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# Using Signs for Learning and Teaching Physics: From Semiotic Tools to Situations of Misunderstanding

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"Language is the source of misunderstandings."

The Little Prince, Antoine de St-Exupéry, 1943, chapter XXI.

#### Abstract

This chapter investigates various usages of semiotic objects in science education, such as arrows and graphics. We propose a series of examples drawn from physics schoolbooks, school tasks, and research data to investigate the *semiotic roles* of these objects in their specific context of use, which is to teach physics. It is not necessary to know physics prior to the reading of this chapter: we are analyzing *signs* and possible interpretations. The aim is to illustrate potential situations of misunderstanding related to *semiotic objects*, taking into account a novice standpoint. For instance, the comparison of various uses of *arrows* on a single sketch reveals the diversity of *semiotic roles* played by the same object. It illustrates the need for coordination between *semiotic registers* by the interpretant for a successful mediated communication. The results also stress the particular challenges of such coordination in science modeling. It advocates for more practice of modeling and for students to take a more active part in the process, in order to prepare them to interpret models more easily, and for teachers and students to share more explicit discourses and usages of semiotic objects.

**Keywords:** physics, science education, modeling, schoolbook, mediation, misunderstanding



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# 1. Introduction

Science education is known for being challenging, and has led to an abundant research literature interested notably in students' conceptions [1–2] and conceptual change [3–5], teaching methods, and approaches [6–12]. The mediation of teaching and learning through language and semiotic tools of various sorts has been largely overlooked [13]. Yet, the few research including language and semiotics in the analysis of teaching and learning bring interesting results, see for instance [14, 15]. In cognitive psychology, most research assume in their method of data collection and analysis, that the interpretation of questions and tasks by students and research participants are nonproblematic [16], and that students' use of language is similar to the teachers' use when referring to concepts, which leads researchers to assimilate students' answers to their own conceptions of knowledge [17]. When assessing students' understanding in problem-solving tasks, for instance, the measured performance is typically indistinctly challenging students' conception in physics and ability to make sense of the question.

This chapter proposes an investigation of a few *semiotic objects* mediating the communication in physics classroom, and show that signs are both facilitating understanding and providing specific pitfalls for misunderstanding. The work presented is a semiotic analysis of teaching material in physics, mainly schoolbooks for college or high school. It may be of interest for educational psychology, science education research, cognitive psychology—in which language and semiotic analysis are often missing—and for suggestion of further research in semiotics.

The research methodology is inductive: starting from peculiar practices experts have grown used to, from writing conventions or commonalities, we propose a set of examples illustrating the fact that signs commonly used in physics can be challenging for interpretation due to various reasons. We proceed to the analysis of possible interpretation, in a fashion that can be assimilated to Artigue [18] and Brousseau [19] *a priori analysis*. One example is the challenging task of coordination between various semiotic registers and objects, which we exemplify in the next section. Another reason is the lack of clues or conventions in the use of semiotic objects which can play different *semiotic roles*. We will address this issue in the third section, taking the example of the *arrow*. In the last section, we will discuss the communicative counterpart of the use of semiotic tools for mediating knowledge, as a risk for situation of misunderstanding to emerge.

# 2. Coordination of semiotic objects and registers

This first section investigates a few situations where students in physics must deal with *semiotic objects* of various kinds. Duval develops the idea that learning concepts sometimes requires a *coordination of semiotic registers* [20]. He proposes to approach the problem raised by the *change of semiotic register*, typically when dealing with a problem-solving exercise using both a natural language and a formal language such as mathematics, not only as a form of expression but as a task of *coordination*, in the piagetian sense. Duval argues that for reasoning

with several semiotic registers, these must be *coordinated*. We propose here to extend the analysis of the problem of *coordination* stressed by Duval about *semiotic register* to *semiotic objects*, and to *semiotic standpoints* in order to analyze specific cognitive tasks of interpretation of signs of various kinds within their specific semiotic context. We draw on this contribution of Duval's work, which fits with the piagetian theory, yet his distinction between various types of representation based on *information processing* theory seems problematic for the purpose of our analysis, for the reason raised in the introduction. Moreover, signs are not only used for expressing one's thought—as Duval defines it—but also as a mediator or semiotic tool for thinking [21]. Here is a first example.

## 2.1. A first example

A physics student in her oral examination tries to remember why a stone dropped from the top of the Eiffel tower is *theoretically* not falling quite vertically [22]. To help her, the teacher lets her draw a sketch and ask her to trace the stone's trajectory on it. She draws a vertical line (reproduced in **Figure 1**).

The obstacle on which the student stumbles over here is about the meaning of *vertical* across the two semiotic registers at stake, i.e., the natural or scientific language in which the question is addressed, and the sketch. The coordination of the drawing of a line and the concept *vertical* is achieved, from the teacher's standpoint, through the relativity of the *vertical* to the center of gravity of the Earth. Hence, an expected *vertical fall* would be drawn on the sketch as a line starting from the top of the tower to the center of the circle representing the Earth. From this coordination, the teacher aims at displaying the influence of the rotation of the earth on this specific *verticality*. The teacher uses *vertical* as a concept, in the sense that concepts are related to a broader set of meaning, and more particularly here to a formal system [23]. It is literally impossible for the teacher to declare a line *vertical* without a reference point such as the center of gravity of the Earth which, together with the falling object, defines the system.



