ASEE 2019 Annual Conference
CHARGED UP FOR THE NEXT 125 Years
126TH ANNUAL CONFERENCE & EXPOSITION
ASEE

Paper ID #27672

Board 44: Engineering Design in Scientific Inquiry

Dr. Leslie Atkins Elliott,

Leslie Atkins Elliott is an Associate Professor of Curriculum, Instruction and Foundational Studies at Boise State University, specializing in Science Education. Her research focuses on fostering participation in the practices of science - particularly writing and design - and how science instruction can reduce barriers between classrooms and everyday life. Her work with scientific practices emphasizes students' rights to their own ideas and the emergence of scientific practices, including design, from disciplinary engagement with those ideas.

Engineering Design In Scientific Inquiry

Abstract

The Engineering Design in Scientific Inquiry (EDISIn) Project addresses the engineering preparation of secondary science teachers by embedding engineering design into a science course for single-subject STEM education majors (future secondary teachers), and developing a sequence of lesson plans and annotated video for faculty who seek to embed engineering design in their science courses. While undergraduate laboratories are rich with designed experimental apparatus, it is rare that students themselves play a role in designing and producing artifacts in the service of scientific inquiry. Our expectation is that (1) existing science courses offer opportunities for students to engage meaningfully with engineering practices, by solving design challenges that emerge in the construction of scientific ideas; and (2) doing so can capitalize on existing curricula that science education has developed, facilitating the adoption of engineering design into preservice teacher education. As part of NSF's Improving Undergraduate STEM Education (IUSE) funding program, this proposal is part of a broader effort to transform undergraduate science education, preparing students to be innovators and leaders in STEM.

Background

The Next Generation Science Standards (NGSS Lead States, 2013) calls for engineering — and particularly engineering design — to be part of students' science education throughout K-12, with engagement in engineering practices integrated into students' learning of disciplinary core ideas. However, few prospective science teachers have an engineering background, nor are they likely to receive even a cursory training in engineering while in their undergraduate degree program. Adding an engineering course to their undergraduate program is problematic for several reasons: (1) the current list of courses that a credential-seeking student must take is already extensive, as they must take courses that address standards from across the disciplines and courses that prepare them to meet students' multicultural, social and developmental needs. Adding a course to that list is often prohibitively difficult. (2) If they could add a course, few universities have existing engineering courses that address the needs of future teachers with respect to the NGSS engineering practices and standards. And (3) not only do few universities have such courses, but we have few models of undergraduate courses that integrate engineering into the development of scientific ideas. That is, while engineering design is central to scientific activity — a critical component of how scientific ideas are constructed — curricular examples of engineering *for* science are rare. Instead, existing curricula that integrate science and engineering primarily treat engineering as an *application* of scientific theory or a way of *engaging* students and inspiring scientific questions (e.g., Apedoe & Ford, 2010). For preservice programs that hope to prepare science teachers to integrate engineering design into the development of scientific content, in ways consistent with NGSS, there are few models to draw from.

The work described in this paper is one step in addressing this need by embedding engineering design into a science course for STEM majors pursing a career in teaching, and developing a sequence of lesson plans for faculty in who teach engineering design to preservice teachers to use. We expect that (1) existing science courses for future teachers offer opportunities for students to engage meaningfully with engineering practices, by solving design challenges that emerge in the construction of scientific ideas, and (2) doing so can capitalize on existing curricula that science education has developed, facilitating the adoption of engineering design into preservice teacher education.

Throughout the three years of this project, we are modifying curriculum in Research Methods (Marder, 2011), a required science course for STEM majors receiving their secondary teaching credential. This course has been adopted and adapted from the University of Texas's widely-adopted model, UTeach, and will be described in more detail below. Our rationale for incorporating engineering design in this course is that:

- the course is a science content course required of all STEM majors pursuing a secondary teaching credential, so the curriculum will reach across STEM disciplines, not just one discipline;
- an analysis of this course — a lab-based course that promotes understanding of scientific research by engaging in student-designed inquiries — suggests that there are significant opportunities to engage in a more explicit attention to engineering design; and
- as part of the UTeach program, versions of this course are taught at 44 universities, with a coordinated network of faculty and conferences, thus facilitating dissemination of the curriculum.

