Low cost hands-on experiments for Physics teaching

EDVCATIO PHYSICORVM
QVO NON ASCENDAM?

Michael Vollmer, **Klaus Peter Möllmann**
University of Applied Sciences, Magdeburgerstr 50, 14770, Brandenburg, Germany.

E-mail: vollmer@fh-brandenburg.de

(Received 26 August 2011, accepted 3 December 2011)

Abstract

Experiments are essential in any kind of phyiscs teaching. We will focus on one category, low cost hands-on expriments, which have many advantages for physics teaching, in particular concerning motivation of students. After a short discussion of criteria, advantages, critics and problems of such experiments, a number of selected hands-on experiments are treated in more detail.

Keywords: Low cost experiments, hands-on experiments, student motivation, teacher training.

Resumen

Los experimentos son esenciales en cualquier tipo de enseñanza de Física. Nos centraremos en una sola categoría, experimentos manuales de bajo costos, que tienen muchas ventajas para la enseñanza de la física, en particular con respecto a la motivación de los estudiantes. Después de una breve discusión de criterios, ventajas, críticos y los problemas de los experimentos, un número de una selección de experimentos prácticos se tratan con más detalle.

Palabras clave: Experimentos de bajo costo, experimentos prácticos, motivación del estudiante, formación del profesorado.

PACS: 01.40.-d, 01.40.J-, 01.50.My **ISSN 1870-9095**

I. INTRODUCTION

"Physics is a science based on experiences. It is based on facts found experimentally". This statement from RW Pohl, a German physicist from the 20th century, who was famous for his lecture demonstrations, is one way of describing the importance of experiments. Obviously many important scientific developments also in theoretical physics do depend on experiments. One example is the introduction of the constant h, now known as Planck´s quantum constant in order to be able to quantitatively describe the result of very precise measurements of the blackbody radiation from heated cavities. Nowadays experiments are not only essential for the scientific discipline physics, but they are also indispensable in any classroom where physics is taught.

There are various possibilities to classify experiments for teaching, here we will focus on the two extreme categories. First there are cognition oriented experiments, *i.e.*, those supporting knowledge. These are mostly performed with special apparatus under controlled but variable conditions. Such experiments allow reproducible tests of predictions of physical theories. At the introductory level, think *e.g.* of a free fall experiment where a metal sphere is falling through light barriers and time differences are measured accurately with some counters or, *e.g.*, of measuring the index of refraction of air using the change of interference fringes in a Mach Zehnder interferometer. Obviously special equipment is needed and costs for schools are high. In contrast, there are second low cost hands-on experiments which are primarily of the category motivation oriented. Usually such experiments can be performed with all kind of apparatus which allows student encounters with physics, technology, and/or natural phenomena. Whereas the former type of experiment usually only attracts a limited number of students, the latter offers the possibility of reaching more students and raising interest in the natural sciences in general. Of course there are also a large number of experimental types in between these two extremes. In this paper, we will focus, however, mostly on the low-cost hands on experiments. In Sect. 2 we will briefly define what is meant with this type of experiment outlining also the typical criticism, their advantages and also the problem areas. Sect. 3 will present a number of selected hands-on experiments and give brief explanations. Sect. 4 gives a summary and conclusions.

II. HANDS-ON EXPERIMENTS

One possibility to define low cost hands-on experiments is by listing some typical criteria. These are:

- The equipment is in general available (*e.g.* hardware stores, supermarkets etc.), it is easy to get, and has a low cost (a few Dollars or Euros).
- The set up is simple, maybe rising tension.
- The presentation should not last long.
- Sometimes the experiments may be motivated by potential technical applications.
- In any case, it should cause special affective effects (surprise, doubt, enthusiasm,...).

The latter effect may lead to a rise in motivation for physics. This is quite important, since students have many other distractions. Physics must *e.g.* compete with other time consuming events of the daily life like love affairs, watching movies, discussing fashion, attending or participating in sports events and many more.

