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Students' ideas about equilibrium, friction and dissipation

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ABSTRACT. Students' ideas on the explanation of motion phenomena will be presented. It will be shown that the researches have taken as the framework in which to place students' ideas, the scientific model of Newtonian mechanics centered on the force concept with little, if none, consideration on the real life motion phenomena which may be considered an important experential source of students interpretations. Equilibrium, friction and dissipation are key concepts for the analysis of these real life experiences. The analysis will also focus on the epistemological aspects related to the methodology of an experential science in the relation *observations/experiments/theories/models.* Historical considerations of the key concepts mentioned above will give evidence, besides furnishing a cultural background, of the problematic aspects of friction and dissipation. Suggestions for teachers' training will be discussed with a focus on conceptual change and on thinking about the possibility of changing the content organization of physics teaching in such a way as to take into consideration the experential roots of intuitive physics scheme.

Key words: friction, dissipation, equilibrium, conceptual changes, history and epistemology of physics.

RESUMO. Concepções dos estudantes sobre equilíbrio, atrito e dissipação. Serão apresentadas aqui algumas concepções dos estudantes acerca do fenômeno do movimento e a pesquisa que lhes deu origem, além do referencial no qual são classificadas estas concepções e que, geralmente, estão centradas no modelo da mecânica Newtoniana. O esquema de classificação está centrado sobre o conceito de força, desconsiderando a experiência do cotidiano, o que poderia ser essencial como fonte experencial dos estudantes. Equilíbrio, atrito e dissipação são conceitos fundamentais para a análise da fenomenologia cotidiana do movimento. A análise do presente artigo focalizará os aspectos metodológicos de uma ciência experencial baseada na relação *observações/experimentos/teorias/modelos.* Considerações históricas serão feitas para localizar os aspectos problemáticos do atrito e da dissipação. Algumas sugestões para o aprimoramento de professores serão discutidos com base em esquemas de mudança conceitual.

Palavras-chave: atrito, dissipação, equilíbrio, mudanças conceituais, história e epistemologia da física.

The researches on the spontaneous reasoning of students' in elementary dynamics (Viennot, 1979) may be considered as opening the line of research on "alternative conceptions" (spontaneous or common sense or naive physics).

Based on the bibliography given by Duit and Pfund (1991), the number of research works after 1979 grew up to more than 2,000 articles.

In these works one sees, for what concerns motion phenomena, on one side the search of students' conceptions and on the other proposals of a possible framework for common sense physics focusing on the phenomenological aspects (Ruggeri *et al.*, 1985; Ogborn, 1985).

However there seems to be little communication between these two trends: the research on students' ideas has focused on concepts of relevance in the frame of Newtonian mechanics with scarce consideration of the possible origin of the conceptions from the motion phenomena of everyday life while the discussion of a possible frame of intuitive physics has rarely been connected with the concepts of Newtonian mechanics.

In this article we will try to analyse the research results focusing the attention on the relation between the phenomenology of motion as it appears on our planet and the scientific model given by Newtonian mechanics: equilibrium, friction and dissipation are then the three scientific key words for all phenomena that are the experiential basis for the construction of interpretative models of common sense physics (Horton, 1982).

As it is well known in many researches a parallelism between students' ideas and Aristotelian physics is proposed. We then deemed necessary to frame our analysis in historical perspective again guided by our key words.

This perspective, reported in section 2, makes a point in favour of the criteria of analysis reported in section 3. The results of the analysis are then reported in section 4. Since from the research on alternative framework a number of didactical suggestions aimed at the conceptual change towards Newtonian mechanics have appeared in the literature, in section 5 we will present an overview of these proposals. In section 6 we will conclude with suggestions both for pursuing the research and for the didactical practice.

A perspective from history

A large number of studies have examined the history of the concept of force and the development of Newtonian mechanics. In these studies one finds discussions about the difference between the physics of Aristotle and Newtonian mechanics aimed at a confrontation with the research results on students' ideas about motion which reveal characteristics of Aristotelian flavour.

However, often the physics of Aristotle is looked at as a step toward the formulation of the "correct" Newtonian physics and not as a conceptual structure aimed at the explanation of natural phenomena in our terrestrial dissipative world. Thus, in the light of the unification of the phenomena of motion on Earth with those in the sky, the physics of Aristotle is seen as lacking logical coherence.

From our point of view (friction, dissipation, equilibrium) an analysis of history reveals that the physics of Arsitotle has a strong logical coherence which starts from the separation of the two worlds (the "supralunar" and the "sublunar") which are ruled by different qualities for what concerns the nature of the objects and their motion. The aim is not to unite the two worlds but to find a description and eventually an explanation to the phenomenological observation of earthly events where friction plays a basic role.

Let us look at what we may define as the empirical referents of his physics:

- the "natural" rectilinear motion in the vertical direction (up or down);
- the tendency to static equilibrium;
- the need of a "cause" for the "violent" motions which persist for a while after ceasing the impulse action which produced them;
- the existence of an all pervasive medium (air) in which motion takes place.

