

OBSTACLES MODELLING REALITY: TWO EXPLORATORY STUDIES ON PHYSICS DEFINED AND UNDEFINED PROBLEMS

**María Elena Truyol,
Vicente Sanjosé,
Zulma Gangoso**

Introduction

For some researchers, and perhaps for many teachers, problem-solving is strongly related to thinking (Mayer, 1983). Several reports highlight the importance of developing suitable skills to solve complex, ill-defined and boundless real-life problems in educated people (NSF Standards, U.S. Department of Labour, ABET engineering accreditation organization, and American Institute of Physics, mentioned in Etkina & Van Heuvelen, 2007; Bureau of Labour Statistics, U.S. Department of Labour, 2014; Competency Model Clearinghouse, 2012).

Problem-solving is virtually the core of the professional activity of a physicist (Etkina, Van Heuvelen, White-Brahmia, Brookes, Gentile, Murthy, Rosengrant & Warren, 2006; Sensevy, Tiberghien, Santini, Laubé & Griggs, 2008). According to its importance, problem-solving is a central activity in physics courses at university to teach and to assess learning (Van Heuvelen, 1991; Nersessian, 1995). Therefore, instructional problem-solving has to be connected to the fundamental Science (Physics) educational goals. One of these Science main goals is to generate explanations about why the natural world is as it is. For that purpose Science generates, evaluates, contrasts and applies models. Modelling the real world to describe, explain and predict events in an accurate way is one of the main skills a physicist has to possess (Murthy & Etkina, 2004; Etkina et al, 2006; Sensevy et al, 2008).

As these skills are not innate abilities in subjects and they are not part of people's standard knowledge (as shown by the vast literature on children's ideas about nature), they would not be developed if they were not involved in instructional tasks. A previous study (Truyol, 2006) showed that these particular skills were not properly developed in many university physics students. However, there is empirical evidence on the possibility of contributing to the



JOURNAL
OF • BALTIC
SCIENCE
EDUCATION

ISSN 1648-3898

Abstract. *One important skill to be developed in future physicists is modelling reality using physics. Problem-solving is the activity most used to teach, learn and assess physics skills at the university level. However, most of the problems habitually used in physics subjects seem not to encourage developing this skill. Two empirical exploratory studies were conducted. Educational materials were analysed to contrast the hypothesis asserting that most of the academic problems would not help students to develop the modelling skills. Secondly, with the proposed 'Physics Problem Understanding Model', two kinds of experimental problems were elaborated. A small group of experts solved the experimental problems in an interview. The hypothesis stated that there would be evident differences between skills associated with the solving procedures of each type of experimental problem. Results served to contrast the cognitive model proposed for sufficiency and supported the hypotheses even though further studies are needed to obtain external validity.*

Key words: *cognitive model, modelling skills, problem solving, problem statements, university level.*

María Elena Truyol

*Institute of Physics Enrique Gaviola,
CONICET, Argentina*

Vicente Sanjosé

University of Valencia, Spain

Zulma Gangoso

*Institute of Physics Enrique Gaviola,
CONICET, Argentina*



development of these important physics skills through specific instructional strategies (Sensevy et al, 2008; Fortus, 2009; Truyol & Gangoso, 2010; Bilal & Erol, 2012) based on solving a particular kind of instructional problems.

Aims and Goals

This research aims at building knowledge of teaching strategies for the development of physics skills, in particular, modelling. The first step to be done is an empirical-based diagnosis on the actual development of those skills at university. Problem-solving is focused as a central teaching and learning activity to study whether or not the instructional problems usually used in university Physics grades contribute to the development of the professional skills physicists are supposed to possess. Two specific goals are proposed:

1. To analyse wide-ranging collections of instructional Physics problems at the university and to classify them according to the Physics skills necessary to solve them.
2. To design and empirically contrast experimental instructional problems able to give evidence for differences in Physics skills required to solve them.

Knowing the cognitive obstacles students find in solving different problems, more effective instructional materials and methods could be designed to better achieve science education goals. In this work the 'Physics Problem Understanding model' (Truyol & Gangoso, 2010; Truyol, Gangoso & Sanjosé, 2012; Truyol, 2012) is used to describe solving procedures and to relate them to specific Physics skills.

A Cognitive Model to Analyze Understanding Processes in Physics Problem-Solving

As to other authors, problem-solving is conceived as a 'building mental representations' process (Kintsch & Greeno, 1985; Nathan, Kintsch & Young, 1992). For Physics problem-solving, Greeno (1989) proposed a four-domain model relating concrete to abstract representations of reality, as well as common language to formalized language to express meaning. However, and due to its simplicity, in this work we will assume the Truyol and Gangoso's (2010) 'Physics Problem Understanding model' (PPU model), proposed to analyse problem-solving mental processes and to relate them to Physics skills. These authors postulate that solvers have to elaborate three mental representations in order to correctly understand and solve Physics problems. Table 1 shows these mental representations and their main characteristics.

Table 1. Main characteristics of the Physics Problem Understanding model.

	Situation Model	Conceptual Physics Model	Formalized Physics Model
Components	Objects and their attributes. Events and their spatial and temporal characteristics.	Models of objects, events and features.	Abstract symbols or formal expressions that represent objects, events, their characteristics and relationships.
Guided by	Everyday principles on how the world works.	Physical principles and laws. Conditions of application or validity.	Mathematical formalism. Mathematical conditions for applicability and validity.
Ontological categories	Non abstract, perceptible elements of everyday life.	Abstract, theoretical representations of objects, events with their attributes and characteristics.	
External representation format	Concrete representations (scale models, etc.). Drawings, diagrams, charts. Symbols. Words.	Diagrams, charts, graphs (specific). Symbols. Scientific words. (i.e. conceptual maps)	Symbols. Equations.
Language	Natural	Technical	Mathematical
Utility	Describing, analysing, predicting on a qualitative level.	Describing, analysing and predicting in terms of orders of magnitude. Analysis of extreme, prohibited, or impossible situations.	Computations. Analysing expressions in terms of the formalism.