In this presentation for ASEE, we will describe the first iteration of this course, focusing on the design challenges that emerged in an inquiry into energy and the ways in which these challenges and their solutions both mirrored and differed from more traditional engineering design challenges. In particular, we call attention to the ways in which "clients" for traditional engineering tasks have their analog in scientific contexts that drive the design considerations for experimental and for representational designs.

The course

Research Methods, a 300-level course in the UTeach program, has historically been used to introduce or strengthen students' understanding of statistical methods in scientific research. In our version of the course (EDISIn), instead of focusing on data collection and arguments that can be statistically supported from that data, we focus on the development of coherent, mechanistic models of phenomena, and a range of ways in which students can justify those claims.

In addition, while students have always developed and pursued their own research questions in the course, in EDISIn version we do this in a single over-arching context for inquiry, with different groups pursuing questions related to a central phenomenon. In this way, students are more tightly connected as a research community, and serve as a critical audience for one another's work (e.g., Atkins Elliott, Jaxon & Salter, 2016).

Within this context, we explore opportunities for design work, and examine ways in which this work is consistent with the NGSS call for engineering design, and ways in which it is not.

This first semester, we focused on energy - a cross-cutting (CITE) concept across the sciences and engineering, with relevance to all of our majors. In particular, we began with the observation of a Gaussian Gun: a simple arrangement of metal ball bearings and strong disk magnets, as shown at top in Figure 1. When ball A is released, it accelerates towards the magnet, strikes it, and ball D is ejected at great speed. The sudden appearance of kinetic energy is surprising and offers a rich context for exploring potential energy and serves as a context for modeling energy for a range of disciplines. In physics, this arrangement provokes critical questions about modeling potential energy, potential wells and escape velocity (Atkins Elliott, Bolliou, Irving, and Jackson, in review); in chemistry, this generates questions regarding the nature of exothermic reactions, SN-AR reactions, and metastable states (Atkins Elliott, Sippola & Watkins, 2018); and in biology, the core biological transition of ATP to ADP.

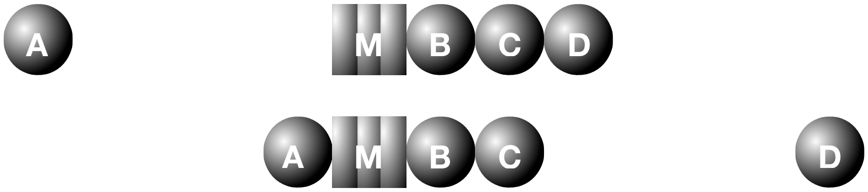

Figure 1. A Gaussian gun of four ball bearings and a set of strong magnets. Top: before release, bottom: after.

The class of eight students, working in three lab groups, developed a range of ideas to explain the phenomenon. Through our conversations with as a whole class and in their groups, the ….

Group A: The "physics" group

As the students debated ideas regarding the origin of the energy in this phenomenon, one student rolled a ball down a three-ring binder to represent the energy of the incoming ball, losing potential energy as it increases in potential - a counterargument to a group locating potential energy in the magnet. This led to a conversation about whether or not this shape - a linear slope - adequately represented the ball's energy as it rolled toward the magnet. With this question posed, the lab of three (one physics major, two engineering majors) sought to characterize and build a slope that re-created the motion of the ball in the Gaussian gun.

