A Proposal for the Use of Structural Models in Physics Teaching: the Case of Friction

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Abstract

Formal models are insufficient for learning at school age and unsatisfactory for the student's need to understand. We believe it important to propose *structural models* which can favor reasoning, interpretations and predictions, and are intellectually fruitful because they stimulate inquiry into entities and processes supposed to exist in material systems. We developed a teaching learning sequence on friction grounded on these ideas and based on a didactical reconstruction of the physics content, which has been tested in pre-service teacher education.

1. Teaching friction: how it is usually handled and students' difficulties

In secondary education, friction is generally presented as a marginal phenomenon and in a schematic way. Thus all the complexity and variety of friction phenomenology, which is object of numerous studies, go unrevealed.

Apart from a brief mention of the effect of surfaces "roughness", the solid bodies at contact are nearly always considered rigid bodies and represented by regular rectangles moving on planes indicated by segments. The rigid body schematization hinders any attempt to create an image of the mechanisms which can be the basis for a causal explanation of friction. It is just the image that many students seem to need to understand physical situations, as previous research has proved (Brown 1992, Ogborn 1993, Besson & Viennot 2004). This is a typical situation in which schematization is sufficient to *calculate*, on the basis of simplified laws, physical quantities requested in problems, but it is unable to make students *understand* the physical situation, for which deformations of solids are essential (Besson 2004).

Physics education research has shown some specific difficulties and conceptions on friction (Caldas-Saltiel 1995, Besson 1996), e.g. a tendency to refuse the possible motive role of friction, to identify normal force with weight, to consider only the friction force acting on the object in motion or stimulated to move, etc.

2. Reconstructing the physics content within a teaching perspective

A teaching proposal on a scientific subject demands reconstructing the topic to transform scientific knowledge in teachable knowledge (Chevallard 2005, Kattman et al 1997), taking into account the cognitive and didactic problems.

When consulting some modern treatises of tribology (Quinn 1991, Persson 1998, Bhushan 2002), one realizes how complex the topic is and how vast the problems, applications and theories are. Amongst all this material a choice has to be made of content-matter, models and examples which are suitable for secondary school.

Moreover, some recent developments are unknown to most teachers and many experimental and theoretic results, not even very recent ones, *contrast* with the laws normally proposed in physics handbooks. A few examples may illustrate this problem.

For sliding friction, handbooks generally present the classic laws, attributed to Amontons and Coulomb, according to which the friction force F is proportional to the normal force W, independent of the contact area A and, in the dynamic case, independent of the speed. However, things are not so simple.

For some materials relations have been found of the type $F \propto W^n$, with $n<1$ (e.g. textile fibers, polymers, numerous rocks). In many cases, the relation between friction force and load is complicated and cannot be expressed by a mathematical formula.

Moreover, there are various *sticky materials*, which present friction even without a load or with a "negative" load, such as plasticine, putty, resin…

Similar behavior has been observed in *nanotribology* experiments, founding relations like $F=\mu W+kA$, with an adhesive term kA, proportional to the area.

The independence of the kinetic friction force from the velocity is not generally valid.

The mechanisms at the origin of friction have been the object of doubts and controversies.

According to Amontons and Coulomb, the origin of sliding friction lies mainly in the interlocking and deforming of the surface asperities, whilst Desaguliers (1734) and Vince (1785) emphasize the importance of adhesion and Tomlinson (1929) the role of phononic energy dissipation. Today different mechanisms are considered, the relevance of which varies according to situations (adhesion, deformation and plowing of surfaces, elastic hysteresis, breaking of asperities and wear).

3. A teaching learning sequence on friction

To overcome the common difficulties concerning this topic and to help acquire the elements of an explicative model which allows constructing an image of the mechanisms producing friction, we have elaborated a Teaching Learning Sequence on friction between solids, based on the didactic choices summarized below:

- ✓ Present friction as an almost omnipresent set of phenomena that are crucial for most everyday activities.
- ✓ Start by giving examples where friction is presented as a positive "resource", rather than merely as an "obstacle" or "loss".