Expert's problem-solving implies the ability of building these three mental representations (or some of them) and also the ability of coherently connect each one to the others. Several skills are involved in these construction-and-linking processes. Table 2 shows these skills and some excerpts from case analyses as examples.



Table 2. Skills involved in the Physics Problem Understanding model. Examples in italics are excerpts taken from experts' problem-solving.

Skills involved in PPU	Description and examples
Developing the Situation model	A deep understanding of what is happening in the ordinary world is a necessary condition to properly use Physics to describe, explain or predict events. 'A 150 kg driver is not the same as a 60 kg driver' 'I'm thinking how it is organized ... in a house ... the electrical network'
Building the Conceptual Physics from the Situation model.	The 'modelling reality' skill is important in characterizing a Physicist. In this phase, solvers have to reject (or hold in abeyance) irrelevant parts of the reality, as well as simplify other parts of it. It involves deciding on particular Physics models for objects and events, and/or for some relevant characteristics of objects and events. Events become science phenomena. Event characteristics and object attributes are associated with magnitudes. 'In this collision...we do not know the mass of the drivers' '...but the iron must have an internal resistance'
Developing the Conceptual Physics model.	Mental operations connecting modelled objects and events to coherently represent reality as a whole using Physics concepts, laws and principles, and perhaps running the model in the solver's mind to check it before going ahead. 'If there is no friction I can use ... uh ... the conservation of momentum' 'Since the resistors are in series, well, I put them like this (drawing a graph)'
Building the Formalized Physics model from the Conceptual Physics model.	Using mathematical or/and formal logic expressions for Physics laws and principles to relate numerical magnitudes and describe Physics phenomena. 'The movement is one-dimensional so I'm not going to worry about vectors' '...then to represent the iron in this circuit I'm going to call it "I" of the iron...'
Developing the Formalized Physics model.	Formalized algebraic, arithmetic or geometric rules are used in reasoning to obtain unknown quantities or unknown magnitudes. 'The mass 1 multiplied by the speed 1, vector, plus the mass 2 multiplied by the speed 2, vector, is equal to the mass 1 multiplied by the speed 1, final, plus the mass 2 multiplied by the speed 2, final (writing the expression)' 'And that "I" of the iron is equal to "V" divided by "R" of the iron (writing the expression)'
Physics Interpretation.	The backward transition from the Formalized Physics model to the Conceptual Physics model involves making sense of the numerical data according to Physics. 'So this is negative, so this should be moving to the other side' 'For this to be right (the problem requirement), I will need twice the value of the resistance that I originally had (analysing the value obtained from a calculation)'
Instantiation.	It is the transition from the Conceptual Physics model to the Situation model then coming back to the ordinary world. '...but since we talk about cars ... eh ... actually... common sense indicates that (collision) can not be elastic' 'The mass m1 should be ... uh ... smaller than ... the mass m2 ... just because one knows the cars ... on a large scale'

However, academic problems frequently do not request building all, but only some of these mental models to the solver. They do not offer adequate opportunities to develop modeling skills (Meng-Fei, Jang-Long, Ying-Chi, Hsiao-Wen, Tsung-Yu, & Deng-Min, 2014)

Defined and Undefined Problems in Physics

Some time ago, Gil-Perez & Martínez-Torregrosa (1983) and other colleagues (Gil-Pérez, Martínez-Torregrosa, Ramirez, Dumas-Carrè, Gofard & Pessoa de Carvalho, 1992) claimed that most of the academic problems in Physics were not authentic problems but application exercises. From a contemporary epistemic basis, these authors claimed that the solving procedures for these 'closed problems' would be far from the scientific methodology and thus, they would be inappropriate or insufficient for suitable Physics learning.

To provide a cognitive basis and a descriptive model associating scientific skills to different problem-characteristics, a step further is certainly needed. First, the types of problems considered in this research have to be accurately defined. The definition given by Gerace, Dufresne and Leonard (1997) for 'instructional physics problems' seems



appropriate to clearly differentiate the problems considered here from application exercises. Those 'instructional problems' are problems in academic contexts with a statement introducing plausible stories involving objects and events suitable to be modeled with science, designed by experts and having at least one solution (Gangoso, Coleni, Buteler & Gattoni, 2004).

Even though several taxonomies for academic problems have been suggested, as well/ill-defined problems (Leonard, Dufresne, & Mestre, 1996; Ringenberg & VanLehn, 2008, Fortus, 2005, 2009) or closed/open-ended problems (Escudero & Moreira, 1999; Reid & Yang, 2002), we will propose a classification for 'instructional physics problems' based on whether some of the mental representations considered in the PPU model (see Table 1) are facilitated or impeded in the statement of the problem (Truyol & Gangoso, 2010; Tuyol, Gangoso & Sanjosé, 2012). In fact, most instructional problems provide the objects and events involved as already modelled Physics entities, so facilitating the solver's elaboration of the 'Conceptual Physics model' representation. We will focus on the mental representation 'Conceptual Physics model' and its connections to other representations, such as the 'Situation model' and the 'Formalized Physics model', to classify instructional Physics problems as 'defined' or 'undefined' problems. In 'undefined problems' common and well-known objects and events are involved in a coherent real-world problematic situation (the story) and belong to concrete ontological categories. The Physics topic or the Physics model to solve the problem is not explicit or suggested, neither are the variables necessary and sufficient to solve the problem. Numerical data are not provided, so the answer to the problem has a conceptual format instead of numerical format. Otherwise the problem will be a 'defined problem'. In these defined problems some or all the entities involved in the story belong to abstract ontological categories. The topic and/or the Physics model to solve the problem are explicit, or partially explicit. In most defined problems only the set of the necessary and sufficient variables to solve the problem is given together with their numerical values and units. The problem unknown(s) is usually a particular value of one of the implied variables and its value is to be obtained through formal reasoning and calculations. Thus, some defined problems are closed problems as well.