Figure 1. Reproduction of the student's sketch.

From the student's standpoint, however, *vertical* is a standalone notion, which stands for something like "from high to low in a straight line, or vice versa." The coordination between the drawing of a line and the use of the word is relative to this notion of *vertical* which, in terms, poses problem because the conventions of drawing is to consider the top of the paper higher. Conclusively, the students must draw a line from the top to the bottom of the paper (or vice-versa) to make it *vertical*. In other words, the coordination of the vertical line (graphical register) and the vertical fall (natural language register) fails in making a single meaning, what Duval calls a *semantic univocity*. The student failed to coordinate drawing conventions and modeling in physics.

To raise the issue analyzed here, a teacher can simply ask the following surprising question:

"Why is the attraction of the Earth vertical and towards the lower?"

The answer is disquieting, precisely because it is unusual at school: the attraction of the Earth is vertical and towards the lower per definition of *vertical* and *lower*.

The ambiguity is nevertheless not only linguistic: it is precisely the coordination of drawing conventions from which, most often, *vertical* is understood by children as a notion of natural language, and the *vertical* as a concept of physics, which can be represented geometrically or mathematically with a direction and a sense, but only relatively to a gravitational field.

In a piagetian theoretical framework, the coordination is a higher-order process relating operations on objects. Transposed in semiotics, the objects are symbolic—they are *signs*—and the operations are operations in the interpretation of the signs, i.e., operations (co)constructing the meaning for a particular subject. In order to avoid the theoretical reductionism inherent to formal logic, we rely on Grize's logico-discursive operations [24] rather than on Piaget's *logic of signification* [25]. Grize's Natural Logic provides an open-system logic allowing the researcher to investigate operations specific to the tasks under scrutiny, to the interpreting *psychological subject* in his/her particular situation, context, and history. Moreover, when the semiotic coordination involves several registers, it can be described as the coordination between operations of different kinds. Based on this approach, the challenge posed to the student in this first example, while interpreting the physics task, can be analyzed as the coordination between logico-discursive operations transforming the object-class {vertical} and concrete operation transforming the sketch, i.e., |drawing a line|.

## 2.2. A second example

The following task can be used for inducing to use trigonometry in problem-solving. It is designed for first grade college (high-school) students in *Neuchâtel*, a small town of Switzerland south of which we can see the Alps, but not the sea. The sea is further south, at the other side of the Alps. Here is the problem:

• Evaluate the relevance of the saying: "Raze the Alps to the ground, to let us see the sea!"

Students will come to the conclusion that razing the Alps to the ground is probably insufficient to see the sea, because of the bend of the Earth. An observer should stand higher to have a chance to spot the sea side in Genoa. Students can evaluate the constraint for a *Neuchâtelois* to see the sea, and they probably will produce a sketch alike the one reproduced in **Figure 2**.

This task is an alternative version of the first example: students must succeed a coordination of two semiotic registers, a linguistic one for the question in natural language and an analogical one for the drawn sketch.

Here, the coordination of various semiotic registers involves the coordination of semiotic standpoints, i.e., standpoints taken semiotically, a standpoint in reference of a position that is not concretely adopted by the interpreter. In Piaget's famous *mountain experiment*, children are alternatively moving physically to adopt a different *concrete standpoint*, or asked to adopt a standpoint in imagination, semiotically, i.e., through the use of signs such as the drawing of the mountains and a dot representing the standpoint from which to look at the mountains. In this second example, the student must coordinate two semiotic standpoints for his problem-solving:

- 1. The standpoint of the *Neuchâtelois* who desires seeing the sea;
- **2.** A standpoint from space, looking at the Earth from far enough to see it round, and to imagine the line from the observer to the sea in Genoa, in order to check wherever this line is interrupted by the Earth surface or not.

Hence, in this task, the *coordination of standpoints* is required not only to evaluate the consequences of the bend of the Earth on the horizon of a *Neuchâtelois*, but also for the actual drawing of a sketch as the one reproduced above (**Figure 2**), since the students have to make their own sketch and use it as a *semiotic tool* to solve the problem, not just as a way of expressing the solution. The coordination of standpoints is hence constitutive to the problem-solving, and to (some aspect of) the concept of curvature of the Earth.

This analysis contributes to explain the difficulty of this apparently simple question. As pointed by Mounoud [26], coordination of standpoints remains a challenging cognitive task until late in the cognitive development, and also for adults.



Figure 2. A simplified sketch.

#### 2.3. A third example

The trajectory of the free fall of a thrown object corresponds to (a part of) a parabola (see **Figure 3**, the graphic on the left). Yet, the time graph of vertical free fall also corresponds to a parabola (see **Figure 3**, the graphic on the right).

