

Upper-Division Activities That Foster “Thinking Like A Physicist”

Corinne A. Manogue¹, Leonard Cerny¹, Elizabeth Gire², Donald B. Mountcastle³,
Edward Price⁴, and Emily H. van Zee⁵

¹*Department of Physics, Oregon State University, Corvallis, OR 97331*

²*Department of Physics, Kansas State University, Manhattan, KS 66503 and
Department of Physics, University of Memphis, Memphis, TN 38152*

³*Department of Physics and Astronomy, University of Maine, Orono, ME, 04469*

⁴*Department of Physics, California State University San Marcos, San Marcos, CA 92096*

⁵*Department of Science and Mathematics Education, Oregon State University, Corvallis, OR 97331*

Abstract. In this targeted poster session, curriculum developers presented their favorite upper-division activity to small groups of session participants. The developers and participants were asked to identify hidden curriculum goals related to “thinking like a physicist” and discuss how the different styles of activities might help students achieve these goals.

Keywords: upper division, active learning, “thinking like a physicist”.

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INTRODUCTION

This article is a report from a targeted poster session *cum* research working group. Five curriculum developers were asked to present their favorite upper-division activity to small groups of session participants. The developers and participants were asked to identify aspects of the activity that engage students in “thinking like a physicist”, the in-class actions of the instructor that foster this skill, and the types of resources that students must employ when working with the materials. The group as whole then discussed the affordances of different activities and attempted to reach a rich description of what “thinking like a physicist” means and how we can foster these capabilities in our students.

GOALS

The participants in this PERC session, viewed as experts in teaching, curriculum development, and/or physics education research, were asked to brainstorm a list of hidden curriculum goals. Only 15 minutes were spent on this activity, so the list cannot be expected to be comprehensive, nevertheless, their list might be expected to include examples of many if not most of

the categories that this group particularly values. Here is their list, divided by the first author into categories.

- ❖ Modeling
 - Understand assumption *vs.* fact *vs.* principle *vs.* theory
 - Know how/when to refine, reject, reconsider models.
 - Evidential reasoning
 - Model building, limits, validity, tests of the model, knowing what a model is.
 - Apply math to do something with the model
 - Assumptions/estimates
- ❖ Epistemology—problem-solving
 - Equation as a math description of the physics model (not entity in itself from equation sheet)
 - Can’t see the endpoint and ok with that
 - Willing to make mistakes (view as an opportunity)
 - Question everything
 - Know that problems are solved in degrees
 - Know that useful understanding is almost always incomplete
- ❖ Epistemology—other
 - Aware of the developmental nature of science—answers generate new questions
 - Connectivity & structure of the discipline (physics)

- ❖ Skills
 - Fundamental basic problem solving skills
 - Interpret using multiple representations
 - See how solution is modified as you go deeper
 - Good at some experimental/computational interface (labview/Matlab etc.)
 - Longer multistep problems
 - Representational fluency
 - Lab skills
 - Choose/design
 - Carry out
 - Evaluate results
 - Read & synthesize research paper.
 - More content (physics and math)
 - Advanced math facility
- ❖ Communication
 - Talking & writing
 - Communicate ideas—ability to articulate what they want to express.
 - Scientific discourse/argumentation
 - Critique claims—*e.g.* alternate explanations
- ❖ Community/professional identification
 - Co-community of physics students who collaborate, learn how to study (identity/agency).
 - Collaborative learning/team
- ❖ Metacognition
 - Consciously aware of productive and unproductive learning strategies that they employ.
 - Know what to do when they don't know what to do
 - Know when they do or don't understand something
 - Evaluate reasoning
 - Identify what they do/do not understand
 - Assess own skills (necessary but not sufficient for confidence)
- ❖ Confidence
 - Being more comfortable with open or ill-defined problems and recursive approaches.
 - No fear of mistakes
 - Autonomy
 - Independent thinking

THE ACTIVITIES

Two of the presenters have separately written their presentations for these proceedings: Dedra Demaree, from Oregon State University, describes employing an “ISLE”-inspired philosophy in an upper-division quantum mechanics group activity in: *Applying ISLE ideas to Active Engagement in the Spins Paradigm* [1].

