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Teaching rituals and students' intellectual satisfaction*

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Abstract

Given that enhancing the motivation of young people for science is a widely shared goal, the question posed is how to raise intellectual satisfaction among students by showing the consistency and conciseness of physical theories. I argue that certain rituals in our teaching practices can make physical theories seem inconsistent, even absurd. Using examples of such rituals from the secondary school and college levels, I discuss how we might better highlight the consistency of ideas, and give evidence of students' and teachers' reactions to the proposed changes. I conclude by considering possible actions relating to teacher training and to assessment.

L A French translation of this article is available online.

Introduction

We, as teachers and physicists, value physics for the beauty of its theories: for their unity, conciseness, predictive power and consistency. This should surely be one of the ways in which we seek to attract students to physics—not, to be sure, the only way, but certainly one essential way.

I will give some examples of how a number of well-known, widely approved and very common, even habitual, ways of teaching some topics in physics actually tend to the contrary. Having shown some examples, I will suggest ways to remedy them, and offer evidence of teachers' and students' reactions to the proposed changes. Finally, I will offer suggestions for improving the situation.

The selected examples come from optics and the behaviour of gases; many others could be given. The examples may well seem at first to be mere matters of detail. They have been chosen as examples of teaching rituals, that is, of things that we commonly do which seem to be quite unproblematic, but which can often have important negative outcomes, not least in making the ideas taught seem inconsistent or absurd, or in encouraging popular misconceptions [1]. For this reason I give them the label 'critical details' [2, 3]. As is often said, the devil is in the detail, and thorough attention at this level can have highly beneficial effects.

Some rituals that make physics seem inconsistent

Rays and shadows: when concepts are thought of as 'objects'

It is very common to 'show rays of light' with a beam passing through dust or smoke, or with a horizontal sheet of paper lit through vertical slits. Such experiments have long been criticized (see for instance [4]). They readily encourage the common idea that light is visible from the side, as if it were an ordinary object. Consider the frequently used ray box, used to 'show rays of light going in straight lines'. Figure 1 shows a shocking variation on it, in which wavy slits produce wavy

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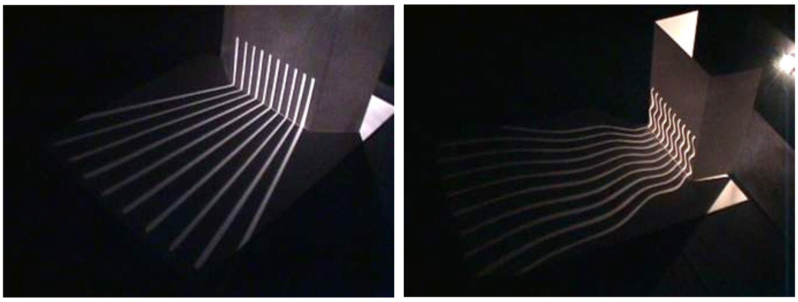


Figure 1. An example of a ritual experiment (left) often presented as 'showing' rectilinear propagation of rays of light and of a way (right) to avoid oversimplification in this respect. In both cases what is seen is a set of shadows [16].

'rays'. Plainly, in this kind of experiment, what we see is *not* 'rays' but *shadows* of the mask and its slits. That we see such shadows attests in *both* cases to the rectilinear propagation of light, but neither experiment 'shows rays of light'. So a well-meant and visually effective demonstration is fundamentally incoherent (recall that the bulb is a few centimetres above the bench and therefore the illuminated streak on the paper—in fact a succession of spots each lit by different beams—constitutes a line which does not even contain the source of the so-called 'ray').

This archetypal teaching ritual is much in favour in classrooms and in museums. I expect that many readers will feel very annoyed with me at this point, for challenging something so long taken for granted. It has been shown to be very resistant to change [5, 6]. This is probably to be ascribed both to the commonly accepted view that 'to see is to understand' [4–6], and to a well-known tendency of common reasoning, which frequently likes to think of concepts as ordinary objects [7]. Put briefly, figure 1 appears to undermine our best efforts to make an important idea simple and concrete. And it is annoying in showing that this way of presenting a concept is fundamentally inconsistent, in a way one had not previously realized.

