Pitfalls in Elementary Physics
4. Light

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Everyone has intuitive notions of light, image, shadow, reflection, colour, etc. Some of these are embedded in our language and they have informed the historical growth of the subject. When these get mixed with poorly learnt scientific notions in school/ college, the result is a loose, inconsistent framework of ideas among many students. Several systematic studies on students' notions bear this out.

Light and Sight

What is light? In a deep sense, perhaps no one really knows! But here we are referring to the notion at the cognitive level of children. Most school students equate light either to its source or to its effect (i.e. brightness) but do not give it a clear autonomous status as an entity existing in space between the source and the effect. It might seem amusing to us, but many children do not appreciate that light from a source propagates in every direction and to any distance; for them light 'stays' on a burning candle or it comes out to us but not farther. How do we see objects? Interestingly, vision is 'explained' differently depending on whether the object is self-luminous or not. We see the former since light comes out from it. For non-luminous objects, vision is explained by giving the eye an active role. Light comes out of the eye to see the objects! If you ask a child to draw a free drawing of how she thinks she sees say a book on a table, chances are that the figure will show rays coming out of the eye, striking the book and going off in other directions. If this seems absurd, let us remember that this is exactly the ancient idea of Parmenides and that Euclid's book on geometrical optics used for more than a thousand years employed the same model of 'seeing'. Fortunately, in geometrical optics, diagrams satisfy reversibility of the paths of rays. Hence, if you simply reverse the directions of arrows, the rest of the book is probably correct!

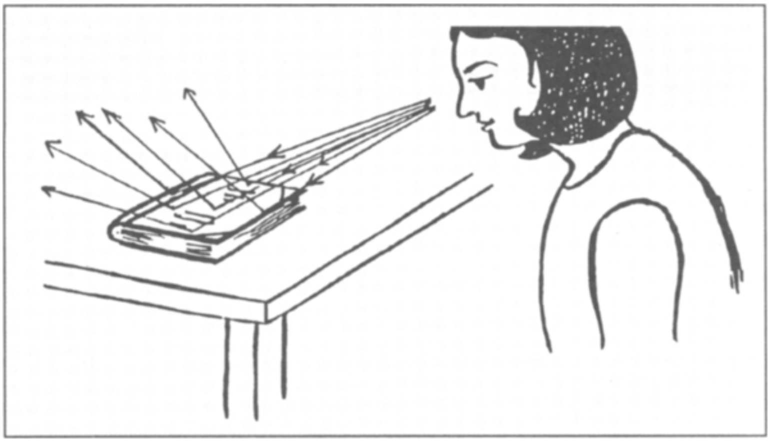


Figure 1. Children often regard the eye as the source of light rays, not a detector that it is, for explaining how we see objects that are not self-luminous. (Adapted from [1])

Many languages embed this intuitive model of vision. Phrases like 'the twinkle in his eyes', 'her eyes shining with pride' engender or reinforce the wrong model. Metaphorical statements that appear in many Indian languages (e.g. "The flame in his eyes extinguished at last") clearly give the eye the role of a source, not of a detector that it is.

When the correct model of seeing is emphasized to children, they sometimes over learn it! Ramadas and Driver [1] noted that children with the learnt model find it difficult to agree that light reflected from objects could be passing over their heads or around their ears. If they are seeing the objects, all reflected light can go nowhere except into their eyes!

All this is about seeing objects. Can we see light? Do we actually see rays or beams of light that we draw in geometric optics diagrams? Many students believe so, not realising that what we 'see' as a light beam in air is actually the objects (small particles) in the path of the beam which scatter light into our eyes.

