Fundamental Patterns in Common Reasoning: examples in Physics

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1. Introduction

Numerous studies have been published in the last fifteen years on the ideas of pupils or students concerning physics. One of the main features of such research is that it is content-specific. Starting from the idea that students actively build their knowledge from 'where they are' and with 'what they have' it is necessary to know as much as possible about the 'where' and 'what' of diverse topics in science, especially those that are usually taught at school.

Different terms were used to designate what was documented in this part of the students' knowledge (Driver e.a., 1985; p.8). From the beginning we used the word 'reasoning' in our laboratory. Soon the adjectives 'spontaneous' or 'natural' were simply replaced by 'common', as we shall see later.

This paper draws on fundamentally content-dependent studies, in the sense that all the analysed results concern answers and arguments about physics. Some of these studies have been deliberately focused on transversal aspects of common reasoning, i.e. on aspects that can be observed about very different domains of physics. Some others have been designed to document the students' ideas on a very specific content, but have given results that appear similar to other studies, if read afterwards in a certain light.

The goal here is to illustrate some of these transversal aspects, in an organised presentation, and with emphasis on what seems the most important, i.e on the ways of reasoning used by many people for many topics. Of course, not everything is discussed here and the framework used for this paper is not presented as a theory of common thinking that can be applied to everything else.

2. Thinking with 'objects'

In common arguments a first trend appears to be very general, from one topic to another. When analysing physical phenomena people like to use 'objects'. As well as real objects they ascribe a realistic character to physical concepts or models. They build their reasoning on these 'objects' as if they were material. There are diverse aspects to this trend:

"Grasping a thing"

- A wave travelling along a rope is seen as a material object. It is said, for instance, that it goes faster if the initial shake is stronger, or that the length of the wave is unaffected by a change in the rope thickness (Maurines, 1992).
- An optical image seems to be understood as travelling in space as a whole: it is said that it can be seen on a screen without an optical device between the source and the screen, or that a coin on a lens will make a hole in the image previously visible on a screen (Goldberg and Mac Dermott, 1987; Feher and Rice, 1987; Fawaz, 1985; Kaminski, 1989).
- A trajectory is seen as a thing in itself, irrespective of a reference frame: a straight line will remain a straight line in any frame of reference. The same can be said of 'a vertical trajectory' (there are other factors to keep the trajectory vertical: Saltiel and Malgrange, 1980). Travelled distance, a reference-dependent quantity, is also manipulated as an intrinsic quantity, such as the length of a stick.
- A ray of light can be seen as an object, it cannot be divided (refraction and reflection are mutually exclusive)(see for a review: Perales e.a., 1989).
- Microscopic particles are seen as macroscopic objects, and endowed with corresponding properties. Particles would swell, shrink, melt, etc, to account for dilatation, contraction, melting of solids (Driver e.a., 1985; and the 'macro-micro' conference in Utrecht, 1989).

Animism

It has frequently been noted that a certain amount of animism was observed in common arguments, especially, but not only, in children and adolescents: the air 'wants to', 'molecules need room', 'the mass is stronger than the spring', etc. Then not only things are considered as real objects, but they are seen, to a certain extent, as living objects.

Absolute properties ascribed to objects

Driver e.a. (ibid., p. 194) describe, under the heading 'limited focus', 'the propensity of children to interpret phenomena in terms of absolute properties or qualities ascribed to objects rather than in terms of interactions between elements of a system'. Among the quoted examples, iron would be 'naturally cold', or the fact that 'a substance burns or not' would be 'solely a property of the substance itself'. This aspect of common reasoning meets with what will be said below concerning 'functional reduction'.

'Supplies of...' ascribed to objects

Frankly not animistic, but in fact not very far from it, is the observed tendency toward ascribing a 'supply of something' to moving things, in order to explain their motion. Especially worth noting is the following type of statements: the upward force of the mass (Viennot, 1979), 'the force stored in the bump' (Maurines, 1991, see also about sound: 1993). Surprisingly enough, this very important aspect of common reasoning, for example in elementary dynamics, has not retained much of the attention of the researchers community. It seems in fact quite decisive in the way students analyse situations in mechanics. This trend, indeed, blurs the question of what a force is acting on, and therefore favours an undifferentiation between Newton's second and third laws: interactions are seen as conflicts between objects of which the stronger wins, which leads to the writing of equations between balancing forces which are not acting on the same objects.

