Learning hypotheses and an associated tool to design and to analyse teaching-learning sequences

Christian Buty *, Andrée Tiberghien *, Jean-François Le Maréchal *
* UMR ICAR, Université Lumière Lyon 2-CNRS-ENS de Lyon, ENS-LSH-INRP, 69342 Lyon Cedex 7, France

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Christian Buty (Christian.Buty@univ-lyon2.fr), Andrée Tiberghien, Jean-François Le Maréchal, UMR ICAR, Université Lumière Lyon 2-CNRS-ENS de Lyon, ENS-LSH-INRP, 15 parvis René Descartes – BP 7000, 69342 Lyon Cedex 7, France

This contribution presents a tool elaborated from a theoretical framework linking epistemological, learning and didactical hypotheses. This framework leads to design teaching sequences from a socio-constructivist perspective, and is based on the role of models in physics or chemistry, and on the role of students’ initial knowledge in learning processes. This tool, formatted as a ‘grid’, is applied to one example in physics (optics, grade 11), and to one example in chemistry (conductivity, grade 11). Both these examples are taken from the important activity our team has developed from several years, in collaboration with upper secondary school science teachers, in order to design teaching sequences and experiment them in real classrooms.

Introduction

For almost 10 years our research group has been designing teaching sequences in collaboration with upper-secondary-school teachers in various phenomenological fields in physics and chemistry. The present paper aims to elicit the processes that go from a theoretical framework to the design of teaching sequences, and to propose a tool that can be used to design or to analyse teaching–learning sequences. The way to check the consistency of the teaching sequences with regards to the hypotheses, and feasibility in the educational system is also described.

Previous studies

Many studies have analysed the process of construction of sequences as a research activity and, in few cases, dealt with their validation. Several of these studies are discussed here.

Lijnse (2000: 309) proposed a ‘problem-posing approach’ as a guideline for constructing teaching sequences. His approach is grounded on three main hypotheses:

1. In the case of the particulate nature of matter, Linjse hypothesized that students ‘have no alternative ideas about particles that need to be changed’ (2000: 317). He indicates here that the designer of a teaching sequence can use different fundamental hypotheses, depending on the relation between the knowledge to be taught in the sequence and the set of a priori ideas that
common life leads each individual to form, and thus, depending on the
phenomenological domain, the learning of which is expected.
2. Lijnse (2000: 320) also considered that the design of a teaching sequence,
as many results of didactical research, depends not only on the knowledge
to be taught, but also on the particular educational system in which it is
carried out.
3. He also claimed that motivation is a prime aspect of the design of a
sequence. Giving students good reasons to find interest for entering the
study of a given topic (and that is the aim of a ‘problem-posing approach’) is
as important as proposing a well-organized set of tasks.

Based on these three hypotheses, and for each sequence on a given domain, Lijnse
(2000: 321) elaborated ‘didactical structures’, horizontally organized in three levels
– the content level, the motivational level, and the reflexive level – between which
the sequence progress switches, going from an initial questioning to a deeper
understanding of the issue. Kortland (2001, see particularly figure on p. 47) refined
Lijnse’s didactical structure in the case of the waste management issue, by
distinguishing five phases: motivation, question, investigation, application, reflection.
These eventually cyclical five phases led the author to develop a grid traducing the
importance of taking student’s motivation into account.

From this study, we retain the idea of basing the construction of teaching
sequences on clearly defined hypotheses and using a structuring table to describe
the content of the teaching sequence. However, we place a higher priority on
processing both the knowledge to be taught and the initial knowledge of the learner;
thus the categories of the table will be quite different. We also include the refining
of the constructed sequence after successive implementations in class (one to three
in general).

In the field of mathematics, many teaching sequences have been constructed by
researchers. From this work, Artigue (1992) developed the concept of didactical
engineering drawing a metaphor between the activity of the engineer and that of the
designer of a teaching–learning sequence. It supports the idea that constructing a
teaching sequence is a complex task involving several convoluted parameters and
levels. Artigue distinguished macro-didactic engineering (the coherence of a whole
sequence) and micro-didactic engineering (implementing this coherence at the level
of each session). These levels are linked, for the designer of the sequence (although
it could be seen as rational to determine the large-scale design before the micro-
scale one, the feasibility of each micro-level influences the design of the sequence as
a whole) as well for the teacher (it was shown that micro-decisions taken on the spot
may have consequences on the general scrolling of the sequence). We consider that
this distinction is particularly important and we shall use it in this paper.

Artigue (1992: 55) also pointed out a number of problems inherent to the
validation of research-based teaching–learning situations. Using comparisons
between a control group and an experimental group of learners is justified by a
(generally) implicit hypothesis: the observed differences are linked to the experi-
mental variables that have been manipulated to differentiate the experimental group
from the control group. Such a hypothesis neglects the psycho-cognitive history of
learners, the interactions within the group and the role of the teacher(s). This
hypothesis is probably too simple to be applied to sophisticated and complex
didactical phenomena as teaching–learning sequences. Thus, in the framework of
didactical engineering an approach of internal validation is preferred. Such a validation consists of ‘comparing two different models of the same object (the teaching sequence), which are an a priori analysis and an a posteriori analysis’ (Laborde 1997: 103).

In our work, we have generally adopted internal validation for the analysis of teaching sequences. We followed the same group of students during a whole teaching–learning process to describe as much as possible the complexity of the didactical situation, and to compare their behaviour to predictions.

In the field of didactics of physics, Méheut (1997) clearly described the learning hypotheses underlying the construction of a teaching sequence about the thermo-elastic properties of gases in French lower secondary schools. The sequence involved the use of a computer simulation and emphasized the relation between a kinetic model of gases and the observed phenomena in the experimental set-up.

These learning hypotheses were more or less linked to some specific aspects of the knowledge to be taught. Very close to this knowledge was the hypothesis that ‘learning difficulties brought to light by didactic research could be easily understood by remembering some specific features of the historical development of the atomic models . . . Atomist philosophers considered sensations are misleading. They asserted that reality remains concealed; it can be brought to light by reasoning, not by direct perceptions alone’ (Méheut 1997: 648).