The obvious advantages of hands-on experiments are that one usually needs very little preparation and can perform them nearly everywhere. Since very often objects of everyday life are used, the apparatus does not lead to any distraction (*e.g.* by cables or unknown apparatus like power supplies, pulse counters, etc.). Also, regular experiments do often have a quite complex set up, which cannot be understood by students immediately. In such a case, the set up may be seen as black box and there is often the chance that students think, that any outcome of the experiment is possible, in particular the one desired by the teacher. The simpler the set up, the easier it is to convince students that there are indeed no technical tricks involved in the outcome of the experiment. Hands-on experiments can be used in all phases of teaching, *e.g.*, in the introduction of a new topic as motivation, then later on while gathering more facts and finally when deepening the understanding. Such experiments are fun, they often stir up the desire in students to repeat them and to present them to friends and family. If they are performed successfully, this can enhance the self esteem of the student. Finally, the surprise effect which often goes along can lead to cognitive conflicts. This may finally help to shift from the everyday way of perceiving our surroundings to the physics way of observing.

It must however, also be admitted, that since often equipment of everyday life is used in simple set ups, a severe problem can arise: the phenomena to be observed are usually not isolated as in typical science oriented laboratory experiments. In the latter, all possible disturbances are usually suppressed, filtered out, or corrected for, such as friction or air resistance. In contrast, simple hands-on experiments usually involve all kinds of such effects. Hence, the analysis and detailed explanation of some of these experiments can be quite complex and the most simple experiment can have the most difficult theoretical explanation. This is, however not a real drawback, since such effects need also to be discussed in the other type of experiments when motivating of how to suppress them or how to correct for them.

It should be mentioned that there is also criticism from physics professionals. A typical prejudice is that such experiments are childs play, stopgaps, or gadgets. If there is no money available it may be acceptable but they should be replaced as soon as possible by real equipment for real experiments. The negative assessment is probably due to the perceived close relation to magic and conjuring tricks. Also such experiments are often seen as playing which seems to violate the principle of seriousness in science. But: any play that creates knowledge cannot be dubious or wrong. And conjuring and magic tricks have a very close connection to perception and physics and a lot of physics can be learned, in particular also when studying the physics of modern toys. Therefore we are convinced that hands-on experiments have a lot of justification for use in teaching, also besides the advantage of being low cost.

The following experiments were tested multiple times at many in-service teacher training seminars in Germany, Switzerland, Austria, Mexico and Namibia.

III. EXAMPLES OF HANDS-ON EXPERIMENTS

A) The breaking rod: Karate

An old and well known experiment uses a wooden rod which is lying on two easily breakable objects, *e.g.* on two glasses, on two raw eggs or hanging in two paper loops, such that the ends of the rod are supported (see Fig. 1).

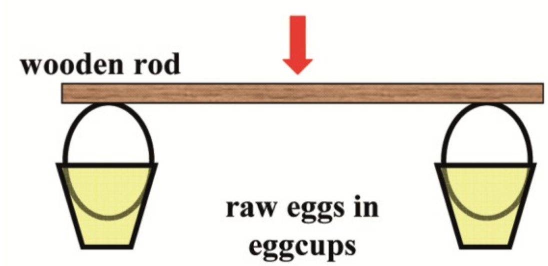

FIGURE 1. Set up of breaking rod (Karate) experiment. A wooden rod is supported by two very fragile objects, *e.g.* raw eggs or champagne glasses.

Hitting the rod in the middle very hard leads to breaking of the rod. Subsequently, the two parts fall down without damaging the supports. This is indeed happening as is shown in Fig. 2, recorded with a high speed camera. Although scientific cameras are still rather expensive, there are now also inexpensive ones available starting at about 100 €, *e.g.* from the Casio Exilim series, which are regular digital cameras which just include a high speed option (details see [1]). Images shown here were recorded with a more expensive camera in order to have higher spatial resolution (but all experiments can also be recorded with the Casio with satisfying results).

FIGURE 2. Three snapshots of the breaking rod (times in ms) recorded with a scientific high speed camera at 1000 frames per second.

The motion induced upon hitting the rod can be decomposed into a translation and a rotation. The translation of each half rod is just due to momentum transfer $\Delta p = m \cdot \Delta v$ as a result of the applied force for contact time Δt. Since Δv corresponds to the initial center of mass velocity v_{CM}, we find

$$m \cdot v_{CM} = F \cdot \Delta t. \qquad (1)$$

On the other hand, the force also created a torque M which in contact time Δt leads to an angular momentum ΔL. Since $L = J \cdot \omega$ where J is the moment of inertia, we can relate the angular frequency to center of mass velocity and from the equation of motion of a rotating rod find the velocities of the rod at each point. Initially, *i.e.* right after breaking, the situation is depicted in Fig. 3: The half rod, here the one supported on its left side, has v_{CM} at its middle as well as 4 v_{CM} at the right side, where the longer rod was hit. This corresponds to the hand velocity. However, on the left side, where the rod was initially supported, the velocity points upwards, *i.e.* the rod is lifted away from the support and thus has no chance to damage the support (more details, see [2, 3]).

