The many challenges of Inquiry Based Science Education: Toward multiple learning benefits?

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Given what we know from physics education research, how might we go about maximising the learning benefits of Inquiry Based Science Education (IBSE) in terms of conceptual attainments, whilst keeping its motivational potential? To document this question, a series of examples are presented and discussed. They concern some simple experimental settings that typically constitute a starting point for IBSE activities in physics. They illustrate both some potential obstacles to a fruitful use of inquiry based teaching and some alternatives to ritualistic teaching practices. Such rituals are shown to originate in a teacher tendency to put students' common ways of reasoning in resonance, using what is called here an 'echo-explanation'. In order to overcome the corresponding drawbacks, it is advocated to favour conceptual links in students. This plea relies in particular on the first evaluation conducted on a large recent IBSE project. It is associated with several concluding questions, especially that of how to manage the necessary transitions between teaching mainly relying on IBSE and a more conceptually organized strategy.

Introduction

It has often been argued that using what is now called Inquiry Based Science Education (IBSE in the following) can improve children's and students' interest in science. This view underpins some strategies that aim to promote physics in formal or informal contexts and to influence young people in their professional orientation. Such a practice may be seen as a good way to show children or older students how science works, by placing them in a context in which they can be active. This view is widely shared among researchers in physics education research and is agreed on by many academic authorities. Reports from various institutions or groups of experts (e.g. Rocard *et al.* 2007, Osborne & Dillon 2008) echo each other impressively. The "existing success" (Léna 2009a) of such a method seems an incitement to dissemination. The comments advocating this approach mention a variety of expected benefits, ranging from students' engagement with science to the development of their critical sense and responsible citizenship. Concerning learning benefits, it is not suggested that these will be less than with more traditional teaching. As claimed for instance in the report by Rocard *et al.* (2007), higher attainments levels seem to be, for many authors, an expected outcome of the recommended approach.

Given this impressive unanimity, it might be useful to examine carefully these optimistic claims, in order to discuss how to maximize the chances of success of this movement.

Some caveats

Being not a new idea, the inquiry based method – broadly speaking – has long been the target of caveats. A figure (fig. 1) in a paper by Euler (2004, 193) encapsulates the essential of this question by displaying a structural loop: you understand what you see, you see what you understand. "In creating new knowledge", Euler adds, "experimental evidence is only a piece of a puzzle, a step in a longer process, and very probably not even the decisive step".

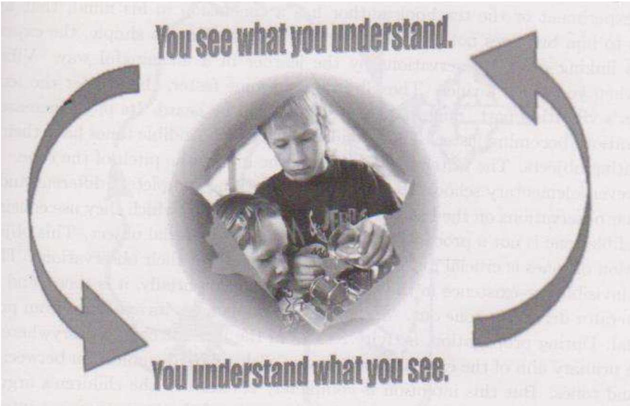


Figure 1. A figure by Euler (2004), in support to his plea for a cautious use of experiments in teaching.

Some of these long claimed caveats were very general, but they strongly resonate in the present context: « The constructivist model of learning does not carry any necessary message about models of instruction » (Millar 1989, 589); « Too often, the quality of instruction is judged on the basis of student and teacher enthusiasm, this is not valid indicator . » (McDermott 1978). There was an emphasis on the fact that any teaching method was ineffective without a thorough consideration of the taught content. (Lijnse 1994, 1995, 2002; Fensham *et al.* 1993), a viewpoint that is constitutive of what is called in Europe "didactics of" , say, "physics". Correspondingly, several authors stressed the necessity that a teaching sequence be designed and evaluated at the *micro level* (Millar 1989 ; Lijnse ibid.). Finally, the promoters of recent "inquiry based" attempts at improving science education were themselves aware that there had been, « Along the 60s-70s, (…), an impressive number of reforms that all failed » (Charpak 1996, *in French*, p. 9).

All these caveats, as it seems, are rather consensually accepted, at least are they not explicitly denied in the contemporary pleas for IBSE. This paper intends to contribute to a reflection about this question: how to conciliate that awareness and the loud stated claims concerning the expectable benefits of such an approach to teaching science? In particular, can we hope to have students more "excited", more "engaged with physics" and, at the same time, have them significantly understand what we intend them to learn? Can we do better than providing learners with a scattered set of exciting teaching sessions? Can we conduct them to a view of science as a widely unified description of the material world, constructed on the basis of parsimonious and predictive theories?