Aristotle is then led to deny the possibility of existence of vacuum also because of the axiom (in a medieval assertion) *"cessante causa cessat effectus"* air is needed both to sustain motion and stop it.

We may quote Aristotle [1993]:

"Further, in point of fact, things that are thrown, move though that which gave them their impulse is not touching them, either by reason of mutual replacement, as some maintain, or because the air that has been pushed pushes them with a movement quicker than the natural locomotion of the projectile wherewith it moves to its proper place."

The quotation indeed shows the logical coherence of Aristotle kinematics on earth.

One can also try a modern formulation in algebraic language for the fall of heavy objects leading to

$$v = k\,(P / \rho) \qquad (1)$$

where v is velocity, P is weight and ρ is the medium density.

Vacuum is impossible because in it an object would reach an infinite velocity (incidentally this prediction may be derived also from Newtonian mechanics if a force always induces an acceleration).

An interesting comment on the physics of Aristotle is found in Toulmin [1961] *(free translation):*

"Aristotle paid attention to the motion of bodies against an appreciable resistance and to the time duration necessary to a change of position from a place to another. By several reasons, he did not consider the problem of defining "velocity" as an expression of periods, each time, with short durations, e.g., the instantaneous velocity. He did not ask about how the bodies would move if all the causes of resistance were effectivelly or completelly removed. (...) if we paid attention to the kinds of motion which Aristotle considered typical, we would find that the rudimentary relations of proportionality estabilished by him have a respectable place in the physics of 20^{th} century. Interpreting it (this proportionality) not as a rival nature's law with respect to that pronounced by Newton, but as a generalization of the daily experience, means that most things claimed by Aristotle are true. We can also say that he was saying things more acute than what he never had imagined. Because of his reasoning based on terms of rudimentary and qualitative proportionalities (...) contemporary physics individualizes an exact mathematical equation ... This equation is known as "Stokes' law", which puts in relation the velocity of a body in a medium, for example, a liquid, the force acting on it and the density (viscosity) of medium. According to Stokes, the velocity of the body, under this condition, will be directly proportional to the force that caused the motion and inversely proportional to the viscosity of the liquid. Suppose that we let a ball fall, each time, inside containers filled with liquids of different viscosities, like water, honey and mercury; in each case the ball will accelerate until a limiting velocity is reached and then will continue to fall with constant velocity. If the impressed force is doubled, the velocity of the fall will be doubled; if a liquid is two times more viscous than another, the ball will fall with half the velocity."

Indeed, it is true that a generalization from the earthly experience, in which the inertial contribution is appreciable only in the initial states of motion, to the formulation of the inertia principle is not so straightforward.

After Aristotle one sees a development from the idea that motion always requires a cause to the law of inertia.

In all this development Aristotle's description is always considered be it as a necessary confrontation of new ideas or for criticisms. Already Hypparchus criticizes Aristotle's kinematics proposing that a "force" is communicated to the moving objects and then dissipated in the motion.

For Philoponus, the existence of vacuum is already possible and, in modern terminology, his kinematic equation may be written as

$$v = k' (F - a\rho) \qquad (2),$$

where a is a constant.

(Air does not contribute to the persistence of motion).

However, again in the Middle Ages, one finds that the questions to be discussed (Albert from Saxony) are:

- if vacuum exists;
- if in any movement a medium is needed;
- the possibility of motion in the vacuum.

We see that, following Aristotle, it is not the reaching of equilibrium which poses a problem but the inertial part of motion, where velocity is not sufficient to the description.

The initial inertia finds an explanation in the "impetus" concept (Buridan) and a somewhat complete frame from mechanics is proposed by the thinkers of Merton College. In this frame one starts to see a distinction between kinematics (description of motion) and dynamics (causes of motion) and a consideration of the (future) concept of acceleration is advanced.

These studies had an influence on Galileo who, starting from the idea that velocity is proportional to space, after a series of experiments on inclined planes, changes to a proportionality between s (space) and t^2 (time).

It is interesting to compare Galileo's arguments for the motion of a flying stone in air against Aristotle's arguments (Wanderlingh, 1995, *On Galileo*). In the second day of *Dialogo dei Massimi Sistemi* the question is debated with Simplicio defending the position of Aristotle (the stone needs a cause to continue its motion) while Salviati defends common sense (Newton is, of course, unknown).

For Simplicio, it is the air, that, put in motion at the time of throwing the stone, with the persistence of its motion drives the stone. For Salviati, if it is difficult to think of the persistence of motion of the stone, it should also be difficult to think of the persistence of motion of the air: it is a fact that the air moved by the agitation of a tissue, in a very short time comes to rest: the effect of air is to slow the stone. In fact both of them were right and both of them were wrong: one needs an Aristotelian air for a Newtonian stone and a Newtonian air form an Aristotelian stone. It is the beginning of the dychotomy about conservation and dissipation.

