Entertainment-education

in science education

the monograph edited by

Grzegorz Karwasz & Małgorzata Nodzyńska

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Introduction

Jan Amos Komensky in „Great Didactics" (Amsterdam, 1657) defined didactics not as a mere process of teaching, but as teaching efficient, lasting and pleasant. He wrote (p. 131) "The school itself should be a pleasant place, and attractive to the eye both within and without. […] If this is done, boys will, in all probability, go to school with as much pleasure as to fairs, where they always hope to see and hear something new." Further (p. 167) Komensky added: "The desire to know and to learn should be excited in boys in every possible manner."

The idea of linking the fun with didactics finds many followers, expressed also in tittles of activities like "Science is Fun" or "Physics is Fun". In (Karwasz, Kruk, 2012) we defined three complementary aspects of any bit of information (an exhibition object, a film, a lecture): entertainment ("ludico" in Italian), didactics, and science. The first aspect gives an impression to a student/ visitor/ listener: "how funny it is!". The didactical aspect induces: "How simple it is!" And the aspect of scientific curiosity induces in best students a question: "How complex it is!" These three functions add-up like three basic colors to give a full spectrum of enlightenment.

The entertainment function can be performed in different forms – school, extra-school, complementary to school. The target groups can be pre-school children, secondary school students, adults, and so no. Different approaches are needed for inducing interest in chemistry, in ecology, in physics. The present book shows some sampling of these different tasks.

A general introduction into forms and implementations of teaching by playing is done by Małgorzata Nodzyńska, Ewelina Kobylańska: educational games, "universities" for children, science festivals, science musea and exploratoria in Poland and Czech Republic. More examples of children universities in Poland and a study of motivations to follow them are given by (Małgorzata Krzeczkowska, Emilia Grygo-Szymanko, Paweł Świt and Patryk Własiuk). Apparently funny, but detailed in chemistry and serious in conclusions is the study of one popular beverage (Wiola Kopek-Putała and Małgorzata Nodzyńska). A special form of teaching by entertainment is a didactical excursion – and example of developing special paths in chemistry and ecology at different levels of teaching is done by Vlastimil Chytrý, Simona Čábelová and Martin Rusek. Examples of multimedia in Physics, Chemistry, Astronomy and Biology, available on Polish market are given by Anna Kamińska, Andrzej Karbowski and Krzysztof Służewski. Constructing of Live Action Role Play educational form is discussed by Zuzana Václavíková. Unusual ways of triggering interest in mathematics (tangrams, magic squares, futoshiki) are presented by Věra Ferdiánová and Petra Konečná. Effectiveness of using virtual labs and "competence-based" textbooks in chemistry are discussed by Martin Bílek and Wioleta Kopek-Putała. An amusing study how insects are described (and personalized) in children literature is presented by Małgorzata Mielniczuk and Elżbieta Rożej-Pabijan. Finally, an extensive use of didactical fun with everyday objects in teaching optics is given by Krzysztof Służewski and Grzegorz Karwasz.

All these single contribution, spacing from the educational trends (Nodzyńska & Kobylańska) and pedagogical aspects (Chytrý, Čábelová & Rusek) to technical observations (Mielniczuk & Rożej-Pabijan, Kopek-Putała & Nodzyńska, Służewski & Karwasz) form an interesting overview how new, "pleasant" forms can enrich the traditional didactic.

Please, enjoy reading!

Grzegorz Karwasz & Małgorzata Nodzyńska

Comenius, J. A. (1967) *The Great Didactics*, trans. by M. W. Keatinge, Russell & Russell, New York,

Karwasz, G. P. & Kruk, J. (2012) *Idee i realizacje dydaktyki interaktywnej. Wystawy, muzea i centra nauki.* Wyd. Naukowe UMK,

Fun with Optics - teaching by images

1. Searching for Fun with Physics

Learning physics, in any place, seems a difficult, and therefore a boring task: “Physics is not my favourite subjects” – you can hear from a driver in a taxi, from Seoul to Sao Paolo. In times of Aristotle, physics was still a narrative science, not much different from philosophy. Aristotle’s Zoology was much more detailed than Physics, which dealt mainly with defining the motion (Aristotle 1965, 1957). For Galileo Physics (Galilei, 1610) started becoming mathematical, but even Galileo did not use any symbol notions and his dialogues resembled more those by Plato than Euclid’s Elements. However, an earlier to Galileo, Copernicus’ De Revolutionibus was already a very “tough” treaty, filled with tables and mathematical considerations (and therefore, probably little read through centuries). Full of mathematics is just Netwon’s Philosophiæ Naturalis Principia Mathematica. At that time physics became the reason for inventing new disciplines of mathematics, like differential calculus. Without this mathematics (and modern computers) it would not be possible to shut “New Horizon” spacecraft to a distance of 5 billion kilometers towards Pluto with a precision of 5 thousand kilometers. How can we convince school pupils on that?

The same mathematics that become an extraordinary source of scientific successes, is the reason that physics is highly unwilled in school. School textbooks from elementary, say in Poland, (Poznańska, 2002, p. 28) to academic in Italy, see for ex. (Allegrini, 2000) focus on mathematical aspects. Mathematics, of course, is the precise language of physics: laws of physics, are expressed in a mathematical form. But teaching becomes ineffective if the other, human side is forgotten. R. K. Wassef (1995) writes: The “Human face” of physics could be shown by this contextual approach, highlighting the people involved, their motives and how they achieved what they reached. On the other side of approach is some “conceptual” teaching, or teaching just by images: beautiful, colorful album about light, but without any physical equation (Parker, 2006).

