INT. J. SCI. EDUC., 1991, VOL. 13, NO. 2, 159–170

Students' reasonings in thermodynamics

S. Rozier and L. Viennot, L.D.P.E.S., University of Paris 7, France

Some tendencies in common reasoning aim at reducing the complexity of multi-variable problems. Two main aspects of these tendencies are illustrated here with results of an investigation of students about thermodynamics:

1. A physical quantity which depends on several others may be treated as if it were depending on only one. Such a reduction of the number of variables may also be obtained by combining two of them, as if they were two facets of the same variable. For example, mean distance between particles and mean speed are treated as equivalent aspects of thermal motion. This results in a linear shape of argument $\phi_1 \rightarrow \phi_2 \rightarrow \phi_3 \rightarrow \ldots$, where each phenomenon ϕ_n evoked is specified with only one physical quantity.
2. Some apparent contradictions in students' responses may be understood if one admits that there is a chronological connotation in the argument: an arrow, '→', or a 'then', means not only 'therefore', but also 'later'.

The pedagogical implications of the findings are discussed, mainly in relation to teaching goals.

Introduction

Thermodynamics is a subject that involves multi-variable problems. The behaviour of a large number of particles is described using a small number of variables which represent mean values or macroscopic quantities. These variables can be linked, at thermodynamic equilibrium, by certain relationships, for example $pV = nRT$ for perfect gases. In any transformation, such relationships hold for initial and final equilibrium states. In transformations considered as *quasi-static*, these relationships also hold for any intermediate state which are then also considered as equilibrium states. That is to say, we have to consider *several variables*, usually more than two, *changing simultaneously* under the constraint of one or several relationships.

Such a mental activity involves obvious difficulties. Piaget and Inhelder (1941) have shown that children, dealing with three kinematic variables (s, v, t), actually consider one of these quantities to be linked to a single other one: 'the faster, the further'. Other studies have shown similar difficulties (Viennot 1982, Maurines 1986).

In this paper, we will illustrate, in the domain of thermodynamics, how students and others commonly reduce the intrinsic complexity of such problems. These tendencies towards 'functional reduction' in common reasoning will be shown to range from a simple reduction in the number of variables considered, to a more elaborate procedure where all the variables are taken into account, but in a simplified way involving 'linear causal reasoning'.

The experimental facts supporting our analysis come from a study by Rozier (1987). The students in the study ($N \simeq 2000$) were drawn from courses in the first four years at the University of Paris 7 and from a selective course preparing French 'grandes écoles d'ingénieurs' (two years after baccalaureat). In addition, 29 teachers on an in-service training programme also participated in the study. After undertaking exploratory interviews ($N = 9$), this study was conducted mainly on the basis of written questionnaires. The complete study draws on results obtained with eleven questionnaires. Only four of them are mentioned here, for the sake of brevity. Their main characteristics are shown in table 1. These questionnaires were selected because of the relative simplicity of the physical situations involved – although nothing in thermodynamics is really simple. Because of the similarity of results for the different population subsamples, we do not report the results for each separately. We also quote excerpts from textbooks, popular science books and research papers in science education, as well as teachers' reactions in training sessions, in order to show to what extent and in what manner students' common ways of reasoning are shared by different categories of professionals in science.

Reducing the number of variables

(*a*) *Forgetting some of them*

The first question (Q1) illustrates students' most general and obvious tendency in coping with multi-variable problems, which is to forget some relevant variables.

Figure 1 summarizes the questions posed (a written test) and the most frequent responses. When asked to explain in molecular terms why pressure increases in an adiabatic compression of a perfect gas, 50% of the students gave answers such as:

> The volume decreases; therefore the molecules are closer to one another; therefore, there are more collisions and the pressure increases.
> The volume decreases; therefore, there are more molecules per unit volume and, hence, the pressure increases.

These responses may be outlined in the following way: $V \searrow \rightarrow n \nearrow \rightarrow p \nearrow$.

In the students' comments, an increase in pressure is ascribed only to an increase in the 'number' (per unit volume, which is often implicit) or 'density' of particles. Nothing is said about the other relevant aspect from a kinetic point of view, i.e., the mean speed of particles. Other questions in this study confirm this preferential link between pressure and 'number of particles'. In what follows, we will refer to such links as *preferential associations* between two variables.

