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Computational simulations at the interface of physics and society: A teaching-learning module for high-school students

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Summary. — The increasing role of computational simulations as the basis for policies and decision-making processes imposes the educational community to think about ways to introduce them in upper high-school teaching of physics as the third pillar of scientific research. In this paper, we present the principles at the basis of the design of a teaching-learning module on simulations of complex systems and implemented in a course organized by the Department of Physics and Astronomy "A. Righi" of the University of Bologna for university orientation. Specifically, we discuss the value of computational simulations as interdisciplinary and future-oriented objects that can act as bridges between physics, STEM disciplines, and society.

1. – Introduction

In this paper we present a teaching-learning module on simulations of complex systems targeted to upper high-school students. The module was situated in the context of PLS (*Progetto Lauree Scientifiche*, Scientific Degrees Project), the national program that aims at orienting high-school students to the choice of a scientific university curriculum. Every year, the Department of Physics and Astronomy of the University of Bologna (DIFA) offers "laboratories" to make students know the frontiers of research in physics and show them what the jobs of physicists can be (`www.pls.unibo.it`). Since the academic year 2020-2021, the educational offer of the DIFA has been enriched with this course aimed at making students reflect on the wide potential of computational simulations to show the role that physics can play at a societal level, to reflect on interdisciplinarity, and to enlarge their imagination and ways of thinking about the future. So far, two complete editions of the course have been carried out with high-school students, but some parts of the teaching-learning module have been adapted and implemented also with pre-service teachers in national and international contexts to make them experience first-hand examples of STEM education activities. In total, more than 180 participants have been engaging in the module.

The goal of this work is to illustrate the main ideas that guided the design of the teaching-learning module, the selection and organization of the contents to teach, and the presentation of the activities to the participants. We refer to them as "design principles" and they are as follows: i) exploiting interdisciplinary nature of simulations;

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ii) valuing the role of simulations as tools to bridge physics and society; iii) using simulations to develop future-scaffolding skills (*i.e.*, skills in terms of foresight and anticipation to construct visions of the future that empower actions in the present).

2. – Simulations as interdisciplinary objects

In the '50s, simulations became a standard technique in the domain of physics [1] but nowadays their use is widespread in all disciplines. Simulations, for their widespread application, are also a booster to trigger interdisciplinary collaboration between experts in different fields. The pandemic has been an example of how a common issue to be addressed can mobilise researchers and professionals with different expertise to work together in the design and analysis of models and simulations [2]: physicists have been collaborating with virologists, epidemiologists, data scientists. We can recognize a further meaning of interdisciplinarity if we look at a concrete simulation artifact. Let us consider, for example, the SIR epidemiological model [3], expressed as a system of three differential equations that account for the evolution of population as divided in three compartments of susceptible (S), infectious (I), and recovered (R) individuals. We can decide to simulate it with an equation-based or an agent-based approach [4]. In the former case, we numerically integrate the equations obtaining the time evolution of the system; in the latter, we formulate rules to describe the behaviour of the individual agents, and these rules generate the dynamics of the system. The two approaches profoundly differ on many levels, not last their suitability to different types of problems in which the choice of an approach instead of the other will play a decisive role. However, comparing the simulations obtained with the two approaches, different roles of mathematics can be exploited too, and each corresponds to a specific computational implementation. Hence, focusing on the comparison between equation- and agent-based approaches is a way to exploit the conceptual interplay of disciplines within simulations [5]. The interdisciplinarity of computational simulations can lead us to consider them as "boundary objects" [6] *i.e.*, artifacts that bridge different domains and trigger interdisciplinary collaboration and understanding [7, 8].

In the module, the reflection on interdisciplinarity was implemented in different ways, within the framework of the IDENTITIES European project (`www.identitiesproject.eu`). For example, a round table was organised with PhD students and early career researchers who, at the DIFA, work with simulations in different fields (epidemiology, nuclear physics, accelerator physics, climatology, astronomy) and further enlargement of this team is planned for future editions in order to include physicists who deal with simulations of social systems. The module itself was part of the outreach activities of OPH (Open Physics Hub), a project that collects expertise in computing, simulation, and sensing of all the DIFA's research fields.