The dychotomy however is not explicitly recognized and the solution to Aristotle's and Galileo's problem is found considering air as a negligible factor: conservation wins over dissipation. When acceleration is defined as the leading kinematic variable in the production of motion, friction assumes the role of something that may be neglected (in Galileo's words: one needs "to neglect all that may be considered as accessory and contingent in order to generalize and quantify") and the road to the unification of the two separate worlds of Aristotle is open.

The definitions used by Newton for the formulation of his axioms, reported in "Appendix", exemplify this point. In particular one may note the distinction between "inherent force" and "impressed force": the first one seen as the "inertia" to alter the status of motion or rest of an object and opposed by the second which produces the changes. The attention is clearly focused on the initial part of a movement from a rest situation. The air resistance is mentioned only in the comment to first law where it is invoked for the slowing down of motion. The state of rest is considered only in Definition 3 in a phrase related to "common opinion" which is constrasted by the statement that motion and rest are not really different states.

Anyway we are far from the formalization of the axioms that we are used to find in textbooks in the form,

$$m_k \, d^2x_k /dt^2 = F_k \qquad (3)$$

This formulation is due to Euler and as Truesdell says: "occur nowhere in the work of Newton or of anyone else prior to 1747. It is true that we, today, can easily read them into Newton's words, but we do so by hindsight." And we may add: an hindsight which has been freed from friction, equilibrium, dissipation.

These aspects however cannot be forgotten in the technological applications and experimental organization. The history of pure science unfortunately often forgets the technical development where the ideal worlds of the theories have to confront the real world of objects.

Then we will conclude by quoting, on the applied science side, the introduction of friction coefficients by Leonardo da Vinci, the studies on lubrification (Muendel, 1995*)* and the production of experimental apparatus like Atwood and Morin's machines (Morin, 1834; Danhoni Neves, 1993; Cannata *et al*., 1996).

History then tells us that the phenomenology of motion on Earth needs a long way to go in order to be freed from friction and dissipation and thus confirms that our keywords are a good point of view for analysing the researches on students' ideas.

Criteria of the research analysis

As for Aristotle also every contemporary human being is faced since birth with a phenomenology of motion in which a very important factor is the existence of equilibrium situations and the final decay of every motion to rest. As for Aristotle the sublunar and the supralunar world are two different worlds. The similarities between Aristotelian physics and students' conceptions should then not come as a surprise.

To take, as usually done, the point of view of Newtonian mechanics, will not shed the right light on an analysis of the research. It is more reasonable to assume as criteria of analysis the key words (equilibrium, friction, dissipation) that characterize the phenomena on Earth.

More precisely the questions that will guide the analysis are:

A) Questions concerning the phenomenology:

- A_1) The research refers to motion phenomena in their complete evolution from an initial rest situation to the final equilibrium?
- A_2) In the research the inquiry, on one and the same phenomenon, looks at the meaning attributed to one single concept (e.g., force) ore more (e.g., force, inertia, impulse, energy, momentum)?
- A_3) Are there research works which focus, in particular, on the reaching of equilibrium from motion?

B) Questions concerned with the theoretical frame:

- B_1) Newtonian physics is the explicit theoretical referent? *In toto* or just part of it?
- B_2) Do the researchers explicit comments on the meaning of the scientific concepts?
- B_3) Does one find an analysis of the concepts of equilibrium, friction, dissipation?

C) Questions concerned with the epistemological frame:

- C_1) The presentation includes explicit comments on the relation phenomena/theory/model?
- C_2) The presentation includes a discussion on scientific language in comparison with everyday language?
- C_3) The presentation includes reference to the physics of Aristotle?

D) Questions concerned with cognitive and didactical aspects:

- D_1) The research is concerned with students' ideas, students' reasoning or both?
- D_2) The research proposes suggestions for the didactical practice?

Before entering into the analysis of the research it is useful to recall the characteristics that the questions used to elicit students' ideas should have in order to activate answers framed in the spontaneous physics conceptualization. These are:

a) the use of scientific words which are used in everyday language with the meaning redundance proper to it;
b) the avoidance of any reference to the use of mathematical formulas;
c) the framing in phenomena of everyday life or, at least, in situations that are atypical in the school context;
d) the introduction of elements which, while totally irrelevant for the answer, may act as a facilitating factor for the activation of naive schemes (the "negligible" in a scientific context which is hardly negligible in real life).

Good examples of questions of this kind are the juggler question by Viennot (1979), the questions of McCloskey and Caramazza and Green (1980) on the motion of a ball after leaving a curvilinear horizontal guide and more others. However, not always the questions conform to these requirements. Therefore, in the analysis while searching the answers to our A, B, C, D questions, we will also examine the questions formulation.

Analysis of the research

We started the analysis on two recent review articles for a first overview of the conceptual frame on which to focus the most significant researches to be subjected to a more detailed analysis.