The challenge for interpretation appears immediately: the drawing of a graph triggers generally a spatial or spatiotemporal representation by the reader, thus both graphs are interpreted as representing a trajectory. Two comments must be done here, to specify the use of a semiotic tool such as a graph by physicists:

- **1.** The *free fall* is for a physicist the movement of a *material dot* in the absence of any other forces than gravity or, in any other case where all other forces would be exactly balanced. Hence, it is not a parachute jump before parachute opening...
- **2.** A *graph* is not a *drawing*—however one can *draw a graph*. This last expression is introduced here provocally, in order to stress the difference between the graph as a mathematical object and the drawing of the graph, its graphical representation which we will call *graphic* here.

In this third example, students need to coordinate the analogical semiotic register of the graphics with the observation of a falling object. Moreover, it is with the coordination of the two graphics—two objects of the same semiotic register—that students may achieve a more complete understanding of the mathematical object *graph*. Hence, the cognitive task requires the coordination between two specific semiotic objects of the same semiotic register: the progressive construction of the two graphics can be displayed with a simulator, in order to support students understanding the parabola as a mathematical object, a semiotic tool, independently to what it represents in a particular use.

The congruence between the two graphics and the observed trajectories of the object "falling" freely is achieved through a common timetable, here, through *synchronization*. This *synchronization* 



**Figure 3.** Drawing of the graphs of, on the left, the trajectory of the free fall of a thrown object (*x*- and *y*-axis in meters) and, on the right, the position-time graph of a vertical free fall (*x*-axis in seconds, *y*-axis in meters).

is a specific type of *coordinations* of *semiotic objects* which can be supported by the simultaneous construction of the two graphics on a simulator. Both graphics are nevertheless referring to a common *semiotic tool* in mathematics: the *graph*.

#### 2.4. A fourth example

**Figure 4** presents an *electrical diagram*, conventional representation of the assembly of various *resistors* and an electricity source of 12 V.

The *resistors* are assembled in series, yet the diagram displays them in parallel. The expected coordination between the diagram and the electrical assembly it represents is a differentiation: students have to differentiate a parallel setting on the diagram and the parallel assembly.

Remark: an usual French translation of the word *resistor* is *résistance*. Thus the French signifier *résistance* is used as a metonymy, since it denotes [24] an object which *has a resistance* as a physical property, which can be measured in order to define the *resistance* with a number—the name of which is taken from the process of opposing resistance to the electrical flow. What a lot of pitfalls for the students' interpretation!



# 3. This is not an arrow

Diagrams and sketches are complex semiotic objects and play an important role both in the making of scientific models and in supporting students to understand these models and the related concepts. In order to investigate this complexity, we propose here to approach it through the description of the diverse usages and functions played by a specific object commonly met in diagrams and sketches: the arrow.

Arrows are commonly used in physics classroom. Schoolbooks and exercise sheets frequently offer sketches to illustrate the verbal instructions or explanations. In these representations, the arrow is a *semiotic object* aiming at a better communication and transmission of knowledge, and eliciting the cognitive task expected from the students. Yet, arrows are in turn used by students to support their reasoning, or formulate their answers, i.e., as *semiotic tools* for learning or doing physics. The way students will use the arrows as semiotic tools may be influenced by the way it is used to elicit the taught knowledge. In order to investigate this question, we will present examples from schoolbooks and exercise sheets. These examples tend to show that *arrows*, as *semiotic objects*, are neither used in a way supporting a regular and rigorous congruence for the coordination between semiotic registers, neither according to well-established conventions as for the electrical diagram, for instance.

Our analysis of *arrows* as *semiotic objects* is descriptive—it stresses the properties of the signs themselves, such as the sense and direction, the line and/or color of the arrow—and functional. For the functional analysis, we investigate the *semiotic role* [27] played by a specific arrow in its particular context.

The examples presented below are analyzed following two steps.

First, we provide examples where *arrows* sharing the same properties play various roles. The *semiotic role* is differentiated from the *semiotic function* of Piaget, which refers to the general capacity of using signs, symbols, and icons. The semiotic role of a sign, symbol or icon is always specific to the objective of communication or interpretation and is situated historically, socially, relatively to a domain of knowledge (such as physics), etc. It is relatively to the specific objectives of communication in a school context of teaching physics that we will analyze the challenge of interpretation for the learners, when a sign such as an arrow plays several semiotic roles within the same sketch or schoolbook. Novices in physics are confronted to the double task consisting in (1) the assimilation of the semiotic object as tools to support their learning, reasoning, and to produce relevant answers.

Second, after distinguishing various *semiotic roles* for *arrows*, examples will be provided of a diversity of *semiotic objects* for a particular *semiotic role*. Just like the diversity of *roles* for *arrows* can lead interpretants into difficulties, we argue that the diversity of *semiotic objects* for playing the same *role* may be challenging for whom has to infer the meaning from the regularity and the congruence between *semiotic register*, i.e., the regular association of a specific *semiotic role*.

## 3.1. A first analysis: a single object for various semiotic roles

The analysis shows that a single *semiotic object*—the arrow—can play various *semiotic roles*. **Figure 5** presents a sketch of "simple levers" from a schoolbook for secondary school [28].