Image

Students often use words like 'image', 'reflection', 'shadow' indistinguishably. There are deep-seated confusions regarding image formation by mirrors and lenses, location of images, real and virtual images, etc. Some of these are revealed vividly in two beautiful investigations by Goldberg and McDermott (see [2] and [3]. In the first study, the authors set up some very simple tasks for students. A vertical rod is placed in front of a plane mirror and students who can see the image are asked to put a finger at the position of the image. Most answer correctly, but many locate it on the mirror! Next, the investigator seated on the left a few feet away from the students asks the students to predict the location of the image if they were to view it from the investigator's position. More than half the students think the image location would change! For the third task, the rod is placed beyond the right edge of the mirror, the mirror is covered and a student seated beyond the right edge (*Figure 2*) is asked whether she or the investigator or both would see the image of the rod when the mirror was uncovered. Many students say that both would see the image; the student would see it on the line of sight to the rod and the investigator would see it because the usual image (drawn by a ray diagram) would be visible to the investigator. [Correct responses to the three tasks: The (virtual) image of the rod is located behind the mirror at the same normal distance as the rod from the mirror; the location of the image does not change with the observer's location; only the investigator would see the image.]

Why are such naive confusions so widespread? Part of the reason is that ray diagrams with mirrors and lenses in most textbooks simply deal with objects and images and not the act of them being seen by some observer. But more important, a clear meaning of image in geometrical optics is not easily grasped.

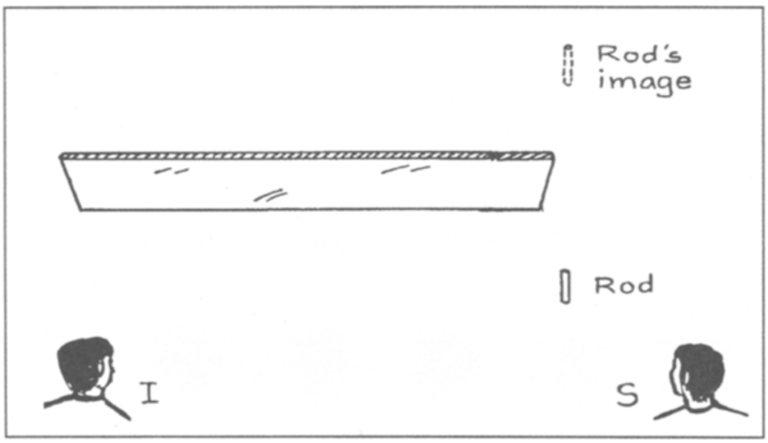


Figure 2. Who would see the image of the rod in the mirror: student S, investigator I or both? Many students answer: 'both' – S would see, they are likely to say, because the line of sight from S to the rod meets the mirror; I would see because the image of the rod is in the line of sight of I. (Adapted from [2])

This comes through clearly in the second study by Goldberg and McDermott on image formation by thin converging lenses [3]. Here the diagnostic apparatus consists of an optical bench, a luminous filament of an unfrosted bulb, a converging lens and a translucent screen. Students see an inverted image on the screen, which they know is real since it is captured on a screen. First, they are asked what would happen to the image if the lens were removed. Students' response to this question (even after a course in geometrical optics) is very telling. Many believe that the image would still be there, but it would turn erect! (They feel less sure of this if the object is non-luminous.) That this totally contradicts our daily experience (one never sees the image of a burning flame on a diffusely reflecting wall) shows how poorly learnt textbook physics can play havoc with our common sense.

Next, the students are asked what would happen if the upper half of the lens were covered with a piece of cardboard. A great majority of students respond that half of the image would vanish. This again is a notion fed through conventional (correct but inadequate) ray diagrams. These diagrams would generally show a ray from the top of an object going parallel to the axis of the lens and hitting the upper half of the lens. We show, less frequently, a ray from the top going to the lower half of the lens, getting refracted and reaching the same point as the upper ray. Naturally, a student thinks, if the upper half is covered, rays from the upper half of the object get blocked and the corresponding part of the image would disappear. It takes some practice (or thinking) to realize that each part of the converging lens is producing the same image (if the lens is thin). Covering some part of the lens would reduce the brightness of the image as a whole, but no part of the image would disappear.

