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Objects, Demonstrations, Visualization, and Concept Learning

ED VAN DEN BERG, *Centre for International Cooperation, Vrije Universiteit, Amsterdam, Netherlands*

Introduction

Objects and demonstrations in science can be used for a lot more than verifying laws and phenomena. Often simple visualization is more useful than verifying and measuring. The first part of the article gives suggestions on how to *visualize* science, and provide visual support for building science concepts and relationships. The second part deals with the limits of visualization.

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1. Thou shalt not teach words except as they help to build mental images in which knowledge and understanding reside;
2. Thou shalt encourage the building of such images by rewarding their owners above the repeaters of phrases;
5. Thou shalt be aware always that concrete examples and graphic imagery are required by some students, lest they be forced to attempt to satisfy thy quizzes by repeating words which thou has spoken;
6. Until thine eyes are bleary and the midnight candle flickers shalt thou strive to devise visible analogs of abstract relations and of phenomena which cannot be directly observed, for it is by such analogs that the human mind gains insight into that which our senses cannot otherwise experience;
7. Thou shalt use demonstrations and labs to aid in the formation of images and the crystallization of knowledge, and to encourage the practice of observation, but not for the purpose of pretending that discovery can take place in a 53-minute hour;

Figure 1. Five of Walt Scheider's, "27 commandments for physics teachers," *The Physics Teacher,* 18, 32-33 (1980).

Propositions, Images, and Episodes

Five of the first seven of Scheider's 27 commandments for physics teachers mention the importance of images and visible graphic analogs in learning physics. The commandments are equally important for the other sciences. Students need images and visualizations in addition to words. Science learning is about creating images in the mind, and teaching should support such image formation. Recent articles on an analysis of Einstein's preserved brain mentioned the over-development of the parts of his brain that work with images rather than language. Einstein seems to have said that he did his physics in images and then tried to convert these images into language in order to communicate them to others. In other words, Einstein's physics may have been conceived in images rather than in words. Of course, our students are not little Einsteins, yet their brains may need much visual support as well. So many of the hardcore physics misconceptions are found worldwide (Thijs & Berg, 1995) and, thus, must be independent of language. This indicates the importance of non-verbal forms of memory. In short, a picture can be worth more than 1000 words. A picture can convey meanings, which words can*not* convey.

Scientists and science teachers often limit this visualization to a small set of demonstration and laboratory experiments. Our students may need a much wider set of visual experiences than what is offered traditionally. They may also need a different approach to the presentation of experiments: use of experiments as a teaching aid to visualize concepts rather than experiments for verification. Furthermore, there are *other* kinds of experiences, which might help the development of mental images, such as role-plays and analogies. This paper identifies several categories of support for the formation of mental images, and these are illustrated by examples.

Richard White in his book *Learning Science* (1989, p. 23) identifies seven elements in memory. Three of these have special importance for science:

a) *Propositions* are statements relating concepts. For example, all definitions and formulas could be considered propositions, such as Newton's Second Law: $\mathbf{F}_{\mathrm{net}} = m\mathbf{a}$.

b) *Images* are mental representations of a sensation: pictures in the mind or other sense impressions, like smells and sounds.

c) *Episodes* are memories of events one has witnessed: stories of experiences or *film clips* in the mind.

White (1979) suggests that laboratory experiences and demonstration experiments might be valuable as they get encoded in the brain through images and episodes. So, if images and episodes are powerful components of memory, then we must look for all teaching and learning experiences, which could generate strong images and episodes. Such images may include experiments, but they may also include many other kinds of experiences.

In Science teaching too often we use experiments and equipment only to "prove" or verify something. For example, with a pendulum we "prove" the formula for the period of the pendulum: $T = 2\pi\sqrt{\frac{l}{g}}$ or we "prove" Newton's Second Law that $\boldsymbol{F}_{net} = m.\boldsymbol{a}$, or we prove that $g = 9.8$ m/s^2 through a pendulum or a free fall experiment with timers. However, in teaching, we should look at the *educational* value of experiments, not only at the scientific value. This educational value might then be the potential to produce strong images and episodes. In the case of Newton's second law, it might be more useful to visualize the difference between velocity and acceleration than to "prove" the law through measurements.

