Soft Matter

EDITORIAL

The challenge of teaching soft matter at the introductory level†

Cite this: *Soft Matter*, 2013, **9**, 5316

Edit Yerushalmi

DOI: 10.1039/c3sm90028b

www.rsc.org/softmatter

Teaching soft matter at the high school or introductory undergraduate level might seem a strange choice: could students struggling to understand ideal gases learn to model the complex phenomena of molecules that self-assemble into mesoscopic or larger-scale aggregates, such as polymers or membranes? On the other hand, the traditional focus of disciplinary science curricula on ideal systems of non-interacting particles does not expose introductory-level students to the wide variety of fascinating and important phenomena that exist in interacting molecular and macromolecular systems. Neglecting a quantitative discussion of cooperative behavior in interacting multi-particle systems fails to equip students with the conceptual tools that are fundamental to the understanding of many phenomena at the heart of physics, chemistry, biology and materials science. In particular, it fails to provide an important part of the intellectual foundation that science and engineering students are likely to need in their future fields of study.

Can one define a set of powerful enough concepts that can be feasibly taught in introductory level courses, which would allow students to simplify and analyze complex multi-particle systems? Moreover, can one introduce an interdisciplinary topic such as soft matter in a quantitative and systematic manner, thus, serving to remedy the compartmentalized manner in which introductory science courses are commonly taught at the high-school level and to promote recognition of the importance of interdisciplinary approaches in current scientific research and technology? And, last but not least, how should one incorporate such content into the already busy program of high school or introductory level students?

Based on my experience in leading the development, research and teaching of an interdisciplinary program for high school students entitled "Soft and messy matter", I maintain that soft matter is an appropriate choice for an introductory level interdisciplinary course that supplements the core science courses that students take in the field in which they major. On a practical level, I note that the central methods used to teach the theory can be presented in a manner suited to the mathematical background of high school students. In addition, the concepts do not require extensive scientific background such as complex mechanics, electrodynamics or quantum mechanics. They also focus on everyday materials near room temperature and atmospheric pressure, which are familiar to students.

The program on "Soft and messy matter" is an ongoing project that involves a group of scientists and science educators at the Weizmann institute. It introduces a unified and quantitative approach to analyze the statistical thermodynamic and structural properties of systems of interacting particles of interest to applications in chemistry and biology, such as colloidal dispersions, amphiphilic self-assembly and polymer networks. It was taught in three cycles to interested and capable 11^{th} and 12^{th} grade science students, whose major subject was either advanced level physics and/or chemistry. To bypass the constraints of rigidly fixed school curricula, the course was taught as a regional program within the well-equipped labs of a university outreach center.[1] It encompassed bimonthly afternoon meetings and granted matriculation credit for independent experimental projects.

In addition to this more specialized program, the place of soft materials in introductory level courses is also related to calls for reforms of undergraduate life science education (2004 National Academies report Bio2010,[2] 2009 Scientific Foundations of Future Physicians[3]). These reports advocate greater integration of biology in the introductory physics course for life science students, including pedagogies centered on solving complex, real-world scientific problems that require interdisciplinary tools. Follow-ups to these reports were meetings such

Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel, 76100. E-mail: edit.yerushalmi@weizmann.ac.il

† This article is part of a collection of editorials on Soft Matter Education.

as the 2009 conference on Physics in Undergraduate Quantitative Life Science Education and projects such as NEXUS,[4] a multi-university multi-disciplinary project focused on the development of an introductory physics course appropriate for the analysis of biological systems.

In determining the most powerful but still manageable set of concepts that would allow introductory level students to study multi-particle systems, we followed the proposal of prominent science educators (Reif[5] and Chabay and Sherwood[6]) to use a microscopic, statistical presentation as a way to help students associate concrete meaning with abstract thermodynamic concepts. Pioneering introductory physics curricula such as Matter and Interactions[7] have implemented this approach, emphasizing the atomic nature of matter, intertwining mechanics and thermal physics. This approach was successfully implemented with both first-rate students at upper tier universities, as well as with more average students. Inspired by this approach, we anchored many of the topics in the "Soft and messy matter" program to lattice gas models, initially to introduce entropy, and later to model the phase behavior of fluid mixtures, wetting of interfaces, self-assembly of surfactants, and polymers from a statistical perspective.

Students enter high-school (and commonly graduate education) thinking that there are only three states of matter (liquid, gas or solid), based both on their experience and on what they are taught. Thus, we began the program with discussions of unconventional materials such as silly putty, which takes on the properties of a solid or fluid, depending on the time scale of the applied force. To allow for variations in the prior, middle school education of the students, we took a spiral approach, first discussing in a qualitative manner fundamental principles and concepts of statistical thermodynamics. We applied this terminology to have students explain an experiment on "Egyptian ink", described in the popular book by P. G. de Gennes and J. Badoz.[8] This experiment required students to explain that in some cases the colloidal particles remain dispersed (entropy-dominated) and in other cases the particles aggregate, due to large attractive interactions between them, which dominates the entropy of dispersion.

We then moved on to a more quantitative analysis of the phenomena. We discussed configurational entropy in terms of a lattice model in the context of binary mixtures; this has not only scientific but also pedagogical advantage over the more traditional presentation of entropy associated with energy distributions in the context of a continuum ideal gas. The lattice model allows for concrete visualization, which supports the abstract derivations used later on that predict the equilibrium properties of systems of interacting particles *via* free energy minimization (*i.e.* phase separation). Moreover, this construction allows us to make explicit the simplifying assumptions that are needed to derive the mean-field expression for the internal energy of the system. These simplifications allow us to approximate the free energy change upon mixing without considering the partition function, making it appropriate for introductory students.