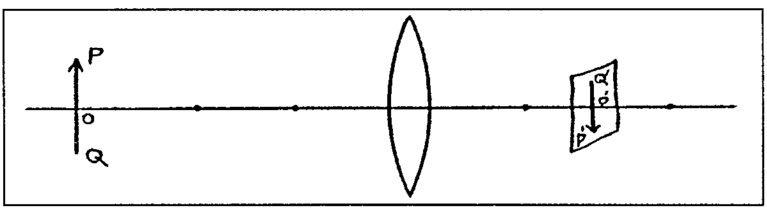


Figure 3. What would happen to the image P′Q′ of the object PQ if the upper half of the lens were covered? Many students would anticipate (wrongly) that the image of the upper part of the object would be cut off. Very few appreciate that each part of the (thin) lens is producing the same image. Covering some part of the lens can only reduce brightness of the image as a whole. (Adapted from [3])

The final task in this study is once again very revealing. Students are asked whether there would be an image if the screen were removed. This question leaves most students puzzled, perhaps because they cannot reconcile to an image 'suspended in air', as it were, without some surface, a screen. The role of the screen is obviously not clearly grasped. The screen is simply a diffuse reflector, so the image can be viewed even away from the bench. Without the screen, the image is there at the same position. But the idea is hard to swallow for many students. Can they see the image without the screen? Many think it is possible if you keep your eye at the position of the screen! Clearly, they think the image becomes real only if there is something to hold the image! At this point, if the investigator asks students to view from the side facing the lens and at a certain distance away from the original screen position, students are able to see the inverted image. The observation surprises pre-instruction students, but they still cannot grant the existence of an aerial image; many think that the image they are seeing is 'at or in the lens'.

These studies show that it is important for a teacher to explicitly clarify a number of points regarding images in geometrical

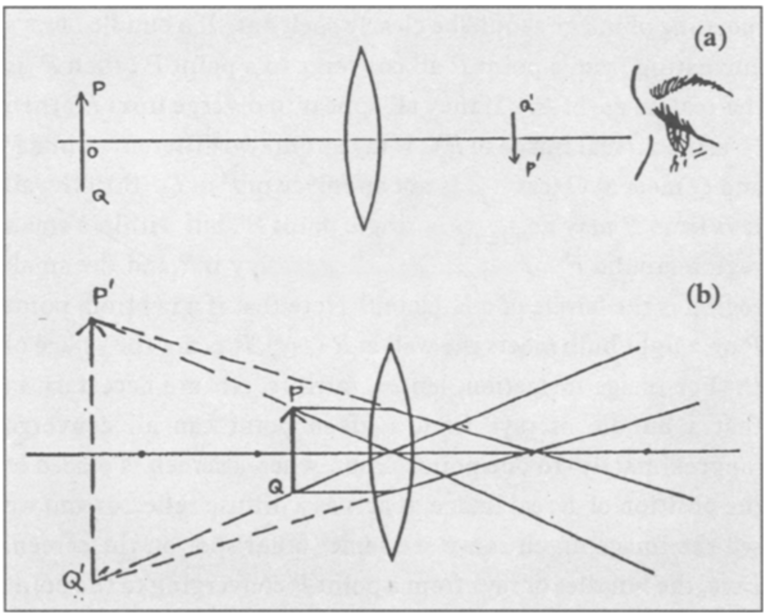


Figure 4. a) Can we see the image PQ in Figure 3 if the screen were removed?
b) How are we able to see the image even though it is virtual and cannot be collected on a screen? The puzzlement of many students to these questions is a telling indicator that the notions of real and virtual image are not properly grasped.