This sketch contains two arrows with identical outlines. The first arrow, circled by us in red, denotes the application of a force and represents the sense, direction and maybe the intensity



Figure 5. A sketch about simple levers, extract from [28], p. 323.

(yet without any scale) of the vector used for modeling the force. A second arrow, circled by us in blue, points to a location on the sketch and associates a caption "rotational axis" to it. These arrows play two different semiotic roles.

First, the arrow encircled in red indicates some of the properties (and more) of the mathematical object used for modeling the force, the vector: the arrow materializes the application point, the sense, direction and (maybe) the magnitude of a vector. There is a conceptual congruence between the analogical semiotic register to which the arrow belongs, and the linguistic semiotic register to which the vector belongs (mathematical language). Yet, the arrow can only be congruent with the vector for a specific instant of the application of the force. A brief instant later or earlier, the vector modeling the force could be of a different magnitude, direction or even sense, depending on the situation.

In addition, the arrow encircled in blue plays a role of pointing to a location, of guidance of the interpretant's attention. In this sense, the meaning of this arrow is similar to a verbal deictic such as "this one," yet in an analogical semiotic register. It can contribute to a joint attention in the social interaction mediated by the written schoolbook. The arrow encircled in blue is not the only semiotic object used in **Figure 5** to guide the reader's attention: a caption "object which resists" is related to the sketch of the object by a simple line playing the same role. Hence, two different semiotic objects are used in this sketch for a single semiotic role.

Moreover, the "object which resists" applies a force—the "resistance"—on the crowbar, but there isn't any arrow to represent this particular force. In addition to use arrows for various semiotic roles, and to use various semiotic objects for the same semiotic role, there is no systematic use of arrows for a single semiotic role in the sketch: while the red arrow represents a vector modeling one force, no arrows can be found for representing the vectors modeling other forces.

## 3.2. A second analysis: arrows and movement

In the previous example (**Figure 5**), the sketch does not suggest any change or movement, but rather a static situation. *Arrows* are nevertheless often associated with movement in other contexts, such as the sketch below, taken from the same schoolbook (see **Figure 6**).



In this sketch, the arrow plays a different semiotic role: it allows to represent a movement on a semiotic support (paper) that cannot move or be transformed itself in a way that displays movement (contrary to a luminous screen, for instance, which can be used to trigger the illusion of movement). There might be a difference in the interpretation of **Figure 6** between novice and expert: for the common reader, the arrow may directly represent a movement. With some imagination, the reader may even see the various wheels "turning" in the direction denotated by the arrows. For a trained physicist, the same *semiotic objects*—the arrows—may rather denotate a theoretical object, a concept, i.e., vectors, which are in turn used to model the velocity of the wheels. If interpreted as vectors, the various lengths of the drawn arrows in Figure 6 raise questions: are they corresponding to various intensities of the vectors of velocity, are they depending on the diameter of the wheels or just random and meaningless? The directions and senses of the drawn arrows are also problematic to interpret as directions and senses of each corresponding vector: the arrows have no direction and the sense would rather correspond to a "rotational vector" perpendicular to the disk than to a vector modeling velocity. Hence, the congruence between the two semiotic registers is difficult to establish with this sketch.

Moreover, the arrows as *semiotic objects*, are more than vectors, since they have a position (on the sketch), while vectors are "nowhere." This particular point may lead students to consider that the arrow *is* the vector — and it is indeed a common misunderstanding. This misunderstanding has obvious consequences on the reasoning, questions, and answers. Moreover, it is meaningless to draw arrows curved if they represent vectors in **Figure 6**: the vector is never curved... this curvature has more to do with the trajectory. These various ambiguities about the arrows of **Figure 6** provides an illustration of the difficulties a novice can encounter when interpreting a sketch in physics where the semiotic roles are undifferentiated: arrows in **Figure 6** could represent movements, velocities, trajectories, vectors or a mix of these. On the other hand, learning physics entails differentiating movement and trajectory. This differentiation made Newton able to set a radically new approach, according to Koyré [29]: a mathematical model connecting forces and movement, and not only prediction of trajectories, which was the concern of medieval physics—in particular for shooting cannonballs accurately.

This analysis shows that the differences of interpretation of arrows on a sketch between novice and expert can lead to specific misunderstandings. When the arrows are interpreted by experts as vectors, logico-discursive objects used to model a physical phenomenon at a chosen instant, they can be interpreted by novices as movement, trajectories or an undifferentiated mixture of the two, leading them to imagine a movement from the sketch while the attention of the expert is on a specific instant, making of the sketch a static representation.

Let us go back on the first example with this new hypothesis and examine how it could work on the sketch of **Figure 5**. Could students interpret this sketch as designating a rotational movement of the crowbar? The caption "rotational axis" may support such misunderstanding. Indeed, learners should not use the convention associating arrows and movement; otherwise, the confusion between force and velocity—often observed by physics students [30]—may be strengthened all the better. The confusion pointed here concerns also the sketch as a whole: if it represents a static situation—which is the case of **Figure 5**—vectors are modeling a motive force at a given instant, and hence there is no movement at all to be considered. Students can nevertheless be tempted to think of such movement, since the effect of the motive force *in reality* is a movement: when one presses on the crowbar, it is for *moving* the nail out of the plank. However, modeling the movement of the crowbar and the nail requires different semiotic means, a different sketch, or more than a sketch.

