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Rui Gomes Neves

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Physics Education with Interactive Computational Modelling

Rui Gomes Neves[1, 2, a), b)]

[1]*Departamento de Ciências Económicas e Empresariais (DCEE), Universidade Autónoma de Lisboa (UAL), Portugal*
[2]*Unidade de Investigação Educação e Desenvolvimento (UIED), CICS.NOVA – Centro Interdisciplinar de Ciências Sociais, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa (FCT/UNL), Portugal*

[a)]rneves@autonoma.pt
[b)]rgn@fct.unl.pt

Abstract. The development of knowledge and cognition in physics and other fields of contemporary science, technology, engineering and mathematics (STEM) is based on modelling processes increasingly requiring advanced methods of scientific computation. Physics education for STEM education should then involve learning sequences featuring modelling activities with computational knowledge and technologies. Such sequences should manifest epistemological and cognitive balance between theory, experimentation and computation, be interactively collaborative, and ensure the development of meaningful knowledge in physics, mathematics and scientific computation, appropriately considering the diversity of STEM contexts. To address this challenge we have proposed an approach based on the creation of sequences of interactive engagement learning activities with computational modelling that explore different kinds of modelling, introduce scientific computation progressively, generate and resolve cognitive conflicts in the understanding of physics and mathematics, and comparatively analyze the various complementary representations of the mathematical models of physics. In this work we discuss a learning sequence about fluid mechanics for introductory physics students of STEM university courses, during which they built and explored in the computer mathematical physics models and animations helping them resolve difficulties persisting after theoretical lectures and problem-solving paper and pen activities.

INTRODUCTION

Contemporary physics epistemology emerges from the interaction of individual and group research processes where modelling involves a balanced interplay between theory, experimentation and computation. In their diversity, such modelling paths share a cyclic structure that goes through distinct cognitive phases, namely, qualitative contextual description, definition, exploration, interpretation and validation of the relevant mathematical models, communication of modelling results and the development of generalizations. The resulting knowledge and cognitive structures are built out of rigorous declarative, operational and conditional specifications of abstract concepts and of their interconnections, which require operational familiarization and reification, high theoretical and methodological consistency and a precise relation with the relevant referents. In all cycle phases, computational modelling has been growing in importance for allowing increasingly enhanced calculation, exploration, visualization and validation capabilities.

However, most current physics courses remain unable to fully manifest such epistemological and cognitive features. In introductory university education the general physics courses of the first 2 or 3 years are usually organized around expositive theoretical lectures, supplemented by recipe based problem-solving and experimental laboratory classes. In general, these are courses that superficially cover an extensive series of physics topics and limit the application of computational methods and technologies to the presentation of text, images or simulations, or to an automatized role in data acquisition and analysis. Today, as in the past, the evidence continues to be for the

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development of a highly fragmented and inconsistent knowledge of physics [1, 2] and for average expectations that decrease over time [3].

Improvement is possible if physics education is structured by pedagogical strategies and methodologies able to reflect contemporary physics modelling processes. Meaningful learning should then occur when students go through problem-based learning activities involving epistemologically balanced interactive explorations of the different cognitive phases of the modelling cycles. Evidence supporting this expectation has been accumulating over the years with many research results showing enhanced learning processes when students work on activities that approximately recreate the epistemological and cognitive involvement of the physics research processes [4, 5]. In this context we have put forward an approach involving the development and implementation of sequences of interactive engagement learning activities with computational modelling that explore different kinds of modelling, from exploratory to expressive modelling, progressively introduce scientific computation without requiring prior working knowledge of programming, generate and resolve cognitive conflicts in the understanding of physics and mathematics, and comparatively analyze different and complementary representations of the mathematical models of physics [6-12].

