VIENNOT L. 2010. Physics education research and inquiry-based teaching: a question of didactical consistency, In K. Kortland (ed.): *Designing Theory-Based Teaching-Learning Sequences for Science Education.* Utrecht: Cdβ press, 37-54.

Physics Education Research and Inquiry-Based Teaching: a question of didactical consistency

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Introduction

The ideas on which Physics Education Research was founded during the 1980s were, by and large, very consensual. It was claimed that students should actively contribute to the construction of their understanding of physics. "Research-based-teaching-learning sequences", as they were labelled later (Méheut & Psillos 2004), were supposed to take into account students' previous ideas/knowledge/ways of reasoning in order to encourage their active involvement in learning. Indeed, and this was perhaps the most striking point of convergence, the goal was to have learners understand and learn some conceptual elements of a given targeted content.

Given the premises above, often referred to as "constructivist", a prototypical experimental activity was supposed to make ample room for the students' intellectual activity; therefore, a question was to be solved, taking into account the learners' prior expectations. In some cases, the emphasis on this aspect was reduced, but still with a particular stress on students's engagement, via a "problem posing approach" (Lijnse 1994, 1995, 2002). In any case, discussions were expected between the students and/or between the students and the teacher (or a "mediator"), and any possible conflict between what was expected and what had been observed was supposed to be negotiated.

Some *caveats* were soon formulated by researchers in this domain. A very explicit one was enunciated by Millar: "The constructivist model of learning does not carry any necessary message about models of instruction" (Millar 1989, 589). Moreover, Lijnse (ibid.) rather radically claimed that a model of instruction was not sufficient to inform the design of what he thought was needed: "a didactical structure". Both authors insisted on the necessity of conducting a sound content analysis of the targeted content. Several books (e.g. Fensham *et al.* 1994) also contributed to disseminating this idea. Among the other essential ideas emerging at that time was that "a didactical structure", or any teaching learning sequence, should be designed and evaluated at the *micro level* (Millar 1989, Lijnse 1994, 1995), on the basis of a fine grained analysis of the planned teaching strategies. The label "critical detail" used later (Viennot *et al.* 2004, Viennot & Kaminski 2006) was just another way of underlining this idea: the devil – and not only him - is in the details. In parallel, it was acknowledged that initial views on conceptual change (Posner *et al.* 1982) had to be reconsidered. Indeed, a "cognitive conflict" supposedly organised by the designer of a sequence did not necessarily arise in learners, and a term-to-term substitution of ideas could not be realistically expected (see for instance Duit 1999).

In any case, the goal was that students should gradually reach a view that was compatible with accepted physics, and/or formulate new questions. A quote by McDermott in the preamble to the booklet *Physics by Inquiry (1)* is very explicit: "All the modules have been explicitly designed to develop scientific reasoning skills and to provide practice in relating scientific concepts, representations, and models to real world phenomena" (McDermott 1996). A comment by this pioneer of what is now called Inquiry Based Science Education (IBSE in the following) leaves no doubt: "Too often, the quality of instruction is judged on the basis of student and teacher enthusiasm, this is not valid indicator" (McDermott 1998). This author was not aiming *first* at students' motivation and engagement with science but at improved understanding of scientific ideas.

The present situation seems somewhat different if judged through a series of more or less official reports and loudly-stated claims about the teaching of science particularly to a young and/or non specialist audiences. For example, the Nobel laureate Georges Charpak, commenting on the movement "La Main à la Pâte", pleaded for a strategy "(…) showing that, without lowering the level, we can have fun with science" (Charpak 2005). We can also read in a report to the Nuffield Foundation that "The emphasis in science education before 14 should be on engaging students with science and scientific phenomena" (Osborne and Dillon 2008). A report to the European Community by a group chaired by Michel Rocard, formerly Prime Minister in France, praised "… a pedagogy using an inquiry-based approach that succeeds to develop excitement about science" (Rocard 2007, p. 16). In these years of declining student numbers, numerous militant articles echo this call for excitement and engagement with science. Clearly, engagement with science is at the front of the stage, even if it is more or less explicitly assumed that a certain understanding of scientific methods, and possibly of concepts, with necessarily follow, as suggested by this type of comment: "IBSE has proved its efficacy at both primary and secondary levels in increasing children's and students' interest and attainment levels (…)" (Rocard, ibid., p. 3).

Given this contrast between the initial approach of Physics Education Research (PER), firmly orientated towards conceptual development, and a recent movement toward IBSE, at least in those versions which emphasise only excitement and interest and say almost nothing about concept learning, we might pose explicitly the question suggested by Figure 1: Is there an incompatibility between an appealing presentation of physics and a recognition of its theoretical essence, as though we had cautiously to keep hidden this formal aspect? Can we hope to engage youngsters with physics whilst denying the very nature of the subject: a set of models and theories with remarkable predictive power, internal consistency and elegant parsimony, as recently underlined by Ogborn (1997, 2009)?

As acknowledged above, some pleas for IBSE may suggest, even if this is not explicitly stated, that there is an unquestionable link between these two poles. On the other hand, some authors take more extreme positions, such as Nillsen (2009) who expresses his concern about contemporary trends that he thinks neglect conceptual aspects: “*if the primary objective is to make students “feel good” about themselves, then it is unreasonable to expect them to learn very much.”* (p. 5). Do we really need to see this kind of intrinsic incompatibility between pleasure and a first access to a conceptual activity?

Distancing itself from such an extreme view, this chapter will discuss the following question: Given what we know from PER, how might we go about maximising the learning benefits of IBSE in terms of conceptual attainments, whilst keeping its motivational potential? To this end, a series of examples will be presented and discussed. They concern some simple experimental settings that typically constitute a starting point for IBSE activities in physics.