- ✓ Emphasize how friction is necessary to establish equilibrium after stress or motion.
- ✓ Refute the idea according to which friction always has a resistive effect, generating a force which opposes motion and acts only on the object in motion or stimulated to move.
- ✓ Avoid too much focusing on situations with horizontal friction forces which can favor identification between normal force and weight.

As for the use of models, we believe that formal models, in terms of functional relations expressed by formulas, are insufficient for learning at school age and unsatisfactory for the student's need to understand. We propose using appropriate *structural models* which allow, although to a limited extent, reasoning, interpretations and predictions. The incompleteness of the model is discussed at the very beginning, together with the degree to which it fits physical reality, i.e. its similarity to material elements and mechanisms *which really do exist.* These models have an *explanatory function* and are cognitively fertile, because they stimulate research on the entities and processes which are presumed to exist within the material system.

The sequence is organized into six parts, briefly described below.

3.1 Introductory observations and experiments

Simple qualitative experiments illustrate the different typologies of friction, in situations in which friction is considered to be a disturbance or a useful phenomenon. First, experiments are based on the question "What would happen if there were no friction?" in daily activities such as picking up a bottle, walking, weighing with a spring scale, pouring liquid into a container, carrying glasses on a tray etc.

Observation of damped oscillations of liquids, springs and metal wires, introduces internal friction while other experiments emphasize the role of adhesion and the particular behavior of "sticky" materials.

3.2 Vertical friction: definition of descriptive quantities and first qualitative relations

To keep the student from identifying normal force with weight, an experiment is proposed in which a vertical friction force is present and normal force is not related to weight: small wooden boards are pressed against a wall first by a finger, then by a force probe, so as to allow measurements.

The teacher shows other ways of producing a normal force (a magnet, an accelerated paddle).

A first theoretic framework is provided, introducing some quantities essential to a scientific and not merely empirical study (normal force or load, friction force, friction coefficient, contact area). Students are encouraged to propose schematic models of the surfaces in contact, which could help account for the observed behavior.

3.3 Phenomenological laws on static and kinetic friction

A more systematic experiment is carried out, in a situation of horizontal motion, by using a computer Data Acquisition System: students analyze the variation in time of the friction force and its dependence on the load and on the contact area.

3.4 Static friction and rolling

The knowledge acquired is applied to the case of rolling, which causes difficulties to many students (Rimoldini-Singh 2005). A logical progression is proposed, starting from an analysis of the overturning of a cube and of an octagonal prism, and leading to the physical mechanism of the rolling of a cylinder, considered as a limit case of a prism. Emphasis is placed on the role and direction of static friction force in different ways of rolling (cylinder pulled by a force applied to the axis or rolling due to a torque), by using specific experiments.

3.5 Structural models: topography of surfaces and mechanisms producing friction

The classic friction laws are discussed as phenomenological laws, requiring explanations on the underlying phenomena. It is emphasized that in many cases different empirical relations are found.

The surfaces topography and the distinction between apparent and real area are presented, by means of figures and drawings. Some mechanisms producing friction are presented in a simplified and intuitive way: adhesion between the surfaces asperities; deformation, tracking or scratching of surfaces; impact and interlocking among asperities; wear; deformation and abrasion due to particles trapped between the surfaces. Some historical explanatory models of sliding friction phenomena are presented together with some more recent ones.

3.6 Friction phenomena from the point of view of energy

Qualitative experiments are discussed, emphasizing the energy transfers towards *internal* parts of systems: damped oscillations of metal blades and of cylinders containing lead shot, inelastic collisions of a cart equipped with many oscillators…

The process can be modeled as a double passage of energy, first from macro to mesoscopic level, then from mesoscopic to microscopic (Besson 2005).