TEACHING PHYSICS WITH INTERACTIVE COMPUTATIONAL MODELLING

In our approach a physics course for science, technology, engineering and mathematics (STEM) education involves 4 interconnected complementary components: theoretical lectures, paper and pen problem solving classes, computational modelling classes and experimental laboratories. To create in all components an interactive engagement environment, always open to free questioning and discussion, students are organized in collaborative groups of 3 to 5 students. Firstly, the learning sequences involve the definition of the relevant theoretical, experimental and computational backgrounds as well as the analysis of a set of worked out examples. The groups then move to interactive and exploratory learning activities, involving paper and pen problem solving activities, computational modelling activities and experimental laboratory activities. All around the aim is to set up epistemologically and cognitively balanced meaningful learning atmospheres, with clear contact with observable phenomena, approximately recreating research modelling environments.

The computer is to be applied as a cognitive artifact to help student cognitive activity during modelling and generate enhanced familiarization and reification processes. The computational modelling activities, ranging from explorative to expressive, complement theoretical framing, paper and pen problem solving and experimental activities, in triggering and resolving cognitive conflicts in the understanding of the mathematical models of physics, and in developing performative competency across their distinct and complementary representations. The integration of computational modelling activities can be based on a set of computer modelling systems, e.g. Modellus [6-12], EJS and Physlet [13], and PhET [14], and on programming languages like Python [15]. The range of available complementary functionalities allows the design of more versatile computational modelling activities focusing on physics and mathematics that can make a progressive introduction of scientific computation without prior development of a working knowledge of programming and with an effective control over student cognitive load.

AN ILLUSTRATIVE LEARNING SEQUENCE IN FLUID MECHANICS

The phenomenological setting is that of a water dam and the goal is the analysis of the associated hydrostatic pressure forces and torques. The educational context is that of an introductory physics course in STEM university education. Prior background knowledge involves knowledge obtained from observations of real dams, basic secondary education in physics and mathematics, knowledge about vectors, kinematics and some applications of Newton's laws, and knowledge defining fluid, density, pressure forces and static equilibrium. The complete learning sequence is divided in three parts, the first introducing the resultant pressure force as a vector and determining it for a dam with a vertical rectangular wall, the second analyzing the resultant pressure force torques and determining the center of pressure, and the third considering generalizations to other surface geometries and inclinations. Here we briefly describe the first part of the learning sequence. More details about the research referring to this and the other parts of the complete learning sequence will be published elsewhere.

The first part of the sequence starts with a theoretical framing phase. Considering the model of a vertical rectangular wall with length L sustaining a body of water with depth h_f, the following mathematical physics reasoning is discussed to deduce the hydrostatic pressure force applied on the wall of the dam. Take the orthogonal reference frame $Oxyz$, where Oz is perpendicular to the wall and points to the water, Oy marks the depth y, and Ox

marks the length along the wall. Then divide the wall in a large number N of very small surface strip elements each one with area $\Delta A = L\Delta y$. This partition defines the Oy sequence $y_0 = 0, y_1, \cdots, y_N = h_f$ where $\Delta y = y_{j+1} - y_j, j = 0, \cdots N-1$. The limit of this partition is $N \to +\infty,\ \Delta y \to 0$. The pressure $P(y)$ on the surface element ΔA located at depth y is $P(y) = \rho g y + O(\Delta y)$. The hydrostatic pressure force applied on this surface element has magnitude $\Delta F = \rho g y L \Delta y$ and is perpendicular to the surface element pointing away from the water, $\overrightarrow{\Delta F} = -\Delta F \vec{u}_z$, where $\vec{u}_z$ is the unitary vector of Oz. The resultant pressure force applied on the wall is obtained summing all the elementary forces applied to all the surface elements, taking at the end the limit $N \to +\infty,\ \Delta y \to 0$. Since all elementary vectors have the same direction this force is given by $\vec{F} = -F\vec{u}_z$ where

$$F = F(h_f) = \rho g L \lim_{\substack{N\to+\infty \\ \Delta y \to 0}} \sum_{j=0}^{N-1} y_j (y_{j+1} - y_j) = \rho g L \lim_{\substack{N\to+\infty \\ \Delta y \to 0}} \frac{1}{2} \sum_{j=0}^{N-1} (y_{j+1} + y_j)(y_{j+1} - y_j). \quad (1)$$

The limit sums in Eq. (1) are equivalent Riemann sums defining the integral $\int_0^{h_f} y\, dy$. They can be explicitly calculated, leading to the exact analytical result $F = F_{\text{analytical}} = \rho g L h_f^2/2$.

