Learning Introductory Physics with Computational Modelling and Interactive Environments

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For the modern physics research community there is no doubt that the development of physics knowledge and cognition involves modelling processes that balance different elements of theory, experimentation and scientific computation. However, the majority of the current introductory physics curricula and learning environments for science, technology, engineering and mathematics education do not always reflect this range of epistemological characteristics. Changing this situation requires introductory physics curricula and learning environments structured around pedagogical methodologies inspired in the modelling cycles of physics research, to help students create and explore balanced learning paths that go through the different cognitive stages associated with the modelling processes involved in the development of physics knowledge and cognition. In this paper we present an approach to this problem that is based on the development of interactive engagement learning activities built around exploratory and expressive computational modelling experiments implemented in the Modellus environment. We illustrate with activities implemented in the general physics and biophysics courses of the biomedical and informatics engineering majors at FCT/UNL. We report on student receptivity to our modelling approach and discuss its effect on the learning process.

Introduction

In the diverse and deeply interconnected areas of science, technology, engineering and mathematics (STEM), professional communities recognize that physics is fundamental for the progressive development of STEM knowledge and cognition. Moreover, for such communities it is also clear that the epistemology of physics, much like in other STEM areas, involves modelling processes that balance different elements of theory, scientific computation and experimentation.

However, most introductory physics curricula and learning environments for STEM education do not always reflect this range of epistemological characteristics. Traditional general university physics courses are an example. In general, these courses are considered too difficult and disappointing by many students and have low exam success rates. Also, students usually have a fragmented knowledge of physics and mathematics with numerous conceptual and reasoning weaknesses which persist even after they pass their examinations (Halloun & Hestenes, 1985a, 1985b; McDermott, 1991). Furthermore, student expectations about physics often deteriorate after completing these courses (Redish, Saul & Steinberg, 1998).

To change this situation introductory physics curricula and learning environments should be based on pedagogical methodologies inspired in the modelling processes of physics research. Meaningful learning (see, e.g., Mintzes, Wandersee & Novak, 2005) should then occur when students go through balanced interactive explorations of the different cognitive phases associated with the modelling cycles of physics research, starting from a qualitative contextualization phase, setting the stage for the definition, exploration, interpretation and validation of the relevant mathematical physics models, and ending with the communication of modelling results and the development of generalizations.

As shown by many research efforts (see, e.g., Blum, Galbraith, Henn & Niss, 2007; Handelsman et al., 2005; McDermott & Redish, 1999; Slooten, van den Berg & Ellermeijer, 2006), the learning processes in various STEM areas can effectively be enhanced when students are embedded in environments with activities that approximately recreate the cognitive involvement of scientists in modelling research activities. As opposed to traditional instruction, these approaches have shown to be able to engage students in interactive learning processes that are better suited to promote knowledge performance and resolve cognitive conflicts with common sense beliefs or incorrect scientific ideas.

Fundamental for the development of research based modelling approaches is an early balanced integration of activities with computational knowledge and technologies. However, professional languages like Fortran (Bork, 1967), Pascal (Redish & Wilson, 1993) or, more recently, Python (Chabay & Sherwood, 2008), or even educational languages like Logo (Papert, 1980) or Boxer (diSessa, 2000), require the development of a working knowledge of programming, a fact that also holds with professional scientific computation software like Mathematica or Matlab.

To reduce such cognitive load and focus the learning activities on the concepts of physics and mathematics, several computer modelling systems have been developed, for example, the DMS (Ogborn, 1985), Stella (Richmond, 2004), Coach (Heck, Kadzierska & Ellermeijer, 2009), EJS (Christian & Esquembre, 2007), Modellus (Neves, Silva &Teodoro, 2011; Neves & Teodoro, 2010; Teodoro & Neves, 2011) and Phet simulations (Wieman, Perkins & Adams, 2008).

In spite of these advances, a balanced integration of computational modelling knowledge and technologies in introductory physics courses remains an open problem, critically dependent on both curricular and technological innovations. In this work, we present an approach to improve such balanced integration that is based on the development of interactive engagement learning activities built around exploratory and expressive computational modelling experiments implemented in the Modellus environment.

Physics Knowledge, Cognition and Learning Processes

Let us start with a brief discussion of the fundamental theoretical aspects underlying our approach. As in other STEM areas, the development of physics knowledge and reasoning requires rigorous declarative and procedural specifications of abstract concepts and of the connections existing between them (Reif, 2008). A successful construction of models or theories involves operational familiarization, theoretical consistency requirements and a precise relation with the relevant referents, either in the universe of phenomena or in abstract mathematical worlds. Physics knowledge and reasoning are then related but distinctly different from the corresponding every day or common sense structures. An important cognitive barrier for the learning processes is thus the need to distinguish between different but closely related concepts. When students try to adjust their prior knowledge to the new physics contexts, unresolved cognitive conflicts arising from the superficial similarity between elements of everyday and physics knowledge and reasoning can create persistent learning difficulties.

