Low-cost, high-tech experiments for educational physics

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The advantage of low-cost experiments is obvious and the real-life aspects of high-tech experiments appeal to pupils. The benefits of hands-on experiments that are both low-cost and high-tech are described here. Four detailed examples are given, which include the use of contact lenses and CDs, and other ideas are provided.

In recent years a variety of new materials and techniques have found their way into everyday life and into the hands of pupils, e.g. audio CDs, cellular phones, remote controls etc. In contrast to this tendency, no experimentally and methodically equivalent approach can be claimed in teaching—in terms of the full-scale implementation of new materials and techniques into teaching as well as in terms of a straightforward and cost-saving approach. The objective of this article is to give examples of low-cost experiments with a high-tech background. It will further be explained how these experiments can be integrated into the classical collection of low-cost experiments.

Hands-on experiments are not a recent phenomenon. Hands-on experiments were known rather as magic tricks, where astonishment and entertainment were preferred to the explanation and understanding of the physics behind the experiment. It was in the 19th century that the 'classical' hands-on experiment found its way into teaching. The quality of the experiment was merely determined by the teacher's choice of materials and instruments (from daily life). Since then, the classical definition of a hands-on experiment has been as an experiment that is based on the use of everyday gadgets or simple set-ups that can be assembled very easily.

The overall number of books on the American and German market dealing with hands-on experiments and their application in educational physics has been estimated to be around 50. Some of these books also cover how toys or other low budget gadgets can be incorporated into teaching physics. Many of these 50 books can be seen as mere lists of experiments. Only 15 of them are available to the public (e.g. [1–6], a more complete list is available from us). However, the number of articles in magazines and journals about teaching, which give further ideas for hands-on experiments, is approaching 1000—in English as well as in German. The articles, however, are not systematically distributed in the literature. Our main point of criticism is the fact that most of the experiments, when tested, did not work out: the descriptions contain not even a simple schematic diagram on how to set up the experiment, they give only qualitative results and deal with very special cases instead of the broader phenomena. For the most part, a discussion of the historic development of hands-on experiments into their modern form (with new materials and everyday items) is practically non-existent.

Physics is among the least liked subjects in today's schools in Germany as well as in other countries. The reasons for this have been addressed by pupils and teachers alike: too much mathematics, no obvious relation to everyday life, only a small number of experiments (which are then conducted by the teacher, not by the pupils), and too much scribbled writing on the blackboard instead of practical work.

One approach to a better way of teaching physics

Taking into account the above, our suggestions are therefore that:

- Teaching physics has to consider the pupils' real-life experience and daily life.
- The educational context of implementation should be broadened.
- Experiments should be based on simple set-ups and low-cost items that can be found in any typical household or school.

These suggestions take the reasons for disliking school physics into account, but they are also based upon the following:

- our own experience with hands-on experiments and the 'improvements' found, as well as on
- completely redesigned experiments based on new materials (e.g. Teflon, Velcro tape, Gore-Tex) and modern devices from everyday life (e.g. electric toothbrush, audio CD, cellular phone, airbag sensor).

We consider these experiments to be **low-cost** and **high-tech**. The introduction of the high-tech aspect to the traditional understanding of low-cost experiments is proposed because the role of hands-on experiments has changed in recent years to become more and more important in terms of motivation, explanation and simplification. As an example: the trajectory of a thrown balloon will illustrate the effects of friction, after having discussed the ideal trajectory with a computer simulation.

Four experiments will be presented on the following pages. The instructions follow a straightforward format: the tabulated heading contains information about the area of physics being discussed, about the level of experience necessary to conduct the experiment in order to achieve the greatest advantage, and about the time necessary to prepare and actually perform the experiment†. These experiments cover four different areas:

- traditional hands-on, low-cost experiments (three-dimensional magnetic field),
- new materials (contact lenses),
- new technologies (airbag),
- the integration of all three: traditional materials, new materials and new technologies (audio CD as a spectrometer).

About 60 low-cost, high-tech experiments covering subjects from table 1 have been developed in detail in the same manner as the examples presented above. The entire discussion can be found in various theses (*Staats-examensarbeiten*), which resulted from the project. In addition, about 20 experiments have been evaluated in didactically oriented seminars (one seminar per semester). The overall results of the developments will be published in a book in the near future.

