International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: http://www.tandfonline.com/loi/tsed20

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To cite this article: Ugo Besson & Laurence Viennot (2004) Using models at the mesoscopic scale in teaching physics: two experimental interventions in solid friction and fluid statics, International Journal of Science Education, 26:9, 1083-1110, DOI: 10.1080/0950069042000205396

To link to this article: http://dx.doi.org/10.1080/0950069042000205396

Published online: 22 Feb 2007.

INT. J. SCI. EDUC., 16 JULY 2004, VOL. 26, NO. 9, 1083–1110

Using models at the mesoscopic scale in teaching physics: two experimental interventions in solid friction and fluid statics

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This article examines the didactic suitability of introducing models at an intermediate (i.e. mesoscopic) scale in teaching certain subjects, at an early stage. The design and evaluation of two short sequences based on this rationale will be outlined: one bears on propulsion by solid friction, the other on fluid statics in the presence of gravity. Both concern students in the first university year and were designed with common conceptions of students on these topics as a guide. The common points and the differences of the two sequences are discussed, and particularly the characteristics of the mesoscopic approach. The evaluation is made by analysing the recordings of class discussions and comparing the results of control groups via written questionnaires. Teachers' reactions have also been documented. These elements show that the proposed mesoscopic models encourage a more articulated reasoning on the physical situation, helping students to reconcile a global description with the analysis of local interactions.

Introduction

Modelling seems central to physics, given that concepts and theories are constructed, and not a mere translation of 'reality'. Researchers in didactics have emphasized the critical importance of making students and teachers aware of the distance that exists between reality and elements of a model. This said, it is not so simple to find a clear line of demarcation. Finally, one might say that nearly every entity involved in accepted science, including apparatus, is, ultimately, part of a model. On the other hand, some elements of a model have reached such a high unifying power in the physical description that they also have a quasi-ontological status: who would seriously put in doubt that atoms do exist? Correspondingly, when one decides to involve a model in the teaching–learning process, it is not easy to convey clearly whether this is to teach the value of models and modelling (Méheut 1997, Vollebregt 1998), or to give access to entities whose 'existence' is universally taken for granted (Brook et al. 1984).

A second aspect worth discussing is the actual explanatory power of one scale of modelling versus another, especially in teaching at secondary school or college levels. This explanatory power, we think, should not be taken for granted on the sole basis of the role that a model plays in academic physics. As Millar wrote several years ago:

International Journal of Science Education ISSN 0950–0693 print/ISSN 1464–5289 online ©2004 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0950069042000205396

> We may, in the aspects of kinetic theory we have emphasised, have been unduly influenced by the elegance of the kinetic theory explanation of the gas laws. (1990: 290)

This distinction between elegance and opportunity is especially critical as regards the kinetic molecular model. This model is of greater use in helping to understand the geometric-kinetic properties of gases — change of volume, diffusion — than the thermo-elastic aspects, which involve the dynamic properties of molecules. More generally, a microscopic description often proves to be excessively complicated and too difficult to master. Liquids are an even more difficult case, because interactions between molecules contribute to pressure at the same order of magnitude as molecular dynamics. Friction between solids is no simpler in this respect.

On the other hand, there is often a need to find an alternative to a purely macroscopic description. As we will show in the following, we are often left, at the macroscopic scale, with an explanation of the type: 'things *have to* be that way [for such and such law to be respected]', which is insufficient to satisfy the students, especially when a common conception stands in the way.

This is why we propose to introduce models at an intermediate scale (i.e. mesoscopic) in the teaching–learning process of some topics. Such models are less powerful than the kinetic molecular model, from the viewpoint of physics, but may be very useful to introduce some ideas at an early stage, as Millar (1990) has already recommended.

In contrast with their quasi-inexistence in didactic research papers, such models are very commonly used in physics, especially in hydrodynamics, electrostatics (no electron is static!) or electrodynamics, and solid friction. In this sense, the didactic introduction of models at this scale is justified not only because they are simpler than molecular models; it is also a question of accustoming students to work with a scale that has its own importance in physics. Moreover, it is a question of making them aware of the usefulness of passing from one to another of the various levels of description at which to build explanations, in many contexts in physics, and in science more generally.

We will present two research-based teaching sequences; that is, the principles of their design, their implementation and their evaluation. These sequences are presented together here, despite the brevity this imposes on the presentation of each sequence, in order to underline and discuss what they have in common — the mesoscopic approach.

Some common aspects of these two sequences can be stated as follows. The goal is to reconcile the students with classically taught physics on two topics — solid friction and pressure in liquids — and to enable these students to use a model to explain and predict simple phenomena, despite common difficulties. We think, very classically, that it is very important to take the common ideas of students on a given topic very seriously, not only as targets in teaching, but also as a guide in designing courses. The spotlighting of content and the models we propose correspondingly echo some of the students' views, in order to facilitate a bridging approach (Clement 1993, Clement et al. 1989).

In particular, we take into account the strong preference of students for causal explanations and their need for a mechanism showing how it happens that things come about as they do. Many previous research works on teaching electric circuits (Gutwill et al. 1996, Psillos and Koumaras 1993, Sherwood and Chabay 1993) have taken this approach and proposed to stimulate causal reasoning by using situations of change (e.g. transient states in electric circuits), considered closer to students' intuition, before studying steady-state descriptions. This preference is also expressed in economics by Walliser:

> A more authentic explanation of phenomena requires that the general principles employed take the form of 'mechanisms', that is, of networks of causal dynamic relationships between quantities. (2002: 150)

The conceptual path proposed to students should, we think, appear at least as consistent as their common ideas, some of which may have been inadvertently reinforced by previous teaching. It should, in a first step, be more accessible than the accepted kinetic molecular model that involves (at least elementary) statistical mechanics. The teaching process itself is to be staged in a way that respects step-by-step progress and interactivity with the teacher and between peers.

The sequences proposed here take only a short time to teach, about two and a half hours; the objective is to see whether something could be changed in the teaching–learning process through seemingly 'marginal' action (Viennot and Rainson 1999: 15). Our aim is to produce a change in students' conceptions concerning specifically targeted points, through apparently small modifications in the teaching of traditional content. All kinds of costs are to be considered very seriously, we think, and deserve at least to be precisely specified.

We provide and discuss some elements of evaluation, either quantitative — comparing large experimental and control groups — or qualitative, using analyses of tape-recorded debates between students. As regards the teacher, we are conscious of his/her decisive role (Pinto et al. 2001, Viennot 2002) and we will give corresponding details in each case.

We focus here on how the content in these two sequences is spotlighted. In both cases, we propose an intermediary model, the full sense of that adjective. They are models at an intermediary scale, as recalled by the etymology of the word 'mesoscopic'; they are not as developed nor appropriate to formalization as models used in accepted physics are expected to be; and they are like stepping-stones between perception and theory, 'between seeing and thought', as Utaker (2002) wrote.

They are analogical qualitative models whose aim is mainly to serve as an intuitive, familiar and simple support to students' reasonings, to encourage a change in their view of the physical situation and an enrichment of their means of argumentation and analysis. We consider these models as catalysts of conceptual progress, as 'stepladders' for overcoming the observed difficulties and the overly simplistic reasoning that are a source of error and misunderstanding. In this sense, these models are close to what Gilbert and Boulter (1998) call 'teaching models', 'specially constructed models used to aid the understanding of a consensus model'.

The limits of application of these models will be discussed; their value in a few specific situations makes them good examples of the relative character of all models. This prevents students from giving too much of a realistic status to elements of a model, which could become an obstacle to subsequent improvement or when the model is abandoned.

The final discussion will bear on the value and limits of the mesoscopic approach adopted in both cases, in relation with the aims and the hypothesis on which our proposals are based.

Solid friction and propulsion

Content analysis and students' difficulties

One topic seems beyond hope for teachers at secondary or early university levels: propulsion through friction. Research studies on solid friction have shown how deeply rooted in students' mind the idea may be that friction only results in braking (Caldas 1994, Caldas and Saltiel 1995). This goes with a still more common misunderstanding of Newton's third law. These results have inspired some teaching suggestions that coherently take into account the nature of the observed difficulties. Figure 1 outlines both a common diagram showing this lack of understanding and a 'fragmented diagram' intended to promote a more appropriate view on this topic (Viennot 1996, 2002). The diagram is fragmented to facilitate a clear distinction between the third law — which concerns *two* different objects — and the second law — which associates the forces acting on *one* object to its acceleration — as well as a proper use of both laws.

This last type of analysis, a balance of forces exerted on clearly identified objects (and not on the so-called 'contact point'), leads to the idea that a net forward force *has to* be exerted on each accelerating object, the driver as well as the car that he is pushing toward a garage. The ground *has to* be seen as exerting a forward force on the driver, and being reciprocally submitted to a backward force from him, if the third law is to hold.

It was expected that such a clarification would be very profitable, particularly in bringing to light students' misunderstandings, but, as exemplified in the following, it is not sufficient for every student to accept the canonical diagram.

The limits of a macroscopic analysis

To help solve these difficulties a short teaching sequence was experimented with. The sequence is described in detail in appendix 1 (see also Viennot 2002: chapter 2).