Taking the challenge

The perspective of this paper is to discuss how to conciliate students' excitement and their conceptual structuring. The latter component, indeed, is no less constitutive of science that the former one, and it refers to 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).

How can we manage such a challenge, in the frame of IBSE?

A now classical approach to IBSE is the following. IBSE is meant to make ample room for the students' own intellectual activity. Therefore a question is to be solved, taking into account the learners' prior expectations. When the question refers to a phenomenon that can be practically illustrated on a small scale, an experiment is designed and carried out. Expectations on the outcomes of the experiment should be formulated and explicitly justified, in order to generate and fuel a discussion between students and/or between the students and the teacher. Once the experiment has been carried out, any conflict between what was expected and what has been observed should be negotiated. The goal is that learners should gradually reach a view that is compatible with accepted physics, and/or formulate a new question.

As recalled in introduction, these views are widely consensual nowadays. In principle, they are compatible with the various goals assigned to this type of teaching, in particular with student conceptual structuring. It might well be, however, that a predominant use of that strategy does not particularly foster an organized understanding of the taught concepts. We can search to overcome some expectable limitations in this respect. For the sake of brevity, this question will be envisaged here with a discussion focused on learners, leaving aside, though essential it may be, what concerns teachers and teacher trainers (see a few remarks in Appendix 1).

Some possible obstacles to learners' conceptual achievement are listed and discussed below, then some examples of alternatives to common practices are proposed, alternatives in line with the concern of stressing conceptual links.

The obstacles considered in the following are referred to three main ideas: the complexity of physical phenomena, some ritualistic teaching practices and what is defined below as 'echo-explanation', a type of discourse used by teachers or science mediators especially when they want to be easily understood.

The intrinsic complexity of physical phenomena

We would like physics to be an engaging topic and therefore we search not to frighten our audience with too complicated explanations. Yet, several difficulties may arise.

Beyond a search for relevant factors?

A very reasonable approach to the complexity of phenomena, in inquiry based teaching, is precisely to help learners isolate the relevant variables, whenever possible. This is a considerable inspiring source for IBSE designers (see, for example, the emblematic theme of the hourglass in Pollen project).

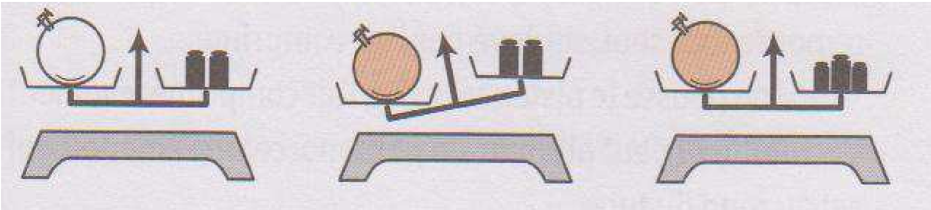
For instance, experimenting with a pendulum and finding that the mass of the oscillating object does not affect the period may be considered as very enlightening and exciting for children. No doubt that this type of activity constitutes a first step in an initiation to science, and that it is by no means obvious. It is not so easy, however, given the limits of the available explanations, to ensure transferability of the knowledge thus acquired. For instance, how could we answer the question: *How* is it that the mass is irrelevant to the period of oscillations? How could we *justify* that, with an oscillating mass-spring system, mass is now crucial? We have therefore to be aware of the limited satisfaction that some students may derive of such investigations. Consequently, a fine negotiation is needed, for any particular population, between the easy use of some practical settings and the students' possible desire for satisfying explanations.

When the control of variables does not tell all its reasons

This said, it is by no means questionable that the first step in an inquiry based approach should involve a careful control of variables.

In some cases, the proposed experiment is well designed and uncontestable in this respect, thus witnessing that its designer is aware of a potential difficulty. Such is the case when Marie Curie (1907: 27), or official documents in France for pupils aged 10 (MEN 2008), or else Leach *et al.* (2010: 19) show how to weigh the air in a rigid container first emptied then filled with air (fig. 2). The constant volume of the container ensures an unchanged Archimedes up-thrust on this recipient. The larger reading of the scale in the second case can therefore safely be ascribed to the larger weight of the container, itself due to its air content.

