



Modellus: Interactive computational modelling to improve teaching of physics in the geosciences

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ABSTRACT

Many aspects of modern research and other professional activities in the geosciences require advanced knowledge about mathematical physics models and scientific computation methods and tools. In-depth meaningful learning of such knowledge skills is a difficult cognitive process which involves developing strong background knowledge of physics, mathematics and scientific computation appropriately contextualised in the geosciences themes. In this paper we describe an interactive engagement teaching approach that is based on Modellus, a freely available computer software system allowing (1) mathematical modelling ranging from explorative to expressive modelling, (2) the introduction of scientific computation without requiring the development of a working knowledge of programming and (3) the simultaneous manipulation and analysis of several different model representations, namely, tables, graphs and animations with interactive objects having properties defined in a visible and modifiable mathematical model. As examples of application, with insights for the development of other activities in a wide range of geosciences courses, we discuss a set of interactive computational modelling activities for introductory meteorology we have implemented in undergraduate university courses.

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1. Introduction

Physics and mathematics are fundamental subjects for the development of knowledge in geosciences and related industrial or technological fields. Their modern epistemologies, like those of geosciences, involve interactive modelling processes that balance different elements from theory, scientific computation and experimentation. However, the majority of current introductory physics and mathematics courses for the diverse areas of science do not always reflect this range of epistemological characteristics. For example, introductory physics courses at university level, even when equipped with modern technologies, usually involve expository theoretical lectures and recipe experimental laboratories and problem solving classes which brush through a very large number of topics. In general, these courses are considered too difficult and disappointing by many students and have low exam success rates. Also, for many students the acquired knowledge of physics and mathematics is fragmented and possesses numerous conceptual and reasoning weaknesses which persist after they

pass their examinations (Halloun and Hestenes, 1985a, 1985b; McDermott, 1991). Furthermore, student expectations about physics often deteriorate after completing these courses (Redish et al., 1998). Similar learning problems with fundamental earth sciences concepts have also been documented (see, e.g., Libarkin and Anderson, 2005; Libarkin et al., 2005).

Many research efforts have been able to show in a wide range of contexts that learning processes can be effectively enhanced when students are embedded in atmospheres with interactive engagement activities that approximately recreate the cognitive involvement of scientists in modelling research activities (see, e.g., Blum et al., 2007; Handelsman et al., 2005; Klosko et al., 2000; Kortz et al., 2008; McConnell et al., 2006; McDermott and Redish, 1999; Meltzer and Thornton, 2012). Contrary to traditional instruction approaches which end up reducing the learning processes to a rote accumulation of facts or rules, these research-based approaches have shown to be able to engage students in interactive and exploratory learning processes that are better suited to promote knowledge performance and to resolve cognitive conflicts with prior knowledge associated to common sense beliefs and incorrect scientific ideas.

In many areas of the geosciences, professional modelling activities are often based on knowledge about advanced mathematical physics models which are rich in computational elements.

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In-depth acquisition of such knowledge involves cognitive processes which require the progressive development of a strong background in physics, mathematics and computer programming. At an introductory level, for example in the first two year cycle of university education, when such background is still forming, it is thus of interest to design research based geosciences curricula which integrate sets of relatively simple computational modelling activities involving computer software environments. In this paper we show how to use the computational modelling software Modellus to accomplish this goal. The examples we describe have been developed in the context of teaching activities we have implemented in introductory meteorology courses for first cycle undergraduate university students. These examples are illustrative and insightful of functionalities and potentialities which can be used to develop other computational modelling activities to teach mathematical physics models in a wide range of topics in geosciences courses. The objective is to give students the opportunity to improve their knowledge of physics, mathematics and scientific computation and simultaneously focus on the learning of the relevant geosciences concepts and processes.

2. Teaching approach

An effective application of Modellus in a geosciences classroom requires a carefully designed teaching strategy. In our field activities the courses are divided into three complementary components: lectures where the theoretical foundations were first introduced, paper and pencil problem-solving lessons, and the computational modelling classes based on Modellus. The goal is to create an interactive engagement environment based on approaches already shown to be highly effective to teach introductory physics in other contexts (see in particular, e.g., Beichner et al., 2007; Crouch et al., 2007; Mazur, 1997; McDermott et al., 1996; McDermott and Shaffer, 2002; Neves et al., 2011).