Such a tendency in reasoning is not limited to students. As an example, let us quote an excerpt from a book of popular science (Maury 1989) considered as very good by many physics university teachers (informal evaluation, in France): 'Planes fly very high, at an altitude where molecules of air are much less numerous, and therefore the pressure of the external air on the window is much lower than at sea level'. This explanation may be summed up in the following way: $n \searrow \rightarrow p \searrow$; note that nothing is being said about temperature. The same single variable dependency as in students' comments is observed, despite the fact that at the altitude considered, ($\simeq 10$ km), the temperature is much lower than at sea level (there is a 25% decrease in absolute temperature), which also contributes to the lowering of pressure.

Teachers in different training sessions (secondary education: $N = 30$, first cycle, Paris; $N = 25$, both cycles, Milan) were invited to criticize the excerpt. In every session, more than 95% accepted it without any modification and, when the change in temperature was pointed out, the great majority of teachers said that it was 'not the important phenomenon' and that it was not necessary to specify what happened to this quantity. Five pages further in the same book, the hot air balloon is presented and 'explained' using the fact that when the temperature increases, it contains 'less and less air'. So the 'number of particles . . .' decreases. Yet, in the hot air balloon the

Table 1. Main features of the four written questionnaires quoted in this paper.

Question	*Physical situation*		*Type of question*	*Sample*	
				Students	*Teachers*
Q1, Q1 bis (Figure 1)	Transformation of a perfect gas	Adiabatic compression	Explain why . . .	111	29
Q2 (Figure 2)		Heating at constant volume	Predict . . . Explain why . . .	255	28
Q3 (Figure 3)		Heating at constant pressure	Explain why . . .	120	0
Q4 (see text)	Change of state	Liquefaction	Comment on a text	181	0

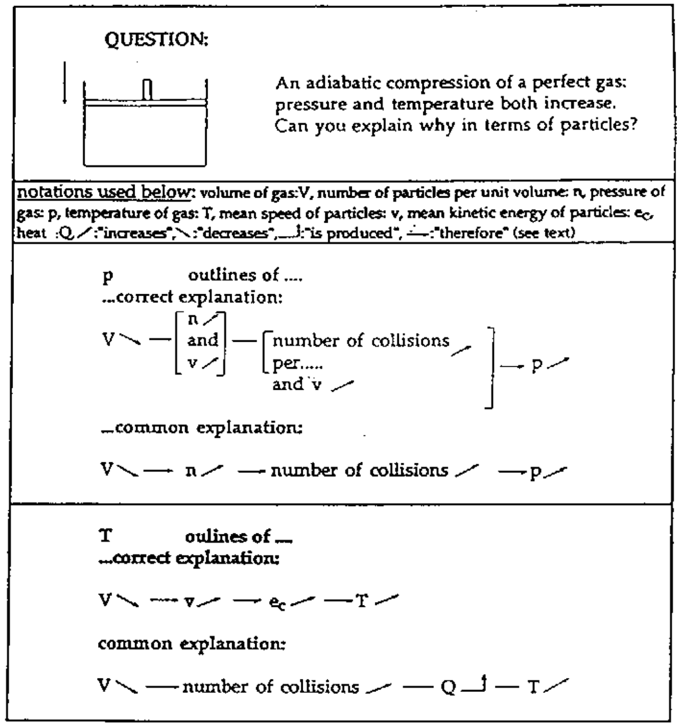


Figure 1. Questions about an adiabatic compression, and correct and typical responses.

pressure inside is not lower than that outside, due to temperature. No connection is made with the explanation previously proposed for low pressure outside the aircraft.

Such *ad hoc* variations on the equation of state for perfect gases, $pV = nRT$, are typical of the inconsistencies introduced by the common tendency towards ‘functional reduction’ and a call on preferential associations with no mention of other relevant variables.

