An Epistemological Approach to Modeling: Cases Studies and Implications for Science Teaching

GÉRARD SENSEVY
European University in Brittany, Centre de Recherche sur l'Education les Apprentissages et la Didactique, EA 3875, University Rennes 2—IUFM de Bretagne F-35000, France

ANDRÉE TIBERGHIEN
UMR ICAR, University Lyon 2, F-69, France

JÉRÔME SANTINI, SYLVAIN LAUBÉ
European University in Brittany, Centre de Recherche sur l'Education les Apprentissages et la Didactique, EA 3875, University Rennes 2—IUFM de Bretagne F-35000, France

PETER GRIGGS
UMR ICAR, University Lyon 2, F-69, France

Received 31 March 2007; revised 14 November 2007; accepted 23 December 2007

DOI 10.1002/sce.20268
Published online 19 February 2008 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: Models and modeling are a major issue in science studies and in science education. In addressing such an issue, we first propose an epistemological discussion based on the works of Cartwright (1983, 1999), Fleck (1935/1979), and Hacking (1983). This leads us to emphasize the transitions between the abstract and the concrete in the modeling process, by using the notions of *nomogical machine* (Cartwright, 1999), *language game* (Wittgenstein, 1953/1997), and *thought style* (Fleck, 1935/1979). Then, in the light of our epistemological approach, we study four cases coming from the implementations of research-based design activities (SESAMES, 2007). These four case studies illustrate how students are engaged in constructing relations between the abstract and the concrete through modeling activities, by elaborating at the same time specific language games and appropriate thought styles. Finally, we draw some implications for science teaching. It is suggested that considering *didactic* nomological machines as embedding knowledge on the one hand, and classes as thought collectives, on the other hand, may relevantly contribute to science education and science education research. © 2008 Wiley Periodicals, Inc. *Sci Ed* **92:**424–446, 2008

Correspondence to: Gérard Sensevy; e-mail: gerard.sensevy@bretagne.iufm.fr

INTRODUCTION

This paper presents an epistemological position on modeling and discusses how this position plays a role in physics teaching. In the first part of this paper, we present an epistemological discussion of the notion of model. Mainly relying on the works of Cartwright (1983, 1999), Fleck (1935/1979), and Hacking (1983), we propose a particular way of describing scientific activity that seems to us both more rigorous and respectful of the reality of this activity than most of the classical descriptions, and of a heuristic potential for research in science education. This leads us to emphasize the importance of the transition from the abstract to the concrete and from the concrete to the abstract in the modeling process. In this respect, the notions of *nomogical machine*, *language game*, and *thought style* play a prominent role.

The second section of the paper is devoted to four case studies (in high school mechanics), in which we make concrete some of the main theoretical points we have previously elaborated.

In the third part of this paper, we envisage some possible implications for science teaching resulting from the reflection carried out in the two first parts of the paper.

MODEL, THOUGHT STYLE, EXPERIMENTATION

What Is a Model?

The conception of what a model is depends on a system of ideas relating to what science and scientific activity are. Depending on the epistemology one is using, the model, inside the theory integrating it, may be considered differently. In the following, we present a conception that we call empirical for two reasons: empirical in that it tries to reevaluate the importance of experiments, of the situation, and of the instruments used, in the continuing production of models (e.g., of the atom, Justi & Gilbert, 2000; or of acids and bases, Erduran, 2001), but also empirical in that it tries to produce an epistemology of "science in action," and not according to the more or less "scholastic" description that some classical epistemologists may have produced.

Model, Localism, and Multiplicism: The Dappled World. According to a certain description, conceiving a model is producing a law. What may be the nature of such a law? Cartwright wrote in 1983 a book with a provocative title, *How The Laws of Nature Lie*. Contrary to what the title might imply, it is not a book of relativistic epistemology, which contests the claim of science to tell the truth. Rather, it is an invitation to distance oneself from a "universalistic" conception of science, in which the "laws of nature," which apply everywhere and in all cases, govern our experiments. Since then Cartwright has developed this point of view (Cartwright, 1999). Science uses precise concepts linked by exact deductive relationships. But to get this kind of exact relationship, abstract concepts (like force) must be mediated by more concrete ones (like two compact masses separated by a distance r, or the model for a charge moving in a uniform magnetic field, etc.). At the core of the modeling activity lie complex relationships between the abstract and the concrete, in that the "more concrete concepts . . . are very specific in their form: the forms are given by the interpretative models of the theory" (Cartwright, 1999, p. 3). The consequences of this concrete specificity are threefold: (1) the abstract concept receives a very precise content because of the highly specified models, but (2) it can be attached to only some situations that can be represented by these highly specialized models, (3) these models *interpret* the abstract concepts (Cartwright, 1999, p. 3). Science produces explanatory models of the

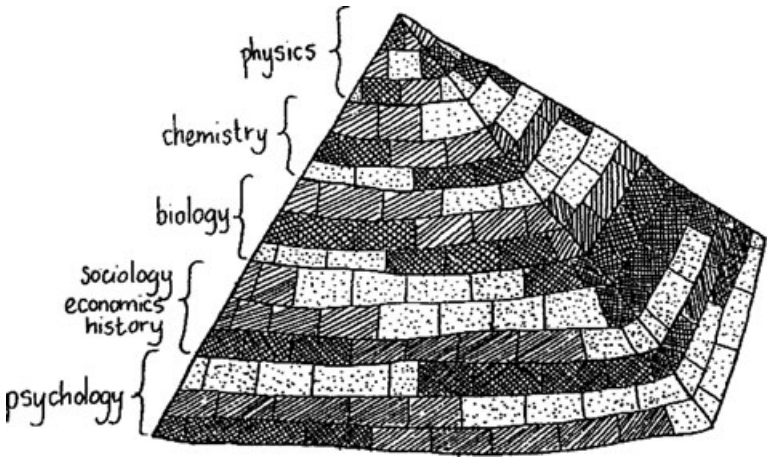


Figure 1. Pyramid (Cartwright, 1999, p. 7).

world, but not of the world as it is, rather of the world as it is reconstructed in the experimental enclosure. The concern is then to reevaluate the importance of the situations in which the truth is elaborated.

Cartwright may then state one of her fundamental theses: "The laws of physics apply only where its models fit, that, apparently, includes only a very limited range of circumstances." She next places the epistemological work in a very particular background by borrowing most of her argument from Otto Neurath (1882–1945). One of the functions of this background consists in combating the strong tendency to represent the edifice of sciences as a pyramid with physics at the pinnacle and psychology at the bottom (Figure 1).

The core of this representation consists in the fact that "the laws and concepts of each scientific domain are reducible to those of a more fundamental domain, all arranged in a hierarchy" (Cartwright, 1999, p. 6). There is a strong logical link between the universalism of the laws of physics and the type of reductionism this pyramidal conception supposes. To consider the laws of physics as universal justifies this particular reductionism that is physicalism: since the laws of physics are universal (and independent of the contexts), they are valid everywhere and we may then reduce all processes (especially vital processes) to physical processes without distorting them.

Cartwright, relying on Neurath (1983), then proposes an alternative view that can be represented as in Figure 2. She comments on this picture in the following way: "The sciences are each tied, both in application and confirmation, to the same material world; their language is the shared language of space-time events. But beyond that there is no system, no fixed relations among them. There is no universal cover of law" (1999, p. 6). In a similar way, Erduran (2001) argues against the reduction of chemistry to physics and consequently against the reduction of biology to chemistry. We see then taking form a *dappled world*[1] made of scientific domains partly incommensurable to each other. Not only does this point of view disparage the idea that there exist fundamental concepts of physics to which the concepts of the other sciences may be reduced, it implies also that no hierarchy between the sciences of nature and the human and social sciences is a priori stated.

[1] This is the title of Cartwright's book (1999): *The Dappled World: A Study of the Boundaries of Sciences*.