Among the challenges they faced was (1) understanding how the shape of a slope would relate to measurable quantities; (2) determining how to measure the relevant quantities; and then (3) how to translate that measurement into a physical slope. Very briefly, their response was to measure the force felt by the incoming and outgoing ball as a function of its distance from the magnet; to develop a technique using a force probe, a "harness" of sorts, and spacers (index cards) to

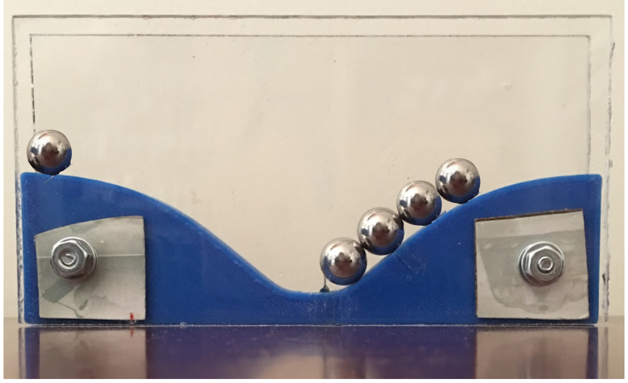

Figure 2. A 3-d printed analog of the Gaussian gun.

measure the force; and then, through a series of iterations, they translated the data to a slope, used a 3D printer to construct slope, and created a simple mechanism (more complex ones failed) to hold the balls in place. This final product is shown in Figure 2.

Research questions relevant to this project are: in what ways are these questions design challenges, or, more specifically, *engineering* design challenges? This will be addressed below; first we describe the work of the two other groups.

Group B: The "chemistry" group

This group of two, one chemistry major and one engineering major, were intrigued by parallels between this interaction and chemical reactions, curious to what degree the analogy between this phenomenon of macroscopic ball bearings and magnets on the one hand, and exothermic reactions between molecules on the other hand, held.

As this group worked, they too first struggled to operationalize their question: what could they do to further explore the analogy? With the idea to construct a reaction progress map, they were then faced with the question of how. In chemistry, these plots are inferred from heat output in reactions, for example, as *moles* of substances react. What does that mean in the context of a physical, tangible analog like the Gaussian gun? And, ultimately, does their final product consistent with the idea that this is a macroscopic model of exothermic reactions?

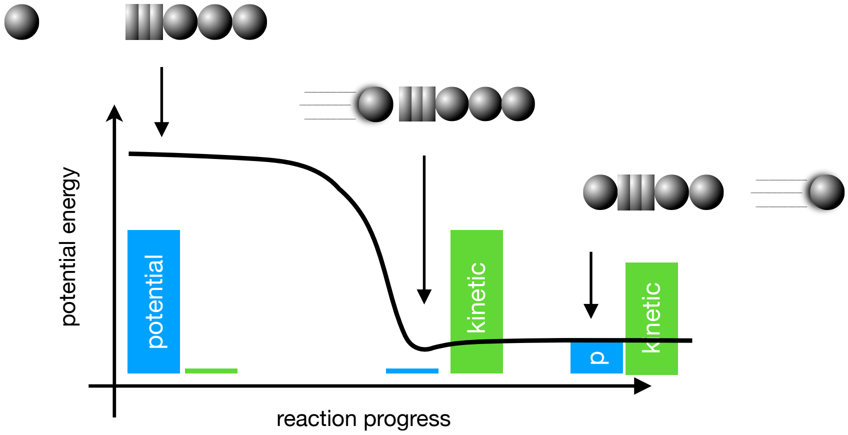

Figure 3. The chemistry group's reaction progress graph.

Ultimately, as they shared ideas and challenges with the other groups, they were led to measure force using a similar technique to the group above, and then translate this not into an energy well but a related potential energy plot. This is shown in Figure 3. The lower energy at the final stage is consistent with exothermic reactions; the presence of a dip in the middle of the plot is what led them to argue that the reaction has a reactive intermediate — a state that would be a stable molecular state were the energy released in the reaction not so great. In addition, this led them to argue that the particular reaction most similar to the Gaussian gun is an SN-AR reaction (a form of aromatic ring).