In conclusion, the fact that the arrow only represents a vector at a given *instant* is crucial for understanding the physics of the phenomena. Using a written semiotic object such as an arrow to represent a model which has kinetic features—possibly better represented by a video document for instance—consists in a reductionism which is impacting differently on the interpretation depending on the objective of the communication. Yet, even when the teacher's objective is to address with a sketch a static situation for which the reduction to an instant is of no consequences, students may interpret the same sketch thinking of a dynamic phenomenon, trying to establish a congruence between the sketch and a movement. It seems therefore important that the use of a sketch comes to the interpretant with explanation about the specific objectives it may be useful for, be it in the communication or modeling.

## 3.3. A third analysis: differentiating arrows

In this analysis, we present examples of sketches dealing with semiotic challenges with a diversity of arrows. We start with examples providing clues to support the coordination between semiotic registers by the interpretants, and pursue with an ambiguous sketch about *forces*, discussing the question of *norms* for semiotics in physics.

In the following extract (see **Figure 7**) of an old schoolbook [31], arrows are used for pointing to the representation of a scale, on which the reader is invited to read a value (called  $\alpha$ ).

In order to represent two situations of equilibrium on the same sketch, one without any weight and one with a hanging weight "A," arrows are differentiated: one has a dotted line, the other a full line. This precaution may avert the misunderstanding of arrows as movement, which we discussed above. Indeed, the plurality of arrows may be interpreted as signifying that each arrow only represents a particular state of affair, and not a movement or process.

In this sketch, arrows do not denotate vectors which are used to model forces, but rather designates the orientation of the look of the physicist measuring the force applied by the weights



Figure 7. Illustration of the measuring of a force [31], p. 17.

"A" and "B" on a bending stem at the moment of equilibrium. In both cases, the target concept of the communication is the force, yet the approach is different: arrows denoting vectors play a role of modeling, while arrows pointing to a scale play a role of directing the attention or designating a measuring activity.

The semiotics of this sketch relies on a double representation — the representation of two situation of equilibrium — in order to communicate the semiotic role of the arrows as representing static balance of forces. This representation is reinforced with the representation of a *variable* (called  $\alpha$ ) and by another similar sketch representing another weight ("B"), which suggests a difference in mass with a difference in shape and size on the sketch. In reference to physics, the semiotic role of the sketch, which is to refer to static situations, is better supported than we could show in the first analysis (see **Figure 5**). Yet, the reader needs, for making sense of the measuring on the scale, to understand the process of bending of the stem after hanging the weight at one end which refers to an the asymptotic situation of equilibrium — when the stem has stopped bouncing up and down — which *theoretically* happens after … an eternity!

If arrows all play the same semiotic role of pointing to in this sketch, other roles can be found for the arrow in the same book, and not further than the next page. It will be the example discussed in our third analysis, and raises the question of the coherence of semiotic roles within a schoolbook or, more generally, within physics. The following example provides an explicit caption for an arrow. In the first sketch of the chapter on *forces* in a schoolbook [31], one arrow is used to denotate the vector AF (see **Figure 8**).

The congruence between the semiotic registers is explicited in the caption of the figure, next to the sketch, which states: "Any body is subject to the attracting force of the Earth: its weight. The vector  $\overrightarrow{AF}$  represents such a force, of an intensity equal to 300 kilogram-force." The differentiation between the vector and the force is explicitly addressed, by stating that the former "represents" the latter. The congruence between the arrow on the sketch and the vector it denotates is also explicated, by several signs. The naming of both ends of the arrow (A and F) allows to *call* the arrow "AF" and add this signifier a miniature horizontal arrow indicating that "AF" is actually a vector. Moreover, not only the sense and direction of the vector are represented on the sketch with the two ends "A" and "F," but a scale is provided which explicitly makes the length of the arrow meaningful: it is the intensity of the vector, which is expressed in "kilogram-force." Yet, by doing so, the arrow AF gains several properties that exceed the meaning of the mathematical object vector. As mentioned before, the arrow AF has something more than the vector  $\overrightarrow{AF}$ : a point of application. There is no congruence between the sketch and the mathematical model about this point of application, and the drawing of arrows for representing vectors can become tricky, particularly on sketches representing objects in a realistic form, rather than just with a *dot*. More importantly, the point or *dot* F used for calling the end of the arrow has no corresponding meaning in the linguistic semiotic register of mathematics: a vector is only defined with a direction, sense, and intensity. Alternatively, the arrow AF could be representing two dots on an axis of forces in an abstract space, but it would make of A something else than a point of application, and AF would not represent the vector  $\overrightarrow{AF}$  anymore. Confusion may occur here, despite the effort to make the correspondence between semiotic registers more explicit, all the more so since the letter "F" chosen for the mysterious end of the arrow may suggest a relation with a force...