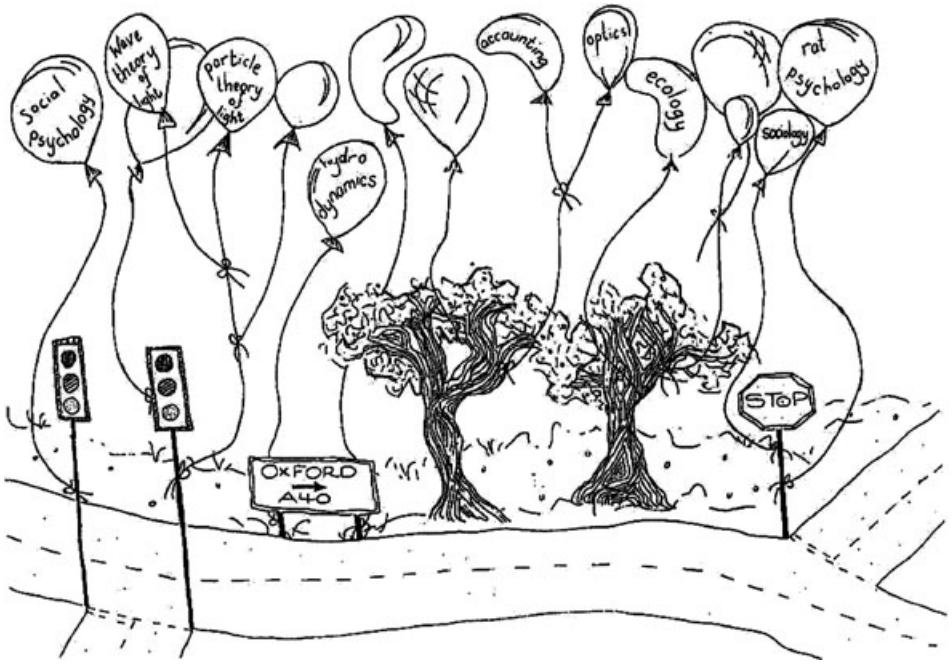


Figure 2. The dappled world (Cartwright, 1999, p. 8).

From Abstract to Concrete: The Fable–Model Analogy. In the *dappled* description of empirical epistemology, a major issue is the understanding of the transition from an abstract theoretical concept (e.g., the concept of force in physics) to more concrete structures—the "highly specialized models" that interpret these concepts more concretely. To comprehend science modeling is then to comprehend this passage from the abstract to the concrete. Here lies a crucial point in Cartwright's line of argument. To understand this passage, we have to think about fables and their morals: "fables transform the abstract into the concrete, and in so doing, I claim, they function like models in physics. The thesis I want to defend is that the relationship between the moral and the fable is like that between a scientific law and a model" (Cartwright, 1999, pp. 36–37).

Cartwright gets her argument from an author of the German Enlightenment, Lessing (1729–1781). The fundamental idea of Lessing[2] is that "intuitive knowledge"[3] is clear in itself, and the symbolic knowledge "borrows its clarity from the intuitive [knowledge]" (Lessing, quoted by Cartwright, 1999, p. 38). For Lessing, to make clear a *general* symbolic idea, one has to reduce it to the *particular*. This reduction to the particular plays an essential role in the mechanism of the fable. Cartwright then makes a useful comparison between the ways the fable and the model work. The abstract–concrete relation, at the core of the fable, is also at the core of the models of physics. Cartwright carries the analogy to its end: for example, $F = ma$ is an abstract truth with respect to claims about positions, motions, masses, and extensions, in the same way that Lessing's moral "the weaker are always prey to the

[2] Cartwright elaborates on the following Lessing fable: "A marten eats the grouse; A fox throttles the marten; the tooth of the wolf, the fox," and its moral: "The weaker are always prey to the stronger."

[3] In the context of the German Enlightenment, the knowledge coming from the ideas that we have about things is intuitive, and is figurative (or symbolic), the knowledge coming from the signs we have substituted for things. For an insightful analysis of the relations between ideas and signs, one can notably refer to Hacking (1975).

stronger" is abstract with respect to the more concrete descriptions (the narrative of the fable, with "eat," "fox," "marten," "tooth of the wolf," etc.).For Cartwright, the analogy is obvious:

> To be subject to a force of a certain size, say F, is an abstract property, like being weaker than. Newton's law tells that whatever has this property has another, namely having a mass and acceleration which, when multiplied together, give the already mentioned numerical value, F. That is like claiming that whoever is weaker will also be prey to the stronger. (1999, p. 43)

We have to point out that these abstract entities exist only in particular structures: force in particular mechanical models, moral in particular narratives.

Context and Nomological Machine.[4] After having shown all the benefits, in particular in the subtle comprehension of the abstract–concrete relation, that can be gained from the analogy fable = model, Cartwright endeavors to determine how a scientific model could be specified. To do this, she invents the notion of "nomological machine," which she defines as "a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behavior that we represent in our scientific laws" (1999, p. 50). In the same way, Koponen (2006) emphasizes the role of empirical reliability of models in physics.

The focus on the notion of nomological machine allows us to specify a fundamental aspect of the relation between laws, models, and contexts: it is a relation of mutual dependency, which prevents us from thinking about a given law without the context in which it is true. To describe a nomological machine is precisely to describe this kind of relationship between "interpretative model" and context. An essential aspect of these relations lies in the *shielding conditions*. For example, when Newton establishes the intensity of the force required to keep a planet in an elliptic orbit ($F = -GmM/r^2$), the following shielding condition is a crucial one: an elliptic orbit is observed only if the two bodies interact in the absence of all other huge bodies, and of all other factors that can modify the movement.

We can now turn our attention to the vocabulary: "capacities" and "behaviors." It is partly by using these terms that Cartwright constructs an epistemology that makes it possible to get rid of physicalism and to link the epistemology of science to the one of everyday life. There is a close kinship between the notion of capacity that we can attribute, in everyday life, to such-and-such an object or person and the notion of scientific capacity that one makes use of to give shape to the notion of nomological machine. To think in terms of capacities is indeed to make ourselves perceptive to the fact that such an object (in a large sense) holds a power, a potentiality,[5] and that the description of the behavior of this object may benefit from attributing it the potentialities that belong to it. For example, if we deal with someone irritable, carrying on the example used by Cartwright, to attribute to him this capacity of irritability will make it possible to understand—and predict—some aspects of his behavior that would remain opaque if we did not.

However, to elaborate such a kinship between everyday capacities and scientific capacities is not at all the same as assimilating them.

To understand that point, it is worth comparing two kinds of capacities: on the one hand, the ones we get from saying about someone that he is irritable and, on the other hand, the ones we can see working in a nomological machine (the chosen example being Coulomb's law).

[4] The adjective "nomological" refers to the Greek *nomos*, meaning law. A nomological machine is then a law-producing machine or a law-illustrating machine.

[5] The conception of human action in terms of capacities takes its source in Aristotle and his notion of *dynamis* (the latin *potentia*) that has been translated by power, potentiality, trend, or *capacity*.

Cartwright points out three salient differences. The first one is the following: beyond the fact that these two kinds of capacities are "highly generic" and "give rise to a great variety of different kinds of behaviour," the relationship between the capacity and its manifestations applies to scientific activity. It consists in finding what systematic connections can be proved, and devises a teachable[6] method for representing them (1999, p. 54). The second difference between an everyday life capacity and a scientific capacity like those described by Coulomb's law is that the latter holds an "exact functional form" of mathematical law.The third difference is that explicit rules describe how the scientific capacities will combine with each other.

Nomological Machines, Capacities Versus Dispositions. Nomological machines enable scientific activity to attain contextual truth. Thinking the models and the laws in terms of capacities and behaviors provides a means to establish some kind of continuity between everyday life epistemology and scientific epistemology, while accurately identifying some elements of opposition between the two types.[7]

According to Cartwright, it is worth considering science as knowledge of capacities rather than knowledge of laws. Cartwright shows in particular that a capacity cannot be assimilated to a disposition in that the terms of dispositions are usually linked one by one to law-like regularities. This can once again be illustrated by Coulomb's law ($F = -q_1q_2/4\pi\varepsilon_0 r^2$, for two particles of charge q_1 and q_2 separated by a distance r). What does Coulomb's law tell us about the motions of the pair of particles? Nothing, according to Cartwright, for without a specific environment, as is displayed in a specific nomological machine, no motion is determined (1999, p. 59). So, continues Cartwright, what we might call *natural behavior* for opposed charges is to move toward each other and for similar charges to repulse each other. But this does not constitute an in abstracto effect. We can even imagine, as the author shows us, specific environments in which "the Coulomb repulsion between two negatively charge particles causes them to move closer together" (Cartwright, 1999, p. 59).

So, what differentiates a capacity, in its openness, from a disposition, is the fact that it may give rise to highly varied behaviors, whereas dispositions are tied to a single manifestation (Cartwright, 1999, p. 64). At the same time, the language used to name capacities reflects this openness, with a higher degree of specificity when we go from the general capacity to the specific manifestation.[8]

Models and Thought Styles

The preceding considerations aim at contributing to the characterization of the models and of the process of modeling in that they are specific to sciences. It appears important to us also to establish the generic dimensions to the process of categorization itself. To do

[6] Here we see how scientific activity has included an organic didactic dimension since its first moments.

[7] The central question of the epistemological relationship between *common sense* and *scientific thinking* may be then rethought in a dialectic between opposition and continuity that makes it possible to unite the contributions of Bachelard and Dewey—on the following, cf. Fabre (2005).

