Computational models and experimental validation at the physics teacher training college using Scilab and Arduino™

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Abstract. This work provides an overview of the main activities developed for an Information Technology course at Physics Teacher Training College - an 80 minutes per week, two semesters long course in a four-year physics teachers program - which incorporates the modelling process as a core topic. It proposes the implementation of software tools to aid this process, focusing mainly on physics models rather than technicalities associated with the underlying math, which is solved using numerical techniques. It also focuses on the experimental validation as a fundamental part of the process which in this case is solved using low cost and easy accessible materials as Tracker software or the Arduino boards and sensors, and describes the teaching strategies implemented to reach that goal, assessed through students’ productions.

1. Introduction

The value of simulation and computational modelling in the curriculum of physics has been discussed many times and it has been proved that the use of pre-built simulation is valuable to the learning-teaching process [1] and that the development of the modelling process by the students has a didactic value to the future physicists [2].

In the education of future certified teachers, however, the graduates will teach physics in middle and high school settings and they will work with simple deterministic models. Here, the modelling process as a means for solving problems has real value in terms of learning, but computational modelling is a technique not so widely researched in the field of physics education.

In this paper, we describe the teaching strategies and tasks that we develop during an academic year with the third year students from the physics teaching program offered in the National Technical Teaching Institute from the Argentinian National Technological University (INSPT-UTN from its initials in Spanish: “Instituto Nacional Superior del Profesorado Técnico - Universidad Tecnológica Nacional”). These tasks and strategies were implemented as part of the STEM curriculum of the course Information Technology III (Original name “Computación III”) which since 2014, has had 32 students who have passed it.

The program we are referring to is a course of studies to get a bachelor degree which is not the same degree as the one held by the physicists who work in research and industries. Teacher trainees have less math and physics credits, but they are required get some credits in education courses. Getting this degree means national certification for teaching physics in middle and highschool and that is the main career the graduates can pursue.

The main goal of the course is that the students must be able to make connections between dynamical models represented by ordinary differential equations which describe ideal situations, and the real
physical phenomena which they have to measure using technological tools like Tracker software and the Arduino platform with sensors, generalizing the proposals of Calderon [3], Rubinstein and Schenoni [4], between a great variety of works and dissertations with this theme.

1.1. Theoretical framework and context
There are numerous published works about different uses of simulations in physics education, and about how students assess learning with different approaches and theoretical frameworks [1][5][6][7].

This course is oriented to future teachers who will use simulations in their pedagogical practices. One of the main goals is that they learn to recognise possibilities and limitations of specific simulation or computational models, while they gain some familiarity with the process of construction of these. Future teachers are probably not going to develop their own simulations to teach a topic, but in this course they will reflect about them and the important elements to be considered when using these tools.

In Argentina, to be a physics teacher you must obtain a specific four years degree (“Profesorado”) that is similar to a bachelor degree which you can get in some colleges. To be a physicist, on the other hand, you must study in different colleges, and get a 5 or 6 year degree. These are by tradition, different courses of studies with different careers and different social backgrounds. This means that people who study to be a teacher, will only be able to use their degree to work as a teacher. There are exceptions but this means that the curriculum is not the same for teachers as for physicists.

The course has a duration of two semesters, with an 80-minutes lesson per week, so it is not an important course, but it is a mandatory one.

We can distinguish between two types of computer models in physics. These are exploratory models, which allow students to interact with pre-built models handling their parameters to visualize different results and behaviours, and expressive models which are the richest. The expressive models allow students to express their own ideas on a domain, specifying relationships between concepts and different variables and exploring the consequence of those representations. In this line of work, they learn through an active process [5].

In a constructivist learning environment, students do not receive the knowledge, they are not passive listeners. Bonwell and Eison say “it is proposed that strategies promoting active learning be defined as instructional activities involving students in doing things and thinking about what they are doing” [8].

Students at INSPT-UTN already possess the basic physics knowledge but through the models they build, they can go deeper into the topics and strengthen the existent relations from the explicit model. One of the main advantages of the computational models is that they allow students to add relations and parameters beyond the point where the math model is virtually unsolvable, or really hard to solve using the traditional methods for differential equations, but is still within the range of numerical calculation methods.