However, a potential difficulty remains. Even though the experiment is uncontestable, students and teachers might have some problems in terms, once again, of generality. Let us consider the case when they are not explained why the container is chosen rigid. Just suggesting that this is a matter of control of variables might lead them to an end point: Why choose volume constant and not pressure? How might a pupil understand that two similar bags filled with air at same atmospheric pressure and temperature this time, one with little air and one with much more air inside, exert exactly the same force on a scale?



a	b	c
In the glass balloon: a vacuum	In the glass balloon: air at atmospheric pressure	In the glass balloon: air at atmospheric pressure

Figure 2. A way to weigh the air, according to Marie Curie (Chavannes 1907)

Emphasizing conceptual links in physics would mean, in this example, to have learners understand that the force exerted on the scale by an object does not necessarily equal its weight (see Appendix 2). We would also have to explain why we choose volume as the constant quantity, not pressure and temperature, therefore – inevitably – to speak of Archimedes' up-thrust. Then, the impression of simplicity might well vanish.

If we intend to have students engaged with physics *and* trying to extend their investigative practice, then it might be risky not to reveal what is behind the curtain when we design an unquestionable experiment. Consequently, we have to carefully consider the balance between utility and risks, for a given population, when choosing a situation for an IBSE session. As regards the targeted explanation, the possible price to pay for seemingly 'neutral' simplification is to be taken into account. Whatever the decision made, we should be conscious of its limits and prepared to react to children's questions.

"Yes, but this is so exciting"

We want physics to be engaging, this for many people, and therefore we tend to select exciting phenomena while searching to explain them as simply as possible. In the negotiation of the explanation that can be expected to emerge from an IBSE session, we may be impressed by the potential of motivation of a given context. Two examples follow, with the attached risks.

- How planes fly: We really would like to present a simple account of this wondrous phenomenon. Quasi inevitably, Bernoulli is then called on. The same happens when it comes to balls "floating" in an air jet, or various analogous experiments. But what remains of the theorem in many explanations is just “larger speed then smaller pressure, larger pressure then smaller speed”, this without the least condition of validity. The main difficulty, then, is the problematic generality of what is said. For many simplified statements, there are counter examples. Windsocks are not sucked in by a lower pressure in their narrow part, yet the speed is larger there than at the entrance. An incompressible fluid flowing in a cylindrical horizontal pipe is at lower pressure at its exit than at the entrance, because of friction forces, but the speed is the same everywhere. Etc. Such apparent contradictions are consequences of simplification, which includes disregarding the conditions of validity of Bernoulli theorem. Therefore, it is worth wondering, in such occasions, if the price to pay is worth it. Of course, it may be decided to reinforce the explanation with more precise considerations. But then, it is extremely difficult to avoid that simplicity fade away.

Our second example presents a case when it is easier to get out of such a dilemma.

- In order to introduce colour phenomena, we may be tempted to choose a familiar context and use a television set. This is an everyday object, and you can see the red, blue and green spots on the screen with a magnifying glass. If the only goal is to have children realise that the fact that the screen is white has something to do with red, blue and green colours, the experiment can be retained. But if we intend pupils to differentiate additive mixing of lights from subtractive mixing of pigments, this setting is likely to be misleading. Indeed, it is not at all obvious how coloured points - that are *visibly separate* on the screen - might have the same effect as the simultaneous impact of light beams *at a given point* of a screen or of the retina. The mechanism of that “biologic mixing”, so to speak, is far from simple. Understanding how lights are involved at all in this story is already problematic. If the conceptual target is to differentiate colour phenomena, it seems advisable to choose another experiment (for instance Chauvet 1996, 1999: fig. 3 and 4, see also Viennot 2003; Planinsic 2004: Planinsic & Viennot 2010), despite the familiar context that pleads for the television set.