Table 3 shows three versions of the same problematic situation, starting from the (full-) defined ending to the undefined one.

Table 3. Three versions for the same problematic situation in the defined-undefined continuum.

Version	Problem statement
Defined	A point mass $m = 0,5$ kg is moving vertically upward starting from a height $h_1 = 1,5$ m above the ground. If the movement is done under the only effect of gravity, find the minimum initial speed needed for the mass will reach a height $h_2 = 4,0$ m.
Traditional or frequent form	A construction worker placed on the street throws a brick to his workmate placed on a house roof. The initial height of the brick is $h_1 = 1,5$ m and the final one is $h_2 = 4,0$ m. What is the speed necessary for the brick will reach the second man's hands if the only effect on motion is due to gravity?
Undefined	A construction worker throws a brick from the street to his workmate placed on a house roof. Determine the conditions necessary for the brick to reach the second man's hands.

On this theoretical background different hypotheses from the above mentioned goals 1 and 2 are formulated.

Hypotheses

Hypothesis 1.1. In university Physics, most of the instructional problems are 'defined problems', i.e. problems whose statements provide the Physics model for the objects or for the object-attributes implied, and/or the Physics model for the events or the event-characteristics implied in the problematic situation.

According to the PPU model, these problems only need elaboration of the Formalized Physics model from the explicit Conceptual Physics model and computing mathematical calculations in order to solve them. Thus, most of the academic problems would not help university students to develop one important Physics skill: elaborating the Conceptual Physics model to solve real-life problems (modelling reality).



Hypothesis 2.1. Solving 'undefined problems' will involve Physics skills different from the ones implied in solving 'defined problems'. 'Defined problems' will probably only need the elaboration of the formalized Physics model, whereas solving 'undefined problems' involve other skills such as elaborating the conceptual Physics model from reality and, inversely, connecting the Physics model back to reality.

The 'Physics Problems Understanding model' is used to describe and relate the solving procedures for 'instructional problems' to Physics skills. On this way, the PPU model could be validated using experimental data. The solvers' actions and comments can be classify and then judge the model adequacy to account for solvers' mental processes in academic Physics problem solving.

Hypothesis 2.2. The proposed PPU model manifests sufficiency to account for solving procedures and give evidence on differences in Physics skills required to solve defined or undefined problems, and on other procedural indicators.

Two studies were conducted to achieve the goals. In Study 1 instructional materials were analysed to contrast hypothesis 1.1, related to goal 1. In Study 2, a small group of experts solved experimental defined and undefined problems in a think-aloud way, in order to contrast hypotheses 2.1 and 2.2 related to goal 2.

Study 1

Research Methodology

Sample

A random selection of 114-problem sample was done among 280 suggested or fully solved Physics problems included in authorised guides for physics courses at a large South-American university. The problems included in these guides were very similar to the problems included in any well-known international university textbooks. The problems belonged to the following subjects: 'General Physics I' (mechanics), in the 1st year, 'General Physics III' (basic electricity and magnetism), in the 2nd year, and 'Electromagnetism' (advanced electromagnetic field theory and applications), in the third year. The sample represented approximately 40% of the complete universe of academic problems used in each course, and was distributed as is shown in Table 3.

Table 3. Distribution of problems in the sample according to their subject. Frequency and percentages.

Subjects	Total sample	"Non-instructional" problems		"Instructional" problems	
	Freq	Freq	Percent	Freq	Percent
General Physics I	43	5	11.63	38	88.37
General Physics III	37	5	13.51	32	86.49
Electromagnetism I	34	9	26.47	25	73.53
TOTAL	114	19	16.67	95	83.33

Data Analysis

Hypothesis 1.1 was contrasted analysing specific problem statement characteristics. Only 95 of the 114 problems in the sample were 'instructional physics problems' according to the definition given. The rest were application exercises or formal developments to be performed by the student and were not considered in further analyses.

For every remaining problem in the sample the amount and percentage of objects, events, object-attributes and event-characteristics present in the problem stories were considered. According to the defined-undefined classification, whether the suitable Physics model was explicitly provided for these entities in the statements (modelled entities), or not (non-modelled entities), was accounted for. The amount of mentioned object attributes (i.e. mass, size, colour, density, velocity, roughness, etc.) was computed independently of the amount of objects (point mass,



sphere, train, surface, etc.): if an object (or a Physics model) was mentioned as a whole, it was computed in the category 'object', but if only certain attributes or characteristics were explicit, then the amount was considered in the category 'object-attributes'. The same was done for events and event-characteristics. The percentage of occurrence for each entity was computed independently. For instance, the percentage of modelled objects was computed in every problem dividing the total amount of modelled objects by the total amount of objects (modelled and non-modelled) mentioned in each problem statement, and the percentage of modelled object-attributes was obtained from the total amount of modelled object-attributes divided by the total amount of object-attributes mentioned in each statement. The same procedure was followed for modelled events and event-characteristics. When these percentages were obtained for each problem in the sample, mean values and standard deviations were taken to contrast hypothesis 1.1.