Discussing experts’ practices

When considering an experimental setting classically used, it is worth keeping a sharp eye on some ritualistic practices. Some ways of acting, indeed, are much more often adopted than discussed, as if they were incontestable. It may happen that they go with regrettable limitations in terms of educative potential (Viennot 2009a, b). In such a case, we should go beyond being vigilant, and seek some alternatives to widen the range of benefits we can expect from them. This double approach – vigilance and reconstruction – may involve at least four components. Two of these are very classically considered in Physics Education Research, as already mentioned: a thorough content analysis, and a sound consideration of students’ common ideas and ways of reasoning. Here, two other components will be also considered. One is an analysis of experts common practices and the other is a search for alternatives designed in order to stress links. Indeed, as recently expressed by Kluvánek “a person understands some information available to him or her only if he or she grasps the connections, the relationships, between phenomena, concepts and ideas to which the information refers. It can be said that the understanding of information consists precisely in the grasping of such relations." (quoted by Nillsen 2009). This goal is consistent with that of having learners grasp a first idea of the nature of physics.

Two examples in fluid statics

The inverted glass of water

Figure 2a shows a very simple experiment often associated with the role of atmospheric pressure (Viennot 2009a). A glass full of water is covered with a piece of cardboard and turned upside down, in a vertical position. The water stays in the glass, the cardboard apparently stuck below. Students commonly say that the cardboard does not fall down because the atmosphere “supports the water’s weight”. This explanation makes use of two relevant forces, but it suggests a Newtonian balance between them. In fact, the upward force on the cardboard is about a hundred times as large as the weight of the water. Therefore the above explanation is, at best, very incomplete, and at worst, quite misleading.

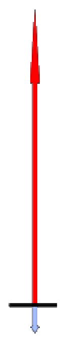
a	*b*	*c*
	Statements often found in common explanations : -The water exerts on the cardboard a force equal to its weight. -The force due to atmospheric pressure supports the carboard which (therefore) does not fall down.	A diagram that suggests the disproportion (in fact about x100) between the values of the forces mentioned in (*b*): Upwards: force due to atmospheric pressure on the cardboard Downwards: weight of water 

Figure 2. A simple experiment (*a*) that is often “explained” with problematic arguments (*b, c)*

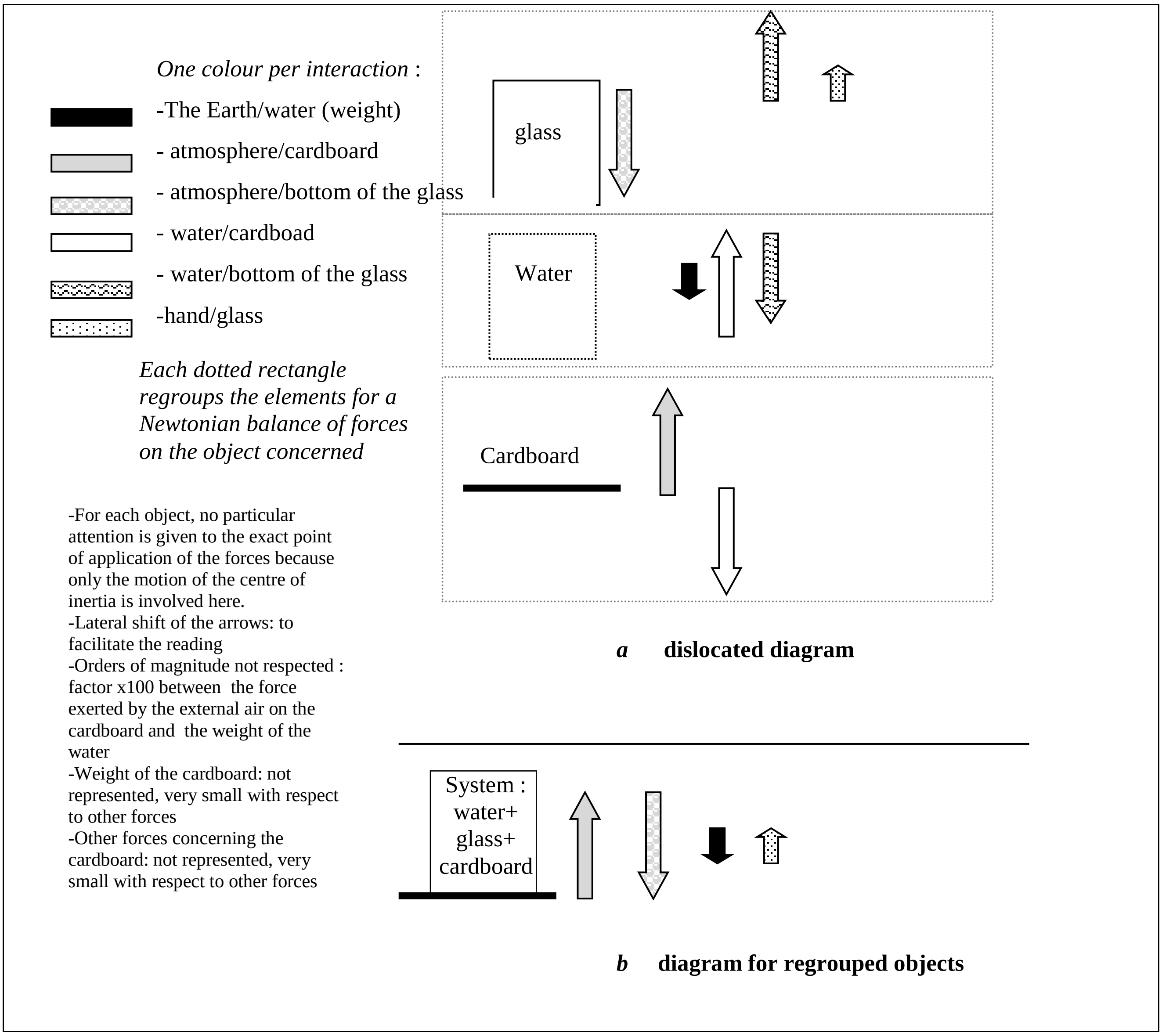


Figure 3. Main forces (vertical components) in the situation of the glass full of water held upside down (for more detail, see Weltin 1961, Viennot *et al.* 2009c): (a) shows an exploded view of the water-glass-cardboard system in which the arrows indicate the interaction forces, (b) shows the balance between the various forces acting on the system water+glass+cardboard.