optics, simple though they may seem. One, from every point of an object, luminous or non-luminous, emanate not one but a bundle (of infinite number) of rays. For a non-luminous object, this arises from reflection (or scattering) of ambient light. If there is no ambient light, there will be no light emanating from a non-luminous object. Each point of a luminous object sends out bundles of rays on its own. Apart from this, there is no difference in the geometrical optics of luminous and non-luminous objects, a point not well grasped by many students. Two, as far as vision is concerned, an object is defined by its optical contrast with the background. Each point of the object and the background that we see is sending out bundles of rays converged by our eye. But the bundles differ in intensity, pattern, colour, etc giving the perception of the object. Precisely how these patterns are recognized by our brain is a difficult matter, but irrelevant to our purpose here. Still the point needs to be properly internalized. For vision, the 'object' in space need not be a material object; a region of space from which bundles of light rays are emanating in contrast to its background is good enough to be an object for vision. If we understand this, we would grant the aerial image in the preceding discussion the status of a real object as far as vision is concerned. Three, the meaning of image should be clearly spelt out. If a bundle of rays emanating from a point P all converge to a point P', then P' is the real image of P. (If they all appear to diverge from P', then P' is the virtual image of P). If rays from two different points P and Q meet at O (say), O is not an image of P or Q. Strictly, all rays from P may not reach a single point P', but within a small region around P'. P' is then a fuzzy image of P and the small region is the 'circle of confusion'. Note that if a ray from point P on a light bulb meets the wall at R (say), R is not the image of P. For image formation, lenses, mirrors, etc. are necessary so that a bundle of rays from a given point can all converge (approximately) to one point. Four, when a screen is placed at the position of a real image, it acts as a diffuse reflector and we see the image much as we see some other spot on the screen. Five, the bundles of rays from a point P converging to the point

P' (its image) do not stop there. (Surprisingly, so many students make this error, perhaps because in textbook ray diagrams, rays 'end' at the image and go no further!) They diverge. This is precisely the reason the eye placed not at the image location but at an appropriate distance away can converge the bundle (on the retina) and see the image. Lastly, the difference between specular and diffuse reflection should be spelt out clearly. When we are reading a newspaper, ambient light diffusely reflected by the particular part of the paper we are reading reaches our eyes enabling us to see it. But we do not see our own image in the newspaper. Why not? Because for our image to be formed, ambient light reflected by us should be specularly reflected. A paper is not a mirror, each microbit of it may be a mirror but the bits are not aligned as in an ordinary mirror, so the bundle of light rays emanating from say the tip of my nose striking different tiny bits do not appear to diverge from a single point i.e. do not form an image of the tip of my nose. Here the surface roughness is on a scale larger than the wavelength of light. And so on. (See also *Box 1.*)

The preceding ideas can be consolidated further through the following questions. Answers are given briefly and some background is assumed. Interested readers can look up [4] for details.

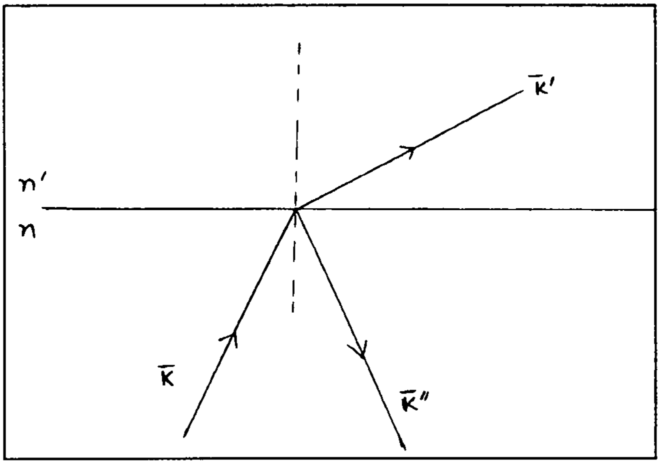
Q1. A virtual image cannot be caught on a screen. Yet we can see it. How is this possible?

A virtual image corresponds to divergent reflected or refracted rays, which 'appear' to come from a certain region, the position of the virtual image. Since there are no actual light rays at that location, a screen placed there will not show the image. We are still able to see it since our eye lens converges the divergent rays at its retina. (Likewise, the divergent rays can be brought on to a screen by means of an appropriate converging lens.) In other words, the virtual image serves as an 'object' for the converging lens (of our eye) to produce a real image.