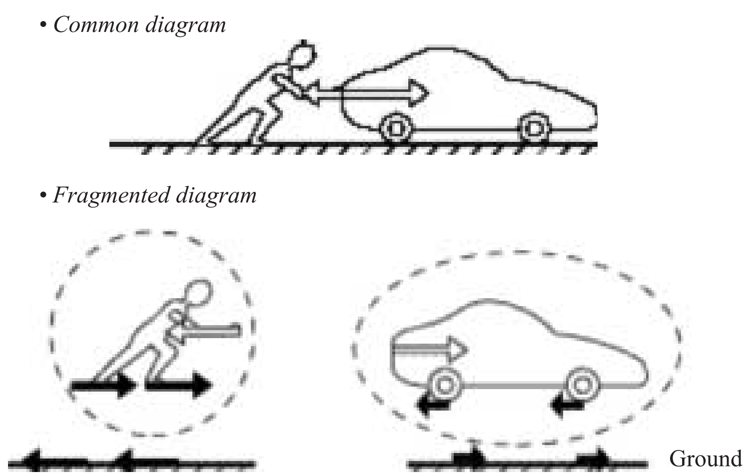

Figure 1. A driver whose car has broken down is pushing it: forces in play (horizontal components).

Part of the results collected in a third-year university class (degree in physical science) was the beginning of a tape-recorded class discussion with students (n = 10). This discussion between the students (S_i) and the teacher (T), concerning the situation in figure 1, took place after a first session of about two hours, recalling Newton's laws and introducing the fragmented diagrams. It brought to light the different obstacles that hinder straightforward acceptation of all these 'have to be':

S_1: I have a problem with that, the force on the driver is in the opposite direction from the movement.
T: So you don't agree with this arrow here on the diagram, the one pointing to the right?
S_1: No.
T: But it is necessary for …
S_1: Yes, it has to be there, but it bothers me …, I don't know.
T: It has to be there for the balance of forces on the driver because of the basic law. There is even a syllabus for the third year of secondary school entitled 'propulsion by friction'. It's the friction that enables the driver to push the car. You can't do it on roller skates…it's not possible to push on roller skates… And it's the same when you walk, it's the friction that allows you to move forwards; try it on ice!
S_2: Yes, but …
S_1: You have to have the arrow there, but the friction isn't forward, it can't make you go forward!
T: Just a minute …
S_3: But the ground doesn't move, it can't push…
T: Look [the teacher places her hand on the wall, her arm bent] what will happen if I try to straighten my arm?
S(all): [Silence]
T: What direction will I move in?
S(all): [Silence, then three students point in the opposite direction to the wall]
T: That way? [The teacher does it, with the anticipated effect …] You see! [… and draws the corresponding fragmented diagram on the blackboard]. Well, when I walk it's the same, it's like pushing on little walls …
S_3: The ground is horizontal, it's smooth, it can't push!

Clearly, the macroscopic approach was not sufficiently explanatory, and students needed to be provided with something else. This excerpt shows their difficulties and at the same time it leads, quite consistently, to the kind of model that we propose.

A mesoscopic model for propulsion via solid friction

After this phase of the discussion, which showed the students' dissatisfaction, the ground and the sole of the walker's shoe were described as surfaces full of rigid asperities with a saw-tooth profile (figure 2). The model's lack of realism was pointed out in that the asperities are actually far from regular — they are in fact much smaller in size and non-rigid. This decision was made because the deformation of these asperities makes the analysis more difficult: an asperity that bends, say, backwards, should be seen as pushing the object responsible for that deformation forwards (Caldas and Saltiel 2000). This complicates matters from the outset. Having said that, this rigid-surface model is intended to be abandoned subsequently, since deformations (elastic and plastic) are essential, especially for the study of sliding and the associated dissipation of energy (see, for example, Besson 1999, 2001b, Sherwood and Bernard 1984).

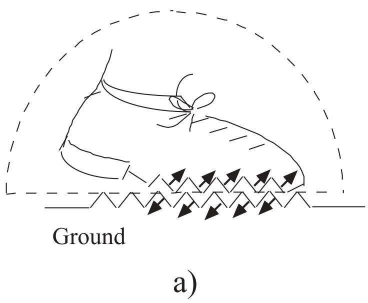

Figure 2. A model for contact interactions between a shoe and the ground. Fragmented diagrams for a walker who accelerates (a) or slows down (b).

Illustration of the benefits

This scenario conforms to what was planned in the sequence (point 5 in the detailed description given in appendix 1). After introducing the mesoscopic model of asperities, the problem of the horizontal nature of the ground in the diagrams in figure 1 no longer arose: the inclination of the faces in contact made the case comparable with that of the starting blocks analysed just before.

The continuation of the previous discussion illustrates these benefits.

T: The asperities are like little sloping walls, little starting blocks; a starting block is like a sloping wall.
S_4: Er … er, yes …
T: Are you convinced?
S_3: Me … er … just a minute …
T: Let's look at it more closely. [The teacher draws a shoe with a saw-tooth sole slightly above the ground; the ground is horizontal and also has saw teeth; figure 2] That is a shoe …
S_1: It's a Nike.
T: All right, it's a Nike. Now, if the man starts to move forwards, which surfaces will come into contact, these or those?
S(all): Those [correct] … there, there, yes …
T: And how do we draw the forces corresponding to that ground-shoe interaction, like this or like that?
S(all): Like that [correct].
T: You see, it's sloping, but apart from that it's like the wall just now.
S(all): Oh yes …
T: Does everyone agree, even you over there?
S_3: OK, yes, yes.

Other elements of evaluation

The two following years, a similar discussion was recorded, in similar circumstances (small groups in the third year at university; $n = 5$, $n = 8$, and $n = 9$). What is especially convincing as to what was gained in these three successive trials is that almost all of the students were able to use the model to predict what happens when a walker accelerates or when the shoe is pulled, but also to transpose this situation to that of car wheels, both drive and non-drive (figure 3), with the surfaces represented as saw teeth. They could do this on the spot (only a few errors) as well as two

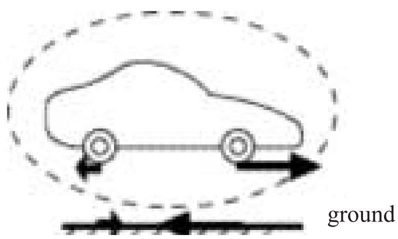

Figure 3. Interaction forces between ground and wheels for an accelerating car. Front, drive wheel; rear, non-drive wheel. Only the horizontal components are shown.

weeks after the sequence. For the second — unchanged but delayed — test, respectively 9/9, 5/5 and 7/8 students answered completely correctly.

More quantitative elements were provided by an implementation of the sequence in the first university year. Students in their first term at university (n = 107) were given a test from Caldas' (1994) work concerning the interactions between two stacked rectangular blocks, one of which, being pulled along from the outside, partially drags with it the other, the two blocks moving relative one another. Their answers showed the common difficulties described earlier. In particular, the proportion of students representing or mentioning *pairs* of reciprocal forces reached one-third (36/107) in only one case, the one where the top block was pulled. This initial test therefore confirmed that the common difficulties and inadequacies of analysis were indeed present among the students.

Then, the students were taught the sequence described in appendix 1, as discussed in the preceding section. A considerable part of this sequence (two hours) was devoted to work on Newton's laws via fragmented diagrams. It started with vertical situations: a man carrying or lifting a suitcase, a mass hanging from a spring, out of equilibrium, and so on. When horizontal situations such as the ones commented on earlier were considered, their participation was very similar to the scenario already illustrated. A test was given at the end of the sequence; it bore on the direction of the forces (horizontal components only) mutually exerted between the ground and the wheels — drive and non-drive — of an accelerating car. This gave the same astonishing score as for the third-year students (table 1).

Whereas the sample of students concerned here initially showed the difficulties identified in previous studies, the answers collected after the sequence, about a new situation, showed a near-inversion of the rates commonly observed for correct and incorrect answers for this test. In her questionnaire about the horizontal components of the forces acting on a wheel that is either powered or passive, Caldas (1994) recorded that around 80% of the diagrams (49 teachers, 75 students, final year of secondary school–first university years, similar results) showed forces having the same direction in both cases, the most common explanation given being that friction opposes movement (or translation or rotation).

Concerning the reaction of teachers to this proposal, a written questionnaire was used with 25 trainee teachers in their first teaching year, who had been placed in the learning situation described earlier, in order to investigate what they thought they would do with this sequence and what changes they might make.

Table 1. Rates of answers to a written test about an accelerating car; students were asked to draw the forces acting on the objects listed in the first column of this table.

	Correct answer (%)	*Incorrect answer (%)*	*No answer or unusable (%)*
Drive wheel			
On the wheel	86	6	8
On the ground	84	6	10
Passive wheel			
On the wheel	90	0	10
On the ground	82	6	12

n = 106. See figure 3 for correct answers.

Initially, this group was not particularly at ease with the content, since only seven of them were *a priori* determined to show the ground exerting a force *forwards* on the man pushing the car. In reply to the question 'Would you use this sequence for your pupils and if so at what level?', 16 trainees answered 'yes', seven were not sure and only one trainee gave the equivalent of a 'no' answer, arguing that it could not be inserted in the syllabus for his class. Use of this sequence was, in the main, suggested for the last years of secondary school. All the trainee teachers said that the sessions had helped — them, at any rate — to understand the topic better.