Incidentally, we are not suggesting here that such textbooks *generate* the kind of reasoning described in this paper. We simply note that their content reflects, or at least is highly compatible with, the same typical features as the reasoning commonly observed in students or teachers. Rather than propose an oriented causal relationship between the contents of textbooks and students’ reasonings, we should probably think of a kind of mutual resonance. Other quotations from textbooks given later in this paper are to be understood in the same way.

(*b*) *Combining two variables*

Reducing the number of variables may be obtained by another process also observed in other domains: two physical quantities seem to be ‘stuck together’: This is the case, for instance, for the mean distance between particles and the mean kinetic energy of particles (Rozier 1987). The name frequently used for this compound notion is ‘thermal motion’, and its cement is the idea of disorder. In fact, only one of these quantities is determined only by temperature, namely the mean kinetic energy of particles. The other is also linked with other aspects: pressure and shape of potential of interaction between particles for solids and liquids. Students’ reasoning and comments in this respect will be analysed in detail in what follows. Let us now start with teachers’ and researchers’ quotations.

In the book previously mentioned, one may read: ‘Particles need more room to move faster.’ In research reports, so-called ‘accepted ideas’ often give the impression of an adherence between these two – kinetic and geometrical – aspects. For instance, about thermal expansion (Lee *et al.* 1989):

> When a substance is heated, the molecules of the substance move faster and, therefore, move faster apart, which causes the substance to expand. In contrast, when the substance is cooled, the molecules move more slowly and move closer together, so the substance contracts.

Or, still more simply, a very commonly accepted idea is that thermal motion is much higher in gases (larger mean distance between particles) than in liquids (smaller mean distance between particles), and larger in liquids than in solids. This is illustrated by the following excerpts from French textbooks or printed university materials:

> In some solids, such as glass, and many plastics, molecules are squashed against each other and cannot move. (Sciences Physiques 1980)
> When cooling down a liquid, particles become motionless without any order; it is an amorphic solid. (Centre de Tele-Enseignement 1985–86)

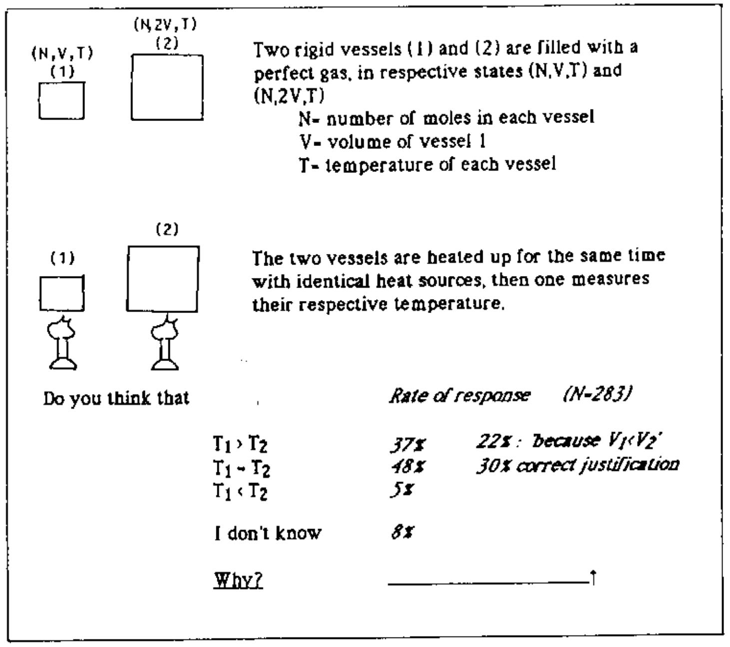
However, as already mentioned, thermal motion, if meant as mean kinetic energy of particles, is only a function of temperature. It is therefore the same for the water in the sea, the air just above, and a stone on the beach, in as much as they are all at the same temperature.

(*c*) *Lack of symmetry in implications*

A striking feature in the way single-variable dependencies are commonly handled is a lack of symmetry in implications. Indeed, in the accepted theory of quasi-static transformations, variations are simultaneous and, therefore, the implications are symmetrical (provided that the variables which are kept constant are specified). A typical example is the following: the commonly accepted implication $V\searrow \rightarrow p\nearrow$, which was discussed above, seldom appears to be applied in reverse: $p\nearrow \rightarrow V\searrow$.