Example 1. The three-dimensional magnetic field

school level	secondary
general theme	magnetism
special theme	ferromagnetism field lines
theoretical level	●
practical level	■
preparation	5 min
experiment	15 min

A three-dimensional magnetic field is made visible by iron filings.

Materials

- an empty jam jar or pickling jar which can be tightly sealed
- a bar magnet, with length equal to the radius of the jar
- paraffin oil, approximately 1 litre = volume of the vessel

† The theoretical level necessary to understand the physics is denoted by the symbol ●, the practical level by ■. There are from one to three symbols, one meaning easy and three rather difficult.

Table 1. Topics of low-cost, high-tech experiments.

New techniques	New materials
ABS (anti-lock braking system)	aluminium foil
airbag sensor	aluminium tin cans
autofocus camera	(anti-)reflective coatings
barcode reader	bubble-gum wrappers
camera flash	building materials
car tyres	catalyser
winter & summer	CD (compact disk)
asymmetrical	ceramics
CD Walkman	contact lenses
central locking system	drink mixes
coin sorter	fibreglass
computer mouse	Gore-Tex/Sympatex
computerized tomography	glasses
electric Christmas candle	phototropic (self-darkening)
electric toothbrush	sunglasses/UV protection
firecrackers	high-T_c superconductor
forgery identifier	in-line skates
garbage sorting	insulated windows
mechanical	IR sensor foil
electromagnetic	jewelry
density of material	Brinell hardness
glass cutter	colors/absorption/polarization/interference
household techniques	piezoeffect
toaster (pyrometer)	laser pointer
microwave oven	lavalamp
IR motion detector	liquid crystals
IR remote control (TV)	electrosensitive
joystick	thermosensitive
LCD (liquid crystal display)	magic blackboard
LED (light-emitting diode)	magnetic liquids
level control	metallic coatings
loudspeaker	memory metal
electrostatic speaker	packing & insulating material
piezoelectric	polarizing foil
metal detector	razor blade
magnetic tools	reflecting oil
mobile phone	shark’s skin
photocopier	surface-coated glasses
Xerox principle	text marker/UV colours
thermostatic principle	(fluorescence)
piezo fuse	
pocket calculator	
radar emitters & detectors	
radio-controlled clock	
signature reader	
smoke detector	
thermometer	
electrical	
IR radiation	
touch-sensitive switches	
touchscreen	
ultrasonic	
cleaning bath	
echo sounder/bats/sonography	
parking distance sensor	

Figure 1.

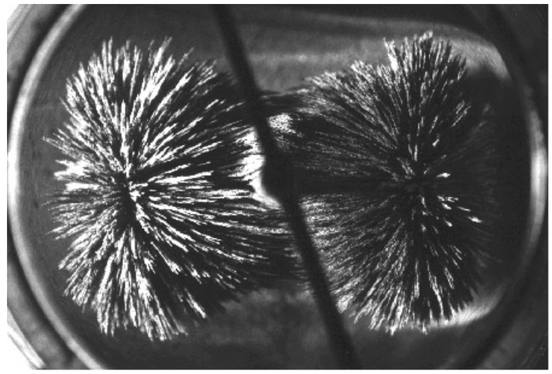

Figure 2.

- a pencil
- reel of thread
- iron filings‡, about 250 g.

Experiment

The magnet is first of all attached to the pencil with the thread such that the thread is in the middle of both magnet and pencil. The magnet can thus be suspended such that it sits exactly in the middle of the jar, both horizontally and vertically. The magnet should not hang too deep in the vessel, because otherwise lines of field will not be visible: a lump arises as the iron filings sink. Remove the magnet from the jar. The iron filings should be placed in the jar to a depth of about 5 mm. It is recommended not to use too many iron filings, since the fine details of the lines of field may not be seen. The vessel can then be filled with the paraffin oil to within about 10 mm of the brim. Cooking oil is unsuitable for the experiment because of its high water content and because it is stained by the filings. The vessel should be sealed and shaken well, until all the filings are evenly distributed in the fluid. The jar should then be opened and the magnet placed inside immediately (figure 1).

‡ The filings can be ordered from any company that supplies scientific equipment.

Explanation

Most of the iron filings arrange themselves along the magnetic field lines (figure 2). A three-dimensional magnetic field is made visible. The iron filings that are not drawn into the three-dimensional magnetic field sink to the bottom of the vessel. This is due to their having been too far away from the magnet as it was introduced, thus they could not be sufficiently magnetized. Typically, after a quarter of an hour the paraffin oil is clear again and the experiment is finished.