Images and Vocabulary

Physics is rich in technical vocabulary. Some terminology can be visualized easily. For example, light can pass through materials which are transparent (teacher holds a piece of glass or an OHP transparency in front of his/her face.... *light bouncing off my face passes through the glass/transparency to you such that my face is clearly visible...the glass is "transparent"*). Light cannot pass through materials which are opaque (teacher holds a piece of paper in front of his/her face and says *light bouncing off my face cannot pass through the paper, so you cannot see my nice nose, paper is "opaque"*). Many other terms can be visualized like that: putting a picture next to a definition. In the many countries where physics is taught in a second language, like in large parts of Asia and Africa, as well as in schools in Europe and the USA with large migrant enrollments, one might also want to visualize non-technical terms, such as *on top of, below, inside, next to, length as opposed to width,* etc. In the 1970s, Paul Gardner did extensive research to show that non-native speakers often misinterpret such words (Gardner, 1978). So, saying *inside the bottle,* why you do not point into it, or *under the table,* why you do not point to under the table! Doing that might help many students whose English is not fluent. A teacher who plays theater with technical terminology and with common prepositions can be extremely helpful.

Using Objects to Visualize Spatial Relationships (3-D Visualization)

Many physics phenomena require insight in spatial relationships. It often helps to use 3-dimensional objects to show these relationships. For example, Moon-Earth relationships can be modeled easily with a basketball or balloon as Earth, and a tennis ball as Moon. When teaching Earth Science, I usually have a balloon in my pocket. I just blow it up when needed. When showing the Earth's position in space, I draw an equator on the balloon and mark the North and South poles, and then I show how the rotation axis of the Earth is slanted with respect to the plane of the Earth's motion around the Sun. Of course, a globe would be better, but the balloon fits in the pocket and is cheaper. With a tennis ball as Moon and the balloon as Earth, one can show how the phases of the Moon come about. By then adding the slanting plane of the Moon's orbit compared to the plane formed by the Earth motion around the Sun (the ecliptic plane), one can show why we do not have a solar eclipse once a month. This has to be seen as demo, from words and two-dimensional textbook pictures, the students cannot picture the situation.

A parallax angle to determine distance of objects including stars can be easily put into a two-dimensional picture, but it might help even more to demonstrate it in the classroom using a cloth line or any other piece of rope (Figure 2[1]). Two stu-

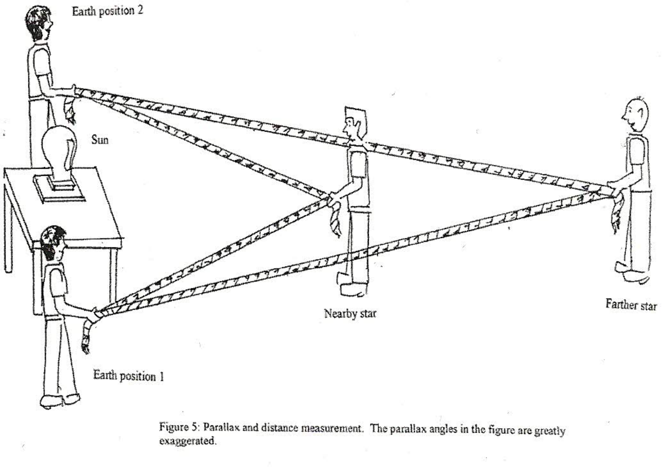

Figure 5: Parallax and distance measurement. The parallax angles in the figure are greatly exaggerated.

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[1] Drawing by Mr. Renante Embalzado, Physics Teacher in Cebu City, Philippines

dents who represent two different positions of the Earth, for example, the position in January and the position in July form the base of the angles. Two other students play a far away and a nearby star. The difference in angles will be obvious for the class. The picture cannot be replaced by words!

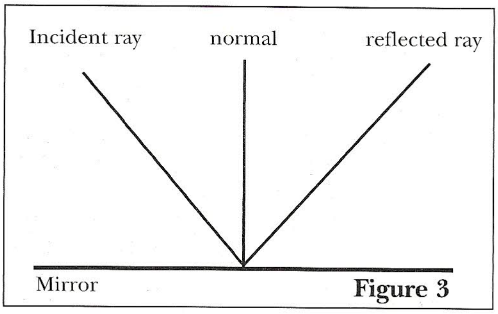

Figure 3

The Laws of Reflection and Refraction consist of two parts each. One part concerns the angles (*angle of incidence = angle of reflection*, or for refraction *sin i/sin r = constant*) The other part concerns the point that the incident light ray, the normal, and the reflected or refracted light ray are in one plane. One cannot make that clear in words and not very well in a two-dimensional picture either. It has to be shown using meter sticks or other rod-like objects. One could take three meter sticks, one representing the incident light ray, one the normal, and one the reflected light ray. Then show how it looks when the three are *not* in one plane. That would be the equivalent of one ray sticking out of the paper towards the reader in Figure 3.