We further applied the principles of a free energy minimization to specific soft matter systems in which inter-particle interactions are important, such as wetting/capillarity, self-assembly, and polymers. To scaffold students' understanding we used concept maps, which make explicit the major steps in applying statistical thermodynamics principles to construct simplified, theoretical models for the equilibrium behavior of common soft matter phenomena.[9] All these maps involved a common set of steps, which include appropriately defining the phenomenon of interest and its experimental manifestation, identifying the macroscopic degrees of freedom, and the construction of a simplified model of the system. The internal energy and entropy are calculated and combined to yield the free energy, which is then minimized with respect to the relevant degree(s) of freedom to predict the thermodynamic behavior of the system (for an example, see Fig. 5 and 9 in ref. 9). Such an approach allows students to understand how the competition between interactions and entropy is resolved, to determine how molecules self-organize to form mesoscopic structures.

The problem of phase separation of similarly sized molecules required quite a significant time investment by the introductory level students. To keep them motivated, it is important to show them that what they learned can be extended to the analysis of more complex soft-matter systems. However, treating more complex systems in detail would burden students with even more tedious derivations. We bypassed this challenge by presenting the core of the derivation mapped onto previously studied theory. As an example of how one can extend the problem of similarly sized molecules to polymers in solution, we introduced a research paper by Shultz and Flory[10] using the method of adapted primary literature (APL).[11] APL is a text genre that retains the authentic characteristics of primary literature, while making it accessible to high school students; this allows the instructor to acquaint students with authentic scientific discourse. Specifically, we re-structured the text, mapping the theory of polymer solutions onto the model for binary mixtures of small molecules of equal size that was already studied in class.[12]

However, we found that when students were asked to identify the major steps behind the theory presented in the adapted research paper by Flory they focused almost exclusively on the stages that entail quantification of the interactions and the entropy. The stages related to the selection of the relevant degrees of freedom and the construction of the simplified model were either absent or mentioned only in an implicit manner in students' worksheets. These findings suggest that one must provide more instructor support so that students understand how the degrees of freedom are chosen and the model itself is developed.

Finally, our program also provides students with an opportunity to conduct experimental or computational inquiry projects that allow them to apply the concepts they have learned. In a final paper, they are expected to discuss their experimental observations in the light of theoretical analysis. However, we do not expect students in high school to construct the analytical analysis in an autonomous manner. We resolved this tension by having students determine the phenomenon and research question they would study and set up the experiment or model the phenomenon computationally in a simulation. However, the analytical scientific explanation was reconstructed from an explanation presented in a primary source (published scientific paper). Examples of these projects include observations of changes in wetting and in micellization as the system properties were changed, as well as simulations of lipid rafts.

To help the students link the simple analytical models taught to more complex systems, we are currently exploring the use of computational modeling tools with a strong visual component. This also supports the development of basic physics concepts, even before they are introduced in a more formal, analytical presentation. Computational modeling also allows students to develop some intuition regarding the dynamical approach to equilibrium, the meaning of entropy *etc*. Integrating computational models of various types (molecular dynamics, Monte Carlo) to represent simple phenomena such as random walks will also allow students to explore the nature of models in physics.

Our program has shown that students who take a supplementary, introductory level course in soft matter can learn to quantitatively understand basic statistical thermodynamics and its applications to cooperative behavior in interacting multi-particle systems, which are important in current research in a wide cross-section of physics, chemistry, biology and materials science. Being able to understand the spontaneous formation of the complex and beautiful structures in the world surrounding them is not only motivating for young minds, it also equips them from the start with a language and vision of science that is coherent rather than fragmented.

Edit Yerushalmi, Weizmann Institute of Science, Israel

References

1 School of Contemporary Science at the Davidson Institute of Science Education, Weizmann Institute of Science.
2 National Research Council, *Bio 2010: Transforming Undergraduate Education for Future Research Biologists*, National Academy of Sciences, Washington, DC, 2003.
3 *Scientific Foundations of Future Physicians*, AAMCHHMI Committee, Washington, DC, 2009.
4 http://www.hhmi.org/grants/office/nexus/.
5 F. Reif, Thermal physics in the introductory physics course: Why and how to teach it from a unified atomic perspective, *Am. J. Phys.*, 1999, **67**, 1051.
6 R. W. Chabay and B. A. Sherwood, Bringing atoms into first-year physics, *Am. J. Phys.*, 1999, **67**, 1045.
7 R. W. Chabay and B. A. Sherwood, *Matter and Interactions: Modern Mechanics*, John Wiley & Sons, New York, 2002, vol. 1.
8 P. G. de Gennes and J. Badoz, *Fragile Objects: Soft Matter, Hard Science, and the Thrill of Discovery*, Copernicus, New York, 1996.
9 E. Langbeheim, S. Livne, S. A. Safran and E. Yerushalmi, Introductory physics going soft, *Am. J. Phys.*, 2012, **80**, 51–60.
10 A. R. Shultz and P. J. Flory, Phase equilibria in polymer–solvent systems, *J. Am. Chem. Soc.*, 1952, **74**, 4760.
11 A. Yarden, G. Brill and H. Falk, Primary literature as a basis for a high-school biology curriculum, *J. Biol. Educ.*, 2001, **35**, 190–195.
12 E. Langbeheim, S. Safran and E. Yerushalmi, Design guidelines for adapting scientific research articles: an example from an introductory level, interdisciplinary program on soft matter, *AIP Conf. Proc.*, 2013, **1523**, 23–26.

