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Bringing Simplification Assumptions to the Forefront in Chemical and Biological Physics: Research-Based Development of an Introductory Computational Science Curriculum.

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Abstract

In the world of contemporary research and technology, the boundaries between the disciplines have become blurred. For example, simplified models in physics are used to conceptualize phenomena in multi-particles systems that are of interest to chemistry, biology and material engineering and can be solved with analytical or numerical tools. However, the current high school science curriculum does not engage students in simplifying complex phenomena, nor does it equip them with the conceptual foundation and numerical tools they need to analyze phenomena in multi-particle systems. Thus, it fails to provide students who are interested in science and engineering with key pillars of their intellectual foundation that they are likely to need in their professional future. Central position papers have called for introductory level science curricula to better reflect the growing interest in contemporary science, interdisciplinary work, scientific modeling and computational tools.

The "Interdisciplinary Computational Science: Chemical and Biological Physics" (ICS) program developed as a collaboration between the Department of Science Teaching, the Department of Chemical and Biological Physics, and the Davidson Institute for Science Education in the Weizmann Institute for Science responded to this call. This novel three-year program (10^{th} to 12^{th} grade) is oriented toward capable motivated high school science students who are interested in interdisciplinary, project-based work. It takes place as a regional class at the Davidson Institute and at the University of Haifa (for the Arab sector), and grants matriculation credit for an advanced science course.

How can instruction help introductory level students construct physics-based models for phenomena involving multi-particle systems? A number of educational programs in the literature have addressed this challenge in the context of introductory courses in physics, some of which have been successfully implemented in several universities. These programs include an introductory statistical thermodynamics course, some even provide computational tools, but they do not emphasize the process of modeling, or in particular the simplification assumptions of complex phenomena in a multi-particle system such as structure formation in materials. The ICS program was based on these pioneering programs, in order to address the missing aspects.

This dissertation describes the design-based research accompanying the curricular design of the first unit of the ICS program, entitled "Particle Dynamics", that lasts one year (10^{th} grade). The Particle Dynamics unit engages students in constructing a series of computational models intended to explain Brownian motion and diffusion. Analysis of the development in time of the particles' trajectories at different time scales serves to justify the shift from the Newtonian model of the particle motion in a vacuum (anchored in students' prior knowledge of Newton's laws) to a Random Walk model for colloidal particles in a solvent, with fine-grained and coarse grained-modeling. Instruction explicates the simplification methods, and challenges naive perceptions of simplification and modeling that are widespread among high school science students. The use

of computational tools allows the students to explore the behavior of “messy” phenomena in multi-particle systems that cannot be treated analytically.

The study consisted of both a formative evaluation of the curricular design leading to refinements of the curriculum during three consecutive cycles, as well as an investigation of the students’ perceptions of modeling that emerged as the result of their participation in the program. In particular, the ways in which the students integrated and differentiated the scientific principles of the discipline from the programming procedures, and their conceptions of the simplification assumptions were explored in the context of two-particle and multi-particle systems.

This dissertation makes a methodological and theoretical contribution to the study of students' conceptualizations of simplification assumptions in the modeling process. The methodological contribution includes a category system that was formulated to serve as an analysis tool, which specifies the extent in which students portray expert-like motivations for simplification and consider the components of simplification assumptions that are used by physicists. The theoretical contribution relates to the data analysis collected from the midterm exam, and to the two case-studies investigated in the context of students' final projects. The analysis characterizes students' perceptions which were shaped through their exposure to the Particle Dynamics unit combining knowledge in physics, programming and scientific modeling. The findings showed that at least half of the students developed rich and complex views of the simplification process: they perceived the goals of modeling in relation to the phenomena measured, discussed timescales to characterize models, and understood the key characteristics of coarse-grained modeling. These results suggest that interested and capable high school science students can develop expert-like simplification approaches to coarse-grained and fine-grained modeling.