Searching for the possible origin of this widely accepted explanation, we find several good candidates, of increasing range of application.

First, it seems as if the weight of a body, in this case the water, is thought to *always* “act” on the supporting surface, in this case the cardboard. In fact, the force exerted by the water on the cardboard is of the same order of magnitude as that exerted by the atmosphere on the cardboard (fig. 3), that is, about a hundred times greater than the weight of the water.

Second, we might also argue that Newton’s third law is disregarded in this explanation. Indeed, if we were to acknowledge that the cardboard necessarily exerts on the atmosphere a force equal and opposite to the large force exerted on the cardboard by the air, it would become difficult to explain how this might happen through the effect of just a small force exerted on the cardboard by the water.

Third, this very disregard of Newton's third law might be ascribed to an "Agent-Patient" scheme (Anderson 1986) which conceals the reverse force exerted by the "Patient", namely the cardboard, on the "Agent", i.e. the outer air.

Finally, we observe that the proposed explanation is focused on the cardboard, and does not take into account the other end of the system, i.e. the upper part of the glass. It is a local viewpoint, a feature very often observed in students' ways of reasoning.

So, four hypothetical origins of this expert explanation, all compatible, coincide with some very common aspects of learner's ways of reasoning. It is in that sense that the label "echo-explanation" is used in the following. An expert "echo-explanation" can hypothetically be ascribed to the same features of reasoning as those commonly observed in learners and possibly misleading as regards accepted physics. This label does not imply any particular causal relationship between what is commonly claimed, respectively, by experts and by non-specialists. It just designates a mutual resonance.

The test tube full of water over a tank of water

A second example is that of a test-tube full of water, held upside-down over a tank of water, the top of the tube being 2m above the level of the free surface of the tank (fig. 5). This situation is analogous to that of the inverted glass of water, because at the level of the free surface (i.e. at the bottom of the column of water) there is atmospheric pressure, as is the case at the level of the cardboard. As with the first example, the contact interaction between the glass and the water at the top of the tube involves large forces – corresponding here to four-fifths of the atmospheric pressure.

An expert explanation for this phenomenon was provided by Marie Curie. A book recently published presents notes taken by Isabelle Chavannes during lessons given in 1907 by Marie Curie to a few of her friends' children (including Isabelle). Referring to the setting shown in Figure 7, Isabelle Chavannes reported Marie Curie's words: "*What is raising this column of water up to 2m ? It's the atmospheric pressure that is pushing on the water in the tank. In the tube, there is no air, and no pressure is exerted on the water* " (Chavannes 1907).

With this comment, we are very close to the common and problematic explanation of the inverted glass discussed above. A column of water is said to be raised by atmospheric pressure (the active agent?), and this suggests an (unbalanced) equilibrium between two forces, given that it is (erroneously) claimed that there is nothing else acting on the water at the top of the column of liquid. This expert explanation echoes, term for term, the explanation of ordinary learners.

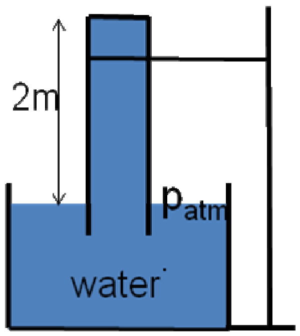
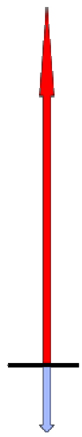
a) A test-tube filled with water, above a tank of water.	**b) A questionable explanation**	**c) Considering orders of magnitude**
	"What is lifting this column of water up by 2m ? It's atmospheric pressure that is pushing on the water in the tank. In the tube, there is no air, and no pressure is exerted on the water." * *Translated from an explanation by Marie Curie, ([22], 46)	Comparing orders of magnitude of the forces acting on the column of water that are mentionned in the explanation (col. b). 

Figure 5. A situation that can be analysed like the glass of water turned upside down (fig. 3, fig. 4): a test-tube full of water and turned upside down over a tank filled with water.

Suggesting alternatives

Once a common practice is analysed and some interpretative hypotheses are proposed, it is possible to design some different - complementary - ways of staging the simple device concerned. In the case of our first example, this can be done by changing the physical situation slightly. In order to avoid reinforcing the idea that the atmosphere is playing the role of a stand "supporting" the weight of the water, we can put the glass horizontally (fig. 6).

Figure 6. In a horizontal position, the water also does not flow out of the glass