Our key idea is that in the first approach physics should become again a qualitative science (Karwasz, 2003), without the necessity of introducing complicated mathematics: physics deals with phenomena of all-day life – the intrinsic understanding of the laws of motion allows to one-years infant to walk on two legs. In the same manner we would never expect a ball thrown horizontally (unless it is a boomerang) to come suddenly back. So, in the first instance, physics is a qualitative science and only later, mathematical one (Karwasz, 2003, 2011).

Phenomenological descriptions of physics date from at least a century (Perelman, 2011) and were written in all different languages and by highest ranks physicists, see for ex. (Landau, 1965; Frova 2001), Ernst; 2010; Hewitt, 2014). The social role of these volumes is difficult to be overestimated: they trigger interest in physics, even if do not constitute real-type textbooks.

The second strategy would be school experiments. It is widely acknowledged in contemporary science education, that the observation is an important skill to be developed in students. Teachers should encourage their students to use all their senses (Delagrey, 2001). Students love to watch all kinds of experiments, therefore demonstrations are a traditional part of teaching physics (Hendolin, 2011). However, usually in schools experiments are ready-to-use: "switch on the current and watch happens". Obviously, something will happen: we hardly trigger the sense of observation in this way.

Nowadays real experiment are subject to substitution by a virtual world. Students, in particularly teenagers, love to scroll over virtual experiments (Cegła, 2014). They find physical applets on internet with a surprising velocity. However, internet resources are frequently not didactically (and scientifically) correct: they can happen to be programmed by non-specialists, so they do not necessarily reflect the physical reality. In this sends real films are better as they reflect the reality of the physical instruments.

Still another strategy to publicize physics are interactive exhibitions. In Poland they were introduced some 20 years ago, imported from Trento University in Italy (Karwasz, 2000). The first, portable exhibition, of some 40-50 objects were shown in 1998 at II Science Festival in Warsaw and in Słupsk in the Municipal Hall, with 14,000 visitors; next year at National Congress of Polish Physical Society in Białystok, then at the Congress in Gdańsk in 2003 and Warsaw in 2005. In some 10 years, interactive centers, mainly for physics, exploded all over Poland, with 1 million visitors in one year only at "Kopernik" center in Warsaw, see (Karwasz, 2012).

Fig. 1. a) Interactive exhibition "Fiat Lux" organized by authors at Regional Museum in Toruń (2008) (Karwasz 2010); b) "Schrödinger's cat" – burned inside a glass cube shows both the left and right profile; c) - d) two semi-cubes filled with liquids and a gap in-between them: a crocodile picture is inserted in the gap; depending on the angle of observation the crocodile is visible or not (due to the total internal reflection between the liquid and the air in the gap) – the object noticed by Maria Karwasz in a TV shop.

However, in parallel with this extraordinary success, the main risk of "Physics and Toys" is to show objects, without prior preparation of cognitive categories: why do I show this object. This reflects in comments frequently heard from some (semi)professional science divulgators: "I have also got it!" or "I have already seen it!". Such comments prove that the interest of spectators is still concentrated on the object and not on the phenomena itself, or more precisely – on physics.

In this work we show a methodological extension of interactive physics: visiting an exhibition or participating in an interactive lecture is only a departure point for own, independent search for phenomena around us. We concentrate on optics, as the vision is our most important sense. A thematic, interdisciplinary exhibition on optics "Fiat Lux! or playing with light" was organized in collaboration with the Regional Museum in Toruń in the medieval cellar of Toruń Town Hall in 2008 and then travelling to other 20 musea all over Poland for several years. Teaching optics is a powerful tool to trigger interest in the external work: we use our vision continuously but between the light, the object seen and our impression there is also our eye and our brain. So optics is not only physics but also psychology and arts.

The main scope of the present report is not to numerate optical phenomena but to go beyond "organized" exhibitions and ready books: the aim of this paper is to induce the reader (or rather spectator) to search in any time and any place of optical impressions. For didactical simplicity one should follow three branches of optics: geometrical optics, wave optics (interference, diffraction), and chromatography, which for us is the science of colours (Karwasz 2012). Due to the black-and-white printing limitations, here we concentrate only on the geometrical optics.

2. Fun with flat mirrors

Modern geometrical physics starts from Vitelo (1237-1300?), Türingen - Polish medieval priest and scientist, who studied the laws of reflection. Nowadays, several centuries later, the mirror image is one of the phenomena most misunderstood in early physics education (Böhm 2011, p. 7): to determine in what way is formed is not always easy (Goldberg 1986, p. 472). Students have their (not always correct) beliefs on this subject (Galili 1996, p. 847).

Among the objects drawn in Vitelo's Perspectiva we find a periscope, one of the most simple optical devices. It consists of two flat mirrors positioned at 45º, see fig. 2a. The resulting image is virtual, straight and of the same size as the object. If mirrors are positioned at +45º and -45º, see fig. 2b, the image is inverted. If you want to observe the whole horizon you must to turn your head with the periscope.

Fig.2. Fun with periscope: a) a scheme of a correct construction and b) its application – how to see the world like an adult (“Fiat Lux” exhibition in Toruń, 2007); c) a toy periscope that allows to rotate the upper part: the images rotate with turning the periscope; d) a scheme of a “wrongly” mounted periscope.

Two flat mirrors can be placed also in another ways: one behind another, like in fig. 2c, giving an infinite number of successive reflections. This is what happens staying between two mirrors in a hair-dresser workshop. In fig. 3a we show a parallel positioning of two mirrors in which the front mirror is semitransparent and the reflected object is placed behind it (i.e. between the two mirrors). An infinite number of successive reflections – every next smaller – is seen. But if the photographer is illuminated, he is also reflected from the front glass, see fig. 3b.

