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Analysing students' reasoning in science: A pragmatic view of theoretical problems

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Introduction

Conceptions of children or students in various fields of knowledge, especially science, have been widely investigated. There is a general consensus that students' knowledge in science does not originate only in school learning. This knowledge, the personal construction of an individual, appears to be at least partially organised in structures more or less dependent on the conceptual domain in question, and is sometimes extremely resistant to change. Different expressions – 'conceptual frameworks', 'alternative frameworks', 'mental structures' or simply 'conceptions', 'spontaneous or natural reasoning' – all refer, in a more or less equivalent way, to this fact. There is similarly a consensus that we have to take this 'natural reasoning' into account if teaching is to be effective.

Thus a programme for research in Science Education would be, in summary:

(*a*) to demonstrate regularities in different kinds of students' productions, and to describe these regularities in terms of 'conceptual frameworks' or 'ways of reasoning'

(*b*) to investigate the conditions under which these conceptual frameworks can be changed.

This paper deals with the first of these points. It addresses the question: how can we infer elements of mental organization from regularities in students' answers or comments? This question can be formulated more simply: how can we 'understand' and so effectively describe students' reasoning? The answer is crucial in characterising our research.

A prior question, though very important, will not be discussed: can we discover something about the reasoning of individuals from collective studies, according to a kind of 'cognitive ergodicity'? My personal answer is that we can, but this very serious question would deserve a whole discussion to itself. Thus in what follows, the expression 'students' answers' is to be read either as 'answers of a given individual' or as 'answers shared by a non-negligible number of students', depending on which type of investigation the reader considers most relevant.

What remains essential, in both cases, is the observation of regularities.

A second group of questions, again not addressed here, is the following: can we classify aspects of students' reasoning according to gross categories such as common or formal knowledge; declarative knowledge; and theories in action.

Also, what is the specific impact of different types of question such as:

- Can you do this?
- Can you tell me what will happen?
- Can you explain me why?
- Can you teach me?

I shall however try to set the discussion 'upstream' of these points. I shall therefore include in the word 'question' all the possible kinds of situations in which a student is prompted to say something about Physics and in the word 'answer' the whole range of possible comments or actions of students presented with a question.

The 'natural' interpretation

The game we play when we analyse students' answers in terms of 'inferred rules', 'inferred reasoning' or even 'categories of typical answer' is always more or less the same: the researcher makes a hypothesis about a certain 'logic of the student', tries it out on the observed answers, and if the fit is good, defines a corresponding 'category of answer'.

This phase is crucial but it is very difficult to make explicit its mechanism. A limiting case, very frequent for obvious reasons, consists in making the assumption that only one interpretation is possible: 'read such and such a comment and you will understand'. These 'self-explanatory' comments are invaluable in guiding the research, but they present some dangers. Of course the interpretation is all the more questionable when the 'distance' between interpretation and comment is large, but this very concept of 'distance' is still to be defined. The appendix gives an instance of an answer to a problem having several different possible interpretations. This is just one example among many of the range of possible ways of 'reading' a comment. There are thus some limits on the 'read and understand' procedure.

What should a theory be like?

In general, then, we have to admit that the 'facts' do not say anything on their own. As for any scientific fact, results in this kind of research are the products of a researcher's construction, which implies a choice of a field of investigation, units of description, observed characteristics, hypotheses and corresponding ways of grouping the data, and so on. It follows that as researchers, we cannot dispense with what has to be called, despite many necessary reservations, a theory. For the sake of brevity, I will not comment excessively on these reservations, which relate also to a necessary modesty about where we are now in Science Education. This being said, a theory, even if only sketched in, brings in a lot of constraints. What do we expect in return; on what criteria should we evaluate a theory? Very roughly, two points seem essential.

Firstly, the theory should be 'specified', i.e., it should be possible to distinguish this theory from another. This seems to be a provocative triviality, but we all know for instance that the use of new words does not suffice to say new things. An ideal way of characterising a theory would be to define experimental facts compatible with this theory and incompatible with others. In Science Education we are, however, still far from being able to relate every new assertion to anything which truly resembles a critical experiment. To recognise this is a necessary act of modesty.