A more general hypothesis was that ‘a model can be accepted by pupils only if it seems to be a “better” tool for explaining or predicting phenomena’ (Méheut 1997: 650). This represents a particular version of a more global assertion of Posner et al. (1982) about conceptual change. As a consequence, Méheut expressed a need to look ‘for phenomena about which pupils of this age have difficulties in predicting or explaining’ (Méheut 1997: 650).

The main idea that we retain from this work is the necessity to take into account initial conceptions of learners about knowledge at stake in the learning hypotheses.

Leach and Scott (2002) offered a perspective for constructing teaching sequences, ‘based on the concept of learning demand, and a social constructivist perspective on learning’. They claimed that considering the effectiveness of the sequence of teaching tasks upon learning is not enough. The teacher’s role in staging those teaching tasks should also be considered. In particular, every improvement in the teacher’s understanding of the sequence, for example, after discussion with researchers, is likely to have consequences on the level of his/her engagement and the effectiveness of learning in the classroom.

Consequently, their approach for developing a teaching sequence must:

- ‘Identify the school science knowledge to be taught’;
- ‘Consider how this area of science is conceptualized in the everyday social language of students’. At this step, the alternative conceptions or everyday reasoning, which have been identified by research literature, must be used.
- ‘Identify the learning demand’ by considering the differences between the two first points;
- ‘Develop a teaching sequence’.

We have followed a very similar approach in identifying the gap between what the learner knows from everyday life and what he/she is expected to learn. In this paper we develop several methods to tackle the fourth point.
These several studies show the variety of approaches of the design and the study of teaching sequences. The conclusions we draw from these studies consist of:

- Grounding the design of a teaching sequence on a well-structured theoretical framework, including learning hypotheses taking into account initial conceptions of students.
- Using a methodology of *a priori* and *a posteriori* analysis for the validation of the teaching sequence.
- Recognizing the critical role of the teacher in the teaching sequence.

From the theoretical framework to the design of teaching sequences

Designing teaching sequences is a complex activity that necessitates taking into account the classical three poles – knowledge, learning, and teaching – without forgetting the institution in which the teaching and learning activities take place and the artefacts by which the activities are mediated (Cole and Engeström 1993, Laborde et al. 2002). Each pole can be linked to a root domain of our theoretical framework: epistemology, psychology and didactics. Here we shall provide the key hypotheses we used to construct teaching sequences. Each of these hypotheses involves all three root domains, although in each case one pole is identified as predominant.

Often there is a long way from the theoretical framework to the design of the teaching sequences. They are not a direct consequence of the framework; several choices must be made. One of the main aims of our research has been to make these choices as explicit as possible. In this perspective, we introduced two roles of the theoretical framework: it can exert constraints, and it can provide hints. As the design of sequences had to respect the hypotheses of the theoretical framework, this framework acts as a constraint. Simultaneously, these constraints lead to search for new aspects of knowledge, new tasks to propose to students, new organization of the class, and so on, and so the theoretical framework can provide very useful hints to sequence development.

**Hypotheses on knowledge**

The theoretical position of knowledge is based on Chevallard’s (1991) work. He dealt with knowledge using the metaphor of life and ecology. Knowledge ‘lives’ within groups of people called institutions and the *relation* between an individual and a piece of knowledge is termed ‘understanding of knowledge’.

From this perspective, the process of going from scientific knowledge to the knowledge to be taught and then to the knowledge effectively taught is called the didactical transposition. The process of designing the knowledge involved in a teaching sequence corresponds to a didactical transposition. The elaboration of this knowledge is based on the official curriculum, in particular in France where such a text is law. Nevertheless, this elaboration requires more ‘manipulation of knowledge’. The designer may reorganize the curriculum and must decompose it into smaller pieces and integrate it into activities. In this *manipulation* of knowledge, the designer calls upon scientific and possibly historical knowledge.
In a research-based design of teaching situations, this manipulation should be theoretically based and made explicit (rather than being treated, implicitly, as being as close as possible to a ‘true’ knowledge). Two complementary hypotheses to analyse knowledge are presented: modelling and semiotic registers (Tiberghien 2000).

**Hypothesis on modelling.** In our theoretical framework, the first choice is based on epistemological grounds and on learning hypotheses, both aspects being intrinsically related. For us modelling processes are at the core of physics and chemistry. The meaning of physical and chemical concepts at the primary, secondary or early university levels requires links between, on one hand, direct knowledge and perceptions of the material world, and on the other hand, theories; one of the main difficulties for learners is to establish such links.

This theoretical choice is transformed into a constraint in the design of teaching sequences: instruction must explicitly distinguish the theoretical aspects and the direct description of the material world (that is involving the perceived objects and events). It is important to understand and to take into account that any direct description of the material world involves a part of theory, embodied in the wordings. Most of the time, the students’ problem lies in the fact that the theory they use is common sense, everyday-life inherited, and has little in common with the theories of physics they are expected to use and to learn. The hypothesis associated with this theoretical choice states that establishing such distinctions and relations between the direct description of the material world and the theories and models, requires the students to be aware of the theory/model status, its relevance and fruitfulness. Making explicit the theory/model helps the students to confront it with their own ‘theoretical ideas’ and thus to discuss it either in the whole group class or in small groups.

This hypothesis on modelling has implications at the macro-level of the design of the whole sequence and at the micro-level of the design of a specific task (Artigue 1992). At the macro-level, the theory/model has to be formulated in order to make it coherent at least with the set of experiments, or more largely the material situations that can be studied. At the micro-level, this hypothesis requires the designer to explicitly consider the extent to which the students can carry out the task given their own knowledge and the information that is available in the class (from texts, from the experimental setting, etc.). Thus the designer is lead to analyse the knowledge and the practices involved in the task (Bécu-Robinault 1997). The articulation between the micro-level and the macro-level allows the establishment of coherence between each step of the sequence.

Attention to model/theory status often provides hints, because it leads to analyse very finely the knowledge involved in teaching at both macro-level and micro-level. For example, in the domain of optical image formation, the preoccupation for clarifying the differences between theoretical elements and the reality leads to thorough study of the issue of the focusing scope, including the resolution of the eye. Students themselves, when using a screen to observe the image of an object, asked why they had found a wide range of positions where the image was visible, around the position given by the formulas. Thus, the importance given to the relationships between the direct description of the material world and the theories and models leads to specify the teaching content.