The review articles analyzed are "Research on Alternative Conceptions in Science" (Wandersee, 1994) and "Cultural Factors in the Origin and Remediation of Alternative Conceptions in Physics" (Thijs, 1995). The first one is addressed to High School teachers and inserted in the context of the experimental sciences. The second one is addressed to researchers in physics education and inserted in the context of general physics. The two articles share the analysis of a large bibliography mainly from the research of Anglo-saxon works and with a scarce consideration of works produced outside this cultural context, also if published in English language in international journals. It follows that the two articles in question present a partial review while giving a synthetic presentation of a large spectrum of researches.

The authors pay attention to the necessity to analyze *a priori* the terminology used in the research in order to focus on the choice of the words *"alternative conceptions"* as the best expression for the characterization of the students' ideas. In the case of motion and the concept of force, then Wandersee *et al.* summarize students' ideas in four features: (1) force produces motion; (2) if F is constant, the velocity is also constant; (3) velocity is proportional to force; (4) in the absence of force, velocity decreases or is equal zero. On the other hand, Thijs *et al.* demonstrate the universality of a common sense scheme that: (1) considers force and motion; (2) does not differentiate position/velocity/ acceleration; (3) considers "force" as the only causal agent; (4) takes the terrestrial referential frame as an absolute referential frame.

We see here a seemingly different way of identifying alternative conceptions characteristics, more focused on the relation force/velocity the first, more on general features (causality, reference system) the second.

The authors discuss explicitly the problem of the origin of the alternative conceptions, pointing out the importance of the experiences of the natural world and to social communication with particular attention on the role of language.

On this basis, the authors point out the personal-subjective character of students' ideas but do not make an analysis of everyday phenomenology of the terrestrial world, which, being shared by all human beings of this world, would have pointed out the intersubjective features (Vicentini, 1996).

In fact, Thijs *et al.* discuss about the necessity of identifying the features of the shared knowledge, taking into account the universality of empirical data relative to cultural diversity. They quote the causal thinking suggested by Ogborn: *locality* (the cause is near the effect), *asymmetry* (the cause is precedent to the effect), *productivity* (the cause must produce an effect), *constance* (if there is a cause there is an effect), and *unicity* (the same cause always produces the same effect). However, these attributions are not compared with the features of causal scientific thinking (that are very similar to Ogborn's scheme, except for possible superpositions of causes and situations of non-linearity), and do not consider linguistic problems. These last ones, in particular for the meaning attributed by students to the word *"force"*, could have guided the discussion to an eventual confrontation between the causal thinking derived from Ogborn's scheme and the ideas of force.

It is clear that in the two articles there is not a reflection about the relation *"phenomenology/theory"*. There is not an analysis of the possible difference in the phenomenology for the support of the scientific theories and of the students' conceptions, and above all there is not an analysis of the students' ideas as theoretical elaborations, supported by the everyday phenomenology, and aimed at an understanding of reality for prediction and control of facts/events/actions more than at the construction of "scientific" knowledge. Thijs *et al.* suggest, acritically, that in the western countries the schemes of scientific culture are universally diffuse, without consideration of the diffusion of spiritual values and beliefs of all types (non-scientific or pseudoscientific).

In summary, from the analysis of the two articles one may conclude about the agreement concerning the empirical validity of the research results with the suggestions for a didactical practice, which involves students in an active participation. The understanding of the relation theory/ phenomenology is not, however, considered as an important aspect.

We then pursued the analysis with the examination of the bibliographical review by Carrascosa and Gil (1991), an article about the force conception by Hestenes (1992) and another one about the epistemological context by Hewson (1990). In the bibliography a list of the arguments used in the research may be found: throwing of objects in several directions, motions of spacecrafts, motions in several referential systems, trajectories and constraints, situations of statical equilibrium, springs and pendulums without friction, phenomena involving falling objects, collisions and kinematical problems. We see thus that in some cases, e.g., in all cases involving situations of motion without friction, the features of the questions more appropriate to elicit students naive conceptions are not taken into account. This is in particular the case for the "Force Concept Inventory" questionnaire devised by Hestenes.

In other articles, one finds comments about the diffuse and ambiguous use of the words *force* and *energy* in the daily language but these comments remain on the generalities, with little analysis of the linguistic ambiguities. In particular, "force" is the concept to be investigated and the possible ambiguity of the word in everyday language with the other scientific concepts (inertia, energy, momentum, etc.) involved in the explanation of motion is not considered. From the references in the articles we then found that concepts like energy, inertia, static equilibrium are all investigated as separate themes (Minstrell, 1982). Furthermore, the situation of rest in a referential system is considered either as static equilibrium or as the initial condition of motion, but there are no investigations on the reaching of equilibrium. Attention however is given to the equivalence of a motion with a constant velocity with a rest situation by a change of referential system. In conclusion, all researches, despite explicit reference to a constructivist model, seem to deny a possible coherence in students' conceptions, which are looked at from the Newtonian physics frame in its conservative form, with no consideration of the dissipative phenomenology of our terrestrial world. The parallelisms, also, with Aristotelian physics do not focus the attention on the essential role, for the construction of alternative conceptions of the experiences of motion in a dissipative world. Of our three key words we then see that "equilibrium" is investigated only as the static situation to be explained by the force scheme, "dissipation" is never considered and often explicity neglected. What about "friction"? We have found only one work (Caldas *et al.,* 1995) which focuses on the role of the friction and also this work, while an exception in an ocean of repetitions of investigation on the conservative aspects of the force concept, is restricted to the possibility of a drag, due to the friction between solids, between objects.