Possible differences among Physics subjects were analysed in order contrast hypothesis 1.1 independently of this factor so increasing validity. ANOVA was used to look for statistical differences when normality was present. When normality was not achieved, non-parametric statistics was used: the Kruskal-Wallis test for paired groups and the Mann-Whitney test for independent groups.

Results of Study 1

As explained before, percentages of occurrence were computed for modelled objects and events, and modelled object-attributes and event-characteristics in each of the problems in the sample. Table 4 shows the mean values and standard deviations for the percentages obtained for the four indicators in the three considered subjects.

Table 4. Mean values and standard deviations for the percentages of occurrence of the selected indicators in the sample.

Category	General Physics I N= 38		General Physics III N= 32		Electro-magnetism I N= 25		Total N=95	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Objects-modelled	18.2	30.0	47.6	43.1	53.0	44.9	37.5	41.7
Events-modelled	20.1	27.7	72.9	36.8	65.6	40.3	50.4	42.1
Object-attributes modelled	85.9	24.7	76.7	22.9	91.1	13.6	84.1	22.2
Event-characteristics modelled	73.8	30.0	96.4	18.9	97.9	10.2	87.8	25.1
Total Modelled Entities	52.6	20.1	74.5	19.5	82.2	13.7	67.7	22.3

Only one problem in the sample did not include any modelled entity in their statement. Moreover, 89 problems out of 95 in the sample included modelled objects or object-attributes and in addition included modelled events or event-characteristics in their statements.

Although objects and events appeared frequently together in the statements (Pearson's $r = 0.55$; $p < 0.001$), this did not happen to modelled object-attributes and modelled event-characteristics ($r = -0.106$, $p = 0.308$).

As the considered variables were not distributed according to Gaussian curves (K-S; $p > 0.10$ in all cases), possible differences among subjects were analysed using non-parametric tests. There were significant differences in the percentages of modelled entities due to the 'Subject' factor in all the categories, as shown in Table 5.



Table 5. Kruskal-Wallis test for problems comparison. Dependent variable: mean percentage of occurrence. Grouping factor: subject.

Category	Chi Square (df=2)	Sig.
Objects-modelled	12.144	0.002
Events-modelled	30.861	<0.001
Object-attributes-modelled	6.752	0.034
Event-characteristics-modelled	26.638	<0.001
Total Modelled Entities	31.486	<0.001

Different Mann-Whitney tests showed significant differences between General Physics I (mechanics) and the other two subjects, associated to basic ($U < 378.5$; $p < 0.003$) or advanced electromagnetism ($U < 278.0$; $p < 0.003$) except for the category 'object-attributes-modelled' (respectively: $U = 450.5$; $p = 0.06$; $U = 444.5$; $p = 0.755$). However, General Physics III (basic electricity and magnetism) and Electromagnetism (advanced) were not significantly different in each of the considered categories for modelled entities ($U > 334.5$; $p > 0.47$), except for 'object-attributes-modelled' ($U = 258.0$; $p = 0.012$).

The global percentage of modelled entities (objects + events + object-attributes + event-characteristics) showed a distribution non-significantly different from a normal curve (K-S, $p = 0.511$). This percentage was significantly different in the three topics with a great effect size and good statistical power ($F(2,92) = 22.649$; $p < 0.001$; $\eta^2 = 0.33$; $P = 1.0$): it was greater in the specialised 3rd course Electromagnetism, and lesser in the basic 1st course Mechanics, as can be seen in Table 4. *Post-hoc* paired comparisons showed a clear subject effect, as electricity (2nd course) was not significantly different from electromagnetism (Scheffé: $p = 0.30$), but both were significantly different from mechanics ($p < 0.001$ in both cases).

Discussion

In the 'instructional physics problems' sample there was a clear predominance of modelled entities, attributes and characteristics, necessary and sufficient to solve each Physics problem. Eighty-nine problems out of 95 included modelled objects or object-attributes and also included modelled events or event-characteristics in their statements. This fact suggests that most of the problems analysed demanded the solver use the given 'Conceptual Physic model' to elaborate the 'Formalized Physic model', perform some calculations or reasoning, and come back to the 'Conceptual Physic model'. In addition, modelled object-attributes and modelled event-characteristics did not appear frequently together in the statements, suggesting that the problem statements are designed to focus the solver attention on particular Physics aspects related to objects or to events (but not both). In addition, we did not find activities devoted to using Physics to model reality, in the three topics considered. The scarce ordinary-world stories found in some statements were not crucial to solve the problem, but a scenario to make the problem credible.

It was obtained a clear 'subject effect' as General Physics III (basic Electricity and Magnetism, in the 2nd year) and Electromagnetism (specialised aspects, in the 3rd year) did not differ in the global percentage of modelled entities, but both subjects significantly differed from the percentage in General Physics I (basic Mechanics, in the 1st year). As basic Electricity did not differ from advanced Electromagnetism, the subject effect seems not to be associated to the knowledge level.

In summary, most of the academic Physics problems proposed and solved at the university can hardly help students develop the 'modelling-reality' skill (associated with the elaboration of a suitable conceptual Physics mental representation). Thus, it seems important to design and validate academic problems fostering students' ability to connect reality to Physics principles, laws and concepts, as well as using logic and mathematics to formalize Physics, as most academic problems do. Study 2 is aimed at finding a way to design and validate different instructional problems able to help students develop different important Physics-modelling skills.