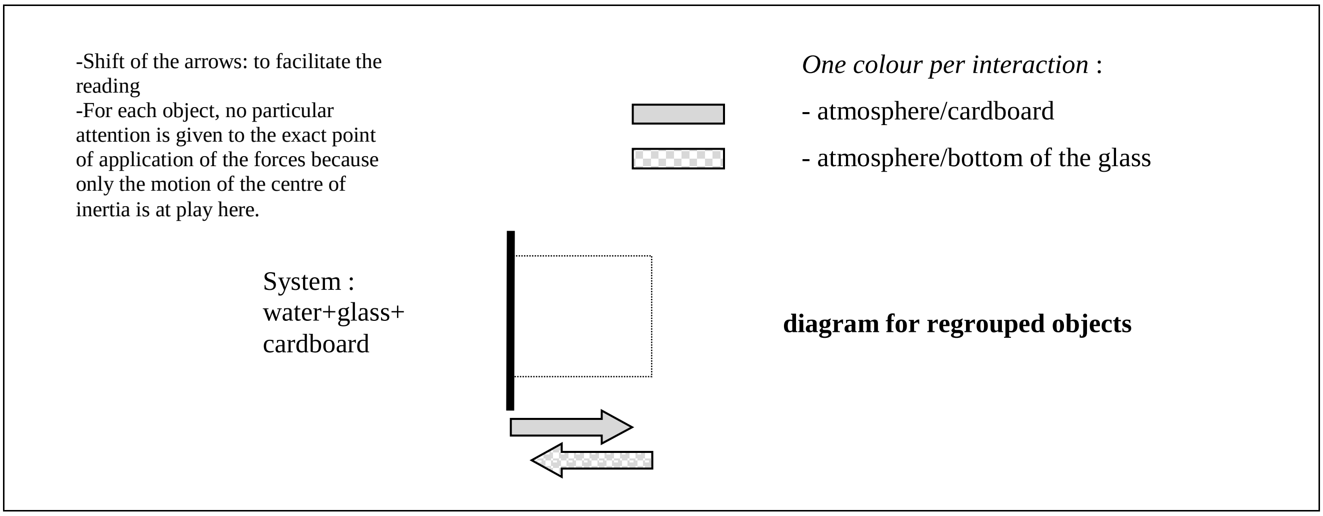


Figure 7. Main forces (horizontal components) acting on the glass of water in a horizontal position

Then, a simple analysis of the horizontal components of the main forces (fig. 7) leads to a more symmetrical view, which is systemic and involves both ends of the glass. The atmosphere appears as playing the role of a press rather than that of a stand. It is likely that the learning outcomes would be different, or at least that the conceptual obstacles would not be the same.

The second example does not lend itself to that kind of change, as the test tube cannot be put horizontally. But it is still very relevant to focus on the systemic aspect. As in the case of the inverted glass, both ends of the column of water deserve attention. Indeed, at the top of this column, the interaction between the water and the glass is equivalent to that generated by four fifths of atmospheric pressure. Stressing the links between the two situations, inverted glass or test tube, is likely to lead to a better understanding of this idea. It is even possible to discuss what a Torricelli barometer is, and to underline that there is a very small interaction, in this case, between mercury vapour and the top of the tube ($\approx 2.10^{-1}$ Pa). By stressing similarities and differences, via a systemic analysis, an investigation of an inverted glass, an inverted test tube and a barometer gives access to a rich and consistent conceptual content.

Similarities and differences: going further with familiar experiments about fields

The next example illustrates a particularly big gap between a targeted conceptual content and the relatively simple messages conveyed – at first sight – by the experimental facts in play. It is commonplace to use iron filings in order to show the action of a magnet in the space around. Faraday (1852) called the lines that can be drawn at a tangent to these iron filings “lines of force”, and advised us "(...) to consider magnetic power as represented by lines of force", given that "the lines of force, well represent the "nature", "condition", "direction", and "amount" of the magnetic forces".

A first way to widen the conceptual content related to this kind of experiment is to demonstrate its three dimensional aspect, using a device like that shown in Figure 8.

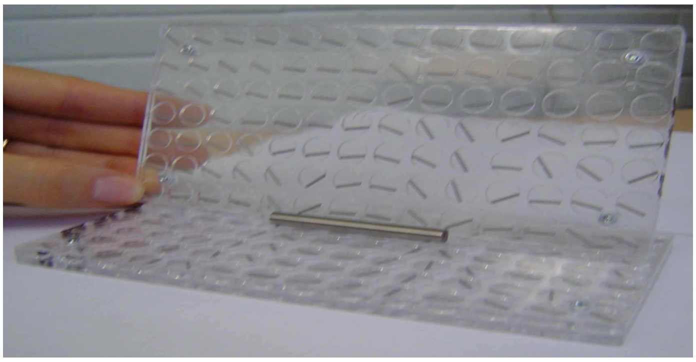


Figure 8. Demonstrating the three dimensional influence of a magnet

In a teaching-learning sequence tested experimentally at grade 4 and 5 levels (Bradamante & Viennot 2007), this is just a first step. This sequence was designed to stress the similarities and differences between gravitational and magnetic fields. Although this target may seem excessively ambitious for children aged 10-11, it was considered worth investigating, in particular because it is well known that pupils tend to ascribe the Earth's gravitational action to the fact that this planet is a magnet (see for instance Arnold *et al.* 1995, Bar *et al.* 1994, Nussbaum 1985).

The authors of the teaching-learning sequence hypothesized that, for children, geometrical aspects were very salient (Saltiel and Malgrange 1980) and, hence, that what we prefer to call 'lines of fields' might be an appropriate entry point for comparing gravitational and magnetic fields. The idea of "mapping" the influence of the Earth and of a magnet in the region surrounding them was central to the sequence. Figure 9 shows how a child in grade 5 represented some gravitational detectors – in fact, balloons attached to a tree by a string, or pendulums – all around the Earth.

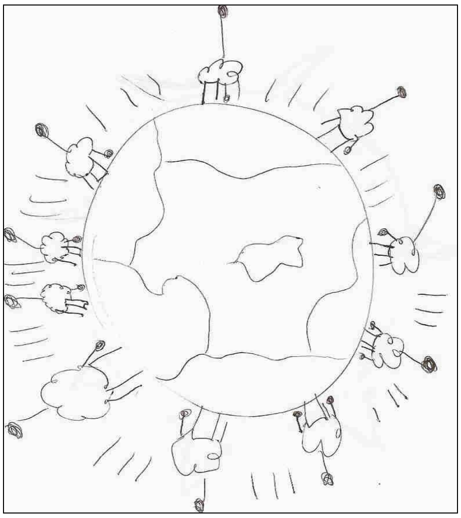


Figure 9. Drawing by a child in grade 5 (aged 11), showing the positions of pendulums and balloons attached to a tree, around the Earth.