Next there is a paper and pen problem-solving phase with 2 stages of group work: (1) Discussion and explanation of the theoretical framework and (2) Application of the deduced formula to solve example problems. For many students it turns out to be a difficult challenge to understand the abstract mathematical physics reasoning involving Riemann sums developed to define $\vec{F}$. To help making it more concrete and meaningful with enhanced cognitive contact between the mathematical physics model and its referents, the learning sequence follows on with a phase of computational modelling activities, where the Riemann integration is done numerically applying the trapezoidal rule to define an iterative process that implements the Riemann sums with an adjustable finite step. In this iterative numerical solution $F(y + \Delta y) = F(y) + L\rho g y \Delta y$. Given a starting value it is possible to determine $F(y)$ going through a succession of step Δy iterations. The numerical value of the Riemann integral in Eq. (1) is then given by the accumulated value $F(h_f)$, and approximates the exact analytical solution. Since the method converges, a smaller iteration step will produce a better approximation, that is, the approximation error given by $\varepsilon_F = |F - F_{\text{analytical}}|/F_{\text{analytical}}$ will decrease with the iteration step Δy, although with a larger computation time.

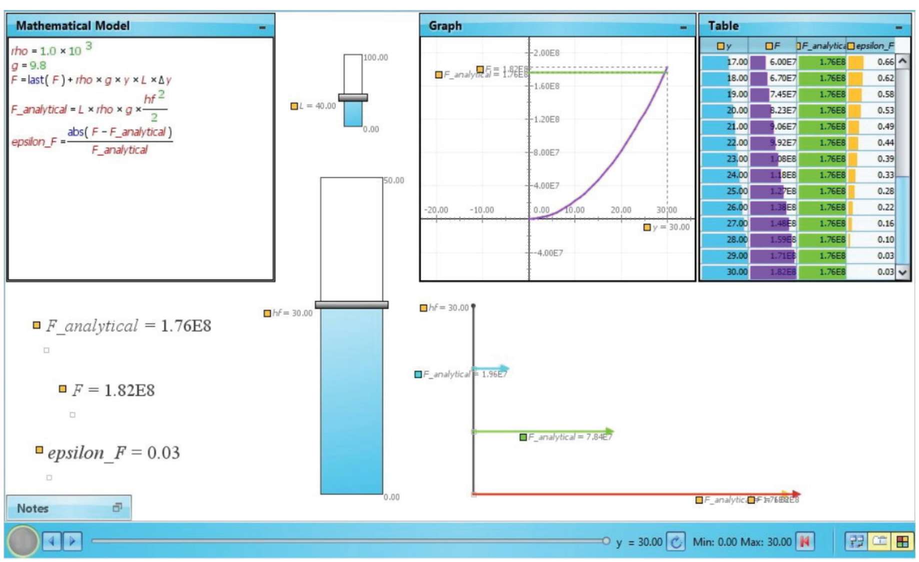

FIGURE 1. Modellus model to determine the resultant pressure force applied on a dam with a rectangular inner wall of length L which sustains a body of water with depth h_f. For $L = 40$ m and $h_f = 30$ m, the integration with step $\Delta y = 1.00$ m leads to $F = 1.82 \times 10^5$ kN, $F_{\text{analytical}} = 1.76 \times 10^5$ kN, and $\varepsilon_F = 0.03$, and the integration with step $\Delta y = 0.100$ m leads to $F = 1.770 \times 10^5$ kN, $F_{\text{analytical}} = 1.764 \times 10^5$ kN, and $\varepsilon_F = 0.003$.