Q2. What does one mean by 'image formed at infinity'? How

Box 1. Reflection and Refraction

Many young students are unaware that the usual laws of reflection and refraction at a plane interface follow in a simple way from the fact that boundary conditions on the fields exist and have to be satisfied at all points on the plane.



We know the spatial variation of a monochromatic plane wave is like $\exp(i\bar{k}\,.\,\bar{r})$ where k is the propagation vector. Consider a plane interface $z = 0$ between two media of refractive indices n and n'. For boundary conditions to be valid at all points on the plane, the phase factors describing spatial variation must be the same for incident wave ($\bar{k}$), reflected wave ($\bar{k}''$) and refracted wave ($\bar{k}'$) i.e.

At $z = 0$, $\bar{k}\,.\,\bar{r} = \bar{k}'.\bar{r} = \bar{k}''.\,\bar{r}$

It is a simple exercise to show from this equation that $\bar{k}$, $\bar{k}'$ and $\bar{k}''$ must lie in a plane, and further that

$\sin i \,/\, \sin r = k'/k = n/n$

Why is the frequency of the wave unchanged at reflection and refraction? The time variation of the wave is like $\exp(-i\omega t)$. Clearly, if frequency changed, the boundary conditions on fields satisfied at one time would not hold at another time. For the boundary conditions to be satisfied at all times, the frequency of incident, reflected and refracted waves must be the same. (See [5] for more details.)

are we able to see such an image?

When reflected or refracted rays are parallel (as when an object is placed at the focus of a concave mirror or a biconvex lens), they appear to come from a large distance (infinity). We are able to see it just as we see far away objects – parallel rays are converged by our eye lens at the retina.

Q3. A source illuminates a narrow slit. When light emerging out of the slit is converged by means of a lens on to a screen, do we see the image of the slit or that of the source?

Each point of the slit is a source of a bundle of rays which all converge (approximately) to a single point on the screen. Each point of the slit, however, receives light from all the different points of the source. The image we get is the image of the slit, not of the source. Of course, if the slit is wide, we can get the image of the source too at a different location from the image of the slit.

Q4. In a compound microscope, why is the location of the image of the objective formed by the eyepiece (called the eye-ring) the best position for viewing the object under the microscope?

Our eyes placed at the eye-ring collect all the rays refracted by the objective so that the (magnified) image of the object looks brightest. Note, do not confuse the image of the object (which is virtual and magnified) with the real image of the objective.

Q5. In a slide projector, a condensing lens converges light from the source on to the slide. The (magnified) image of the illuminated slide is then obtained on a screen by means of a projection lens. Where is the source imaged – on the slide, projection lens or the screen?

On the projection lens, for maximum effect.

Q6. If say the 'upper' quarter of the source above is covered, which part of the image of the slide has lost it at all?

Each part of the image corresponds to a unique part of the slide which, however, is illuminated from different parts of the source. Covering the source partially will reduce the overall brightness of the image but not delete any particular part of the image of the slide on the screen.

Q7. A point source placed in front of a circular opaque object produces a dark circular region on a screen. Is the region the image of the object?

There is no one to one correspondence between the points on the object and the dark points on the screen (except at the edges.) At the edges also, bundles of rays from a point are not converging to a point on the screen. The dark region is a shadow, not the image of the object.

Wave Speed

A stationary motorboat in a lake has its engine on and water waves emanate from it at a certain speed v, as measured by an observer at rest relative to the lake. The motorboat now moves with a speed u away from the observer. What is the speed of the waves for the same observer? This question if posed before a class of physics undergraduates draws an instant and almost unanimous response: $v-u$. The response comes out even more strongly if the teacher acts out the question i.e. shows by gestures the motion of the motorboat. For a moment, nearly every student forgets what is learnt in standard topics like elastic waves, Doppler effect, etc., and gives the answer that is true if we were talking not of water waves but of bullets fired from the boat. The correct response is that the speed of water waves produced by the moving motorboat will continue to be v.