The damped oscillations of metal blades represent a bridging analogy for a first explicative model of energy exchanges in sliding: the asperities of the contact surfaces are depicted as mesoscopic blades-springs, the motion causes a deformation in them, thus transferring macroscopic energy in elastic mesoscopic energy. Then the asperities-springs separate and oscillate, with a rapid damping, thus transforming the mesoscopic energy into microscopic energy.

This model is immediately criticized because it does not account for various aspects such as approximate independence from area, while the usefulness of partial models, explaining only particular aspects of the phenomenology is stressed. Another model is then proposed with more widespread asperities, which can be deformed and crushed under the load, as a step through the adhesive junctions' model of Bowden-Tabor (1950).

4. Evaluation of the sequence

The sequence was first tested with two groups of student teachers (N_1=24, N_2=22), then six of them proposed it in three high school classes in which they carried out their training, and later it was proposed to expert teachers, which adapted and used it in their classes. To facilitate the reproducibility of the sequence in a real school context, we have designed an *open source structure*, in which there is a *core* of contents, conceptual correlations and methodological choices with a *cloud* of elements that can be re-designed by teachers who can create new versions of the sequence. The teachers' work provides a feedback useful not only to test the effectiveness of the proposal or to identify its points of weakness, but also to enrich it with new elements.

The evaluation was carried out by means of a pre-test, two post-tests, work-sheets and reports written by the students, reports and comments provided by teachers and observers. Significant positive results were found. We give here only some examples.

4.1 Friction force as motive force and direction of static friction force

The motive role of friction force, with the correct indication of its direction, is understood only by a minority of students in the pre-test (16%, a block placed on a cart), and by 100%, 86% and 72% in the post-test, respectively, in three different cases: a block pulled over a mat, a dish lying on an accelerated cart (fig. 1a), and an object on a rotating carousel (fig. 1c).

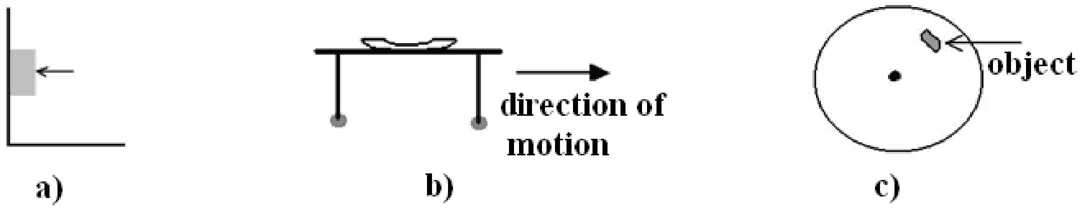

Figure 1. Examples of situations proposed to students in the final test.

a) A wooden block is pushed against a wall by a horizontal force. b) A cart with a dish placed on it is put in motion with a small acceleration, then moved at uniform motion and finally slowed down. c) An object is placed on and remains at rest with respect to a carousel rotating at constant speed

4.2 The phenomenological and approximate nature of the classical laws of friction

In the answers to the post-test, many students underline that the independence of the frictional force from the contact area and the proportionality between frictional force and normal force are only approximate and not always true. Some quotations: “the proportionality between frictional force and normal force is not fully respected”, “for sticky materials this proportionality is not valid”, “the kinetic friction force does not depend on velocity, but sometimes it does”, “the usual empirical law is not always valid”.

4.3 Use and effectiveness of a structural model

The consideration of a structural model, nearly absent at the beginning, increases progressively. Many students (86%) used, in different situations, a mesoscopic structural model (represented by drawings and verbal descriptions involving asperity interactions) to support their answers and explanations. In the situation of the dish on a cart (fig. 1b), *none* of the students (8) who indicated a wrong direction of the friction force during the acceleration of the cart had done drawings regarding the model; on the contrary, among those who did such drawings (30) *all* answered correctly for the phase of acceleration and almost all (78%) for the three phases of acceleration, uniform motion and deceleration. In this case, the model is not merely a figurative representation, but it takes on an operative explicative function, even if in a very simplified form, because the asperities are depicted deformed in a different way in the situations of acceleration, deceleration and uniform motion.