Fig. 3. Parallel mirrors and the question of reflection from glass surfaces: a) an infinite number of reflections of a chain of lamps positioned between a mirror behind and a glass window in front. b) The same object but the photo taken not in darkness – a reflection of author (GK) is seen. c) a pile of transparences: a piece of paper with printed text is positioned under 20 of them – the text is still visible; another piece of paper positioned under 50 transparences (lower half of the photo) is barely visible, instead – the reflection of the photographer can be seen. d) internal car mirror (here shown vertically) – two reflections of the author are seen: on in the mirror behind and one in the protecting glass in front of the mirror.

The latter photo induces us to the question of reflections – is a window glass transparent or is it a mirror? An answer is given in fig. 3c – where a stack (about fifty) of transparent plastic foils is positioned. If they are few (a dozen) they are transparent – a piece of paper below them is quite well visible even if a reflection of the objects above the stack (including the photographer) is also present. To conclude the question of semitransparent and non transparent mirrors in fig. 3d we show an object that we see every day – an interior car mirror. At darkness, in order not to get blind due to lamps of a car behind, we "switch" the mirror off. In practice, we change the angle of the mirror in a way, that the light from behind is reflected above our eyes. Why, therefore, we see anyway the lights of the car behind? The light reflects from the glass[1] that is placed in front of the mirror, fig. 3d. Check it before you start driving!

A number of other plays can be done with flat mirrors, the most funny is so-called kaleidoscope, i.e. "nice vision" in Greek. It consists of three mirror, forming angles of 60º, see fig. 4a. Other configurations, see fig. 4b are also possible. In front of the mirrors small objects – pieces of colorful glass, beads, feathers are placed. Their casual position is reflected in the mirrors giving a symmetric, "nice" picture, see fig. 4c. A variation of the kaleidoscope includes a big glass sphere in front of the tube with mirrors. Images of objects in front of the sphere are formed immediately after it, inside the tube. Such a kaleidoscope can be used to multiply the external world.

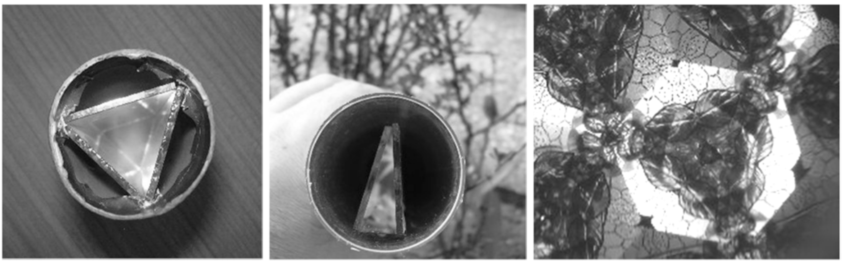

Fig. 4. a, b) Two types of kaleidoscopes and images formed in them: b) a flower from outside, c) small pieces of colorful glass. (Photo GK)

Other kaleidoscope-like configurations of mirrors are shown in fig. 5. In fig. 5a there are three mirrors in a "classical" configuration of 60º but the spectator is inside. An infinite number of successive reflections of the author (KS) crowd the image. Exactly 6 images are obtained when two mirrors are positioned exactly at 60º. But taking two flat mirrors from bathroom (for make-up) one can experiment all different angles, as shown in fig. 5b. Check, which of the images are non-inverted and which are left-right flipped.

[1] The coefficient of reflection from the front (and rear) surface of a window depends from the dielectric constant of the glass. Typically 4% of impacting light intensity is reflected from each surface. So the intensity of light transmitted from a single glass sheet is (0.96x0.96) = 0.922.

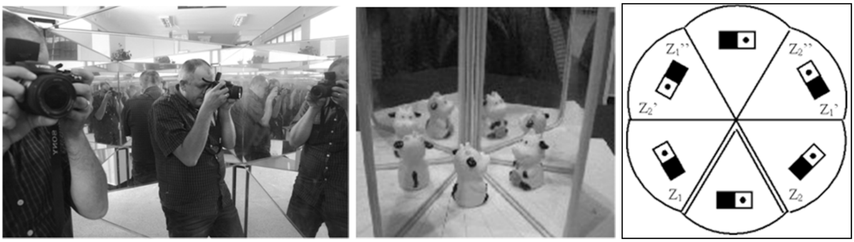

Fig. 5. Fun with flat mirrors, continued: a) inside a giant kaleidoscope made of three mirrors positioned at 60°; b) similar to the previous - photo taken from outside and the angle slightly smaller than 60° (Open Days at University Udine, 2008); c) a scheme of successive reflections.

Similar to the previous configuration is the hair-dresser room (author M. Brozis, 2006), with three mirrors in 3D configuration at 90º angles, fig. 6. Depending on the angle of observation, several reflections can be seen. In photo 6b we show not only the two primary reflections (left-right inverted) but also reflection of reflections (twice inverted, i.e. non-inverted) – the first from right.

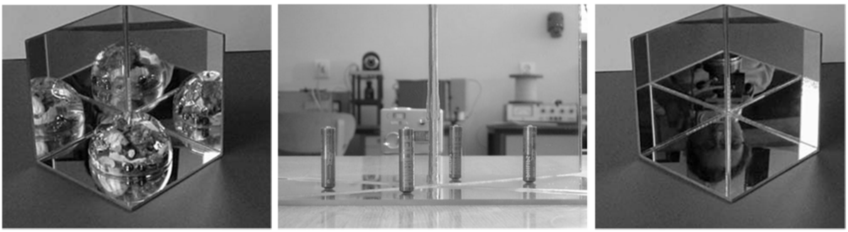

Fig. 6. "Hair-dresser room", i.e. three flat mirrors under 90° - a) reflections from three mirrors (the picture taken along the symmetry axis) ; b) in pictures from left to right we see the reflection of the battery in the left mirror (inverted left-right), the battery itself, the reflection of the battery in the right mirror (inverted) and reflection of the reflection (non inverted). c) Photo of the author – the image is upside-down. Photo GK & dr Tomasz Wróblewski.