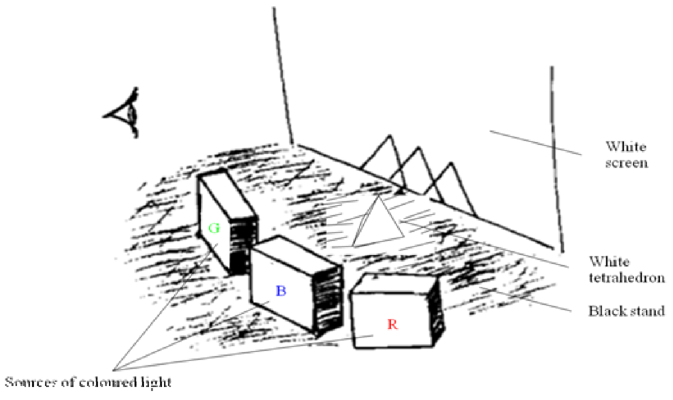
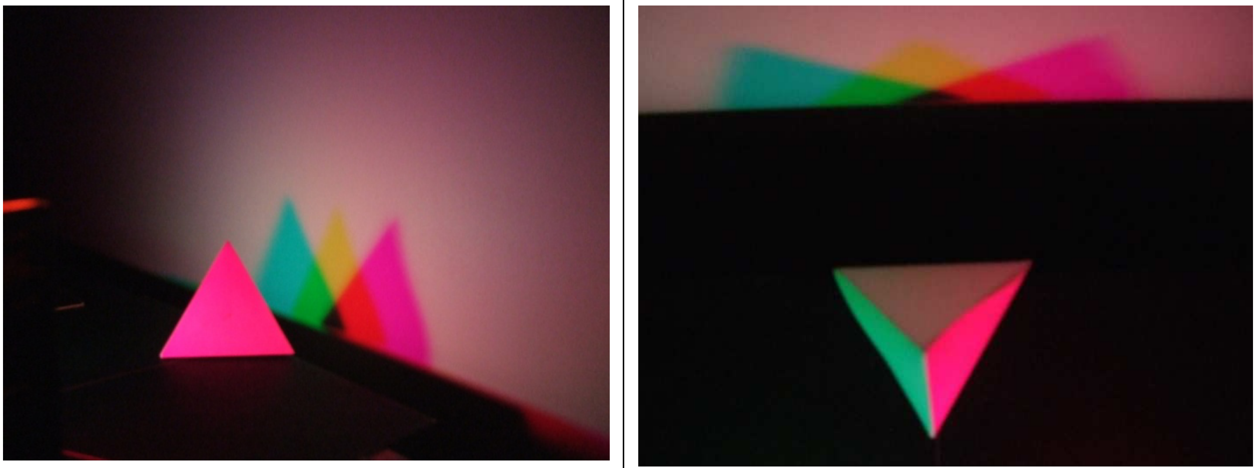


Figure 3. Sketch of setting used to perform the experiment of “coloured shadows” (Chauvet 1996, Chauvet 1999, slightly modified version: the tetrahedron has one edge parallel to the screen)



a) View from the side	b) View from above

Figure 4**:** Colours of the different zones of the setting shown in Figure 3, once the lamps are switched on (photos: P. Sauvage, ref.: Planinsic and Viennot 2010).

With these first examples, we are confronted with some central questions, such as: Given a phenomenon involved in an IBSE session, will students have any means to consistently interpret what they observe? What kind of concepts can we help them construct? Will an engaging topic suffice to ensure learning benefits? Is everydaylife always the best entry? Clearly, for each given population, there is a need for a carefully motivated choice of phenomena, taking into account, first of all, the kind of explanation that is likely to emerge from an IBSE session.

But, in this kind of negotiation, the choices may be obstructed, in particular, by some ritualistic pratices.

Beyond rituals

There are many teaching strategies, ways of staging an experiment or explanations that we use repeatedly as if they were unproblematic. Such practices may rely on mature experience and thorough reflection. Let us term “rituals” those that, most probably, are just an effect of habit.

An example is when an inverted glass of water is used to demonstrate the role of atmospheric pressure (Viennot 2009, Viennot 2010a,b). Then, a glass full of water is covered with a piece of cardboard and turned upside down, in a vertical position (fig. 5). The water stays in the glass, the cardboard apparently stuck below. Students are often told that the cardboard does not fall down because the atmosphere "supports the water's weight". Is there any problem with such a practice, in particular as regards the targeted explanation?

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.

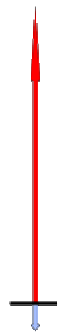
a	*b*	*c*
	Statements often found in common explanations : -The water exerts on the cardboard a force equal to its weight. -The force due to atmospheric pressure supports the carboard which (therefore) does not fall down.	A diagram that suggests the disproportion (in fact about x100) between the values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

Figure 5. A simple experiment (*a*) that is often "explained" with problematic arguments (*b, c)*

A way to show that this example is not anecdotal is to consider a second situation: 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. 6). 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 (see Appendix 1).

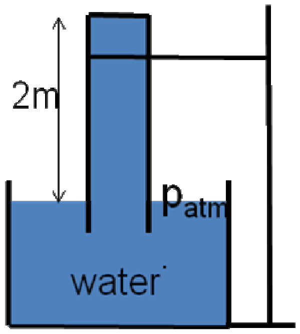
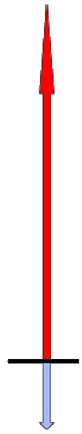
a) A test-tube filled with water, above a tank of water.	**b) A questionable explanation**	**c) Considering orders of magnitude**
	"What is lifting this column of water up by 2m ? It's atmospheric pressure that is pushing on the water in the tank. In the tube, there is no air, and no pressure is exerted on the water." * *Translated from an explanation by Marie Curie, (Chavannes 1907)	Comparing orders of magnitude of the forces acting on the column of water that are mentionned in the explanation (col. b). 