> It makes you think …
>
> You understand what is happening without just saying 'it has to be'.
>
> 'Demystification' of friction because the contact phenomena involved can be explained simply, even to secondary school pupils in the third year (to be verified).
>
> Lets you rely on your mechanistic 'intuition' a bit more (image of saw teeth).
>
> Uses a simple model to clarify certain ambiguities about interactions. The toothed shoe and the toothed ground are two good examples for tackling the problems that arise with the man and the car.

The main drawbacks were said to be the difficulty of the undertaking (13 responses), that it is unusual and not intended in the official syllabus (three responses) and the amount of time involved (three responses). Only a few made any suggestions for changes (seven), and these were diverse. The remaining comments were questions (two) — 'do pupils really make the same mistakes as we do?' — remarks on 'needing time to think about it' (three), else no suggestions at all — 'I can't see how it might be changed'.

In brief, the trainees were very happy to have their own ideas clarified but were less certain that they could help their pupils in the same way. The difficulties anticipated had to do with the method, its lack of conformity, its complexity, and the time required to introduce it. These concerns were expressed by a non-negligible number of teachers, who never questioned the conceptual objectives it sets out to serve, however, any more than they proposed important changes.

Solid friction and propulsion: a relatively simple systemic analysis

The main points discussed can be summed up as follows. The aim of this teaching sequence was to improve the usual analysis of solid friction so that it *would explain* things better. Errors commonly made by students were taken into account in evaluating the difficulty of teaching a diagram of forces that fits both the second law and the third law. It appeared that, in order to accept an analysis that satisfies both of Newton's laws, pupils must be led to have a more detailed understanding of what is happening. To this end, a mesoscopic model was given of the interaction between surfaces in contact. The audience was made aware that this model was very incomplete (unsuitable for studying the energy involved in sliding friction) and provisional.

Classroom discussions as well as quantitative indicators based on answers to written tests showed a considerable improvement in students' understanding. It seems that the model acted as a kind of catalyst for comprehension. As one teacher said: 'It makes you think …'.

Although it is hardly debatable that such success was due to the intermediate scale of analysis, there were also, most probably, some favourable factors associated with solid friction. Among them is the fact that the mesoscopic asperities could be seen here as a set of parallel starting-blocks. Thus, moving from a local analysis to a global one was not difficult: a simple addition of forces was all it required.

The following example bears on a more complex case.

Fluid statics

Content analysis and students' difficulties

The first investigations on pupils' reasoning about pressure in liquids (Besson 1995a, Engel Clough and Driver 1985, Giese 1987, Kariotoglou and Psillos 1993, Kariotoglou et al. 1995) showed that most pupils think, correctly, that pressure increases with depth, but many of them think that pressure also depends on the total volume of the liquid (they believe it is greater in a larger container) and that it acts only downwards or is stronger downwards than on the sides. According to Engel Clough and Driver (1985), pupils apply to liquids their experience of solids, for which 'weight acts vertically downwards'; an idea that often goes with a failure to differentiate between pressure and force (Kariotoglou et al. 1995).

A more recent study (Besson 2001a) showed that students have difficulty in connecting the global behaviour of fluids with a local description, and in reconciling the rules or formulas that assert things *must be* so, with reasoning based on what occurs in a given spot of fluid. Students more frequently consider a global description or shift between global and local views, without finding a coherence. For example, concerning the situation in figure 4, a student wrote:

> It is true that they [the fish] are at the same depth, so they ought feel the same pressure. But the water above the fish in the sea is a greater mass than the mass of water that is above the fish in the cave. The fish in the sea therefore feels greater pressure than the other fish.

A discussion between two students concerning the bowls in figure 5 contained this passage:

Figure 4. To compare the pressure for two fish — one in the open sea, the other in an underwater cave — at the same depth.

S_1: Normally, all the particles which are at the same height are supposed to be at the same pressure.
S_2: No, because we know … Yes, it's at the same height, but here [bowl __/] there's a difference, you've got more weight, you see … and since you've got a stronger weight, well, that presses down more, of course.
S_1: Yes … it makes sense.

The conception of pressure as a manifestation of weight (total weight or that of the fluid directly above the point considered) is a key factor in the difficulties of students.

Our hypothesis is that to promote understanding, it is not enough to say what a given quantity 'has to be'; it is also necessary to explore how the state has 'come about'. For that, it is necessary to activate a systemic form of reasoning, for which students need the support of a causal explanation, of a 'mechanism', in terms of a transmission of local changes.

A mesoscopic model of liquids

To connect the local and global descriptions, and to suggest an analysis in terms of a transmission of changes and interactions in all directions and in all parts of fluid, we need to consider a smaller scale of description. But here, that scale cannot be the microscopic molecular one, because, as already explained, a totally static treatment is not possible at this scale and taking into account molecular kinetics would call for

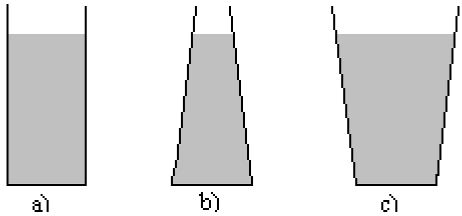

Figure 5. Three containers, whose bottoms are equal, are filled of water to the same height. Students are asked to compare the forces exerted by water on the bottoms of three containers.

developments that would be too complicated for our didactic purpose. This is why we suggest the use of a model at an intermediate (i.e. mesoscopic) scale, with beginners in fluid statics.

To achieve the aims stated here, and in the clearly delimited context of elementary situations of fluid statics in the presence of gravity, we propose to mentally break down liquids into small parts interacting with each other. This is, in fact, a standard method in fluid mechanics and more generally in continuum mechanics: by effecting a breakdown into 'elements' or 'particles' or layers of fluid, considered at the mesoscopic scale, it becomes possible to avoid the discontinuous description of matter at the molecular scale (see, for example, Batchelor 1967: section 1.2, Guyon et al. 2001: chapter 1, section 3.2), as the kinetic aspects remain hidden inside the mesoscopic elements and are represented in their effects by the average quantities (pressure, temperature, etc.). But this decomposition into small parts is generally made in an abstract and mathematical way. Moreover, in fluid statics it is often made only in a vertical direction, using thin layers of height Δh, in order to make the limit as $\Delta h \rightarrow 0$, so that the mesoscopic breakdown is only done on the vertical axis and as an intermediate procedure, with the aim of returning at once to a continuous macroscopic representation.

The idea is to make this mesoscopic breakdown accessible to the students' intuition by referring to objects that can be seen as behaving analogously, in the closely circumscribed field of fluid statics in the presence of gravity. In our proposed model, the objects chosen for this analogy were little rubber balls: liquids are imagined as made up of many little elements, analogous to rubber balls that fill the container and are in contact with each other. The small 'elementary quantities' typical of the language of calculus become objects that are capable of interacting, exerting pressure and being compressed. Unlike molecules, these mesoscopic elements keep the essential properties of macroscopic objects, and can therefore be treated as small pieces, small objects, that have a temperature, a density, a degree of elasticity, and can act on one another through contact interactions. The important thing is that one can form an image of their behaviour using the intuition derived from ordinary experience with objects of daily life; this would be open to criticism with molecules (Lijnse et al. 1990).

Besides, to activate reasoning based on transmission of local interactions, one should avoid asserting that liquids are incompressible, as that seems to exclude any local modification in a fluid, and therefore any difference in its action on the side of a container or on surrounding fluids. How can an element of a fluid transmit the effect of a disturbance to adjacent elements if that element is not changed in any way? As a matter of fact, the compressibility of liquids constitutes an important line of scientific research (see Aitken and Tobazéor 1998, Bridgman 1958). It is true that variations in the volume of fluids are often negligible in calculations, but we think they are essential to an understanding of what is happening. That is why the basic elements of the model — the rubber balls — are considered as compressible: they are somewhat rigid, their relative variations of volume $\Delta V/V$ are very small for the forces considered, but they can be deformed and compressed, and they react to deformations by elastic forces acting in the same way in all directions (figure 6). This is consistent with the common conception associating pressure with crowding and the common idea, 'if you push on something, you squash it'.

Thus, we consider that common ideas of this sort, as well as the widespread preference for causal explanations, may serve as *anchor conceptions* (Clement et al.

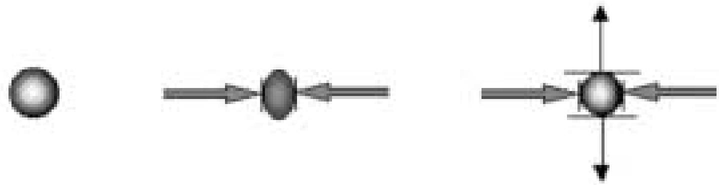

Figure 6. The rubber balls: they are slightly deformable and, if pressed on, they react in all directions.

1989), from which to orientate learning towards a new conceptual organization, in which the physicist's formalism and the needs of common thought unite fruitfully.

The proposed model has to be understood as a very makeshift aid to understanding, which is clearly distinct from the microscopic models, whose greater unifying value is well known. The limitations of the model are obvious. We will see that the idea of disorder, which is essential when discussing liquids, is temporarily glossed over. Also, while the image of the rubber balls encourages the idea of a transmission of pressure changes, it may suggest friction between balls. Moreover, with or without friction, granular media such as a bag of ball bearings or a heap of sand are very different from liquids, even in their static behaviour (see, for example, Cantelaube 1997, Duran 1999). But in teaching hydrostatics, the discrete and ordered nature of the basic elements of a mesoscopic model is rather less misleading than the belief in incompressibility or the classical decomposition into cylinders or parallelepipeds, like boxes stacked upon one another.