The Rutherford experiment is sometimes also mentioned at the Junior High school level. One could take a basketball (representing a gold nucleus), and have a student hold it up in the middle of the classroom. Then the teacher could throw tennis balls (alpha particles) through the room. The tennis balls should have the general direction of going from front to back in the room, but the thrower could be blindfolded as he/she does not know exactly where the basketball (nucleus) is. Most tennis balls will travel until they hit the wall at the back of the classroom. Once in a while, one will hit the basketball. In my demonstrations, I never let them hit the basketball as students might be hit, but they seem to understand the argument of the analogy. At the end of the demonstration the teacher gives the magnitudes of a typical radius of an atom (10^{-10} m) and of a nucleus (10^{-14} m). Then it turns out that if a classroom is the analog of the atom (7 m), then the nucleus should be a grain of salt (0.7 mm) rather than a basketball. If students have already learnt about charge, then one could also add that the basketball represents 79 units of charge (gold nucleus) and the tennis ball represents 2 units. In the Rutherford experiment, it is a combination of charge and mass that counts and determines that in the few cases where there is interaction between alpha particle and nucleus, it will be the motion of the alpha particle that is most affected.

Creating "Muscle" Memory

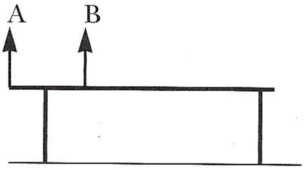

Figure 4

In Physics, there are ample possibilities for letting students "feel" Physics with their muscles. For example (please try this yourself while reading), let students lift one side of a table by pulling up the edge at point A (Figure 4). Then let them lift one side of the table by pulling up say 10 cm from the edge (at point B). In the latter case, the table feels much heavier, one needs greater force and the explanation goes back to simple machines and the

work – energy theorem. The energy needed to lift one side of a table to a certain height is constant and is W = $F.S_A$ where S_A is the vertical distance the table edge moves. When pulling say 10 cm from the edge of the table, the force moves over a smaller distance (S_B) thus has to be greater. There are many similar situations: rotating a door by pushing on the edge farthest from the hinges, or nearer to the hinges, etc. Once a teacher has good classroom control, it is easy to let students stand up and try to lift one side of their tables, and feel the difference of force needed when pulling at the edge, or pulling at a place closer to the center of the table. Another example of using "muscle memory" is to let students stand up, keep their body straight, but then lean forward more and more. First, they feel their weight moving to the front part of their feet and stress in their toes. Leaning forward more, they will have to take a step forward to keep their balance. When the center of mass passes over the toes, balance is lost. In mechanics, there are many possibilities to link concepts with "muscle memory" and create powerful images and episodes as well (next section).

Experiments/demonstrations and Images, Experiences, and Stories

One can make a real event out of this by lining up some students with their heels against the wall and then ask them to pick up money, which is put on the floor right in front of their feet (Figure 5). They are not allowed to move their feet. It cannot be done, as soon as they bend forward, their center of mass moves over their toes, and they have to take a step forward to prevent falling.

The previous demonstrations can be continued with: *How does a man with a beer belly walk? Or a woman who is 8 months pregnant?* Well, the man and the woman really have to lean backwards in order to make sure their center of mass is above their feet rather than in front of the toes! So they walk with the shoulders a bit backwards. Of course, the teacher should act this out, how people with big bellies walk, perhaps by putting something big under his shirt. Meanwhile the students record the little film of this funny teacher in their brains. Images and experiences are stored with the center of mass concept!

But, experiments take time and we have to finish the syllabus? Not necessarily. Too many teachers automatically assume that physics experiments have to be done as laboratory activity. Demonstrations by the teacher often are more helpful in concept formation than student laboratory, as the chaos inherent to laboratory lessons can clutter up the concepts rather than clarify them. Whenever teachers do experiments for the purpose of supporting concept development, they have to decide between student lab activities and demonstrations. Demonstrations, if well guided, can be clearer, less time consuming, and cheaper than student laboratory experiments.