[8] Cartwright pursues here the distinction produced by the English philosopher G. Ryle (1949) between the verbs referring to "highly generic dispositions" (the capacities according to Cartwright) and the verbs referring to "highly specific dispositions" (the dispositions according to Cartwright). We can describe the work of a fisherman by saying he is fishing (specific disposition), but not the work of a grocer by saying he is doing grocery (we will rather say that he is cutting some ham or that he wrapping up some food, etc.), precisely because the work of grocery refers to a *highly generic* disposition, that is, a capacity according to Cartwright. Let us notice that this distinction is not at all absolute but relative as is the distinction between generic and specific.

that, we will first emphasize elements that are always specific to scientific modeling but whose consequences seem important to us in the perspective of a broader understanding of the modeling process. We will then address the question of the thought style.

Model and Reference: The Holism of the Model. A scientific model, if we consider it as the blueprint for a *nomological machine*, cannot be understood independently from a background which is necessary to its understanding. This background may be described at different levels of specificity: to understand Newton's law, for example, it is necessary and, as we have already seen, not sufficient to share some conceptual knowledge (e.g., the notion of force, of mass and of acceleration). But one must also have more common notions, such as "equality" and "multiplication."[9] Beyond that, these are the notions of "action," of "reaction," and of "object" that must be appropriated. Indeed, the meaning of these notions is related to common sense, but goes beyond it, with common sense supplying a sort of first basis redefined within the use of the law. We will show that in the second part of this paper. This redefinition is a matter of language: the language games of physics (with respect to the terms of *action* and *object*, e.g.) are not the language games of everyday life, which explains why language has to play a key role in the construction of school theoretical models (Izquierdo-Aymerich & Adúriz-Bravo, 2003). If we consider things even more generically, we conclude that an almost infinite number of pieces of knowledge, none of them specific to the model, are, however, necessary to the operations of categorization on which the model depends. We will call holism of the model this dependency of the specificity of the model on the group of generic objects and operations of thought that are crystallized in language. Since we consider a model in its effective usage, we become conscious of a very great number of necessities (a lot of them being trivial), conditioning its application.

Thought Styles. Thus, the use of a model must be envisaged in a holistic way, based on general categories coming from the common sense as it is embedded in language. But this dependency must be detailed. Consequently, it seems useful to acknowledge that common sense is itself mostly specific to a domain of thought in which the model is used. To explain this, Fleck (1935/1979) created the concept of thought style. In *Genesis and Development of a Scientific Fact*, on the example of the usage of the Wassermann reaction[10] in the study of the history of syphilis, Fleck shows that one cannot comprehend the modern concept of syphilis without understanding its genesis and what it owes to the ancient and mythical conception of the disease—for example, the fact that being ill with syphilis supposes "rotting blood." The dependency of the scientific model to the broader and more common conceptions is thus manifest. Fleck also shows, by announcing features of the Khunian paradigm,[11] how the thought style necessarily relies on a thought collective, which can

[9] Certainly more "common" notions but which must, however, be reprocessed in their use inside Newton's law.

[10] The Wassermann reaction is a test, used since the beginning of the 20th century, to diagnose syphilis. It involves the identification of an antibody of a microbe in the serum of an infected individual.

[11] It is interesting to note that Kuhn wrote the foreword to the English edition of Fleck's book. Latour, for his part, in the postface of the French edition, contests this kind of kinship. For Latour, Kuhn "rerationalized" and "desocialized" Fleck's invention (Latour, in Fleck, 1935/2005). It is edifying to read in Kuhn's postface foreword that he reproaches Fleck with oscillating between a psychologizing view of the thought collective and a sociological view which effectively accounts for the logical stress exerted by the collective: "What the thought collective supplies its members is somehow like the Kantian categories, prerequisite to any thought at all. The authority of a thought collective is thus more nearly logical than social, yet it exists for the individual only by virtue of his induction into a group." Thus Kuhn's thought is not *desocializing*, as Latour thinks, but it tries on the contrary to explain how the social factor produces logical constraints, in

be viewed as "a universally interconnected system of facts" that "created a feeling both of fixed reality and of the independent existence of the universe." The concept of thought collective is a functional one (not substantial), and may be compared to the concept of field in physics (Fleck, 1979, p. 103).

These thought styles and thought collectives may concern very small collectives (even only two people), but their strength is that first of all they characterize the institutions.[12] Indeed, it is worth noticing that a thought style, according to Fleck, affects almost inexorably any stable enough collective. From this point of view, education can be viewed as the elaboration of a thought style. For example, in chemistry education, it is not easy for students "to see a certain chemical explanation as educators or chemists would see them" (Erduran, 2001, p. 581). Indeed, a thought style constitutes a formal functional structure: it is formal[13] in that it constitutes a theory of the world; it is functional in that it is both the condition and the result of the collective activity. Such a conception of the thought style might, however, give rise to an intellectualism very far from Fleck's preoccupations.

Thought Style and Perception. To distance oneself from this intellectualism, in which the thought style would appear as a system of conceptions partly detached from reality, we can adopt Fleck's definition, according to which a thought style is characterized by "the readiness for directed perception and appropriate assimilation of what has been perceived" (1979, p. 142). That is to say that talking about thought style means first envisaging how the perception itself is affected by the cognition and affects it in return.[14] Fleck relates direct perception of form [Gestaltsehen] and experience. The ability to perceive form and meaning in a given thought style is acquired only after much experience. An important point is that at the same time we gain thought style perceptions, we loose the ability to see something that contradicts these forms, a distinctive feature that Fleck called "the harmony of illusion" (1979, p. 92). A thought style, like the abstract concepts and interpretative models of science, is a seeing as (Wittgenstein, 1953/1997), which enables us to see only some "useful" aspects of reality, and to ignore what is purposeless.

To envisage the model on the background of a thought style is thus to consider it

- in its productive power of facts and relationships as a blueprint for a nomological machine that is recognized in a thought collective,
- in its productive power of a perception that is directed through this nomological machine by this thought collective, and
- in its inhibiting power of other facts and other relationships inside the "harmony" that is intrinsic to a thought style.

the sense not of mathematical logic, but in Wittgenstein's sense (1953/1997) of the grammar of thoughts and actions. It seems to us that it is exactly the project of Fleck to show how thought style, sociologically produced, runs as a kind of Kantian a priori. Cf. infra.

[12] By giving to this latter term the sense of "legitimized social group," in the manner of the British anthropologist Mary Douglas (1987, 1996), for whom Fleck's book has constituted a constant reference (her 1996 book being expressly entitled *Thought Styles*).

[13] According to Douglas (1987, p. 59), "mathematical theories are institutions, and vice versa."

[14] Here, we see how Fleck breaks with what the American logician and philosopher Hilary Putnam describes as "a disastrous idea that has haunted Western philosophy since the 17th century, the idea that perception involves an interface between the mind and the "external" objects we perceive" (Putnam, 1999, p. 43). This break with perception as (solely) an interface is undoubtedly close to the modern notion of affordance (Beauvois & Dubois, 2000; Gibson, 1986; Norman, 1988) providing that the latter is freed from the biological connotations that are often attached to it, so as to recognize what the affordances owe to the sociologically constituted categories.

Model and Experimentation

Envisaging the model inside a thought style thus leads us to conceive the perception, and so the observation, in relation to a thought collective. It is in the perception itself, as Cartwright and Fleck would say, that we achieve this transition from the abstract to the concrete that Cartwright points out as the peculiarity of the fable and the model. A (too) quick reading of Fleck might, in a sort of primary Kantism, lead us to think that we can only observe what we have in mind. But it seems that the effective study of "science in action" shows a much more materially complex relationship. On the one hand, theory translates Nature itself into semiotic systems registering the observations (power of the abstract) and, on the other hand, the phenomena produced by the instruments reach some sort of autonomy that gives feedback on the theory (power of the concrete). We will briefly develop this point by making use of a study by Hacking (1983).

Experimentation, Theories, and Instruments. Hacking begins the second part of his book *Representing and Intervening* by a reevaluation of the importance of experimentation in science. He thus asks the question of the relationship between experiment and theory. Hacking's answer is complex, relying on the description of a large number of examples and its discussion is beyond the frame of this paper, but we would sum it up, as part of our epistemological approach, by the following lines:

> Some profound experimental work is generated entirely by theory. Some great theories spring from pretheoretical experiment. Some theories languish for lack or mesh with the real world, while some experimental phenomena sit idle for lack of theory. There are also happy families, in which theory and experiment coming from different directions meet. (1983, p. 159)

This profoundly nominalistic answer, where the adjective "*some*" abounds, is not about questioning the importance of the theory in science, but about restoring the balance in favor of the experiment, by contesting an intellectualistic philosophy of science, and by admitting that "experimentation has a life of his own" (Hacking, 1983, p. 150).