Sometimes, vectors are insufficient and what arrows provide in addition is needed. It is the case for representing a point of application.

2. FORCES





Figure 8. First illustration of the chapter on forces [31], p. 16.

In the sketch of **Figure 9**, the authors have used two types of line to deal with the issue of the point of application: the reaction force of the wall is drawn with a dashed arrow, and the two points of application are related with a dashed line across the door which represents the *lever arm*, all the way to the rotational axis of the torque, on which the action and reaction forces are articulated. The semiotics of this sketch supports the link between the Newtonian theory—in the linguistic semiotic register—and the sketch—in the analogic semiotic register. None of these precautions have been taken in **Figure 5**, for instance.

We have seen an example dealing with the *point of application* an arrow denotates alongside with the *vector*. The next example presents a case where the differentiation of arrows remains open to several possible interpretations, and where the caption introduces ambiguity rather than a clue for inferring the meaning of a specific arrow.



Figure 9. Illustration of a torque [31], p. 49.

In the sketch of **Figure 10**, two arrows are differentiated graphically: the arrows have dotted or continuous lines, and start from two different faces of the object.

The dotted line starting from the center of the base of the object is associated with the caption "friction," while the continuous line starting from the surface of a side of the object (alternatively the right and left side) is associated with the caption "sense of traction." The dotted arrow plays a role for modeling a *force of friction*, the arrows itself denotating the sense and direction (and maybe magnitude) of a *vector*. The localization of the starting point of the arrow may also represent the *point of application* of the force of friction, even if it is here simplified by reducing it to a mathematical dot situated at the center of the base of the rectangle, on the line of contact with the ground.

What the continuous arrow represents is more difficult to infer from the sketch. It could denotate a vector modeling a *pulling force*. Yet, the caption refers exclusively to the "sense of traction," which cannot be understood literally since the direction of the arrow should also be taken into consideration if the arrow denotates a vector, the direction of the vector and the direction of the arrow are congruent. Nevertheless, pairing the sense of movement and forces is typically the common sense a physics teacher opposes: friction forces and traction

forces may have the same direction and sense, e.g., when holding a sledge slipping down a slope, and friction forces are not always in the opposite sense of acceleration, e.g., when a car accelerates. Since it is inducing such an association or confusion between force, acceleration, or movement by the lack of specification, the sketch of **Figure 10** may support interpretations confusing the concepts of *force* and *movement*, which has consequences on the learner's cognitive tasks of coordinating sketches and concepts, and more generally of reconstructing the concepts with the support of sketches.

Moreover, this sketch also supports the confusion mentioned earlier between the study of static and dynamic situations. **Figure 10** actually represents a stationary situation (i.e., with constant velocity), if the pedagogical objective is indeed to demonstrate that the friction force is a reaction force in the same direction and opposite sense to the traction force. Yet, the confusion between *force* and *movement* introduced by the caption "sense of the traction" supports the imagination of a "story," a process: the object is first immobile, is then pulled — the arrow could even stand for the rope in this interpretation — and thus it moves, braked down by the friction force. In such a representation, the acceleration phase is completely overlooked. The friction force is a friction between the two surfaces instead of a resistance to start moving, while the stationary situation could be standing for both cases.

The graphical differentiation of the two arrows is also operated through the choice of a different starting point for each arrow. The continuous arrow starts from the surface of the object. We have seen the semiotic challenge posed by the graphical representation of a point of application of a force, in particular when sketches are representing *objects* rather than *dots*. Following the modeling of objects as mathematical dots, any point of application of a force exerted on an object should be the center of gravity, according to the specific model used here. While we understand that the point of application of the dotted arrow in Figure 10 is not quite the center of gravity, but the horizontal center on the line of contact with the ground, this leads to confusion when the interpretant tries to coordinate the dotted arrow with the continuous arrow. These arrows represent vectors which only need to be added to each other to be coordinated as a sum of forces exerted on the rectangle. But a novice reader could wonder whether he/she must think of torque. When representing a torque, in Figure 9, the author of the same schoolbook chooses to connect the points of application of the forces across the door, in order to represent the lever arm. Here in Figure 10, the sketch is not about torque and such semiotics would be irrelevant. Now, the point of application of the continuous arrow—on the surface of the object—is difficult to justify if the arrow is meant to denotate a vector. It rather supports an interpretation where the arrow designates a rope, a concrete object rather than an object of discourse [24] such as a vector. The problem identified here can be analyzed in terms of an ambiguous coordination between semiotic registers within the sketch. The sketch uses two different semiotic registers: one represents something; it is representational or figurative, while the other represents a model; it could be named *modelative*.<sup>1</sup> The rectangle or the line representing respectively the object and the ground are *figurative*, while the point of application and the arrows are *modelative*. It is

<sup>&</sup>lt;sup>1</sup>In French, the adjective "modélisant" could avoid us to introduce a neologism, here. In English, yet, the lack of adjective corresponding to modelling, the active form of the verb to model leads us to prefer a neologism to avoid ambiguity.