Do experiments lead to better understanding? Not necessarily, that depends on how well we integrate them into our lessons; to what extent we are able to weave a network of images, experiences, and stories; and particularly on whether we make an effort to find out how students interpreted the demonstrations and follow up with some corrections. The crucial interaction is necessary to constantly check whether student interpretations match with the intended conceptual development, is integrated in the next example of visualization.

Role-plays

Isn't it confusing? Atomic number (A) is the total number of protons and neutrons in a nucleus and atomic mass is some number with many decimals. Students do not get it. The formal definition does not help much. Just line up some kids one by one. They are Hydrogen nuclei consisting of just one proton. Then take one *pair* of kids: they form a Deuterium nucleus consisting of one proton and one neutron, a Hydrogen isotope. Suppose you have four single kids lined up and one pair. Then add the masses 4 x 1 + 1 x 2 = 6. What is now the average mass? (6 mass units)/(5 nuclei) = 1.2. The atomic mass is averaged over all Hydrogen atoms in the universe, which includes some Deuterium and Tritium isotopes! Of course, the demo can be refined by taking girls as protons and boys as neutrons so the difference is visible. In reality, about 15 of every 100,000 Hydrogen atoms are Deuterium (proton + neutron), while the other 99,985 are single protons. Of course, there is a problem with students playing Hydrogen atoms or isotopes. Students all look different and that could create unwanted confusion. Instead one could also put 4 single balls on the table (say yellow tennis balls) and one pair of balls taped together (one yellow:, the proton; one green: the neutron). Figure 6 shows the situation with grey balls representing protons and a white ball representing a neutron[2].

Figure 6

Role-plays can also assist in 3-dimensional visualization. For example, one can role-play motion of planets around the Sun, the Moon around the Earth, planets with respect to each other (Box 1). Example role-plays are included in Box 1. More elaborate instructions on the use of role-plays in Astronomy can be found in Berg (2000). It is crucial to observe the students while role playing and to keep asking their explanations for the motions they make. Even if a particular planetary motion has been demonstrated in front of the class, students will still make errors in the way they visualize and play the motion themselves. Therefore it is crucial that demonstration is followed by students role-playing in small groups in the hall or another big space in the school.

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[2] Of course when getting into the decimals things turn out to be more complicated due to binding energy and mass deficits, and to the different masses of protons and neutrons.

Box 1. Examples of Role-plays in Astronomy

Earth/planet revolution around the Sun: A student can walk around a light bulb (the Sun, figure 2). The teacher asks questions about the timing and position, for example, let the student (Earth) go forward 3 months, or let him/her go forward and ask the class how much time elapsed. Points of non-correspondence obviously are the relative sizes of the light bulb (Sun) and student (Earth) and the shapes (non-spherical) as well as orientation (Earth rotation axis should be slanting). Use a circular orbit rather than an elliptical one to prevent students from exaggerating the varying distances from Earth to Sun (remember the popular misconception that seasons are caused by varying Earth-Sun distances so eminently displayed in the video The Private Universe?). The difference between aphelion and perihelion is only 5 million-km compared to the average Earth-Sun distance of 150 million km.

Earth rotation: Now introduce night and day. Let students suggest how to do that (while walking around the bulb, the student who plays Earth should keep spinning). A point of non-correspondence is the fact that the student's rotation axis is upright rather than tilted at 23o. One could demonstrate the tilting using a ball and a stick as axis. Another point of non-correspondence is that the demonstrating student is unlikely to rotate 365 times while going around the light bulb (Sun) in a circle once.

Other planets: One could have several planets go around the Sun at the same time. Just take only 3 planets in order not to confuse. For example, take Venus (revolves around the Sun in 224 days), Earth (365 days) and Mars (687 days). The Earth revolves almost twice during one revolution of Mars. This way one can show the different periods of revolution and *how that looks as seen from the Earth.* Several students could accompany the Earth in order to see the apparent motion of the planets as seen from Earth. The points of non-correspondence are again the relative distances of the planets to the Sun and the timing (one revolution in a minute instead of a year).