An accurate way of describing this "life" may consist in reevaluating the importance of the instruments used in sciences.[15] The example of the microscope appears completely edifying to combat the idealistic conception according to which we can only observe what the theory makes possible to see.[16] Hacking thus shows that microscopes relying on different theories and so on different phenomenotechnics (e.g., fluorescent micrography and electronic micrography) may be used to detect bodies and so to prove that the identified visual configurations do not constitute artefacts. This does not only constitute a plea for a moderate form of epistemological realism (the phenomena that we observe have an existence in themselves). The concern is especially about understanding that instruments create specific worlds whose practice (repeated and insistent practice) is indispensable for a lasting theory to emerge. As they create a "world of phenomena" in which we may act, the instruments then produce an environment, partly independent of the theorizations, and causally constraining. They play a fundamental role in the design of nomological machine.

A nice example is Galileo's well-known inclined plane experiment, where the setup is constructed to obtain experimental data as close as possible to those given by the theoretical

[15] We are then in the Bachelardian perspective of phenomenotechnic (cf. infra, section "Models, Thought Styles, Experimentation: Epistemological Positioning").

[16] That is far different from the idea of Fleck according to which there are no semiotic systems independent from a theory.

model (here the time-dependant free fall).[17] A set of technological solutions was chosen to permit accurate time measurements (Galilei, 1638/1954). We can see here at work how "the empirical reliability of models is established by construction" in a "3-fold match" (Koponen, 2006, p. 767)

1. between the empirically reliable model (the fall of a ball along a channel in an inclined plane) and theory (the free fall of a ball with no rubbing effect) by reducing the rubbing effect with a "groove very straight, smooth, and polished, (. . .) with parchment, also as smooth and polished as possible (. . .) a hard, smooth, and very round bronze ball."
2. between the empirically reliable model and the phenomenon itself by designing precisely the inclined plane, notably in its dimensions and inclination, to slow the time-dependant phenomenon in order to be capable of "noting, in a manner presently to be described, the time required to make the descent."
3. between experimental data and the empirically reliable model by designing a way to measure the time of the descent, using a water clock, claiming that "the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results." But, because Galileo's experiment reconstructed by the Oldenburg team (Rieß, Heering, & Nawrath, 2006) gave some problematic time measurements,[18] the setup was adapted with adjustable strings all along the channel to create a steady rhythm and it was then shown that it is "possible to use an inclined plane in order to demonstrate the law of the free fall" (Rieß, 2006, p. 7) for teaching purposes.

Thus we see how Galileo's nomological machine, for science or science education, is constructed by designing an instrument, the inclined plane, that here eliminates the disturbances and generates a specific "right sort of stable (enough) environment" (Cartwright, 1999, p. 50) dedicated to the model to be tested or learned.

As Duschl (2000, p. 191) remarks, the observational practices of science are more and more instrument and theory-driven observations, the data texts of science have become more complex, while a "concomitant shift has not taken place in the kind of science presented to learners in school." So, the issue of "the dialectic between data and theory, observation and theory, and fact and theory" (Duschl, 2000, p. 189) is not addressed frequently in school science. In our case studies, we will focus, on the one hand, on the dialectic between observation and theory and, on the other hand, on the dialectic between fact and theory.

The Ant, the Spider, and the Bee. To consider the relationship between experiment and theory, Hacking begins a reevaluation of Bacon, by commenting his famous metaphor, in which he considers "the men of experiment" (the ants), "the reasoners" (the spiders), and the bee, whose activity can be seen as a metaphor of efficient scientific practice, in that it lays the matters gathered in this activity up "in the understanding altered and digested" (Bacon, quoted by Hacking, 1983, p. 247). It is worth noticing the educational implications

[17] Very shortly, the time-dependant "free fall" model is characterized by a law (the distance s is proportional to t^2) in a no-rubbing environment (i.e., without air).

[18] "Thus, it appeared to be questionable whether our setup differs in some relevant detail from Galileo's, whether we have to develop necessary skills to achieve data with a deviation as little as indicated by Galileo, or whether Galileo's claim with respect to the accuracy of his measurements can be taken as justified" (Rieß et al., 2006).

of such a claim, for example, against the "cookbook view" (van Keulen, 1995) under which are considered chemical experiments in the classroom (Erduran, 2001). So, science can be viewed as a synergy between two faculties, the rational and the experimental, and the main idea for Bacon and Hacking is that *reduced to itself* each category (the experimental and the rational) produces little knowledge. Hacking continues by asserting that the main characteristic of the scientific method is to bring these two abilities in contact by the use of a third one, that is called articulation and calculation[19] (Hacking, 1983, p. 248).

We then encounter, by another route, the crossroads reached by Cartwright. Indeed, a nomological machine can be seen to be made of these three abilities. With respect to the shielding role of the experimental enclosure, it converts the abstract form of the law in capacities and behaviors, by the means of what Hacking calls "articulation."

What Is a Representation? Before drawing epistemological and didactic implications from the previous analysis, we would like to end with some considerations relating to the notion of representation. All that precedes tries to convey a view of science both closer to experimentation and effective experiment, and to a conception of models and of the activity of modeling more dependent on the actual materiality of scientific activity. In such a perspective, the semiotic systems on which this activity rests play a fundamental role. That is to say that the notion of representation itself has to be freed from the mentalism which is so often inherent in it,[20] to take on a meaning that is both material and public. Again, we will here follow Hacking, who explains that the word *representation* has been used to translate Kant's word *Vorstellung*, "a placing before the mind, a word which includes images as well as more abstract thoughts" (Hacking, 1983, p. 132), a word that Kant needed to replace the "idea" of French and English empiricists. By paraphrasing Hacking, we can say that this is exactly what we do *not* mean by representation in our perspective. For us, a representation is material and public. This is consonant with a conception of science in which the scientific activity is deployed within thought collectives that structure (and are structured by) thought styles. Indeed, if the first characteristic of a thought style is to organize perception, then the most decisive perception in scientific activity is the adequate perception of the specific semiotic systems—*representations* in Hacking's sense—which express the interpretative models.

Models, Thought Styles, Experimentation: Epistemological Positioning

A New Empiricism. It seems to us possible in the preceding lines to find a coherent epistemological position, to which we could associate epistemologists such as Cartwright, Fleck, and Hacking, but also an art historian such as Baxandall (1985), in the lineage of English philosophy or American pragmatism. The relationships one can establish between these authors are not the fruits of this sole study (e.g., Koponen, 2006, refers to Cartwright and Hacking alike). Indeed, Cartwright and Hacking, both professors in Stanford at the same time, recognize a common lineage to the Stanford School, in which may also be placed the philosopher of biology John Dupré.[21] Such an epistemological tradition finds in

[19] Hacking produces, for the notion of articulation and of calculation, the following definition: "I do not mean mere computation, but the mathematical alteration of a given speculation, so that one brings into closer resonance with the world" (1983, p. 214).

[20] On this question, cf. notably Sensevy (2002).

[21] So Cartwright wrote in *The Dappled World*: "This book is squarely in the tradition of the Stanford School and is deeply influenced by the philosophers of science I worked with there. It began with the pragmatism of Patrick Suppes and the kinds of views he articulated in his *Probabilistic Metaphysics*. Then

Ludwik Fleck a decisive predecessor: Hacking (2005a, 2005b) thus spent a great part of his 2005–2006 course at the Collège de France carrying on and working again on the concept of thought style (*Denkstil*) as it is passed on to us by Fleck. This coherent conception might, in a certain manner, be considered as a *new empiricism*. It is an *empiricism*, we said, in that the emphasis is put on the peculiar relationship between science and experimentation and the effective study of science in action. In that way, it helps us to see "that experiments and experimental knowledge are an integral part of model construction" (Koponen, 2006, p. 768). It is a renewed empiricism, notably in the sense that the concern is to *rehabilitate the experiment*, but in a new relation between experiment and conceptualization. Perception is not conceived any more as an interface between concept and reality (in the Cartesian conception underlying the identification of the *sensations* as it was produced by Locke and Hume), but as indissolubly linked to the concept. This conception supposes a peculiar relationship between the concrete and the abstract: the abstract makes the concrete possible, but it has only meaning in the actualization of this concrete. This emphasizes the correlative importance, for scientific practice, notably in the instrumentation, of the creative activity of characterization/production of contexts, from "everyday situations" to nomological machines. This renewed empiricism is thus a *contextualism*.

All teaching practice supposes an epistemology, a theory of the knowledge it transmits. Recent works in the field of science education have addressed this issue (e.g., Grandy & Duschl, 2007; Izquierdo-Aymerich & Adúriz-Bravo, 2003; Koponen, 2006). So, one can spread a dogmatic conception of science by teaching them, or a positivist, a relativistic or a sensualistic conception. Does the *nonpyramidal* and *nonphysicalist* view of sciences that Cartwright, Fleck, and Hacking defend, each in his/her own manner, in feedback imply a peculiar manner of teaching?