This lack of symmetry may even occur in implications concerning some variables which are, most of the time, simply stuck together and therefore interchangeable in a symmetric relationship. This is the case for two variables combined in the compound notion of ‘thermal motion’: temperature and volume. As shown further in the paper, students are familiar with the $T\nearrow \rightarrow V\nearrow$ implication for a heated gas. But it is not so common, as classroom practice shows, to say that expanding a gas results in an increase in temperature.

Another result also suggests, although indirectly, that students would not unconditionally reverse the preceding implication. This follows from a question given to students in Rozier’s (1987) inquiry (Q2, see figure 2) in which the following situation is presented: an equal amount of heat is transferred to two systems consisting of the same numbers of particles of a perfect gas at the same temperature, but in containers of different volumes. Twenty-two per cent of students ($N = 255$) or teachers ($N = 28$) gave responses equivalent to this: ‘The amount of heat is more diluted in the larger container, so the temperature does not increase as much as in the



Two rigid vessels (1) and (2) are filled with a perfect gas, in respective states (N,V,T) and (N,2V,T)

N= number of moles in each vessel
V= volume of vessel 1
T= temperature of each vessel

The two vessels are heated up for the same time with identical heat sources, then one measures their respective temperature.

Do you think that

	Rate of response (N=283)	
$T_1 > T_2$	*37%*	*22% : ‘because $V_1 < V_2$’*
$T_1 = T_2$	*48%*	*30% correct justification*
$T_1 < T_2$	*5%*	
I don't know	*8%*	

Why? ____________

Figure 2. A question from Rozier’s (1987) study and corresponding rates of response.

smaller container.' This can be summarized as 'larger volume→smaller increase in temperature'.

In conclusion to the first section we suggest that common types of reasoning observed in students and teachers are characterized in the following way:

In the implications used, $\phi_1 \rightarrow \phi_2$, '$\phi$' refers to *a phenomenon specified with only one variable*, for instance, 'p increases' or 'input of heat'. When several variables are mentioned (see figure 1), this is done through an argument which links the variables in a linear chain:

$$\phi_1 \rightarrow \phi_2 \rightarrow \phi_n \rightarrow \ldots$$

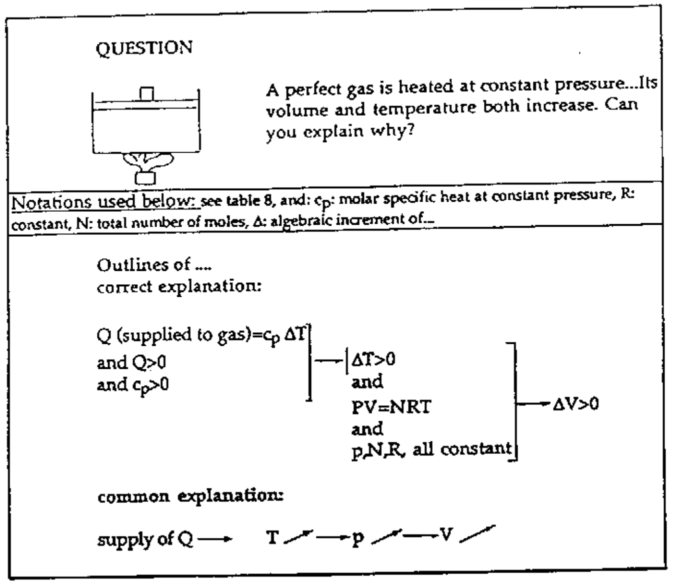
However, each specific implication $\phi_n \rightarrow \phi_{n+1}$ does not imply that the reverse implication would be accepted by the same person.

Causality and chronology: the linear causal reasoning

A very common (43%, $N = 120$ students) 'explanation' of the increase in volume resulting from the heating of a perfect gas at constant pressure is of the following type (Q3, see also figure 3):

> The temperature of the gas increases. Knowing that in a perfect gas $pV = nRT$, therefore at constant volume, pressure increases: the piston is free to slide, therefore it moves and volume increases.