This idea of a mapping, introduced by the designers of the teaching-learning sequence, was seemingly well accepted, and some pupils were subsequently able to produce some drawings like in Figure 10, to compare the “maps” representing the influence of each object

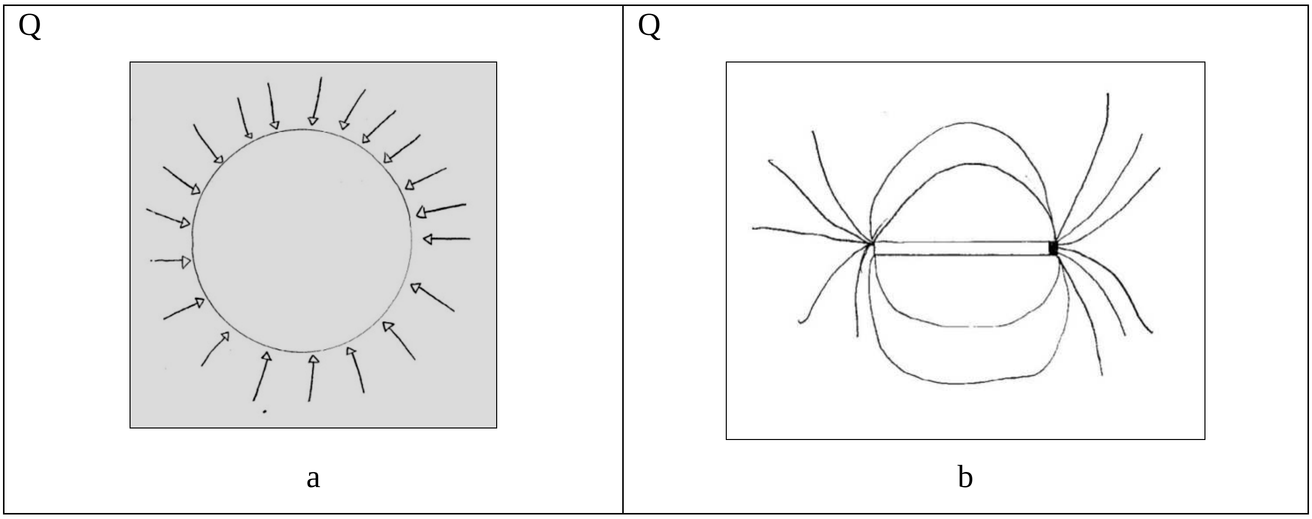


Figure 10. A drawing by a child aged 11 to compare the “maps” corresponding to the Earth (a) and to a magnet (b).

But it was also observed, particularly in the final test (fig. 11), that a different mapping for the Earth and for a magnet was not enough to have the children fully accept that the two phenomena were really different. Despite the recognition that the maps were different, some children also claimed that there was a similarity, and drew some lines heading for the centre of each of the objects considered, with comments like: “It heads for the Earth” (11 years old).

Are there any similarities ? *Yes*
If so, which one(s) ?
Explain: *It heads for the Earth*

Are there any differences ? *Yes*
If so, which one(s) ?
Explain

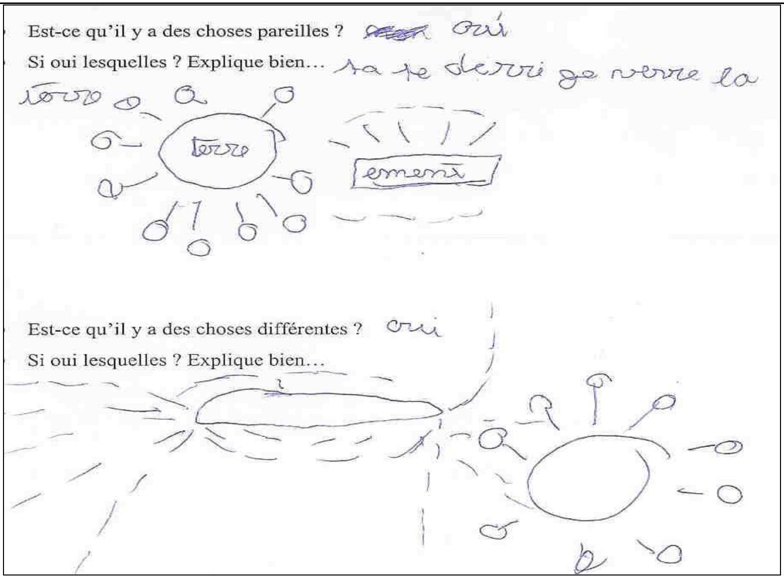


Figure 11. Comparing the influence of the Earth and of a magnet: response of a child aged 11 in the final test.

This final state of affairs echoes some responses given earlier in the course of the teaching-learning sequence, when children were asked to predict the position of a small compass placed on a map of field lines drawn around a magnet. Table 1 shows that a noticeable proportion of pupils, in the two age groups, drew a the compass pointing towards the centre of the magnet.

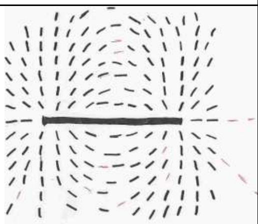
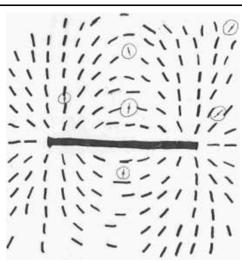
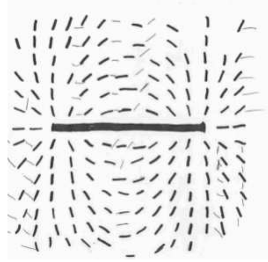
	Correct	Mixed Correct near the ends of the magnet, toward the « middle » on the transverse plane of symmetry	Mixed (other) Correct near the ends of the magnet some “erect” needles elsewhere
			
G1 N_1=17	4	4	9
G2 N_2=16	7	5	4

Table 1: Interpolation of magnetic interaction: drawings of compass needles near a magnet by children in grade 4 (aged 10, *G1*) and 5 (aged 11, *G2*).

Clearly, the idea of mere attraction remained prevalent among these pupils.