Even a single mirror can produce quite a fun. In photo 7a, our colleague Waldek seems to levitate. In practice he stands on his left leg, hidden behind a big mirror. In a "Soviet bank" ("Insert a coin and you will never get it back!"), fig. 7b, a flat mirror is placed in a small box under 45º and half of a star is glued to it in the center. The other half, seen by the observer is just the image in the mirror. The bottom of the box is lined with a design not allowing to evaluate the perspective; the distance between the image and the observer eye is constant for every point of the mirror, see fig. 7d. In this way the observer is convinced to see he whole box, but the "bank" is hidden behind the mirror and inserted coins disappear.

Fig. 7. Fun with single flat mirrors. a) Waldek, apparently hanging in air, is standing on his left leg behind a big flat mirror, and his right leg is in front of the mirror. b), c) "Soviet bank" – a mirror placed at 45°: the observer is convinced to see the whole box but coins are dropped behind the mirror – one can hear them but not see; an additional Fresnel lens shows the coin "shrunk" d), e) Creating the image in moneyboxes. Photo KS.

3. Fun with spherical mirrors

Vitelo's treaty on optics De perspective (Vitelo 2003) was used as an university textbook till times of Newton – even Kepler wrote a comment on it. His imaginary portrait (painted by Giangacomo del Forno in 1942) is shown as one of 40 most prominent scientists at the Rectorate Aula of Padova University, fig. 8a. Vitelo was first to study experimentally reflections, not only from flat mirrors, but also spherical and cylindrical, both convex and concave. His experimental set-ups (reconstructed on the project by prof. Andrzej Bielski at UMK) are shown in fig. 8b and 8c.

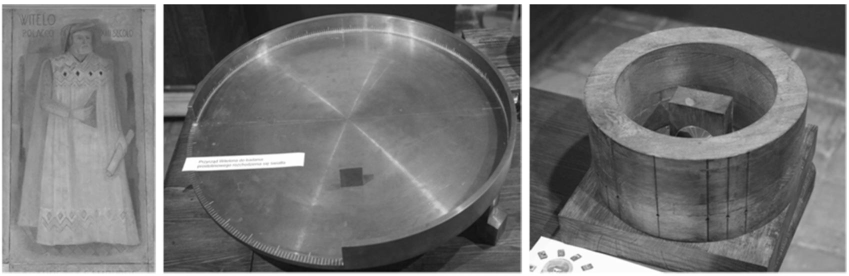

Fig. 8. Vitelo and his experimental set-up. 8a Imaginary portrait by Giangiacomo del Forno (1942) in Sala dei Quaranta, Palazzo Bo', University of Padova (shown here with kind permission from Università degli Studi di Padova). b) set up (diameter 60 cm) to study the angle of reflection with 1° precision (reconstruction by A. Bielski, UMK). c) set up to study angles of reflection from cylindrical and spherical mirrors (diameter 30 cm).

Today, cylindrical mirrors are rarely used but spherical ones, in particular convex are on every second crossing of narrow streets in old Italian cities (and inside shops, see fig. 9a). They allow to observe wider angles than flat mirrors; the image in convex mirrors is reduced and but straight (non inverted). It would be a disaster to see in a mirror a car coming upside-down! Also external mirror in cars are frequently convex. In Australia a warning is written on these mirrors: an image is reduced, so a car approaching from behind seems to be more distant than it is in reality, see fig. 9b.

Fig. 9. a) A semispherical convex mirror in a shop with newspapers facilitates the surveillance. b) An external mirror in Australian car is convex: a warning (barely visible above the lower edge) says: "Objects in mirror are closer than they appear". c) A concave mirror (in a window shop in Paris) gives an inverted image of buildings behind the observer. Photos Maria Karwasz.

Convex spherical mirrors can be found in many other places: in shops - to see clients in every angle, in cities – to reflects the architecture etc. In Chicago a big sphere (or rather an ellipsoid) is a part of the urban landscape itself, fig. 10a. Taking a photo of the city reflected in such a sphere is not an easy task – if you stay too close, the photographer is so big that it obscures the rest of the landscape. Clearly, the size of the image depends on the distance of the object that is taken, fig. 10b. Moreover, the reduction in size depends also on the radius of the ball. It is particularly visible on the Christmas tree, fig. 10c.

Fig. 10. Fun with spherical mirrors. a) A giant ellipsoidal ball, with pigeons on the top, as a part of the urban landscape, Golden Mile in Chicago (2009): nothing is inverted in convex mirrors, independently of the distance. b) Buildings in London (going down to Millennium Bridge) reflected in a street sphere (2014): convex mirrors give reduced images – more distant is the object, more reduced is the image, the effect is greater than in flat mirrors. c) Skating at Stanislas Square in Nancy reflected in Christmas ball (2010): images in small mirrors are more reduced than in big ones. Photos Maria Karwasz.

However, to get convex and concave mirrors there is no need to go to France or Australia – just ask a spoon in a good restaurant, where spoons are not washed in automatic machines so they shine. A convex surface gives always a straight image, while the concave – straight only if you put your nose close to it (automatic camera hardly makes a photo for such a short distance), fig. 11a and b. Moreover, in Korean restaurant (they always use spoons apart from sticks) you can check another law: smaller spoon, at the same distance from the object gives a smaller image. This logic! but not so easy to calculate.

Fig. 11. Spoons as mirrors: a) a convex surface gives non-inverted image, b) a concave mirror – an inverted image (hand of Ula Kordowska, a constant distant from the spoon was kept). c) In Korea two types of spoons are used at table: the smaller one gives a smaller image (a concave surface, image of the rose on the table that was above the spoon).

As far as convex mirrors give always reduced (and upright) images, independently from the distance of the objects, concave mirrors, like that used for make-up, can give images:

1) upright and enlarged (when the object is close to the mirror)
2) inverted and enlarged (when the object is "somewhat" further)
3) inverted and reduced (for large distances).