This hypothesis about modelling has its roots in an epistemological judgement on the deep nature of physics and chemistry. Associated with a socio-constructivist
framework, as we present later, it leads to elaborate essential elements of teaching situations such as to give a written text for the model to students.

**Hypothesis on semiotic registers.** The written description of the experimental field and theory in physics and chemistry invariably involves a variety of semiotic registers: natural language, vectorial language, algebraic language, drawings, and pictures. Following Duval (1995), it was stated that different semiotic registers associated with a concept should be used and related to construct its meaning. In the case of the force concept, several registers such as natural language, vectorial or algebraic representations, must be involved to grasp its meaning.

The role of natural language in the passage between different semiotic registers, such as from the algebraic to the vectorial register, should thus be explicitly addressed by the designer of teaching sequences. This role of natural language is coherent with the importance given to language as mediation in the socio-constructivist approach (Vygotski 1956/97, Wertsch 1985).

This hypothesis matters at the micro-level of a sequence. It requires the designer to decompose knowledge and to associate various clearly distinguished semiotic registers to a given concept; furthermore, it requires calling students’ attention to the existence of and the relations between these different semiotic registers.

This hypothesis also provides the designer hints as to some of the possible difficulties encountered by students. These difficulties can occur when carrying out tasks involving different semiotic registers like numbers in measurements, graphs and algebraic formulas. Another example would be the student in optics who must locate an image both by using algebraic formulas, and by constructing the image as the intersection of all the emerging rays through an optical system.

**Hypothesis on learning**

We take up the constructivist hypothesis recognizing the role of students’ previous knowledge. Moreover, our socio-constructivist approach about learning is grounded on the Vygotskian ideas of the internalization process associated with the back and forth motion between the communication language with others and the internal language, and the role of mediation in learning (Vygotski 1956/97). The role of adult mediation is associated with the zone of proximal development: what a learner can do first with an adult’s mediation can be reproduced by himself/herself later.

**Students’ initial knowledge in relation to the zone of proximal development.** The ‘distance’ that the learner must travel between his/her initial knowledge and the knowledge to be taught is analysed in terms of the general question: can this distance be covered by the learners during the assigned teaching duration? In other terms, is this distance in the zone of proximal development? This comparison is similar to the learning demand proposed by Leach and Scott (2002).

The distance between these two sets of knowledge can be analysed in terms of modelling and semiotic registers with an extra hypothesis: some parts of students’ initial conceptions have a more important role than others in the students’ construction of physics or chemistry concepts. The learner is supposed to develop new knowledge from some facets of his/her initial knowledge without too many difficulties, because they are not in contradiction with the new knowledge. For
example the learner can refine, extend meaning, or restrict meaning by differentiation of a facet; the facets that have this potentiality are called *founder notions* (Küçüközer 2001). Hypothetical founder notions can be stated from research on the evolution of students’ conceptions. This hypothesis does not suppose there is a unique founder notion for a given part of the knowledge to be taught; several candidates may play this role.

This specific hypothesis has implications at macro-level and micro-level. The approach thus requires that a teaching sequence on a new domain originates with everyday notions, even if this changes the usual rational order of the introduction of the concept. In fact, more or less explicitly, it seems that several researchers have used this approach, with effects on the order of presentation of concepts in the teaching sequence. For example Psillos et al. (1988) and later on Leach and Scott (2002), in teaching sequences on electric circuits, started from the idea that electricity (named current, energy, etc.) has three properties: it is necessary in order that things in the circuit work, it is used up, and it circulates.

The teaching sequence thus begins by differentiating the notions of energy and ‘current’ from the global notion of ‘electricity’ – the concept of ‘current’ at this point still being undifferentiated from voltage by students. Only in a second session is differentiation between current and voltage taught.

The careful examination of initial knowledge is a powerful aide in making explicit aspects of knowledge that are usually considered obvious by teachers, but are not known by some students who are then in a difficult situation. This hint leads to the conception of tasks aiming at developing new meanings for words used in the everyday context such as current, energy or acting, interaction, object, and so on.

Another consequence of the analysis of the distance between the knowledge to be taught and the students’ initial knowledge happens when this distance is judged too large; that is, when learning would take too long. This leads the designer to elaborate ‘intermediate knowledge’ closer to the knowledge to be taught than the students’ initial knowledge, but still different, and which could even be considered incorrect by experts. For example, an intermediate knowledge would be to implicitly accept the association ‘no force, no movement’, when students learn to differentiate the concepts of velocity and acceleration (Dykstra 1992).

**Hypothesis on the role of mediation.** In the socio-constructivist approach, the mediation through the language leads to consider that verbal interactions, between students and between students and teachers, favour the development of the meaning of knowledge and of the meta-knowledge like judgements and other control processes involved in the teaching situation.

Depending on interactions, the teacher plays several roles: besides the role of managing the class, he/she is a tutor of students and a mediator between the world of scientific knowledge and practices, on one hand, and the students, on the other (Dumas-Carré and Weil-Barais 1998). As a tutor, he/she has not only to help students when they encounter difficulties they are not able to solve alone, but also to avoid giving the solution of problems before students can try to solve them (Brousseau 1998). As a mediator, the teacher has to give a scientifically appropriate linguistic expression to the knowledge, but at the same time he/she must use a language that students can understand.

This approach constitutes a constraint as, on one hand, a significant fraction of the teaching time should involve work in small groups in which the management is
mainly up to the students, and on the other hand the various roles played by the teacher (which are made explicit in the following) are taken into account.

We also consider that sharing a same meaning among a class is favoured when an explicit referent is involved, particularly when the meaning is the goal of learning. For example, in science classroom the referent could be the experimental devices, an everyday situation and/or a scientific theory. This hypothesis leads to introduce a referent in the teaching situation or to conceive it when it is not available. In this latter case, an explicit referent of the physics or chemistry theoretical parts is introduced in the form of a written text.

Didactical hypotheses

To construct these hypotheses, the theoretical framework elaborated within the community of didactics of mathematics in France has been helpful. In the theory of didactical transposition, a crucial aspect is the teaching time coming from the organization of the educational system and inside in the schools (Chevallard 1991). This constraint plays an important role on the sequence at the macro-level and on each task or set of tasks that have to match series of teaching sessions. It constrains the ‘sequentialization’ of the knowledge to be taught.