We may now draw our conclusions for the questions concerning the phenomenology (questions A in section 3): 1) No research considers the phenomena of motion in their complete evolution from an initial rest situation to the final equilibrium state; 2) No research looks at one and the same phenomenon, at the meanings of the different concepts needed in the scientific explanation. On the contrary, many researches look at one concept (and "force" is the principal one) in different experimental situations. The situations are often ideal situations with negligible friction; 3) No research has been done on the explanation of the reaching of equilibrium.

Newtonian conservative physics is the privileged angle for the inquiry and we may also draw conclusions about our questions concerning the theoretical frame (questions B of section 3):

1) Newtonian physics is the explicit theoretical frame, generally not in a complete conceptual structure. Hestenes and Reif are two exceptions as they explicitly present the conceptual structure. We will come back on this point.
2) Comments on the meanings of the scientific concepts are generally explicited also if not always framed in the conceptual structure.
3) Equilibrium is considered only in static situation. Friction appears only in one research on friction between solid surfaces. Dissipation is never considered.

Let us give a better look at the works of Hestenes and Reif for their definition of the conceptual structure of Newtonian physics. In the words of Hestenes, Newtonian mechanics is seen as the basic "modeling game" of physics in which it is important to underline the various logical components of the theoretical frame.

This logic is structured in four steps for the analysis of the system/object of study which are put in a one to one correspondence with four steps of the scientific model as shown in Figure 1.

System/Object	**Model**
I. Organization	**Scheme of system**
(composition, environment	- constituents (internals)
connections	- agents (externals)
reference system)	- connections
II. Basic Properties	**Descriptors**
(intrinsic/interactive	- object variables, for ex;, m, q, I
	- state of variables, for ex., x, v
	- variables of interaction, for ex., F, V
III. Structure (internal/external)	**Laws of Interaction**
	$F = GmM/r^2$
IV. Behaviour	**Laws of Change**
	$m\,a = F$
	$L = T$

Figure 1. Specification of the Model

The scheme explicits the important distinction between kinematical (descriptive) aspects and dynamical (explicative) aspects and also the *a priori* prerequisite of defining a reference system.

However, on the model side one step seems missing as, from the descriptors of motion (step 2), one goes directly to the expression at the explicative level of the laws of interaction and the laws of change bypassing in fact the step of the empirical laws descriptive of the experimental behaviour (in the motion case the relation $s = s(t)$). This missing step, of course, breaks the one to one correspondence between reality and the model as shown in figure 1 because step 4 on the object side should correspond to the formal description given by the missing step of the empirical laws.

The important point of Newton contribution to the solution of motion problems (Bernardini, 1996) seems to disappear: a kinematic general relation $s = s(t)$, requires, in principle, the knowledge of the velocity, the acceleration, and all higher order time derivatives of s. Newton's conjecture $F = ma$ corresponds to stopping this endless kinematic chain at the second derivative level by putting the acceleration in a direct relation with an independent function $F(s,v,t)$. In fact, in first instance the algorithmic compression by Newton forgets about the functional dependence on v and t and considers only conservative forces.

We will return to this point in the next section as both Hestenes and Reif propose a didactical approach based on this logical organization.

At this point we may conclude, for what concerns our questions about the epistemological frame (questions C of section 3) that:

1) In general, there is an absence of comments on the relation phenomenology/model (in agreement with the negative answer to question *A*) and, at the best, epistemological considerations are restricted to the theoretical Newtonian frame (Hestenes, 1992).
2) The several meanings of determinate words in everyday language are not confronted with the univocal meanings of scientific language.
3) A parallelism between students' conceptions and the physics of Aristotle is often made. However both are considered in a negative way, without an effort to search the good sense of the schemes regarding the terrestrial world phenomenology. The researches are coherently framed in a logical scheme where the phenomenological aspects have little, if no, weight for the construction and evaluation of a theoretical frame, whose logical and conceptual coherence is underlined.

With regard to cognitive questions, the most significant works are those produced by the group of the University of Paris VII. The first work of Viennot (1979), by the title "The spontaneous reasoning in elementary dynamics", shows that the focus is more on the reasoning procedures than on content understanding. Viennot wrote: "these experiments and other similars suggest the existence of an intuitive "law", by the students, expressed by a pseudolinear relation between force and velocity, $F=\alpha v$, as follows:

1) If $v=0$, so $F=0$, also if the acceleration is not equal zero;
2) If $v\neq0$, so $F\neq0$, also if $a=0$;
3) If the velocities are not equal, the forces are different, also if the accelerations are equal."