In the domain of elementary dynamics as well as signal propagation, this feature of reasoning goes with the idea of 'using up' the supply - at the top of the trajectory, at some distance along the rope - (Viennot, 1979; Maurines, 1991). The physical nature of the 'supply' is discussed below, but in any case, ascribing it to a moving object fills a need for a cause: the cause is stored in the object, a nearly animistic view, as suggested above. Links between realism in thought and difficulties in dealing with algebraic quantities are very strong: they are discussed in Viennot (1981).

3. Functional reduction: several converging modalities

By 'functional reduction', we mean that not enough variables have been taken into account for the problem considered. Reasoning with only one variable at a time is a well-known tendency (Piaget, 1972, concerning the relationship $l=vt$), and the first reason for this trend is obviously a need for simplicity. I shall comment here on the importance of this phenomenon for physics, and on its possible reinforcement by other aspects of common reasoning (Viennot, 1988a, 1992).

Understanding of the word 'constant' as 'characteristic of an object'

One manifestation of the functional reduction in students' reasoning is a truncated comprehension of statements implying the word 'constant'. Often such statements convey a functional meaning, especially because they refer to non-evident independencies. Instead, they seem to be understood as if the word 'constant' was only synonymous for 'characteristic of an object'. Then, only variables that might affect the 'constant' are envisaged, while variables of which the constant is independent, i.e. the interesting ones, are ignored. Results and further analysis can be found in Viennot (1988).

Undifferentiated notions

One of the findings very strikingly similar across different pieces of research is the fact that common arguments put into play undifferentiated notions, or, in other words, mono-notional reasoning, where the physicist would use several concepts. Different physical quantities thus appear, in such arguments, as different facets of the same notion. Saying that two or more physical quantities X, Y, ... are 'combined' into an undifferentiated notion does not imply any hypothesis about the genesis of the global notion. It only means, in this paper, that X and Y are indifferently used in common statements. It also refers to arguments that express a systematic co-variation of the 'component concepts X, Y', for instance: 'X ↑→ Y ↑', etc. Such an adherence in fact constitutes a functional reduction since at least two physical quantities are manipulated as a single one.

For instance, 'supplies' mentioned in the preceding section can be indifferently expressed in terms of the 'force', 'motion', 'velocity', 'energy', 'impetus'... 'of the mass', or the 'force', 'velocity', 'height', 'power'...'of the bump'. Such quantities might be, in students' reasoning, only different aspects of a kind of 'tonus'. A similar combining of physical quantities is crystallised in the expression 'thermal motion'. Asked about the meaning of this expression, students use almost indifferently the words 'energy', 'velocity', 'disorder'. Collisions between molecules are also mentioned. It appears (Rozier, 1988; 1991) that the mean speed of molecules and the mean distance between particles are often manipulated by students as two adherent notions, combined into the idea of thermal motion: 'molecular kinetic energy in a gas is larger than in the corresponding liquid', as students quasi-unanimously say about two phases still at thermodynamic equilibrium. This view might be underlaid by that of a collective 'tonus': 'molecules need more room to move faster'.

Another example is the very well known undifferentiation between current and voltage in electric circuits. Again, one might say that these two words serve, in common statements, as indicators of the 'strength' of 'electricity' (Closset, 1983; Shipstone e.a., 1988).

Considering these 'combined notions', one can envisage them from a causal point of view: 'cause' and 'effect' seem not to be differentiated, with sometimes a misunderstood 'effect'. Other examples are force and velocity (instead of acceleration), potential difference and current, electric field and current (Viennot and Rainson, 1992), density of charge and potential

(Benseghir, 1989). This point of view is probably relevant in the case of 'heat and temperature', one of the most famous couples of undifferentiated concepts.

When the 'effect' is a movement, the causal content of the combined notion is especially manifested, as mentioned before. It is attested, in particular, by the situation-dependency of this feature of reasoning. Thus the 'supply of force' ascribed to a moving body is preferentially invented by students in situations where a motion is salient and not easily explained by a well known interaction force (gravity, push,..) (Viennot, 1979). This is what Gutierrez and Ogborn (1992) call, after De Kleer and Brown (1983), a 'mythical cause'. If only data about forces are given, the same students much less frequently use this combined notion in their reasoning and often correctly associate force with acceleration, i.e., with different possible velocities (Viennot, 1979). This asymmetry with respect to the axis cause-effect can be interpreted in different ways (effect better analysed when not salient, or more frequent non-univocity of the cause → effect link as compared to the effect → cause one), but in any case, it seems to confirm the validity of a causal interpretation of the observed amalgams.