We illustrate it in fig. 12. A single mathematical model describes all these three cases (and the convex mirror also). We come to mathematics later.

Cylindrical mirror act in the same way as spherical: convex make straight (and reduced) images and concave – depending on a distance. For short distances (as compared to the radius of curvature) the image in a concave cylindrical mirror is of the same type as in a spherical mirror when the object is close, i.e. non-inverted and enlarged. Obviously, cylindrical mirror "deform" objects only in the direction in which the mirror is curved, fig. 13.

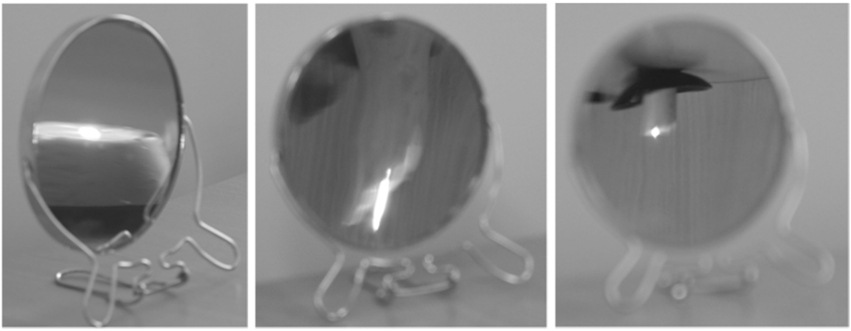

Fig. 12. "School-like" images formed in a concave mirror: a) enlarged and non-inverted, with the candle close to the mirror (less than R/2 where R is the radius of curvature), b) enlarged and inverted at the distance between R/2 and R, and c) inverted and reduced, with the distance higher than R.

Fig. 13. Cylindrical mirrors. a) This mirror ("Questacom" Science Center in Canberra, 2006) seems to enlarge in the horizontal direction, so it could be concave with the vertical axis; but, as seen from its borders, it is convex with a horizontal axis: the image is shortened in the vertical direction what makes the same impression as enlarging in the horizontal. b) Publicity of a diet drugs: a cylindrical convex mirror with a vertical axis, c) Berlin modern architecture: a convex cylindrical wall reflects buildings on the other side of the street – images are shrunk (look at the right edge of the cylinder). Photos MK

Resuming, spherical mirrors (and also cylindrical) give several different types of images. For convex mirrors these are always reduced (and non-inverted). Dimensions of the images are smaller when objects are more distant. However, dimensions of images depend also on radii of mirrors: smaller radii give smaller images. The mathematical formulation waited Newton.

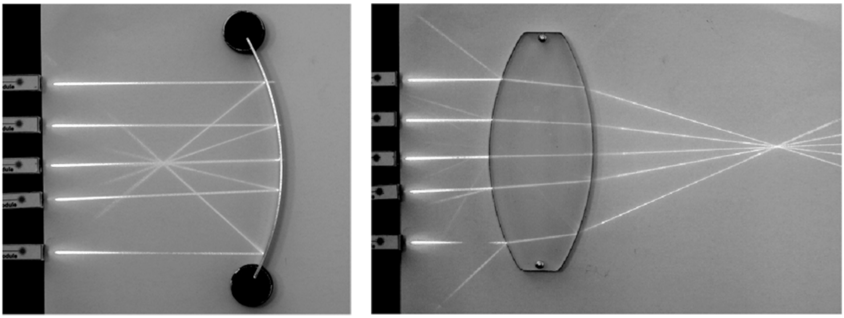

Fig. 14. Parallel rays of light reflecting in the concave (cylinder) mirror intersect at the focal point of the mirror. b) The same light passing through the convex lens intersect at the focus of the lens. Note the rays reflected from the left surface of the lens: four of them seem to come from the same point, which would be a (virtual) focus of a convex mirror. Additional reflected rays apparently coming out from the reflected central ray are in fact refracted rays, which entered the lens and reflected from the inner (i.e. right) surface. Photo KS.

4. Fun with refraction

First optical instrument, that revolutionized navigation, astronomy and war was the telescope. Made of two lenses it was constructed by a Dutch optician H. Jansen in 1604, but he might have used the existing Italian construction. Laws for the refraction of light, needed to understand lenses were formulated by Snelius in 1621. The exact mathematical formulation of it contains sinus of two angles: of the incidence α and refraction β and the intrinsic property of the material, that is called n – the index of refraction (1.33 for water, about 1.5 for glass).

$$\sin \alpha / \sin \beta = n \quad (1)$$

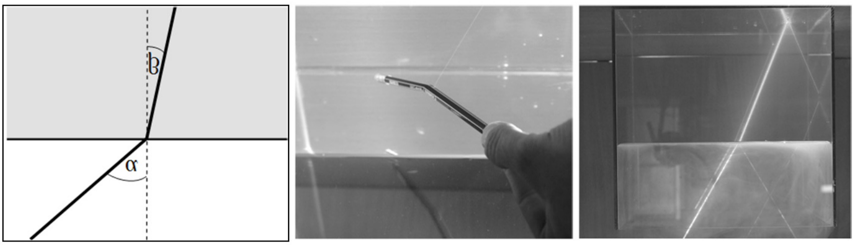

Fig. 15. a) The law of refraction: light is coming from air into glass (n>1); in this way the angle of incidence α is greater than the ingle of refraction β. You can see it observing a stick standing in water b) or laser beams entering an aquarium c). Note reflected rays in the latter photo. (KS)

As seen from fig. 15a, for light rays coming from air to glass the angle $\alpha > \beta$, in accordance with n>1 for glass. It seems that the ray is attracted into the glass. This could make think that light is a kind of particle; of this opinion was even Newton.