A teaching sequence on fluid statics

On this basis, a short teaching sequence was designed and is described in detail in appendix 2 (see also Besson 2001a, Besson et al. 2001, Viennot 2002: chapter 3). The sequence was implemented and evaluated for two years among science students in the first university year at the University of Louvain-la-Neuve (Belgium), after a

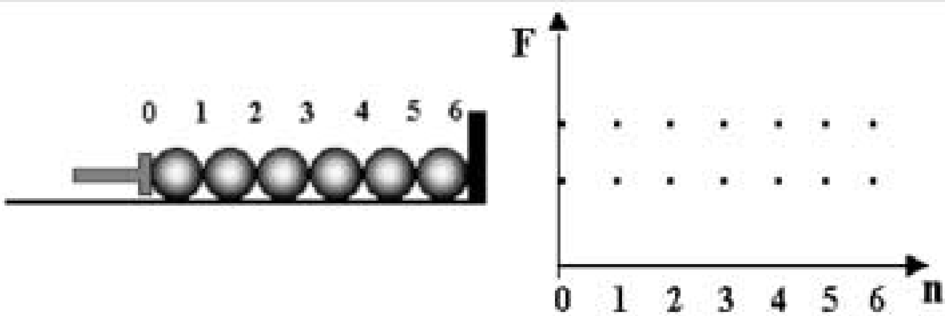

Figure 7. Mechanics of rubber balls: horizontal situation. The graph represents the magnitude *F* of the forces of the interaction between adjoining balls and with the barrier according to the order number *n* of the contact points.

traditional lecture on the subject. The general part of the theoretical class on fluid statics was left unchanged. The students involved in the experimentation (n = 71 in the first year, n = 169 in the second year) participated in the sequence in small groups of 12–17, while control groups (n = 77, n = 94), also divided into small groups, did classical exercises on the same topic. No extra time or additional teachers were devoted to the experimental sequence. The intervention was conducted by three teachers, only one of whom (Jacques Lega) had been involved in the design of the sequence. We will refer in the following only to the results of second, more complete, experimentation.

The sequence began with a mechanical consideration of the rubber balls. Three situations were studied, involving a series of balls first aligned horizontally (figure 7) and pushed against a vertical barrier, then in set a vertical position and pushed downwards by hand, then vertically with an upward push (figure 8).

The teacher helped the students to represent the forces between adjoining balls as vectors on a graph, and then to draw a graph of the function $F(n)$ representing the magnitude F of these forces according to the order number n of the contact points. In a situation of equilibrium, the forces of the interaction between adjoining balls must have the same magnitude in the horizontal situation, and they increase towards the bottom, each in a value equal to the weight of one ball, in vertical situations.

Pushing harder on the balls causes small deformations, and the forces increase, but *equally*, so that the difference between one force and the next remains unchanged. The graphs are still a straight line, parallel to the first and situated higher up.

Then, the analogy between the rubber ball model and liquids was proposed. Horizontal and vertical situations were discussed once more, an analogy being made between the force diagrams for the rubber balls and that concerning pressure in

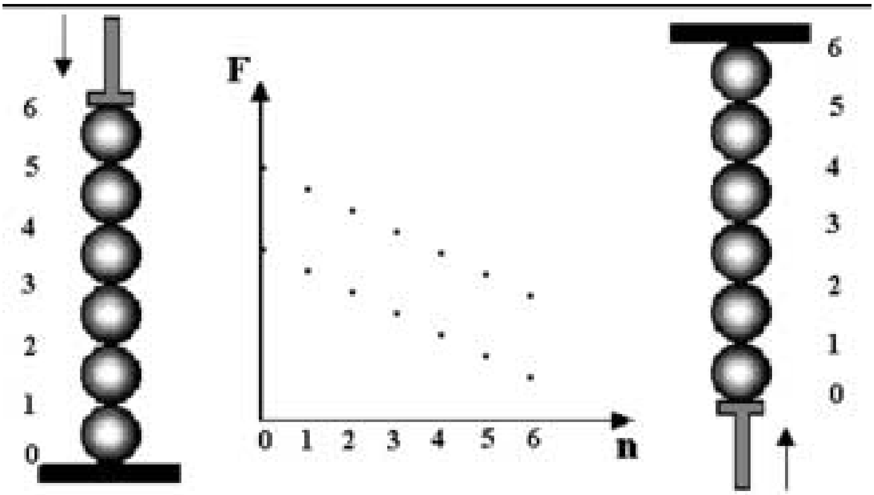

Figure 8. Mechanics of rubber balls: vertical situations. The graph represents the magnitude *F* of the forces of the interaction between adjoining balls and with the barrier according to the order number *n* of the contact points.

fluids, for each situation. Indeed, in the model we studied forces on each ball. This idea of *force per ball* is close to that of force *per unit of area* in the fluid and can serve as introduction to the idea of pressure as an intensive quantity. However, the distinction between pressure and force does not constitute a specific objective of the sequence.

Next, the sequence discussed the pressure in closed containers filled with water, in which a piston could push on the water (figure 9). In the discussion it was stressed that pushing upwards, downwards or horizontally on a column of liquid that is blocked at the other end has the effect of changing the magnitudes of all the interactions and of pressure while preserving the *differences* between them, just like when the hand was pressing on the rubber balls.

In the final session of the sequence (in the second experimental trial only), students worked and discussed the problem in groups of two or three: they were asked to compare the forces exerted by the water on the bottoms (of equal areas) of three differently-shaped containers (|__|, /__\ and __/) that were filled to the same level (figure 5).

The sequence did not involve any hands-on activity. The situations were simply described. The benefits were expected from a progressive conceptual construction, supported by discussion and analysis of graphs and diagrams. According to our *a priori* analysis, the difficulties observed could not be resolved simply by measuring the values of the pressure here or there. Blockages were in fact observed in pupils who were very familiar with the standard relation $\Delta p = -\rho g \Delta h$, but who were unable to integrate it into an overall analysis of the situation. It is on this precise point that our evaluation is focused.

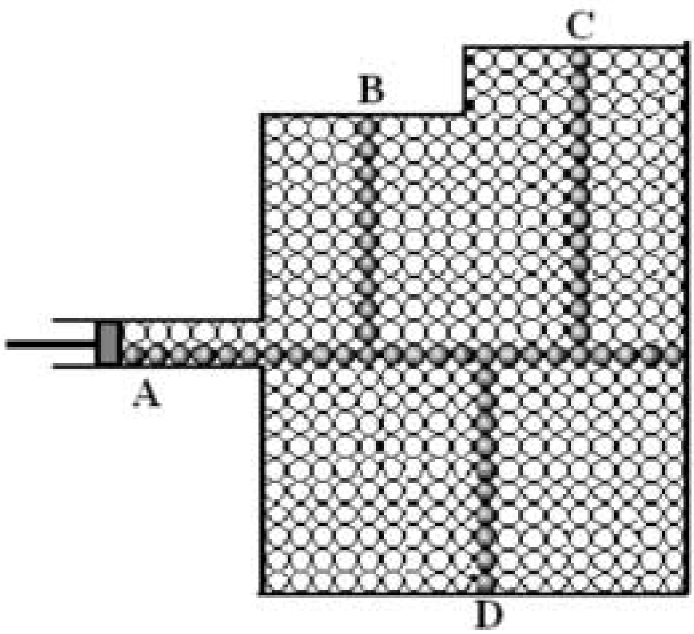

Figure 9. A container with a piston: analogy between liquids and rubber balls.

Evaluation of the sequence

The final discussions on the 'Three containers' situation (figure 5) enabled us to evaluate how the proposed didactic elements were integrated into the students' ways of reasoning. The observed sessions occurred one week after the model and its analogy with liquids were introduced. The students, working in groups of two or three, were asked to compare the forces exerted by the water on the bottoms (of equal areas) of three differently-shaped containers (|__|, /__\ and __/) filled to the same level. Some groups volunteered to be recorded; the discussions lasted between 15 and 20 minutes. We collected nine recordings and 14 answer sheets with drawings and comments.

The students' participation was lively; they felt a strong personal commitment in the discussions, as was evidenced by the frequent changes in speaker, by their objections, changes of opinion, or determination to stick to the points of view expressed.

S_1: … Well, *I* think it's 'c' [/__\], even if you don't.
S_2: But it's not all the same case; well, oh, I don't know!
S_1: It is, it is, you've got this ball here and this ball there that have the same pressure
S_2: But they *don't* have the same pressure.
S_1: Well, they do, just say they do.
S_2: Yes but they don't! (Discussion 1)

Some of the comments show that these difficulties were keenly felt:

> Well, I have a lot of trouble with these things. (Discussion 9)

> Yes, yes, all right, you mean the … your second container you've got here … At least we've got the feel of the thing, but to quantify it … (Discussion 8)

Discrete entities such as those in the model used in the sequence were referred to in most of the discussions. Students spoke in terms of balls, or sometimes of particles, interchangeably.