FORCE DE FROTTEMENT

Figure 10. Illustration of friction forces [31], p. 27.

interesting to note that the linguistic register does not always allow to differentiate such an ambiguity: the word *attraction* is also ambiguous, as *attracting* does not mean *making some-thing come* in physics, but rather *pulling* even without any resulting movement.

This analysis would not be complete without considering the effect on interpretation of the arrows that are *not* drawn on the sketch. Since the interpretant, and more particularly the novice, must rely on inferences for meaning making and on what there is on the sketch, the absent arrows may also influence such inferences. Typically, one may interpret arrows as representing forces rather than movement, ropes or anything else, if there is one arrow on the sketch for each of the expected forces to be considered. Piaget shows in his theory how the whole system of operations allows a deeper understanding of each operation constituting such system. We may consider a sketch as a system—at least the interpretant expects the sketch to "work" consistently like a system—and the single operations used for interpreting it as depending on the interpretation of the whole. Following this hypothesis, the fact the earth attraction and the supporting force exerted by the ground on the object are not drawn in Figure 10 does not support the interpretation of the arrows as forces in this sketch, and would allow them various semiotic roles. If all the forces exerted on the object at a specific moment were drawn on the sketch it would support the interpretation of the arrows as denotating vectors and as modelative of forces and support the interpretation of the sketch as a whole as modelative of a stationary situation rather than of a dynamic, or of a truncated "story."

Hence, not only what is on a sketch may open the possibility for misunderstandings, but also what is lacking. It is not surprising, considering that interpretation relies greatly on inference processes, for which consistency and repetition are important criteria. If a sketch contains four

arrows, among which one is ambiguous and the other three are clearly denotating vectors, the ambiguity is easily solved in favor of a consistent use of arrows that grants the semiotic object the same semiotic role within the sketch: the fourth arrow will also be interpreted as denotating a vector. These *a priori* analyses draw the attention on the importance of consistent use of semiotic objects in science education, in order to support the desired interpretation. More detailed is the analysis, more problematic the consistency appears. We will continue to refine our investigation with a last analysis, interested in the differentiation between what arrows are modelative of.

## 3.4. A fourth analysis: vectors for various physical quantities

In this analysis, we provide several examples to raise the issue of the various physical quantities vectors can model, and to provide illustration of clues that can be used in order to support the interpretation.

The graphical representation of a trajectory "equipped" with vectors for velocity, acceleration and force constitutes a classical example of a sketch with arrows, which we use for presenting, explaining, or using the second Law of Newton. **Figure 11** illustrates a sketch with arrows for three types of vectors mentioned.

The arrows in **Figure 11** are not distinguished according to the various physical quantities that the learner needs to differentiate. The sketch could raise nonsense questions as: "Why is the arrow representing velocity longer than the arrow representing the acceleration?" Meaningless practices could also be grounded on this sketch, such as adding or subtracting vectors modeling different physical quantities. In **Figure 11**, single letter captions have been added for each arrow, which could work as clues for the physical quantity represented by the arrows. As useful as it can be, the interpretation remains subject to the interpretant's knowledge of implicit convention. For instance, "F" generally refers to the sum of all forces applied on the object, rather than to a specific force exerted on the object, but a modelative object. Moreover, the arrow associated with "F" has its arrow end on the object instead of its starting point, suggesting the idea that the force is "pushing" the object. Generally, the arrows



Figure 11. Illustration of a graphical representation of various vectors implicated in Newton's second law [32].

denotating vectors are starting from the object, its center of mass if it is drawn as a figurative object. Yet, once again, a diversity of practices is not rare in science education, and often comes without a word of explanation. The linguistic register seems more consistent with arrows starting from the object, yet vectors are not only modeling properties *of* the object (such as velocity or acceleration) but actions *experienced by* the objects (such as forces). These relations that physical quantities have with the object are not signified by the mathematical expression of the second law – written on the caption "F" of the sketch – and can only be interpreted here from the knowledge of the interpretant.

In the following example (see **Figure 12**), arrows of various colors have been used to differentiate between the various physical quantities the arrows are modelative of.

This trick allows the teacher to address his students with the provocation presented in **Figure 13**: "this is not a triangle"

**Figure 14** shows more examples of a color and shape scheme for arrows, depending on whether they are denotating a vector modeling velocity, acceleration, or forces.

The shapes and colors provide a clue for interpreting arrows as denotating vectors modeling different physical quantities (i.e., *force, acceleration,* and *velocity*). Yet, there are no explicit criteria for the shape and colors: the author simply mentions that a particular care has been given to these representations. The practice of arrows in the schoolbook nevertheless shows that vectors modeling acceleration have generally a double line and the color red, while trajectories or movements are represented with black lines and arrows. Vectors modeling forces are denotated by arrows of various colors throughout the book.

Figure 15 presents an example using colors, but from another book [35].



Figure 12. Exercise about vector quantities implied by Newton's second law [33].

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Figure 14. Illustration of vector quantities implied by Newton's second law [34], p. 121 and p. 152.



Figure 15. Forces exerted on a car and velocity vector [35], p. 43.