A slightly more subtle case—coloured shadows—illustrates a related problem. Shadows themselves are commonly misunderstood as being like travelling objects ('cast', as one says, on a screen), as if the permanence of the shape indicates the existence of a quasi-material object. Figure 2 shows a classical demonstration with two sources of coloured lights, one red and one green,

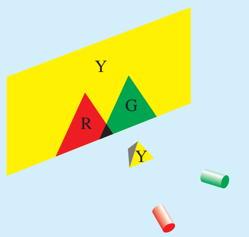


Figure 2. 'Coloured shadows': a teacher's comment. Y: yellow, G: green, R: red.

and a pyramidal object that prevents some light from reaching the screen. Teachers often provide arguments like this: 'We have seen two projected shadows and the black zone is the part which is common to these two shadows' [4, 5]. This extremely common explanation mentions two 'projected shadows', thought of as like travelling objects coming from the pyramid. Again, something is badly wrong: how could *one* of these 'projected shadows', for instance a source of *red* light falling on an object, result in a *green* shadow? What is striking in this description is the lack of vigilance on the part of many physics teachers about the adequacy of a ritual form of explanation.

Elementary ray optics: reified concepts, overselection and overstated representative cases

Another example of a ritual is to stress, when teaching optical imaging, the kind of simple diagram shown in figure 3, which shows just two 'construction rays' only, as if this is enough to explain how the image comes to be formed. Often, little or no time is taken to explain and illustrate the

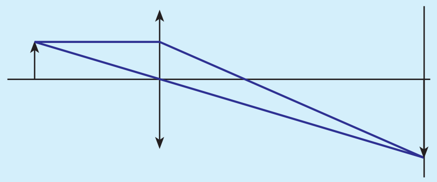


Figure 3. Typical ray diagram for formation of an image by a lens.

very principle of optical correspondence between a point and its image: that (given Gaussian conditions) *all* rays from one point in the source, which pass through the lens, meet at one point in the image. The rush to the archetypal diagram bypasses the essential physics.

Many students think that a mask over the centre of the lens would result in a hole in the image, as if this image had travelled (horizontally) in space as a whole (see for instance [8]). This time, the ritual I want to expose does not betray a clearly incorrect analysis of the physical phenomena under scrutiny. It is instead just much too compatible with common and undesired students' views (see for instance [9]), and does nothing to combat them. It can also encourage a misinterpretation of the rays drawn on the diagram. There is a risk of seeing them as generating the image, whereas they are merely two representatives of a whole set of rays originating in a point object and passing through the lens. A teacher can be tempted to rely solely on this heavily overselective diagram, because it is (minimally) sufficient to find the position and size of the image (when Gaussian conditions apply). And if that is all that assessment demands, the temptation not to think about how lenses form images is strong. Consistency and unity yield to getting the job done.

The hot air balloon: risks of an exclusively global approach

This final example [10] is one where what is commonly taught is, once one sees the point, simply inconsistent nonsense. However, few if any teachers or students notice this fact until it is pointed out.

It is common practice to suggest that in a hot air balloon, open at the bottom, the air pressure must be the same inside and outside. A classic exercise, indeed, consists in asking students to determine, for a hot air balloon of volume V, what must be the temperature T of the air in the balloon to achieve lift-off, given the total mass of the balloon and its load. The aim of such exercises is to rehearse Archimedes' principle. The pressure inside the balloon is used, with the density required, to find the temperature needed. The text classically reads something like this: 'Whatever the temperature of the air in the balloon, its pressure is the same as that of the air outside it'. This statement, unless accompanied by further discussion, is, as soon as one thinks hard about it, extraordinarily problematic. If there were the *same* pressure inside and outside near each small part of the envelope, it follows that *no net force* is exerted by all of the gas. Inevitably then, whatever Archimedes might say, there can be *no upthrust*. On this account, the balloon must simply fall to the ground due to its weight. The textbook cannot be right.

What has gone wrong is not to notice that the pressure in the warm, less dense air in the balloon decreases less rapidly with height than does the pressure in the colder denser air outside. So the pressure inside at the top of the balloon is greater than the pressure outside, and the balloon can stay up, or rise.

In this example, there is a clash between a global approach of Archimedes' principle on the one hand, and a local mechanistic analysis on the other. What is rather shocking is that, as will be seen below, teachers do not spontaneously detect the slightest problem. Traditionally, local and global points of view are not confronted with one another, and the global approach is considered sufficient. But this has allowed a shift from using a mean value for the air pressure to implicitly considering this pressure as uniform. This risk is very commonly ignored, and it might be said, in this respect, that most teachers unconsciously contribute to presenting physics as inconsistent (even self-contradictory) theory. The defence that their students do not notice is a poor one, especially if the goal is to show the consistency and economy of physics.