Secondly, the theory should be effective in describing experimental facts. Even if not yet highly predictive, our theories can be evaluated according to a degree of effectiveness defined roughly as the ratio of the number of different 'questions and students' answers' taken into account divided by the number of 'inferred rules' used to describe these results. If we consider (figure 1) the various situations that prompted a student to express his or her ideas on the one hand, and the different features of the observed answers on the other hand, a description of the assumed underlying reasoning would be more or less of the form

IF (*set of situations*) THEN (*features of responses*).

(No specific allusion to the use of such a formulation in information processing is intended.) We could then say that the student answers as if he had in mind a 'conceptual structure', or a 'way of reasoning' described by this 'IF . . . THEN' rule. Shown as in figure 1 an effective description would imply few arrows and large 'bubbles'. An ineffective description would be a mere catalogue of one-to-one correspondences between situation and response features.

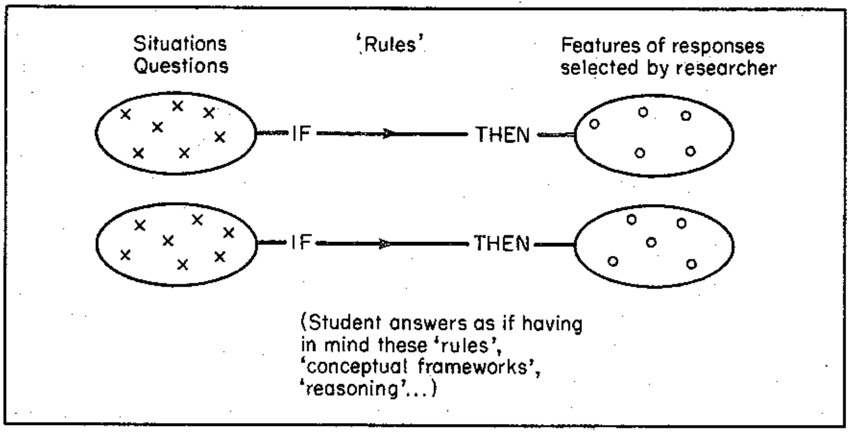


Figure 1. Groups of situations and responses related by rules.

The nature of the description: Phenomenology or explanation?

If we are now to illustrate, and refine this first outline of an effective description, some further questions arise. I will first consider the case in which the schema drawn in figure 1 apply rather directly.

The simplest case: answers strongly determined by the type of question

Let us imagine that, on a given conceptual domain, some regularities are actually observed in a student's responses in that some types of questions give rise to responses which present similar features, or, even better, similar 'groups of features'. This case thus simply described in fact implies two non-trivial operations:

(*a*) types of situations have been selected.

(*b*) types of responses have been selected.

The most fruitful choices of types of both kinds, according to our criteria of effectiveness, are not obvious. In particular, it is not obvious that the best selection will be on the basis of concepts deriving from the subject matter as it is taught, or as it is construed by experts. Indeed questions often appear to be grouped (implicitly) in students' minds according to unexpected characteristics. In other words the mapping of the subject matter is not necessarily the same for a student and for his/her textbook.

The statement of the 'inferred rule', or 'underlying reasoning' corresponding to the observed regularity can now be given in terms of an 'IF', specified by the type of question, and a 'THEN', followed by a list of features of answers. But it is also possible, and tempting, to describe the type of answer in a more global way, for instance, with a metaphor which is assumed to evoke through one expression all the features of the list. Table 1 gives some examples, borrowed from different studies:

There is clearly a choice to be made between two alternatives:

(*a*) One proposes the metaphor as a simple way of *suggesting or encapsulating* a list of features. Even the hypothesis of an internal consistency in these features is not strictly compulsory: the simultaneous occurrence of some features in the answers could be merely the reflection of a grouping of corresponding characteristics in the question. Such would be a purely phenomenological account of a regularity.

(*b*) Alternatively, one ascribes *explanatory power* to the metaphor: 'the student answers in this way because he is thinking of electricity advancing round the circuit, . . . because he is thinking of a supply of force, etc. . . .'. This is all the more tempting here, where the characteristics of the situations are included in the very description of the reasoning, so that a WHEN suggests a BECAUSE: the student is thinking of a supply of force because,

Table 1. Examples of situations, features of responses, and global descriptive metaphors, from various studies.