Study 2

Research Methodology

Participants

Twelve expert Physicists were the solvers in this exploratory study. They were selected among other possible candidates by three referees. The referees were both physics professors at university and researchers in physics education with a broad experience in both fields. They had high social and professional knowledge about colleagues and students and a deep knowledge about the objectives and the requirements for the study. Referees were asked to select solvers having equivalent expertise and physics knowledge, but also good metacognitive skills to explain their thoughts while solving Physics problems. The implicit assumption was that this subject's behaviour has little variability, so few of them are needed to obtain relevant data.

Materials

Eight experimental problems were designed for this study. Two different Physics subjects were selected (classical Mechanics and basic Electricity). For each topic, two 'defined problems' and two 'undefined problems' were designed. From traditional and very frequent defined statements, were elaborated the new 'defined' and 'undefined' problems. In this exploratory study it was decided to use the extreme end points in the defined-undefined continuum, trying to maximize the possible differences in solving procedures. There were obtained four 'couples' of problems. In every couple it was tried to keep the problem variables constant, except those implied in the defined-undefined differences. 'Undefined' (UP) and 'defined' problems (DP) in a couple required the same Conceptual Physics model to be correctly solved.

According to hypothesis 2.1 it was expected that the solving process of DP would foster the elaboration of the 'Formalized Physics model' from the 'Conceptual Physics model' that is facilitated from the information included in the statement. However, solving UP would need the elaboration of the 'Conceptual Physics model' from the 'Situation model' that can be constructed from the statement, and also the inverse transformation, the 'Instantiation', and perhaps also the elaboration of the 'Formalized Physics model' and the 'Physics Interpretation' (see Table 2).

Every expert solved two problems of the same topic, one 'defined' and one 'undefined', but not of the same couple (to avoid solving the same problematic situation twice). This within-subjects design for the factor 'defined/undefined' diminishes the error variance and differences in solving procedures can be better associated to problems features and not to solver individual factors.

Procedure

The solving sessions were individually recorded in audio and video format. Solvers were asked to elaborate the solution in an accurate way while explaining aloud every thought and step done. They had paper sheets to write down any information they needed or they wanted to provide. A video-camera was placed on a second table aside, so the experts' writings on the paper would be clearly visible and recorded, but not their faces.

Solvers were left at their own pace, without time limitations. The interviewer (one of the researchers, M.E.T.) participated only when some written or oral expressions needed to be clarified or confirmed, so that data reliability was increased. Solvers' writing, actions and related thoughts were analysed with the PPU descriptive model.

Measurements

Previous studies have identified indicators related to the construction and use of the different representations involved in the instructional problem-solving process (Truyol, 2006). From these indicators for written problem-solving it is possible to recognize actions that might be associated with modeling skills. Solving procedures were transcribed and analysed according to the PPU model and those indicators constructed. The skills involved in the problem-solving process were inspected and coded as the examples shown in Table 2. They were accounted for: a) amount and type of actions, oral locations or written information given by the solver; b) time taken doing each action. For a more complete description of the coding phase please see Tuyol (2012).



Results of Study 2

Due to the small number of solvers we used the Wilcoxon-rank non-parametric test to compare 'defined' to 'undefined' problem-solving. Analyses were aimed merely to unveil whether or not differences between 'defined' and 'undefined' problems in some Physics skills, go in the desired way. The PPU model was used to describe the solving actions and to relate them to Physics skills, according to Tables 1 and 2.

Solving actions

Figure 1 shows the number of every considered solving action in the PPU model. The total amount of solving actions in the DP-type problems ($M_{dp} = 134.2$; $SD = 52.0$) was lower than in the UP-type problems ($M_{up} = 179.3$; $SD = 134.1$), but not significantly lower ($|Z| < 1$). The time the solvers' read the statements was not significantly different in both types of problems ($|Z| < 1$). The same resulted for non-solving actions, as pauses, interviewer's comments and non-defined actions ($|Z| < 1$ in all cases).

DP gave the conceptual Physics model explicit in their statements. Therefore, solvers did not have the necessity of elaborating the problematic situation in the ordinary world (building the 'Situation Model', SM) or elaborating the Physics model from the SM ('Physics Modelling', CPhE). The opposite action, coming back to the real world from Physics, was less necessary as well. Obviously, there were significant differences in each of these actions ($Z = -2.936$; $p = 0.003$; $Z = -3.063$; $p = 0.002$; $Z = -3.062$; $p = 0.002$, respectively). If the DP and UP were well designed, these would be the expected results, according to the hypothesis 2.1.

Once the 'Conceptual Physics model' has been elaborated in UP or understood in DP, the solving actions working inside the conceptual Physics model were not significantly different between UP and DP ($|Z| < 1$). Actions associated to elaborating the mathematical 'Formalized Physics model' from the 'Conceptual Physics model' ($Z = -1.297$; $p = 0.195$), developing and reasoning inside the 'Formalized Physics model' ($|Z| < 1$) and the opposite action, the 'Physical interpretation' from the numerical results ($Z < -1.060$; $p = 0.289$) for DP and UP were very similar as well.