The cycle for making a simulation or building a computational model has a vital step which is ‘Validation’, which is fundamental in engineering and science to guarantee the predictions of the model will be reliable. The results obtained from the computational model must be validated comparing them with empirical data, providing feedback to improve or change the model [9].

One important clarification about computer models and simulations is that they do not necessarily predict every phenomenon corresponding to a given field. There will always be a set of initial conditions for which the model will not be able to predict valid results and there will be an uncertainty associated with that model. For example, we could have a computer program which runs a simulation according to Newtonian dynamics, but if the size of the objects were comparable to the size of atoms, the model would not represent the reality.

The modelling process proposed by Hestenes [9] constitutes not only the description of the models construction process from an epistemological point of view but also the main topic of his ‘theory of physics instruction’ [2] which has now been further developed but still has value for future teachers.
The students are not going to be physicists or do formal science, but they are going to teach it and they must have some scientific abilities to do that. The tasks they must perform to build a computer model, validate it experimentally, and use the results of these comparisons to describe the limits of validity of the model, plus the writing of a final paper describing the whole process, requires them to practice the seven scientific abilities: A. the ability to represent physical processes in multiple ways; B. the ability to devise and test a qualitative explanation or quantitative relationship; C. the ability to modify a qualitative explanation or quantitative relationship; D. the ability to design an experimental investigation; E. the ability to collect and analyze data; F. the ability to evaluate experimental predictions and outcomes, conceptual claims, problem solutions, and models, and G. the ability to communicate[10].

2. Methods

2.1. Implementation

During the course a lot of different activities with the computer were conducted with the goal of providing students with the necessary Information Technology skills for developing their own computer models, designing their own experiments with Arduino and being able to analyze and compare results.

The software packages involved have changed with the years but the core toolkit consists in a programming language (currently we use Scilab and Python), numerical methods to solve ordinary differential equations [11][12] and some apps which allow us to digitize physical information such as Tracker software, or Arduino with some sensors.

Once students achieved sufficient competence with these tools, they were able to move forward to the main activity, and develop their own model for a real situation, with the respective validity tests.

2.2. Simple models and numerical solutions. How to build a model?

The course standard procedure to build a dynamical mechanical model, starts by applying Newton’s second law of motion for every element in the system. The goal is to get an expression for the
acceleration of every particle in the system (1). Once the student has a differential equation system for
the accelerations of the particles, the remaining step is to integrate those equations to get the position
and velocity of the elements of the physical system.

The integration of the equation system is not an ability we are trying to develop in this course, so the
students use numerical methods to get the results. Once they have built the model, they can modify the
parameters, add new parameters to analyze the qualitative behaviour of the system, or if they want
reliable numerical results, reduce the time step and improve the numerical results.

Figure 2. Position, velocity and acceleration of
the throwing of a spherical body considering
friction with the air, done by a student.

Figure 3. Two bodies problem. Trajectory of
Jupiter around the sun, solved using Euler-
Cromer method in Scilab by another student.

The numerical method we chose to solve the differential equations is the Euler method (figure 4), for
its simplicity, and as a means to keep the focus of the task in looking for the right parametrization of the
formal model and not spending time in the implementation of more complex algorithms. Some students
have chosen to implement more advanced two and four steps algorithms, but they are allowed to do it
only once they have understood the goal of the task.

Figure 4. Euler algorithm for a particle traveling
in one dimension considering friction with a
viscous fluid as a linear term. The core of the
“simulation” has only five code lines.

2.3. Experimental measures and data acquisition

There are numerous tools for measuring and digitizing data from a physical system. In this course the
selected tool to get position values and time intervals with a camera was Tracker, and since 2017
Arduino has been incorporated into the course syllabus. The reason behind this incorporation was that
the majority of schools in Argentina where future teachers are going to work have poorly equipped labs,
and Arduino represents a cost-efficient solution to this problem, with capability for handling digital and
analog sensors for a wide range of physical variables.