To build this kind of environment students are organised in group teams of two or three. During each computational modelling class, the teams work on a set of activities, all of which are to be completed using only Modellus as computer modelling tool. These activities are designed to be interactive and exploratory learning experiences structured around specific topics and aim to set up an atmosphere for meaningful learning (see, e.g., Mintzes et al., 2005) where students approximately work as scientists do in modelling research activities. In class the student teams are motivated to analyse, discuss and solve the proposed activity problems on their own using the physical, mathematical and computational modelling guidelines provided by the class documentation and software resources. Note that these activities are appropriately articulated with the complementary theoretical and paper and pencil problem solving classes. In addition, the teams are not left working alone but continuously helped during the exploration of the activities to ensure adequate working rhythm with appropriate conceptual, analytical and computational understanding. Whenever necessary, global class discussions are conducted to keep the pace, to introduce new themes, to clarify any doubts on concepts, reasoning or calculations common to several teams and for students work presentations.

The supporting class documentation and software resources for the courses we have implemented included Modellus package examples and a set of activity PDF documents. For most of the class activities these PDF documents contained complete step-by-step instructions to build the Modellus mathematical models, animations, graphs and tables. However, some activities, including those for assessment, involved computational modelling problems with instructions having various challenging levels of incompleteness.

3. Getting started with Modellus

Modellus latest version is programmed in Java and is able to run in all operating systems. It is freely available and the installation instructions as well as the user manual can be found at the Modellus website.¹ The installation package includes many sample models and others are regularly added to the website which, in addition, contains several other supporting documents. In the rest of this section we briefly describe the most important elements of the graphical user interface and discuss the main steps to create a model with Modellus.

Upon starting the Modellus window interface (Fig. 1) displays at the top the Menu bar containing 9 ribbons labelled Home, Independent Variable, Model, Parameters, Initial Conditions, Graph, Table, Objects and Notes. The Mathematical Model, Graph, Table and Notes windows can be expanded, minimised or moved within the Workspace area. The Animation Control bar lies at the bottom and contains, for example, a green Play and Pause button, a red Reset button and blue buttons for Replay, One step back and One step forward. Fig. 1 also shows the Home definition panel which allows the user to change aspects of the global interface appearance, such as the interface language and the way numbers are displayed, or to introduce background grids or images in the Workspace. The model set up includes the following steps:

- (1) Write the mathematical expressions in the Mathematical Model window. This window works just like a calculator and allows the user to program functions, differential equations and numerical iterations with standard mathematical notation. Modellus has a set of pre-defined functions whose syntax is displayed upon clicking on the Help button of the Model panel (Fig. 2).
- (2) Define the independent variable along with its interval domain and running numerical step in the Independent Variable ribbon. Note that it is not possible to define simultaneously more than one independent variable.
- (3) Specify the parameters and initial conditions either directly in the Mathematical Model window or in the Parameters and Initial Conditions ribbons.
- (4) Choose the representation options (Graph, Table or Animation). We emphasise that these different representations can be displayed simultaneously alongside the mathematical model, a fundamental advantage of Modellus to help building a full understanding of the underlying principles of a model.
 - The Graph ribbon allows the user to define which variables are attributed to the graph horizontal and vertical axis, adjust the corresponding scales or select graph line properties like colour and thickness.
 - The Table ribbon allows up to 8 column variable entries and the introduction of table data bars.
 - The Animation representation is constructed with the set of animation objects available in the Objects ribbon. The object is first selected from the object's list (for example a Particle or Pen object) and then placed in the Animation area with a left mouse click. Whenever an animation object is created a new ribbon labelled Animate appears in the top Menu bar displaying the object definitions panel. The advantage of animation objects is that they are interactive. A simple example is to assign a mathematical model parameter to the Level Indicator and vary its value by sliding the Level Indicator bar.
- (5) Perform the computation of the mathematical model over the independent variable domain. This is done by clicking on the

¹ See the website page at <http://modellus.fct.unl.pt>.

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