We have used the concept of devolution to specify the relationship between the teacher and the students (Brousseau 1998): ‘Devolution is the act by which the teacher makes the student take responsibility for a learning situation or problem, and accepts the consequences of this transfer him/herself’ (p. 303). This concept is associated to another concept, the didactical contract, which consists of the ‘rules of the game’ and of the management of the teaching situation (Balacheff et al. 1997). In this theoretical framework, it will be stated that devolution occurs for a given situation when the knowledge or processes that the students treat are those intended by the designer. This statement does not mean that students treat the knowledge in a correct way, but that they commit themselves to the intended subject. An example is given in the later chemistry sequence.

In the didactical situation there is a particular phase called ‘institutionalization’ that is also relevant in this framework. It means that the teacher presents the knowledge involved in the previous tasks as a part of the scientific knowledge (in fact the knowledge to be taught). Such hypotheses lead to several consequences at the macro-level and micro-level, particularly on the teachers’ role. In this perspective the teacher is responsible for staging the sequence and particularly for establishing a relevant didactical contract. In this contract, the status of error is deeply different from the usual one at this level of teaching. For example, in tasks requiring to predict events and to give arguments, the students have to write their predictions, which obviously can be wrong, in their exercise books. In this framework, such productions are considered as pertinent for teaching and learning because they help to confront his/her ideas with other information. However, many teachers and also students consider that writing wrong matter is not acceptable. Empirically, it has appeared that changing the students’ point of view on the status of error is not easy. A teacher may need months to establish a new didactical contract in his/her class.

Finally, the design of a sequence needs to be refined after trials by one or several teachers. As Lijnse (2000) stated, successive refinements are necessary. This aspect is presented in the sequence about chemistry later.
A tool to respect these constraints and to create from these hints

As already stated, the path from theoretical framework to the design of a sequence is more than a rational deduction; it also requires the designer to make choices based on teaching practice such as estimating the duration of a task. Even using this theoretical framework requires putting together several hypotheses to design the structure of the sequence (macro-level) or the specific tasks (micro-level). For this purpose, a tool called ‘the grid’ has been elaborated. This grid integrates several types of hypotheses.

The grid integrates our hypotheses on knowledge and on the role of initial students’ knowledge in relation to the zone of proximal development. It allows the designer to analyse and decompose both the knowledge to be taught and the students’ knowledge, and to compare and evaluate them. It helps to appreciate the notion of distance between the knowledge to be taught and the students’ knowledge. On the basis of this grid this comparison is done according to two dimensions of knowledge analysis: the everyday knowledge and the scientific knowledge, on one hand, and the modelling levels on the other (table 1). In each cell of the grid are indicated the pieces of knowledge involved in the task or in the sequence. In a row, every piece of knowledge is classified according to the modelling levels: they can refer to the level of ideas, to the one of material world, or make a link between these two levels. In the columns, pieces of knowledge are classified according to learning processes: they can belong to previous knowledge, either from previous instruction or from everyday life; they can also have to be constructed during the teaching sequence or session (Le Maréchal et al. 1999). This tool can help researchers and/or teachers to design and analyse a teaching sequence.

Using ‘the grid’ to design a teaching sequence

Using this grid at the macro-level when designing a teaching sequence allows the construction and verification of global coherence between the experimental field and the theoretical domain. Moreover, it helps to ‘sequentialize’ the knowledge to be taught according to the teaching time allowed.

At the micro-level, this grid allows one to specify the kinds of modelling processes that are expected from students during the task, and which part of their previous knowledge is used to construct new meanings. In particular, it helps to
make explicit the selected founder notions. The grid has not always been actually used as the very first step in the various sequences that we have elaborated, but it was always a rationalization of a first attempt, mainly grounded on the necessity to take into account both the knowledge to be taught and the students’ knowledge. Using the grid in a rationalization process makes new pieces of knowledge to appear, which can be tested in class. This feedback process is part of refinement leading to a stabilization of the sequence, which is discussed later.

Moreover, designing a complete teaching sequence is a collective work in which both researchers and teachers provide important competences. The use of a common tool, such as the grid, by the different participants proved to be useful for discussions, to evaluate and to improve the common production in the design process.

**Use of ‘the grid’ to analyse a teaching sequence**

Most of the time, the teachers borrow parts of their teaching contents from specific sources such as textbooks. It is therefore useful to provide teachers with few criteria to understand the main choices in the design of the teaching sequence they intend to work with. The ‘grid’ may be a relevant tool as it provides two key criteria:

- Is the task more theory/model oriented or experimental field oriented?
- What is supposed to be known by students, from their previous instruction and from the influence of everyday life, and what is supposed to be learnt?

The grid may help teachers to take into account their students’ approaches not only in a discussion introducing a new subject, but all along teaching.

To illustrate these theoretical considerations, we shall give some details about two teaching sequences, one in the field of physics (case of optics) and the other in the field of chemistry (case of conductimetry). Although both use the grid as structuring tool, these two examples highlight different aspects of our technique. In the first, knowledge analysis and the use of initial conceptions of students are stressed; in the second, the refinement of the sequence from the analysis of students’ activities in class on the bases of knowledge analysis in relation with devolution and founder notions is emphasized.

**An example in physics: the case of optics, grade 11**

This part deals with the construction of a teaching sequence about elementary optics in grade 11 (expected duration 15 hours, among which three practical sessions of two hours each). The main lines of the official curriculum are presented in table 2.

**Macro-level: comparison of two points of view**

Our analysis of both the knowledge to be taught and the difficulties encountered by students when studying image formation in geometrical optics draws upon three key points:

- An object can be modelled as a juxtaposition of object points.
- An image point is the point where all the emerging rays through an optical system (coming from a single object point) pass and gather.
The image of an object is the juxtaposition of all the image points corresponding to every point of the object.

It is obvious that this view is an analytic one: both the object and the image are split into points, and the correspondence is made by the theory of optics between a point of the object and a point of the image; Galili (1996) calls this point of view ‘point-to-point light flux mapping conceptualization’ (see, for example, table 3 on p. 851).

