Rationale for and implementation of an empirical-mathematical modelling approach in upper secondary physics in Norway

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Abstract
We present a rationale and a framework for empirical-mathematical modelling in upper secondary physics, and report on a project focused on empirical-mathematical modelling in Norwegian physics classrooms. The project particularly aims to give students experience with the many forms of representations applied in models of physical reality.

Introduction

A contemporary education in science is expected to serve two broad purposes: To provide society with a *competent workforce* and with *scientifically literate citizens*. In this paper we focus on how *upper secondary school physics* may contribute to developing students' competencies and literacy in the field of physical science, and we suggest an approach – *empirical-mathematical modelling* – that we believe can meet some challenges facing physics education and thereby contribute to serving these two overall purposes. By empirical-mathematical modelling, we mean an approach where 1) students work with open-ended experiments and gather data which they use to construct mathematical models of the phenomena under study, and 2) teaching has a general emphasis on physics as a collection of "models of natural phenomena", and "doing physics" means working with models in a wide sense of the term.

Our choice to look into empirical-mathematical modelling was motivated by a previous research project (Angell, Guttersrud, Henriksen, & Isnes, 2004) and six more specific challenges facing physics education, all of them related to the two overall purposes of science education. Research on students' understanding and learning indicates that physics education needs to focus on:

1. the use of, and interchange between, *multiple representations* of physical phenomena
2. the *role and purpose of experiment* in physical science
3. the *relationship between mathematics and physics*
4. *the nature of science*
5. fruitful *learning strategies* for gaining understanding in physics
6. skills in *scientific reasoning*

These are by no means the only challenges facing a contemporary physics education; nor can we expect to meet all of them fully through a single approach. However, these are important challenges which have informed our work and which we believe that we can to some extent meet by a stronger focus on empirical-mathematical modelling in upper secondary school physics.

In this paper, we draw on science education research as well as experiences from a research and development project in Norwegian upper secondary school physics in view of the following purpose:

to examine the rationales for, and implementation of, an upper secondary physics education developed around the central concept of empirical-mathematical modelling

In the science education literature, there is a vast number of publications concerning "models" and "modelling", but the terms are used in a wide range of meanings. For instance, much research has focused on analogical models as a teaching tool (such as the water analogy for electric circuits). Another research strand is the use of computer modelling as a means of offering students a deeper understanding of complex phenomena (Sins, Savelbergh, & van Joolingen, 2005).

There is much less research focusing on the empirical and mathematical aspects of modelling. Some projects, however, have focused on mathematical modelling. For example, Oke and Jones (1982a; 1982b) provided two examples of mathematical modelling and argued that it should form an important part of undergraduate courses in science and technology. Indeed, one might argue, mathematical modelling of the physical world should be the central theme of physics instruction (Hestenes, 1987).

Empirical-mathematical modelling in Project PHYS 21

Overview of the PHYS 21 project

The research and development project termed "Physics education for the 21st century" (PHYS 21), emphasising empirical-mathematical modelling, was developed as a response to the six challenges listed above. 10 schools, almost 20 physics teachers and almost 300 students participated in the project, trying out new material and activities involving empirical-mathematical modelling along with a focus on scientific reasoning. The project started with development of material and teacher workshops (2003-2004) and went on to a "pilot year" (2004-2005) and a full implementation year (2005-2006). Workshops and meetings for participating teachers took place during the whole period. A student booklet and a teacher booklet introduced project participants to the view of physics applied in the project, aspects of scientific method and scientific reasoning, examples of scientific models and the modelling process, and suggestions for student modelling activities.

Researchers visited all project schools during modelling activities, made notes, took video clips or sound recordings, and interviewed some of the teachers (note: not all the mentioned methods were employed in every school). During the pilot year, focus group interviews were held with students. A written test was developed to test students' modelling skills, and a questionnaire was designed to investigate students' learning strategies, views on the nature of science, and experiences from the physics classroom. Results from the test and questionnaire are reported in Guttersrud (2006).