Group C: The "biology" group

The final group was composed of three biology majors and a computer science major. In our initial debates, this group thought (quite reasonably) that the ejected ball leaves at a higher speed than the incoming ball; they consequently decided that the magnet itself must supply the energy to the outgoing ball. (It was this debate that led the physics group, described above, to construct their argument that the incoming ball has more energy than anticipated, and similar to a ball at the top of a hill.) With a skeptical audience for their claim, they sought to determine the speed of the outgoing ball, as compared to the incoming ball. Here, the design question of how to measure the speed of an object that gains and loses speed very rapidly became the core activity of their group.

This group began by simply using a slow motion camera to capture the motion of the balls in the Gaussian Gun, however it became clear that the motion was too fast to make any claims. (In particular, the incoming ball speeds up exceedingly rapidly in the final millimeter of its path.) The group brought in higher-speed slow motion cameras, but again with no success. They then decided to carry out the reaction in a viscous fluid, brought in maple syrup, and submerged the balls and magnets. While the reaction was slower, it was qualitatively quite different, with the balls separating when struck instead of one ball being ejected. A range of other techniques (motion detectors from physics lab courses, and modifications to those) were attempted. As its final step, the group thought to roll it over a ridged surface and record the sound - anticipating that the faster the ball goes, the higher the pitch (like scratching corduroy or, as one student described it, like "singing roads" made of rumble strips).

After trying to use readily-available ridged surfaces (cds, fabrics), the group found that these did not produce enough sound, and the students 3-d printed a ridged surface, shown in Figure 4. (For this group, it was their first time ever using a 3-d printer, and represented a source of great frustration and, ultimately, pride.)

Figure 3. The biology group's 3-d printed ridged surface to determine speed.

Ultimately, this, too, failed to answer the question — a literature review of rumble strips offered suggestions as to why — but with the semester nearing its end, we never did obtain convincing data on the relative speeds of the two balls.

Engineering design in scientific inquiry

The class was oriented towards developing a scientific model; our task was to explain, or model, the energy in the Gaussian Gun system. As instructor, there was no explicit requirement that students produce any artifact or engage in design as part of the work. That is, our focus as a class was in developing a scientific explanation. The design was emergent from this, rather than a requirement in itself for the course.

Based on the above work that the students did, we pose the following questions regarding design in scientific inquiry:

1. For each group, how did their particular design challenges emerge?
2. What role did their designed artifact(s) play in their inquiry?
3. In what ways did their design mirror the work of design in engineering, and in what ways is it different?

(Additional questions, including the role of constraints, iteration, and “client” are also being explored but are not part of the work described here.) Below, we offer preliminary answers the above questions — the work below is ongoing, and any one of the questions above could constitute a thorough research project in its own right.

How did their particular design problem emerge?

The NGSS distinguishes science and engineering by describing science as one of “asking questions” and engineering as “defining problems.” For all groups, we began with the question of how to model the energy of the Gaussian Gun. For groups A and C, the two groups had competing ideas regarding the source of energy for the phenomenon: did it come from the incoming ball, as Group A argues and seeks to justify via analogy? Or did it come from the magnet, as Group C argues, and which implies the outgoing ball is faster than the incoming ball. This led one group to experimental design challenge (group C): how to measure speed for a fast, and rapidly acceleration object; and another (Group A) towards the design problem of construction of an analog.

For Group B, their work was much less driven by interactions with their classmates, and much more by the gap between their understanding of chemistry and the purported analog to the Gaussian Gun before them. They addressed existing representations from their Chemistry textbook, and became curious about how to replicate that - if possible - with the Gaussian Gun. The emergent design problem — in particular, what measurements to make of the Gun to compare with those made in chemistry — emerged from that gap.

In all cases, we see that a gap - between two group's explanations or between two related ideas - is responsible for the instigation of their design challenge. Such gap is often a rich opportunity for scientific inquiry; we do not do experiments simply to prove known or anticipated phenomena, but, more often, to weigh between competing claims (Atkins Elliott, Jaxon, Salter, 2015; Radoff, 2017).