Basic to this common error is our fixation with causality. We are aware that it is the boat (i.e. its engine) that is producing water waves (and also sound waves), and it is difficult to concede that the speed of the source (relative to the medium) has nothing to do with the speed of something that is 'coming out' of the source. Interestingly, in a context-free situation, the same students could easily give the standard textbook response: "the speed of waves in a medium is determined by the elastic properties of the medium and does not depend on the motion of the source". Many would also give the correct answer: $v-u$, for the situation when the boat is stationary in the lake but the observer moves away from the boat. Some of the better informed students could even invoke relativity: "it does not matter whether the source is moving or the observer is moving; what matters is the relative motion". This is, of course, a wrong invocation of relativity; the two situations are not symmetric, since there is a third thing, the

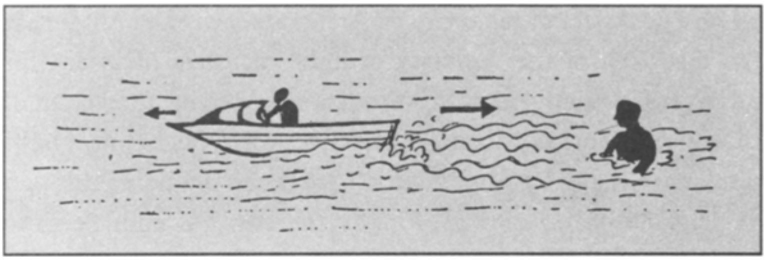


Figure 5. A motorboat with its engine on is sending out water waves with speed v as observed by a man stationary relative to the lake. What speed of waves would he measure if the motorboat moved away from him with speed u. Most students naturally adopt the 'emission theory' model and answer: v – u

medium. In the first case, the observer is at rest relative to the medium and in the second case it is moving. The speeds of waves for the observer are, therefore, different: v for the first case and $v - u$ for the second.

In short, the so-called emission theory (wave speed depends on the motion of the source) comes rather naturally to most students. In introducing the highly counter-intuitive special relativistic postulate of the constancy of the speed of light in vacuum, we have found it useful to go through the motor boat example above. This helps us first correct the natural (but wrong) emission theory kind of thinking for speed of light from a moving source. Next, one says that since light needs no medium, the source moving or the observer moving are symmetric situations in vacuum (by the principle of relativity) and thus the speed of light in vacuum is independent of the motion of the source or the observer (or said better, independent of the relative motion between the source and the observer). This, of course, does not amount to 'proving' the constancy of c (speed of light in vacuum), which is basically an axiom, but the motorboat example makes students feel more comfortable with the axiom.

As pointed out earlier, students sometimes overlearn an idea. The constancy of c in special relativity is emphasized so much that beginning students sometimes hesitate to take components of the velocity of light (if light is coming obliquely, say): $c \cos \theta$ and $c \sin \theta$, fearing that this goes against the invariance of c in all directions! While this feeling may be rare, the unfortunate use of the word velocity in place of speed in the statement of the

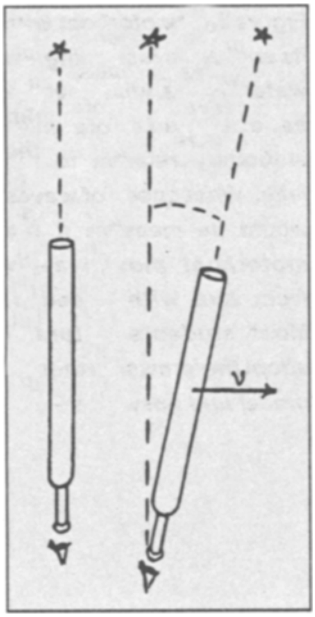


Figure 6. An example of 'overlearning' of the postulate of constancy of c (for observers in uniform relative motion). Some students do not readily concede that the direction of velocity vector of light in vacuum is not invariant. Stellar aberration can be invoked as an example to correct the misconception.