5. Conclusions and implications

This research has touched many different aspects involved in the design and implementation of a teaching sequence, confirming the importance of a critical reflection on the content matter in view of its reconstruction for teaching purposes.

We aimed at avoiding premature schematizations, at presenting phenomena in a way which is faithful to reality and to the current scientific knowledge, and at accustoming students to reason qualitatively on complex real situations.

The testing of the sequence with prospective teachers has provided encouraging results, from the point of view of overcoming some typical difficulties with the topic and of activating new, richer reasoning. Positive elements emerged from the comments of teachers and students, in terms of motivation, interest, challenge and feasibility.

As regards the use of structural explicative models, which we consider important for understanding physical situations not merely with manipulations of formulas, the reception has been positive. The characteristics of the proposed models have been the basis for articulate qualitative explanations. The reasoning produced by the students, although incomplete, rises to a much more refined level than the simple repetition of fixed and abstract rules based on idealized objects.

List of references

Amontons G. (1699) De la résistance causée dans les machines, Mémoires de l'Académie Royale A, in Histoire de l'Académie Royale des Sciences, Paris, 1732, pp. 206-227.

Besson, U. (1996) Le frottement solide sec de glissement, Rapport de tutorat, Université de Paris 7.

Besson U. (2004) Some features of causal reasoning: common sense and physics teaching. Research in Science & Technological Education, 22 (1), 113-125.

Besson U. & Viennot L. (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), p.1083-1110.

Besson U. (2005) Le mésoscopique en physique et en didactique, Le BUP, n. 873, p. 441-462.

Borghi L., De Ambrosis A., Lunati E. and Mascheretti P. (2001) In-service teacher education: an attempt to link reflection on physics subjects with teaching practice. Physics Education, 36, 299-305.

Borghi L., De Ambrosis A., Mascheretti P. (2005) Sliding and rolling: the role of friction. In Michelini M. & Pugliese S. (eds) Physics Teaching and Learning, GIREP book of selected paper, Forum, Udine, pp. 133-147.

Bowden F.P. & Tabor D. (1950-1964) Friction and Lubrication of Solids. Oxford University Press, vol. I-II.

Brown, D.E. (1992) Using examples and analogies to remediate misconceptions in physics: factors influencing conceptual change, Journal of Research in Science Teaching, 29, 17–34.

Bhushan B. (2002) Introduction to tribology, John Wiley & Sons.

Caldas, H. & Saltiel, E. (1995) Le frottement cinétique: analyse des raisonnements des étudiants, Didaskalia, 6, 55–71.

Chevallard Y. (1985) La transposition didactique, La Pensée Sauvage, Grenoble.

Coulomb C.A. (1785) Théories des Machines Simples. Mémoire de Mathématique et de Physique de l'Académie Royale, X, Paris, p. 161-342.

Desaguliers J.T. (1734) A Course of Experimental Philosophy, vol.1, London.

Hähner G. & Spencer N (1998) Rubbing and scrubbing. Physics Today, Sept. 1998, p.22-26.

Kattmann U., Duit R., Gropengießer H., Komorek M. (1997) Das Modell der Didaktischen Rekonstruktion. Zeitschrift für Didaktik der Naturwissenschaften, 3 (3), 3–18.

Ogborn, J. (1993) Approche théorique et empirique de la causalité, Didaskalia, 1, 29–47.

Persson Bo N.J. (1998) Sliding Friction. Berlin, Springer-Verlag.

Quinn T.F.J. (1991) Physical analysis for tribology, Cambridge University Press.

L.G. Rimoldini and C. Singh (2005) Student understanding of rotational and rolling motion concepts. Physical Review ST-PER, 1, 010102, 1-9

Tomlinson G.A. (1929) A Molecular Theory of Friction, Philosophical Magazine, 7, 905-939.

Vince S. (1785) The Motion of Bodies affected by Friction, Philosophical Transactions of the Royal Society of London, pp. 165-189.