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# Tinkering with Theoretical Objects: Designing Theories in Scientific Inquiry

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**Abstract**

The EDISIn Project (Engineering Design in Scientific Inquiry), taught in an undergraduate teacher preparation program, is investigating where engineering design opportunities emerge within contexts of scientific inquiry, with implications for how science teachers might productively engage in engineering design in their science courses without compromising on either the science or the engineering. In some inquiries, the opportunities for engineering were obvious, particularly with respect to novel experimental designs and in developing physical representations of models. In other inquiries, however, the investigations were either largely theoretical or the experimental designs were readily developed without a need for deliberate attention to design practices. However, in these inquiries we notice commonalities between how students iteratively construct and manipulate theoretical objects in pursuit of scientific explanations and theories, and how they construct and manipulate physical objects. In particular, we call attention to playful, iterative, goal-oriented activities that have strong parallels to tinkering within the engineering design literature. In this paper, we provide an analysis of one student's "idea tinkering" as she constructed a model of color mixing. We consider how literature from engineering education might be leveraged to support playful, iterative construction of theories in science - not only for its role in supporting the design of physical objects, but also theoretical objects.

**Overview: Idea tinkering in scientific inquiry**

The study reported here is part of a broader study to identify where opportunities for engineering design emerge in the context of an undergraduate course on scientific inquiry. While students in the course generated rich examples of engineering design - both highly structured activities and informal "tinkering" activities - as they produced *physical* artifacts to support their inquiries, we were also struck by their activities as they produced "*knowledge*" artifacts. That is, there were clear hallmarks of tinkering [1, 2]– playful, iterative, self-directed, unplanned yet goal-directed activity – as students manipulated theoretical "objects" that populated their developing models, particularly for one student, Lainie.[1] This led to the follow question that frames this paper: **how is students' engagement with theoretical objects in the design of theory similar to students' engagement with physical objects in engineering design?** In particular, we will argue that their playful, iterative work with ideas as they construct theory is consistent with ideas from the literature on tinkering, and offers opportunities to think about more substantive overlaps between engineering design and scientific inquiry.

[1] All student names are pseudonyms.

We begin with, first, a brief discussion of the research on tinkering. We follow by describing the broader research context of this study, and then the course in which this work is situated and the scientific ideas students are working towards. We describe and characterize Lainie's work in the course, drawing parallels between her ”idea tinkering” and narratives around tinkering in more physical contexts. Finally, we conclude with implications for instruction and future research.

**Tinkering: defining, affordances and design priciples**
In the context of engineering education, there has been increased interest in the relatively unstructured, informal approach to design that can be described as tinkering. Tinkering activities and orientations are positioned in contrast to more structured activities with instructor-imposed goals that have characterized engineering education. Features of tinkering include its self-directed nature, the role of rapid iteration, minimal planning, a goal-orientation and playful orientation. These descriptions are summarized briefly in Table 1.

| **characteristic** | **description** |
|---|---|
| iterative | “Successful tinkering activities emphasize the processes of pursuing ideas, becoming frustrated, and achieving breakthroughs through one's own ingenuity and persistence” [3]. “We therefore understand tinkering as a disposition towards design and making characterized by iteration” [4] “The tinkering approach is characterized by a playful, experimental, iterative style of engagement, in which makers are continually reassessing their goals, exploring new paths, and imagining new possibilities”[1]. |
| self-directed | “It is in this process that authorship, purpose, and deep understanding of the materials and phenomena are developed” [3]. “The emphasis on participants' own questions and objectives is part of what distinguishes tinkering from engineering challenges that set predetermined goals” [3]. |
| goal-oriented | “participants in tinkering author their own goals and ideas” [5] “Sometimes, tinkerers start without a goal...they begin by messing around with materials ... and a goal emerges from their playful exploration” [1]. |
| playful | “We therefore understand tinkering as a disposition towards design and making characterized by iteration and playful experimentation” [4] |
| improvisational/ ad hoc | “...improvisational, ad hoc approach to a design problem” [6] “Tinkering as a branch of making that emphasizes creative, improvisational problem solving.” [2] |

Table 1. Characteristics of tinkering and descriptions

In addition, the research literature suggests that these characteristics of tinkering can have particular affordances for meeting educational goals, including tinkering as a potential “step” between the initial exploration and more formal solution [7], as consistent with engineering practice [8, 9], as having potential to align with equity goals [4, 10], as allowing for more rapid progress [9], as supporting a social orientation to design [4], and as a valuable form of activity in its own right [9].