Beyond rituals: raising intellectual satisfaction

If one of our teaching goals is to show that physics is a consistent, parsimonious, elegant and powerful set of theories, we must be prepared to avoid relying only on such rituals, even if they are very effective for 'standard' calculations or if they concern topics that are supposedly attractive. Better guidelines for teaching are at least worth considering.

Stressing phenomena: coloured shadows

This example, outlined above, was accompanied by a teacher's comment borrowed from Hirn [5] (see also [4]). Worryingly, this comment was in fact an answer to a pupil's explanation that can be considered much more appropriate:

> 'The object prevents the colours *(coloured lights)* from mixing . . . colours *(coloured lights)* mix on the object *(and on the yellow background)* but not on the paper *(in the non-yellow parts)*. When red and green (*lights)* are mixed and you take away the green *(light),* red *(light)* is left.'

Of course, this pupil could not—without further investigation—be credited with what has been added here *(in italics)*, needed to render the explanation compatible with accepted physics. Also, one might see in the pupil's actual statement some important signs of 'reification' of colour, and observe that he does not mention explicitly the crucial element: *light*. But the point here is to highlight a paradox: the teacher's ritual argument was *even less* appropriate to a proper understanding of the situation than was the pupil's. The student at least paid close attention to the phenomena. Highlighting phenomena seems an evident and commonplace recommendation. For all that, it is easy to miss the point.

Overselective diagrams: representatives and the whole

The role of a lens. The selective focus on just one very reduced diagram is an example of a common ritual practice, which might be termed 'dimensional reduction'. Other examples are: analysing an extended source as a set of point sources; and representing a flux of light as 'rays'. Of course these ways of modelling have important merits, but it is wrong to treat them as we often do, as if they were simply self-evident.

A recent investigation [11] evaluated a change in one 'critical detail' of practice: simply using an additional introductory diagram which was designed to be more explicit about the role of a thin lens in optical imagery. This 'basic' diagram has two key features: many rays and beams are represented, as well as some rays which do not impinge on the lens. Although apparently unimportant, these undeviated rays are shown to highlight the fact that even the whole lens concerns only *a part* of the flux, thus favouring—supposedly—the idea that a part of the lens can form the image as well.

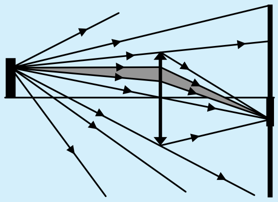
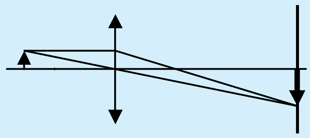
This investigation was conducted with two different samples: degree students (20) and trainee physics teachers already having a degree in physics (60). All had been taught elementary optical imaging previously, probably in a very classic manner. In order to isolate the 'detail' under scrutiny, no innovative course or even short sequence was planned in the research design. The intervention was limited to administering paper-and-pencil questionnaires with two questions commonly giving rise to the 'travelling image' syndrome. In each population, the sample was randomly divided into two subgroups (*a priori* equivalent). The two questions were introduced in each subgroup respectively with the 'basic' diagram and with a classic one, and we compared the results.

Table 1 displays the results obtained for one of the questions (see more details in [11]).

The results are similar for the two samples and more than compatible with the hypothesis that the basic diagram favours a proper understanding of the imaging role of the lens. The high value of the chosen indicator ($\chi^2 = 17.6$, $p = 0.001$) is surprising, given the very tenuous difference in the conditions for the two subgroups. This highlights the often unsuspected importance of reconsidering our teaching rituals, even in seemingly very small 'details'. In this case, both the trainee physics teachers and the degree students consulted were unambiguously convinced, although only informal indicators are available to attest this point. 'To me', said a degree student, 'what was really decisive was to see the unaffected rays on each side of the lens'. As for the trainees consulted, the short and quantitative testing procedure just outlined was 'worth a thousand theories', as one of them said.

Wave interference does not mix with geometrical optics. This case is not isolated. For instance,

Table 1. Linking a few representative elements to the whole: answers of trainee teachers and degree students to the basic and classical versions of a classical question [11].

Question	Situation introduced with basic diagram			Situation introduced with classical diagram		
A mask is put on the centre of the lens: what can we see on the screen now?						
Exclusive categories ↓	Trainees $N = 29$	Degree $N = 10$	**Together** $\mathbf{N = 39}$	Trainees $N = 31$	Degree $N = 10$	**Together** $\mathbf{N = 41}$
The same thing or A′B′, + sometimes: less sharp, Gauss approx, less luminous	26	8	**34**	17	2	**19**
‘Travelling image syndrome’: A black spot at the centre of the screen *or* variants	3	2	**5**	14	8	**22**

[a] Regrouped results: $\chi^2 = 17.6$, $p = 0.001$.