It is clear that it is different to distinguish between the reasoning procedures and the concepts used in the reasoning. In fact we find here the so-called Aristotelian relation, $F = \alpha v$ which is now attributed to spontaneous reasoning and compared with a scientific reasoning leading to the relation $F = ma$.

The principal feature of spontaneous reasoning is identified in a linear relation of cause (force) and effect (velocity) and not compared with the scientific reasoning where the difference lies only at the definition of the acceleration as the effect and retains the linear relation. It is very surprisingly that the relation $F=\alpha v$ is not related to the physical phenomena involving dissipation, and the lack of comments in its scientific use as an expression for friction forces in a medium.

The reasoning, or intuitive thinking, of students is analyzed with a very different approach in the works of Bliss and Ogborn (1989) and Mariani and Ogborn (1995). In these works alternative conceptions and reasoning are analyzed as a common sense theory of motion phenomena, or other phenomena belonging to the natural world, considered as a possible origin of alternative conceptions. The Newtonian frame is practically absent from these articles. However, there are some indications that alternative conceptions are grounded on a reasoning which does not differ from scientific reasoning except for the use of different concepts than those used today in the scientific discourse. We may then conclude with our question concerned with cognitive aspects (question D_1, see section 3) that the conceptual structure is not at all clear from the research results. The best conclusion for the moment is given by Eckstein and Shemesh (1989):

> *It is true that their (the students) comprehensions of scientific concepts are frequently confused, using uncorrectly scientific terminology, but this does not change the fact that students make analysis and*

previsions about physical phenomena in a clear and not ambiguous way.

An overview of some recent didactical proposals

With the repeated confirmation of the research results eliciting the existence of naive physics conceptions in the students, which have an intercultural similarity and a resistance to the traditional didactical approaches, the problem for the transmission to students of scientific knowledge may be formulated in how a teacher must organize his/her teaching strategy in order to transform the students' initial knowledge into a knowledge that conforms to the scientific frame (Viard, 1991).

For the case of motion the problem is then explicited in how to lead students from naive (Aristotelian) physics to Newtonian physics.

This conceptual change problem focuses on the importance of being able to communicate to students the "intelligibility, plausibility and utility" (Hewson, 1990) of scientific models (Newtonian mechanics in the case of motion).

We then see the appearance, in the literature, of studies which, by a reflection on the conceptual structure of Newtonian mechanics, try to localize the cognitive obstacles to its understanding.

The most complete of these studies is the work of Arons (1990) who does not limit the study to mechanics but examines other physics sectors besides commenting on linguistic and epistemological aspects. The book, "A Guide for Teaching Physics", is full of useful suggestions for teachers who may derive from them stimula for didactical strategies.

For the case of mechanics the most complete works are those by Hestenes and Reif. These authors propose a very similar approach in which it is declared that the students must understand Newtonian mechanics as an exemplary case of "Physics as a Modeling Game" (in the words of Hestenes). Students' ideas, while worth of consideration, are seen as being faulty from the logical point of view, the "correct" logic being the Newtonian one.

Reif says:

> *Students acquired scientific knowledge is often quite incoherent. Like much of everyday knowledge, it tends to be fragmented, consisting of separate knowledge elements that can often not be inferred from each other of from other knowledge.*

Therefore, acknowledging the inefficacy of traditional teaching, it is important to ask:

a) *"Can one understand better the underlying thought processes required to deal with a science like physics?*

b) *How can such an understanding be used to design more effective instruction?"* (Reif, 1995).

However, the acknowledgement that the effect of teaching is not the conceptual change to Newtonian physics but at best the insertion of words-scientific concepts in the naive physics conceptions in a sort of hybridization, does not lead to the consideration, for didactical purposes, of experiences and experiments in a dissipative situation.

Even the analysis of textbooks (e.g., Baumann, 1992) showing the presence of misconceptions even in the authors (presumably, physics experts) does not seem to suggest the importance of the issue.

Among the few exceptions we may quote Hawkins (1996):

> *(...) a careful study of motion in, and of, various fluids, might well precede that of classical mechanics. Such laboratory studies, at elementary levels, are a small but important part ... of the map of nature's territories. What it means to extend experience ... is to become more observant, more questioning of a wide range of everyday phenomena, too easily unnoticed.*

Newtonian mechanics, with the fundamental role of the concept of force, is anyway considered as the exemplar of "scientific truth" to which students may have access with the help of good didactical tools. This is true also for those authors, with an interest in epistemology and history, who deem important to communicate to students not only scientific knowledge, but also its character of being "conjectural" more then "true". As far as suggestions for didactical practice are concerned a recurring point is made for the need of giving the students the opportunity of expliciting their understanding by stimulating the discussion with the teachers and among them (sometimes this strategy is labeled "construtivistic teaching" with a strange misunderstanding of the fact that if constructivism is a model for learning procedures, it does not make sense at all to speak of constructivistic teaching!). Seldom, however, teachers are stimulated to develop the ability of listening to students' ideas and interpret them in the light of the experimental evidence of everyday life.