This response can be outlined in the following way: supply of heat $\rightarrow T \nearrow \rightarrow p \nearrow \rightarrow V \nearrow$ (with obvious notations). In such comments, one of the evoked events, $p \nearrow$, contradicts data presented in the problem, namely that p is kept constant.



QUESTION

A perfect gas is heated at constant pressure...Its volume and temperature both increase. Can you explain why?

Notations used below: see table 8, and: c_p: molar specific heat at constant pressure, R: constant, N: total number of moles, Δ: algebraic increment of...

Outlines of ....
correct explanation:

Figure 3. A question about an isobaric heating of a gas, and correct and typical responses.

Table 2. Shift in meanings from logical to chronological levels.

Level	*French*	*English*	*Spanish*
Logical	donc	therefore	por eso
Intermediate	alors	then	entonces
Chronological	ensuite	later	despues

Such a contradiction (and others, as we will see) disappears if one admits that this form of argument is interpreted *temporarily*. An arrow, then, does not mean only 'therefore', but also 'later'. Table 2 shows how, in three and probably many other languages, these logical and chronological levels melt into a single word, totally ambivalent; this, in English, is 'then'.

As usual, there is no reason to consider that language is more a cause than a consequence of a common kind of reasoning. Let us simply note the high degree of compatibility of several languages with the feature of common reasoning analysed here: a subtle input of time in a logical argument.

Seen from this point of view, the previous chain subdivides into two steps:

First step: 'Supply of heat $\rightarrow T \nearrow \rightarrow p \nearrow$', with the volume being implicitly or explicitly kept constant. Notice that such a constancy of volume is a sufficient condition for the two first implications to be straightforward. At constant volume, an input of heat, in the accepted theory, necessarily results in an increase in temperature (no work being transferred to the exterior of the gas). The same condition also allows the otherwise not obvious conclusion that, if the temperature increases, the pressure increases.

Second step: '$p \nearrow \rightarrow V \nearrow$'. The piston is now released (this is said explicitly by some students) and moves until the internal pressure is equal to the external one. In such a chronological view, the seemingly contradictory argument '$p \nearrow$ (during isobaric heating)' becomes acceptable, as well as the statement 'at constant V', followed by this other: 'volume increases'. These events indeed are understood as *successive*, and therefore as *temporary*. So they seem no longer contradictory.

To sum up: this kind of response supports the hypothesis that a linear type of reasoning is used, namely, $\phi_1 \rightarrow \phi_2 \rightarrow \phi_n \rightarrow \ldots$, in which, as said earlier, each phenomenon ϕ is specified with only *one* physical quantity, and where the causality referred to by the arrow has *both* a logical and chronological content. The temporal connotation of such an implication accounts for the lack of symmetry described above. This way of reasoning contradicts the accepted theory of quasi-static phenomena, in which the changing physical quantities are all supposed to change *simultaneously* under the *permanent* constraint of one or several relationships. But this makes it possible for variables to be coped with two by two, and for different things to be said about one of them at different stages of the argument.

Other inconsistencies become acceptable in this linear causal reasoning, as it will now be shown.

Linear causal reasoning and the problem of steady states

Another question (Q1 bis) from Rozier's (1987) study provides evidence of how the features of linear causal reasoning just described fit in with students' most common responses and allow comments which, in the accepted theory, lead to contradictions. Asked to explain in molecular terms why an adiabatic compression of a perfect gas results in an increase of temperature (see figure 2), 42% of students ($N=140$) gave comments of this type:

> 'When the piston is pushed down, the volume decreases; therefore, particles are closer to each other, so more collisions occur between them... and there is an increase in temperature.'
> 'Same number of particles in smaller volume, then particles more squashed, more collisions, more heat produced.'
> 'More collisions between particles, more energy produced due to friction.'

These responses can be outlined as follows: $V\searrow \rightarrow n\nearrow \rightarrow$ number of collisions $\nearrow \rightarrow Q$ is produced $\rightarrow T\nearrow$, the fourth statement being justified by the fact that 'collisions produce heat'. Again a linear form is observed. Let us see now how the hypothesis of a temporal content is supported by this last comment, namely, 'collisions produce heat'.