Conceptualizing empirical-mathematical modelling in physics

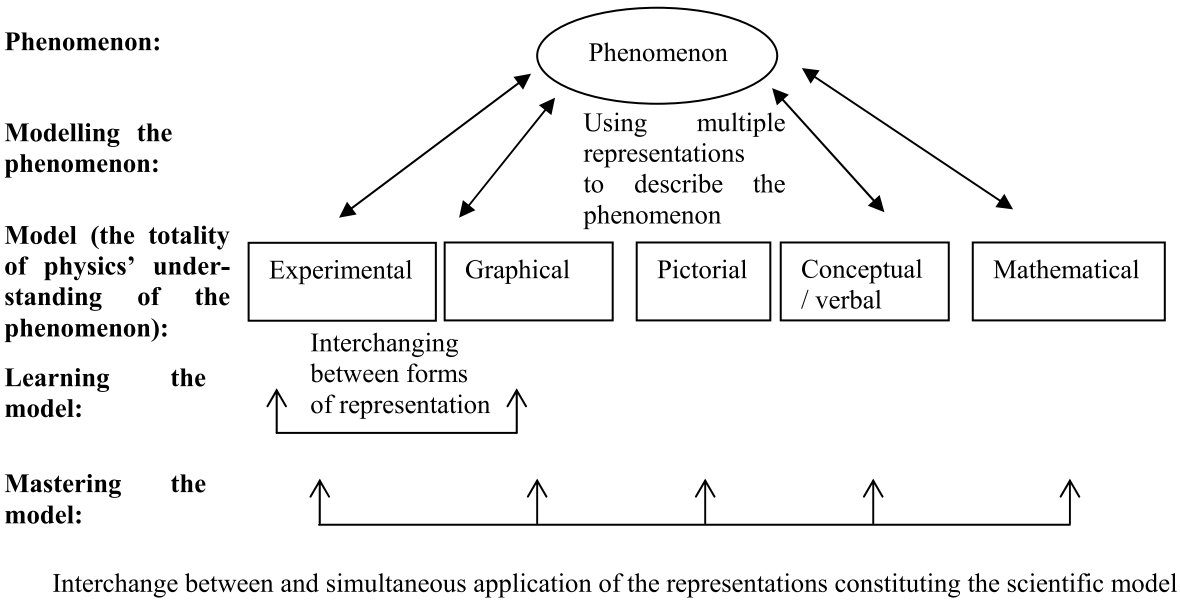
Our understanding of modelling in project PHYS21 is strongly influenced by Jens Dolin's (2002) characterization of physics in terms of multiple forms of representation (experiments, graphs, pictures and diagrams, verbal descriptions, formulas). Part of the challenge of learning physics is to get an overview of all these different representations simultaneously and to manage the transformation between them (Dolin, 2002). In the project PHYS21, efforts were made to make the transitions between the various forms of representation in physics explicit to students.

As a part of our thinking relating to this project, we have developed a conceptualization of physics as a set of models of natural phenomena, each model encompassing a range of different forms of representation (figure 1). This description of models in physics guided our research and development in the project.

As indicated in figure 1, the starting point for a scientific model is a phenomenon observed in nature. The phenomenon may in physics be represented in a number of different ways (represented by the boxes in the figure): experiments, graphs, pictures and diagrams, verbal/conceptual descriptions, and mathematical equations. As an example, consider the phenomenon "free fall". Dropping an object is a simple experimental representation of this phenomenon, and a sketch of a falling object is a pictorial representation. Defining change in velocity with time as acceleration takes conceptual representations into account. The formula $v = v_o + at$, which in this case reduces to $v = gt$, is one of the mathematical representations, and the velocity may be represented graphically as a function of time.

Learning to master the model involves both learning to simultaneously apply and interchange between the various representations, and to refine one's mastery of each representation, for instance by acquiring the appropriate physical concepts and terminology and the mathematical "tools" such as derivation and integration.

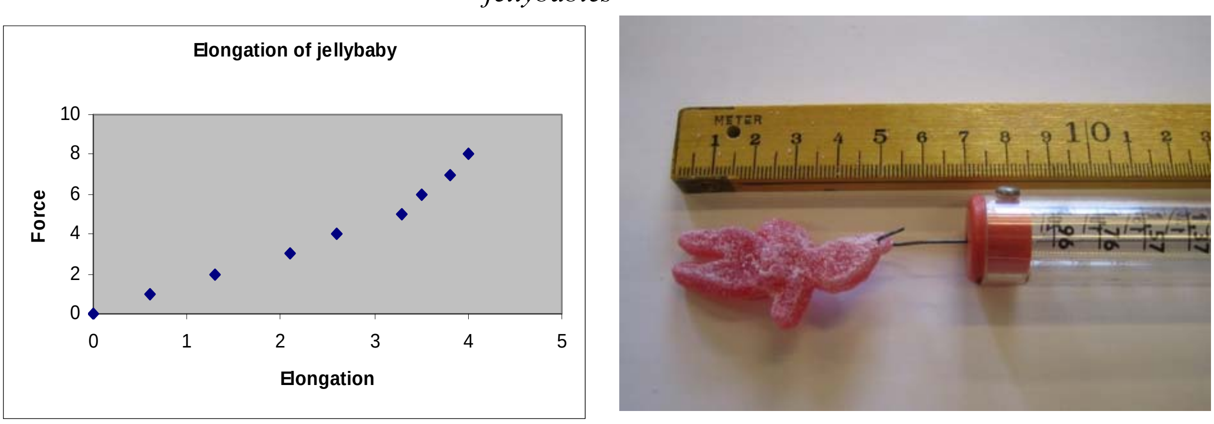
Figure 1: The processes of modelling and learning a model.