FOUR CASE STUDIES IN SCIENCE EDUCATION

In this section, we analyze four cases coming from a research-based design activities in the light of the first part. These case studies come from teaching activities at secondary school level designed in the context of a research development study carried out by researchers and teachers (SESAMES, 2007). This design is research based (Buty, Tiberghien, & Le Maréchal, 2004; Tiberghien, Buty, & Le Maréchal, 2005; Tiberghien & Vince, 2005). However, the epistemology on which it is based was not deeply enhanced until the present study. This study has been an opportunity to work on it and make it explicit, in line with the orientation proposed in the first part of this paper. Two main components of the epistemological orientation taken by the designers allow us to make these analyses in the light of the "new empiricism" presented in the first part: considering the theoretical components of the physics content as giving meaning and the consequent close relationships between theory and experiments.

As often in a design activity, the working hypotheses are simultaneously based on several domains: epistemology, didactics (in a European sense), and learning. In our case, the learning hypotheses are intertwined with our epistemological approach. The main

there was Ian Hacking, John Dupré, Peter Galison and, for one year, Margaret Morrison" (Cartwright, 1999, p. ix). Hacking, for his part, emphasizes in the acknowledgements of his book (*Representing and Intervening*, 1983) the close relationship between his conceptions and Cartwright's: "What follows was written while Nancy Cartwright, of the Stanford University Philosophy Department, was working out the ideas for her book, *How the Laws of Physics Lie*. There are several parallels between her book and mine. Both play down the truthfulness of theories but favour some theoretical entities . . . We have different anti-theoretical starting points, for she considers models and approximations while I emphasize experiments, but we converge on similar philosophies" (1983, p. IX).

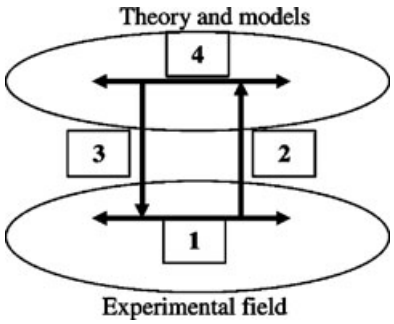


Figure 3. Types of constraints of the modeling choice on the design of the activities.

epistemological choice is modeling as a basis of knowledge processing in physics. Let us note that in mathematics most of the time, there is a consensus among mathematicians and epistemologists to state that problems are the source of new knowledge; therefore, the main reference on the way of introducing or constructing new knowledge in the design of a teaching sequence is "problem." In our case, we have considered that modeling is the basis of physics and consequently should be one of the main lines of the design of teaching sequence in relation to learning hypothesis (Laborde, Coquidé, & Tiberghien, 2002).

This choice has led us to state that (1) knowledge of physics (until the beginning of university) involves relations between two worlds: theory-model and object-event worlds, and (2) students' conceptual understanding necessitates establishing relations between elements of knowledge inside a world and between worlds (Figure 3). These statements are the result of a combined association of epistemological positions and learning hypotheses. In particular, we suppose that students can develop their understanding through new relations constructed, most of the time, from small elements of knowledge even if we do differentiate understanding a series of elements and understanding the set constituted by this series.

The consequence of these statements is that the designed activities of a teaching sequence, including carefully chosen experiments, should lead the students to construct relationship types 1, 2, and 3 (in two directions between theoretical elements and objects or events), and 4 (Figure 3).

The teaching activities analyzed in the following come from two teaching sequences designed in mechanics for grades 10[22] and 11 (Guillaud, 1998; Küçüközer, 2000, 2005). We select activities illustrating components of modeling, which are not frequent in usual teaching and at the same time which are relevant for it as Duschl (2000) and Grandy and Duschl (2007) show.

Relationships at the Object-Event Level: Role of Theory

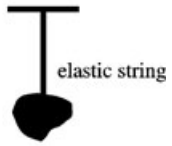
This type of activities is not frequent in ordinary teaching at the upper high school level. Most of the time teachers consider that they are too obvious for the students. In our approach, we consider that students have to learn how a physicist describes the material situations in terms of objects and events since this description is not the same as the one spontaneously done by the students that corresponds to everyday life description. To describe the material situations in a relevant way for mechanics, students have to learn new terms or more exactly new meanings of some terms that are carefully chosen by the designer to fit the theoretical approach introduced in the following parts of the teaching sequence.

[22] This teaching sequence has been designed in the context of the French official program. At this level in France, physics is taught to all students, not only to those who take a scientific orientation.

Part II Interactions and forces, activity 1

You have at your disposal: a support, an elastic string, a stone.

The stone is hanging from an elastic string. It is motionless.



Questions

a) What are the objects which act on the stone?

b) On what objects does the stone act?

Figure 4. Activity statement aiming to help students describe a situation in terms of objects and events in a relevant way to interpret it in physics.

In fact, in the light of the first part of this paper, this Type 1 constraint (Figure 3) does not only correspond to relationships inside the object-event world. The designed activities aim at helping students to "see as" a physicist who is seeing material situations from a theoretical point of view. This implies using relevant terms with a physics meaning as we show in the following case.

Words Giving Meaning to Theory. The first case study ("the stone hanging on the elastic string") comes from the teaching sequence at grade 10 at the very beginning of dynamics. It is the first activity in the part dealing with dynamics situated just after the kinematics part (see statement in Figure 4).

The activity statement introduces two terms: the verb "to act" and the noun "object." It aims at helping students to describe the situation (a motionless stone hanging from an elastic string) using these terms with a physics meaning. In this situation, the verb to act would not be used in an everyday description, since no change is observable and motionless is the "normal" state in this case (similar to a pen on a table, etc.). According to this statement, the students have to use this verb (to act) to answer the question in a different meaning from the one they use normally. The answer to the first question is that elastic string and the earth act on the stone. The analyses of students' exchanges when they work in small groups and the whole class correction done in several classes show that almost all students consider that the elastic string acts on the stone. For the earth it is more difficult. Whereas they know that there is gravity, they have difficulties answering that the earth is the other object which acts on the stone. Answering this question requires students to accept that the elastic string and the earth belong to the same category, that of object. It is a physicist's view of the material world, not an everyday view. These difficulties should not hide the fact that there is some continuity between the everyday and physics meanings of the terms to act/action and object. The action of the stone on the elastic string or the reverse can be interpreted in the everyday meaning with a thought experiment: if we cut the string then the stone would fall down; in this case a change happens. In fact, the students use very often this reasoning in these activities. Thus we can say that the terms "action" or "object," in mechanics, are both in a close relationship with common sense (if we do not know the common sense of the word "action" or of the word "object," we get no chance to correctly describe a mechanical system) and in opposition with common sense (since we can talk about the object "earth" or of "the action of a pen on the table") in a specific language game whose understanding may possibly constitute an obstacle for the students.

Differentiate Theory and Model. In the light of the first part, the activity requires the students to "see as" a physicist who has in mind Newtonian mechanics. This description is based on an essential meaning of the concept of force (at this level of instruction): force

models action between systems, a system representing a part or a combination of objects. Then in Cartwright's sense, we can say that action and object express the "capacities" of the abstract concept of force. This analysis has consequences. The relationships are not only inside the world of objects and events but also with the theory, in its qualitative component, in Hacking's sense (1983). Then the relationships involve the qualitative theoretical component of the theory/model world. Consequently, making explicit these relationships leads us to distinguish theory and model. In fact, in our initial epistemological analysis (Tiberghien, 1994), in reference to Suzanne Bachelard (1979), we made a distinction between theory and model where model is an intermediary: "the model, in its most abstract sense, functions in an ostensive way and, in its most concrete sense of display model, allows theoretical aspects to become apparent. [. . .] . . . in any model there is a bipolarity of theoretical and ostensive aspects" (p. 8). However, under the pressure of teachers with whom we worked to design teaching materials, we put together theory and models considering that it is too complicated to introduce this distinction in physics teaching. Teachers have considered that taking into account a modeling approach in their teaching is a sufficiently difficult task.

Choosing the "capacities" of the basic abstract concepts to be taught and their associated language is of crucial importance to design relevant teaching activities helping students to construct meaning in physics. Students can start to play the language game of physics (here that of simple Newtonian mechanics) in order to begin to build what Hacking calls "a qualitative understanding of some general feature of the world" (Hacking, 1983, p. 213). In fact, the actual design of this activity (Figure 4) is the result of several comings and goings between teaching it in classrooms and refining it. At the beginning, we did not expect the students to have difficulties with the idea of "object," but in several classes this difficulty appears very explicitly. Then we recognize how it could appear strange to put together on the same level earth, sun, stone, pen, etc. As a student said: "It [the earth] is an object but a bizarre object." In that case, the students force us to deepen our epistemological analysis of the abstract concept capacities in particular by choosing the words that give meaning to the theory. However, making explicit this type of capacity may be only relevant in the case of education at a rather low teaching level to the extent that it is so obvious for experts that they do not need to make it explicit.