The object is represented figuratively and there is here the problem of the point of application discussed earlier. There is an additional ambiguity due to the oblique vectors R1 and R2, which are not modeling additional *forces* experienced by the car, but the result of a composition of *forces already* represented on the sketch.

# 4. Discussion and ideas for further research

This brief inquiry about the *semiotic roles* played by arrows in a few sketches mediating communication in physics led us to consider several roles:

- (1) a role in directing attention: pointing to a specific location on the sketch, in which the arrow works as a graphical deictic;
- (2) several roles in signifying:
  - (1) designating a movement;
  - (2) designating a trajectory;
  - (3) designating an action such as pulling or pushing;
  - (4) denotating a vector which, in turns, is modeling several physical quantities, notably:
    - (1) a velocity of an object;
    - (2) an acceleration of an object;
    - (3) a single force experienced by an object;
    - (4) a sum of forces experienced by an object.

If it were not for the role in directing attention, for which the arrow does not represent anything, we would be tempted to consider arrows signs with several significations, just like words can have several entries in a dictionary. A "pound" means both a quantity of money and a mass. However, even without this role in directing the attention, analyzing arrows in science education is not that simple. Indeed, the arrow itself, as a semiotic object, has some properties such as the sense and direction, and the length, which are or are not congruent with the corresponding object of discourse in the linguistic register, depending on the semiotic role played by the arrow. For instance, the direction and sense of an arrow denotating a vector are relevant, while the precise direction of an arrow denotating a pulling action on a door is not necessarily congruent with the linguistic correspondent-the force exerted on the door or its movement. Moreover, depending on the particular sketch in which the arrow is used, its length may be relevant or not: when a scale is associated to the length of the arrow and the arrow denotates a vector, its length can be interpreted as congruent with the magnitude of the vector. On a sketch with arrows denotating vectors modeling various physical quantities, however, the comparison of the length of the arrows is meaningless. The direction and sense of an arrow pointing at a specific location of a sketch is also partly irrelevant: it is only the combination of the two that achieve the pointing.

Hence, it appears that the actual coordinations the interpretant can or should do while interpreting sketches in physics depends on the semiotic roles played by the arrows on the sketch, and depends on various other choices made during the design of the sketch.

When the arrow denotates a vector, there is congruence between the arrows direction and sense, sometimes its length, and the vectors direction and sense, sometimes its magnitude.

Establishing this congruence requires from the learner to coordinate two semiotic registers together: an analogic register used in the sketch, and a linguistic register using mathematical language and, more precisely, a mathematical *object of discourse*, i.e., *vector*. Within the analogic register used in sketches, the analysis has shown that two semiotic subregisters must be differentiated: a *figurative* representation of objects which represents objects as they appear in real, and a *modelative* representation which represents objects according to a specific model, operating specific reductionism following specific and systematic rules (e.g., representing an object by a material dot).

Moreover, some semiotic roles are not exclusive and can be used simultaneously or can be undifferentiated in a particular sketch. For instance, an arrow can indistinctively refer to the direction and sense of a movement and the vector modeling velocity. After all, if nothing is explicated, the coordination of semiotic registers largely depends on the knowledge of the interpretant. Many not-so-well-made sketches work fine for those who know not to look at what could otherwise appear as "mistakes" in the representation.

We have raised the question of the coherence of the clues used to support the interpretant inferences in single sketches. This question can be addressed for physics in general, questioning the coherence of the way arrows are used and how the diversity of usage is associated with clues (graphical differentiation, captions, etc.). Despite an overall convention that arrows are used to denote vectors, more particularly vectors senses and directions, the few examples analyzed here advocate for a rather nonnormative use of arrows in science education. Detailed features such as the graphical rendering of the arrow, the point of application or the way to distinguish between various physical quantities modeled by vectors are not *normed* and vary within a single book, sometimes even within a single sketch. For the book, we showed with **Figures 8–10** that dotted arrows could refer to various types of arrows, and despite a great care to graphical representation in this particular schoolbook [31].

The many challenges and risks of misunderstanding we could stress from a few examples of sketches only, build an overall impression of a *wild language*. The various ways sketches, and in particular arrows in these sketches, are used to mediate communication in the examples analyzed show that sketches are indispensable semiotic tools—some sort of *proto-language*—and yet, the lack of systematic usage and conventions or norms stresses how *uneducated* these semiotic tools are. If it may be some sort of graphical proto-language, specific to physics or even to a chapter in physics, it does not follow the rules of other semiotic tools such as *technical drawing*, *algebra*, *English syntax*, etc. Sketches we examined remain for most of them unsystematic in the way they use semiotic objects such as *arrows*, and their interpretation depends highly on rules specific to each particular sketch, when there is any. The *wilderness* is not related to a lack of existing means, since older schoolbooks are sometimes better, and there are a number of means to provide the interpretant with clue to support the desired interpretation, which we stressed throughout the analysis.

Future research is needed to elaborate a more systematic semiotics for science education, both for describing existing practices and innovative ideas and for testing various semiotic norms, in order to investigate which ways are making the interpretation easier for specific issues.

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