It is well known, on the contrary, that students spontaneously use another theoretical framework, which Galili (1996: 850) qualifies as ‘holistic conceptualization’, involving in particular the ‘travelling image conception’ (Viennot 2001: 24–29); in this conceptualization, the object and the image are considered entire, and the correspondence between them is made by the emission of a global image by

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### Table 2. Content and expected competences of the official curriculum in optics, grade 11.

<table>
<thead>
<tr>
<th>Content</th>
<th>Expected competences</th>
</tr>
</thead>
</table>
| **Conditions for the visibility of an object**  
Role of the eye in the direct vision of objects. Light propagation: light ray model; object point  
Converging and diverging lenses; criteria for sorting | Knowing that:  
- an object can be seen only if it is lightened or if it emits light by itself  
- an object can be seen only if light coming from this object gets into the eye |
| **Images through optical systems**  
Images given by a plane mirror: observation and localization of the image of an object given by a plane mirror; image point of an object point; laws of reflection  
Images through a converging lens: observation and localization of images given by a converging lens. Geometrical modelling of a thin converging lens; optical centre, focus, focal length. Analytical modelling: formulas for location and magnification of thin converging lenses. Magnifying glass | Knowing that when an image is seen through an optical system, the light coming from the object gets into the eye after a non-rectilinear path and that the brain interprets it as coming in a straight path  
*Localizing experimentally an image*  
Determining graphically the position and the size (sic) of the image of an object point in the case of a plane mirror  
By schematizing a converging thin lens and indicating the positions of its focus and of the optical centre  
Determining graphically the position of the image of an object point through a converging lens  
Using the formulas of the converging thin lenses. Using the magnification  
*Being able to realize an experiment allowing measuring the focal length of a converging lens*  
*Being able to predict the sense of the movement of an image when the object is moved*  
Understanding the roles of the constituents of an optical system using only converging lenses and plane mirrors |
| **An example of an optical instrument**  
Experimental modelling of a simple optical instrument: astronomical telescope, refracting telescope, binoculars, slide projector or overhead projector | *Experimental competences are in italics.*
the global object, carried by the light coming from the object, and passing through the various optical systems with some transformations. The consequence of such a conception is that the image can appear at any place after the optical system: it is not localized. This discussion had previously been incorporated in the construction of a teaching sequence in optics, grade 12 (Buty 2000, 2001, 2003).

All these considerations can be summarized using the ‘grid’ in the following way (table 3).

We can notice that in table 3 some boxes are empty: a global view of the teaching content does not necessitate specifying the material references that could have taken place in the last row.

It also appears that the official curriculum for optics in grade 11 is based on a very small amount of students’ previous knowledge; even the elementary notions about light emission and propagation are studied again.

As any change in curriculum in France, the new curriculum in geometrical optics for the 11th grade has been designed by a group of experts, including a few science educators. Although the hypothetical foundation of the official curriculum is not clearly identified, our previous content analysis leads us to infer that the general line is to base the sequence on everyday knowledge as if it could directly help to construct physics knowledge. The main choice of the official curriculum is to show that the image is localized: consequently, the teaching order is first the image through a mirror, then through a magnifying glass, and at last the real image through a converging lens. Such an order is appropriate when the sequence design is guided by the objective of using everyday life examples and showing that the image is localized.

From our point of view, the main objective being to promote a conceptual understanding of the image and its localization, we consider it necessary to

<table>
<thead>
<tr>
<th>Theory/model</th>
<th>Relation between theory/model and objects/events</th>
<th>Objects/events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Already known in optics (taking into consideration the curriculum of previous classes)</td>
<td>Already known from everyday life</td>
<td>To be constructed (physics)</td>
</tr>
<tr>
<td>Light propagation</td>
<td>Modelling of light by rays</td>
<td></td>
</tr>
<tr>
<td>Travelling image conception</td>
<td>Global object and global image</td>
<td></td>
</tr>
<tr>
<td>An image point is the point where all the emerging rays pass The image of the object is the set of the images of points</td>
<td>An object can be seen as a juxtaposition of object points</td>
<td></td>
</tr>
</tbody>
</table>
introduce point-to-point mapping. Consequently, it is better to begin by studying a real image through a converging lens, because it is easier to show the link between the decomposition of an object into elementary points and the image localization, in the case of a real image that you can make appear on a screen. Then a magnifying glass introduces the idea of a virtual image; that is, the extension of the model and reasoning used for a converging lens to another case. At last the image through a mirror, virtual as in the case of a magnifying glass, allows understanding that this model applies to another optical system.

Consequently, the sequence that has been constructed is divided into 14 ‘tasks’ that are summarized in table 4.

Our analysis emphasizes the idea that the macro-level design of a teaching sequence depends both on the aspect of the physics concept you want to point out, and on the expected difficulties for students.

**Micro-level: using the ‘grid’ as a tool for designing a task of the sequence**

A central point of the teaching sequence we have elaborated in optics deals with the image formation through a converging lens. It is related to tasks 4 and 5 (see earlier) of the sequence; for this set of two tasks, the corresponding grid is presented in table 5.
We can notice that one of the elements appearing in this grid can be used as a founder notion to construct a relevant view of optical images: the idea that an image looks like the object. On the contrary of the travelling image conception, this similarity can co-exist with a scientific view; it even must be explained by an element of the model; namely, that each point of the image corresponds to one single point of the object (an idea that is also in the earlier grid). On this basis, it is possible to develop activities allowing the construction of the image concept, as shown later.

Obviously, the constitution of such a grid is a direct consequence of our hypotheses about modelling processes and the importance of conceptions in physics learning. In fact, what previous work in science education has constructed as conceptions is used as everyday theoretical elements in the third column, second row. We have also to notice that the ‘starting point’, already established physics knowledge (second column), depends on the rank in the teaching sequence of the studied task; it looks like the items of a curriculum. The last column is the objective to reach.

What help does such a grid provide to the construction of teaching activities? One example can be the idea that ‘the image looks like the object because a unique image point corresponds to each point of the object’, which has guided the design of task 5. In this task, a mask with a small hole is placed between the object and the lens, and the image is projected onto a white screen. The students are asked to foresee what would happen if the screen is placed in such a position where a hole produce a small light spot (i.e. when the screen is not on the image of the hole), and
An example in chemistry: the case of conductimetry, grade 11

In France, chemistry teaching in grade 11 aims to introduce ionic solutions, conductimetry, acid–base chemistry, oxido-reduction chemistry then titration. Here we shall first consider the macro-level of the whole sequence, then we shall look into an example at the micro-level of the case of a part of the introduction of conductimetry.