Colin and Viennot [12] (see also [13]) have pointed to the overselectivity of a diagram classically used in the elementary teaching of waves (figure 4(a)), and to the associated difficulties. The diagram in figure 4(a) has been observed to give rise to the following student comment: ‘light is deviated’.

The student appears to be talking about rays deviated by the slits, as if the problem were one in geometrical optics. Indeed the oversimplified drawing suggests that what is seen on the right of a slit is the mere continuation of the ray arriving on the left; hence the idea of deviation. This is compatible with a view of a ray as the hero of an individual story, which is at odds with the accepted—quantum or wave—view of interference. After the slits, it is nonsense to think of each path of light considered as being a ray, i.e. as of an individual entity of geometrical optics. According to this analysis, a different diagram (figure 4(b)) appears to be more appropriate. This second diagram suggests the phenomenon of diffraction occurring at the slits, and the fact that *only two paths* of light have been selected, among many others, *for each arrival point*. This *backward* selection is a crucial notion in wave optics [12].

In brief, these two examples in optics concern ritual diagrams that are problematic in that they are overselective, and in being all too compatible with the common tendency to think of concepts as ordinary objects: an image travelling as a whole, or a ray simply deviated when passing through a hole. In both cases, more explicit diagrams are likely to better back up students’ comprehension (regarding Young’s slits see [2], pp 172–5).

The last example also illustrates that it is possible to overcome a ritual—this time an oversimplified modelling hypothesis—in order more effectively to increase students’ intellectual satisfaction.

One argument may not be enough: linking local and global aspects

The problem with the hot air balloon is that one argument—the global one using Archimedes’ principle—is not enough, if one wants to avoid the inconsistency denounced above and, more positively, to show that physics works [10]. What the global perspective permits us to ignore is the small difference between the gradients of pressure inside and outside the envelope. Admitting that the pressure is the same inside and outside at the aperture level (bottom), it is inconsistent to say that the same balance holds at the top of the balloon.

The smaller diminution of the internal pressure with altitude accounts for the fact that this pressure is larger than the external pressure at the top of the envelope, which enables the balloon to stay in the air (figure 5). Of course the cost of such

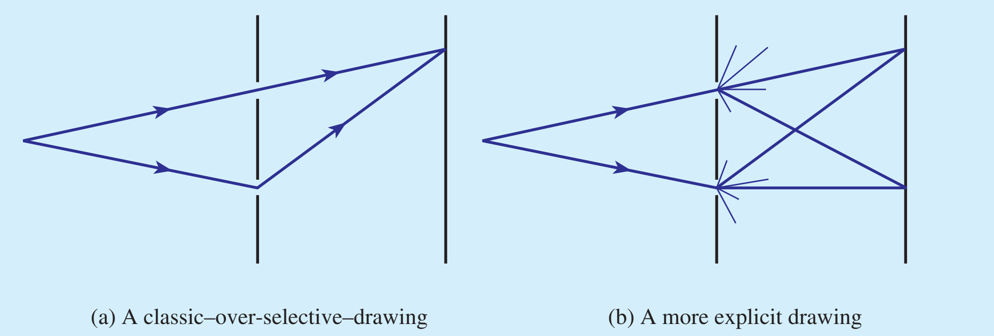


Figure 4. A ritual drawing illustrating interference with Young's slits (a) and a more explicit diagram (b) which shows the diffraction that occurs at the positions of the slits, the different status of a path of light after a slit as compared with the ray of light arriving at this slit, and the *backward* selection used to calculate an amplitude at a given point on the screen.