In such a comment, one can see an emergence of the well-known preferential association between temperature and heat, which is that an increase in temperature is ascribed, in common reasoning, to a supply of heat. One can also say that macroscopic properties of bodies colliding inelastically are ascribed to microscopic particles.

Valid though these interpretations may be, they do not explain how it is that none of these students recognized the incompatibility between the statement 'collisions produce heat' and the idea of steady state. Indeed, if in an adiabatic vessel collisions between particles were continuously producing heat, an explosion would soon occur. But if the statements 'collisions produce heat' or 'there is some heat produced' refer to a temporary phenomenon, as in the 'chronological' interpretation of students' reasoning, there is no longer any incompatibility with the idea of steady state. Interestingly, some students in this inquiry (and others informally questioned in a classroom) stated that more collisions produced more heat *during the transformation*, but that at the end of the transformation the production of heat stopped: the end of the argument is also the end of the story...

So, it seems that seeing the evoked phenomenon as temporary avoids the difficulties inherent to the analysis of steady states. Such states are not envisaged for themselves, but as the result of transitory phases, themselves analysed as a step-by-step and variable-by-variable processes. All this is done, in common reasoning, without saying it, and probably without being aware of it.

Most probably, teachers largely share this tolerance towards explanations incompatible (according to accepted logic) with steady states. Some teachers were asked during training sessions to consider what answer they would give to a student who says 'collisions between particles produce heat'. None of them proposed a counter-argument in terms of steady states... Other examples of this teachers' tolerance are given by Rozier (1987) (see also Viennot 1991).

Interpreting a common idea in terms of linear causal reasoning: changes of states and thermal motion

As already stated, the idea that thermal motion is more intense following the order: solid→liquid→gas, is wide-spread among students and teachers. At first sight, this might be simply a manifestation of an adherence to the connection between mean

kinetic energy and mean distance between particles that is commonly referred to by the expression 'thermal motion' and cemented by the idea of disorder.

An experiment was performed by Rozier (1987) using university students in order to explore this point of view and to see whether linear causal reasoning was of help in interpreting common ideas in this field. The following excerpt from a textbook (Valentin 1983) was first given to students:

> Thermal energy possessed by each molecule is large enough to prevent the molecules of the gas from being bound: in a gas, molecules are continuously hitting each other and bouncing. But if the temperature is lowered, the system will be able to become liquid and even solid. Such physical phenomena occur when, with decreasing temperature, molecules have so low a mean kinetic energy that they cannot any longer resist the electromagnetic interaction. They first gather in liquid state and finally get bound in solid states.

The questions posed (cf. table 1, Q4) were:

1. Do you think that this text suggests the following statements?

   Statement 1: At a given time during the liquefaction, the mean kinetic energy of a molecule of gas is larger than the mean kinetic energy of a molecule of liquid (liquid and vapour are in thermal equilibrium at the time considered).
   Statement 2: At a given time during the liquefaction, the mean distance between particles is larger in the gas than in the liquid.

2. Do you think that

   statement 1 is true or false?
   statement 2 is true or false?

   Give your reasons.

Among 181 students in the three first years at university, 77% thought that the text does suggest the first statement, and 69% thought this statement to be true. The corresponding percentages for statement 2 were 80% ('the text suggests statement 2') and 85% ('statement 2 is true').

As mentioned earlier in the paper, in terms of classical thermodynamics, mean kinetic energy depends only on temperature; it is, therefore, the same for systems at same temperature, for instance two phases of a substance in thermal equilibrium. The author of the text makes this point one page after the excerpts, but it was not reproduced in the test.

In interpreting these facts, one may first notice the strong input of temporal connotations in the text: 'If... the system will be,... they cannot resist any longer,... first... finally... .'

This implied chronology superimposes on the logical chain, as follows: $T\searrow \rightarrow e_c\searrow \rightarrow$ electromagnetic interactions win→liquid state→...→solid state. Employing both linear and chronological argumentation, this text seems in perfect resonance with the features characterizing the 'linear causal reasoning'. The idea subtly induced by such a chronology is that the story begins with high temperature and gaseous state, and finishes with low kinetic energy and the liquid state, with no room being left to envisage simultaneously gaseous and liquid states at same temperature. All these students knew, however, that at thermal equilibrium the two phases are at same temperature.