Figure 6. A situation that can be analysed like the glass of water turned upside down (fig. 5): a test-tube full of water and turned upside down over a tank filled with water.

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 6, 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. Such a similarity suggests that the ritual just illustrated with the first example – an inverted glass - is not simply an accident. We may then decide that it is worth suggesting alternatives, beyond just signaling the incompleteness of the ritualistic explanations.

A first strategy is to change slightly the staging of the inverted glass, by putting it in a horizontal position (fig. 7). Then, it is less tempting to ascribe the immobility of the cardboard to a balance between a force exerted by the atmosphere and the water's weight.

Figure 7. In a horizontal position, the water also does not flow out of the glass

A simple analysis of the horizontal components of the main forces 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.

Expert echo explanations

The two preceding examples also illustrate the idea of an expert echo-explanation (Viennot 2009, 2010a,b, Viennot and Planinsic 2009).

Let us consider the common and problematic explanations that are commonly given for these two situations. A column of water is said to be raised by atmospheric pressure and this suggests an (unbalanced) equilibrium between two forces, given that it is (erroneously) claimed or simply suggested that there is nothing else acting on the water. These two forces are, on the one hand, that due to atmosphere pressure at the basis of the column of water and, on the other hand, the weight of this column, itself assumed to be exerted on the water in the tank. Only the basis of the column seems to be considered, as though no interaction was intervening at the top.

Such explanations are compatible with some very common ideas or ways of reasoning that are repeatedly observed in students. It is often thought, indeed, that an object "exerts its weight on the stand" (to put it briefly; see previous discussion *a propos* of weighing the air), and more generally that a localized analysis is sufficient. We may then consider some expert explanations as echoing some students' common views, in that they seem to rely on the same common trends of reasoning. To sum up, 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.

Explanations that echo linear causal reasoning

Very often, echo-explanations are mapped on a very common way of thinking in science:

Linear causal reasoning

This way of 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. 8), 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.

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 suggests that 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 8 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.

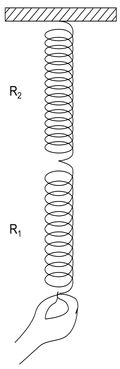
In quasi-static physics	An example	**Linear causal stories**
- several variables - simultaneously changing - constrained by permanent relationships		- simple phenomena (one variable each) - seen as successive (hence as) - temporary
$\mathbf{F}_{ext}$ (t) = $\mathbf{T}_1$ (same t) = $\mathbf{T}_2$ (same 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 8. The main features of linear causal reasoning, compared to those of a quasi-static analysis.

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 was much more recently pinpointed (Viennot 2010a,b, Viennot and Planinsic 2009).

A siphoning process

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.*

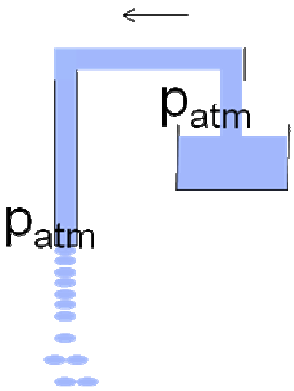


Figure 9. A siphoning process.

Using the schematic presentation shown in fig. 9, we might paraphrase this explanation as follows:

φ_1 (left end of the tube, on fig. 9): *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. 9) *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

Rituals and echo explanations are often concomitant. An improved awareness , a critical analysis and a deliberate specification of teaching goals may open wider the conceptual space that is potentially accessible to students.

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 9 but with a mask hiding the right-hand side (fig. 10a); the student could be asked to predict: What would happen if the lower end of the left-hand branch, initially blocked, were freed?

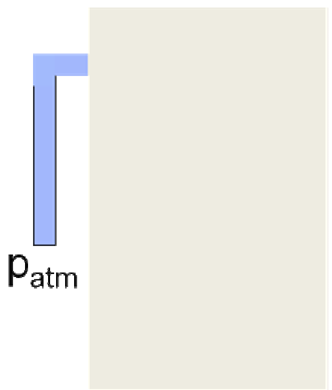
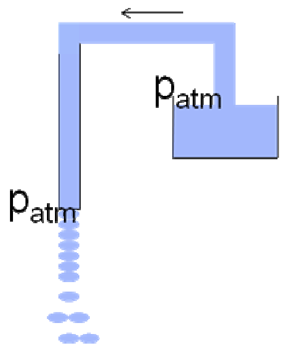
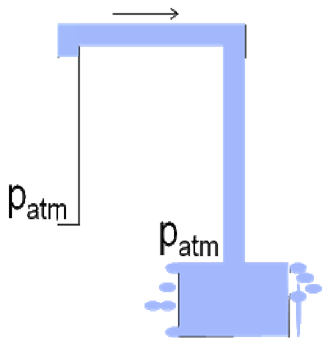
		
a What will happen when the left-hand branch is opened at its lower end? (Right-hand part of the system: hidden)	b A case currently explained by experts (e.g. Marie Curie: Chavannes 1907)	c With the same left-hand branch, a different outcome is observed

Figure 10. Without considering both sides of a siphon, the outcome of the experiment cannot be predicted.