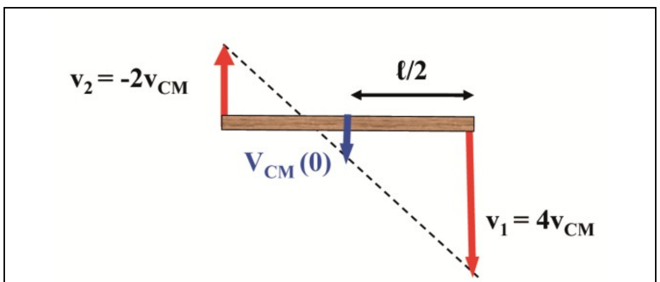

FIGURE 3. Initial velocities at center and sides of one of the half-rods (supported at left side) directly after breaking.

B) Strange superball movements

Superballs were invented several decades ago and are still a popular toy due to their special properties upon reflection. On the one hand, they have a very high coefficient of restitution, *i.e.* they jump back much higher when falling to the floor than other balls like tennis balls. In addition, they also behave differently when hitting a boundary at an angle. Whereas most balls tend to slide along the boundary, superballs more or less stick to it which leads to a rolling on the surface upon contact. As a consequence a ball colliding with a wall will gain angular momentum, *i.e.* it rotates. If such a ball with spin collides with another surface the ball will behave similar to a billiard ball which hits a wall with spin: it will be reflected sideways depending on spin direction. This property leads to a peculiar behavior: when such a ball is thrown at an angle towards the floor such that it can hit a table from below (Fig. 4), it will change angular momentum *i.e.* spin, twice and will be reflected back to where it came from. The complete dynamics (*e.g.* [4, 5]) and related experiments have been treated elsewhere. In particular, high speed videos of such experiments can be found in the internet [3]. This behavior was well known for quite a long time and inspired experiments with other geometries. Fig. 5 depicts what happens when a superball is thrown at an angle into a vertical cavity, realized *e.g.* by two parallel oriented tables.

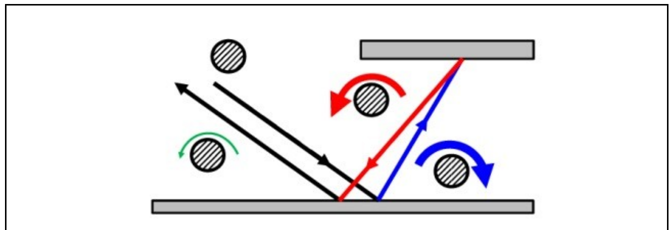

FIGURE 4. Schematic trajectories and spin of superball, thrown onto the floor and hitting a table from below.

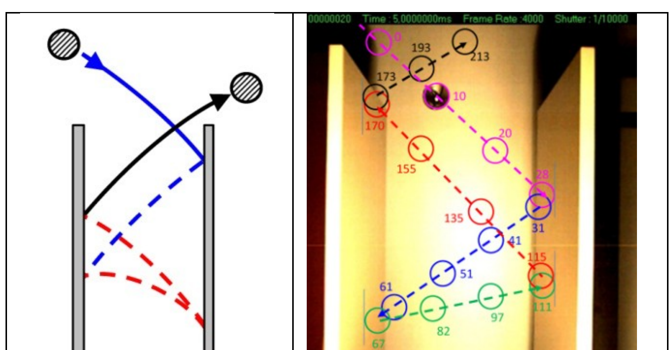

FIGURE 5. Schematic trajectories of a superball, thrown into a vertical channel (left) and image of real trajectory superimposed onto the snapshot at 10ms (numbers give time in ms).

Due to the spin acquired upon each reflection and, hence, the reversal of direction after two reflections, the ball may even exit the vertical channel again, *i.e.,* if thrown hard enough, its properties of retroreflection may even overcome gravity. Again, a description with videos can be found in the internet [3].