What makes this law difficult to students is the way of measuring these angles. Pupils, deceived by a flat picture (like fig. 14b) forget that lenses are 3D objects: it is much easier to measure an angle to the normal to the surface than angles between surfaces (ask your math professor). By the way, already in the "apparatus" by Vitelo angles were measured between the ray and the normal to the surface.

The light passing through a cube of glass undergoes two refractions, see fig. 16a. As a consequence, the image is shifted in respect to the objects, see fig. 16b. It also seems closer to the observer. Again, reflections on the inner surfaces of the cube can be seen, fig. 16c.

Fig. 16. (a) Light passing though a flat piece of glass (or a cube) is deviated twice. As a result, rays entering parallel exit also parallel. b) In this manner, the object below seems to be shifted. c) If the cube is rotated, not only the shifted image is seen but also a reflection of the object on the inner face of cube.

The law of refraction found recently a new fun: high power excimer lasers allow to print 3D images inside glass volumes – usually cubes. These cubes allow to see objects inside from three sides at a single glance, see fig. 17. What is seen in such cubes, is not the object but projections of it on the three perpendicular walls, fig. 17d. The projections are seen under difference angles, so they are re-dimensioned.

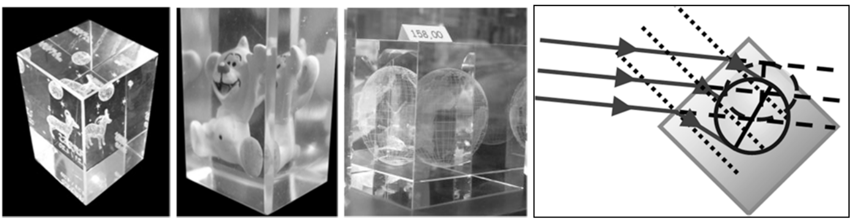

Fig. 17. Fun with refraction: seeing objects from three sides at the same time – objects are printed inside glass cubes and what is seen are projections of thee perspectives onto three perpendicular surfaces (a-c). As shown at c), i.e. an image of he sphere, these projections are rescaled in the directions of observation, as shown on the scheme d).

Another play with refraction is the magic eye, fig. 18. The “eye” resembles a plane-convex lens, but its convex surface is not spherical but shaped into a rosette from gothic temple - an array of radial planes, with a little circular centre, as if it were a bunch of glass prisms. Each of those prisms deflects the incoming light beam. We see a whole rosette of virtual images, set in a circle around the non-shifted image. By the way, several ways of shaping the “eye” are possible, so different types of multiple images are created.

Fig. 18. The “magic eye” uses the law of refraction. a) It is like a rosette with several surfaces cut under different angles. An object (shelter of the neighbor, b) is multiplied (c) into as many images as the number of separate surfaces in the “eye”.

The equation (1) for refraction allows to predict a strange phenomenon: if the ray goes from a medium which is optically more dense (like from water to air), above a certain angle β, $\sin\alpha$ would go above 1, what is impossible. In other words, for a certain limiting angle β a ray will not exit from water. This phenomenon is called “total internal reflection” – you can spot such reflections from inner surface in fig. 16c and 17b. The limiting angle γ, above which the ray will not get out from water (or any other dense optically medium) is determined by the condition

$$\sin \gamma = 1/n \qquad (2)$$

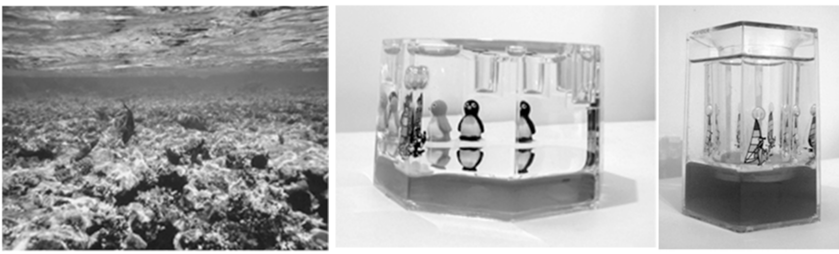

Fig. 19. a) While diving the sea bottom is nicely visible, and also its reflection in the wavy surface of the sea above; this comes from a total reflection for angles bigger than the limiting angle in eq. (2).

b) In a hexagonal prism there are only two penguins; the remaining ones come from the refraction (half of the central one) and other form total reflection on inner surfaces. c) In this prism, with a cylindrical hole in the center the reflected images are additionally shrunk. Objects and photos GK.

Under water, this phenomenon makes visible only a limited circle of the landscape above the head of the diver (the limiting angle is 49º) and the borders of the visual field seem to be a perfect mirror, see fig. 19a.

5. Fun with lenses

Vitelo studies of convex mirrors allowed to visualize the concept of focus, i.e. the place that rays coming from a distance converge to one point. It easy to show the focus (and measure the focal distance f) with a convergent lens, see fig. 20a. In the evening time the image of a lamp above our head, formed by a glass of water can be seen on the table, fig. 20b. In thick glasses, like that from Charlottenburg Museum, fig. 20c, the focus can fall inside that glass.

Fig. 20. a) Ad hoc showing the focus of a convergent lens (GK at "Fiat Lux" exhibition in Grudziądz, 2010-2011). b) Light focused by a water-filled glass: both the spot lamp and lateral stick-like neon lamps are focused on the table. Note also reflections from the concave surface of the glass. C) In these caliches the light coming from behind and above is focused in their basis (Berlin, 2006, photo MK).

Fig. 21. a) Convex lenses seem to behave like concave mirrors: they give enlarged or reduced images depending on the distance of the object. Concave lenses (the glass of the author, in the upper right corner) act like convex mirrors – they produce reduced (and non-inverted) images. Ad hoc lesson for lower secondary school in Grudziądz, 2010. Photo MK. b) A convex lens. With the object close to it gives non-inverted and enlarged picture, like a bathroom concave mirror, when used by girls for make-up. Opening of "Fiat Lux" in Frombork, 2011; in the background postcards with Fresnel concave and convex lenses. Photo W. Andrearczyk.