Whenever a full explanation was sought and/or an important difficulty came up, *contiguous* balls appeared on the drawings collected or were mentioned in the discussion transcripts. In fact, where the balls were drawn or imagined as being scattered, the students did not really take the model into account in their reasoning; it was, most probably, only a visual memory. Yet when contiguous balls appeared, the model became *operational* and triggered a new set of questions, arguments and solutions.

This aspect contributes to show the relevance of the mesoscopic nature of the model. In fact, as said earlier, any molecular model requires a consideration of kinetic aspects, so that it cannot describe the effects of weight statically.

Interactive forces between balls, the propagation of actions and the image of balls pushing in all directions, all of which are characteristic of the proposed model, often came up in the discussions; these considerations were important, sometimes decisive, for the resolution the cognitive conflict. For example:

> There are forces … from both directions, too … This ball here … the one in the middle was transmitting it downwards. (Discussion 5)

> There, see, if you push harder, you'll be pushing harder on that one, that one will push harder on the second ball, the second ball will push harder on the third, and then as a reaction the wall will push on the last ball and that will send everything back into your hand again. (Discussion 7)

> I mean, when you take an isolated ball, it will receive or exert an equal force, that's what we saw, too … anywhere, in the three directions, so what we have here is that those balls receive a pressure like this, so they will exert a pressure on the wall …

> These balls … if they receive a pressure from one side, they exert the same pressure in the three directions, in fact the pressure will be exerted … you will get the same pressure exerted downwards as well. (Discussion 8)

These excerpts and the ones following, show that students, in the course of the discussion, use the terms 'pressure' and 'force' indiscriminately, and used expressions such as 'vertical, horizontal, perpendicular, oblique pressure' when they meant the pressure force. In any case, these expressions show the emergence of a form of reasoning that considers actions in all directions.

Sometimes taking into account the *compressibility* or *deformability* of the rubber balls was essential in order to understand the situation:

> Because the balls have weight they tend to be squashed and therefore to exert a lateral … horizontal force on the balls next to them, and that force is transmitted to the walls and as the wall is sloping it induces a force … towards the bottom. (Discussion 6)

Explicit references to specific situations and arguments used in class when the model was presented were observed in almost all the discussions:

- The action of wall like 'a hand that's pushing' (discussions 1, 3, 7). For example:

  > and then as a reaction the wall will push on the last ball and that will send everything back into your hand again. (Discussion 7)

- The equality of pressure on a horizontal straight line, due to interactions transmitted step by step (discussions 1, 3, 5, 9). For example:

  > Well, there … on each horizontal straight line, you have the same pressure … In fact, horizontally the balls have the same pressure, they make the same pressure, pressure x, say, here, and also there, and there again, because it does not change.

- The similarity with the containers mentioned during the sequence:

  S_1: Because, you know, what we saw last time, one time we pushed towards the ceiling, and then, we pushed towards the bottom, and this is the first case, we'll use that again, and the third is …
  S_2: For what we've got here, we've followed the same line of reasoning as when we made a complex container last time and … (Discussion 8)

Often the reference to these elements of the sequence played a decisive role in negotiating a critical obstacle in the discussion. In discussion 1, after a spontaneous allusion to the action of a hand on a column of balls, a new solution was quickly found:

> OK … we'll do it like the one with the hand pushing, because the force [of the wall] won't be the same. (Discussion 1)

The walls were always taken into account, although generally not at the beginning of the discussion. Sometimes, their only function seemed to be to provide support or compensate for weight, but it often happened that students switched rapidly from a consideration of the role of walls solely as a support to taking into account the forces exerted by the walls, and this aspect was very often essential in solving the problem.

S_1: Only the force of gravity is at work, not the force of the glass.
S_2: Yes, yes, yes, I *know* there is no force exerted by the glass, but …
S_1: But there *is*. There is so a force … provided by the glass.

> S_2: A reaction to the force …
> S_1: The thing is, is this force of reaction of the glass stronger than gravity … I think it would make no difference because the forces of reaction of the glass, when the bowl is triangular [bowl /__\], compensate for the force of gravity that was lost. (Discussion 5)

> In fact, as the sides of your bowl [bowl __/] exert oblique pressures upwards … (Discussion 2)

> Well, so what does that boil down to? All the balls press vertically on the wall, and as there is a reaction from the wall, that diverts the force towards the centre. (Discussion 4)

> If you have a perpendicular pressure, that means it pushes like this, here in the first case [bowl |__|], it is completely horizontal, and in the second [bowl /__\], it pushes downwards a little also, if you decompose it into a horizontal and a vertical direction, well, you have a part that pushes downwards, that's why your pressures would be …

The decomposition of forces into two perpendicular directions seemed to give some students trouble. Unless this decomposition is mastered in part, there may be a blockage, as the model itself — that is, the mechanics of rubber balls — cannot be used properly. It seems that a minimum level, a *threshold of competence*, must be reached for the model to be useful. Students must be able to handle the basic mechanics of forces, especially vectorial decomposition.

In any case, even when the model did not solve all the students' difficulties, it encouraged students to approach these on a higher level, giving them a different and more probing view of the proposed physical situation and a better articulated reasoning, as the discussions proceeded. Sometimes both students started the discussion with arguments concerning the total weight of water or the height of water directly above, but when one of students brought up the ball model, the discussion moved on to an analysis of forces and the role of the walls, and the other student was quickly destabilized and unable to back up his/her views. For example, in one discussion, student A immediately took the 'more water, then more force' tack, whereas student B advocated an equality of forces. As soon as student B referred to the model, his arguments became richer and student A backed down; finding no significant objections, he gave only brief replies: 'Yes, OK, you're right there', 'Yeah, but that isn't the case', 'Just a minute …'.

The proposed model may be considered as a *bridge model*, an intermediary step, taking students beyond the naive idea of 'just weight', and directing their reasoning towards a consideration of reciprocal actions and local variations. Even when some lines of reasoning were still hesitant, they bore witness to a less simplistic, more nearly correct form of argumentation. At any rate, the use of the model activated more powerful and productive reasoning in the discussion among students and provided them with more convincing arguments.

Other elements in the evaluation

We also conducted an external evaluation, with a comparison between the experimental groups and the control groups. Before the beginning of the sequence, a common pre-test was given, and about four weeks after the sequence three questionnaires ('Fish', 'Ball in water', 'Syringe') were given to both groups as a post-test. As mentioned earlier, the session with the model was conducted by three teachers, two of whom had not been involved in its design. The results obtained in this evaluation showed no advantage in favour of the groups of students of the teacher involved in the design of the sequence compared with the other groups.

In the ‘Ball in water’ questionnaire, students were asked whether a force was exerted by the water on four discs drawn on the top, the bottom and two sides of an immersed ball, and if so, to list these forces in the order of their magnitude. There was a marked difference in the responses to this question, revealing a better conceptual grasp of the situation in the experimental group: 58% of completely correct responses in the experimental group compared with 33% in the control group (a difference statistically significant at the 0.01 % level in the chi-squared test).

In the ‘Fish’ questionnaire, comparing the pressure for the two fish in figure 4, the experimental group showed an 11% increase in correct answers (equal pressure), which constitutes one-third of the population that usually fails on this question (Besson 2001a); although this improvement is less marked than it was in the previous question, it is statistically significant, at the 5% level, in the chi-squared test.

But the difference between the two groups can also be seen, very clearly, in the formulation of their justifications. The experimental group showed a more detailed analysis and reasoning that sought to reconcile the various aspects of the situation, the formula learnt at school, and local interactions.

Several students of the experimental group — 21 (i.e. 12%), as opposed to only 3% in the control group, but many students gave no justification at all — reasoned in terms of horizontal actions, often referring to the proposed model: ‘The pressure is equal … if you consider the rubber ball model, the ball at the far left is submitted to forces, which are reproduced from ball to ball till they reach those in the cave’. There were more elaborated responses than common simplistic arguments such as ‘there is more water’ or ‘the height of water above is different’, or even certain correct but insufficiently thought-out answers, such as ‘equal pressure because equal height, formula $\Delta p = -\rho g h$’.

Among the students of the experimental group who gave the correct answer, 29 (18%) mentioned the force exerted by the roof of the cave on the water to justify that the pressure is equal for the two fish, even though they have different heights of water over them: ‘The pressure is equal, because the difference in height is compensated for by the force which the wall exerts’; ‘The force exerted by the roof of the cave on the water is equal to the force which would be exerted if there were water above instead of rock’. No student in the control group did this.

All these answers may be seen as stemming from a better understanding of the mechanism of mutual adaptation between the states of the various parts of the system studied. They show the first elements of a form of reasoning that may be called systemic, with the aim of reconciling the local and global descriptions.

The same can be said of the greater number of responses in the experimental groups in favour of a slight compressibility of liquids in the ‘Syringe’ questionnaire; students were asked whether, if one pushed on the piston of a syringe filled of water, the volume and the pressure of water would decrease, increase or remain unchanged. The justifications of the experimental group were much richer in descriptions of the changes in the internal state of liquid and sometimes referred explicitly to the model of the sequence, and some drawings were provided:

> Since water is compressible, the particles of water get deformed and exert a force on the sides, which will be compensated for by a force of reaction from the walls, which will increase. [The student includes a drawing of round balls in a syringe, and another next to it, of the balls deformed into ovals in the syringe]

> The pressure of the water increases, because water is slightly compressible, like rubber balls being compressed, they push harder towards the outside, so the pressure in the water is greater.