C) Measuring reaction times

Reaction times of humans are among the experiences that every student can make of his own. A very simple and well known experiment along these lines consists of holding a ruler and ask a volunteer to make a gap between his thumb and index finger with the ruler inside. The volunteer is asked to react and close the gap between the fingers as soon as the ruler is released (see Fig. 6).

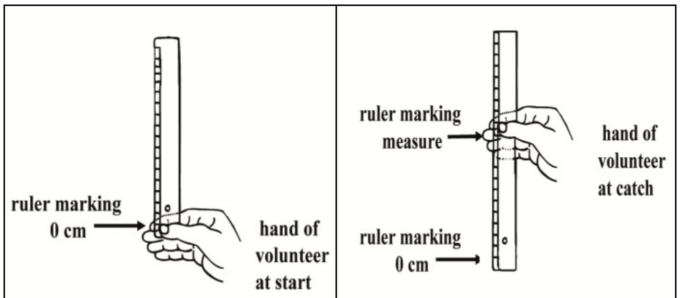

FIGURE 6. Measuring total hand reaction times using the free fall of a ruler (after [6]).

If there is no cheating (trying to close fingers without release) the ruler falls a certain distance which is related to the total reaction time, *i.e.*, the real reaction time until the brain has send information to the muscles and the following time needed to close the gap.

Since the ruler will be in free fall, the falling distance before the catch is related to the total reaction time by

$$t = \sqrt{\frac{2s}{g}} . \quad (2)$$

Table I gives results of reaction times versus distance for up to 30cm of a typical ruler.

TABLE I. fall distance of a ruler as a function of time.

Distance in cm	*Time in s*
5	0.10
10	0.14
15	0.17
20	0.20
25	0.23
30	0.25

This experiment can be done easily with many students at the same time, but it is useful to also extend the method to reaction times of feet, since those are needed every day while driving a car when there is the sudden need for braking. Obviously, a typical preconception is that the reaction time should be longer than for the hand, because the distance from brain to feet is longer than to the fingers. Try it out by yourself by using a set up as shown in Fig. 7. A volunteer is lying on his/her back on a table, the floor etc. One leg should be at an angle of about 90° at the knee and the foot should have a distance of a few cm towards a wall or a plate etc. A ruler is placed between foot and wall and the volunteer is asked to close the gap when the ruler is released. Similar to the hand experiment, the falling distance gives the total reaction time. This experiment is a lot of fun and usually all students present in a classroom want to do it.

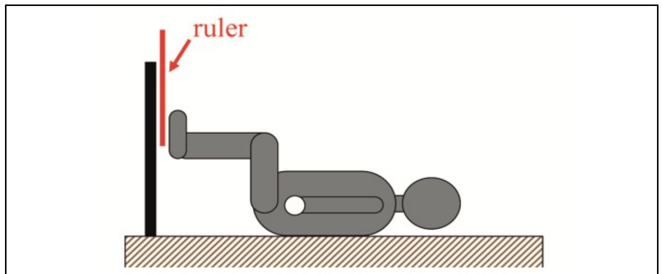

FIGURE 7. Measuring total foot reaction times using the free fall of a ruler.

D) The empty bottle and the cork

An example for a really surprising experiment uses a wine bottle (with cork) and a piece of very thin and light cloth, *e.g.,* of silk. The bottle must be prepared the previous day. The cork is removed, *i.e.,* the bottle opened, usually by means of a corkscrew. Whereas the empty bottle, which should be dry inside, and the cork are needed, the wine is not essential for the experiment.

The cork is pushed inside of the bottle (which may not be easy due to the friction between cork and glass). Then the problem is to remove the cork from the inside of the bottle without destroying neither bottle nor cork. The only equipment allowed is a silk cloth, *e.g.*, a silk scarf.

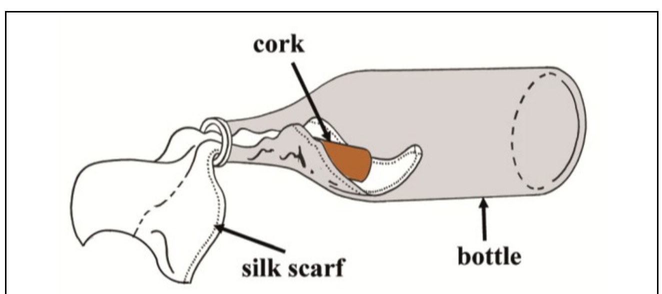

FIGURE 8. Set up to remove a cork from an empty bottle using a silk scarf (after [6]).