This investigation thus underlined some facts that may remain disregarded in a more ritualistic introduction of magnetism. For instance, it is common to say that a magnet attracts ferromagnetic materials, and attract or repels other magnets. Such statements, although correct, do not facilitate the comprehension of the fact that two phenomena may occur at the same time: global attraction (or repulsion) *and* orientation (fig. 12).

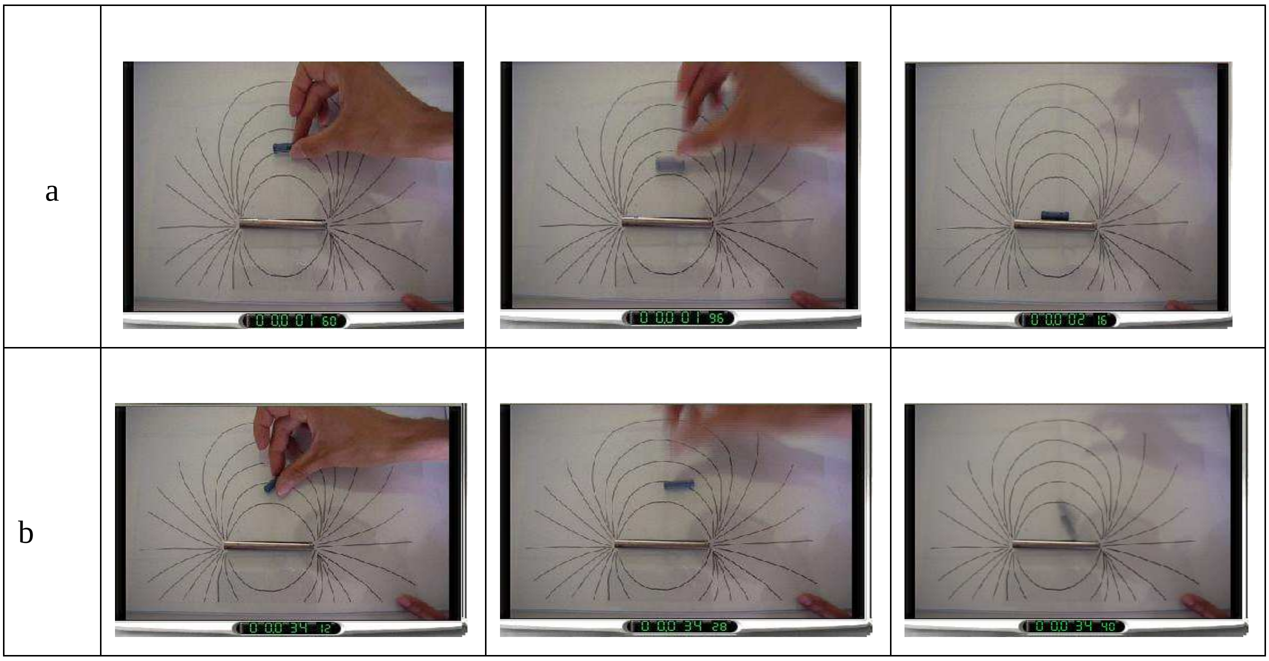


Figure 12. Two situations of interaction between two magnets: global attraction without rotation (a), simultaneous evidence of attraction and orientation (b). Video: F. Bradamante.

Moreover, what is directly linked to Faraday's "lines of force" - now called "field lines" - is not a force, but rather the orientation taken by a magnetic dipole placed on the line. It seems appropriate to stress that these lines are really"lines of orientation".

In brief, with this sequence, we have an example of considerable conceptual added value for a very modest and commonplace experimental starting point: iron fillings oriented by a magnet and a thought experiment with pendulums around the Earth. A preliminary condition for such a conceptual ambition is to distance oneself somewhat from comments that ritualistically accompany some simple experiments and directly echo what a child would spontaneously say.

Here, a very specific spotlighting of the content, i.e. the central role of mapping, made it possible to analyse similarities and differences between two fields, thus pinpointing, ultimately, the distinction between unipolar (central) and dipolar fields. Stressing links, or equivalently differences, opens wider the conceptual space that is potentially accessible on the basis of a simply experiment, provided that the limits of some common practices are recognized and analysed.

The two last examples are intended to buttress once more this idea. In order to better understand their relationship with the idea of echo-explanation, it is necessary to bear in mind the main features of a common way of thinking in science: linear causal reasoning.

Linear causal reasoning

Linear causal reasoning is of particular interest in that it is in stark contrast with some models commonly used in accepted physics, and particularly in elementary physics.

Consider a system comprising several objects, say two springs suspended end to end from a stand and extended by an experimenter (fig. 13), or a series circuit with two resistors and a battery, or two cylindrical vessels filled with gas and separated by a mobile piston. Such systems can be described with several variables that are constrained by simple relationships. Thus, the forces exerted by the two springs on each other are equal to that exerted by the experimenter on the lower end of the lower spring. This relationship implies a situation of mechanical equilibrium at every point in time, the same time argument being ascribed to every specific value of the quantities concerned. In other words, all the parts of the combined system are assumed to "know" all the other parts *instantaneously*, during the – *quasi-static* – evolution of this system. Thus, if the lower end is pulled by an experimenter, the relationship above is assumed to hold at any instant. This is far from obvious. In the case of an earthquake, for instance, this model would not be appropriate for analysing the changes that affect two contiguous parts of a continent. It would have to be changed to a *propagative* model. In passing, we note that it is more common to discuss the relevance of a quasi-static model in thermodynamics than in mechanics.