Linear reasoning

In fact, the trend towards functional reduction extends much beyond the preceding modalities. When considering multi-variable problems, people often give arguments that constitute linear chains of the type: $\Phi_1 \rightarrow \Phi_2 \rightarrow \Phi_3 \rightarrow \Phi_N \rightarrow$ ...., where each phenomenon Φ is specified with only one variable, or more generally corresponds to a single action. In other words, the links are of the type 'one cause → one effect' described also for instance by Gutierrez and Ogborn (1992). One might say: 'one cause is enough for a given effect'. It is worth noting that this feature of reasoning is observed even if other causes have important contributions. An example at university level is the type of comment given to explain the increase of pressure in an adiabatic compression of a gas:

'Volume (V) ↘ → particle density (n) ↗ → number of collisions ↗ → pressure p ↗'.

Concerning pressure, it reflects an exclusive link of this quantity with particle density. The other relevant factor, namely the mean speed of particles, is ignored twice. This constitutes a 'preferential association', here between pressure and particle density. It is very commonly observed. Reasoning with such linear chains about multi-variable problems leads to ad hoc arguments, and to inconsistencies (Rozier and Viennot, 1990): for instance one cannot 'explain' the low pressure in altitude by the implication 'particle density (n) ↗ → pressure p ↗', and a hot air balloon saying 'hot air

→ particle density (n) ↘ ', without a contradiction concerning pressure inside the hot air balloon. Maurines (1986) also reports on contradictions raised by this one-to-one causal analysis.

Induced chronology and story-like arguments

The status of arrows in the preceding outline given for linear arguments is a very important question. These apparently logical connections are in fact revealed to be loaded with a temporal meaning: an arrow does not mean only 'therefore', but also 'later'. The totally ambivalent word 'then' favours this ambiguity between logical and chronological levels (Rozier, 1988). These story-like arguments contradict the accepted theory of quasi-static phenomena, in which several quantities change simultaneously under the permanent constraint of certain relationships.

An example at university level concerns isobaric heating. Arguments frequently have the following structure:

'Supply of heat → T ↗→ p ↗→ V ↗'.

The apparent contradiction between the statement 'p ↗ ' and the data: 'isobaric heating' disappears if the causal chain in fact is interpreted by two steps: first step with volume kept constant, then second step after the piston is released. This is indeed what some students explicitly specify.

Linear causal reasoning: some consistent features

Rozier (1988) used the label 'linear causal reasoning' to designate a way of reasoning showing the two preceding aspects: linear and chronological. The similarity of the corresponding arguments with stories is striking: simple successive events, which are more or less causally linked. This consistently goes with the following features of reasoning:

A lack of symmetry in arguments: Concerning one of the situations described above, namely the adiabatic compression of a gas, one can find the argument 'V ↘ → p ↗ ' which seems quite acceptable at first sight. In the other situation, i.e., isobaric heating, a common comment is 'p → V', while reversing the above argument would give 'p ↗→ V ↘ '. How is it that this last implication seems so surprising? Also, why does the second implication seem so natural despite the fact that it contradicts the contra-variation between p and V expressed in the first one? This is probably because behind the two first arguments, there are stories instead of relationships. If a relationship such as 'pV = Constant' was the justification adopted for the first implication 'V ↘ → p ↗ ', the reversed implication would seem natural. More probably, there is a chronology and a particular story implied in each of the easily accepted arguments: 'One reduces the volume of a gas by pushing on it, then pressure is increased' (first implication), or: 'one heats a gas then pressure is increased, then volume gets larger'. Which story might we imagine for 'internal pressure is increased then volume decreases'?

Thus, chronology is the most important obstacle to reversibility in implications, and therefore, as said before, to quasi-static analysis. Gutierrez and Ogborn (1992) comment on this lack of symmetry and use it to interpret some circular arguments, where an increase in a quantity can be seen as its own effect.

Driver e.a., (ibid, p. 1985) also describe another type of lack of symmetry, which bears on the sense of variation of quantities: 'Pupils appreciate the effect of an increase in pressure of an enclosed body of gas, yet they have difficulty anticipating the effect of a reduction in pressure'. In this case the predominant aspect of linear causal reasoning is probably not so much chronology than taking into account a single cause - internal pressure - instead of a balancing out between internal and external pressure. At higher academic levels, this type of obstacle is, in this particular case of compression or expansion of a gas, of minor importance compared with that of an induced chronology. But it is still present, and both linear and chronological aspects of common reasoning seem to reinforce each other in many cases, especially in the analysis of steady-state situations (see below).