> The pressure increases everywhere, as you were using balls, the forces that they exert on one another increase.

> If you push, you reduce the space, you increase the density … and so the pressure increases. Because pressure acts like this [there is a drawing with small balls in a syringe and three balls with arrows], that is, from ball to ball …

We were also concerned about possible undesired effects of our intermediary model. Among the well-known risks of presenting an analogy is that of establishing too rigid a relationship between source and target, and 'reifying partial models' (Brown 1993). The proposed model could blur the idea that molecules in fluids are not at fixed position, their movement being essential to analyse pressure at microscopic level.

To evaluate whether the sequence had such negative effects, the students were given another questionnaire, 'Saucepan' (in the first experimentation only). At issue was whether the proposed mesoscopic model might act as an obstacle to using the standard molecular model, involving kinetics and empty space between molecules, in cases where it applies. The students were asked whether the pressure at the bottom of a saucepan full of water changes if the water is heated — and, if so, whether it increases or decreases. A justification was asked for. The important thing here is that no significant difference was observed in the percentages of arguments using molecular kinetics between one population and the other; this suggests there was no negative effect of the mesoscopic model.

Finally, given that a favourable attitude of teachers is an important condition for any didactic proposition to be efficiently used in a school situation, we wanted to have the reactions and evaluations of teachers regarding a possible use of the sequence. We therefore presented the sequence to two groups of secondary school teachers in training (n = 22 and n =20, at the IUFM of Lille, France, by a teacher not involved in our research) and a consultation was conducted by questionnaire.

Regarding their intention of using the sequence in class, the teachers were split almost equally between three positions: yes (for the upper secondary school), maybe (depending on the type of pupil), and no. The positive points mentioned were: the 'concrete', 'visual', simple character of the model; that the use of notions from mechanics, especially Newton's third law, would be of help to students in understanding those points; the interesting analogy between mechanics and hydrostatics; and that the presentation clarified a few points for the teachers, too, enabling them to better understand students' difficulties.

> The model gives a concrete perception of the phenomenon, makes it possible to understand what really happens.

> It makes you visualise what happens.

> It is more accessible, because more visual [concrete], and so facilitates understanding.

> Makes modelling possible without simplifying too much. Makes it possible to avoid using laws that are applied mechanically, and instead, to really understand.

As regards the negative points, most of the teachers brought up the difficulty of the sequence, especially the necessity of mastering certain notions of mechanics; the time required for the sequence; and the fact that analogies are often held as real by pupils.

It is interesting to notice that sometimes the same individual mentioned the same point both as a positive aspect and as a drawback. For example:

> Negative aspects: It demands the mastery of a subject (mastery of mechanics) to learn a new concept, [which may mean] immediate failure for pupils already in trouble!

> Positive aspects: Positive aspects = previous negative aspects because if one manages to reinforce notions of mechanics, that is great.

As for the sequence on friction, it seems that several teachers feared that the need for a certain mastery of notions from mechanics required in the sequence might constitute an obstacle for some pupils. But, at the same time, they thought that if it were possible to overcome this obstacle, and thus promote a reusing and a better understanding of these aspects of mechanics, that would be a very positive result.

Concluding remarks

The thread through this paper was the use of a mesoscopic description in teaching about two kinds of physical systems: surfaces of solids in frictional interaction that allows propulsion, and fluids in equilibrium in containers with no vertical sides. An understanding of these systems is problematic to a non-negligible proportion of students. In both cases, the physical laws involved are relatively simple to learn and to apply. But it is observed that accepting or even producing a correct answer is no warrant of the ability to explain the phenomenon involved. In particular, some comments like ‘yes, it has to be so, but it bothers me, I don’t know …’, and the inability of some students to convince doubting classmates seem to attest to some uneasiness, frustration, or at least to a lack of mastery. In both cases, the global, macroscopic description that is usually proposed hides some aspects that are critical for the students’ comprehension.

Concerning propulsion via friction, the ultimate obstacle was the argument: ‘but the ground is horizontal, it cannot push’. It was only with a more detailed, although still rudimentary and provisional, description (i.e. saw-tooth profiles at mesoscopic scale) that the students’ agreement was obtained. Interestingly enough, when they had to solve the problem of which forces act at the interface between the ground and the wheels of an accelerating car, the students appeared to have benefited from the model, but some of them did not need to represent the saw teeth any more. It seems that the model can serve as a catalyst for comprehension, but that it can be left behind subsequently. This is a favourable circumstance because the proposed model must, indeed, be replaced by a more detailed one, with non-rigid asperities, in order to account for energy dissipation via friction. After teaching, the rates of correct answers obtained for the accelerating car were strikingly high, compared to previous research results obtained among similar populations.

Concerning liquids at equilibrium, it is patent that many students lack a systemic view after customary teaching. Clearly, the rule ‘same height implies same pressure’ or the formula of fluid statics $\Delta p = -\rho g \Delta h$ are insufficient to bring about a good understanding of the situations presented, as they do not satisfy students’ need for an explanation. These students may claim that, at points on the same horizontal line, pressure *must be* the same, they are nevertheless distressed if there are columns of water of different heights above these points, as is the case when the container is irregular in shape, with slanting walls, or in an underwater cave. It is precisely on these aspects that the proposed approach turned out to be most effective. More articulated reasoning was brought to bear by the students in the experimental group than in the control group, when it was necessary to reconcile a global description, based on a formula, with the analysis of local interactions, and especially to understand what happens in all parts of the fluid when something is changed.

The improvement in terms of rates of correct raw answers, although statistically significant, was not as spectacular as the one observed for the preceding example, on solid friction. To consider the mesoscopic elements in liquids calls for more complex systemic reasoning than in the case of solid friction, where in order to link the mesoscopic and macroscopic levels it is enough to simply add parallel forces. It is no surprise, then, that a threshold of competence should prove necessary to benefit from the model used for liquids: unless the mechanics of rubber balls was mastered, the model itself was useless.

It is worth noting that, although the mesoscopic entities are situated at the mesocopic scale, they 'work' like macroscopic objects, hence their bridging role. However, they add much more to the analysis than does a simplified macroscopic description (e.g. a horizontal line for the ground or a 'h' in a classical 'ρgh'). In this sense, our proposal has much to do with Clements' (1993) definition of 'anchoring intuitions' and 'bridging analogies', even if it brings to bear a non-trivial intellectual construction at the very source of the analogy.

Our appeal for the use of mesoscopic models in teaching, whatever their limits, is in fact in line with some suggestions concerning electricity, although these were initially presented in the frame of macro–micro relationships. When Sherwood and Chabay (1993, 2002), Gutwill et al. (1996) or Psillos and Koumaras (1993) suggested facilitating the comprehension of circuits in electricity by focusing on changes occurring in the circuit when the switch was activated, they recommended a step-by-step analysis of what happens to electrons, considered as deprived of their thermal motion. We suggest that considering electrons as quasi-static objects is in fact equivalent to making a mesoscopic description (Besson 1995b). Some complicated aspects of the situation were ignored, or averaged out, which brings about the idea of zero global motion of surface charges in steady state. As regards our examples, there is no getting away from some aspects classically in play at the macroscopic level.

Demanding as they may be, the conceptual paths proposed here seem to produce a real satisfaction in most of the students concerned, and are more accessible than the kinetic microscopic models. But a problematic aspect is finding a way for teachers to share this viewpoint, and not be afraid of the 'threshold' that has to be crossed for understanding to be accessible, as was observed in the two sequences analysed here. The comments of several teachers, such as 'if you can reuse it, that's great!', probably provides one of the keys to this question. If the benefits are seen as cumulative, there is more chance for in-depth analysis of physical phenomena to be conducted in the classroom, and with tools that are not too complicated. Of course, one investigation remains to be conducted, in order to inform teacher training and to reconsider this sequence: how would ordinary teachers, however motivated, implement this sequence? How, in their practice, would they transform the researcher's initial design?

This said, the following question remains open and deserves further research: how can the passage and/or the relationship between the mesoscopic and the kinetic microscopic models be understood in optimized conditions? The answers to one of our tests show that the students' knowledge about the kinetic molecular model had not been inhibited by their recent conceptual acquisitions at a mesoscopic level. Obviously, this needs further confirmation. Anyhow, a teaching goal to be seriously considered, we think, is that of promoting students' flexibility concerning the use of different scales of analysis in physics. At least, being provided with the ability to use three scales should limit any tendency to look upon one of them as being closer to 'reality' than the others.

References

AITKEN, F. and TOBAZÉOR, R. (1998). Une histoire de pression: la compressibilité des liquides [A history of pressure: the compressibility of liquids]. *Bulletin de la S.F.P.,* 114, 4–9.

BATCHELOR, G.K. (1967). *An Introduction to Fluid Dynamics* (Cambridge: Cambridge University Press).

BESSON, U. (1995a). La pressione [The pressure]. *La Fisica nella scuola,* 28(1), 8–14.

BESSON, U. (1995b). Schematizzazioni frettolose nell'insegnamento della fisica: il caso dei condensatori [Hasty schematizations in physics teaching: the case of capacitors]. *La Fisica nella scuola,* 28(4), 175–184.

BESSON, U. (1999). Bilans énergétiques: une mise au point conceptuelle [Energy balances: a conceptual adjustment]. *Bulletin de l'Union des Physiciens,* 812, 383–405.