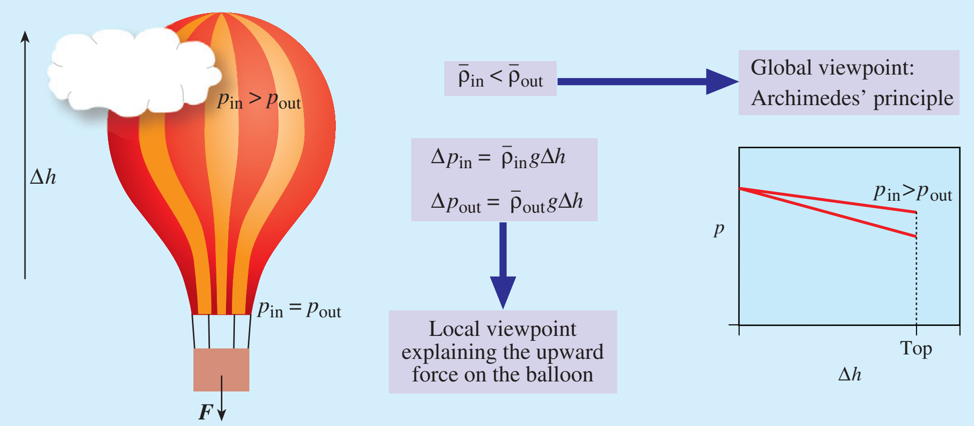


Figure 5. Some elements needed to understand how a hot air balloon holds in the air; ***F***: weight of the system (basket + load + balloon).

an approach is not negligible, in terms of teaching time, but neither is it disproportionate.

In an investigation, we first, before any discussion of these issues, gave respondents the usual ritual text of an exercise concerning hot air balloons, and asked: 'Would you add or change something in this text to make it clearer?' Not one of them (15 first-year university students, 32 degree students, 61 trainee teachers) alluded in the least to the problem pinpointed here. The outcome was very different when all these students and 15 in-service trainee teachers had an opportunity to react after having been presented with a half-hour discussion of the topic, as outlined above.

Their comments are summarized below.

Students' and teachers' reactions

Fifteen first-year university students individually went through this discussion in a teaching-interview. At the end, they were asked if the analysis seemed accessible to them. All answered 'yes', but some (seven students) said they were not sure they could explain the topic themselves. Also,

Table 2. Degree students' reactions to a session on the theme outlined in figure 5. Fourth column: in the case of an answer YES, the students were invited to indicate to what extent they were convinced of this positive answer, on a scale of 1 to 4.

Degree students $N = 21$	NO	YES	*Yes* rated 3 or 4, on a scale of 1 to 4
Did you derive *pleasure* from understanding the proposed situation?	4	17	11
Was it worth it, although it took time?	3	18	15

asked if the discussion was worthwhile, they all answered positively, with comments such as:

- Before, I was very much concerned by marks but later, little by little it became clear; you realize that it's much more important to have understood; critical sense: it's the most important thing, in my life.
- It's always interesting to have exercises like that; sure, explanations, you shouldn't give them thoughtlessly; you made me think; to me, even if it's difficult, it's fine to think . . .. We learn much more . . .. I have learnt a lot.
- It's much more interesting *(than doing classic exercises).*

Some students (7/15) expressed a feeling of frustration concerning the kind of teaching they had experienced before:

- One day I will do research, then I'll look back, I'll find a hypothesis that . . ., in the exercise it's wrong, therefore in the past I founded myself on a mistake.
- Why is it the first time someone tells me this?

One student's remark appears as especially relevant to the question of our teaching objectives:

- *(Is such a discussion more interesting than doing the classical exercise?)* absolutely . . . provided we are taught how to do it.

Finally, the students' concluding comments were often very gratifying for the interviewer:

- Have you got anything else like that?

In addition, 21 degree students were collectively asked their reactions after a similar session. As shown in table 2, the great majority declared, on explicit questioning, that they had got *pleasure* in understanding the point addressed and that the session was worth the cost in time.

The same consultation was organized for a group of in-service trainee teachers. Fifteen upper secondary school teachers of maths and science attended a session about modelling and the relationship between mathematics and physics. Only four of them were physicists. They were presented with the topic of hot air balloons (half an hour); many of them were unfamiliar with this theme. The usual version of the exercise was first proposed, with no reaction on their part, then the more complete discussion outlined in figure 5 was proposed. Finally they were asked to express their reactions with a short paper-and-pencil questionnaire. The results show that they all considered the discussion worth it for themselves personally (rated 3 or 4 on a scale of 1 to 4), but were less confident that this would be the case for students in their last year at school. Answering the questionnaire after a discussion, they suggested a distinction be made, concerning these students, between two possible teaching goals: on the one hand, having a proper idea of what physics is, and on the other, understanding how a hot air balloon works. They proved more ready to take the time needed with the first of these goals in mind than with the second (6/15 against 2/15 ratings 3 or 4—on a scale of 1 to 4). Broadly, most of them thought that what had been good for them would not really be accessible to or profitable for students at grade 12 (age 17).