These uses of action and object lead students to conceptualize this situation. At this step, action is a conceptual construction even if, later on in the sequence and for physics, it remains at the level of objects and events. In this activity, the students have to start to create meaning of terms, which belong to the theoretical framework of classical mechanics. Students enter into a physics language game closely related to abstract concept/principle capacities and then enter into a *physics thought style*.

Then, this analysis leads us to modify our representation of Figure 3 into another one making clear the role of theory in teaching when a situation is described in a compatible way to Newtonian mechanics (Figure 5).

Intertwined Theory and Experiment. Another case (Case Study 2: "Throw and catch the medicine ball") is taken from the year after (grade 11) and relies on the idea that action and acting are already familiar to the students. This activity is at the beginning of the part introducing the three laws of Newtonian mechanics. It aims at familiarizing students with the direction of the action and helping them to differentiate between action and motion. Then, the designers carefully chose an experiment where directions of action and motion are different and observable even with common sense.

In this activity, the students have to throw and catch a medicine ball (heavy ball) and then answer a series of questions. The first one is "locate and note the moment(s) where

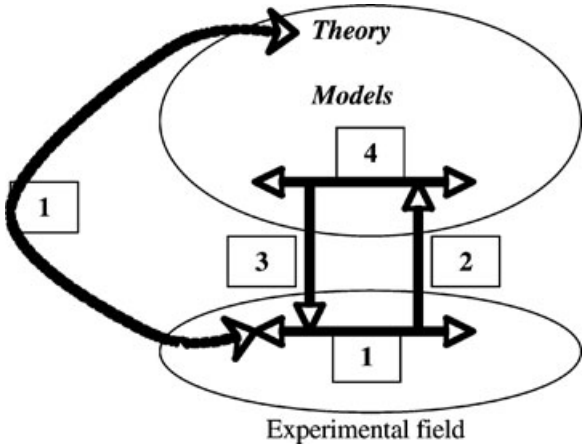


Figure 5. Types of constraints of the modeling choice on the design of the activities modified by the present epistemological analysis (dotted line and italic).

you exert an action on the medicine-ball, each time specify in which direction you exert this action on the medicine-ball." Here is the dialogue extract between two students, L and N, who have a medicine ball on their table. (In this extract the numbers correspond to the turn number since the beginning of the session.)

47. L: (Reads) Locate and note the moment(s) where you exert/did you read the first question (?)
48. N: What (?) which part (?)
49. L: You where YOU exert an action on the medicine-ball (He reads the question) thus it is at the beginning to throw we put a force up towards the top
50. N: Yeah after
51. L: To catch it we exert a force downwards/we lighten
52. N: No a force upwards when we catch it a force always upwards
53. L: (Does the experience) Upwards like that (does the experience again)
54. N: Yeah but when you catch it you exert a force towards the top also to stop it (makes the gesture of catching the ball with his hands)
55. L: But you lighten (does the experience)
56. N: Yeah well (takes the medicine ball) you do (he does the experience) I am sorry I do not move
57. L: When you do it you move (does the experience)
58. N: Yeah but yeah

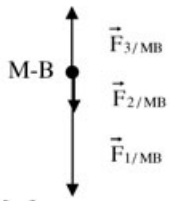
In this case, the role of theory is less obvious than in the previous case. However, it is striking to note that L (turn 49) insists on YOU; he differentiates his body and the ball, which is essential in this case, since when we catch the ball the action of the hands are upward whereas the ball motion is downward. Then, thanks to L, who makes explicit this differentiation, the "seeing as" is clear even in such a trivial experiment.

These two cases illustrate the necessity of a "familiarization" phase, even at upper secondary school, to learn how to see an experiment and to describe it in a specific language game. It shows that designing teaching sequence or activities should rely on the intertwining of theory and experiment (Koponen & Mäntylä, 2006) and, consequently, make explicit the theory and the associated language game and not only the model or its expression in the "nomological machine." Moreover, this familiarization should allow students to develop a

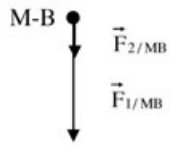
On Inertia principle and other laws of mechanics
Activity 1: "Aristotle or Galileo"
Introduction:
In this activity, different situations are envisaged in which two representations of force are proposed each time:
• one representation is correct from the point of view of the current model of mechanics (initiated by Galileo),
• the other representation corresponds to an intuitive analysis of the situation: according to this point of view (close to Aristotle's) there is always a force in the direction of the movement. This statement is false from the current point of view of mechanics.

We want to analyse different students' answers to the question: "represent the forces which are exerted on the medicine-ball (when it is going upward) represented by a point and noted M-B." Two types of answers have been distinguished:

Students' group A



Students' group B



• 1 [...]
• 2 With the help of information given at the beginning [a medicine-ball is thrown vertically upward, the study is focused when the ball is going up], identify which group (A or B) analyses the situation intuitively.
• 3 (a) Identify the systems 1 and 2 (which are present in the two representations) which act on the system MB. In your opinion, what does the force represent for the student group A? Why did they need to represent this force?
(b) With the help of the interaction model, justify the fact that this force does not model an action exerted by the medicine-ball when it goes upward

Figure 6. Part of activity statement (Questions 2 and 3) aiming to help students to relate elements of model to a material situation.

model (or a nomological machine) without disconnecting it from the theory, and then to construct a physics meaning.

Relationships From Theory/Model to Objects and Events: Developing Together Model/Nomological Machine and Physics Meaning (Type 3)

Case 3 ("The description of the medicine ball when it is moving upward") presents an activity that seems infrequent in ordinary teaching. Our modeling choice "constraints" us as designer to propose such activities. Their design is not obvious because they often require a rather deep knowledge of the theory/model. We present an activity based on the "model of interactions" as given in the teaching sequence (Figure 6).

This activity aims at helping students to use two types of force: contact force and distance force. If two objects are not in contact (in this case, hand and ball) then there is no force between these objects; if, on the contrary, air is in contact and it acts on the ball, the earth is always acting at a distance. This type of reasoning is not spontaneous; it is very likely that students mobilize global causality relations, even if it appears simple. Students have to learn it.

Let us note a comment for teachers associated with the mechanics-teaching sequence[23]:

> We have given up looking for a situation which convinces students that this force (in the direction of the movement) is not necessary for the movement. We can only convince them with an argument such as: there is no force in the direction of the movement because no

[23] http://www2.ac-lyon.fr/enseigne/physique/sesames/outils_seconde.html#m%E9ca

Activity: Pushing on a wall
Situation 1
A student, standing up on the ground, pushes on a vertical wall horizontally
1. Do the experiment (you have the right to push hard) and describe in some sentences what you feel.
2. a) Draw the student-interactions diagram
2. b) Make the list of forces that are exerted on the system "student." Name each of the forces and specify which system exerts forces and on which system forces are exerted.
3. By using the experiment that you just did, propose a representation of the force exerted by the ground on the students. Explain what impels you to propose this answer.
4. By using the laws of mechanics, say if the forces that are exerted on the student compensate for each other or if they do not compensate for each other. Indicate the law(s) to which you refer to answer.
[…]

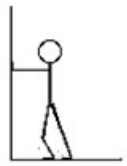


Figure 7. Part of activity statement given at grade 11 in the mechanics sequence involving multiple relations between theory/model and objects/events; question 4 deals mainly with theory/model to objects/events.

system exists to exert it. In this way, we use an argument coming from the taught model (a theoretical argument) to help students to overcome their intuitive knowledge.

In the light of the first part of this paper, it is not surprising that this type of activity can be introduced only after having taught a rather important part of the model. We are in the case where the transition from an abstract theoretical concept (force) to particular situations is necessary to check the validity of the theory. This passage requires a kind of nomological machine to specify the relations between the inertia principle, the model, and the situation. This case illustrates the important roles of representations of (1) an object by a point that is the origin of all the vector forces exerted on the object (it is not obvious for students) and (2) vector representation and vector composition of forces.[24] Moreover, the designers carefully chose the situation: a heavy ball thrown vertically. When teaching all the elements of this machine, the meaning of the theory can be lost and then it is useful to keep this meaning throughout this teaching part with the same language game and thought style anchored not only in the more or less abstract concepts themselves but also in the modeling processes. The following case (Case Study 4: "The pushing on a wall situation") illustrates this aspect.

Question 4 requires starting from the laws of mechanics to decide whether, for the situation on which the students are working, the forces compensate. The previous questions help the students first to be aware of their own feeling and then appropriate the general physics thought style, where the everyday perception is not avoided but included and reinterpreted from everyday perception.