Permanency: a forgotten case

Understanding phenomena as successive, consistently leads to seeing them as temporary, or at least hinders a reasoning in terms of permanency. This is indeed what is observed in common reasoning. Steady states of disequilibrium, such as that of a green-house or of a bolometer, often raise such comments: 'more energy gets in than out, so the temperature is higher'. Here the reasoning correctly takes into account two simultaneous flows, but it is implicitly focused on the (previous?) phase of change ('heating') and fails to explain the steady-state (permanent high temperature). What would result from unbalanced flows of energy in the long term - an explosion - is not envisaged. This implicit focus on a transient phase prevents one from controlling the validity of the argument with an analysis of the long term evolution of the system. We suggest to complete Driver's e.a..'s statement 'an important aspect of childrens' causal reasoning is that change requires an explanation' (ibid. p.195) by the following: 'surprisingly steady states are commonly 'explained' by an argument implicitly focused on change'.

Spatial order: a support for linear causal reasoning

Quite intentionally, most of the examples given above are not chosen from physical situations strongly determined by spatial order. The sequential character of linear causal reasoning is all the more striking when, for example, the pressure and volume of the same body of gas, in the same vessel, are sequentially coped with. But if spatial order is salient in the situation, the sequential trend is all the more important in students' reasoning. The most famous example is the sequential reasoning in electric circuits (Closset, 1983; Shipstone, 1983). A pioneer work in this field is that of Fauconnet (1981), who in particular showed very clearly the context-dependency of common reasoning, about problems of the same mathematical structure, and the determining impact of a spatio-temporal content. Other examples are available, for instance concerning thermal conduction along a rod (Rozier, 1988) and hydrodynamics (Closset, 1991).

Linear causal reasoning: an extension across different domains of knowledge and teachers

Economy and ecosystems are among the numerous domains in which manifestations of linear causal reasoning are very common. A topic not developed in this paper.

Also teachers contribute to these methods of reasoning, in a certain 'resonance' between explanations commonly given and linear causal reasoning. In many pieces of research quoted above, an analysis of teachers' ways of reasoning in the same domains is done. It appears in many cases (mechanics, electric circuits, elementary thermodynamics, optics, etc) that teachers and textbooks often give the same erroneous statements as the students. Popularisation papers also participate in that kind of global reinforcement of common ways of reasoning on the part of the informative or teaching environment.

A point especially worth noting has been made in particular by Closset (1983): a given way of reasoning may seem to have disappeared in a population of higher academic competency, because a typical erroneous answer to a given question is not observed any longer at this level (say: two bulbs in a series circuit are now said to light at the same time). In fact, this is not the case: the problematic situation in question is mastered, but a new question still unusual to this group raises anew the same feature of reasoning (for instance: two capacitors in series are said to be charged in different times, especially if their capacities are different). A 'local' learning has occurred, but the deep-rooted feature of reasoning is still acting.

From the point of view of ways of reasoning, transitions between 'novices' and 'experts' are very smooth (Viennot, 1988b).

Another fact is probably quite determining in students' unawareness about the outcomes of a careless use of linear causal reasoning: when they want to 'make their students understand' using verbal explanations, teachers tend to use story-like arguments. An example is given in Rozier and Viennot (1991):

although written by a very good physicist who perfectly masters the topic, a text may be misinterpreted by students because of a resonance between its chronological connotation and the students' trend towards linear causal reasoning.

4. Common reasoning and common experience

Two expressions are often associated in research papers: 'students' ideas' and 'everyday experience', as if this correspondence was straightforward. It is suggested that common ideas originate in everyday life, kinaesthesic and sensorial experience. Certainly nobody can deny the importance of such factors in knowledge development. But one can easily find counter-examples which show that such a link is sometimes very unlikely, at least if it is understood as a direct connection.

Fauconnet (1981), for instance, brings about examples in which students' personal experience about springs cannot directly account for their answers. The same can be said about sequential reasoning in electricity. White and Gunstone (1992, p.47) also give an example of such an apparent disconnection in 13-15 year old Australian students: given equal volumes of water and cooking oil placed during the same time in the same beaker on the same hot plate, students rarely predict that the oil will have a greater temperature when the water is boiling. Their arguments to support erroneous predictions do not rely on everyday experience.

It is not really surprising, in fact, that personal experience does not necessarily 'speak directly' to students. Students' reluctance in admitting 'experimental evidence' has been described by many researchers (see, for instance, Johsua and Dupin, 1989; Driver e.a., 1985). Common ways of reasoning may screen 'everyday evidence' as well as 'experimental evidence' that teachers try to put into play. Most probably, the more transversal the way of reasoning at stake, the harder it is to accept the contradiction of 'facts': a point to document further.