Steven Pollock, from the University of Colorado, describes using Concept Tests in his upper-division E&M course in: *The use of concept tests and peer instruction in upper-division physics* [2].

Kinesthetic Activities

In the Paradigms in Physics program [3] at Oregon State University, a number of different pedagogical strategies [4] are used to enhance student learning. Several of these activities have been analyzed with narrative interpretations [5]. As one example, kinesthetic activities that require students to interpret a physical situation or concept with movement and postures help students visualize spatial relationships, tapping into their embodied cognition [6].

Elizabeth Gire, from the University of Memphis, presented a kinesthetic activity in which students use rulers to represent a vector field and a hula hoop to represent a surface. The class discussion focuses conceptually on what contributes to the flux. The kinesthetic activity then provides an opportunity for students to connect these conceptual and formal ideas with geometric and spatial reasoning. For example, the class can discuss how to decide the direction of an area element and then rapidly create configurations of vectors and an area element where the flux is positive, negative, or zero. The instructor can bring up the subtlety of including contributions from only the points that lie on the surface of the area element and not from the tips of vector arrows that happen to poke through the area (the rulers/arrows are representations of a physical property, such as electric field, that doesn't take up physical space).

It is recognized that a given style of activity may activate on some of the goals (both content and hidden curriculum) for a given topic. Therefore, kinesthetic activities are typically situated among other pedagogies. The flux kinesthetic activity is preceded by an activity where students are prompted to write down something they know/remember about flux on a personal whiteboard. The purpose of this small whiteboard question is for students to brainstorm and try out writing down their ideas in a representation of their choice. The instructor can display some of the boards to the rest of the class and facilitate a discussion about them, drawing attention to the elements that are important to the concept of flux (a static vector field, an area, the vector nature of an area, the amount of the field perpendicular to that area, integrating over the area), different ways to represent these elements (symbolically, equations, with a picture), and perhaps some familiar, specific cases.

A Maple activity then allows students to explore the flux of the electric field through a cubical surface

due to a point charge. The position of the point charge can be varied so that there are different amounts of flux through each of the six surfaces. Students rapidly seek the special cases that they think might test the bounds of the code by placing the charge on a face, edge, or vertex of the cube and are able to verify Gauss's law for these contexts.

Finally, students engage in a compare and contrast activity in which they are asked to work in groups to find the electric field using Gauss's Law for either a spherically or cylindrically symmetric charge density on a shell of finite thickness. Students must make explicit symmetry arguments using *Proof by Contradiction* as part of their solution.

“Compare & Contrast” Activities

Ed Price uses “compare and contrast” small group problem solving in his upper-division E&M course at California State University San Marcos. In one such activity in a first-semester upper-division electricity and magnetism course, students develop an integral expression for the magnetic field due to a spinning ring of charge. Specifically, students are given a hoop, told that it represents a ring with total charge Q and asked to work in groups to determine the magnetic field in all space if the ring rotates about its axis with period T . This is a direct but complex application of the Biot-Savart Law requiring students to:

1. requiring application of the operational definition of current to relate the spinning charge to current;
2. determine $|\vec{r} - \vec{r}'|$, a vector calculation best done in rectangular coordinates rather than the natural cylindrical coordinates of the problem geometry;
3. determine the cross product $I \times (\vec{r} - \vec{r}')$; and
4. parameterize the line integral over the ring.

The physical prop (the hoop), is useful in determining the current and the geometry of the problem.

Complex analytical calculations such as this are an important skill for a physicist, and performing this calculation cultivates a number of expert-like practices. The structured setting (in class, with support from the instructor and peers) helps students develop the confidence to tackle a complex calculation. Students are encouraged to draw on analogous earlier work; earlier in the course, they found the electrostatic potential and field due to a ring of charge and can reuse part of those calculations. Once students have an integral expression, different students apply different limiting cases (such as evaluating the integral on the axis and in the plane of the ring). A whole class discussion provides an opportunity to compare results from different limiting cases and to explore the role of symmetry.

At Oregon State University, a study investigating how students break a complex problem into manageable pieces uses video and audio to look at actual student groups in the classroom. Some early results of this research specifically address how students deal with finding the electric current from the spinning ring. The students find this subpiece of the problem surprisingly difficult.