Detail studies of images formed by lenses can be done using the glasses of spectators. The optical glasses of short-seeing persons (i.e. concave lenses) give reduced images, see the upper-right corner in fig. 21a. The optical glasses of distant-seeing persons are convex, like the magnifying glass in fig. 21b (and fig. 21a). As in the case of concave mirrors, see fig. 12, types of images in magnifying glasses depend on the distance from the object: with objects far from the lens the image is inverted like fig. 21a; with objects close to the lens the image is straight (and enlarged), fig. 21b.

6. Fun with mathematics

Optics became fully mathematical only with Newton and his Opticks (Newton 1704). Geniality of Newton stands in observing that the laws for mirrors and for lenses are identical: the position q of the image, as compared to the position of the object p, depends solely on the focal length f. And these positions, for geometrical reasons, determine the magnification M, i.e. the ratio between the dimension of the image H and of the object h:

$$M = H/h = q/p \qquad (3)$$

The equation which governs images in mirrors and (thin) lenses is as follows:

$$1/p + 1/q = 1/f \qquad (4)$$

Drawing of light rays in mirrors are show in fig. 22. Usually we draw two rays: one parallel to the optical axis and one incident to the center of the mirror. Note that convex mirrors have focus behind the mirror; we call the focus "virtual". For the real focus (i.e. in the case of convex lenses and concave mirrors) we assume f positive; for de-focusing devices (concave lenses and convex mirrors) we assume f negative.

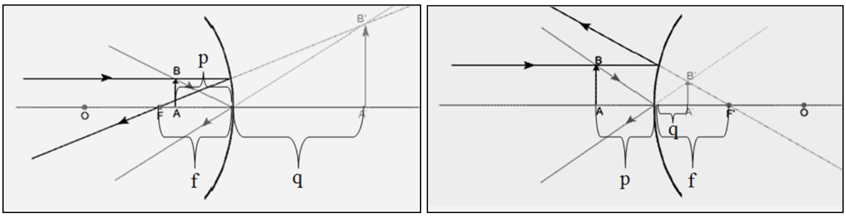

Fig. 22. Deriving the equation of mirrors: searching for similar geometrically triangles containing object and image. Two rays can be drawn easily – one incoming parallel (and reflected to the focus) and one incident to the center of mirror (where it is easy to draw the angle of reflection equal to the incident one). a) For a concave mirror, if the object is placed closer to the mirror than the focus, an image enlarged, upright (and behind the window, i.e. virtual) is formed. b) For convex mirrors, used on the streets, the image is always virtual and reduced.

In order to calculate explicitly the position q of the image we rewrite eq. (4) into the form

$$q = f + \frac{f^2}{p - f} \qquad (5)$$

From experimental playing shown above we note that this is the focal length which determines the kind of the image. Let's make some numerical study, assuming focal length f =1m. For convex lenses it will be with the sign positive, f = +1m. We chose some significant values for p from infinite to zero and calculate corresponding values for q.

p	∞	4	2	3/2	1	1/2	0
q	1	4/3	2	3	∞	-1	0

This table shows that the for p=2f the image is of the same size as the object (q/p=1), for p>2f the image is reduced, in-between f < p < 2f the image is enlarged. It is also clear, that for p = f the image is formed in the infinity; in experiment we observe highly deformed images, like we show it on next photos. For 0 < p< f , i.e. when the lens is close to the object, it works as a "magnifying lens", photo 21b. A negative sign of q informs us that the image is "virtual", i.e. seems to be positioned on the same side of the lens as the object.

A similar table can be done for de-magnifying (i.e. concave) lenses, see author's glasses in fig. 21a. We adopt f = -1m.

p	∞	4	2	1	1/2	0
q	-1	-4/5	-2/3	-1/2	-1/3	0

It is clear from the above, that lenses of a short-seeing person (concave lenses) give always reduced images. Images are always virtual, as the sign of q is always negative.

The equation (5) can be easily presented on the graph: it can be derived from a simpler form, q = f 2/p, which is subsequently shifted up by f and right by f, see fig. 23. The right part of this graph (i.e. for p of the same sign as f) corresponds to focusing devices (like convex lenses) and the left part – to de-focusing devices (like convex mirrors). Enlarged images are formed, when the curve (shown as thicker) lays above the line q=p (with q positive, see graph 23 for details).

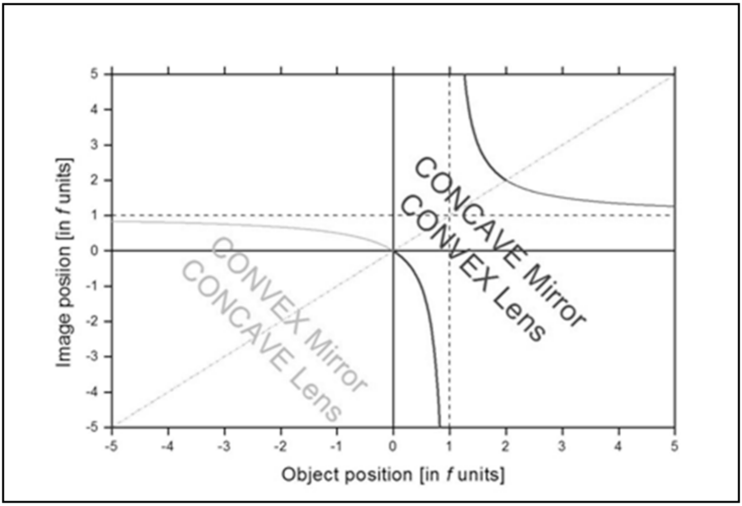

Fig. 23. Image formation in mirrors and lenses – using properties of the mathematical function eq. (5). Note the use of units f for expressing both the distance p of the object from the lens and the distance q of the image from the lens. The left part (i.e. for p < 0) of the graph corresponds to devices giving virutal images: concave lenses and convex mirrors; the images in these devices are reduced (q satisfies the condition |q|<|p|).