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. 10b), 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. 10c). 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.

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 11. 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 11. 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. 12b): 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 12. 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.

A consensual method, a variety of likely outcomes

The preceding examples, particularly the two last ones, suggest a first conclusion. We may well agree on a general pedagogical frame to have the students active, engaged, excited, critical, etc. But inside such a framework, what remains to be decided is considerable, as is the range of likely outcomes. The positive side of that state of affairs is that, provided the limits of some common practices are recognised and analysed, there is room to maneuver in. 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 (Viennot *et al.* 2004), 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.

Some crucial questions

As recently recalled in many pleas for IBSE, "(…) the learning process of scientists *(consists in):* formulating questions, doing experiments, collecting and comparing data, reaching conclusions and extrapolating these findings to more general conclusions. (Allende 2008)

Thus, a recurrent invocation concerning science is that of a questioning approach. Consistently, it would be problematic, concerning IBSE, to depart from this attitude. This paper recalls and/or illustrates some caveats, suggests some reasons and ways to be both cautious and positively engaged with IBSE. That is, of course, far from exhausting the topic. Among the vivid questions left open, we find:

How can we evaluate our assertions about IBSE?

As recalled in introduction, many claims were expressed to justify and accompany the reactivating process of IBSE approaches. Given the preceding failures in the 70s, there was an urgent need, after about a decade of "recent" IBSE, to formally evaluate the outcomes. This paper being focused on learners, it must be noticed that, in this regard, very few results were available until recently, beyond teachers reporting. Recently, a formal evaluation has been conducted on a large scale in the frame of the Pollen project (2006-2009). One of the questions examined was whether IBSE was actually fostering pupils' liking of science. A striking results concerns a cohort of pupils, aged 10-11, who were exposed during two years (in Berlin) to IBSE, with pre and post tests posed to the same pupils. The authors (Jarvis *et al.* 2009) conclude: *"Most of the individual item scores relating to pupils' liking of science experiments also fall significantly over the two years (…), with girls scores falling more strongly. This pattern of decline in liking school and science is common in many countries as primary pupils get older (Jarvis & Pell 2002; Piburn & Baker 1993). It should not be surprising that there should not be a notable change in typical pupil responses because of the Pollen Project.*" This comment is in stark contrast with many loud stated claims. It demonstrates the utility of a lucid, non dogmatic attitude.

First of all, it appears that we should search for relevant variables concerning, this time, IBSE, in order better to master its outcomes. Thus, the investigation by Jarvis and her colleagues provides interesting results. Pupils in Leicester (N= 301-554, aged 7-11), were asked to rank various items on a five-points Likert scale. It was found that the item "science is just too difficult" was ranked significantly lower after one year of IBSE. In contrast, no significant difference was observed concerning the items "(…) Finding out why the experiment works" and "Science makes me think". Strikingly, the same kind of results are reported in the investigation conducted in several European countries by Lindahl (2009), still within Pollen project.

Such studies can help us improve our practice. Here in particular, the results pose the question of developing a more conceptual component in IBSE. Indeed, at least through some pupils' responses, science does not present insuperable difficulties but does not seem more intellectually stimulating after a long period of inquiry based teaching.

How does IBSE affect students' conceptual achievements and intellectual satisfaction?

Physics education research has long been concerned by evaluating students' understanding of scientific concepts, before, during and after teaching. By contrast, the recent reactivation of IBSE was most often accompanied by evaluations that were nearly exclusively focused on students' or on teachers' attitudes as regards science (see for instance the investigation by Pollen, just quoted). As recalled above, there is a need to keep evaluating *at a fine grained level* what students actually grasp of science concepts, in such and such teaching conditions.

Besides the question of students' conceptual achievements, and probably tightly linked to that aspect, the level of students' intellectual satisfaction is a crucial point to be investigated. Intellectual satisfaction is at a junction between affectivity and conceptual progress. It is a feeling linked to the impression of having understood a complex topic to a certain extent, one that can be identified quite clearly, this being accomplished with a good quality/cost ratio (Viennot 2006, Mathé and Viennot 2009, Feller *et al.* 2010). Often, affective factors are envisaged as *conditions* for learning (for instance Pintrich *et al.,* 1993; Rhöneck *et al.* 1998; Glynn *et al.*, 2007, Launkenmann *et al.*, 2003). But seen as a possible *outcome* of learning, intellectual satisfaction is – most probably - crucially linked to one of the main goals of IBSE enterprises: having students engaging with science, *in the long term*.