In one case a group of students started with the generalized equation for volume current density $J = \rho v$ and then tried to determine what they knew about the charge density ρ and the velocity v . The group then makes the determination that since they are dealing with a linear charge distribution that they can substitute λ for ρ . Students then use a drawing of the ring to help them think about the quantities λ and v . When the group gets $\lambda = Q/2\pi R$, one student checks the dimensions and units to verify that this is a reasonable result. Another student gets $v = 2\pi R/T$, which allows them to get the result that $I = Q/T$. The group also notes that the current will be in the $\hat{\phi}$ direction.

In other cases, students realized that $I = \lambda v$ and then started trying to remember relevant equations for each of these two quantities. Students often tried to use known formulas involving the angular velocity ω . In some cases they remembered these formulas correctly, but in other cases they had miss-remembered the formulas, which resulted in temporarily having an incorrect answer. With one particular class of 17 students, a total of 18 incorrect equations were stated or written and these errors came from 11 different students. Most remarkably, every one of 18 incorrect equations was different from all the others.

Tutorials

Donald Mountcastle, at the University of Maine, has constructed tutorials in a one-semester classical thermodynamics course and the separate one-semester course in statistical mechanics. Their research results on the teaching and learning of thermal physics at the advanced undergraduate level can be found in [7].

One such guided-inquiry activity (tutorial) addresses the discrete binomial distribution and its approximation by the continuous normal distribution. The in-class binomial distribution tutorial makes extensive use of *Mathematica*® (available on their computer cluster) for making calculations and plots of binomial distributions, their normal distribution models, multiplicity and probability of the $n/2$ macrostate, total number of distribution microstates, etc. all as functions of n , the number of coin flips. To allow more time for group discussion of answers to the tutorial questions in class, they provide a one-line code

for each of several assigned specific tasks for students to complete as homework, bringing their results to class for the tutorial activity.

In groups of 3 or 4, students use their previously completed assigned *Mathematica*® plots as reference to negotiate answers to a sequence of about 20 guided-inquiry questions that refer often to the students' assigned graphs. We give an abbreviated outline here:

- Predict how $\alpha_n(n/2)$ and $P_n(n/2)$ will change as n increases. Explain your reasoning.
- Compare with your graphs and answer again; then compare with your predictions.
- How do the absolute and relative widths of the binomial distribution change, or not, with increasing n ?
- How do the binomial distribution and the normal distribution compare?
- How are they the same? How are they different?
- Are the graph axes the same? Explain.
- Along with your group members, use the results of this activity to either defend or refute the claim of “overwhelming probability” for a single discrete binomial macrostate to emerge in limits of large n .

DISCUSSION

In the summary discussion for the PERC session, some participants focused on specific affordances of particular styles of activities. For example: kinesthetic activities might help students get over their fear of making mistakes. A participant noted that they were quickly forced into doing something, without thinking about it very much. Later, they looked around to see a great variety of different people doing different things and were led to reflect on this. The ISLE-based activity was highlighted for the explicit way it asked participants to look for patterns and then to evaluate their model based on the (theoretical!) evidence. Concept tests were credited with helping students “know what to do when they don't know what to do next,” but only if the instructor's handling of the discussion makes this process of pulling apart the problem explicit.

Communication was the dominant topic of the discussion. One participant commented: “If I want to get them to develop the practices of science, of argumentation, I have to get them talking to each other.” The activities were praised for helping the students “put the vague fuzzy thoughts in their heads into words.” On the other hand, there was considerable disagreement about how open-ended some of the activities were and substantial discussion focused on how the questions and/or the facilitation of the activities might make them more open-ended. The

question arose of who “owned” the questions during the activities.

Community-building came up from two different points of view. For students: it was mentioned that participating in group activities could build or tear apart communities, depending on how the dynamics were handled. Working in groups might help students learn how to work collaboratively, respect other people's ideas, and show students that what they are currently thinking is valued. For faculty: the discussion centered on what activities might most easily be adopted by traditional lecturers and how a group of faculty might choose a common set of goals.

Finally, a brief discussion highlighted the affordances of these activities for the instructor. Participants claimed that the activities would “allow me to hear the students' prior knowledge,” “to view a piece of their development,” and “make student thinking more visible so I can interact with it more effectively.”

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