second postulate of relativity can generate a wrong notion that the direction of the velocity of light vector is invariant for observers in relative motion. Students need to be drawn out of this misconception by confronting them with aberration of light phenomenon, or by simply letting them see the point through velocity addition formulas. Finally, the word 'vacuum' needs to be underlined in the postulate and the non-invariance of speed of light in a medium needs to be highlighted by looking say at Fresnel's formula for speed of light in a moving medium.

Wave and Particle

That light sometimes behaves like a wave (e.g. in interference and diffraction phenomena) and sometimes like a particle (e.g. in photoelectric effect, Compton effect) has now become a standard cliche that all of us learn at college. Photoelectric effect cannot be explained, we teach students, by thinking of light as a wave. We need to think of it, like Einstein did, as a bunch of particles (photons), each of energy $h\nu$. Einstein's photoelectric equation follows when we view the effect as arising from a photon knocking off an electron from a metal. Einstein probably did think of photoelectric effect in this manner in 1905 when the quantum ideas were in infancy, but later he turned wiser and only a few years before his death is said to have remarked: "if anybody tells you that he understands what $E = h\nu$ means, tell him that he is a liar"! We need not dwell here on the quizzical, so far poorly understood, meaning of wave-particle duality. But there is a problem at a more mundane level in the above explanation of the photoelectric effect. We know that de Broglie wavelength for a photon is just the wavelength of radiation of which it is a quantum. Now de Broglie wavelength of a particle is roughly its extent of localization and, therefore, the size of the structure it can probe. Consequently, if photoelectric effect is to be viewed basically as a particle (photon) hitting another particle (electron), the de Broglie wavelength of the photon should be roughly of the order of inter electron spacing (1A°). This condition is not met in the photoelectric effect. Clearly, a probe with de Broglie wavelength of several thousand A° (wavelength of *uv* or visible light) localizing itself to 1 A° to hit a single electron is a myth. Indeed, photoelectric effect does not need quantization of light i.e. the photon picture proposed by Einstein, but can be explained straightforwardly in a semi-classical theory. There is no doubt that we are perpetuating a myth among students by feeding them 'localized photon' picture to explain photoelectric effect. It would be better if we taught them that the photon is simply a quantum of energy of the electromagnetic field. Like any quantum system, electromagnetic field (of say frequency ν) has energy levels and the minimum spacing between its energy levels is $h\nu$: the quantum of energy called photon. These views are not idiosyncratic. W E Lamb, one of the pioneers of laser theory, is said to have 'banned' the use of the word 'photon' in his department, realizing that it is a widely abused term by students and teachers!

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Suggested Reading

[1] **J Ramadas and R Driver.** ***Aspects of secondary students' ideas about light.*** **Centre for Studies in Science and Mathematics Education, University of Leeds, 1989.**

[2] **F Goldberg and L C McDermott. Student Difficulties in Understanding Image Formation by a Plane Mirror.** ***The Physics Teacher.*** **42, 472, 1986.**

[3] **F Goldberg and L C McDermott. An investigation of student understanding of the real image formed by a converging lens or concave mirror.** ***American Journal of Physics.*** **55 (2), 108, 1987.**

[4] **F W Sears, M W Zemansky and H D Young.** ***University Physics.*** **(sixth edition), Addison–Wesley, 1982.**

[5] **J D Jackson.** ***Classical Electrodynamics.*** **(second edition). John Wiley, 1975.**

We have inherited from our forefathers the keen longing for unified, all-embracing knowledge. The very name given to the highest institutions of learning reminds us that from antiquity and throughout many centuries the *universal* aspect has been the only one to be given full credit.

Erwin Schrödinger