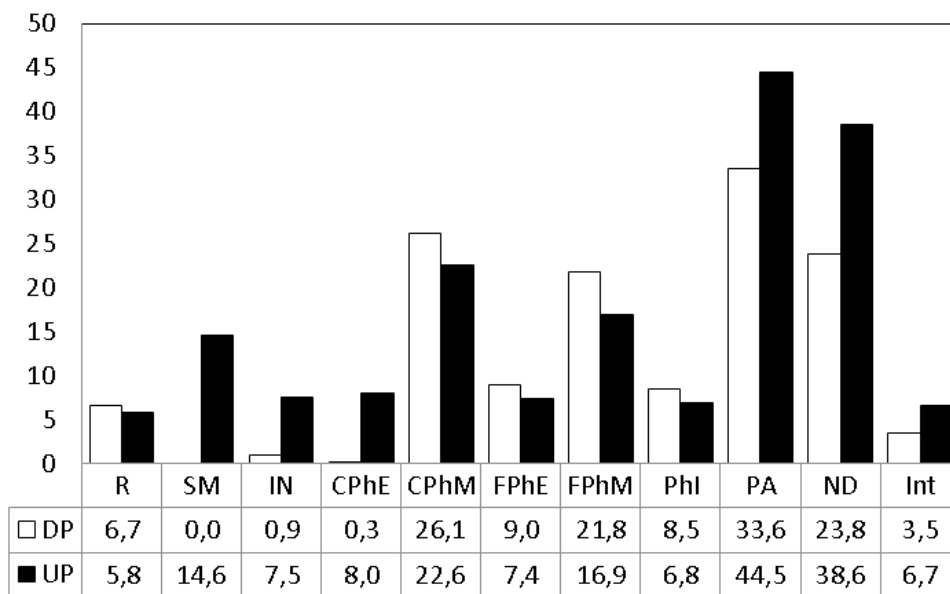


Figure 1: Mean amount of solving actions for defined and undefined problems.

R: reading; SM: situation model elaboration; IN: instantiation; CPhE: conceptual Physics model elaboration from SM; CPhM: developing and working inside the conceptual Physics model; FPhE: formalized Physics model elaboration from conceptual Physics model; FPhM: developing and working inside the formalized Physics model; PA: Pauses; ND: non-defined actions; Int: Interviewer interventions.



When it is referred to solving actions in Figure 1, it really means observed solvers' actions during the solving sessions, because recordings included not only solving actions properly but other non-solving actions and comments (labelled as 'non-defined actions, ND' in Figure 1). This category grouped two types of solvers' actions and comments: a) unfinished comments, cut-off by the solver probably due to self-regulatory activity to find a better way to explain his/her ideas; b) actions and comments about the instructions or the materials given to them except for the problems themselves, that do not correspond to solving activity. The unfinished comments did not have any cognitive or Physics content because the solver aborted the process before making explicit the meaning he/she had in mind. As all the solvers arrived to reasonable solutions to the proposed problems, and all of them explained their mental activity in a suitable way, we have to acknowledge that the hidden content in these incomplete and unclassified actions was given later in other actions and comments accounted for and classified in our PPU model. This type of self-regulatory actions and comments represented about a half of the total 'ND' actions in DP and also in UP.

Solving Time

Although the solving time can strongly depend on individual differences among solvers, the within-subject design let us compare DP-type and UP-type problems.

Solving times followed the same trend as the solving actions. The (mean) total solving time was higher for UP-type than for DP-type problems. Although the difference was not significant ($Z = -1.020$; $p = 0.31$), solvers spent more time solving UP (778 sec; $SD = 486$ sec) than PD (570 sec; $SD = 281$ sec). Solvers' dispersion in solving time for UP was twice that the dispersion for DP, showing personal differences in both, solving procedures and the way of verbalizing their actions and thoughts.

Thus, the only significant differences in solving times were obtained for the mental elaboration of the problematic situation in the ordinary world (building the 'Situation Model', SM), the construction of the Physics model from the SM ('Physics Modelling'), and its opposite action ('Instantiation') ($Z = -3.059$; $p = 0.002$, in each of the three actions). These actions together took in average a 22.2 percent of the total solving time for the undefined problems, UP. As stated before, these are the expected results according to the hypothesis 2.1.

The remaining solving times were not significantly different for DP or UP.

Discussion

Results obtained in this study show that the mean value for the amount of certain solving actions, and the mean time needed to perform some of the experts' solving actions, were higher in the 'undefined problems' (UP) than in the 'defined problems' (DP). These solving actions were: mental elaboration of the 'Situation model' from the problem statement, building the 'Conceptual Physics model' (from raw reality to Physics), and connecting the 'Conceptual Physics model' to the 'Situation model' (from Physics back to reality). These three solving actions together with the UP-DP difference in solvers' silent thinking time ('PA', pause category in Figure 1 and 2), and the UP-DP difference in the interviewer's interventions addressed to make explicit (part of) these silent thoughts ('Int' category), accounted for a total percentage of solving time in UP problems of about 26%.

However, for the remaining solving actions involving working inside the Conceptual or the Formalized Physics models and their connections, there were not significant UP-DP differences. These results suggest that undefined versions were more demanding than defined versions of the same problematic situation, as other researchers suggested from epistemic and methodological bases (Gil-Perez & Martínez-Torregrosa, 1983; Garret, Satterly, Gil-Perez & Martínez-Torregrosa, 1990), but our results also suggest that the differences are concentrated on particular Physics skills, modelling reality with Physics and the opposite instantiation of Physics concepts in a real situation, which represent a step forward in the research and orientate researchers and educators to re-consider mental representations in problem-solving (Solaz-Portoles & Sanjose, 2007).

Along the solving sessions, some of the solvers' actions or expressions could not be classified according to the categories considered in the descriptive PPU model. However, these "non-defined actions" were non-solving actions or meaningless comments that solvers' cut-off in order to find a better way to explain their cognitive processes. As solvers' arrived at suitable answers to any problem, we expected the content for these cut-off comments to be included in other well-classified information segments.



