position measurements obtained from successive frames (figure 1). In order to get reliable measurements, the projectile must move in the plane that is perpendicular to the camera sight and the camera should be as far away as possible (powerful zoom is of great help in this case). The ruler has been added to set the scale of the distances. Analysis of the photographs shows that in the first 18 ms the pit moves nearly at a constant speed of 13 m s^{-1} (47 km h^{-1}). For repeated trials we get similar results for the speed. Note that during the presented time interval the pit has fallen due to gravity only about 2 mm, meaning that for all practical cases the pit trajectory in our case can be regarded as a straight line. Note also that the maximum speed of a javelin at the time of release achieved by Olympic champions (100 km h^{-1}) is only about twice as large as the maximum speed of the cherry pit launched by a middle aged physicist in average sporting condition.

Photographs in figure 1 also reveal that the pit motion is a combination of translation and rotation. Closer examination of the photographs shows that the pit made one complete revolution during the first 10 video frames, meaning that the pit rotational speed ω was about 380 Hz.

Assumptions and simple explanation

Let us first try to estimate the pit's initial acceleration from the data that we obtained above. To do so, we need to make an assumption that acceleration was constant until the pit acquired the final speed. Since we already know the final speed we only need to estimate the distance at which the pit acquires this speed from the rest. It is reasonable to assume that this distance is equal to the long axis of the pit a (in our case 14 mm) since the pit was always launched by pointing this axis in the direction of launching. Using these data we estimate the acceleration to be $a = \frac{v_f^2}{2s} = 6000$ m s^{-2} or about 600 g. Since we know the mass of the pit (0.60 g) we can also estimate the force exerted on the pit during the acceleration. Newton's second law tells us that the force is about 4 N.

Checking the results

Let us pause for a moment and think about the results that we have obtained so far. Compared to $g = 9.81$ m s^{-2}, 6000 m s^{-2} is a remarkable acceleration, but apart from this we have no particular feeling for acceleration. We have more feeling for force though. Anyone who has tried shooting cherry pits will agree that the force, which we have to apply with our fingers, is much larger than 4 N. The discrepancy between the results and independent estimation (based on common sense in this case) indicates that the launching mechanism is not that simple and that we need to do more investigations to improve it.

Additional experiments

Again we use high-speed video, but this time we take a closer look at the launch itself. Figure 2 shows a close view of another launch of the same pit in eight successive frames. Analysis of the photographs shows that in this case the final speed was about 8 m s^{-1}.

Video analysis also reveals that during the launch the acceleration was not constant. The peak acceleration was about 1300 m s^{-2} and it was achieved sometime between the sixth and seventh frames when the fingers slipped down the pointed part of the pit. Roughly speaking this means that the distance on which the main acceleration occurs is about half of the length of the pit. Simple estimation as used above would give in this case an acceleration of about 2300 m s^{-2}, showing that the actual peak acceleration in our previous case was probably around 3400 m s^{-2} (assuming that in both cases the launching mechanism and the way we grabbed the pit were the same).

Improving the model

Closer inspection of the launch and additional analysis of the photographs gave us hints on how to improve the initial model. We decided that our new model should take into account the shape of the pit and the role of the fingers. Of course we will still try to keep the model as simple as possible. We will assume that the pit has the shape of a double wedge and that the thumb and forefinger have equal masses and are subjected to equal muscle tensions. We will also assume that fingers move only in a vertical direction and that friction and gravitational forces are negligible or irrelevant in our case. A pictorial representation of the model with forces acting on the three bodies is shown in figure 3.

Solution of the model and interpretation of the results

The wedge angle θ is determined by the pit dimensions and can be calculated from the equality $\tan\frac{\theta}{2} = \frac{b}{a}$. In our case we get $\theta \approx 65°$. The geometry of the model dictates that if each finger moves by x in a vertical direction, the pit will move by $x\cot(\theta/2)$ in a horizontal direction, which further implies that accelerations of the pit and fingers are connected by the following expression:

$$a_{\mathrm{p}} = a_{\mathrm{f}}\cot(\theta/2).$$

In our case we find $a_{\mathrm{p}} \approx 1.6a_{\mathrm{f}}$. This equation represents a constraint imposed by the geometry of the problem. Writing Newton's second law for the finger and the pit we get two more equations that describe the motion of the three bodies (note that in our model the same equation describes the motion of each finger). Solving these three equations gives expressions for a_{p}, a_{f} and F (the interested reader will find the complete solution of the problem in box 2). We will focus on the expression for the acceleration of the pit

$$a_{\mathrm{p}} = \frac{2T\tan(\theta/2)}{m_{\mathrm{p}} + 2M\tan^2(\theta/2)}.$$