7. More fun with mirrors and lenses

The equation of Newton allows to explain types of images that are formed. However, a number of assumptions are needed to keep the equation applicable. For mirrors it is the requirement that rays travel near to the optical axis. In this case with good approximations all rays coming parallel to the optical axis are focused in one point . For lenses we also assume that they are thin, in a way that trav
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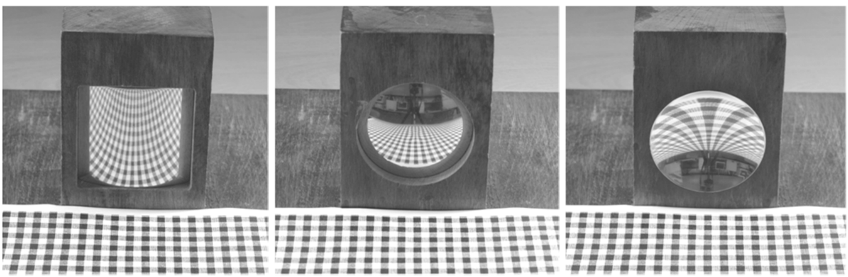

Fig. 24. Optics beyond Newton's approximation of big mirrors (i.e. eq. 2) – mirrors from Witelon's apparatus are small and images seem deformed. In reality this is what mirrors do: to calculate images more complex modeling is needed. a) cylindrical convex mirror, b) spherical convex, c) spherical concave mirror. Photos KS.

Photos in fig. 24 were done in a way to enhance the distortions made by mirrors – a square pattern was positioned on the table in front of the mirror. As far as distant objects (see fig. 24b and 24c) are not deformed, the rectangular patterns on borders of mirrors are strongly deformed. Clearly, the equation of Newton for mirrors, eq. (4) holds only for para-axis rays.

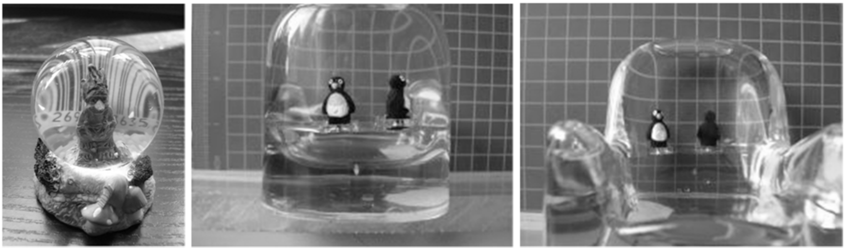

Fig. 25. "Deformations" of images behind these "lenses" come from two reasons: a) non-adequacy of the thin lenses approximation for objects like full spheres, b), c) complicated shapes of focusing objects, like this stand for portable phones. Objects and photos GK.

Figure 25 shows thick lenses – fig. 25 a small full sphere (filled with water) and fig. 25b, c – a complicated, chair-like shape filled with liquid. The latter "toy" forms in some points lenses-like shapes, with small radii: objects are strongly deformed by such lenses. Numerical simulations are needed to describe such "thick" lenses (Karwasz, 2004, 2005).

Till now we supposed that convex lenses are always focusing. But more precisely, it depends on indices of refraction – of the lens n_2 and of the medium outside the lens. This is codified by the equation

$$n_1/p + n_3/q = (n_2 - n_3)/R_2 + (n_2 - n_1)/R_1 \qquad (6)$$

where n_1 is the medium in which the object is placed and n_3 in which the image is formed. R_1 is the radius of curvature of the lens on the side of n_1 medium, and R_2 – of the n_2 medium. Radii are positive for convex surfaces.

A practical illustration of equation (6) is shown in fig. 26. Three batteries are immersed in cylindrical glasses and then in a rectangular aquarium. If the medium in both the glass and aquarium is the same (air or water), the image of the battery is like the battery itself. If water is poured in the glass, the image is broader than the object: the glass acts as a converging lens. If water is poured into aquarium and not into the glass, the latter acts like a diverging cylindrical lens: the image is thinner that the battery. We called this play "a shop with batteries": with no extra objects the seller can display three different types of batteries, differing in diameter, i.e. R6, R14, and R20.

Fig. 26. a) "Shop" with batteries (project Mirosław Brozis): water fills the rectangular aquarium but not the inner glass (left panel); it fills the glass but not aquarium (central panel); it fills both the aquarium and the glass (right panel). b) "A fat penguin" – grows in diameter when water is filled into the (sphere-like) container. Photos KS.

Another yet example of phenomena described by eq. (6) is shown in fig. 27: this is a plastic rectangular ash-tray filled with water; the central part of the ash-tray forms a spherical lens. This spherical part acts as a magnifying lens, see fig. 27a. But if a (spherical-like) air bubble is formed inside, it acts as a de-magnifying lens.

Fig. 27. A toy ash-tray filled with water: the central convex part acts as a magnifying lens, spherical-like air bubbles in water act as a de-magnifying lens. Objects and photo GK.

Resuming, physics contributes in a special way to general education of students. Therefore, physics education may not be restricted to pure physical topics but have to be combined with everyday life phenomena and problems; optics is one of most popular subjects (Schlichting 2005). However, the first step is to train teachers in a way that they understand all possible aspects of experiments, and not only the basics of them (Gioka 2011). Students who develop understanding of simple phenomena but complex, interdisciplinary explanations of them, can be successful teachers not only of physics but of other sciences as well.

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Fun with Optics - teaching by images

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