Fig. 8 depicts the set up for solving the problem. The silk scarf is pushed into the bottle with part of it still being outside (to be able to exert a force from outside). Then the bottle is moved and rotated to place the cork onto the silk such that tearing from the outside will lead to the silk totally surrounding the cork, *i.e.,* it no longer touches the glass. Then one may tear and get the silk scarf outside of the bottle, at the same time removing the cork.

The key point is friction and the coefficients of sliding friction. On the one hand, due to friction between cork and silk, it will stick to the silk while pulling. On the other hand, the coefficient of friction between glass and silk is smaller than the one between glass and cork, therefore rather little force is needed to pull the cork within the silk scarf.

E) Measuring lung volume?

A simple plastic foil cylinder can be used for experiments with gases and Bernoulli´s equation. In Germany it is sold for cooking meat in ovens such that the meat is not getting too dry. One can buy it with a diameter of about 25 to 30cm and a length of 4m in most supermarkets. The cylindrical foil has open ends and for the original use, one just cuts off the desired length such that the meat is placed into it before closing both ends and putting it into a stove.

For physics experiments we use the whole length. A volunteer is asked for a test of his/her lung volume. He should take one end of the cylinder in his hands, form a funnel and blow into it for, say, five times. At the same time, the instructor keeps the other end closed with is hand. After blowing into the cylinder, the volunteer is asked to close his side of the cylinder and the instructor slides his hand from his side towards the volunteers end.

This leads to a cylinder of given length which allows to measure the inside volume from its diameter and the length. In the second part of the experiment, the instructor demonstrates that it is easily possible to surpass the previous volume with just a single blow. The trick is to not form a funnel which is closed such it constitutes the only opening into the cylinder. Rather the blowing should be into a slightly larger opening. Since there is a large velocity of the air within the opening while blowing there will be a reduced static pressure at the entrance of the cylinder due to Bernoulli´s law. As a consequence, air from the surroundings will also start to stream into the cylinder. This additional "bypass" air is usually much larger in volume than the one due to one time breathing alone, *i.e.* if ends are closed after one time blowing into the cylinder, the inside volume will be much larger (see Fig. 9).

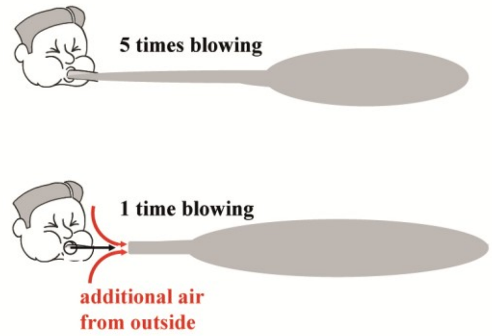

FIGURE 9. Measuring lung volume (top) or inflating a bag utilizing Bernoulli´s law (bottom).

F) Ring and chain

Physics is often used by magicians in their tricks. A nice example which involves rather simple physics just involves a metal ring and a metal chain. It is a lot of fun and students can also test it at home. Rings and chains can usually be bought in hardware stores. The set up (see Fig. 10) is the following: the two ends of a chain of typical length 1m are connected such that it forms a loop. It is placed over a hand. Then the ring is lifted outside of the chain ends and also held by the same or the other hand. The problem is to let the ring fall, such that it does not fall to the ground but stays within the chain. Details of the experiment including videos for download are described elsewhere [7]. Here only a brief description is given of how it works.

FIGURE 10. Holding a ring and a chain with one hand.

Fig. 11 depicts three snapshots recorded with a high speed camera. The key point is to hold the ring with two fingers in a plane perpendicular to the one defined by the two hanging chain segments. Then one finger must move away earlier than the other one. As a consequence the ring starts to rotate. When having rotated by more than 90°, it deflects the part of the chain, still below the ring. The restoring force leads to a movement of the chain. Provided the friction is low enough and the stiffness of the chain is not too high, the chain starts to slide around the outer part of the ring and thus forms a knot around the ring.