BESSON, U. (2001a). Une approche mésoscopique pour l'enseignement de la statique des fluides. Étude des raisonnements des apprenants, élaboration et expérimentation d'une séquence d'enseignement [A mesoscopic approach for teaching fluid statics. Study of students' reasonings, design and experimentation of a teaching sequence]. Ph.D. Thesis, University of Paris 7 'Denis Diderot'.

BESSON, U. (2001b). Work and energy in the presence of friction: the need for a mesoscopic analysis. *European Journal of Physics,* 22, 613–622.

BESSON, U., LEGA, J. and VIENNOT, L. (2001). Using anchoring conceptions for teaching statics of fluids. In R. Pinto and S. Surinach (eds.) *Physics Teacher Education Beyond 2000, International Conference of GIREP, Selected Contributions* (Paris: Elsevier Editions), 281–284.

BRIDGMAN, P.W. (1958). *The Physics of High Pressure* (London: G. Bell and Sons).

BROOK, A., BRIGGS, H. and DRIVER, R. (1984). Aspects of the secondary students' understanding of the particular nature of matter. Children's Learning in Science Project, University of Leeds, Centre for Studies in Science and Mathematics Education, Leeds.

BROWN, D.E. (1993). Refocusing core intuition: a concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching,* 30(10), 1273–1290.

CALDAS, H. (1994) Le frottement solide sec. Le frottement de glissement et de non glissement. Etude des difficultés des étudiants et analyse des manuels [Dry solid friction. The sliding and non-sliding friction. Study of the students' difficulties and analysis of textbooks]. Ph.D. Thesis, University of Paris 7 'Denis Diderot'.

CALDAS, H. and SALTIEL, E. (1995). Le frottement cinétique: analyse des raisonnements des étudiants [Kinetic friction: analysis of the students' reasonings]. *Didaskalia,* 6, 55–71.

CALDAS, H. and SALTIEL, E. (2000). Les étudiants et les forces de frottement solide: le modèle de la brosse [Students and solid friction forces: the model of brush]. *Bulletin de l'Union des Physiciens,* 822, 471–485.

CANTELAUBE, F. (1997). Le trou du tas de sable [The hole of the sand heap]. *Bulletin de la S.F.P.,* 108, 3–6.

CLEMENT, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching,* 30(10), 1241–1257.

CLEMENT, J., BROWN, D. and ZIETSMAN, A. (1989). Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education,* 11(5), 554–565.

DURAN, J. (1999) *Sables, poudres et grains* [*Sands, Powders and Grains*] (Paris: Eyrolles Sciences).

ENGEL CLOUGH, E. and DRIVER, R. (1985). What do children understand about pressure in fluids? *Research in Science and Technological Education,* 3, 133–144.

GIESE, P.A. (1987). Misconceptions about water pressure. In J. Novak (ed.) *Proceeding of the second international seminar on Misconceptions and Educational Strategies in Science and Mathematics,* vol. 2 (Ithaca, NY: Cornell University), 143–148.

GILBERT, J.K. and BOULTER, C. (1998). Learning science through models and modelling. In B.J. Fraser and K.G. Tobin (eds.) *International Handbook of Science Education* (Dordrecht: Kluwer Academic Publisher), 53–66.

GUTWILL, J., FREDERIKSEN, J. and RANNEY, M. (1996). Seeking the casual connection in electricity: shifting among mechanistic perspectives. *International Journal of Science Education,* 18(2), 143–162.

GUYON, E. HULIN, J-P., PETIT, L. and MITESCU, C.D. (2001). *Physical Hydrodynamics* (New York: Oxford University Press).

KARIOTOGLOU, P. and PSILLOS, D. (1993). Pupils' pressure models and their implications for instruction. *Research in Science and Technological Education,* 11(1), 95–108.

KARIOTOGLOU, P., KOUMARAS, P. and PSILLOS, D. (1995). Différentiation conceptuelle: un enseignement d'hydrostatique fondé sur le développement et la contradiction des conceptions des élèves [Conceptual differentiation: a teaching of hydrostatic founded on the development and contradiction of pupils' conceptions]. *Didaskalia,* 7, 63–90.

Lijnse, P.L., Licht, P., de Woos, W. and Waarlo, A.J. (eds.) (1990). *Relating Macroscopic Phenomena to Microscopic Particles: A Central Problem in Secondary Science Education* (Utrecht: CD-β press).

MÉHEUT, M. (1997). Designing a learning sequence about a pre-quantitative kinetic model of gases: the parts played by questions and by a computer simulation. *International Journal of Science Education,* 19(2), 647–660.

MILLAR, R. (1990). Making sense: what use are particle ideas to children? In P.L. Lijnse, P. Licht, W. de Woos and A.J. Waarlo (eds.) *Relating Macroscopic Phenomena to Microscopic Particles: A Central Problem in Secondary Science Education* (Utrecht: CD-β press), 283–293.

PINTO, R., VIENNOT, L., OGBORN, J., SASSI, E. and QUALE, A. (2001). Science teacher training in an information society. Final Report, Universitat Autònonia de Barcelona, www.vas.es/sttis.htm.

PSILLOS, D. and KOUMARAS, P. (1993). Multiple causal modelling of electrical circuits for enhancing knowledge intelligibility. In M. Caillot (ed.) *Learning Electricity and Electronics with Advanced Educational Technology,* NATO ASI series F, vol. 115 (Berlin: Springer-Verlag), 57–75.

SHERWOOD, B.A. and BERNARD, W.H. (1984). Work and heat transfer in the presence of sliding friction. *American Journal of Physics,* 52(11), 1001–1007.

SHERWOOD, B.A. and CHABAY, R.W. (1993). Conceptual model for understanding the behaviour of electrical circuits. In M. Caillot (ed.) *Learning Electricity and Electronics with Advanced Educational Technology,* NATO ASI series F, vol. 115 (Berlin: Springer-Verlag), 23–35.

SHERWOOD, B.A. and CHABAY, R.W. (2002). *Matter & Interactions*, vol. 2 (New York: John Wiley & Sons).

UTAKER, A. (2002). Analogie, métaphore et concept [Analogy, metaphor and concept]. In P. Nouvel (ed.) *Enquête sur le concept de modèle* [*Investigation into the Concept of Model*] (Paris: PUF), 203–221.

VIENNOT, L. (1996). *Raisonner en Physique, la part du sens commun* (Bruxelles: De Boeck) (Trans. *Reasoning in Physics, the Part of Common Sense.* Dordrecht: Kluwer, 2001).

VIENNOT, L. (2002). *Enseigner la physique*, with the collaboration of U. Besson, F. Chauvet, P.Colin, C. Hirn-Chaine, W. Kaminski and S. Rainson (Bruxelles: De Boeck) (Trans. *Teaching Physics.* Dordrecht: Kluwer, 2003).

VIENNOT, L. and RAINSON, S. (1999). Design and evaluation of a research-based teaching sequence: the superposition of electrics fields. *International Journal of Science Education, Special issue: Conceptual Development in Science Education,* 21(1), 1–16.

VOLLEBREGT, M. (1998). *A Problem Posing Approach to Teaching an Initial Particle Model* (Utrecht: CD-β press).

WALLISER, B. (2002). Les modèles économiques [The models in economics]. In P. Nouvel (ed.) *Enquête sur le concept de modèle* [*Investigation into the Concept of Model*] (Paris: PUF), 147–159.

Appendix 1: a teaching sequence on propulsion by solid friction

It is a very short sequence involving a return to the basics of mechanics using fragmented diagrams (about two hours, can be extended to three hours), and a small intervention specific to static friction (about 20 minutes). It can be used as early as the fourth year of secondary school (grade nine in the US) and at all subsequent levels. All it requires is a knowledge of how a force exerted on one object by another is represented by a vector: direction, magnitude, unit, point of application, projection on one direction, the resultant as vector sum, the speed and acceleration vectors for a point to which a value of mass is ascribed, the concept of weight and how it is distinguished from mass, Newton's laws. No elaborate kinematics are involved, since the only important thing is to know that the acceleration vector has the same direction as the difference in the velocity vectors between two adjacent moments in time.

The sequence is described as follows (see Viennot 2002: chapter 2):

1. Start of sequence: prerequisites stated, reminder given of Newton's second and third laws for one and two particles; this is then restated *in reduced form*, that is, in terms only of the overall displacement of each object (one might speak of the centre of mass or confine oneself to translations of rigid objects) in the following two cases:
   - the movement of the object in question is unchanged (constantly zero or of constant velocity), the resultant of the forces acting on the object from outside is zero; and
   - the object's movement is changed (magnitude and/or direction of velocity changed), the resultant of the forces acting on the object from outside is not zero and is in the same direction as the acceleration.

   Stress on the aspects highlighted above:
   - the second and third laws are different; in particular, the second law is concerned with a single object (we often say 'system'), while the third law is concerned with two;
   - in classical mechanics they both apply without further restriction (the third law is not limited to cases of equilibrium); and
   - the force terms are considered at the same moment in time.
2. Discussion of situations involving vertical interactions, contact and remote:
   - a holidaymaker lifting a suitcase;
   - a nail being driven into a plank;
   - a mass hanging on a spring, possibly oscillating; or
   - magnets repelling each other, aligned vertically (in a test tube) on a letter scale: does the scale show the same value as if they were in contact? See the analysis of this situation in Viennot (1996: 99).
   - Or again the situation mentioned earlier of a ball immersed in a glass of water, itself on a scale. Each time, ordinary diagrams and fragmented diagrams constructed by the technique illustrated earlier (figure 1) are compared from the point of view of their ability to clarify the analysis.