Situation and questions	*Features selected in responses*	*Global descriptive metaphor*
Series electric circuit with two identical passive components on either side of a third. Middle component is modified: what happens?	Source gives constant flow Changing middle component only affects what happens 'downstream'	'Sequential reasoning' Closset 1984 Shipstone 1984
A motion is a salient feature of a proposed situation. The forces acting on the moving body are not in the direction of the motion. Questions about the forces.	Confusions between force/velocity force/energy spatio-temporal delocalisation of 'forces' 'Force' ascribed to moving object ('Force of . . .').	'Supply of force' Viennot 1979
Vessels contain air under pressure. Nothing moves. Questions about the air.	The air does not push. There is no pressure.	'Pressure only has meaning if there is a displacement' Séré 1982 Engels 1982

looking at the upward motion of the ball, he cannot find any cause in the same direction.

Two questions arise concerning this choice:

(*a*) Is it possible to find criteria to decide between these alternatives?

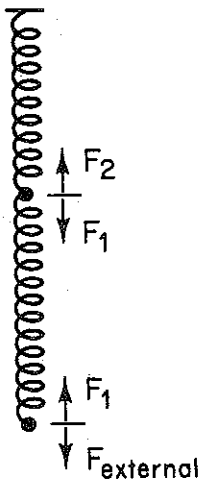
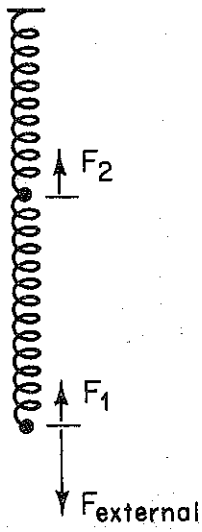
(*b*) Is there anything really at stake behind the choice? In other words, what is changed if a description is presented as phenomenological or explanatory?

I shall return to these questions, after having considered a less simple configuration of results than that just discussed.

A more complex case: correlations between features of responses

The more complex case, in which the question posed does not strongly determine a kind of answer, but in which a given feature of answers appears to be correlated with others, whatever the question that gave rise

Table 2. Two sets of correlated features of responses.

Set A	*Set B*
$F_{external} = F_1$ (lower spring) $= F_2$ (upper spring)	$F_{external} = F_1 + F_2$ Displacement of lower end = extension of spring 1 + extension of spring 2
$F_{external} = k_1 \times$ displacement of end of lower spring	
Schema: 	Schema: 

to it, can be observed. The determining aspect of the situation disappears, or diminishes, while the internal consistency of the response remains. This is the case in the following example, from a study by Serge Fauconnet (1982, 1984). The problem posed can be summarized as follows.

> Two springs of spring constants respectively k_1 and k_2, and free lengths l_1 and l_2 are suspended end to end from the ceiling. One pulls on the lower end and displaces it by 10 cm. What force is it necessary to exert and what is the displacement of the intermediate point?

Two sets of correlated features of answers can be observed, among others, as in table 2. As in the preceding case, it is tempting to ascribe to each set a global designation, more or less metaphoric. In this case the author associates set A with a vision of a force as a 'force transmitted from point to point all along the system', and set B with a vision of a 'force globally opposing internal resistances'.

This time the correlation existing between the features of an answer cannot be ascribed to some particular aspects of the situation proposed, for this situation is not really determining: a given student may happen when solving the problem to change the whole set of characteristics of his or her answer, in a kind of switching from one vision to another.

This case requires, more than the first, internal consistency in the sets of features selected. A global description is now much more than a convenient means of suggesting a list of features, since it is intended that the