Sometimes, it is even possible to find strange interpretations of scientific concepts and principles by the proponents of didactical approaches.

An example may be found in Hestenes who, denouncing the difficulties that students have in accepting a "unitarian" force concepts, a function of position and velocity, does not explicit that the unity must be seen at the level of the relation $F=ma$ and forgets the scientific distinction between conservative forces $F_c = F_c(x)$ related to a potential and dissipative forces $F_d = F_d(x,v)$, related to the loss of energy and the creation of entropy (among which one finds the so despised for its Aristotelian flavour, expression $F_a = - kv$ that scientists use for the friction in a medium). Also Reif, in a recent textbook, underlines the importance of unifying the forces as what must be put at the left of the relation $F = ma$, in the meaning of the "cause" that produces as an "effect" the velocity change with an understatement on the diversity conservation/ dissipation.

Again we find that students should understand that there is no difference between the rest state of an object ($v = 0$) and a motion state at constant velocity forgetting the energy gap between the two states in the same reference system so obvious in everyday phenomena (Vicentini, 1996). Again we may read that "energy and its conservation are so strictly interrelated that it is impossible to treat one without the other" with no comments about energy dissipation (entropy creation).

This last example focuses on the fragmentation of the scientific knowledge, as it is taught, explicitly praised as unitarian and coherent in contrast with the fragmentation of students conceptions (remember Reif quotation).

We have mechanics on one side with energy conservation and on the other thermodynamics with temperature and heat (but why in the teaching of thermodynamics molecules may appear as more important than entropy?).

Every piece of scientific knowledge is seen as "unitarian" and "coherent" in its own with no care of interrelation with other pieces. The hypothesis that students' ideas, in their apparent fragmentation, may have a scientific quality is never considered, as if the interpretation, based on a rigid "scientific" framework forbids the consideration of alternative interpretations.

On the contrary, strategies based on the use of history or modern technologies are studied to convince students that the only possible organization of knowledge is the organization corresponding to the didactical frame that was estabilished at the beginning of this century. Newtonian mechanics is the basic knowledge to be learned in order to enter the world of physics. We do not argue against this, but we are convinced that more attention should be dedicated to the phenomenological aspects and that it should be avoided to focus only on the logic of the theoretical modelling.

In particular, what is missing in the traditional presentations of mechanics (and that does not seem to appear in the new proposals - with the possible exceptions of Arons and Hestenes) is the explorative phase in which one decides the aspects that may be neglected in order to focus on the leading parameters for describing the experimental behaviour.

Dissipation, in mechanics, is in fact the aspect that may be neglected in the initial phase of the motion - but absolutely not in the final. Only an explorative phase of observation of various motions, from the initial to the final states, can give the students the justification of the approximation of a negligible friction and of the experimental tricks (air tracks and the like) needed to obtain data in a situation in which the approximation is valid on our dissipative planet. The explorative phase may also be used for the necessary introduction of the variables needed for the description of the experimental behaviour - normally called kinematics, e.g., position, velocity, acceleration, choice of reference system and the effects of a change of reference. In this way, one could avoid that kinematics appear as a theoretico-mathematical introduction with little relevance for experiments.

The proposals that are advanced in the literature all seem to neglect this experimental phase in favour of the theoretical discussion (that at least in the works of Arons, Hestenes and Reif is logically very coherent in the conservative case). Dissipation is then treated in a marginal chapter where "ficticious" forces (static, dynamic, viscous, friction) are introduced without any comment on their measurability problem. In fact, while for conservative forces a static measurement procedure is avaiable, for all friction forces the only possible measure may be obtained during the process that they should describe thus leading to a sort of tautological description.

From the analysis of the researches on students' ideas one may synthetize four cognitive/ epistemological obstacles to the acceptance of the intellegibility, plausibility, utility of Newtonian mechanics:

1) The importance of a phenomenology in which dissipation is an important aspect in the construction of the alternative conceptions of students compared with the necessity of neglecting dissipation for the introduction of the scientific model of Newtonian mechanics;
2) The non-intuitivity of the concept of force in the alternative conceptions where the word is used as a mixture of the scientific concepts force, inertia, momentum, impulse;
3) The importance of communication to students of the epistemological aspects related to the relation theory/ experiments/ phenomenology/models;

4) The importance of communicating to students the meaning of "unification" and "coherence" in the scientific conceptual structure compared to the implicit meanings in their conceptions.

We do think that the research gives a reasonably complete picture of the problems students have in understanding Newtonian mechanics as not enough attention has been focused on the relevance of friction and dissipation. Future research, instead of searching more details about the force concept, should investigate about the explanation for the reaching of equilibrium and for the importance of many different concepts to explain one and the same phenomenon.

Coming to the didactical proposals we have shown that they take into account, in the large majority, the second cognitive obstacle of our list, with some attention to the epistemological obstacle (point 3) by a few authors.