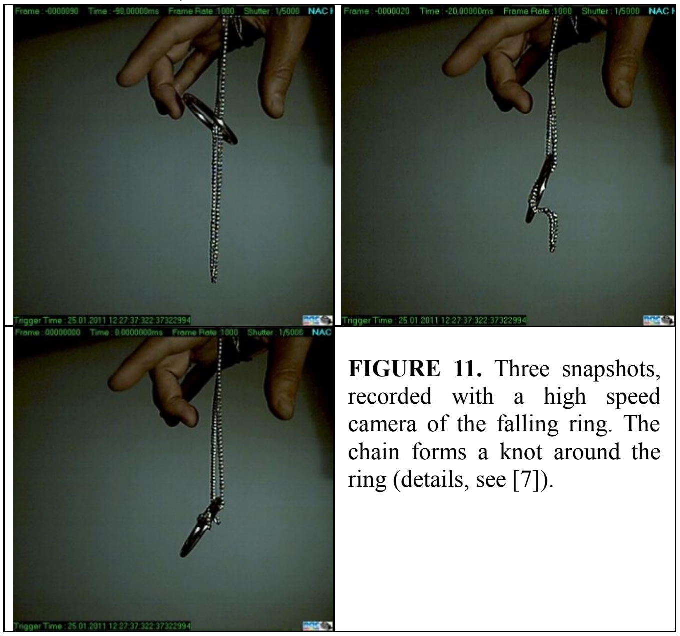

FIGURE 11. Three snapshots, recorded with a high speed camera of the falling ring. The chain forms a knot around the ring (details, see [7]).

G) Easy measure against shortsightedness

A final example from optics shall be given which has the advantage that in the standard version no equipment at all is needed and that it can be done for large groups. It works best for shortsighted or farsighted people, but it can also be demonstrated for normally sighted people. Shortsighted people without glasses usually see unfocused images if objects are far away (*e.g.* Fig. 12/left). If glasses are not available, there is a simple means of still seeing focused images (Fig. 12/right) by looking through a very small aperture of say 1mm diameter. It needs not be circular, for example it may be realized by using the own hand with the fingers creating the aperture, *e.g.,* as shown in Fig. 13. Looking through this aperture close to the eye leads to focused images. Of course there is the drawback, that less light is entering the eye, *i.e.,* the method works best for bright objects and good contrast.

FIGURE 12. Example of unfocussed text as could be observed by shortsighted people or a manually unfocused camera (left). The same text would be focused (right) if looking through correction lenses (glasses) or a small aperture.

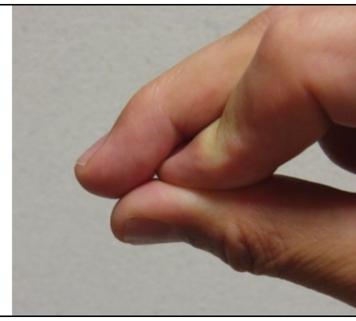

FIGURE 13. How to use thumb, index and middle finger to create a small aperture.

But – if glasses are not at hand, why not use your hand and see sharp, though less bright images. An explanation of the focusing is possible by using the geometrical optics light ray model. Fig. 14/top is a standard ray diagram to find the image of an object G in a distance g from a thin lens with its two focal points F and F'. The image G^* is formed in a distance b. For short sighted people, the retina would be at a distance s>b, *i.e.* behind the image. Therefore the image in the retina is unfocussed as illustrated by width of the region Δ_1 which resembles the image of the top of the object.

If a small aperture is inserted (Fig. 14/bottom) the ray bundle also leads to an image at distance b. However, since the width of the ray bundle is smaller than if all of the lens would be illuminated, the width Δ_2 of this ray bundle on the retina is much smaller than without aperture.

As a consequence, the image gets sharper.