Tips

One problem with the experiment is the time-consuming cleaning required afterwards. It is relatively difficult to clean the the oil but even more so the iron filings from the magnet. The only solutions found to this problem were the use of a solvent and patience, whereby the former also has the disadvantage that it has a deleterious effect on the surface of the magnet in the long term. In a vibration-free environment the experiment can be preserved for several weeks.

Implementation

In textbook literature the magnetic field is explained mainly as being two-dimensional, thereby depriving the pupil of important information. This experiment is a particularly good example of how maximum information can be imparted in an optically fascinating experiment whilst still keeping costs to the minimum.

Example 2. Contact lenses: determination of adhesive forces

school level	secondary
general theme	mechanics
special theme	adhesion surface tension
theoretical level	●
practical level	■
provision	a few days
preparation	15 min
experiment	10 min

The adhesive forces that hold a contact lens to a spherical surface are determined.

Materials

- retort stand (50 cm)
- pulley wheel on rod
- crank wheel
- force meter
- objects (squash ball, animal's eye, glass plates, surfaces of various smoothness)
- contact lens
- contact lens detacher†
- fishing line (50 cm)
- liquids (water: with/without salt).

Preparation

The force meter is connected to the contact lens detacher with a short thin wire. The plastic cap of the lens detacher adheres to the lens, or even a glass plate, and allows removal of the lens from the object. The eyeball of a dead pig or cow is recommended (available from the local butcher or slaughterhouse) since this allows the pupils to conduct the experiment under the most realistic conditions. If objections arise to this thought‡, the experiment can be equally well performed with a squash ball. The contact lens will stick to the ball just as well, since the diameter of the ball (40–50 mm) is comparable to the diameter of the contact lens (35–40 mm).

† Available from opticians.
‡ Many schools have now banned the use of a cow's eye because of the risk of BSE.

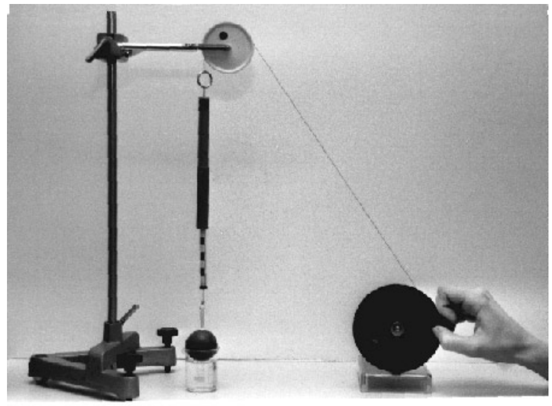

Figure 3.

Experiment

The ball should be wet with a few drops of water for better contact. The lens is then placed onto the ball. The force that holds the lens to the ball is measured with the force meter. It should be pulled straight up by turning the crank wheel (figure 3). For better reproducibility, the force applied to remove the lens should point directly upwards, orthogonal to the top surface element of the ball. As soon as air flows under the lens, i.e. between lens and ball, the adhesive force will decrease, and the lens will no longer adhere to the ball (the effect strongly depends on the angle at which the lens is being pulled off). It should be obvious to the pupil that the adhesive force will have its maximum when the inner diameter of the lens and the outer diameter of the ball are identical. The same rule will apply when two glass plates are used—their radii can be thought of infinite (the glass plates should also be wet, for the same reasons as above).

The experiment should not be conducted on a human eye. The risk of damaging the human eye must be avoided under all circumstances!

The actual value of the adhesive force is influenced by a number of different factors, such as the type of contact liquid between lens and ball, the thickness of the liquid film, the material used as a replacement for the eyeball (e.g. a rubber squash ball), the radius of the ball and of course the pressure applied when the lens is placed onto the ball. Some other factors may also influence the actual value of the adhesive force, but they are not discussed here. The adhesive force has been measured as 0.08 N for the pig's eye and 0.06 N for the squash ball. For the two glass plates the value has been determined to be 0.03 N.

Explanation

The film thickness between the ball and the contact lens strongly influences the adhesive force. Therefore, the amount of water dripped onto the ball should be the same for all the experiments. This is the primary reason why we suggest the use of a pipette to transfer the water to the ball.

Should the lens be pulled off the ball at an angle, the value of the adhesive force will be different (i.e. smaller): as soon as air flows under the lens, the lens will immediately lose contact. However, if the lens is lifted straight up, the liquid film thickness will decrease evenly around the lens (starting at the edge), which is more reproducible.