Finally, efforts to support students in this playful, iterative, self-directed work has suggested generative curriculum design principles. The literature, often drawing on work from informal education, including ”MakerSpaces,” and museums, highlights the importance of student ownership and authorship in this work [3], of contexts that allow for multiple pathways and solutions [4], of materials that provide rapid feedback [1], and of pedagogies that support an orientation to ”mistakes” as simply drafts to be refined [4].

**The context: The EDISIn Project**

The Next Generation Science Standards [11] 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 science teachers have an engineering background, nor are they likely to receive even a cursory training in engineering while in their undergraduate degree program. The EDISIn Project (Engineering Design in Scientific Inquiry), taught in an undergraduate teacher preparation program, is investigating where engineering design opportunities emerge within contexts of scientific inquiry, with implications for how science teachers might productively engage in engineering design in their science courses without compromising on either the science or the engineering which, researchers note, are goals that are often in tension with one another [12].

The course is based on a prior course for future elementary teachers, Scientific Inquiry [13, 14] – a course in which we knew students frequently created designed artifacts as they pursued scientific models. Scientific Inquiry was initially designed to meet the Inquiry standards from the United States' National Science Education Standards (NSES) [15]. Though more recent standards [11] explicitly integrate the practices of inquiry with disciplinary core ideas (and add engineering design practices, too), the NSES put inquiry and its attendant practices on equal footing with traditional science content. While this structure had drawbacks, it afforded the opportunity to teach an undergraduate science course that de-emphasized 'right ideas' as learning outcomes to focus on inquiry-oriented outcomes. That is, although the focus in the course was developing coherent, mechanistic models of phenomena, students were assessed on how they developed and vetted ideas as a class, and not the canonical correctness of the ideas themselves. The course, then, has no textbook or lab manual, but a range of simple materials, an initial question, and extended weeks of inquiry. The course is more fully described in [13, 16].

In some inquiries, the opportunities for engineering were obvious, particularly with respect to novel experimental designs [17] and in developing physical representations of models [18, 19]. In the inquiry that we describe here, however, the investigations were either largely theoretical or the data collection was so readily obtained that there was no need for deliberate attention to design practices. And yet in these inquiries we notice commonalities between how students iteratively construct and "manipulate" theoretical objects in pursuit of scientific models with the ways they construct and manipulate physical objects – particularly with respect to tinkering.

**The course context**

In the iteration of the course described here, students are undergraduate preservice science and engineering teachers in a UTeach replication site. The semester began with the question: ”is every color in the rainbow?” Students are provided with a range of materials - colored gels, printer inks,

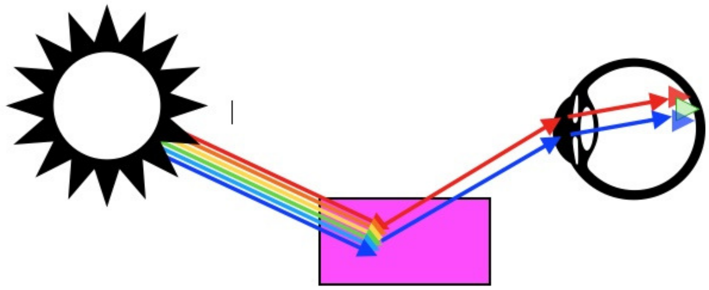

Figure 1: Source wavelengths (left), reflected wavelengths (red and blue), and perception (two cones, indicating magenta.

flashlights, and markers; we also have the science education stockroom of supplies available, with things like scissors, tape, foil, cups, etc. They work in lab groups as they pursue questions that arise from the initial prompt, ultimately working to develop a model of color. We read research in parallel with this, reflecting on scientific inquiry and pedagogy.

To orient readers briefly to the scientific model of color perception (similar to what Lainie will ultimately develop): our perception of color arises from the three different types of cones in our retina, each of which responds to a range of wavelengths of light. Those ranges overlap (for example, the medium wavelength cone responds to wavelengths ranging from 410nm to 650nm; the long wavelength cone responds to wavelengths from 330nm to 680nm). When looking at a colored object, the wavelengths that reach our eye is determined by which wavelengths were emitted from the source, and, of those, which are reflected (or transmitted) and which absorbed by that object. Magenta, for example, is perceived when long and short cones detect similar amounts of light; there is, therefore, no "magenta" wavelength of light. However, there is "magenta pigment" - in that there are molecules that can absorb the middle of the spectrum and reflect the long and short wavelengths of the spectrum. These, essentially, are the constructs and ideas Lainie is beginning to develop.

