Supporting and Sustaining the Holistic Development of Students into Practicing Physicists

Elizabeth Gire*, Mary Bridget Kustusch†, and Corinne Manogue†

*University of Memphis, Memphis, TN 38152
†Oregon State University, Corvallis, OR 97331

Abstract. This PERC workshop leveraged the broad expertise inherent in the PERC community to begin structuring a research agenda that might guide future efforts to support the holistic development of students into practicing physicists. In small groups, participants identified and discussed those concepts, habits of mind, skills, and representations that thread through the sub-disciplines of upper-division physics. Then separate small groups and later the whole group discussed the following questions: 1) What are the characteristics of curricula that scaffold student acquisition of these concepts, habits of mind, skills, and representations throughout the upper-division? 2) What aspects of institutional culture might facilitate the development, support, and sustainability of these curricula? 3) What models of research are currently available to address the questions above and where are new models needed? The conclusions of this workshop are summarized here for the benefit of the entire community.

Keywords: Upper-Division, Curriculum, Instructional Goals, Research
PACS: 01.40.-d

INTRODUCTION

In its 2003 Spin-Up Report, the National Task Force on Undergraduate Physics investigated thriving physics departments. [1] Their site visits and survey revealed that such departments share a number of characteristics including several relevant to the curriculum for majors: "A widespread attitude among the faculty that the department has the primary responsibility for maintaining or improving the undergraduate program, …" "A challenging, but supportive and encouraging undergraduate program that includes a well-developed curriculum, ..." "… a clear sense of the mission of its undergraduate program." and "A strong disposition toward continuous evaluation of and experimentation with the undergraduate program."

At approximately the same time as the Spin-up Report, curriculum development specialists began to turn their attention from their foundations at the lower-division level to upper-division physics. Findings about the importance of active engagement in the learning of students began being adapted to this new level. Simultaneously, a few physics education research groups began to study the unique needs of these nascent physicists and to evaluate the success of reformed curricula (For example, see the references in the AJP Resource Letter on active learning [2]).

Much of the upper-division work that is being done can be identified with traditional physics sub-disciplines: electromagnetism, quantum mechanics, thermal physics, *etc.* However, some of the requirements at this level (*e.g.* a greater need for synthesis and higher-order thinking skills in students) argue against taking a completely siloed approach.

Fifteen years ago, while those coming from the lower division, were building from the bottom up, the Paradigms in Physics project at Oregon State University began taking a holistic approach that looked at the upper-division curriculum from the top down. [3] This project has produced and classroom tested more than 200 upper-division activities and sequences of activities that are designed to meet goals conceived from thinking about the curriculum as a whole. [4] These curricular materials are being beta tested by faculty at institutions that do not share the radical course structure at Oregon State.

Now that the top-down and bottom-up approaches are beginning to meet in the middle, it seems timely to attempt to define the current state of the upper-division physics curriculum, share lessons learned, and evaluate the potential for growth of this emerging field. This article is a report based on a PERC workshop designed to leverage the broad expertise inherent in the PERC community. We hope the results may be useful in guiding various research agendas nationally that aim to support the holistic development of students into practicing physicists.

After a brief introduction to the goals of the workshop, participants, divided into three groups and, facilitated by the workshop leaders, identified and discussed concepts, habits of mind, skills, and representations that thread through the upper-division physics curriculum. After reporting out to the whole group, each group discussed either the curriculum, the culture, or the research that might support student development. The workshop concluded with a whole group discussion of these topics. The next four sections of this paper represent the authors' evaluation and synthesis of the discussion into themes.[1] We conclude with a short discussion.

THREADS IN THE UPPER-DIVISION

What concepts, habits of mind, skills, and representations thread through the sub-disciplines of upper-division physics?

As one might imagine, the list quickly became rather extensive, but there was a great deal of overlap among the groups and several themes emerged. Most groups focused their discussion in two ways: what professionals do and what students should do to become professionals.

Modeling: Since one of the primary tasks of physics is to model the physical world, it is vital for students to understand the importance of modeling, the connection between reality and models (both physical and mathematical), as well as between model and experiment. Additionally, students need to be able to understand and assess the approximations, assumptions, and limitations of models. An important part of this process is learning how to incorporate new information and make predictions about qualitative and quantitative consequences of that information. With the rise of computational modeling in almost every sub-discipline of physics, it is also imperative that students develop computational skills.

Synthesis: A common thread in every group's discussion was the importance of making connections and synthesizing knowledge. In addition to the connections just discussed, there were several others mentioned: connections between mathematics and physics, synthesis of multiple ideas within a topic to develop deep understanding, and isomorphism between sub-disciplines, including mathematical skills that cross content (*e.g.* Taylor series, complex numbers). Two groups also raised some aspect of representational fluency: being able to parse complex and nested representations, coordinate between multiple representations, assess the appropriateness of a representation for a given context, and generate new representations when appropriate.