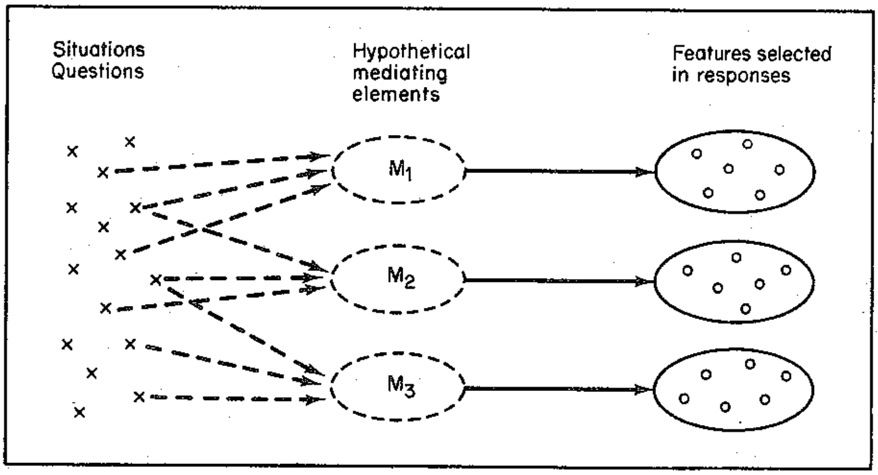


Figure 2. Correlated features of responses and hypothetical mediators.

metaphor, or the vision associated with a set, may constitute a mediating element in the solving process itself: that when confronted with a question, the student would 'read' it (Fauconnet 1982, 1984) or 'envision' it (Driver 1982) or find in it a suggestion of a 'prototype' (Guidoni 1983, 1984; diSessa 1981a, 1981b) in a way that would prompt a simultaneous coming together of the elements of the associated set of response features. Changing the vision would result in changing the whole set, even though the question might remain the same. This type of analysis can be outlined as in figure 2.

Figure 2 introduces two new elements, as compared with figure 1:

(*a*) A set of features of answers has now more than a name; it has a status.

(*b*) The broken arrows recall the fact that the questions are less strongly associated with a particular 'bubble'.

Again if such a description is to be effective, it must propose 'mediators' of a proper size, i.e. likely to appear in the context of more than one question, and specific enough in relation to the correlated features they imply in an answer. The different questions giving rise to the same mediator for a given student can be considered as analogous (in an implicit or explicit way) for this student; we should say analogous 'modulo' this mediator.

The distinction between the two types of description

Instabilities in associations between questions and answers added to correlations between several features of answers lead us to the idea of a 'mediator'. Coming back to the first, simplest, case now raises the following question: does the fact that the question is highly determining exclude the existence of a mediator? Or else: would a description of this type be only a restricted case of description of the more complex type for those cases in which the questions are especially strongly linked with a given mediator?

Nothing *a priori* prevents us from giving to the idea of sequential reasoning in electric circuits, to the metaphor of 'supply of force', or to the identification between cause and effect (pressure-displacement), the status of mediators. We would have only to change one or two words in the statement of conclusions. But the utility of doing so depends on the extension of the conceptual domain concerned, and is the less compelling when the answers seem strongly dependent on some overt characteristic of the questions. The two kinds of description are therefore but extreme cases in a continuum. Driver and Erickson (1983) suggest that conceptual frameworks rooted in kinaesthetic experience and common language are more general than those appearing when a student is presented with a new situation, and then appeals to unforeseeable analogies. This distinction seems quite appropriate, and could partly meet the distinction between the two cases. Such 'more general' conceptual frameworks, indeed, correspond (roughly speaking) to reasoning strongly determined by the situation (figure 1). However one should not consider that *any* rather universal set of features of answers is necessarily rooted directly in kinaesthetic experience. Sequential reasoning in electricity is a patent counter-example: no direct access is possible to the internal physical reality of a circuit, and, indeed, children are not the most fervent adepts of this kind of reasoning. It appears later, somehow catalysed by school learning (Closset 1984). On the other hand, one should not lose all hope of having more predictive information about analogical reasoning. Clements' (1981) work on this theme seems very promising.

Phenomenology or explanation: the unanswered question

Let us come back to our initial questions. Is it possible to decide if a description is only phenomenological or explanatory? Put differently, is a metaphor proposed by a researcher only an evocative label for a set of features of answers, or does it correspond to a functional, mediating, element of a student's reasoning? Of course, no simple criterion is available. As in any other scientific domain what is an explanation at a given level of theoretical development appears as phenomenological when another stage is reached. Human reasoning is an incredibly complex object of research, of which we can only reach some 'surface' aspects. A possible attitude (which is my present personal preference) could be very pragmatic: let us give up trying to sort out what cannot be distinguished, and let us speak simply of more or less effective description, of more or less useful 'mediators'.