Thus, data provide evidence the PPU model is sufficient to describe solving actions for 'defined' and also for 'undefined' Physics problems, and for associating them to specific Physics skills.

Conclusions

First, it was attempted to analyse the characteristics of the academic problems proposed and frequently used to develop Physics skills in university students. The stated hypothesis 1.1 was: in basic Physics, as well as in advanced Physics, most of the proposed academic problems provide the Physics model suitable for the problematic situation. This hypothesis was contrasted in Study 1 by means of a wide analysis of educational materials in three different Physics subjects and courses. Results clearly supported hypothesis 1.1: a high percentage of proposed and solved problems in the analysed subjects explicitly included the Physics model needed to solve the problem in their statement. Thus, most of these problems were 'defined problems'. Solving these defined problems students did not need to think about how to use Physics to give a solution to real world problems. Instead, they had to deal with already modelled Physics entities (not with real world entities) and use formal expressions (as mathematical equations for Physics laws) to solve the problems. The prediction, to be contrasted immediately, is that university students will have great difficulties in developing one of the most important skills for any Physicist: modelling reality with Physics.

The second objective was to design instructional problems that could be used to foster those Physics skills poorly accounted for in the usual instructional collections. The corresponding hypothesis 2.1 was formulated as follows: solving 'undefined' problems will generate solving procedures involving more Physics skills than do 'defined' problems. 'Defined problems' will probably need the elaboration of the 'Formalized Physics model' only, whereas solving 'undefined problems' will involve other skills as elaborating the 'Conceptual Physics model' or, inversely, the 'Physics interpretation'.

This hypothesis was contrasted in Study 2 using a small group of experts in a within-subjects design. Each expert solved one defined and one undefined problem in front of the interviewer. The entire solving procedures were video-recorded and analysed. Results clearly supported hypothesis 2.1. If the DP and UP problems are well designed, solvers have to spend a significant part of their solving time dealing with the situation model (the real world situation), elaborating the 'Conceptual Physics model' from reality, and, at the end, going back to reality from Physics. Although statistical validation is needed, this result suggests that the UP versions obtained from DP versions of Physics problems seems to be a good way to develop the aforementioned important Physics skill: modelling reality.

Finally, the PPU model was used to analyse these data and correlate the experimental problems characteristics and the Physics skills involved in their solving procedures. A kind of working and tentative hypothesis was formulated (Hypothesis 2.2) as follows: the descriptive PPU model will manifest 'sufficiency' to account for solving procedures and give evidence of differences in Physics skills required to solve 'defined' or 'undefined' problems, and on other procedural indicators. Data obtained did not refute this hypothesis because the solving actions were well accounted for by the model. The observed solvers' actions that could not be properly classified corresponded to non-solving actions and comments, or to meaningless comments. Related to the PPU model, the necessary step forward is to check if the Physics modelling skills have relation with the students' performance in problem-solving such as the traditional university grades. This would provide coherence to the theoretical proposal.

Acknowledgements

This work was supported by a CONICET PhD fellowship. We would like to thank Dr. Kyle Forinash of the School of Natural Sciences, Indiana University Southeast for his careful reading of the manuscript and for their suggestions.

References

- Bilal, E., & Erol, M. (2012). Effect of teaching via modelling on achievement and conceptual understanding concerning electricity. *Journal of Baltic Science Education*, 11 (3), 236-247.
- Bureau of Labor Statistics, U.S. Department of Labor (2014). *Occupational Outlook Handbook, 2014-15 Edition*. Retrieved August 5, 2014, from <http://www.bls.gov/ooh/home.htm>