Our first cognitive obstacle is however totally forgotten as it is for the forth. For this last one, on the contrary, Newtonian physics is claimed to be, in a sort of dogmatism, unitarian and coherent.

We think that more attention should be reserved to these obstacles. This attention in our opinion will probably lead to a rethinking of the conceptual structure of physics which, while leaving a central place to the Newtonian conservative model, will also focus on the central role of dissipation and equilibrium. This second central place is also important for approaches related to the Science-Technology-Society issue, as it may be obvious to everyone that the application of science to technology is not done in the ideal conservative world but in the real dissipative one. One should also take into account that many technological appliances are today objects of the experiential world which contributes to the construction of alternative conceptions.

At our knowledge one approach to this line has been developed and is now on trial, by a group of Brazilian researchers, at the secondary school level (Gref, 1993).

Also our group has developed an approach, "Generalized Kinematics and Response Function", which has been tried at the level of physics teachers' training (Vicentini, Wanderlingh, 1996). More should be done in developing this line of research.

Appendix

The definitions used by Newton [1960] for the formulation of his axioms (Densmore and Donehue, 1995):

"**Definition 1:** the quantity of matter is the measure of the same arising from its density and magnitude conjointly.

"**Definition 2:** the quantity of motion is the measure of the same arising from the velocity and the quantity of matter conjointly.

"**Definition 3:** the inherent force of matter is the power of resisting, by which each and every body, to the extent that it can, perseveres in its state either of resisting or of moving uniformly in a straight line." (Bellow this definition, Newton clarifies the notion of "inherent force", explaining: "Whence the inherent force can also be called by the extremely significant name, "force of inertia". A body exercises this force only in the alteration of its status by another force being impressed upon it, and this exercise falls under the diverse considerations of resistance and impetus ... Common opinion attributes resistance to things at rest and impetus to things in motion, but motion and rest, as they are commonly conceived, are distinguished from each other only with respect (to each other), nor are those things really at rest which are commonly seen as if at rest.").

"**Definition 4:** impressed force is an action exerted upon a body for changing its state either of resisting or of moving uniformly in a straight line". (Newton explains "impressed force": "this force consists in the action alone, and does not remain in the body after the action. For the body continues in each new state through the force of inertia alone. Moreover, impressed force has various origins, such as from impact, from pressure, from centripetal force.").

"**Definition 5:** centripetal force is that by which bodies are pulled, pushed, or in any way tend, towards some point from all sides, as to a center." (Newton explains: ..." of this kind is gravity, by which bodies tend to the center of the earth ...).

"**Definition 6:** the absolute quantity of centripetal force is the measure of the same, greater or less in proportion to the efficacy of the cause propagating it from the center through the encircling regions.

"**Definition 7:** the accelerative quantity of centripetal force is the measure of the same, proportional to the velocity which it generates in a given time.

"**Definition 8:** the motive quantity of centripetal force is the measure of the same proportional to the motion which it generates in a given time."

Transcribing the laws or axioms:

"**Law 1:** That every body continues in its state of resisting or of moving uniformly in a straight line, except insofar as it is driven by impressed forces to alter its state.

Projectiles continue in their motions except insofar as they are slowed by the resistance of the air, and insofar as they are driven downward by the force of gravity. A top, whose parts, by cohering, perpetually draw themselves back from rectilinear motions, does not stop rotating, except insofar as it is slowed by the air. And the greater bodies of the planets and comets preserve their motions, both progressive and circular, carried out in spaces of less resistance, for a longer time.

Law 2: That the change of motion is proportional to the motive force impressed, and takes place following the straight line in which that force is impressed.

If some force should generate any motion you please, a double (force) will generate a double (motion), and a triple (force) a triple (motion), whether it has been impressed all at once, or gradually or successively. And because this motion is always directed in the same way as the generating force, if the body was previously in motion, then this (impressed) motion is either added to its motion (if they have the same sense) or subtracted (if contrary), or joined on obliquely (if oblique) and compounded with it according to the determination of the two.

Law 3: That to an action there is always a contrary and equal reaction; or, that the mutual actions of two bodies upon each other are always and directed to contrary parts.

Whatever pushes or pulls something else is pushed or pulled by it to the same degree. If one pushes a stone with a finger is also pushed by the stone. If a horse pulls a stone tied to a rope, the horse will also be equally pulled (so to speak) to the stone: for the rope, being stretched in both directions, will by the same attempt to slacken itself urge the horse towards the stone, and the stone towards the horse, and will impede the progress of the one to the same degree that it promotes the progress of the other. If some body, should change the latter's motion in any way by its own force, the same body (because the equality of the mutual pushing) will also in turn undergo the same change in its own motion, in the contrary direction, by the force of the other. These actions produce equal changes not of velocities, but of motions - that is, in bodies that are unhindered in any other way. For changes in velocities made thus in opposite directions, are inversely proportional to the bodies, because the motions are equaly changed. This law applies to attractions as well ...".

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