**Data collection & methods**

We have videotaped each course session. In addition, an undergraduate researcher (the first author on this paper) maintained daily field notes, indexed to the video, to aid in finding particular instances of the course. The instructor (the second author) also summarized the day's activity in her own field notes. All student homework is photographed, as are student notebooks; in-class artifacts (whiteboards, experimental set-ups, etc.) are captured to the degree possible. Note that this semester (Spring 2020) abruptly transitioned online half-way through the term due to COVID-19, and so we have much more limited progress and data for the second half of the term.

For this paper, we began by noticing that while opportunities for engineering design were minimal, we nonetheless saw rich design-like work as students developed a model of color. Rather than interpreting this design solely through the science-education lenses of modeling [20], mechanistic reasoning [21], or sensemaking [22, 23], all of which are relevant, we interpret this through a lens of design. Drawing on the literature on tinkering, we identified five characteristics

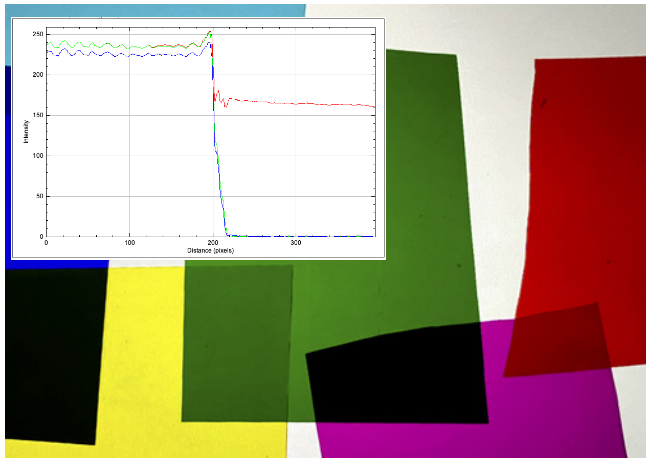


Figure 2: Colored filters. Inset: ImageJ data for white (left) and red (right) regions.

of tinkering (see Table 1), and applied these to one students' work. For the analysis here, we focus on information from Lainie's lab notebook rather than the whole class discussions, as we sketch our argument.

**Lainie's model: Little men, houses, and cones**

Early on in the semester, students realized that increasing the number of red filters decreased the light getting through, but not linearly: it appeared, observationally, to be an exponential drop in transmission as more filters were added. We introduced students to ImageJ [24] for a quantitative measurement of this drop. (This free software - among other things - indicates how much of each "RGB" part of the spectrum is present in a digital image.) With cellphone images of the filters and ImageJ, students collected data on how the light changed after passing through filters. (See Figure 2 for the image and the output of a line of white and then red pixels.) Data, then, includes the brightness for each R, G, and B pixel (from 0 to 255), both with and without the filter (see Figure 2). [2]

Students then described how the red filter attenuated the light. Some described a ratio of the amount of red light that was transmitted as a fraction of the total light transmitted; others considered a different ratio: the amount of red light transmitted as a fraction of the total incident light; still others considered the amount of red light transmitted as a fraction of the red light that was incident on the filter. As a homework assignment, students were asked to consider each of those ratios and decide which was the most meaningful to use for our purposes - that is, in modeling what the filters do to white light.

For this homework, Lainie developed her ideas in her lab notebooks, as seen in Figure 3. She begins by setting a goal for herself, writing in her notebook: "Goal: To create a percentage that represents each component of light. This percentage should be able to be used to predict outgoing in all lighting scenarios and all filter mixes." With that in mind, she starts to interpret the various

[2] Note that some design choices are made in taking the photo: the filters are placed on a white computer screen to capture transmitted light; they do not take a "before" and "after" so that the exposure is consistent in both images. Both decisions are consequential, but also quickly determined.