The following extract shows two students, A and L (at grade 11), who were in different classes the year before. At grade 10, L was in a class with the designed teaching sequence and A was in an "ordinary classroom." Moreover, A started the academic year (grade 11) in a different class and arrived in this class some days before the session from which this extract comes. In this extract, the students start question 4 and the teacher T intervenes briefly to explain what the students need to do (see Figure 7). In this extract, the first column gives the turn number counting from the beginning of the extract.

[24] Moreover, in the first question, not given in Figure 7, the students are asked to draw what we call a system–interaction diagram, where the system is represented by ellipsis and action of contact between two systems (two ellipses) by a full arrow and action at distance by dotted arrows between two ellipses. Then, this semiotic system enriches the nomological machine.

1. A: Thus we should go to question 4 but it is the laws of mechanics and I do not have this thing
2. [. . .]
3. L: (Reads the statement) by using the laws of mechanics say if the forces that exert on the students compensate for each other or do not compensate for each other/ compensate each other
4. A: No
5. L: Yes
6. A: No
7. L: Yes
8. A: No because you do not feel the force of the ground but you feel the force of the wall
9. L: But look at me I am going to tell you something it is [L is looking for something in his file]
10. A: No you do not feel the force no
11. L (to T): In the Inertia principle there is a condition that says that if the velocity of the inertia centre is null then (. . .) the forces compensate for each other
12. T: Null it is a particular case of constant vectors
13. L: Ah yeah
14. T: If the constant is null (T leave*s*)
15. [. . .]
16. L: In fact you are like that there is there is/last year we saw the inertia principle it was er the forces they compensate for each other either the object it did not move like here the forces compensate for each other or there is a uniform rectilinear motion then that is if the vector is constant that is in the same direction same length it was he [teacher] said to us here also the vector we can note (L reads and shows the statement with his finger) if the velocity of the inertia centre of a system is a constant vector then the sum of the forces exerted on the system is null here the constant vector is null
17. A: But it means that in fact all the forces there remains the force of the Earth only
18. L: No even not/all the forces cancelled each
19. A: Pah wait I have to read the summary again (10 s) sure, sure, but I am not sure I wonder if there is not a force that isn't cancelled.

This extract shows two thought styles: L "sees" the situation with the perspective of the inertia principle (turns 9, 11), that is, the student is motionless, its velocity is null then the inertia principle applies and the composition of forces should be such that the total force is zero (turn 18). We could say that L's approach illustrates the relevance of the holism of the model. Student A "sees" the situation with his own view and feeling. In turns 8 and 10, A relies on what he feels, whereas L is looking for the theory (called "model" in the teaching sequence; this text introduces force with vector representation and the three Newtonian laws) in other terms L is looking with the eyes of theory. Moreover, in the teacher's interventions (turns 12, 14), the thought style is shared between T and L; A seems "outside" as his next intervention shows, since he proposed a force that would remain.

Let us note that A's thought style implies a certain relation to knowledge without a "depersonalization" of the teachers' knowledge. The following exchange between A and L

just after the previous one given above deals with the written report; A and L are writing and again disagree on the way of justifying their answers:

1. A: I write according to the Inertia principle or the first law of Newton we can say that all the forces cancelled
2. L: But no you take the thing here (on the text of the "model")
3. A: No, no, I do not want I do not want to copy his [teacher] thing he knows it already we do not have to explain [. . .] it is he who gave the lecture then he knows his thing you are not going to copy again his lecture.

In this extract, A shows that the taught knowledge is strongly associated with the teacher's knowledge; in that perspective, physics is not shared in a community but is limited to a transactional object between the teacher and the students. A's answer has to be interpreted in the frame of *didactical contract* (Brousseau, 1997; Sensevy, Mercier, Schubauer-Leoni, Ligozat, & Perrot, 2005): A tries to act according to the expectations he attributes to the teacher. But for L, the availability of a specific text for the theory/model constitutes a common reference for the teacher and the students. It helps to introduce the status of physics knowledge as shared knowledge in the classroom.

ELEMENTS OF DISCUSSION: SOME IMPLICATIONS FOR SCIENCE TEACHING

In the following, we focus our line of argument on two main points.

The Relations Between the Abstract and the Concrete: The Reduction to the Particular

The conceptions defended by Cartwright relating to the abstract–concrete relationship (which could be summed up in analogy with the model–fable relationship) may lead research in science education to become more perceptive toward the process of concretization and contextualization of the abstract that scientific activity may represent. If we accept the principle that to make understandable a general idea (i.e., a scientific law), one has to reduce it to the particular, and if we assume that the modeling process is the core of scientific activity, then to comprehend science modeling is to comprehend a specific transition (and the associated relationships) from the abstract to the concrete, and vice versa (as shown in Figures 3 and 5). It seems admitted that in scientific activity the students must abstract from the particular, but maybe we have not become conscious enough of the necessity and the difficulty of reducing the abstract to this particular for the purposes of science education. For example, Case 3 shows how the abstract inertia principle is reduced to the particular of a specific situation. To really master the inertia principle, the students have to find it in numerous situations, sometimes very different, where the capacities that this principle supposes are made concrete in different ways. In this respect, this medicine ball didactic situation can be viewed as a nomological machine, which specifies the relations between the inertia principle, the model, and the material situation.

There is a close relationship between the epistemological principle (the concepts of science need to be conceptualized in nomological machines) and a science education principle (the concepts of science need to be worked on in different didactic situations). These situations may function as *didactic* nomological machines, which can enable the students to deal with new situations. Learning goes through a system of situations, which we may call "didactic nomological machines," that the students can link to each other

to understand physics. For example, we can consider Case 4, where L sees the "student pushing on a wall" situation as a case where the forces that exert on the student compensate for each other. We can assume that for L, this seeing as is possible in such a situation because he has in mind not only the "principle of compensation" but some precise situations he have dealt with in previous physics activities.

This prompts designers to pay a particular attention to producing such teaching situations in which "knowledge," or, as Cartwright says, behaviors and capacities are truly crystallized, to make links between theoretical principles and specific situations where the theoretical principles are effective in explaining the models.

Language Games, Thought Collectives, and Thought Styles

To do sciences in the class surely supposes building a specific thought collective. This *thought collective*, as Fleck shows, is characterized both by what it makes possible and by what it inhibits. Then, a major didactic question resides in the concrete conditions of the construction of a thought style in the class. In addressing this issue, a very important point, if we want to understand what it means to assimilate a thought style, is to acknowledge that a thought style stemming from the collective is thus a seeing as (Wittgenstein, 1953/1997) and that it cannot be integrated by students without the mastering of specific language games.[25] This assimilation supposes inculcation, in the long term, of a disposition of seeing as, and the dialectic between knowledge and ignorance that this inculcation has brought into play. This long-term assimilation supposes that in the class there are a series of negotiations and actions, coherent from the modeling perspective, which give shape to the physics activity and not only to classroom practices independent of knowledge involved. This collective thought can, therefore, work as generator of a grammar of possible and necessary actions in the class. For example, in our previous cases studies, we can see that an accurate analysis prevents the students from seeing a force in the direction of motion ("throw and catch the medicine ball"), or to perceive in an isolated way the action of the wall on the student ("the pushing on a wall situation").

In the teaching–learning process, language games and thought style are intertwined. The thought style is a "speech style." It is to say, for example, that seeing the medicine ball with no force in the direction of motion (Case 3) is to be able to practice a certain language game (by using specific terms of natural language and semiotic tools as vectors), which is a physics language game. In the same way, Case 1 shows us that a basic language game, in with "objects act," and "the earth is an object" has to be mastered in order to build the accurate seeing as. A physics thought style needs a certain language game, and reciprocally. By linking this point with the previous one, it is worth noticing that in Case 2 we understand how this language game needs to be related to the proper situation: one can understand what it means to say "the player acts on the ball," but not be able to identify the direction of this action, thus to understand the situation clearly. In the same way in two case studies ("throw and catch the medicine ball" and "student pushing on a wall"), it is difficult for the students to consider accurately the role played by their body. In the first situation, the student tends not to differentiate himself from the medicine ball (he thinks that the action of his hand is in the same direction as the action of the medicine ball) and, in the second situation, the student tends to differentiate himself from the situation (without understanding that his body must be viewed as a part of the studied system). Here, a scientific seeing as consists in giving the "right role" to the body in the modeling process, that is, considering it through

[25] Such a way of considering the teaching–learning process seems to be very close to the works of Per-Olof Wickman and Leif Östman (Wickman & Östman, 2002a, 2002b; Wickman, 2004, 2006).

its function inside a system. The abstract principle, as it is embedded in a generic language game, does not suffice. It has to be made concrete.