Modelling activities in PHYS21 classrooms

Essential to our project is giving students opportunities to develop mathematical models of concrete phenomena, preferably in contexts where they don't know the "correct answer" in advance. The elongation of jelly babies (elastic jelly sweets) is an example of a modelling task in the project (figure 2). Students are expected to draw graphs and construct and interpret mathematical expressions to describe the phenomenon.

Fig 2:Experimental and graphical representation of the force as a function of elongation of jellybabies



In most cases, students found a linear relationship, at least for one part of the measurements. The graph passes through the origin, and the linear part can be expressed as $f(x) = ax + b$ where $b = 0$ which results in $F = kx$ (Hooke's law). Furthermore, the students could realise that the linear model has a limited domain of validity. For large forces, the elastic properties of the jelly change, and the linear model does not fit anymore. Jelly babies with different colours give different slopes of the graph, which may be interpreted as different elastic properties depending of the colouring agent. Also, when a jelly baby is stretched to its maximum without breaking off, the slope will not be the same if a new elongation is carried out. This has to do with the elastic properties of the material, which changes when stretched close to the breaking point. This activity involves a lot of opportunities for challenging students' understanding and concepts in physics. Moreover, the core here is to manage the different forms of representations (experiment, graphs, physical concepts and mathematics) and be able to make a mathematical model within acceptable boundaries.

As can be seen from the example, students in the project were encouraged to use and interchange between multiple representations of physical phenomena; the relationship between mathematics and physics was made apparent for them, and there was a focus on scientific reasoning related to experimental results, particularly by proposing hypotheses and testing them out experimentally.

Some experiences from project PHYS21

- Despite mild, but clear directions from the project management, the teaching strategies used in different PHYS21 classrooms varied widely.
- Teachers appreciated the chance to give an in-depth treatment of fundamental concepts based on the empirical-mathematical modelling approach
- Questionnaire results indicate that teaching approaches were more experiment- and model-based in PHYS 21 classrooms than i regular classrooms, and that students had reflected on this fact
- Students are unaccustomed to aspects of empirical-mathematical modelling such as choosing the appropriate axes for plotting independent and dependent variables.
- An interesting observation was how students used the trend line and regression tool on their calculators. For example when measuring the elongation of jelly babies, several students found complex equations including a lot of factors and corresponding constants. However, none of these constants could be said to have any physical interpretation. It seemed that they just used the tool given on their calculators without thinking of what the result had to do with the actual experiment they where conducting.

Summary and conclusion

In this paper, we have argued that empirical-mathematical modelling should be given a more prominent role in physics education based on the overall purposes of science education and as a response to six more specific challenges facing physics education. There are also other examples of recent approaches which, to various degrees, incorporate (mathematical) modelling and use of ICT, emphasise understanding of basic concepts and the relationship between experiment, reasoning and theory, etc (Carlone, 2003; Feldman & Kropf, 1999; Hestenes, 1987, 1996; Teodoro, 2002; Wells, Hestenes, & Swackhamer, 1995)

Although we have identified some issues that need further development in order for our modelling approach to work optimally in the classroom, we do think, based on our experiences and the arguments for empirical-mathematical modelling presented throughout this paper, that there is reason to develop this strategy further. Among the many demands expected to be made on future citizens and professionals are adaptability, ICT skills, flexibility and creativity. We will argue that empirical-mathematical modelling is relevant to fostering such skills. Empirical-mathematical modelling at its best demonstrates how “doing physics” can be a highly creative activity, and may thereby possibly contribute to improved recruitment.

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