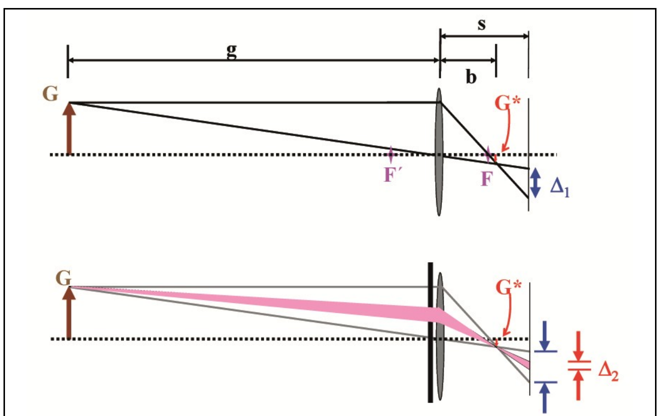

FIGURE 14. Explanation of function of small aperture in front of a projecting lens.

It is also possible to have a big lecture hall demonstration of the same phenomenon by using a video camera rather than the eye in manual focussing mode which is attached to a video projector. First the camera is manually set out of focus. Then a small aperture is placed in front of the entrance lens and the image will get focussed.

IV. SUMMARY AND CONCLUSIONS

A number of well tested simple and low-cost hands-on experiments have been described and explained. Some of them were recorded with modern high speed cameras in order to facilitate understanding of the underlying physics. These few examples shall illustrate the usefulness of such experiments in the teaching of physics. Of course we use many more experiments of this type. Examples include experiments from many different fields dealing, *e.g.*, with vacuum using household items [8], phenomena observed when using electromagnetic fields within commercial microwave ovens [9, 10], thermal phenomena of heat transfer, which can be treated in predict-observe-explain sequences such as *e.g.,* the heating of cheese cubes in conventional or microwave ovens [11], spectroscopy experiments using overhead projectors [12] or even interferometer set-ups for school or kitchen tables [13].

Experiments of various kinds and also simple hands-on experiments can often be found in popular physics education journals such as Physics Education (IOP), The Physics Teacher (AAPT), or Lajpe (LAPEN) and – usually with a larger degree of theory also in European Journal of Physics (IOP) or American Journal of Physics (AAPT). Finally there are compilations of hundreds of experiments in books, published in various languages (see *e.g.* [6, 14]).

REFERENCES

[1] Vollmer, M. and Möllmann, K. P., *High speed slow motion: The technology of modern high speed cameras,* Phys. Ed. **46**, 191-202 (2011).
[2] Mamola, K. C. and Pollock, J. T., *The breaking broomstick demonstration*, The Physics Teacher **31**, 230-233 (1993).
[3] Vollmer, M. and Möllmann, K. P., *Experiments with high speed cameras,* Phys. Ed. **46**, 472-486 (2011).
[4] Garwin, R. L., *Kinematics of an ultraelastic rough ball*, Am. J. Phys. **37**, 88-92 (1969).
[5] Hefner, B. T., *The kinematics of a superball bouncing between two vertical surfaces*, Am. J. Phys. **72**, 875-883 (2004).
[6] Hilscher, H. *et al.*, *Physikalische Freihandexperimente,* 2 Bände, (Aulis, Köln, 2004).
[7] Vollmer, M. and Möllmann, K. P., *Ring falling into a chain: no magic–just physics,* The Physics Teacher **49**, 337-339 (2011).
[8] Vollmer, M., *Vakuumphysik im Alltag: Physikalische Freihand- und Low-cost-Experimente*, PhyDid **1**, 19-32 (2002), see www.phydid.de (in German).
[9] Vollmer, M., Möllmann, K. P., Karstädt, D., *More experiments with microwave ovens,* Phys. Ed. **39**, 346-351 (2004).
[10] Vollmer, M., Möllmann, K. P., Karstädt, D., *Microwave oven experiments with metals and light sources,* Phys. Ed. **39**, 500-508 (2004).
[11] Planinsic, G. and Vollmer, M., *The surface to volume ratio in thermal physics: from cheese cubes to animal metabolism,* Eur. J. Phys. **29**, 369-384 (2008); see also **29**/3, 661 (2008).
[12] Vollmer, M., *Freihandexperimente zur Spektroskopie im Unterricht und als Hausaufgabe,* Praxis der Naturwissenschaften–Physik in der Schule 4/**52**, 9-18 (2003) see also pages 2-8 in same issue (in German).
[13] Vollmer, M. and Möllmann, K. P., *Michelson interferometer for your kitchen table,* The Phys. Teacher **46**, 114-117 (2008).
[14] Edge, R., *String and sticky tape experiments*, American Association of Physics Teachers, College Park, MD (1987).