IBSE from primary school to the end of secondary school: what transitions?

This point leads us to a crucial aspect of IBSE: the transition from a major focus on scientific inquiry, on the one hand, to a more systematic approach to science conceptual organization, on the other hand. As recalled by Rocard *et al.* (2007: 12), "The two approaches are not mutually exclusive, and can and should be combined in any science classroom to accommodate for different kinds of scientific topics, different mindsets and age groups preferences." In practice, the dosage to be adopted in a given context is far from obvious. We can read different suggestions concerning the crucial steps. Thus, according to Léna (2009b), there would be, in some European countries, a "5 to 16" golden age of inquiry based approaches: "In all four nations *(France, Germany, Netherlands, Sweden),* the 'science as inquiry' pedagogy encourages students (from 5 to 16) to develop a sense of wonder, observation and logical reasoning". Osborne and Dillon, recommend that this approach prevail “before 14”: “EU countries should ensure that: (…) the emphasis in science education before 14 should be on engaging students with science and scientific phenomena. Evidence suggests that this is best achieved through opportunities for extended investigation work and hands-on experimentation and not through a stress on the acquisition of canonical concepts.“ (Osborne & Dillon 2008: 9).

It is crucially important that a thorough reflection be conducted on how and when to manage the decisive transitions. In order to inform this question, it is urgently needed to conduct carefully designed research programs.

Concluding remarks

These crucial questions – a few among many others - may seem discouragingly complex. They just echo some of the recurrent debates in science education, and there is no reason why IBSE should get round these. The real challenge is to keep the wonderful impulse recently given to IBSE while keeping in mind those questions and maintaining a lucid effort to progress in these respects.

At least can we say that a condition for success is to reject any manicheism. Phil Scott very recently expressed a concern about this tendency: “*A worrying trend that I detect sees new approaches being set up in opposition to each other in an unhealthy dichotomy (…) Furthermore, and all too often, approaches to teaching scientific conceptual knowledge are cast as being 'traditional', 'didactic' and 'bad', whilst inquiry approaches are seen as being 'innovative', 'child-centred' and 'good'.*” (Scott 2009). Yet, the report by Rocard, just cited, had well specified: “The two approaches are not mutually exclusive, …”. But, in practice, one or two useful sentences in a report are not enough to ensure a generalized, harmonious and efficient ‘full repertoire’ approach to teaching. To this end, it would be highly fruitful, I suggest, to seriously consider this idea: It is essential that students reach a certain degree of intellectual satisfaction. In this regards, a strong lever is – a propos of inquiry based approaches as well - to favour conceptual structuring by stressing links between phenomena and laws. Thus, the different reasons to like science might be reconciled, in an efficient synergy. We might expect to have learners truly engaging with science, beyond mere excitement and in the long term.

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Appendix 1

How better to help and/or train teachers to perform careful IBSE?

Given time constraints, some important themes concerning teachers have not been discussed in the address reported here. Yet, as repeatedly claimed, teachers' role is absolutely decisive. As always when an innovation is launched in an educative system, or even experimented at smaller scale, teachers are active transformers of the suggested design (e.g. STTIS 2000, Leach et al. 2002, Millar 2010, Ogborn 2010).

No doubt that, in order to help teachers take a first step, it is very useful to provide them with general considerations on IBSE along with exemplary items, for instance posted on a resource web-site (LaMap, Pollen, Sinus Transfer), or even kit-boxes. Training sessions *in vivo*, or accompanied teaching sessions, whenever possible, are of course likely to favour a better interaction between the designers and the teachers who are supposed to appropriate the recommended innovation.