However there is a second question which suggests a way to go further: is there really anything at stake behind this alternative, other than an interesting academic game? The answer seems beyond the scope of this paper, restricted so far to the question of describing a kind of 'state of reasoning'. If, however, we wonder how to *modify* students' conceptions, this last question becomes crucial, and transforms into another: if the teacher explicitly evokes the assumed mediator, will the interaction between student and teacher be easier?

Should we make 'mediators' explicit to our students?

Rather than worrying about the alternative between phenomenology and explanation, it might well be more useful to address the question of the implicit or explicit character of the assumed mediators. In this respect, it is important to recall that most of the time conceptual structures 'discovered' in such research seem totally implicit for the students themselves. This is why this kind of research is so difficult. This is also why it is useful; one of its potentially most positive outcomes is to enable students to become aware of their own ways of reasoning. But this access to awareness poses exactly the same problem of valid description – this time of self description – which we raised before: should we teach a student how to recognise a list of features in his/her own spontaneous answers, or shall we present him/her with a functional description of his/her intuitive reasoning? Should we evoke these hypothetical mediators suggested by our preceding investigations, and speak of 'springness' in spontaneous reasoning about motions (Guidoni 1983, 1984), or evoke something as an Ohm's law about a vacuum cleaner which is obstructed (diSessa 1981 a), or explain to the students that they are implicitly thinking in terms of a 'supply of force' or a 'supply of cause' (Viennot 1979)? These categories may fit as an account of the observed answers. But once stated explicitly, with or without previous re-statement, do they have any sense for the student? Do they help him/her act on his/her own reasoning? (See here the companion paper by Peter Hewson).

The simplest and ideal case consists in a 'mediator' effective in the description of students' spontaneous answers, which also gives rise, when explicitly stated to the student, to a fruitful interaction. But one can imagine mediators having only one of these properties. This question could contribute to designing future research.

Conclusions

This discussion of possible ways of describing students reasoning in science was centred on the idea of introducing as few as possible 'inferred rules' on the part of the students, and as few as possible new concepts on the part of the researcher, in order to account for experimental facts in a simple and effective manner. It appeared that the idea of mediating, functional elements of reasoning, suggested by different authors, was especially useful when

(*a*) the questions posed to students appeared to determine types of answers only rather loosely.

(*b*) the different possible answers seemed highly structured, and could be observed in similar forms with different questions.

Rather paradoxically, the case of strongly determining questions does not suggest any particularly straightforward interpretation. However one can then still hypothesise a strong association between a type of question and a given mediator corresponding to the observed answers, especially if this 'mediator' has been 'observed' in other contexts.

In this first part of the discussion the idea of a mediator has only been evaluated with respect to its utility in the description of students' reasoning. Nothing more is said, especially about possible degrees of 'profoundness' of reasoning: in particular there is no *a priori* reason for saying that strongly determining questions do not prompt 'profound' mediators.

The question of mediators can also be discussed along another dimension, directly linked to teaching, and which it is argued is the most relevant: a proposed mediator should be tested for its value in facilitating, when stated explicitly, fruitful discussions between students and teachers. Will the mediator be recognised by the students? Will it help them understand their errors and modify their responses?

Strictly speaking, a positive answer to these questions is not an undeniable confirmation of the existence of this mediator in students' reasoning, nor a negative one a proof of its absence. But it is these questions which are, finally, the most important.

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Appendix: Different interpretations of an incorrect answer

The problem below was discussed at the Workshop on Physics Education, La Londe les Maures, 1983. A number of the different interpretations given to the same wrong answer are described.

The problem (*Clement 1982*):

A rocket is moving along sideways in deep space, with its engine off, from point A to point B. It is not near any planets or other outside forces. Its engine is fired at point B and is left on for 2 seconds while the rocket travels to some point C.

(*a*) Draw in the shape of the path from B to C (show your best guess for this problem even if you are unsure of the answer).

(*b*) Show the path from point C after the engine is turned off, on the same drawing.