It is important to note that physics knowledge and cognition structures evolve over time to resolve analogous cognitive barriers (see, e.g., Chalmers, 1999). Indeed, the establishment of new concepts, models or theories and the substitution of old ones is a difficult cognitive process that involves progressive familiarization and reification processes that lead to cognition states where the new structures are manipulated as concrete and objective realities. Similarly, familiarization and reification are key cognitive aspects to develop in the physics learning processes.

Modern physics modelling processes are strongly enhanced by the more powerful calculation, exploration, visualization and simulation capabilities associated with computational knowledge and technologies. Likewise, physics learning processes should become more meaningful and effective with an ample use of computational modelling. Indeed, with the development of enhanced functionalities, computers can create learning environments where it becomes easier to treat the abstract conceptual entities of physics and mathematics as real objects (Papert, 1980). Students can actually have the opportunity to use computers as powerful intellectual mirrors for their own cognitive activity (Schwartz, 1989), a role which can enhance familiarization and reification, and thus the process of meaningful learning.

Computers also allow an easier introduction of numerical methods in the learning processes. These can be conceptually simpler than analytical methods so more attention can be focused on conceptual meaning and semi-quantitative reasoning (Osborne, 1990). With computers and numerical methods, modelling more realistic physical situations can start at an earlier age allowing a closer contact with the model referents. Student cognitive attention can then be first focused on fundamental physical content leaving for a later stage the analysis of the more advanced mathematical physics structures. Moreover, the learning processes can use computers to explore more effectively different representations, such as graphs, tables and simulations.

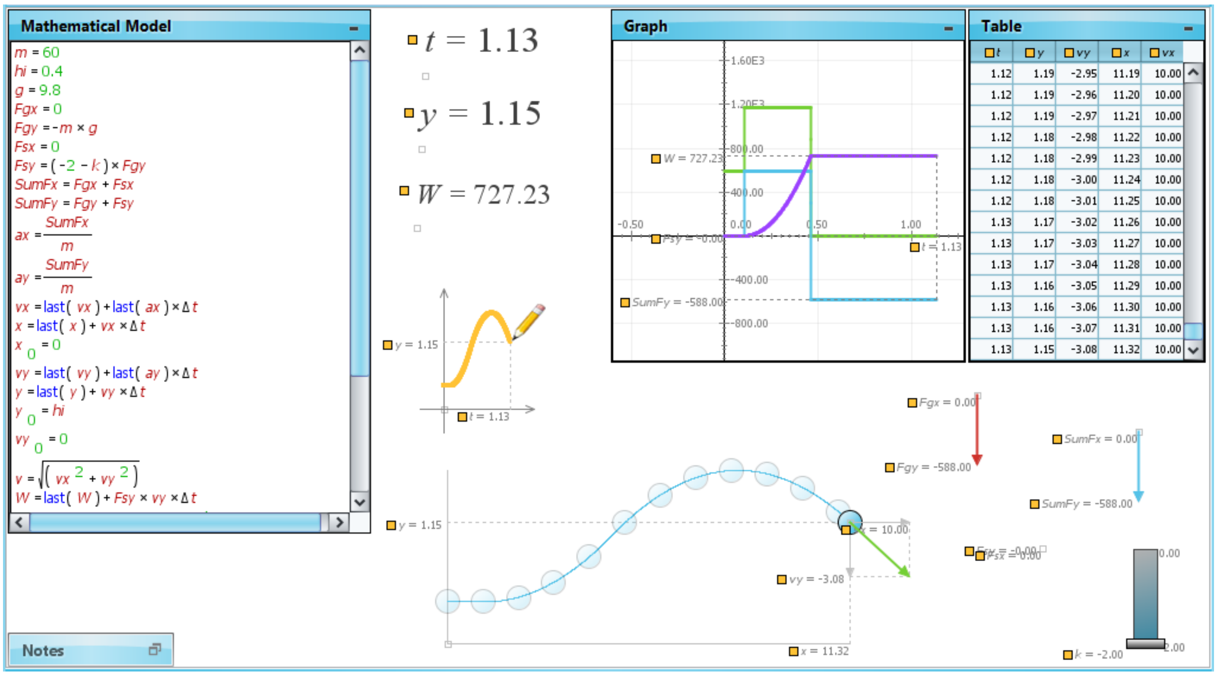
Modellus: An Interactive Environment for Exploratory and Expressive Computational Modelling

To fulfil such learning potential, computers cannot be simply used as display devices for text, images or simulations. They must be tools for modelling integrated in meaningful learning environments reflecting the epistemology of modern physics research, while avoiding cognitive overhead factors such as too much programming and specific software knowledge.

Modellus current advantages in this context come from being a domain general environment for mathematical modelling with the following functionalities: 1) Easy and intuitive creation of mathematical models using standard mathematical notation; 2) The possibility to create animations with interactive objects that have mathematical properties expressed in the model; 3) The simultaneous exploration of multiple representations such as images, tables, graphs and animations; and 4) The computation and display of mathematical quantities obtained from the analysis of images and graphs. With Modellus sequences of learning activities can be designed that span the range of different kinds of modelling from explorative to expressive modelling (Bliss & Ogborn, 1989; Schwartz, 2007). These modelling activities can be conceived to address cognitive conflicts in the understanding of scientific and mathematical concepts, the manipulation of multiple representations of mathematical models and the interconnection between analytical and numerical approaches. With simple numerical methods, the analysis of more realistic problems can also start earlier, an additional contribution for better familiarization and reification processes.