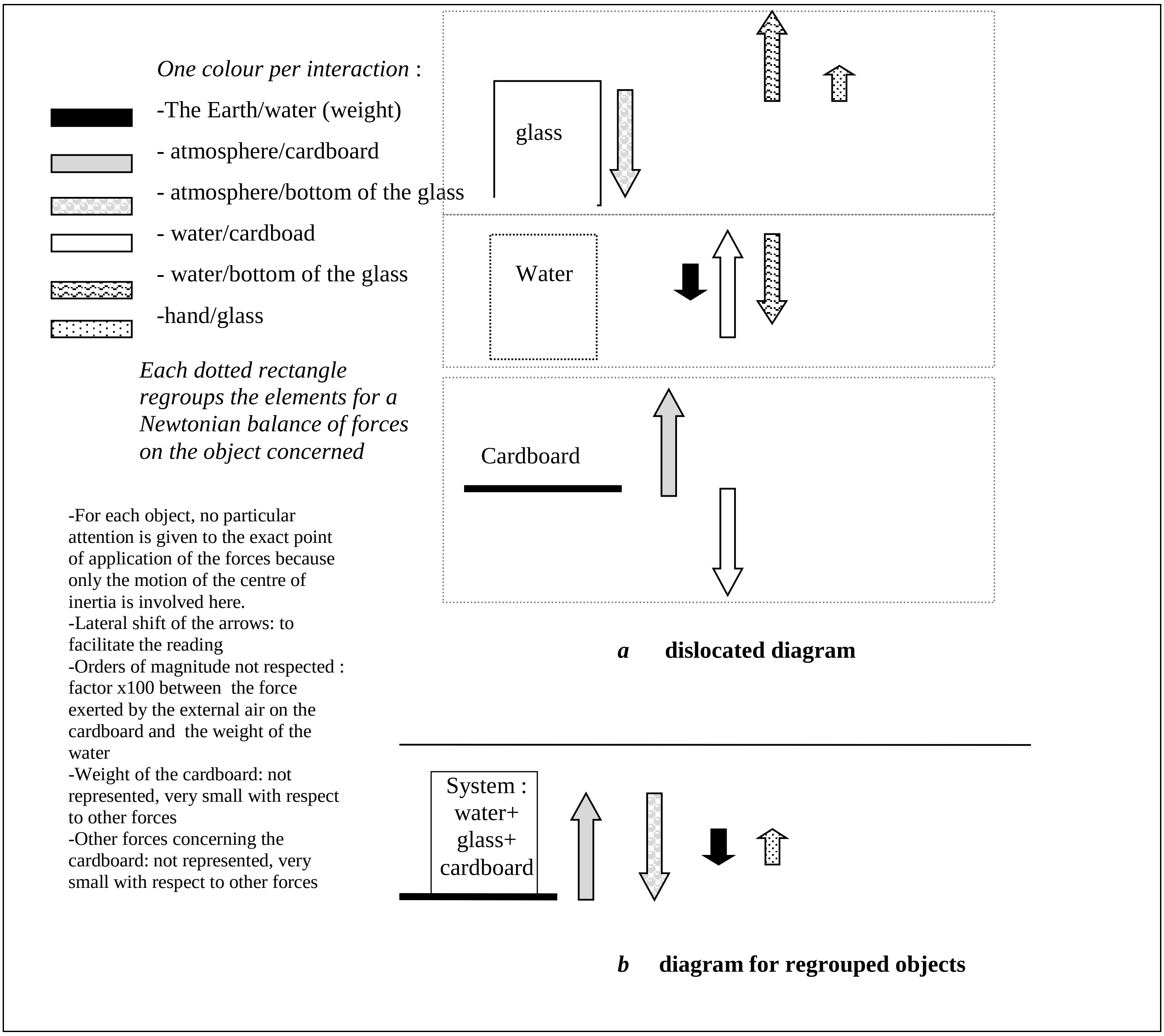
In any case, it would be highly contestable to adopt a transmissive approach: The very label of exemplarity is questionable, because what is advisable in a given teaching context (teacher included), may be very problematic in another one. For instance, as remarked by Jarvit *et al.* (2009): "Kit-boxes are a valuable strategy for supporting schools and teachers with little background in teaching science. (…) Long term, the boxes may inhibit able teachers' creativity and enthusiasm."

Consequently, it is probably fruitful to propose, for any given theme of physics, a menu, be it with a resource web-site or not. That could comprise, besides some information about the content, a description of students' common ideas, a critical analysis of possible ritualistic practices -explanations or ways of staging an experiment-, and suggestions of alternatives *along with their justifications*, constructed accordingly. Given that the teachers trace their own way when they decide what to do the next day, such a format should incite them to take responsibility for the didactic consistency of their personal choice; in other words, to look for an optimized agreement between the retained teaching goals and the chosen strategies, given students' pre instructional ideas and expectable reactions. More widely, this idea of a *didactic consistency* might constitute the master word of teacher training sessions. Then, in line with a problem posing approach (Lijnse 1995, 1998, 2002), teachers could be trained to evaluate to which extent some hypothetical design briefs (Leach *et al.* 2010) are didactically consistent. Several resource web-sites (STTIS , MUSE) are built on such principles.

Appendix 2

An elementary analysis of the "inverted glass" situation, with dislocated diagrams

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.* 2009): (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.



a **dislocated diagram**

b **diagram for regrouped objects**