Arduino is an electronic computer that allows users to process different measurements obtained with
devices like photogates, position and temperature sensors, and it is available for a cost that goes from
five to fifteen american dollars. The students complete some simple tasks to train their programming
and electronics skills: making the connections to measure small currents and voltages directly with
analog ports (figure 5); controlling some actuators like LEDs and DC motors; and configuring some
sensors like ultrasonic position sensor HC-SR04 or photogates made with IR LED and phototransistors
(figure 6).
3. Results and Discussion

3.1 Students’ STEM project and final papers

Students choose the physical situation they want to represent. They define their system, build a simple model and design an experiment to measure one or more of their model’s parameters. As they make measurements, they refine the model to adapt it to reality, and the experiment to find the limits of validity of the model. Once they have gathered enough data, they write a final paper.

Students have developed a variety of projects in topics such as mechanics, electromagnetism and thermal systems. Here we present some examples of the productions highlighting their distinctive characteristics.

Some of the projects developed which involved Tracker to get the experimental data were flying and falling objects - modeled taking on account air viscosity and friction-, ball collisions and pendulum. Using Arduino, students chose to study oscillatory systems more than once, including simple and physical pendulums (figure 7), non punctual pendulums and damped spring-mass systems. Generally they used ultrasonic sensors to measure positions for these systems, but they also measured periods with photogates. Regarding photogates, they studied steel flywheels twice (figure 8) and once a student measured the speed of a little ball launched with a cannon at different heights.

Regarding thermal systems, they used temperature sensors to model a body being heated by an incandescent lamp, and different color bodies with hot water inside cooling down. In electromagnetism the only projects they have developed so far are resistor-capacitor circuits.

It is important to mention that these models and experiments are not original nor special - this is not a requirement. They are simple experiments designed by students to acquire data about one or
more variables of the mathematical model, to compare and obtain information from the physical situation as feedback for the model.

![Graph](image)

**Figure 9.** Example of a first approach to the study of a flying object, when the model without considering air friction is clearly divergent with the data acquired from measures.

3.2. Assessment

The way to assess the project was through examining the final papers submitted by the students. We developed a grid with the fundamental topics that must be included in every student project to prove that the task was satisfactorily completed (table 1). Students who had covered every topic with enough depth in their final productions, passed the course, and students who were not able to comply with the standard, or did not approach some topic, received personal feedback and recommendations to improve upon their work, and reach the minimum expected level.
Table 1. Main indicators for assessing the task success

| Fundamental points | Description |
|--------------------|-------------|
| Relevance          | Choice of a real situation that is pertinent to physics. Which allows students to build a model. |
| Quality of analysis| This topic relates to the model, its complexity, the variables and parameters identified on it and the possible representations. The model must have at least one ordinary differential equation |
| Experiment to test validity | Technical validity of experiment. The design of the experiment, deciding which results are valids, sources of error, dependence between variables |
| Depth of analysis  | This topic refers to the contrast phase. Quantity of observations and experiments, thoroughness, quantity of data obtained and evaluation of the experiment vs model. |
| Validity of computer model | Technical validity of the computer model. Selected algorithm, code, and initial conditions. How much the model represents the chosen situation and how good it is programmed. |

Since 2017, new categories were added to that list, not as minimum requirements to pass the course but simply to give a more complete feedback to students. The added topics related to the identification of hypotheses (explicit and implicit), the decisions taken to simplify or to put boundaries to the model, and other sub abilities related to the experimental design, were taken from the rubrics available in [10].

For the last few years we have been taking the feedback the students have given us into account to modify the tasks and the assessment grid we use to evaluate them.

4. Conclusions
This is a minor course in the general structure of the physics education program, but the tasks are significant for the future teachers as they apply real scientific abilities.

The students take the initiative. They decide what they want to model and how they want to measure a real system. They have to practice their experimental, mathematical, and programming skills and, if they use Arduino to build their experiment, they practice their electronics skills too. Many STEM skills are also put into practice. They are not going to be physicists -because in Argentina that requires a different degree- but before graduating they will have experienced working as if they were scientists, which is fundamental for future science teachers.

While designing their experiments, students try out some low cost technology they can use when teaching in the schools, which usually have low budgets for science and lab equipment. Moreover, they learn how to think about these technologies before using them, taking into account the scope of each sensor and tool.

Finally, as an active learning strategy, it is engaging: students have repeatedly claimed so in their final feedback.

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