   Similar discussion about a driver who starts pushing his broken down car along a horizontal road (figure 1); this situation is analysed into horizontal force components, it first being pointed out that neither the driver nor the car sink into the ground and that we are not interested in the vertical components of forces. The need — from the balance of forces point of view

— for the ground to act on the driver in the direction of the overall acceleration is introduced: the provocative expression 'propulsion by friction' is used.

3. The same approach is taken with the person walking, quickening or slowing his/her pace, on the same horizontal road (discussing only one foot, the other is in the air), each time ending with the corresponding fragmented diagram (as in figure 1).
   Two hours are given to this work (points 1, 2, and 3) — this can be easily extended to three hours.
4. In the light of the questions that arise and the objections that are voiced, we announce the introduction of a very simple model detailing the interactions between the ground and the walker; the model is compatible with the diagram drawn just before. The purpose is stated to be a better understanding of the mechanism of walking; students then find it easier to accept this diagram, which is all right from the point of view of the Newtonian balance but raises a lot of questions.
   We start by looking at the problem raised by one student's comment that 'the ground doesn't move, it can't push'. We do this by discussing, with the help of actions and then with fragmented diagrams, the case of a person who, by pressing on a wall, is moved away from it.
5. The ground and the sole of the walker's shoe are then described as surfaces full of rigid asperities with a saw-tooth profile (figure 2). The model's lack of realism is pointed out in that the asperities are actually far from regular — they are in fact much smaller in size — and, in particular, that they are in fact non-rigid.
   The model's advantages are emphasized: the problem of the horizontal nature of the ground in the synthetic diagram no longer arises: the inclination of the faces in contact brings the case close to that of the wall analysed just before.
6. Students are asked to predict which faces of the 'saw teeth' will come into contact (more precisely, for which the interaction will be strongest) when:
   - the walker increases his pace (forwards);
   - the walker slows his pace; or
   - an empty shoe is dragged along horizontally by a piece of string.

   In the first case, the starting block analogy is used.
   In the third case, the situation of sliding with deformation of the asperities is briefly mentioned.
   In each case, the fragmented diagrams are drawn for the interaction between faces in contact and for a balance of the forces acting on the object whose movement is the subject of discussion.
   About a quarter of an hour is required to introduce this model and its application to walking or to dragging an object (points 4, 5, and 6).
7. The situation of the drive and non-drive wheels of a car is tackled from the point of view of the horizontal components of the forces involved in the ground–wheel interaction and the balance of forces on the car when it is accelerating or braking. It is essential that reference is made to the model with the saw-tooth surface profiles. The situation is first approached by question and discussion, then by presenting the 'model answer'. It is important to point out here that there is no longer an object translation and

that the proposed balance fits but is not strictly determined by an analysis in terms of the resultant alone. It is therefore more a matter of initiating students into the fact that friction can be motive, that it always involves two reciprocal forces between two objects and that frictional forces on drive and non-drive car wheels, respectively, can be in opposite directions even if their axles have the same acceleration.

Five minutes were enough for this third stage during the trials (point 7).

Appendix 2: a teaching sequence on fluid statics

This is a short sequence (about two and a half hours). It can be used in upper secondary school or in the first year of university. It requires a basic knowledge of classical mechanics in static situations only, particularly the concept of weight and the use of forces as vectors: resultant as the vector sum and the resolution of one force into two components.

The sequence begins with a mechanical consideration of the rubber balls. Three situations are studied, involving first a series of balls aligned horizontally and pushed against a vertical barrier, then in a vertical position with a push of the hand downwards, then vertically with an upward push.

In the horizontal situation (figure 7) a series of balls is placed on a table. At one end there is a barrier, at the other end someone pushes on the first ball. In a situation of equilibrium, the forces of the interaction between adjoining balls must have the same magnitude all along the horizontal line. The teacher has the students represent the forces as vectors on a graph, making it clear that the forces on the right-hand side have the same magnitude as those on the left, and then draw a graph of the function $F(n)$ representing the magnitude F of the forces according to the order number n of the contact points between two adjoining balls. Pushing harder increases the intensity of the forces, but *equally*, so that the graph is another straight horizontal line, only set higher up. A graph $F(x)$ is then plotted, where x is the abscissa of the position of the points of contact between adjacent balls. The same results as before are obtained; the points on the graph are still on a horizontal straight line, which moves to a parallel higher position if you push harder. But the points are slightly closer together when the external force is increased because the balls are slightly compressed, and so the distance between the points of contact is reduced.

Two vertical situations are studied (figure 8), in which the balls are placed in a column. In the first situation, the ball at the bottom rests on the ground and someone pushes down on the top ball. In the second, the top ball presses against the ceiling and the bottom ball is pushed upwards. In these situations, the forces between adjoining balls do not all have the same magnitude: they increase towards the bottom, each in a value equal to the weight of one ball. As in the horizontal situation, the teacher helps the students to draw a vectorial graph of the forces (stressing that, for each pair of balls, the upward force has the same magnitude as the downward one), then to make a graph of the function $F(n)$ representing the magnitude F of the forces according to the order number n of the contact points between two adjoining balls. The points of this graph are now on an oblique straight line. Pushing harder on the balls causes small deformations, and the forces increase, but *equally*, so that the difference ΔF between one force and the next remains unchanged, and equal to the weight of each ball. The points of the graph are still on an oblique straight line, parallel to the first and higher up.

Depending on the students' level of proficiency, the teacher can outline that the situation is a little different for a graph $F(h)$, where h is the height above ground of the points of contact between adjacent balls. The points of this graph are not exactly on a straight line. In fact, the difference ΔF, which is equal to the weight of one ball, is always the same, while the distance Δh between two successive points of contact lessens slightly as we move from top to bottom because the deformations are greater at the bottom than at the top. The gradient $a = \Delta F/\Delta h$ is not, therefore, exactly constant. These differences can be considered as very small, however, because the weight of the balls is very small compared with the forces required to produce major deformations. Thus, one can say that the points on the graph $F(h)$ are still, to use a very close approximation, on a slanting straight line, declining with h. If the external force is increased, the straight line is displaced upwards but, because of the deformation of the balls, two successive points on the new straight line are then separated by a distance Δh that is slightly smaller than before, whereas the values of ΔF do not change and are still equal to the weight of each ball. Consequently, the straight line becomes a little steeper, the gradient $\Delta F/\Delta h$ increases, but not by much. One can therefore say that the straight line is displaced upwards while remaining *almost parallel* to the previous one. To conclude, the graph $F(h)$ in question is *almost* a straight, slanted line, which is displaced upwards in an *almost* parallel manner if the external force is increased. These 'almost' statements cover relative variations of the order of 10^{-4} to 10^{-3} or less.

Then, the teacher proposes the analogy between the rubber ball model and liquids. Horizontal and vertical situations are discussed once more, an analogy is made between the force graphs $F(x)$ or $F(h)$ for the rubber balls and that of pressure $p(x)$ and $p(h)$ for fluids. With reference to the negligible values of the deformations caused by the forces in question, the teacher explains that under normal conditions, the approximations made for the rubber balls are valid for liquids but not for gases.

Next, discussion moves to pressure in a closed container completely filled with water, with a piston to push on the water (figure 9).

The teacher gets the students to discuss the following questions, accompanied here by some elements of the expected answers:

- What are all the points where the pressure is equal to that present at a point A near the piston, or at points B, C or D ? The analogy with the horizontal arrangement of balls is used.
- If one pushes harder on the piston, what happens? As with the rubber balls, the diagram showing the pressure $p(x)$ for points x on the same horizontal line gives a higher horizontal line. This means that all the pressures change, while remaining equal among themselves.
- Do the changes in pressure near the piston have effects in a vertical direction? Yes, because, in this model, when p_m increases, balls on the same horizontal line push harder against adjoining balls, even in the vertical direction, upward and downward.

Indeed, this is a weak point in the model; it can help students understand that the push is transmitted in all directions, but does not account for the equality of these forces. The teacher mentions, as part of the accepted theory, the isotropy of forces associated with pressure at a given point, stressing that the model alone does not lead to this conclusion.

The teacher develops the analogy using graphs. The aim is to develop the following argument. Pushing upwards, downwards or horizontally on a column of liquid that is blocked at the other end has the effect of changing the magnitudes of all the interactions while preserving the *differences* between them, just like when the hand was pressing on the rubber balls. Again the discussion makes use of the graph of the function $F(h)$ compared with that of the function $p(h)$, making explicit reference to the columns of liquid in the container under investigation and which are at issue for the study of the pressures at the points considered previously.

The teacher can propose other shapes of containers, to set students thinking about how the water interacts with the walls of the object or of an enclave introduced in the water.

In the final session of the sequence, students discuss the 'Three containers' situation (figure 5), comparing the forces exerted by the water on the bottoms (of equal areas) of three differently shaped containers (|__|, /__\ and __/) that are filled to the same level. Students work in groups of two or three, the instructor moving from group to group.