The very high percentage of students who accepted statement 1 as true supports the hypothesis that they shared the type of reasoning described earlier (linear causal reasoning); they were apparently encouraged by the text to do so.

Discussing our teaching goals: some concluding remarks

There are various points which can be discussed at length about the correctness, or otherwise, of some of the excerpts quoted above. One might then ask whether comments such as 'at high altitude, there are fewer molecules, so pressure is lower' or 'thermal motion is higher in gases than in solids' or 'molecules have so low a kinetic energy that they can no longer resist the electromagnetic interactions . . .' should be banished or not. But this is not the point of interest here. Rather than discussing the correctness of these statements, let us just note that such 'soft qualitative reasoning' glosses over the difficulties of multivariable reasoning; that, most of the time, this is not pointed out; and that the contradictions which may arise from a careless extension of these simple and evocative explanations are not confronted. These facts deserve attention and bring us back to the crucial question: what are our teaching goals? Are they to make students familiar with the particulate, or atomic structure of matter, or with other ideas of phenomena? Or are they to teach students how to reason in a coherent way (in particular with several variables), and to show them the limits of each level of explanation?

The latter question is deliberately put in a provocative way. The fact is that, in the constructivist view so widely shared now among researchers in science education, familiarity with ideas is of no real value if a personal construction of concepts by children has not occurred. In other words, there cannot be any conceptual learning *without* any reasoning. So we can drop our first alternative and replace it by the question:

> Which kind of reasoning do we aim at for our pupils or students when introducing such and such ideas or phenomena? This question itself divides into two subquestions:
>
> Which (available) kind of reasoning will help students to grasp new concepts (for example in an inductive progression)?
>
> Which kind of reasoning will they learn?

It seems to us that it is important to be extremely careful in such a specification. For instance, inductive procedures aimed at introducing particulate ideas raise the question: which experiments in physics support a particulate model rather than a continuous one, and *according to which logic* do they do so? For example, a classical theory, hydrodynamics, accounts for changes of volume and flows with a continuous model which, of course, respects all the necessary conservations, dynamic ones included. Likewise, quantum mechanics is also continuous with respect to space.

Many teachers are unaware of this lack of evidence. In a workshop in a recent international conference (Enciso *et al.* 1989) participants were asked which experiment(s), from the following, were the most appropriate to introduce particulate ideas:

change of state,
dissolution,
difference in colour for different concentrations,

expansion and compression of a gas,
diffusion,
non-additivity of volumes in the mixing of water and alcohol.

About a third of participants chose the expansion and compression of a gas. So, there is a danger of pseudo-demonstrations.

This would support the choice made by, for example, Barboux *et al.* (1987) first, to introduce the basis of a particulate model *ex cathedra* and then ask children to work on it. However, this leads to the question: What kind of work should we involve the students in as their learning activity? Work on the conservation of mass and number of particles through changes of volume or changes of states has been proposed by several authors (for instance, Barboux *et al.* 1987) and would appear to be very appropriate for paving the way to learning the basis of chemistry. Then the difficulty is again to specify what kind of work can be done in a *consistent* way. One may envisage activities of a descriptive type: children or students have to describe in terms of a particulate model changes of volume or changes of states. This may also be consistent with goals which emphasize explanations.

The difficulties stressed in this paper suggest that, at any level of teaching, only two attitudes are self-consistent. One is to be extremely careful about the degree of 'explanation' actually expected, and to specify what cannot be accounted for in the frame of the proposed description. Thus, for instance, the following levels of understanding may be envisaged.

'Gases can change their volume to a large extent, but (without the beginning of a kinetic theory) we cannot explain why they resist compression before molecules are in contact.'

'Solids expand when heated (or contract when cooled), but we cannot (yet) explain why. Knowing that thermal motion increases (or decreases) in such a case, is not enough to explain why this makes the solid expand. Indeed, the particles might vibrate more intensely, and stay around the same place without drifting' (a matter of anharmonicity of the potential of interaction between particles!).