In our case we can simplify this expression by taking into account that the mass of the pit $m_{\mathrm{p}} = 0.60$ g is much smaller than the mass of the

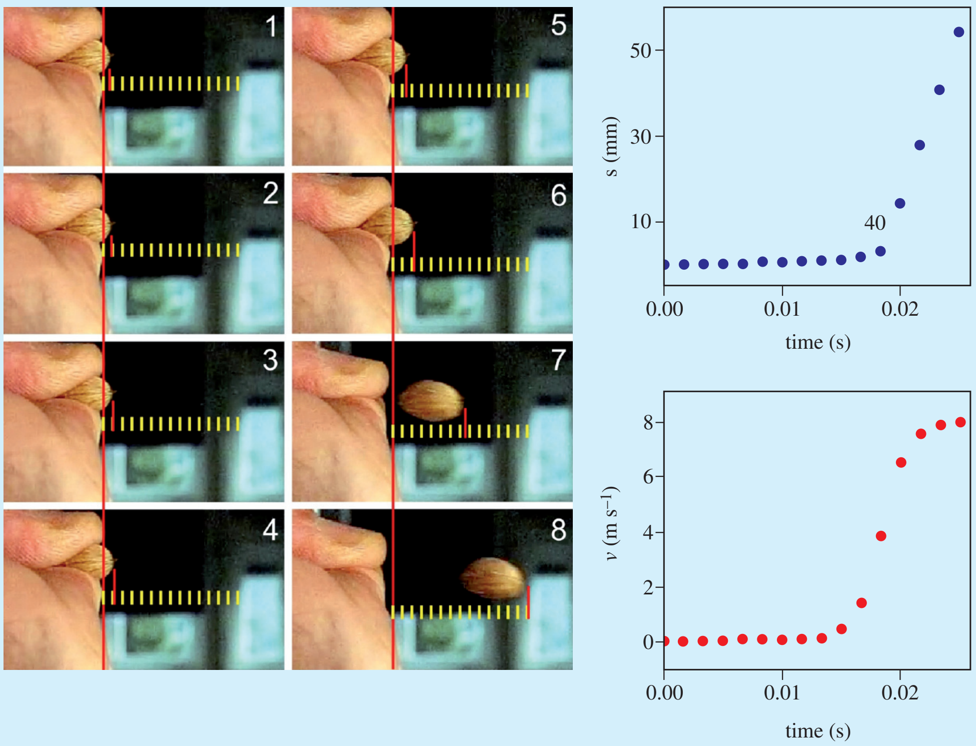


Figure 2. Sequence of eight video frames showing the closer view of the pit launch (left). Using LoggerPro software we have carried out a movie video analysis to obtain position–time and velocity-time graphs (right). The time interval between successive photos is 1/600 s. The yellow ticks on the photos indicate positions that are 2 mm apart.

finger M. Namely, the mass of each finger is approximately 20 g (we estimated the finger volume and assumed the density of the finger is about the same as the density of water). In this case the expression above simplifies to

$$a_p \approx \frac{T}{M}\cot(\theta/2).$$

The result suggests that the acceleration of the pit is mainly determined by the tension force in muscles, masses of fingers and the shape of the pit but it is independent of the mass of the pit. How can we interpret this result? Since $m_p \ll M$, the forces produced by the muscles mainly accelerate the fingers. The pit only slips between the fingertips and has almost no influence on the motion of the fingers. It is only the pit geometry (angle θ in our case) that has some (but not a major) effect on the pit acceleration.

Checking for consistency

The analysis above calls for independent measurement of the muscle force that acts on the finger. This may look easier than it is. We need to measure the force with which the two fingers are acting on each other with the hand and fingers in a position that is as close as possible to the position during the shooting of the pit. Conventional force meters are obviously not suitable for this purpose. We need a thin force meter that can be squeezed between the fingertips. For a rough estimation, simple plastic tubing proved to work well. We used transparent plastic tubing with outer diameter 6 mm and inner diameter 3 mm. The tubing was stiff enough that it became flat only when it was compressed between fingers with maximal force, similar to the force used when shooting the cherry pit (judged by personal feeling), (figure 4, left). The same tubing was then placed on the scales and pressed down until the same deformation of tubing was achieved (figure 4, right). At that point the