Field Actions, Learning Activities and Conclusions

Since 2008 we have been implementing our approach in the general physics and biophysics courses of the biomedical and informatics engineering majors at FCT/UNL (Neves, Silva & Teodoro, 2011; Neves & Teodoro, 2010; Teodoro & Neves, 2011). For example, the 2010 biophysics sequence involved the interactive modelling of a long jump on the computer screen (see Figure 1). Prior student knowledge framing this problem involves knowledge obtained from observations of real jumps, knowledge about vectors, kinematics and constant acceleration applications of Newton's laws, considering analytic, Euler and Euler-Cromer solutions.



Mathematical Model

$m = 60$
$hi = 0.4$
$g = 9.8$
$Fgx = 0$
$Fgy = -m \times g$
$Fsx = 0$
$Fsy = (-2 - k) \times Fgy$
$SumFx = Fgx + Fsx$
$SumFy = Fgy + Fsy$
$ax = \frac{SumFx}{m}$
$ay = \frac{SumFy}{m}$
$vx = \mathrm{last}(vx) + \mathrm{last}(ax) \times \Delta t$
$x = \mathrm{last}(x) + vx \times \Delta t$
$x_0 = 0$
$vy = \mathrm{last}(vy) + \mathrm{last}(ay) \times \Delta t$
$y = \mathrm{last}(y) + vy \times \Delta t$
$y_0 = hi$
$vy_0 = 0$
$v = \sqrt{(vx^2 + vy^2)}$
$W = \mathrm{last}(W) + Fsy \times vy \times \Delta t$

$t = 1.13$
$y = 1.15$
$W = 727.23$

Table

t	y	vy	x	vx
1.12	1.19	-2.95	11.19	10.00
1.12	1.19	-2.96	11.20	10.00
1.12	1.19	-2.97	11.21	10.00
1.12	1.18	-2.98	11.22	10.00
1.12	1.18	-2.99	11.23	10.00
1.12	1.18	-3.00	11.24	10.00
1.12	1.18	-3.01	11.25	10.00
1.13	1.17	-3.02	11.26	10.00
1.13	1.17	-3.03	11.27	10.00
1.13	1.17	-3.04	11.28	10.00
1.13	1.16	-3.05	11.29	10.00
1.13	1.16	-3.06	11.30	10.00
1.13	1.16	-3.07	11.31	10.00
1.13	1.15	-3.08	11.32	10.00

Figure 1: Modellus interactive long jump model with iterative Newton's equations. Approximately, the total work done to jump 8.6 m is 727.2 J.

In the long jump model Newton's equations of motion are written using the Euler-Cromer method. A possible concrete setting is the following. Take the jumper mass *m* = 60 kg and assume that the jumper accelerates to reach a speed of 10 m/s. During the race before the jump the position of the jumper's centre of mass is 1 m above the ground. To prepare the jump, the jumper bends his legs and lowers the centre of mass 60 cm, while maintaining the speed. Then the jumper applies a force on the ground that has an average magnitude equal to twice his weight. The force acts during 0.35 s, the time interval needed to raise the position of the centre of mass by 60 cm. The basic animation is constructed with a particle representing the jumper's centre of mass, vectors representing the velocity, acceleration and the applied forces, and a level indicator to control the magnitude of the force applied on the ground. Several graphs and tables can also be displayed (see Figure 1).

Because the magnitude of the jump force is an independent variable and the model is iterative, students can manipulate this vector at will and in real time perform the jump on the screen. A good simulation/solution is obtained choosing an appropriate numerical time step. While exploring the model, students can determine, for example, how far the jumper jumped and the average work done during the impulse for the jump. Students can change the model settings easily and analyse the jump physics for different jumpers and jump conditions. The possibility to change the mathematical model and immediately observe the consequences on the animation, graphs and tables is a powerful cognitive element to enhance familiarization and reification.

In all the courses the activities were successful in identifying and resolving student difficulties in key physical and mathematical concepts. For example, in the 2010 biophysics course, the average grade was 70 % and all 55 students were able to pass on the computational modelling component. To have real time visible correspondence between the animations with interactive objects and the object's mathematical properties defined in the model, and to manipulate several different representations were instrumental factors to achieve this. Using Modelllus students were able to actively explore and create mathematical physics models and animations. They also built models with differential equations, obtaining analytical and numerical solutions.

Likert scale questionnaires showed that the majority of students reacted positively to the new approach (Neves, Silva & Teodoro, 2011). For example, on the 2010 biophysics course 69 % of the students manifested a clear average positive opinion. Students showed preference for group work with teacher guidance and considered Modellus helpful and user friendly in the processes of learning mathematical physics models. The supporting interactive PDF documents with embedded video guidance and free space for multimedia answers or comments were considered interesting and well designed. However, students also felt that the extra content load of the new computational modelling activities required more than the available class time. Future research will involve improved implementation actions, a more detailed assessment of the effective learning outcomes and the creation of new Modellus functionalities.

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