The pressure applied when putting the lens onto the ball is another major factor that can influence the result. The pressure will determine the amount of air between lens and ball being pushed out. If more air remains between lens and ball, the lens will be removed more easily.

Estimations

If the effective area of the contact area is known ('effective' means the area of the contact lens that actually contributes to the adhesion effect), the tension can be directly calculated after the adhesive forces have been determined, for example

$$p = \frac{F}{A} = \frac{0.07\ \text{N}}{0.56\ \text{cm}^2} = 0.125\ \text{N}\,\text{cm}^{-2} = 1250\ \text{Pa}.$$

This pressure is comparable to a height of 0.12 m of water (pressure). NB: Standard air pressure at sea level is roughly 100 000 Pa, which corresponds to a height of approximately 10 m of water!

Implementation

The experiment can be conducted by the pupils themselves. Their motivation will be enhanced if they are encouraged to bring other items on which the adhesive forces can be determined.

Example 3. The airbag sensor

school level	secondary
general theme	mechanics electricity
special theme	inelastic collision piezoelectric effect
theoretical level	● ●
practical level	■ ■
provision	1 hour
preparation	10 min
experiment	10 min

The function of an airbag sensor will be simulated.

Materials

- piezoelectric crystal (Leybold)
- vehicle (kit)
- board (length: 1 m, breadth: 0.2 m)
- 4 V bulb
- direct current amplifier
- 1 m string
- 0.1 m string
- lubricating oil
- 2 wires (length: 2 m)
- 2 wires (length: 0.5 m)
- metre ruler
- fender block with foam padding
- 100 g mass
- steel ball ($m = 100$ g, $r = 10$ mm)
- pulley wheel with support.

Preparation

The preparation takes about 10 minutes (figure 4). A structure must be constructed upon the vehicle to suspend the steel ball (figure 5). The piezoelectric crystal is attached to the vehicle at a distance of about 5 mm from the steel ball, such that the ball hits the crystal exactly when it is

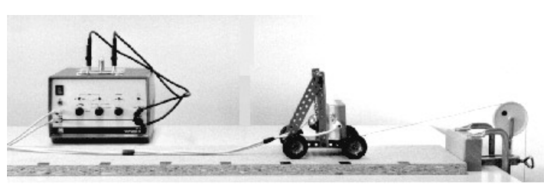

Figure 4.

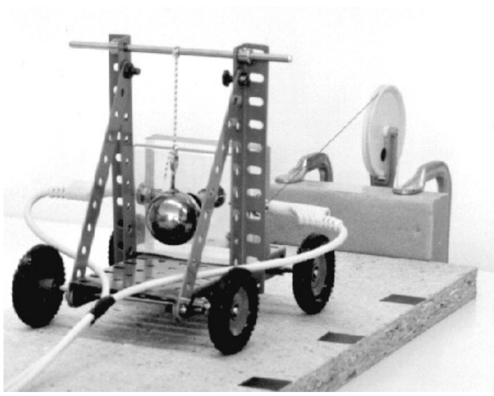

Figure 5.

swung. The voltage produced by the squeezed piezoelectric crystal must be amplified in order to light the bulb. The bulb is therefore connected to the piezoelectric crystal via the d.c. amplifier. The 2 m wires between the amplifier and the piezoelectric crystal should be bound together for better handling. The board should be divided up into steps of 0.1 m. The scale can be attached by short adhesive tapes. The wooden fender block is positioned at the end of the board such that the foam can absorb the impetus of the vehicle. The vehicle itself is connected to the 100 g mass by the 1 m string which runs over the pulley wheel. The vehicle will be accelerated by gravity acting on the mass, which hangs vertically over the edge of the table.

Experiment

The vehicle will traverse various distances. The axles should be oiled to improve running. In order to stop the connecting wires influencing constant acceleration, they should be held up by hand or positioned such that they do not impede the vehicle's smooth running.

The vehicle rolls against the fender block, the steel ball strikes the piezoelectric crystal and the bulb lights up: the brightness depends on the distance, h, travelled by the vehicle. This particular brightness will be determined by the moment of release of the airbag. The velocity of the vehicle after the distance h (in other words, the release moment) will be determined by energy conservation: $\frac{1}{2}mv^2 = mgh$, e.g. after a distance $h = 0.4$ m the velocity v was determined to be about 10 $\mathrm{km\,h^{-1}}$.