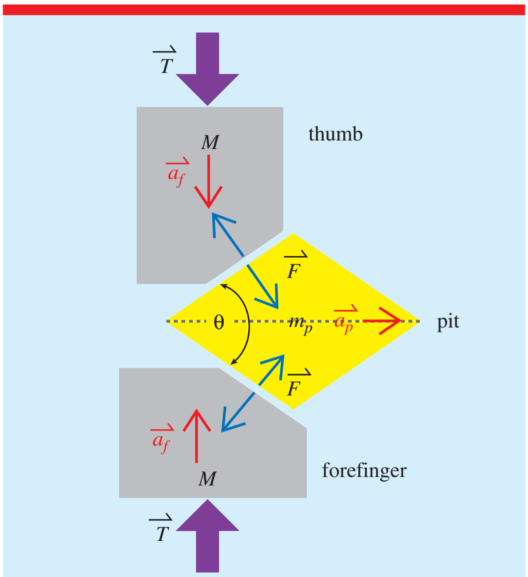


Figure 3. Improved model of the cherry pit shooting mechanism (sizes are not to scale). Acceleration vectors are presented in red and force vectors are in blue. Only contact forces are shown (gravity forces are not relevant in this case): *F*—forces between fingers and the pit, *T*—muscle forces on the fingers.

reading of the scales showed the mass, the weight of which is equal to the muscle force. In our case the average force measured in this way was about $T = 50$ N.

Now we can independently estimate the acceleration of the fingers ($a_f = T/M = 2500$ m s^{-2}) and the acceleration of the pit ($a_p = 1.6a_f = 4000$ m s^{-2}). This value is less than 20% off from the estimated acceleration for the first pit launching. Taking into account all the assumptions that we made in our model, the agreement is good enough that we can accept the proposed model as a satisfactory approximation. The model explains how the motion of the fingers in one direction is transformed into the motion of the pit in a perpendicular direction. The model also shows that for a typical cherry pit the acceleration of the pit is of the same order of magnitude as the acceleration of the fingers.

Limitations of the model

Though the proposed model proved to be useful for our purpose we should have in mind the main discrepancies between the model and the real experiment: in reality friction is not zero, fingers are not equal in mass and size and they do not move along a straight line, a real pit is not symmetric and its surface is not flat but curved. The differences between the fingers and asymmetry of the pit are probably the main reasons for the torque that caused the observed rotation of the pit.

Different views

Let us look at the experiment from the energy point of view. As shown above, the main acceleration of the pit occurred around the sixth frame in figure 2, though the fingers' muscles were under tension long before this moment. The launching mechanism resembles in principle the one used in catapults. First, elastic potential energy is gradually stored in the system and then it is suddenly transformed into the kinetic energy of the launching mechanism and the projectile. In our case this occurs when the fingertips slip along the pointed part of the pit.

Let us compare the kinetic energies of the fingers and the pit. Kinetic energy of the finger can be estimated from the work done by the muscle force $T = 50$ N while moving the finger over

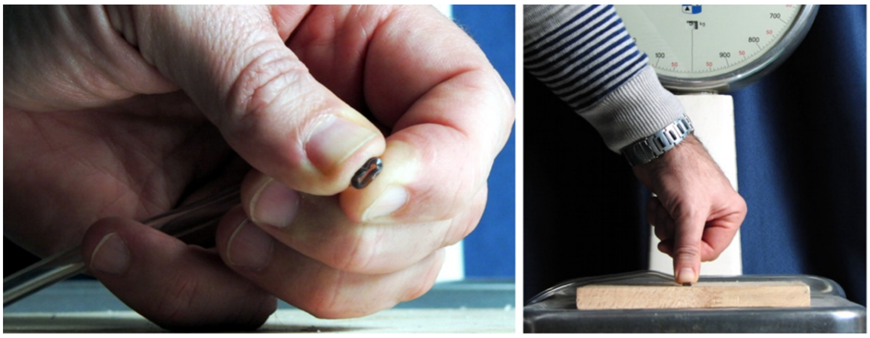


Figure 4. Tubing force meter. Tubing is first compressed by the fingers in a similar position as when shooting the pit (left). After that the same deformation is achieved by pressing the tubing on the scales (right).

Box 2. Mathematical treatment of the improved model.

Newton's second law for one finger and for the pit reads as follows (see figure 3):

$$T - F\cos(\theta/2) = Ma_{\mathrm{f}}$$

$$2F\sin(\theta/2) = m_{\mathrm{p}}a_{\mathrm{p}}.$$

In addition we have a constraint equation determined by the geometry of the problem

$$a_{\mathrm{p}} = \frac{a_{\mathrm{f}}}{\tan(\theta/2)}.$$

Therefore we have three equations and three unknowns (a_{p}, a_{f} and F). Solving this system of equations we get

$$a_{\mathrm{p}} = \frac{2T\tan(\theta/2)}{m_{\mathrm{p}} + 2M\tan^2(\theta/2)},$$

$$a_{\mathrm{f}} = \frac{2T\tan^2(\theta/2)}{m_{\mathrm{p}} + 2M\tan^2(\theta/2)},$$

$$F = \frac{m_{\mathrm{p}}T}{\cos(\theta/2)(m_{\mathrm{p}} + 2M\tan^2(\theta/2))}.$$