Computer implementation of the numerical models follows the discussion of this numerical theoretical framing. This can be done in the Modellus environment. Take, e.g., the determination of $\vec{F}$ for a dam with length L and water depth h_f (Fig. 1). The mathematical model defines g and ρ as fixed parameters and $y \in [0, h_f]$ as the independent variable with step Δy. The numerical integration is programmed using $F = \text{last}(F) + L\rho g y \Delta y$, with $F(0) = 0$ N as the initial condition. $F_{\text{analytical}}$ and ε_F are dependent variables, and L and h_f free adjustable parameters. Students can explore different values of L, h_f and Δy, and interpret graphs and tables of y, F, $F_{\text{analytical}}$ and ε_F, alongside the animation displaying, e.g., $\vec{F}$ and $\vec{F}_{\text{analytical}}$. The build-up of the Riemann sum as the successive iterative terms add up and the increase of F with the square of y are then clearly visible. The Riemann limits $N \to +\infty$, $\Delta y \to 0$ are made explicit and concrete by running the model for decreasing steps Δy. This also shows convergence since ε_F decreases with Δy. The increase in computation time is also clearly observable. Moreover, changes in the initial settings can readily be noted, thus improving explorative and comparative modelling.

CONCLUSIONS

Content analysis of student coursework showed that the fluid mechanics learning sequence was successful in helping students better understand the mathematical physics model developed to analyze the hydrostatic pressure forces in a water dam. Students were able to construct and explore the mathematical physics models and animations, understanding their functioning and meaning in the context of the analytical and numerical theoretical framing, resolving several identified learning difficulties, thus establishing more meaningful and operationally reified relations with the relevant hydrostatic referent, and achieving a significant consolidated expansion of previously acquired mathematical physics knowledge and cognition. With the computational modelling activities, the learning sequence thus demonstrated enhanced capacity and efficacy to develop student knowledge in a structured and consistent way. Computational modelling with Modellus contributed for this for allowing the simultaneous real-time on-screen manipulation and analysis of several different model representations, such as tables, graphs and animations with interactive objects having properties defined in a visible and modifiable mathematical physics model. In future research work new learning sequences with computational modelling, both in classical and contemporary physics, will be developed and implemented, considering comparative analysis of different computer modelling systems and analysis of the effects on student learning, knowledge and cognition development, perceptions and expectations.

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REFERENCES

1. D. Hestenes, Am. J. Phys. **55**, 440–454 (1987).
2. L. McDermott, Am. J. Phys. **59**, 301–315 (1991).
3. E. Redish, J. Saul and R. Steinberg, Am. J. Phys. **66**, 212–224 (1998).
4. L. McDermott and E. Redish, Am. J. Phys. **67**, 755–767 (1999).
5. D. Meltzer and R. Thornton, Am. J. Phys. **80**, 478–496 (2012).
6. R. Neves, J. Silva and V. Teodoro, "Improving Learning in Science and Mathematics with Exploratory and Interactive Computational Modelling", in *International Perspectives on the Teaching and Learning of Mathematical Modelling, Vol. 1, ICTMA14 - Trends in Teaching and Learning of Mathematical Modelling*, edited by G. Kaiser *et al* (Springer, Dordrecht, 2011), pp. 331–341.
7. V. Teodoro and R. Neves, Computer Physics Communications **182**, 8–10 (2011).
8. R. Neves and V. Teodoro, AIP Conference Proceedings **1479**, 1806–1809 (2012).
9. R. Neves, M. C. Neves and V. Teodoro, Computers & Geosciences **56**, 119–126 (2013).
10. R. Neves and V. Teodoro, Revista Lusófona de Educação **25**, 35–58 (2013).
11. R. Neves, Revista Lusófona de Educação **35**, 171–189 (2017).
12. R. Neves, AIP Conference Proceedings **2116**, 410002-1–410002-4 (2019).
13. W. Christian and F. Esquembre, Phys. Teacher **45**, 475–480 (2007).
14. C. Wieman, K. Perkins and W. Adams, Am. J. Phys. **76**, 393–399 (2008).
15. R. Chabay and B. Sherwood, Am. J. Phys. **76**, 307–313 (2008).