Macro-level

The curriculum. The sequence supposed to last 14 weeks was based on an official curriculum, the headers of which are:

- A: Physical variables (in chemistry)
  - Mass, volume, pressure
  - Concentration: case of ionic solutions
  - Application to the measure of the progress of reactions
- B: How to determine the amount of substance in solution from a physical measurement
  - Conductance of an ionic solution
  - Conductivity of an ionic solution
  - Ionic molar conductivity $\lambda_i$ and the relation $\sigma = \sum \lambda_i [X_i]$
- C: How to determine the amount of substance in solution from a chemical reaction
  - Acid–base reactions
  - Oxido-reduction reactions
  - Titrations

According to this part of the curriculum, as far as part B is concerned, the scientific content and the goals to be reached by the students are reported in table 6.

Global analysis with the grid. The first use of the grid (table 7) is a global analysis of the knowledge from which the curriculum was divided into seven parts on several bases. One of these bases considers that, in a given part, there must be enough knowledge for the students to establish pertinent relations. Another one considers that there must not be too much knowledge to keep the whole part inside the students’ zone of proximal development. For example, B1 was treated alone as a
part, whereas our grid shows that the knowledge at stake in B2 and B3 was closely related and thus they were treated together in one part. In B2 and B3 there are two ways the students must learn to determine the conductivity $\sigma$:

- in B2, conductivities can be determined from experiment ($G, S$ and $L$ are measured from the experimental field);
- in B3, conductivities can be determined from theory (the molar ionic conductivity $\lambda_i$ is not observable).

In designing the sequence, we decided that having experimental and theoretical approaches to a central variable, the conductivity ($\sigma$) would fit our main hypothesis on modelling (see earlier).

**Sequentialization.** The grid helped to sequentialize the knowledge into smaller parts that could fit into the didactic time (seven two-hour laboratory sessions; and 14 hours of courses in normal class, out of the laboratory). We did not group B1 + B2 + B3 as, in this case, it would certainly leave the molar ionic conductivity $\lambda_i$ outside of the proximal zone of development if it were to be introduced simultaneously with the variable conductance $G$.

As a case in point, in B1, the words of the curriculum were analysed and shared out between the different levels of our grid (table 7).
Role of the teacher. We consider that it is a macro-level question to decide the context in which a piece of knowledge will be worked out. In the institution where the knowledge was to be taught, there are two main such contexts: laboratory work, with students working in pairs with a rather large autonomy (such a context respects our socio-constructivist hypothesis); and class work, where the teacher talks and the students listen (such a context is more appropriate for the institutionalization process, for debriefing, for exercise practice).

In B1, all the concepts to be constructed were pursued in laboratory work, but in B2 the ‘limit of the calibration curve’ and the ‘interpretations of conductance measurements of several solutions of the same concentration have a common ion’ (see table 6) were not considered for laboratory work, but reserved for the debriefing of the laboratory work. The main reason for these choices stems from the social role of the teacher. Debating on the limit of the calibration curves that were established during the laboratory work is an opportunity to review what the students should have discovered in the laboratory and to add new information on the limits of the method.
**Micro-level**

Going from macro-analysis to micro-analysis is not clear cut. Both analyses influence each other, and working at the micro-level often requires changes in the macro-analysis. On top of that, we are going to see how important the grid is in the process of refinement of the sequence.

*From macro-analysis to micro-analysis.* Reading in the curriculum ‘Knowing that ions are necessary for a solution to be conducting’ (table 6) was analysed as two different pieces of knowledge (table 7): one in the world of theory and model (‘Electric current $I$ in an ionic solution can be interpreted as the motion of ions’), and one in the world of objects (‘Measurements of electrical parameters of an ionic solution’). Therefore, in the task, two different activities should be worked out by students, one in the experimental field (measurement) and one in the world theory and model (interpretation). This example illustrates how the constraint of splitting the knowledge into the grid provides hints on the construction of the task.

*From the grid to the task.* We first designed a short task to have students reactivate a piece of knowledge that appeared in the grid in the column *already known* (*taking into consideration the curriculum*). Students had not worked for two years on the fact that electrical current can be interpreted as the motion of electrons in (metallic) electric circuits. This short task was worked out the week before the main following task. The decision to reactivate such a piece of knowledge means that the description of intensity by a motion of electrons is considered a founder notion.

Then, the design of a task from this grid required setting up an experiment that would give students food for thought. The choice of the experiment was constrained by the fact that we had to use equipment that could let students measure the conductance variable from different solutions, and for a given solution to be able to change the distance between electrodes and their areas. Then, we decided that the measurements would be the starting point of a reflection on the motion of ions in solution. In our task, students had to develop their own microscopic representations of the electrical conduction of ionic solutions.

The text of the task is presented in appendix 2. The design of such an activity resulted from the grid (table 6).

- ‘Electric current $I$ in an ionic solution can be interpreted as the motion of ions’ was involved in question (c).
- ‘Conductance as a variable of the length between electrodes’, the concentration of the solution and the area of the electrodes appeared in question (d).
- ‘Measurements of electrical parameters of an ionic solution’ were considered in the experimental section before question (a).

In this text, the experimental set-up was derived from the goals of the curriculum as well as our grid. In the remainder of the task, such a set-up allowed one to change the distance between the copper plates, their areas and the concentration of the solution.

Question (b), which may appear ‘a bit too easy’, was suggested by our hypothesis to provide an opportunity for the students to have different semiotic registers in play when addressing the question. The relation $G = I / U_{AB}$ could only
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lead to calculus. But asking to order the solutions with increasing conductance should be a way to reformulate this relation into natural language.

The key question is question (c), during which students working in pairs had to construct their own model of the behaviour of ions in solution (socio-constructivist hypothesis; importance of modelling activity). The students were supposed to develop an interpretation of the difference of conductance between NaCl and AlCl₃ solutions, with same concentration, based on two parameters:

- The fact that NaCl solution contains Na⁺ whereas AlCl₃ solution contains Al³⁺. The cationic species of both solutions have different charges (students’ construction of a meaning out of a representation – here the charge of ions in a symbolic semiotic register – in relation to a given situation).
- The fact that the quantity of chloride anion was not the same in both solutions (three times more in AlCl₃ solutions than in NaCl solutions).