If $m_{\mathrm{p}} \ll M$ the expression for pit acceleration takes the following form:

$$a_{\mathrm{p}} \approx \frac{T}{M\tan(\theta/2)}.$$

the distance equal to half of the height of the pit ($b/2 = 5$ mm). The calculated value for one finger is 0.25 J. Note that we neglected friction, so the real value for kinetic energy is somewhat lower than this. Translational kinetic energy calculated from the maximal speed of the pit (13 m s^{-1}) and its mass is only 0.05 J. As observed from the video, the pit also rotates. Rotational kinetic energy of the rigid body is equal to $\frac{1}{2}J\omega^2$, where J is the rotational inertia and ω rotational speed. Since we are only interested in the order of magnitude, we can approximate the pit with a sphere with effective radius $r = (a + b + c)/3 = 11$ mm and use the expression for $J = \frac{2}{5}mr^2$. Taking into account the measured rotational speed of the pit (380 Hz) we calculate the rotational kinetic energy to be 0.002 J, which is only a small fraction of the total kinetic energy of the pit.

The values calculated above suggest that most of the energy that was initially stored in the muscles is transformed into the kinetic energy of the fingers (which is sooner or later transformed into heat) and only a small fraction is transformed into kinetic energy of the pit. Note that this view from the point of energies is consistent with the one we made when we studied forces.

Application of new knowledge

The whole story described above can be used as an illustration of how physicists solve problems and build new knowledge. But at the end of the story students may ask questions like: 'So what? Can we use this knowledge to solve some *real* problems?' The answer is YES!

A chameleon can catch prey located up to 1.5 body lengths away within a tenth of a second by launching its tongue at an acceleration of 500 m s^{-2} [2]. Through history zoologists have suggested several mechanisms to explain the impressive performance of a chameleon's tongue, such as that the tongue is 'erected' through an increase in blood pressure or inflated by the lungs. In 1993 Zoond established the currently held view about how a chameleon projects its tongue [3], but the scientific debate about the role of different parts of the tongue still goes on [2].

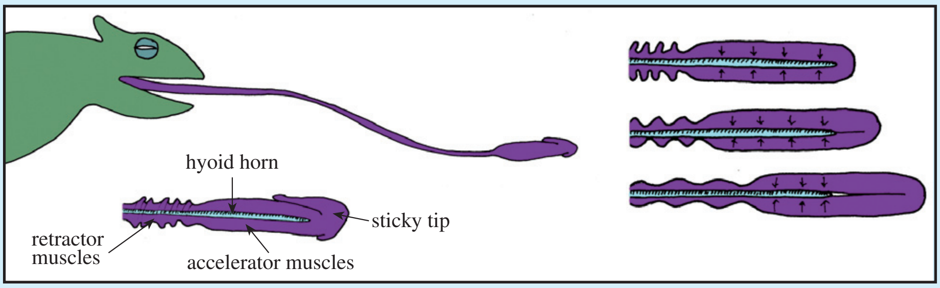


Figure 5. Sketch of the chameleon with projected tongue (upper-left drawing), the structure of the chameleon's tongue (lower-left drawing) and launch of the chameleon's tongue in three successive moments (right).

A chameleon has a hollow tongue that sheathes over a long, tapering cartilaginous spike called the hyoid horn. The hyoid horn is attached to the head bones. The tongue consists of three basic components: the sticky tip, the retractor muscles and the accelerator muscles (figure 5, left).

The accelerator muscles have a cylindrical shape and can contract radially to squeeze against the hyoid horn. The tongue launches when the accelerator muscle begins to slide off the tip of the hyoid horn (figure 5, right).

The effect is similar to shooting the cherry pit, except in this case the pit (hyoid horn) remains stationary and the squeezer (accelerator muscles) is propelled towards the prey. After hitting the prey the retractor muscles bring the tongue and the prey back to the mouth and a delicious feast can start.

Conclusions

We have followed the steps typically taken by scientists in their work. Based on initial observations and assumptions we built a simple model. Since the predictions of this model were not consistent with measured values we designed additional experiments and improved the initial theoretical model. We needed mathematical tools to solve that model and we checked it again against independent measurements. We verified the consistency of different interpretations and we became aware of the limitations of our model. Finally we showed that new knowledge can be applied in completely different situations, which can be described with an analogous model. Students should see the role each of these steps play in building scientific knowledge but also realize that science does not give absolute and definite answers but only approximations that are constantly improved.

Acknowledgments

The authors wish to thank Gary Williams and Eugenia Etkina for valuable discussions and the anonymous referee for careful reading of the text.

Received 15 January 2011, in final form 3 April 2011
doi:10.1088/0031-9120/47/1/21

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