No less probable, such general trends of thought are also rooted in everyday experience, but the link is much less direct. They might be a resurgence of the whole structure of our life, with events succeeding each other, and memories focused on a single dominant feature at a time.

5. The question of pedagogical goals

The research findings presented above may suggest specific pedagogical implications. Given the need for taking into account students' ways of thinking, what more is learnt from the fact that transverse aspects of common reasoning are put in evidence? Does it suggest that we should face these aspects as such in teaching? The preceding results throw some light on the question, but as yet not much light on the answer. Only some remarks can be made.

Different levels of 'transversality' in teaching goals
The same erroneous common statement can be coped with at different levels in teaching, for instance: *'Collisions between molecules produce heat'*,

- any attempt to provoke a conceptual evolution about this idea,
- including these attempts in work about:
  . heat and temperature,
  . macro-micro relationship,
- discussing the problem of steady-states and divergence of unbalanced flows in the long term.

Or, to cope with the statement:

- *'If there is no more lens, the image is no longer affected, it goes onto the wall without being reversed'*
- any attempt to provoke a conceptual evolution about this idea,
- work also on the idea that information may be invisible and diluted in space.

Conceptual teaching goals of higher levels are rarely mentioned in syllabuses, probably because they do not easily coincide with a possible chapter in a textbook. Being transversal, they seem to become invisible in official instructions, as if the only general teaching goals worth mentioning, concern attitudes and experimental abilities.

'Higher level' refers, in the preceding paragraph, to the level of transversality. But such teaching goals may intervene at low academic level, with very simple situations. For instance, multi-variable reasoning might be introduced about the area of a carpet, or about the volume of an aquarium. More research about teaching-learning processes in this field would be very useful.

6. Concluding remarks

The role played by causal explanations in the reasonings described above is prevalent. By the way, it is possible to see causality in nearly every argument given by students. As shown above, linear causal reasoning is a good candidate to account for the observed comments. However, some different modalities in this very general way of reasoning can be tentatively suggested, following Rozier (1988).

Sometimes, the focusing on a real or invented object (the hero of a story) goes with arguments in which time plays an explicit role. Often, then (projectile, bump on a rope, electricity, ...), the analysis of variables is simplified by combining several of them in a single ill-defined notion, ascribed to the object. Then, saying that one of the facets is increasing/decreasing (for instance height of a bump) implies that another (for instance velocity of the bump) also increases/decreases. Such a covariation does not imply any shift in real or 'mythical' time: in this sense, causality is not directly in play. By contrast real time is ruling the evolution of the undifferentiated notion in space, with a very simple handling of causality (give, take, using up of a supply, ...).

At the other end of a continuum, the 'hero' is not globally in motion, and is characterised by several quantities well identified as different (for example a mass of gas). The evolution of the object is then commonly commented upon through a linear causal analysis in which the quantities or simple phenomena are envisaged one by one, in causal chains implying, to various extents, chronology (with real or 'mythical' time). Rozier (1988) suggests that in students' explanations, the two types of complexity - spatio temporal and multi-variable analysis - each develop at the expense of the other.

This is an opportunity to come back to the more or less conjectural status of the type of description of students' reasoning that can be proposed. The last remark, made by Rozier, is at such a distance from the 'experimental facts' that we must indeed consider it as rather conjectural, while keeping a vigilant eye on the idea. To which extent are the other ideas in this paper 'validated by the facts'? Certainly each idea is supported by research findings. But is each proposed idea the only way of accounting for these research results? Shall we simply speak of functional reduction or assume the implicit underlying idea of an invented object? Shall we see such and such covariation as simply expressing the simultaneous evolution of two facets of this object, or shall we decide that it is an instantiation of a causal scheme?

More globally, what size shall we aim at for our 'synthetic description', 'theory', etc, of students' reasoning in science? The pitfalls to avoid are, at the two ends of a continuum, a 'not synthetic at all' description, close to a catalogue of types of comments, on the one hand, and such a general theory that it can be adapted to any observed student's series of comments or actions, on the other hand. These two extreme cases have in common the absence of any risk. I suggest we need to work in between these two ends with several sizes of description. It is what I have tried to do in this paper, in order to allow a separate discussion of each 'brick' - a piece of research referring to a chapter of physics, a paragraph about 'constants', 'combined notions', or 'animism', etc - and permit the reader to keep some 'middle-sized descriptions' even if the more global one (linear causal reasoning in Rozier's sense) is not agreed on. The use of different formats of description is, I suggest, necessary to ensure the best possible control concerning the fruitfulness of our conjectures. This is also important, as shown above, to help define teaching goals of different 'sizes', and therefore to contribute to designing teaching strategies.

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