What role did their designed artifact(s) play in their inquiry?

For Group A, the designed artifact was the goal of their inquiry, and the development of this artifact required developing and justifying a range of claims, including:

- The force is depicted by slope, which decreases the farther you are from the magnet, so it is increasingly easy to pull the ball away from the magnet; this is consistent with a constantly-decreasing-but-never-zero force.
- The energy begins as all potential energy, with the incoming ball having the most potential energy, despite having the least amount of force. At the end, the rightmost ball has gained all of the first ball's energy; most of the energy it gained is now kinetic.
- The minimum speed necessary for a ball to "escape" the well is the escape velocity and is non-zero, as indicated by a finite height.

A more thorough analysis is beyond the scope of this paper, but, we argue, the focus on producing a concrete representation and explicating how it represents the physics of the Gaussian Gun fostered a deep understanding of the physics.

For Group B, the role of a particular concrete designed artifact is less clear; we could argue that their representation (a reaction progress graph), while less tangible, functions similarly to Group A's well. On the other hand, there are decidedly different constraints in creating a printed plot than in producing a 3-d printed artifact. However, in developing a technique to measure the force on the ball, they developed a novel process and artifact.

While, for other groups, we see their inquiry as deepening their understanding of the system to be modeled, for Group C the design challenge took on a life of its own, becoming the focus of their work. For this group, their inquiry became about measurement and construction of experimental apparatus; answering the question of the source of energy was not at the forefront of their work most days. In some ways, this group was then most similar to a "true" engineering design task, developing a solution to a problem; in other ways, their backgrounds - with little experience in physical science and experimental design - limited their ability for this work to generate a solution that would inform their inquiry.

In what ways did their design mirror the work of design in engineering, and in what ways is it different?

A central question for this research is the degree to which design problems that emerge in the context of scientific inquiry are consistent with the work of engineering: if we strive to teach engineering in the context of science courses, can we do so while pursuing scientific ideas, or will the course need to "pivot" if it is to engage students seriously in engineering?

Our preliminary answer for this course is: the parallels between *design for science* and *engineering design* may lie in the degree to which the design problem becomes a problem — one in which a ready solution is not apparent, and multiple solutions must be considered for progress to be made. While all groups engaged in the design of artifacts, it was those whose designs failed where we saw them become truly engaged in engineering design work, with a consideration of a range of solutions, a focus on constraints, a discussion of the goals of the design and what would be "good enough."

Conclusion

We summarize our work - still quite preliminary - as suggesting the following:

1. When students are engaged in developing scientific models, opportunities to engage in design problems emerge.
2. Those opportunities frequently emerge due to a "gap" - a discrepancy between one group's ideas and another's, or a gap between a particular model and a phenomenon.
3. In this context, designed artifacts play a range of roles: some rhetorical (as the gravitational analog of Group A); some experimental (as group C's); and others (Group B) the experimental design was a step towards producing a graph.
4. Deeper engagement in engineering practices took place when a reasonable design solution was not readily constructed.

References

Apedoe, X., & Ford, M. (2010). The empirical attitude, material practice and design activities. *Science & Education, 19*(2), 165-186.

Atkins Elliott, L., Jaxon, K., & Salter, I. (2016). *Composing Science: A Facilitator's Guide to Writing in the Science Classroom.* Teachers College Press.

Atkins Elliott, L., Sippola, E., & Watkins, J. (2018). Modeling Chemical Reactions with the Gaussian Gun. *Journal of Chemical Education*, *96*(1), 100-103.

Black, M. (1962). Models and metaphors: Studies in language and philosophy.
Marder, M. P. (2011). *Research methods for science*. Cambridge University Press.

Lead States, N. G. S. S. (2013). *Next generation science standards: For states, by states.*

Radoff, J. (2017). *Dynamics contributing to the emergence and stability of students' scientific engagement over multiple timescales* (Doctoral dissertation, Tufts University).