Zodiac star patterns throughout a year: One could place the light bulb (Sun) in the middle of the classroom. The student playing Earth can see the stars only at night, that is when the student has his/her back toward the light bulb (Sun). At opposite parts of the bulb, the student will face a different "sky", for example, the East respectively West wall of the classroom. The ceiling and floor can be seen from any point of the orbit of the student, so there are stars (Polaris in the Northern Hemisphere, Southern Cross at Southern Hemisphere) which can be observed all year round while stars closer to the ecliptic plane are seasonal. The major points of non-correspondence are again sizes and distances. The stars are very far away, almost infinitely far. Compared to the stars, the planets are almost infinitely close to the Earth and the Sun. Furthermore, the stars in a Zodiac pattern may have very different distances from Earth even though their apparent brightness might be similar. It is important to include variation of distance in the role-play or in diagrams on the black board during the discussion afterwards. If the role-play is done in a big room, in the hall, or outside, then there is a good opportunity to vary the distance between Earth and the stellar background. Another point of non-correspondence is the fact that with a light bulb as Sun, objects across the light bulb on the other side of the room can be seen. However, the real Sun is so bright and the scattering of light by the atmosphere so strong, that during the day no stars can be seen at all.

Parallax and measurement of distance of stars (See Figure 2 and the accompanying text)

Limits to Visualization

Try the following experiment: Hold up a typical mirror in front of the class or audience. Hold it exactly vertical, put one student in front of it and make sure the student cannot see his/her shoes (by holding the mirror high enough). Now ask your class/audience: What should this person do to see his/her shoes?

Many will say: *walk backwards.* I have had these answers with students, but also with a group of 150 science teachers. The answer is wrong as a simple ray diagram will show (Figure 7). A light ray bouncing of the shoe will have to hit the mirror at a

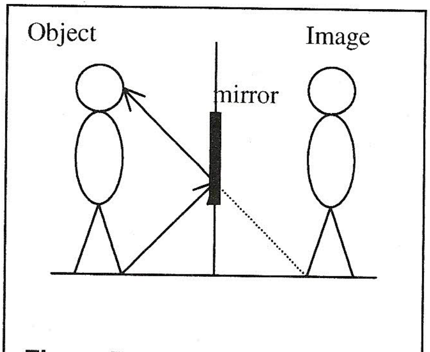

Figure 7

point that is exactly half the height of the eyes in order for the person to see his shoe. If bottom of the mirror does not reach down to that point, then the person will not be able to see the foot in the mirror. This does not change when the person moves away from the mirror. How come that decades of experience posing in front of mirrors still leads to faulty knowledge? There, we run into misconceptions, the intuitive science that somehow gets wired or programmed into human brains. Once we run into areas of known misconceptions visualization might help or hinder and could have unexpected results. Then, only a very high degree of *interaction* between students and teachers can help. Quite a few instances have been recorded in which students conduct observations and measurements which contradict their misconceptions. Then, later these observations and measurements are recalled in a distorted form. We tend to remember more the data which support our views than those which contradict, and the human brain may unconsciously massage the data until they fit.

In many science education studies, doing experiments which expose and contradict misconceptions has not been enough. Additional requirements are: 1) a high frequency of interaction between teachers and students to monitor conceptual development, 2) the supply of analogies and mental images by the teacher as a framework for interpreting the data from experiments, and 3) use of metacognitive techniques (Baird & Northfield, 1992). For example, various analogies are used to explain the behavior of electrons in electric circuits. One of the analogies is that of microscopic creatures running around in the circuit transporting energy in backpacks. The backpacks are filled with Joules of energy in the battery and the Voltage of the battery determines how much energy goes into each backpack. Then at the light bulb the energy is unloaded in the filament and converted to heat and light. However, the creature itself -the electron- returns to the battery. This analogy was able to assist students in overcoming the current consumption misconception (Berg & Grosheide, 1996), and left vivid images as we discovered in interviews 26 years after instruction. So, the visualization in demonstrations and experiments has to be supplemented by other forms of visualization (visual models), particularly in those parts of science which are minefields of misconceptions.

For detailed discussions about how to conduct so called Predict-(Explain)-Observe-Explain (POE) demonstrations we refer to the third chapter of White and Gunstone's (1992) *Probing Understanding*. For a discussion of crucial factors in the effectiveness of POEs, we refer to Limon (2001). The set-up of a series of activities and experiences to remediate misconceptions is no trivial matter. The Constructing Physics Understanding materials of Fred Goldberg and colleagues in San Diego constitute a particular fine example (type Fred Goldberg in Google and surf to the website).

In short, objects, demonstrations and experiments are not only to verify or proof something. They can be powerful means to create images, episodes, film clips, and experiences in the mind which can visualize concepts and support understanding. However, any understanding always needs to be checked through ample interaction. Anything we do in teaching, including visualizing through objects and role plays, can have unexpected effects.

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