Metacognition: Groups also discussed the necessity for sophisticated metacognition, (*e.g.* checking and evaluating one's goals, progress on the current task, and whether one needs additional resources.) It is also important to recognize the extent and limitations of one's knowledge (*i.e.* when you know and don't know something). Additionally, there was discussion about the importance of learning to value failure as a stepping-stone, as opposed to a stumbling block.

Research: The groups strongly highlighted the need for students to be able to conduct research. In particular, they must learn to be comfortable with unstructured problems, understand the iterative nature of attacking these kinds of problems, and develop the perseverance for dealing with these kinds of problems. Additionally, they need to learn how to design a plan for research, represent and interpret data, identify and deal with outliers, and assess when one has a real result as opposed to anomalous data.

Collaboration and Communication: Since these students are becoming a part of a larger scientific community, they need to recognize the importance of collaboration and to develop the skills to collaborate well, which includes the ability to communicate effectively within the discipline. In particular, they need to learn how to parse scientific texts and graphs, as well as develop skills (such as using precise language and presenting ideas in a logical manner) to accurately convey ideas to others in conversation, writing, and presentation.

CHARACTERISTICS OF CURRICULA

What are the characteristics of curricula that scaffold student acquisition of these concepts, habits of mind, skills, and representations throughout the upper-division?

What is curriculum?: This group struggled to find a functional definition of curriculum and spent most of its short time articulating what might best be described as a number of different organizational strategies for the upper division. One participant suggested focusing on the driving themes underlying each course. Another suggested that the curriculum typically follows the same types of problems from the lower-division, through the upper-division, and into graduate work, adding more details at each level. A variant of this strategy, suggested by another participant, would be to use the lower division as a starting point, and then, in the upper-division recapitulation, also to bring in new topics which students did not have the tools to address earlier. Another participant suggested presenting the tools students need and then organizing the curricular structure around the topics that use each tool.

The Role of Experiment: In a related discussion, one participant inquired why upper-division labs are so often seen as an addendum to the curriculum, proposing that they should be a more central feature.

[1] The authors all have a connection with the Paradigms in Physics program (CAM is the Director of the program, MBK is a current postdoc, and EG is a former postdoc and now external evaluator of a dissemination grant)

Upper-division labs can be especially valuable in emphasizing the synthesis between different physics sub-disciplines and to emphasize conceptual themes. It was pointed out that upper-division labs require more theoretical background than lower-division ones, but that theoretical classes often don't require much experimental knowledge. One participant mentioned examples of theoretical courses in which students are asked to reason with an experimental mindset, for example to "design" experiments that would represent various thermodynamic partial derivatives as an aid to understanding what it means to hold a physical quantity, such as entropy, constant. An extreme example of using labs as an organizational strategy was the suggestion that we use a (partially) or completely project-based curriculum so that the classroom would model what physicists actually do.

Curriculum vs. Pedagogy: This group also rapidly realized that it was impossible to discuss curriculum independent of pedagogy and that the pedagogy behind the curriculum might be more important than the curriculum itself. This led to a lively discussion about the differences between "telling," asking students to figure out a concept on their own, and points in between.

Small Departments: This group acknowledged that the particular affordances of small departments might facilitate changes in curricular structure.

Open Questions: The group also articulated a set of questions whose answers might determine the nature of curricular change. We blame the curriculum for a lack of synthesis, but does our current curricular structure facilitate synthesis? Does the transition from lower division to upper division, as currently enacted, create a proper scaffold for the students? Should the curriculum more explicitly address the cyclical nature of model development and experiment? Many of the goals articulated in the previous section are nebulous and imply that we know where students will end up. Do we want to develop physicists as we know of physicists, or are there other models to which we should be open? How can we help faculty remember to emphasize synthesis in their teaching?

INSTITUTIONAL CULTURE

What aspects of institutional culture might facilitate the development, support, and sustainability of these curricula?

Although the participants acknowledged that physics departments exist in broader institutional cultures that ultimately impact physics programs, the discussion of this question primarily focused on culture at the departmental level that might support the desired student development.

Valuing a Broad Set of Skills: Upper-division instruction should emphasize the development of a broad set of skills relevant for future success in a variety of trajectories, including research activities, graduate courses, and both academic and non-academic careers. Explicit reward structures for these skills should exist (*e.g.* contribute toward a course grade or academic credit) to emphasize their value.

Explicit Development of Goals for Faculty and Students: The department should develop a set of goals for both faculty and student performance within the curriculum. These goals should be made public so that they may be recognized, negotiated, and put into practice by these groups.

Sense of Community: Departments should strive to develop an inclusive sense of community that includes both student and faculty groups. This community should ideally allow for interactions between students and faculty so that faculty can model desired behaviors for students as well as coach students as they themselves begin to enact those behaviors. To facilitate these interactions, departments might establish formal mechanisms for informal interactions (*e.g.* regular "tea times"). Additionally, the department should establish a sense of community among the faculty as collaborative educators. These faculty might work as a team to develop instructional goals and practices, and observe each other's teaching to provide constructive feedback and professional development.