Such an interpretation requires the construction of a relation between the values of conductance (got from the world of objects) and the different nature of ionic solutions. In this question, students had to make explicit their conceptions on the motion of ions in solution for the teacher to be able to propose a correct interpretation during the debriefing session.

From the task back to the grid. An analysis of students’ behaviour in question (b) showed that the expected semiotic reformulation of the relation \( G = I / U_{AB} \) took place. For example, in ranking solution by increasing conductance, students rapidly rank them by increasing intensity: ‘moreover it’s like for amp/it is logical as we divide by the same value’. Moreover, students realized that as \( U_{AB} \) was a constant parameter, ordering with intensity (the direct observable) was the same as ordering with conductance (the deduced observable).

Nevertheless, we observed three difficulties.

1. In their written productions, most of the students involved the motion of electrons in solution (instead of the motion of ions) to explain the electrical conductance of the solution. We found that students used information either from their electrokinetic’s course ‘the more electrons circulate the more the current goes’ or from their point of view of the description of ionic solids ‘ions are still/electrons move’. The knowledge that the designer wanted the students to be involved in by themselves – motion of ion – is not present; such a typical lack of devolution indicates that the task has to be improved.

2. We observed that students had trouble understanding the concept of ‘portion of solution between the electrodes’. The designers decided that the teacher should not say that conductimetry determines the conductance of the solution (but the conductance of the portion of solution between the electrodes) as the value of conductance that students measured for different positions and different sizes of the electrode. We therefore had to overcome this difficulty.

3. Only few students proposed reasonable interpretations of the electrical current into ionic solutions.

For the first difficulty, it was decided that the relation between current and the motion of electrons was not an appropriate founder notion. Thus, we decided to no
longer reactivate this knowledge. The result of this change was that during question (c) students did not involve electrons anymore. They considered ions and they used more correctly the concept of portion of solution between the electrodes. The concept of ion was a better founder notion than the one of electron.

For the second difficulty, we told the teacher to, during discussion of question (c), ask the students to debate what exactly they consider the portion of solution in question to be. Such a short debate seemed to be enough for students to assimilate the meaning of ‘portion of solution between the electrodes’.

The analysis of the final difficulty has led us to work out a new version of the task. We found out that data the students had to work with were not sufficient for them to propose a pertinent model for the construction of ionic conduction. We found out that more data (in the world of objects) with which they could establish relations (in the world of theory and model) were necessary. Therefore, two more solutions (numbers 7 and 8) were proposed to the students: a copper sulphate solution of the same molar concentration than the sodium chloride solution, and a more diluted one. The choice of these solutions is justified later. Question (c) was replaced by the following:

c) Knowing that cations are attracted by the electrode connected to the (−) pole and that anions are attracted by the electrode connected to the (+) pole, propose an hypothesis that allows an interpretation, at the microscopic level, of the influence of the concentration on the intensity measured with each concentration of sulphate copper solutions.

d) Measurements with solutions 5, 6, 7 and 8 show that the nature of ions influences the conductance of the part of the solution between the electrodes. How difference in conductance between the cases of solution 5 and 6 be interpreted?

Former question (d) became question (e)

A major difference with what happened for the preceding version of the task occurred in the behaviour of students. The new question (c) provided a theory/model information ‘interaction ions/electrode’ and the students were forced to involve a microscopic-level reasoning. Moreover, key data on the influence of the concentration were provided with the copper sulphate solution.

Although subtle, the copper solutions 7 and 8 are both blue in colour and the difference between them is readily evident (while all other solutions are colourless and look the same). The introduction of the solutions 7 and 8 provided the students with an essential advantage for the construction of the model they had to build: an effect of an essential variable of the model (concentration) was observable in the world of objects. In addition, the influence of the charge could be discussed through the comparison of Na⁺ + Cl⁻ and Cu²⁺ + SO₄²⁻ solutions of the same concentration.

Discussion

The previous developments show that designing a teaching sequence is a multi-parameter enterprise. It is grounded upon a large variety of intricate hypotheses, from different orders, and therefore the validation can be carried out from different perspectives, mainly from the educational system and from the didactical hypotheses in relation with the hypotheses on knowledge and learning. We just mention the variety of possible validations before discussing the tool.
Variety of possible validations of a teaching sequence

From the didactical hypotheses, four aspects of validation can be done in response of the following questions. (1) Do students actually carry out the prescribed tasks? This kind of validation consists of a comparison between students’ actual activities during the session, and what was intended in the design (Tiberghien 1996). (2) Do students construct an appropriate understanding of scientific concepts involved in the sequence? These two aspects correspond to internal validation whereas the following is external. (3) Do students pass the external examinations (such as the baccalauréat in France or the entrance university examination, etc.)?

The validation of a teaching sequence from the educational system leads us to three questions: (1) Does the teacher consider that he/she can teach the sequence in a real class? (Is it feasible?), (2) Can teachers who did not participate to the elaboration of the sequence, teach this sequence? (Is it extensible?), and (3) Can a given teacher teach the same sequence for several years consecutively? (Is it reproducible?).

Advantages and limits of the tool (the grid)

The main tool we have presented in this paper (the grid) is a way of taking into account some aspects of these hypotheses; it aims to ground the design and the analysis of a teaching sequence on theoretical bases. Creating and analysing a teaching sequence are not necessarily separate processes: when a team of teachers and researchers creates a sequence, after a first moment of creation, improving the sequence always implies a critical analysis of the first state of the text; in both steps of creation and analysis, the grid may be used. Moreover, of course, it is possible to analyse a sequence that has been constructed by someone else, in a textbook for example.

In its current state of development, the grid brings some advantages and yet suffers some limits; moreover, it is rather difficult to explain it to teachers.