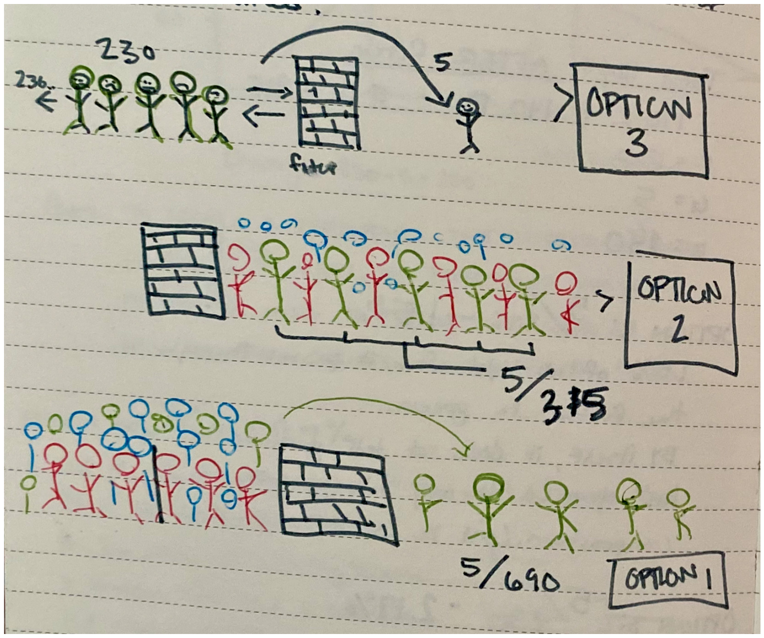


Figure 3: Lainie's description of three different types of ratios for colored light.

ratios. For each, she models the light as what she calls "little men" and the filter as a wall that keeps some little men out. In this analogy, she clearly differentiates between the filter and the color of the light. She is (due to ImageJ) thinking of white light as composed of greens, reds and blues. She "manipulates" these in her diagrams to consider the various ratios others have considered.

Ultimately, she argues that "We care about what happens to individual components of light. [Option3] tells the story. It tells us that there were 230 little men/light, but after it went through the filter 5 remained."

In this vignette, we see a **playful orientation** to the work: she sketches little people and brick walls as she imagines the light interacting with the filter; the work is **self-directed** and **goal-oriented** as she constructs her own sense of why she might create this ratio, and what criteria it should meet. She considers a range of possible ratios and "walks" the little men through those options, **iterating** her work for these. And, we note, that there is an **improvisational** nature to this design work: she is not applying a known theory to a novel scenario to churn out a prediction (common in introductory sciences), nor trodding through a series of steps identified in advance, but developing theory. No two student assignments are the same, nor should they be.

**Lainie's model 2: Little men and houses**

Lainie's model was useful for making predictions; using these ratios, she could predict the color visible from two stacked filters (noting, "I'M SO EXCITED" in her notebook). Over the next classes, we see a range of questions emerge: modeling clearness v. whiteness; yellow as "two things" (yellow light or red and green light); and wondering how can two waves be in the same place and heading different directions.

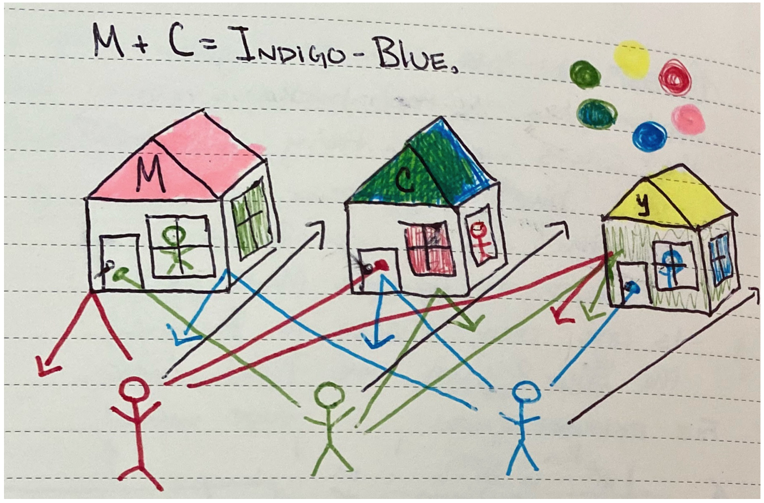


Figure 4: Lainie's description of the interaction of light with ink, modeled as RGB men and houses.