This is not the first time we have found that teachers (or older students) will agree on the value for themselves of an approach which they deny is possible or useful for younger students, this even in cases where there is evidence that the young students are quite comfortable with the suggested approach ([2], p 62; [11], p 176; [14]).

Concluding remarks

These results make less plausible the common remark that 'the students lack critical sense'. True, none of the students consulted detected the problem with assuming uniform pressure in a hot air balloon, for instance. But no teacher did, either. Long-established rituals seem to block both students' and teachers' spontaneous critical reflection. Similar issues have been shown to arise in physics teaching at secondary school level (see for example [11]).

The reasons why such rituals are so resistant to change are multiple. They fit in with the main trends of common reasoning in physics, such as thinking of concepts as if they were ordinary objects (e.g. rays, shadows, an image). They may also be seen as reflecting what are called 'common transforming trends' in the STTIS project (Science Teacher Training in an Information Society, coordinated by R Pinto). For instance, amongst the findings of this project [4], an item such as 'observation is valued at the expense of explanation' is more than compatible with the kind of reasoning just mentioned—if a concept is like an ordinary object, why not show it? Another item—'a one-to-one linkage between a given device and a given didactic approach is observed'—perfectly applies to the case of the optical bench and the ritual focusing on construction rays, both favourable to inducing the travelling image syndrome. As for 'the quasi-general lack of consideration of links', it is easy to see that this tendency does not help one criticize overselective approaches (for instance: only global). Thus the main question is not so much one of finding *the* origin of these and other rituals but rather of finding a way out of so many opposing factors.

What could help teachers to choose more consciously what they do in teaching? Several factors might contribute to this goal.

One is linked to teacher training. Here it has repeatedly been found that teachers often ignore or bypass critical details in a novel teaching sequence, reverting instead to customary ways. This means that, important as they are, really good ideas for teaching physics are not at all sufficient. There is a need to include in teacher training sessions a good deal of very specific work on links between big ideas about the teaching and learning process, the overall rationale of a given teaching suggestion and the link to very particular details of teaching practice. Without such close attention to structure and detail, important general ideas only play the role of slogans, decoupled from practice, in which case critical details end up surreptitiously determining the actual teaching outcome [1]. However, training is not sufficient either.

Teachers can betray a strong pessimism concerning their students' abilities. As we have sometimes heard them say, an enlightening viewpoint would be 'good for us *(teachers)* but not for them *(their students)*', a fact sometimes in contradiction with experimental results. If teachers do not believe it possible, it is easy to predict that, excellently trained as they may be, they will not even try to raise the intellectual satisfaction of their students by the means discussed here.

How can we increase teachers' optimism? It is plausible that providing them with the kind of replicable evaluation outlined above, concerning lenses, might be of interest. Trainees who participated in this comparative test were very impressed by the result. But such a demonstration is rarely accessible [11]. For the rest, there is little hope for them to be convinced without trying, and that in turn means that they have found some time for this activity and have forgotten for a moment the usual stresses on them.

In a more coercive register, a third component is the type of assessment for which students must be prepared. Thus, a recent investigation concerning the French baccalaureat [15] shows that *not a single question* in two years (1999 and 2000) asked for a result to be criticized: this sheds a very special light on recurrent incantations about 'lack of critical sense'. Probably, there would be more effective incentives for assessment to do a better job if good examples of *precise* wording for this type of question were readily available.

Students, for their part, when offered an opportunity to think more deeply about the familiar situations mentioned above, appeared to react very positively. Most probably, their satisfaction has not much to do with the topic in itself, but seems to come from the feeling that they can master a point. So it is not so unrealistic to aim to raise intellectual satisfaction through this type of approach, always of course in line with the student's comment: 'provided we are taught how to do it'.

There exist many proposals for the urgent task of developing scientific culture and motivation for science among young people and for attracting more of them into scientific studies: for example, showing that science has a connection with topics from everyday life, health, and the environment; stimulating intellectual excitement through topics such as the expansion of the universe or the birth and death of stars; and broadening interest through the history of science.

Without denying the importance of these themes, I have tried here to suggest a kind of change that is within our grasp without any large scale change in the curriculum. It is to focus, through careful and detailed improvement of the teaching of often very mundane topics, on increasing students' intellectual satisfaction with what they learn, through attention to consistency and power of argument. And I want to claim, too, that this is also a crucial aspect of providing learners with a proper idea of what science is. Our research so far suggests that it is possible, and is appreciated by students—but that success requires a lot of hard, patient and devoted work.

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