The simultaneous evolution of all the parts of a system is far from intuitively clear. Common ways to deny such a strange hypothesis take the form of the following prototypical comment (Fauconnet 1981: 111; Viennot 2001: 98) "The first spring will extend then, after a while, the second will also extend". Such a comment is suggests the event is seen as 'a story', rather than as simultaneous changes in several variables permanently constrained by the same relationships. Simple events (φ_n), most often specified through only one variable, are envisaged as a series of binary cause-effect links: $\varphi_1 \rightarrow \varphi_2 \rightarrow \varphi_3 \rightarrow (\ldots) \rightarrow \varphi_n$. (Rozier & Viennot 1991, Viennot 2001: chap. 5). The arrow used in the preceding symbolic form is often expressed in words using the adverb "then". This is an intermediate term between the expression of a logical link ("therefore") and a temporal succession ("later"). We can find the same type of ambiguous term in many other languages as well; for instance “alors” in French or “entonces” in Spanish. More or less surreptitiously, common explanations are steeped in time.

Figure 13 outlines the term-to-term opposition that exists between the linear common reasoning and a quasi-static, or quasi-stationary, analysis of a systemic change. Not only do these two different approaches differ in their wording, the corresponding solutions for a given question are also different. For instance, the lengthening of the upper spring for a given total extension can be found to be too large by a student who proceeds as follows: first consider the extension of the lower spring as equal to the displacement of the lower point, then calculate the corresponding force, then apply this force to the upper spring, then calculate the corresponding extension.

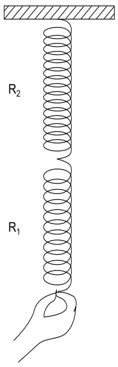
In quasi-static physics	An example	**Linear causal stories**
- several variables - simultaneously changing - constrained by permanent relationships		- simple phenomena (one variable each) - seen as successive (hence as) - temporary
$\mathbf{F}_{ext}$ (t) = $\mathbf{T}_1$ (same t) = $\mathbf{T}_2$ (same t) Δl_T (t) = Δl_1 (same t) + Δl_2 (same t) $\mathbf{F}_{ext}$: Force exerted by an experimenter on the lower end ; $\mathbf{T}_1$, $\mathbf{T}_2$: tensions of each spring; Δl_1, Δl_2 : extensions of each spring, Δl_T total extension.		*A symptomatic comment:* “The first spring will extend then, after a while, the second will also extend.”

Figure 13. The main features of linear causal reasoning, compared to those of a quasi-static analysis.

Expert explanations that echo linear causal reasoning

As already pinpointed by Rozier and Viennot (1991, see also Viennot 2001: chap. 5), some expert explanations seem also to be framed by linear causal reasoning, a tendency that can be particularly perpetrated by authors of science popularizations. The following example, in line with the theme of this paper, is about a simple experiment: a siphoning process (Figure 14).

An explanation, again given by Marie Curie (Chavannes 1907: 62), makes use of the following argument. *The water in the long branch of the siphon flows out. A vacuum is created, and the atmospheric pressure pushes the water of the tank up the short branch.*

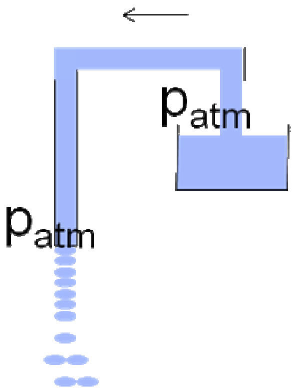


Figure 14. A siphoning process.

Using the schematic presentation above, we might paraphrase this explanation as follows:

φ_1 (left end of the tube, on fig. 14): *The water in the long branch of the siphon flows out* → φ_2 (somewhere in the tube) *A vacuum is created* → φ_3 (right end of the tube on fig. 14) *the atmospheric pressure pushes the water in the tank up the small branch*.

Simple events are envisaged successively, if only temporarily (for instance: "the vacuum"), as though in chronological succession. In particular, this would seem to suggest that it is possible to analyse what happens at one end of the system independently of what happens at the other.

There is one clear problem: The role of the atmosphere is called on for the last link of the explanation, which concerns one end, but there is atmospheric pressure at the other end as well.

The adjectives "long" and "short" constitute a clue which discretely points towards the crucial role of a difference. Most probably, this clue is not sufficient for learners who do not already know how to analyse this system. It might well be thought, for instance, that the water flows out of "the long pipe" simply because its lower end is open. The resonance between this explanation and linear causal reasoning, clearly, may result in improper interpretations.

Stressing links … and the decisive role of some differences

Analysing the possible risks associated with a simple experiment is an encouragement to choose its main teaching goal more explicitly. Thus, still using the same device, it may be decided to stress the systemic aspect of a siphon. To this end, the students can be first presented with a system analogous to that shown in Figure 14 but with a mask hiding the right-hand side (fig. 15a); the student could be asked to predict: What would happen if the lower end of the left-hand branch, initially blocked, were freed? Once performed, the experiment would confirm what is commonly expected: the water in the left-hand branch flows out. When the mask is taken off (fig. 15b), the students can see that the vessel empties, which is the usual goal of a siphoning process. But the experiment could also be performed for a different outcome. Behind the mask, and with exactly the same visible part on the left, it is possible to place the tank of water such that its free surface is *lower* than the end of the left-hand branch (fig.15c). Then, when the left-hand end of the tube is opened, the water does not flow out. Instead, the water rises up the tube and refills the tank.

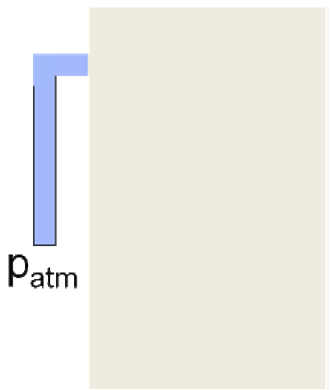
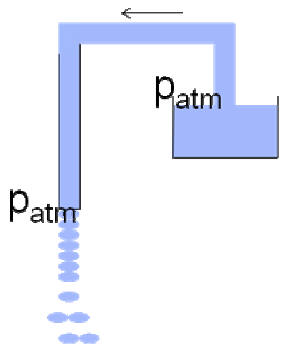
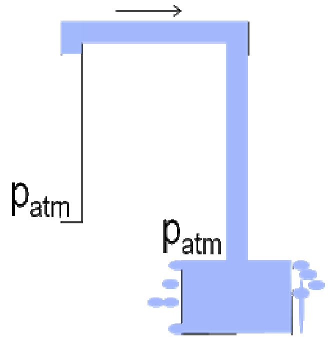
		
a What will happen when the left-hand branch is opened at its lower end? (Right-hand part of the system: hidden)	b A case currently explained by experts (e.g. Marie Curie: Chavannes 1907)	c With the same left-hand branch, a different outcome is observed

Figure 15. Without considering both sides of a siphon, the outcome of the experiment cannot be predicted.