Figure 3 shows the positions A, B and C, the correct answer and a typical incorrect answer. The incorrect answer could be glossed as supposing that the force of the engine combines with whatever was making the rocket go

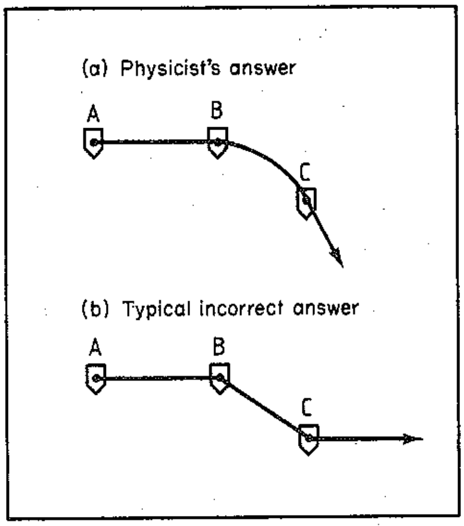

Figure 3. Correct and incorrect answers to rocket problem.

from A to B, to produce path BC. After C, whatever made it go from A to B will take over and make it go sideways again, causing the rocket to return to its original direction of motion.

Some interpretations

Clement: Students reason as if motion implies a force.

Guidoni: This is an example of 'spring-like' reasoning (which is extremely general), according to the following parallel:

1 a spring is in a given state
2 you push on the spring which changes its state
3 you release the spring and the initial state is restored

1 the motion (AB) is of a given kind
2 you fire the engine which changes the motion
3 you stop the engine and the initial motion is restored.

Fauconnet, Viennot: The sideways initial motion evokes a driven motion – like a swimmer drifting in a river. The firing of the engine evokes the idea that the 'swimmer' now swims. The engine stops, evoking the idea that the 'swimmer' is once again just drifting.

References

CLEMENT, J. 1981, Analogy generation in scientific problem solving. *Proceedings of the 3rd International Meeting of the Cognitive Science Society.*

CLEMENT, J. 1982, Students' preconceptions in introductory mechanics. *American Journal of Physics*, Vol. 50, pp. 66–71.

Closset, J.-L. 1984, Sequential reasoning in electricity in *Recherche en Didactique de la Physique, les Actes du Premier Atelier International, La Londes les Maures 1983*, (Editions du CNRS, Paris).

DiSessa, A. (198a), Unlearning Aristotelian physics. *Working Paper 10, Division for Study and Research in Education* (MIT, Cambridge, MA).

DiSessa, A. 1981b, Phenomenology and the evolution of intuition. *Working Paper 12, Division for Study and Research in Education* (MIT, Cambridge, MA).

Driver, R. 1982, *The pupil as scientist?* (Open University Press, Milton Keynes).

Driver, R. and Erickson, G. 1983, Theories in action: some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education*, 10, pp. 37–60.

Engel, M. E. T. 1982, The development of understanding of selected aspects of pressure, heat and evolution in pupils aged 12 to 16 years. PHD thesis, University of Leeds.

Fauconnet, S. 1982, Exploring the way students solve physics problems: a study about problems of similar structure. Rapport interne LEPES, Universite Paris VII.

Fauconnet, S. 1984, Etude de résolution de problèmes analogues. *Recherche en Didactique de la Physique, les Actes du Premier Atelier International, La Londes les Maures 1983* (Editions du CNRS, Paris).

Guidoni, P. *et al.* 1983, Structures of understanding at the roots of science education. Part 1. *European Journal of Science Education*, Vol. 5, pp. 367–375.

Guidoni, P. 1984, Phenomenology of the understanding and misunderstanding of physics. *Recherche en Didactique de la Physique, les Actes du Premier Atelier International, La Londes les Maures 1983* (Editions du CNRS, Paris).

Hewson, P. 1985, Epistemological commitments in the learning of science. *European Journal of Science Education*, Vol. 7, No. 2, pp. 163–172.

Séré, M.-G. 1982, A study of some frameworks used by pupils aged 11–13 years in the interpretation of air pressure. *European Journal of Science Education*, Vol. 4, pp. 299–309.

Shipstone, D. M. 1984, A study of childrens' understanding of electricity in simple DC circuits. *European Journal of Science Education*, Vol. 6, pp. 185–198.

Viennot, L. 1979, Spontaneous reasoning in elementary dynamics. *European Journal of Science Education*, Vol. 1, pp. 205–221.