Thus, this is a necessary conceptualization of the language game, which plays a fundamental role in reducing the abstract to the particular. Even on a "phenomenological level" of the description of events and object behaviors, the language games are theory loaded: they produce and allow a kind of necessary familiarization with the scientific seeing as. So, science educators have not only to design teaching situations but also to specify the peculiar and progressive language games the students have to master in order to express this scientific seeing as accurately. In this respect, the last case study ("the student pushing on a wall") is an instructive one. It enables us to look at the contrast between a scientific thought style shared by a student (L) and the teacher, and an everyday thought style which prevents another student (A) from understanding the situation and from distancing himself from his view of the didactical contract. In such a perspective, the aim of teaching can be described as follows: to elaborate in the class a thought collective in which both the teacher, as far as it concerns him/her, and the students, in their turn, assume true responsibility.

Thus the relationship concrete–abstract in science teaching necessitates conceptualization processes, which have to be coherent to allow a conceptual understanding; the notion of "didactic nomological machine" should enable researchers to create and verify the coherence of these multiple relations involved during a teaching sequence. At the same time, the necessity of creating a thought collective in a rather long term implies taking into account a variety of teaching components, such as relevant supports (experiments, statements, careful texts presenting theory with relevant representations) and accurate classroom organization. In particular, the notion of thought *collective* prompts us to consider the *necessary participation* of the students in the teaching–learning system.

REFERENCES

Bachelard, S. (1979). Quelques aspects historiques des notions de modèle et de justification des modèles. In P. Delattre & M. Thellier. (Eds.), Elaboration et justification des modèles (pp. 3–18). Paris: Maloine.

Baxandall, M. (1985). Patterns of intention. New Haven, CT: Yale University Press.

Beauvois, J. L., & Dubois, N. (2000). Affordances in social judgment: Experimental proof of why it is a mistake to ignore how others behave towards a target and look solely at how the target behaves. Swiss Journal of Psychology,59, 16–33.

Brousseau, G. (1997). Theory of didactic situations. Dordrecht, the Netherlands: Kluwer.

Buty, C., Tiberghien, A., & Le Maréchal, J. F. (2004). Learning hypotheses and associated tools to design and to analyse teaching-leaning sequences. International Journal of Science Education, 26(5), 579–604.

Cartwright, N. (1983). How the laws of physics lie. Oxford, England: Oxford University Press.

Cartwright, N. (1999). The dappled world: a study of the boundaries of sciences. Cambridge, England: Cambridge University Press.

Douglas, M. (1987). How institutions think. London: Routledge.

Douglas, M. (1996). Thought styles. London: Sage.

Duschl, R. (2000). Making the nature of science explicit. In R. Millar, J. Leech, & J. Osborne (Eds.), Improving science education: The contribution of research (pp. 187–206). Philadelphia: Open University Press.

Erduran, S. (2001). Philosophy of chemistry: An emerging field with implications for chemistry education. Science & Education,10(6), 581–593.

Fleck, L. (1979). Genesis and development of a scientific fact (F. Bradley & T. J. Trenn, Trans.). Chicago: The University of Chicago Press. (Original work published 1935).

Fleck, L. (2005). Genèse et développement d'un fait scientifique (N. Jas, Trans.). Paris: Les Belles Lettres. (Original work published 1935).

Fabre, M. (2005). Deux sources de l'épistémologie des problèmes: Dewey et Bachelard. Les sciences de l'éducation pour l'ère nouvelle,38(3), 53–67.

Galilei, G. (1954) Dialogues concerning two new sciences (H. Crew & A. de Salvio, Trans.). New York: Dover. (Original work published 1638).

Gibson, J. J. (1986). The ecological approach to visual perception. Hillsdale, NJ: Erlbaum.

Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. Science & Education, 16(2), 141–166.

Guillaud, J.-C. (1998). Enseignement et apprentissage du concept de force en classe de troisième. Unpublished doctoral dissertation, Université Joseph Fourier Grenoble 1, Grenoble, France.

Hacking, I. (1975). Why does language matter to philosophy? Cambridge, England: Cambridge University Press.

Hacking, I. (1983). Representing and intervening. Cambridge, England: Cambridge University Press.

Hacking, I. (2005a). Façonner les gens II. Paris: Collège de France, Retrieved November 14, 2007, from http://www.college-de-france.fr/media/ins_pro/UPL35833_hackingres0405.pdf

Hacking, I. (2005b). Méthodes de raisonnement. Paris: Collège de France, 14 p. Retrieved November 14, 2007, from http://www.college-de-france.fr/media/ins_pro/UPL32424_raisonnement.pdf

Izquierdo-Aymerich, M., & Adúriz-Bravo, A. (2003). Epistemological foundations of school science. Science & Education, 12(1), 27–43.

Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: Some challenges in the case of 'the atom.' International Journal of Science Education, 22(9), 993–1009.

Koponen, I. T. (2006). Models and modelling in physics education: A critical re-analysis of philosophical underpinnings and suggestions for revisions. Science & Education, 16(7/8), 751–773.

Koponen, I. T., & Mäntylä, T. (2006). Generative role of experiments in physics and in teaching physics: A suggestion for epistemological reconstruction. Science & Education, 15(1), 31–54.

Küçüközer, A. (2000). Une compréhension de la notion d'interaction dans le cadre d'un enseignement de mécanique. Mémoire du DEA Didactiques et Interactions, Université Lumière, Lyon 2, France.

Küçüközer, A. (2005). L'étude de l'évolution de la compréhension conceptuelle des élèves avec un enseignement. Cas de la mécanique en 1ère S. Unpublished doctoral dissertation, Université Lumière Lyon 2, Lyon, France.

Laborde, C., Coquidé, M., & Tiberghien, A. (2002). Situations de formation dans l'enseignement en vue de l'apprentissage du savoir scientifique et mathématique. In A. Tiberghien (Ed.), Des connaissances naïves au savoir scientifique (pp. 107–143). Paris: Programme "École et sciences cognitives," Ministère de la Recherche.

Neurath, O. (1983). Philosophical papers 1913–1946. Dordrecht, the Netherlands: Reidel.

Norman, D. A. (1988). The psychology of everyday things. New York: Basic Books.

Putnam, H. (1999). The threefold cord. Mind, body, and world. New York: Columbia University Press.

Rieß, F., Heering, P., & Nawrath, D. (2006). Reconstructing Galileo's inclined plane experiments for teaching purposes. Online Proceedings of the 8th International History and Philosophy of Science and Science Teaching Conference in Leeds, 2005. Retrieved November 14, 2007, from http://www.ihpst2005.leeds.ac.uk/papers/Riess_Heering_Nawrath.pdf

Ryle, G. (1949). The concept of mind. London: Barnes and Noble.

Sensevy, G. (2002). Représentations et action didactique. L'année des sciences de l'éducation, 2002, 67–90.

Sensevy, G., Mercier, A., Schubauer-Leoni, M.-L., Ligozat, F., & Perrot, G (2005). An attempt to model the teacher's action in mathematics. Educational Studies in Mathematics, 59(1), 153–181.

SESAMES (2007). Séquences d'enseignement en physique et chimie. Retrieved November 17, 2007, from http://www2.ac-lyon.fr/enseigne/physique/sesames/

Suppes, P. (1984). Probabilistic metaphysics. Oxford: Blackwell.

Tiberghien, A. (1994). Modelling as a basis for analysing teaching–learning situations. Learning and Instruction, 4(1), 71–87.

Tiberghien, A., Buty, C., & Le Maréchal, J.-F. (2005). Physics teaching sequences and students' learning. In D. Koliopoulos & A. Vavouraki (Eds.), Science and technology education at cross roads: Meeting the challenges of the 21st century (pp. 25–55). The second conference of EDIFE and the second IOSTE symposium in Southern Europe. Athens, Greece: Association for Science Education (EDIFE).

Tiberghien, A., & Vince, J. (2005). Étude de l'activité des élèves de lycée en situation d'enseignement de la physique. Cahiers du français contemporain, 10, 153–176.

van Keulen, H. (1995). Making sense: Simulation of research in organic chemistry education. Utrecht, the Netherlands: CDBeta Press.

Wickman, P.-O., & Östman, L. (2002a). Induction as an empirical problem. How students generalize during practical work. International Journal of Science Education, 24, 465–486.

Wickman, P.-O., & Östman, L. (2002b). Learning as discourse change. A sociocultural mechanism. Science Education, 86, 601–623.

Wickman, P.-O. (2004). The practical epistemologies of the classroom: A study of laboratory work. Science Education, 88, 325–344.

Wickman, P.-O. (2006). Aesthetic experience in science education. Learning and meaning-making as situated talk and action. Mahwah, NJ: Lawrence Erlbaum Associates.

Wittgenstein, L. (1997). Philosophical investigations = philosophische untersuchungen (G. E. M. Anscombe, Trans.), Oxford, England: Blackwell. (Original work published 1953).