What are its uses or advantages? Three of them are salient:

- It indicates the distance between what may be considered as known, be it from previous teaching or from everyday-life construction of meanings, and what is to be learned. By specifying this ‘learning demand’ (Leach and Scott 2002) at every knowledge level, it helps to decide what kind of action can be carried out in order to answer this demand.
- The process of filling the grid and trying to fill the empty boxes therein stimulates the generation of ideas for tasks. What has been forgotten? Do such activities emphasize a theoretical or an experimental approach? Such a questioning is particularly necessary for the relations between the word of theory and models and the world of objects and events. This is a crucial point, because making explicit the links between the two worlds is one of the most important and difficult points in the design of a teaching sequence.
- It can provide hints for ordering of a sequence or a task in a sequence, to organize the articulation between elements belonging to the two worlds. The grid mainly focuses on what specific knowledge is to be constructed. Nevertheless, even if it is rather beyond its power, using the grid to analyse the knowledge to be taught gives hints about how the construction of knowledge can...
be facilitated. In particular, we claim that explicitly organizing the knowledge to be taught in what refers to the world of objects and what refers to the world of theory is a way to help students to understand physics and chemistry.

What are the limits of this tool? Besides its difficulty, which is discussed next, to be used by teachers, we can point out three problems:

- It is difficult to define exactly which pieces of previous knowledge should be included in the grid. For example, in table 5, writing ‘splitting up of an object into points’ seems necessary for introducing an activity on the real image through a converging lens; but why not also mentioning the element of the model that sets that ‘from every light point independent beams are emitted’? It is often difficult to enumerate all pieces of knowledge really involved in a given activity. They are often too numerous, and trying to write all them down could only lead to a complicated, therefore useless, grid.

- The presentation order of the various pieces of knowledge does not appear in the grid. A global sense of evolution is of course indicated by the differences between the columns ‘previous knowledge’ and ‘to be constructed’. It is always necessary to specify and to decide whether you start from already known theoretical elements or experimental ones, in order to construct elements in the world of theory or in the world of objects and events. The research work about conceptions can help to decide what must be introduced first, although it did not appear in the grid. The order is sometimes up to professional habits from a knowledge point of view or from a practical organization of the class.

- While both the macro-level and the micro-level of sequence construction can be helped by grid construction, the articulation of the two levels is not taken into consideration in an explicit way. The grid is limited to their descriptions, and the designer of the sequence has to make do with that.

Difficulties in explaining the use of the grid to teachers. For us, a crucial issue is the possibility for science teachers to appropriate the theoretical framework, which leads to the use of the grid. Teachers being the necessary intermediary between science and students, any ‘well-designed’ teaching sequence may be betrayed by the way it is taught. We cannot expect that teachers teach a given content in line with the epistemological, learning and didactical hypotheses we developed, if they do not understand and adopt them at a certain extent.

It is certain that many teaching profiles can be found among teachers, based upon various epistemological views and learning hypotheses, even if they are rather unconscious. Therefore it is quite hazardous to give general explanations of an established fact that, most of the time, untrained teachers have great difficulties to use the grid as a tool.

Nevertheless, a major factor of difficulty seems to be that teachers are generally accustomed to make a different knowledge analysis than the one grounding the grid. The necessity to establish a clear distinction between two worlds, in order to make explicit the links between them, is not so strong for physics and chemistry teachers. We can suggest two reasons: first they are already trained to the modelling aspects in physics and chemistry and the links between the experimental facts and the physics model are obvious for them; and second, the ready-made experimental kits,
which are used in school teaching, already take address or even render visible the links between the two worlds, in their very physical construction.

Furthermore, in order to play the various roles discussed earlier, the teacher must try to understand and adopt the student’s point of view; many teachers are not prepared to do so. Despite these limits and difficulties, and despite the necessity to improve the tool we have begun to construct and to use, we are convinced that it constitutes a noticeable aide for science teachers on the path towards a better understanding by students of the nature of science and towards a greater interest in science learning.

References


Appendix 1: extract of the ‘text of the model’

1. Light propagates from a light source to a receptor through a transparent medium. It conveys energy from the source to the receptor.

2. The word ‘medium’ indicates the matter that is passed through by light. When its optical properties are the same everywhere, we say that the medium is homogenous. When its properties are the same whatever the direction of the light may be, we say that the medium is isotropic.

3. In the conditions of geometrical optics, light is modelled by light rays.

4. In an homogenous and isotropic medium, a light ray has:
   a. A straight and unique direction (‘principle of the rectilinear propagation of light’)
   b. No width
   c. A given wave length or a given range of wave lengths, linked to the colour sensation
      It is represented by a line, a half-line or a segment.

5. A light flux is modelled by a light beam, continuous set of rays [. . .]

6. The human eye is an important receptor [. . .] Our brain is trained to interpret light sensations according to the principle of the rectilinear propagation of light.
Note: This text is given to students at the very beginning of the sequence. As you can see, it gathers:

1. some elements of knowledge that students are likely to have already learnt;
2. some new definitions (‘homogenous’, ‘isotropic’);
3. some elements of explicit modelling.

Students are expected to use this text of the model in an autonomous way, during the tasks, in order to find in it the elements of knowledge which are necessary to perform the task.

The text is added during the sequence, when necessary, by the conclusions drawn from the task students have just performed. For example, just after the task 1 (see table 4), students are given the following items:

7. An object is seen when a light flux goes from this object to our eye.
8. An extended object is modelled as a juxtaposition of points-objects. Each point-object is the source of a light beam.

Appendix 2: text of the activity introduction to conductance
(translated from Martineux 2002)

Experimental set-up

The plates will be plunged into each following solutions of the same concentration:

1. Distilled water
2. Tap water
3. Distilled water with sugar
4. Distilled water with alcohol
5. Distilled water with aluminium chloride
6. Distilled water with sodium chloride

For a given solution, set the tension $U_{AB}$ between the plates to 0.5 V and measure the intensity of electric current inside the solution. After each measurement, rinse the plates with distilled water. Report the results rounded off to the closest 0.1 mA into the following table. (Here we give typical values that students would find).
a) Among the above solution, which contains ions? Explain from the measurements.

Definition: We call conductance of the portion of solution between electrodes, the inverse of its resistance. Conductance is noted $G$. Its unit is siemens, symbolised as $S$.

$$G = \frac{I}{U_{AB}}.$$

b) Rank the solution with increasing conductance.

c) For the solution with $G \neq 0$, propose an interpretation to the fact that portions of solutions of the same size and the same concentration in solute have different conductance values.

d) For a given solution, for example the sodium chloride solution, which modification of experimental parameters would you propose to modify its conductance value?