Errors as Productive Opportunities: As a particular example of professional practice, participants reemphasized the importance of establishing a culture where failure is valued as a stepping stone for learning rather than a stumbling block. Faculty should model troubleshooting practices and graceful recovery from mistakes to make forward progress on the task at hand.

MODELS OF RESEARCH

What models of research are currently available to address the questions above and where are new models needed?

This discussion primarily focused on research designed to assess the degree to which physics majors are transitioning into professionals, with the understanding that this would naturally include assessment of curricula and understanding of institutional culture as well.

Theories of Learning vs. Methodology: The issue of collaboration and community became important in the discussion of research models. It was pointed out that the majority of threads identified in response to the first question were framed in terms of individual behavior. However, if one takes a more social theory of learning (*e.g.* Communities of Practice [5]), then these behaviors would be in response to and in the context of a community. A theory of learning like this would then influence the questions one would ask and the methodologies one would use.

Current models: In assessing the strengths, scope, and limitations of current research models and methodologies, the group focused on how upper-division courses, content, and the threads discussed above differ from those in the introductory courses. It was acknowledged that current methodologies for understanding students at the introductory level are rich and varied (*e.g.* conceptual diagnostics, attitudinal surveys, micro-analysis of videos) and that many could continue to be used to assess the upper-division.

Conceptual Knowledge: One of the significant limitations to applying current research models to the upper-division is the high degree of synthesis required at the upper-division, as discussed several times above. Thus, disparate foci on conceptual knowledge or mathematical skills alone falls short when looking at the more complex reasoning required of our physics majors. They must blend conceptual physics knowledge with conceptual mathematics knowledge and mathematical skills. Thus, research at the upper-division must use a more holistic perspective.

Identity: Additionally, in order to study how students transition into being physicists, we also need to find ways to address issues of identity that may be different from those used at the introductory level. Toward this end, the group spent time considering what it means to be part of the scientific community: whether it requires the community to acknowledge one's membership and/or whether one self-identifies as part of the community. There was recognition that to become practicing physicists, students must not only learn the language of and be willing to assimilate into the current community, but must also be willing and able to contribute to and challenge it as well. Additionally, it was pointed out that a significant part of being accepted as a part of the community is one's content knowledge. Thus, research on identity cannot be divorced from research on content, and vice versa.

New models: Finally, in considering how to incorporate issues of identity and a more holistic perspective on knowledge into new avenues of research, it was acknowledged that the need to take so much complexity into account could potentially be overwhelming and paralyzing. Thus, the group suggested that one could restrict oneself to a single topic that spans several sub-disciplines (such as the use of complex numbers) or one that employs multiple representations (such as the infinite square well in quantum mechanics). This would allow one to fully explore the complexity of knowledge in that topic. Then, to address some of the issues of identity, one could explore how the professional community engages with that topic and compare it to how our students engage with the same topic.

DISCUSSION

The differing viewpoints expressed by the workshop participants appear at first glance to be overwhelmingly broad and in some cases, may be mutually exclusive as organizing principles for building an upper-division experience for physics majors. What was particularly interesting to the authors is that there was no verbalized dissension amongst the participants about the expression of these various viewpoints. While the participants may have been just being polite to each other, it seemed rather that all of the ideas expressed were shared values, even if difficult to reconcile within a single organizing curricular structure. We feel that this question of complex shared values warrants further investigation.

When we asked participants to list concepts and skills that span the physics sub-disciplines, we expected answers such as "waves" and "Fourier series." We were surprised when most of the workshop discussion focused at a more encompassing epistemological level. It would be intriguing to examine whether this perspective is common among physics faculty or is more exclusively characteristic of the PERC community.

ACKNOWLEDGEMENTS

The authors would like to thank the 18 workshop participants who so generously shared their ideas, expertise, and time. Our special thanks to the volunteer notetakers! This work was supported in part by NSF grant DUE 1023120.

REFERENCES

1. R.C. Hilborn, *et al.*, editors. Strategic Programs for Innovations in Undergraduate Physics: Project Report. AAPT, College Park, MD, 2003, available at http://www.aps.org/programs/education/undergrad/faculty/spinup/spinup-report.cfm.
2. D.E. Meltzer and R.K. Thornton. *Resource Letter ALIP-1: Active-Learning Instruction in Physics*, American Journal of Physics, **80**, 478 (2012).
3. C. A. Manogue, *et al.*, *American Journal of Physics* **69**, 978 (2001); C.A. Manogue and K.S. Krane, *Physics Today* **56**, 53-58 (2003).
4. Paradigms materials can be found at the website: http://www.physics.oregonstate.edu/portfolioswiki
5. E. Wenger. *Communities of Practice: Learning, meaning, and identity*. Cambridge University Press (1998).