'At equilibrium between, say, liquid and gas, thermal motion (mean kinetic energy) is the same in the two phases, and we cannot (yet) explain this surprising thing. In other words, we cannot explain why, with the same thermal motion, some molecules are linked to each other and others are free. We cannot explain why thermal motion remains the same during the change of state. We know indeed that an input of heat is used to break the links between particles in a liquid. But we do not know why it is used only for this and not also to increase thermal motion.'

A second possible teaching strategy is to work with some 'soft' explanations, but without hiding the dangers of a careless extension of such explanations to other cases. For instance the idea that 'at a high altitude, there are fewer molecules, therefore pressure is lower' requires the addition: 'This reasoning works only if the molecules have (more or less, admittedly) the same velocity in the two compared cases.' Or the idea that 'when a tyre is heated up, it becomes harder because the molecules have a larger mean speed' . . . requires the caveat 'this reasoning works only if the same number of molecules is still in the same volume'. (Obviously, this is not the case since the tyre is harder, but an approximate constancy of volume may be invoked.)

This kind of *harder qualitative reasoning* may be considered too demanding, but it is the price to pay for consistency in dealing with such phenomena.

Of course, if one is interested in fostering the multi-variable reasoning for itself, rather than illustrate phenomena connected with particulate structure of matter, one may choose simpler examples first, e.g., that the area of a rectangle is a function of two variables: hard qualitative reasoning may be trained on similar simple examples.

Teaching goals relating to general features of reasoning, are not much in favour at the moment, overshadowed as they are by more content-specific objectives. However, at least one point must be made clearly: in our students, linear causal reasoning will be the most likely outcome of teaching and yet is not confronted in the teaching. Therefore, we cannot avoid a debate about our teaching goals, which should more explictly consider the kinds of reasoning we expect our pupils or students to learn.

Acknowledgement

The help received from Rosalind Driver in the preparation of the English version of this paper is gratefully acknowledged.

References

Barboux, M., Chomat, A., Larcher, C. and Meheut, M. 1987, Modèle particulaire et activité de modélisation en classe de quatrième. Rapport de fin de recherche INRP no. 1.098485, Paris.

Centre de Télé-Enseignement, Université Paris 6, DEUG SSM 1, année O, Chimie, année 1985–1986.

Enciso, E., Llorens, J. A. and Sendra, F. 1989, La introduccion a los conceptos basicos de Quimica en el nivel 12–16 anos, una propuesta didactica inspirada en los modelos de cambio conceptual. Workshop held at the 3rd International Congress on Research in Science and Mathematics Education, Santiago de Compostela, Spain.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkeimer, G. D. and Blakeslee, T. D. 1989, Changing middle schools students' conceptions of matter and molecules. Paper presented to the A.E.R.A. meeting, San Francisco, USA.

Maurines, L. 1986, Premières notions sur la propagation de signaux mécaniques: études des difficultés des étudiants. Unpublished thesis, University of Paris 7.

Maury, J. P. 1989, *La glace et la vapeur, qu'est-ce que c'est?* (Ed. Palais de la découverte, Paris), p. 27.

Piaget, J. and Inhelder, B. 1941, *Le developpement des quantités physiques chez l'enfant* (Delachaux-Nestlé, Neufchatel).

Rozier, S. 1987, Le raisonnement linéaire causal en thermodynamique classique élémentaire. Unpublished thesis, University of Paris 7.

Sciences Physiques 3ème. 1980, Classiques Hachette, collection libre parcours, Paris.

Valentin, L. 1983, *L'Univers Mécanique* (Hermann, Paris).

Viennot, L. 1982, L'implicite en physique, Les étudiants et les constantes. *European Journal of Physics*, vol. 3, pp. 174–180.

Viennot, L. 1991, Participation des maitres aux difficultés des élèves (in Spanish) 3rd International Conference on Research in Science and Mathematics Education, Santiago de Compostela, to be published in *Ensenanza de las Ciencias*.

Correspondence

Professor L. Viennot, L.D.P.E.S., Université Paris 7, Tous 23, Place Jussieu, 75251 Paris Cedex 05, France.