Explanation

When the piezoelectric crystal is deformed by mechanical forces, electrical charges accumulate at the crystal surfaces. The charge on the crystal is proportional to the mechanical deformation (tension or pressure).

The brightness of the bulb used in the 'airbag sensor' is proportional to the force transferred by the steel ball, which is in turn proportional to the velocity of the vehicle. In reality† the acceleration of the car in the longitudinal direction is registered by a flexible piezoelectric beam to which a mass is attached. In the latest generation of sensors the voltage is fed to a computer via an analogue–digital converter. Beyond a defined deceleration, the voltage produced by the crystal leads to inflation of the airbag within ∼10 ms.

Variations

An oscilloscope can be used instead of the bulb. The voltage deflections one can then see increase in proportion to the distance travelled, h. It is possible to define a threshold graphically, beyond which the airbag would be actuated.

The acceleration can also be achieved without a drawing mass by allowing the vehicle to roll down an inclined plane. The steel ball is removed and the piezoelectric crystal is placed at the front of the vehicle. Upon striking against the block, the accelerated mass of the vehicle itself will deform the piezoelectric crystal.

Estimations

'Why does the airbag not work if the car hits a barrier at certain angles?' This aspect can also be demonstrated by allowing the vehicle to impinge on the block at different angles. Because the direct force on the piezoelectric crystal is not so great, the crystal does not always produce a sufficiently large voltage.

Real forces and energies etc can also be evaluated: the collision energy, the time to release of the airbag or the braking deceleration.

† Mercedes Benz: *Der Airbag, von der Idee zur Serie*, Mercedes Benz AG Public Relations PR/UP D-70322 Stuttgart, Germany.

Implementation

The experiment can be used in a motivating fashion to present both inelastic collisions and energy conservation as well as the phenomenon of the piezoelectric crystal. Pupils are able to carry out the preparation and the experiment themselves, e.g. in a project.

Example 4. Using a CD as a spectroscope

school level	secondary
general theme	wave optics atomic physics
special theme	diffraction continuous and discrete spectra
theoretical level	● ● ●
practical level	■
preparation	10 min
experiment	5 min

Spectra of different sources of light are observed by using a CD.

Equipment

- One CD per person
- an incandescent light bulb
- a compact fluorescent light bulb
- a gas line-emission lamp.

Figure 6.

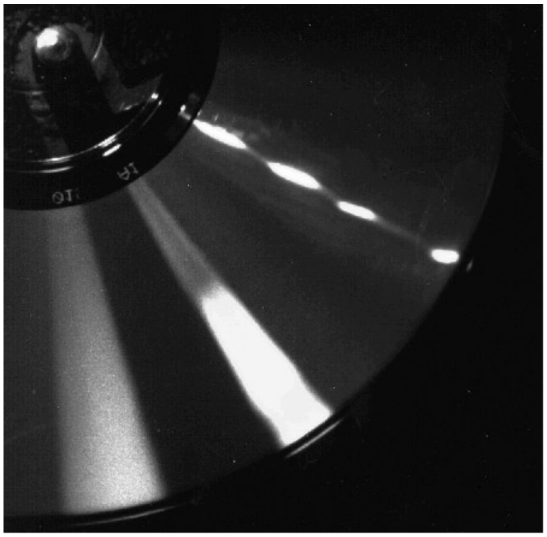

Figure 7.

Preparation

Place the light sources on a desk at a distance of approximately 0.1 m from each other and switch them on. The desk should be positioned opposite any windows in the room so that the person's body can be used to screen the influence of the sunlight (figure 6). Each CD should be held horizontally in front of the observer with the unprinted side upwards. Slowly tilt the CD away from and towards the light sources until their spectra appear on the CD's surface (figure 7). Covering the bulbs one after another makes it easy for the observers to establish the spectrum corresponding to individual light sources.

To prevent eye and skin damage caused by gas line-emission lamps with high UV rates one should wear safety goggles and keep a safe distance.

Explanation

A CD is a reflection grating and takes the function of a grating spectroscope when it is illuminated by a beam of light as described above [7].

By comparing the spectra of the different light sources one can see that the spectrum of the incandescent light bulb is continuous while that of the compact fluorescent light bulb shows small gaps between the colours. The spectrum of the spectral tube lamp is discrete, showing only the characteristic emission lines.