The class begins using inks instead of filters to mix colors, and Lainie mentions in her notes that the yellow ink appears reddish in its concentrated form. She starts to try to model the ink, then, comparing dilute and concentrated forms. In doing so, she creates another theoretical entity to partner with the "little men:" houses, as shown in Figure 4.

In addition to the playful tone we have in class as we pin down the characteristics of these entities (e.g., "little men" cannot be magenta but houses can), Lainie's notebook again suggests she engages with this activity with a **playful orientation**, sketching little houses with men trapped inside, extended the metaphor to talk about "neighborhood" the little men visit. Again, it is **iterative** - she draws multiple versions, some where the insides of the houses are clearly painted the absorbed color; some with houses close together, some more dilute as she jots down the implications of that model and the questions it raises. The work is **self-directed**, stemming from her observations of concentrated ink, and **goal-oriented** as she seeks a model that can explain the data. And, of course, this is highly **improvisational** – a "yes, and..." as she builds on a prior model, extending it to capture a feature she had not considered, again not following a set technique or pattern.

And, like the men, these houses become a locus of inquiry themselves: as Lainie argues, the magenta house traps green men; cyan traps red; yellow traps blue. They construct arguments for possible colors of houses. There could be a white house; a black. Initially the men "bounce" off of houses or are trapped inside. Ultimately she will argue that the trapped men must convert to heat, while the other men pass through (for filters) or reflect (for paints). That is, in the design of theory we continue to revise and reassess these entities we construct for the model.

**Lainie's model 3: Our cones are houses**

Magenta, students argue, is a "user error": there is no magenta light there, only red and blue, and yet we perceive a completely different color than what is present. Yellow produced by a computer screen from red and green lights is also a user error in their classification, but a "real" yellow must also exist. This inspires the class to start modeling perception as part of color, further tinkering

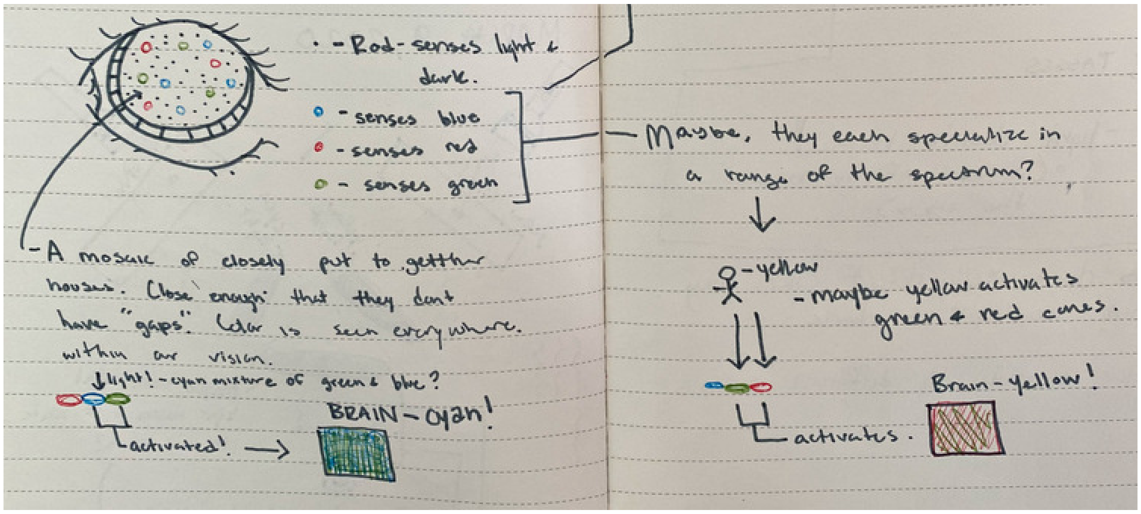


Figure 5: Lainie's initial model of red, green and blue cones in the eye.

with their models of men and houses.

Lainie sees the eye as absorbing light and, in Figure 5, describes the eye as "a mosaic of closely put together houses. Close enough that they don't have 'gaps.' Color is seen everywhere within our vision." We see Lainie building this model from an experience of the world (one we have not rigorously tested) - designing her model of the eye to meet this criteria, and tinkering with the "houses" from before. She conjectures that yellow activates green and red cones.

Ultimately the class decides that cones are like houses, but instead of turning little men into heat, the little men turn into chemical signals. Over four pages in her notebook, we see Lainie modify her model of the cones until she arrives at the final model as shown in Figure 6. The houses, then, are probabilistic houses; the red house/cone, for example, frequently admits red men, but only occasionally admits a yellow man inside.