This is a striking illustration that, without seeing *both* ends of the system, it is impossible to predict what the water will do. This is the most important thing to be understood concerning a siphon. Beyond that, with a modest setting, and with an audience that is still at a low level of competence, it is possible to stress a crucial aspect of physical phenomena: the world runs on *differences* (Boohan and Ogborn 1997).

Keeping in mind this kind of a message – briefly put, the relevance of a systemic approach – the staging of other experiments can be re-orientated accordingly, as illustrated by the following example.

A “love-meter” is shown in Figure 16. Warming up the lower part with the hands results in a nice fountain effect, with the liquid partly filling in the upper part whilst its level decreases in the lower part. The usual explanation is that warming up the gas in the lower part increases the pressure there, which pushes the liquid up the tube joining the bottom of the lower part to the bottom of the upper part. Here, we recognize linear causal reasoning.

Figure 16. A “love-meter” with the classical staging.

In order to highlight the target idea more effectively, we could formulate the explanation more precisely, changing “the pressure increases in the lower part” to “the *difference* of pressure between the *two* parts is increased”, thus taking into account both parts of the system. With such a target in mind, it would become natural to complete the classical demonstration of the love-meter experiment with the following variation (fig. 17b): cooling down the upper bulb, for instance with cold water. The outcome is of course the same as with the usual version, which constitutes a rather striking effect.

a) Starting with the classical use of a love-meter … | b)…then cooling down the upper bulb with cold water

Figure 17. A staging of the demonstration that focuses on a systemic analysis

Among other activities, these two examples – siphon and love-meter – could be used to emphasise the consistency of physics and the power of its theoretical foundations: in this case the idea that the world runs on differences.

Final remarks

This paper is centred on the topic of simple experiments. This theme, in fact, served as a particular basis to illustrate more general ideas. The first – a condition for the relevance of the others – is that even with severe teaching constraints, there are some open choices and levers for targeted actions. Some apparently minor changes in ritualistic practices may bring out important outcomes. These "critical details" of practice, when orientated by a sound analysis of the content and a sufficient knowledge of students' common ideas and ways of reasoning, open up a range of different targets. Being vigilant about our own explanations, which may in fact mirror some problematic features of common reasoning, is a preliminary condition. Among the possible goals that might influence what we choose to spotlight in exploring any given content is that of stressing conceptual links, thus highlighting how consistent, predictive and concise physical theories may be, in specified domains of validity.

A few questions might be posed in this respect, some of them rather pragmatic.

First, are suggestions of the kind made in this paper realistic, or is it inspired by an elitist perspective?

In terms of cost in time and money, the examples outlined in this chapter provide a clear answer.

It is not more expensive to put a glass of water in a horizontal position than in a vertical one; pouring some cold water on top of a love-meter is not much more complicated than warming up its lower bulb. Similarly, staging the siphon as suggested is by no means a difficult enterprise.

This said, the fit between the audience and the complexity of the targeted concepts is, of course, to be discussed and iteratively evaluated and adjusted. This is typically what Physics Education Research has, over a long period, been engaged in doing. For example, as discussed above, the attempt to link the gravitational and magnetic interactions structurally to some geometrical features – the corresponding field lines – is probably better adapted to students slightly older than those involved in the experimentation outlined above.

As regards teachers, a crucial question is: How they can appropriate ideas and suggestions of the kind advocated here? This question is a recurrent one which concerns any innovation. The STTIS project (Pinto *et al.* 2001) for instance, or the Leeds group (Leach & Scott 2002, 2003), among others, have underlined how complex this question may be and searched for ways to deal with it. The mere dissemination of descriptions of "good practices", despite its obvious attractions, is probably insufficient. The very notion of "a good practice" *per se* is questionable, as the particular history and context of a class may strongly determine the choices that are *a priori* the most appropriate.

It might be more profitable for teachers to be provided with some means of consciously reflecting on and making their own choices. For a given well-specified spotlighting of a content, a material setting and a particular staging can be suggested, along with the reasons for using them. Possible links – between concepts and/or between phenomena - can be suggested, and again well justified. Ideally, variants might be proposed, that may focus on such and such an aspect of a phenomenon, this focus resulting from the factors that are to be made explicit.

This suggestion is in line with a view of teacher training previously advocated. Viennot *et al.* (2004) argue that "what should be aimed at in such training, we think, is an ability to link *any* global rationale to precise details of practice." In such "a problem posing approach" (Lijnse 1994-5), the target is to maximise didactical consistency between a global view on what students should understand and some particular teaching strategies. Although illustrated here at small scale, i.e. with simple experiments, the teachers' productions in such a training programme, or the suggestions made to improve science teaching (see for instance MUSE: Planinsic *et al.* 2009), could be described, in Lijnse's words, as "well motivated possible routes to solutions of didactical problems." (Lijnse 2002: 323).

At least we can say that it is not advisable to overrate a particular "method" in itself, and still less, the merits of surprising experiments, if they dispense with these necessities: a critical distance as regards teaching rituals, a serious consideration of the consistency of physics and of students' views, and a thorough discussion of the specific way of spotlighting the taught content that is adopted. All are necessities that have been, to the utmost, stressed by Piet Lijnse.

Acknowledgment

(save if done at the beginning of the book, for all the papers: please, decide the appropriate wording)

The great help received from Robin Millar and J. Kortland in editing this paper is gratefully acknowledged.

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