- Competency Model Clearinghouse (2012). CareerOneStop U. S. Department of Labor, Employment and Training Administration. Summary Report for: 19-2012.00 – Physicists. Retrieved August 5, 2014: <http://www.onetonline.org/link/summary/19-2012.00>
- Escudero, C., & Moreira, M. A. (1999). La V epistemológica aplicada a algunos enfoques en resolución de problemas [The epistemological V applied to some approaches for problem solving]. *Enseñanza de las Ciencias*, 17 (1), 61-68.
- Etkina, E., & Van Heuvelen, A. (2007). Investigative Science Learning Environment – A Science Process Approach to Learning Physics. In *Research-Based Reform of University Physics* (1). Retrieved August 5, 2014, from <http://www.compadre.org/Repository/document/ServeFile.cfm?ID=4988&DocID=239>
- Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D., Gentile, M., Murthy, S., Rosengrant, D., & Warren, A. (2006). Scientific abilities and their assessment. *Physical Review Special Topics – Physics Education Research*, 2, 1-15.
- Fortus, D. (2005). Restructuring school Physics around Real-world Problems: a cognitive justification. Paper presented at The Annual meeting of the American Educational Research Association. Montreal, Canada. Retrieved August 5, 2014, from https://www.project2061.org/research/ccms/site.archive/documents/Restructuring_School_Physics.pdf
- Fortus, D. (2009). The importance of learning to make assumptions. *Science Education*, 93 (1), 86-108.
- Gangoso Z., Coleoni, E., Buteler, L., & Gattoni, A. (2004). El proceso de resolución de problemas en física [The physics problem-solving process]. *Actas II Jornadas de Investigación en Resolución de Problemas en Física*. Jesús María, Córdoba, Argentina.
- Garret, R. M., Satterly, D., Gil-Perez, D., & Martínez-Torregrosa, J. (1990). Turning exercises into problems: An experimental study with teachers in training. *International Journal of Science Education*, 12 (1), 1-12.
- Gerace, W., Dufresne, R., & Leonard, B. (1997). A framework for the storage of knowledge and its implication for problem solving. University of Massachusetts Physics Education Research Group. Technical Report PERG-1997. Massachusetts, United States.
- Gil-Pérez, D., & Martínez-Torregrosa, J. (1983). A model for problem-solving in accordance to scientific methodology. *European Journal of Science Education*, 5 (4), 447-455.
- Gil-Pérez, D., Martínez-Torregrosa, J., Ramirez, L., Dumas-Carré, A., Gofard, M., & Pessoa de Carvalho, A. M. (1992). La didáctica de la resolución de problemas en cuestión: elaboración de un modelo alternativo. *Didáctica de las Ciencias Experimentales y Sociales*, 6, 73-85.
- Greeno, J. G. (1989). Situation, mental models and generative knowledge. In Klar, D. Y Kotovsky, K. (Eds). *Complex Information Processing: The impact of Herbert A. Simon*. (pp. 285-318). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Kintsch, W., & Greeno, J. G. (1985). Understanding and solving word arithmetic problems. *Psychological Review*, 92 (1), 109-129.
- Leonard, W., Dufresne, R., Mestre, J. (1996). Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems. *American Journal of Physics*, 64 (12), 1495-1503.
- Mayer, R. E. (1992). *Thinking, problem solving, cognition (2nd Ed.)*. A series of books in psychology. New York: W H Freeman/Times Books/ Henry Holt & Co.
- Meng-Fei, C., Jang-Long, L., Ying-Chi, C., Hsiao-Wen, L., Tsung-Yu, W., & Deng-Min, L. (2014). Developing explanatory models of magnetic phenomena through model-based inquiry. *Journal of Baltic Science Education*, 13 (3), 351-360.
- Murthy, S., & Etkina, E. (2004). Development of scientific abilities in a large class. In Marx, J., Heron, P., Franklin, S. (Eds) *Physics Education Research Conference*, 790, 133-136. Retrieved August 5, 2014, from <http://www.compadre.org/Repository/document/ServeFile.cfm?ID=9551&DocID=2822>
- Nathan, M., Kintsch, W., & Young, E. (1992). A theory of Algebra-Word-Problem comprehension and its implication for the design or learning environments. *Cognition and Instruction*, 9 (4), 329-389.
- Nersessian, N. (1995). Should physicists preach what they practice? Constructive modeling in doing and learning Physics. *Science & Education*, 4 (3), 203-226.
- Reid, N. & Yang, M. (2002). The Solving of Problems in Chemistry: the more open-ended problems. *Research in Science & Technological Education*, 20 (1), 83-98.
- Reingenberg, M., VanLehn, K. (2008). Does solving ill-defined physics problems elicit more learning than conventional problem solving? In B. P. Woolf, E. Aimeur, R. Nkambou & S. Lajoie (Eds) *Doctoral Consortium, Intelligent Tutoring Systems: 9th International Conference*. Retrieved September 5, 2012 from http://www.pitt.edu/~vanlehn/Stringent/PDF/08ITSMR_KVL.pdf
- Sensevy, G., Tiberghien, A., Santini, J., Laubé, S., & Griggs, P. (2008). An epistemological approach to modeling: Cases studies and implications for science teaching. *Science Education*, 92 (3), 424-446.
- Solaz-Portoles, J. J., & Sanjosé, V. (2007). Representations in problem-solving in science: Directions for practice. *Asia-Pacific Forum on Science Learning and Teaching*, 8 (2), 1-17.
- Truyol, M. E. (2006). Resolución de Problemas en Física Básica: algunos factores explicativos de desempeño [Problem-solving in Basic Physics: Some explanatory factors of performance]. Trabajo Especial de Licenciatura en Física. FaMAF – UNC. T.E.F TRUr – Inventario nº 18198 – Biblioteca FaMAF.
- Truyol, M. E. (2012). Comprensión y Modelado en la Resolución de Problemas en Física. Un estudio en Nivel Superior [Comprehension and Modeling in Physics Problem Solving. A study in Higher Education]. Tesis Doctoral. Facultad de Matemática, Astronomía y Física. Universidad Nacional de Córdoba. Retrieved August 15, 2014, from http://www2.famaf.unc.edu.ar/publicaciones/documents/serie_d/DFis163.pdf



- Truyol, M. E., & Gangoso, Z. (2010). La selección de diferentes tipos de problemas de Física como herramienta para orientar procesos cognitivos [Selection of different types of physics problems as a tool to guide cognitive processes]. *Investigações em Ensino de Ciências*, 15 (3), 463-484.
- Truyol, M. E., Gangoso, Z., & Sanjosé López, V. (2012). Modeling in physics: A matter of experience? *Latin American Journal of Physics Education*, 6 (1), 260-265.
- Van Heuvelen, A. (1991). Learning to think like a physicist: A review of research-based instructional strategies. *American Journal of Physics*, 59 (10), 891-897.

Received: September 22, 2014

Accepted: November 30, 2014

María Elena Tuyol	PhD in Physics for the Faculty of Mathematics, Astronomy and Physics, National University of Córdoba, Argentina. Postdoc Fellowship at the Faculty of Education, University of São Paulo, Brazil. E-mail: mtruyol@famaf.unc.edu.ar
Vicente Sanjosé	PhD in Physics, Professor of Science Education at the University of Valencia, Spain. E-mail: vicente.sanjose@uv.es
Zulma Gangoso	PhD in Physics, Full Professor at the Faculty of Mathematics, Astronomy and Physics, National University of Córdoba & Researcher of the Institute of Physics Enrique Gaviola, CONICET, Córdoba, Argentina. E-mail: zulma@famaf.unc.edu.ar