Again, the work is **playful**, with exclamation points as the brain deciphers color; **iterative**, as the houses adapt and take on new meaning in the eye. The model has been **goal oriented**, now explaining the students' **self-directed** color categories, and quite **improvisational** as Lainie again generates a novel model in response to her observations and questions.

**Discussion**

Lainie, in conversation with her class, instructor and the matierals, has constructed a coherent, and relatively accurate, model of color. In particular, two entities she invented - colorful "little men" and the "houses" that can absorb and change them (into heat or a signal) - are used to generate this model. She approaches the design of the model in ways consistent with the literature on tinkering: improvisationally, playfully, and iteratively addressing self-generated goals.

Note that at in her model there are mechanisms missing and other gaps. Students wonder if the "little men" map easily onto photons; they believe the "houses" to be molecules but are unsure why they absorb colors probabilistically and only in certain parts of the spectrum. They know the

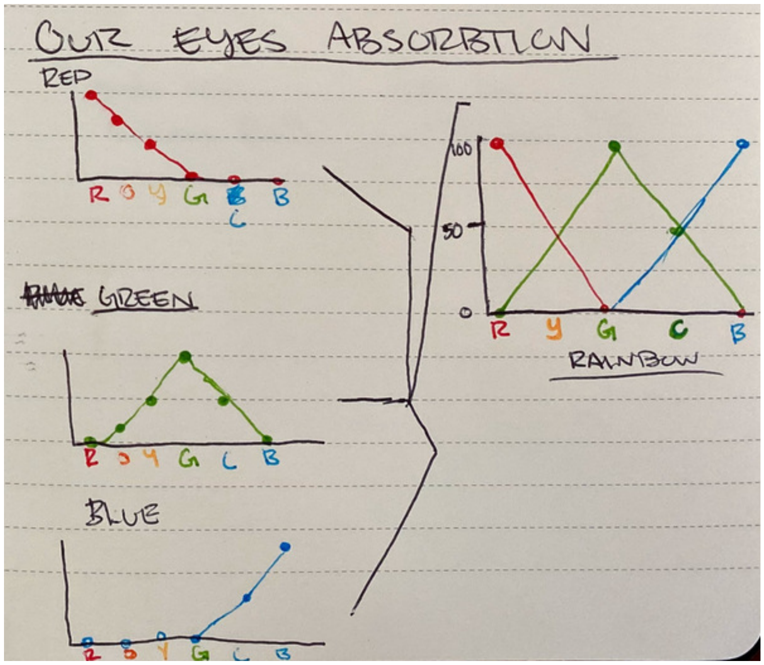


Figure 6: Lainie's model of cones as having a variable sensitivity to a range of wavelengths.

scientific name for the "houses" in the eye are cones, but not how they signal to the brain. Lainie wonders in her notebook what happens to blue light striking a red cone and why the eye looks black at all.

In this way, then, even the the product of the work is like tinkered solutions. As Resnick & Rosenbaum [1] describe the tinkered solution, there is value in "having an artifact to point to – an artifact that may be rickety or lopsided, but yet has resolved the problem that so puzzled the learner." That is, for physical "tinkered" artifacts, they can appear to have a haphazard quality that belies the intentional, iterative decisions and success at addressing design goals. Similarly, a "little men and probabilistic houses" model of color vision may seem too simple a toy model, and yet such a description would miss the careful, iterative, deliberate work in this design.

In looking at how researchers have described designing for tinkerability [1], we also see parallels between this course and tinkering: the importance of student ownership and authorship is a hallmark of tinkering and of this course [3]; contexts that allow for multiple pathways and solutions is another feature of both (in the many years of teaching this course, a little-men-and-houses description has never emerged) [4]; we engage with materials that provide rapid feedback [1], and our pedagogy that supports an orientation to "mistakes" as simply drafts to be refined with grading focused on students' scientific engagement and not the accuracy of their ideas [4].

We anticipate that – while engineering can be positioned as distinct from scientific activities, and even in tension when part of the same course [12]– there is a deeper sense in which both of these disciplines are fundamentally engaged in design work: the design of engineered products and - while frequently absent from science courses - the design of theory. And the broad structures and techniques that support the creative design of tangible or computational objects can also be engaged to support the design of scientific models and theories.

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