Variations

With a DULUX EL (OSRAM†) lamp—a compact fluorescent light bulb for demonstration purposes—one can show the difference between the spectrum of a bulb with and without a UV-absorbant surface coating.

Implementation

The spectra can be used to discuss the various means of producing light. Technical papers from the manufacturers are usually good sources of information about the properties of different lamps.

Conclusions

Our discussion of low-cost, high-tech experiments will satisfy both present and future demand. We not only supply teachers with a list of well documented and tested experiments, but are also updating the classical method, here for the case of educational physics, in terms of its content. The classical method of teaching physics starts with the physical phenomenon and deals with it in an academic manner (say, the demonstration of electromagnetic induction by means of coils, magnets and voltmeters). The result is then translated into a formula. The relevance and the implications of the result to everyday life are just the final point of discussion, and they are often neglected. A reversed procedure, starting with a gadget known from everyday life ('How does a speedometer work?'), and leading to the discussion of the phenomenon afterwards, will establish a higher level of motivation. Questions about the relation of the physics subject to real life will hardly come up.

It is self-evident that such high-tech hands-on experiments offer the following:

- they are cheap to set up (low cost);
- they allow a broad field of application in terms of the role of the experiment (demonstration, hands-on group lab work, project, homework) and teaching methods (analytical, synthetic, learning by models, learning by doing);
- they can be applied in a wide range of school types at different levels (depending on the extent of mathematical evaluation in the experiment and the physical background knowledge of the pupils);
- they allow a reduction of a variety of phenomena in the pupils' everyday experience to a small number of elementary laws of physics;
- they offer an interdisciplinary approach to education.

The individual objectives of physics teaching *per se* need not be further discussed at this point. However, in the context of teaching in general, certain overall objectives—which can be more easily achieved through low-cost, high-tech experiments—will be discussed with regard to the following.

The approach to physics. This type of experiment offers the possibility of acquiring a more practical handling of and a deeper insight into modern techniques and new materials. Highly complicated devices are often based on a few elementary laws of physics, e.g. the law of inertia in the case of the airbag sensor, adhesive forces in the case of contact lenses or the modulation of infrared radiation in the case of remote controls. The *black box* is no longer a mystery, the way in which the device works gains transparency (in a physical sense) and, with respect to application in the school, the box will be experienced directly or through a model.

Safety. Such experiments are pre-eminently suitable for the development of the pupils' sense of responsibility by means of practical handling as well as by discussion in lectures. For example, the microwave cooker or the cellular phone leads on naturally to the question of the effects and risks of electromagnetic radiation and the practicalities involved in its avoidance.

The approach to the future. Low-cost, high-tech experiments contribute to a higher degree of motivation for physics and the application of physical laws. Moreover, the experiments can remove fears of modern techniques and materials. The pupils can develop their awareness and sense of responsibility (for example by discussing environmental electromagnetic pollution caused by cellular phones or new materials in general). Their power of judgement and a critical attitude based

† OSRAM GmbH, Marketing Information, Hellabrunner Str. 1, 81543 München, Germany.

on their understanding of physics can be intensified (e.g. by comparing the efficiency of an immersion heater and a microwave cooker).

Skills. Methods of gathering and handling information and material can be learned by the pupils (e.g. by contacting the manufacturers, by searching the Web). Practical work (in a project or in homework) is particularly suitable for the training of manual skills and problem-solving strategies. The integration of low-cost, high-tech experiments into lectures appropriately organized with regard to pupils' engagement will help them develop such key skills as cooperative learning, planning and organizing, listening and a critical approach.

Interdisciplinarity. Besides the relation of low-cost, high-tech experiments to technical and electronic problems of interest, these experiments give occasion to think about aspects of human society itself: a deeper insight into the development and utilization of new materials and techniques (e.g. the airbag) will be gained. The significance and understanding of the physics in question can be further extended by discussion of personal data protection (chip cards) in connection with civic law or radiation protection (handy, microwave cooker) in connection with biology.

We have now gathered initial experience in the development and practical application of such methods. The overall positive response (from students in a special seminar, pupils and teachers in workshops, and industry) forces us to undertake more work.

For further information please contact Professor Dr H J Jodl at Fachbereich Physik, Universität Kaiserslautern, Erwin-Schrödinger-Strasse, 67663 Kaiserslautern, Germany (e-mail: jodl@physik.uni-kl.de) or take a look at our web page: www.physik.uni-kl.de/w_jodl/lc-ht.html.

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