3. – Simulations as bridging objects between physics and society

As the 2021 Nobel prize for physics to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi has contributed to highlight, science of complex systems has been unveiling an image of physics beyond the "traditional" meaning of this discipline [9] as essentialist, deterministic, reductionist and in search for universal natural laws [10]. In this regard, a crucial role is played by statistical physics, whose methods have been applied also to the modelling of social phenomena. If the search for statistical laws for social sciences had been a dream for physicists and philosophers of science for a long time, it was only with the big data revolution that a philosophical declaration of principles was transformed into a concrete research effort carried out by many physicists [11]. The increased capacity to generate, collect, store, and process social data has allowed widening the spectrum of phenomena addressable with methods typical of physics, up to extraordinarily complex systems as human societies [12].

In the module, we addressed the potentiality of applying physics to phenomena traditionally conceived as societal with the voter model [13, 14], starting from the analogy with the Ising system. Indeed, as we can model a ferromagnet with 1 or -1 spins occupying a grid where they begin to align following the spin value of their neighbours, the same dynamics can be observed and used to model social systems to describe the reach of social consensus. In place of $1/-1$ spins there are yes/no opinions hold by voters and in place of ferromagnetic properties of the material what is observed is the reach of consensus or not on a certain decision. This example clarifies the connection between physics and social sciences: not only the inquiry methods of physics are used to analyse, investigate, and experiment with social phenomena, but the inner dynamics of physical systems become models to describe behaviours in other fields.

4. – Simulations as future-oriented objects

Simulations can have different purposes like proof, prediction, explanation, and policy formulation [4]. The issues of policy formulation and prediction are related; with the climate change emergency, and even more in the last months, due to the COVID-19 pandemic, we have seen simulations used to make decisions on the basis of the predictions they were able to produce [15]. In this sense, the pandemic has raised the attention of the general public to an issue that has been routine for decades for the community of experts: the role of models and simulations to elaborate future scenarios and, as a consequence, to support political, technical, and personal actions in the present [16]. Even if the predictive character is an important feature of many computational simulations used in real-life problems, this issue is rarely addressed in science education. Indeed, most studies about the use of simulations in educational contexts focus on their explanatory character [17]. As an original contribution to the educational research field, framed within the recent body of literature in future-oriented science education [18, 19], in this module we address simulations as educational objects which can stimulate students' reflections on the future. The simulations involved in our teaching activities are not meant to predict the future perfectly or produce realistic pictures of the future [20]. According to the European projects I SEE (`www.iseeproject.eu`) and FEDORA (`www.fedora-project.eu`), within which this work is situated, the aim is rather to make students explore the mechanism to build a plurality of different scenarios, enhance their imagination on their personal future and the future of cities, countries, and society, and develop so-called future-scaffolding skills [19] to navigate the complexity of these futures.

The role of simulations as future-oriented objects was made particularly explicit with the students in the final activity of the module, where participants, divided in groups, were asked to identify a problem of their interest in the present and imagine possible, probable, and desirable future scenarios for that issue. In conducting future-oriented activity, students had to choose a pre-existing NetLogo agent-based simulation or, using the NetLogo basics learnt during the course, they had to design a new one from scratch in order to model their problem and explore, through it, possible evolutions of the system.

5. – Final remarks

In this paper we have presented three main design principles lying at the basis of a teaching-learning module on computational simulations. This model is targeted to upper high-school students, adolescents who choose to attend the course in a delicate moment of their life in which they are exploring possibilities of future careers, within the university or as professionals in different fields. We believe that, because of the pillars on which it has been designed, the module we presented is particularly suitable to foster the development of the "transversal skills" that students are supposed to achieve - in Italy, the attendance at the course is recognized as an experience of the PCTO (*Percorsi per le Competenze Trasversali e l'Orientamento*, Paths for Transversal Skills and Orientation). Engaging with computational simulations, they are guided to recognize the variety of disciplines at stake in designing, implementing, and using these tools, to break the Manichean distinction between hard and social sciences, and to understand that simulations are artifacts that can shed light to new ways of figuring out personal and societal futures.

In future works we will address, comparing pre and post surveys, the module's effectiveness in impacting the participants' projects for future careers.

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