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6. Towards a Reverse Engineering Pedagogy (REP) in Physics Classrooms

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Abstract

Applying physical principles is important for designs of various products with tailored performances. However, one of the long-standing issues of the students' design projects (or school's interdisciplinary projects) is the post-hoc imposition of the knowledge learned in their content subjects. This post-hoc imposition significantly diminishes the authenticity of designs through the lens of first principles provided by science and mathematics, but also reflect the fact that many students could not see the connections between these physical first principles and their design decisions and therefore could apply them in their designs. To overcome this problem, we propose the concept of reverse engineering in physics classrooms. This work describes the framework for our proposed reverse engineering pedagogy (REP), where students embark on a series of activities, where they (i) dissemble the device, (ii) analyse the inner physical principles of the device and its components, (iii) appreciate the design principles involved in such device, (iv) augment their understanding of the physical principles by repeating the process through a virtual dissection, and (v) incorporate the process in their own design projects. We will also discuss how such approach may be implemented in a physics classroom, as well as its significance in contributing to a design-centric learning environment.

Towards a Reverse Engineering Pedagogy (REP) in Physics Classrooms

Introduction

There has been a significant drive towards multi-disciplinary curriculum in the recent years, with much attention being given to the work in STEM education (National Research Council, 2014). Such a direction is necessitated by the changing workforce climate, which demands the workforce not only have disciplinary expertise, but also a multi-disciplinary outlook. In the face of the Fourth Industrial Revolution, the labour market is expected to face a disruption, with many new job opportunities that do not exist today being created, but at the same time many of the roles will be made obsolete by automation (World Economic Forum, 2020). Indeed, it is under such a backdrop, the traditional mode of disciplinary learning may no longer be sufficient, but instead students must acquire a breadth of knowledge and be able to tackle a complex problem from multiple lens and viewpoints. As a result, there has been a greater desire to incorporate problem-based, project-based, and design-centric learning within the curriculum (Telenko, et al., 2016; Kazerounian & Foley, 2007; Klukken, Parsons, & Columbus, 1997).

A manifestation of such learning is in the form of *designettes* (Wood, et al., 2012) within Singapore University of Technology and Design (SUTD), where students engage in "intense periods of design or planning activity" to tackle a real-world challenge. A prominent feature of such activity is that the instructors of different courses come together to derive a cohesive problem statement and tasks that allow students to incorporate the knowledge that they have learnt in their courses coherently in the designette projects. An example of such project has been demonstrated by Koh et al. (2021) for the year 1 undergraduate curriculum, where the students in their groups are tasked to design a scaled-down chemical launcher to launch a projectile that mimics the food delivery to a city under siege. Students have to make use of a multitude of concepts, such as kinematics and energy in physics, numerical methods and optimization in mathematics, chemical energetics in chemistry, as well as ethics, strategies, and impacts of war in their humanities and social science classes to holistically tackle the problem. Similarly, in the 2^{nd} term of the undergraduate curriculum, students will be exposed to the design thinking as part of a formal course (Budig & Elara, 2021), where students have a greater freedom to identify problems that they would like to tackle under a prescribed general theme and to create prototypes as a potential solution to their identified problem.

Challenges in Cohesive Implementation of STEM Activities

The activities discussed in the previous section could be viewed as examples of practical implementation of integrated STEM education, where the students acquire scientific knowledge, synthesise the scientific and mathematical knowledge into their engineering product design processes, and create technological prototype to solve problems. However, unlike traditional disciplinary learning where there is distinctive learning goals and well-agreed problems to tackle, such integrated STEM activities are diffused (Toulmin, 1972) with problems that are open and need not necessarily have any set solutions. Furthermore, as summarised by Tan et al. (2019), the integrated STEM education faces the problems of (i) the lack of operational knowledge in execution, (ii) disciplinary-based assessment and (iii) infrastructure that still largely supports mono-disciplinary forms of learning. While problem (i) can be gradually overcome, albeit partially, with experience in execution, as in the case of the Koh et al. (2021) and Budig & Elara's (2021) implementation within the university, problems (ii) and (iii) are more structural and would require extremely significant paradigm shift across all education levels, both at pre-tertiary and tertiary levels.

One could further argue that given that the notion of multi-disciplinary education and STEM education are relatively young compared to the deeply entrenched disciplinary education systems and curriculum, such shifts are challenging for the implementers, namely the instructors and administrators, whose pre-conception of education and learning is rooted on their own experiences. The persistent self-feedback loop between institutional and curriculum structure with the stakeholders own pre-conception therefore makes any changes almost immutable.

It is in this backdrop that the multi-disciplinary education, at the current stage, is one that builds upon the foundation of disciplinary-based education. Indeed, Tan et al. (2019) mentioned that "to expect a science or mathematics teacher to carry out a truly integrated STEM curriculum that require in-depth knowledge of engineering and use of technological tools is unrealistic", given the necessity of any stakeholders to hold a wide array of working knowledge and perspective in order to meet the ideal demand of delivering such courses. As such, a more pragmatic approach would be to retain the disciplinary core but for stakeholders to work together in tandem to deliver a cohesive multi-disciplinary curriculum. Again, this requires a deliberate and concerted effort, rather than one that can happen organically without intervention.

Returning to the students' learning, the result of such general climate would be the limited opportunities for students to relate the disciplinary-based theory in class with the real-world context, which are typically highly complex and requires the analysis through multiple domain knowledge viewpoints *concurrently*. Even if there are various physical applications that are discussed, they often stop at the using the theory to provide an explanation on how the applications work. As a result, there appears to be an apparent disjoint between the theories afforded by the sciences and the real-world problems and solutions. When finding solutions to a problem, the ability to incorporate the first-principle physical concepts into their design consideration of the problem becomes limited.

The Idea of Reverse Engineering Pedagogy (REP)

To this end, this article calls an introduction of reverse engineering pedagogy (REP) in the physics classrooms. Reverse engineering has been practised in the industry to understand more about their competitor products through the dissection of the products and has since been explored in the education setting (Dalrymple, Sears, & Evangelou, 2011). Much of the work so far has been investigated within engineering education (Bothe, 2001; Wood, Jensen, Bezdek, & Otto, 2001; Calderon, 2010; Rad, 2012; Barr, Schmidt, Krueger, & Twu, 2013; Ogot & Okudan, 2006; Toh, Miller, & Simpson, 2015; Wiesen, et al., 2018; Bertoni, 2018), though there has also been studies within computer sciences (Aycock, Groeneveldt, Kroepfl, & Copplestone, 2018; Klimek, Keltika, & Jakab, 2011; Asghar & Luxton-Reilly, 2018) and programming classes in high schools (Hodge & Steele, 1995). Much of the existing works focuses on teaching engineering design through reverse engineering, and typically study students' self-efficacy and engagement from participating in such activities. Given the roots of reverse engineering in industry practices, it is of little doubt that such activity would be translated and explored in the engineering education context. From the lens of physics education, there has been limited discourse (Badraslioglu, 2016; Stansell, Tyler-Wood, & Stansell, 2016) on the use of reverse engineering within the curriculum as a hands-on activity.

As such, the REP activities that are discussed below aims to fill the following gaps: (i) a translation of physics concepts and theory into real world application and (ii) building the ability for students to view design through the lens of physics principles. In other words, one would go beyond *understanding* how it works and *apply* the knowledge into their everyday problems. Indeed, this is in line with the 21st century skills proposed by World Economic Forum (2015), where the various foundational literacies provide for affordance in terms of "how students apply core skills to everyday tasks". Through the REP activities, this creates an enabler for students to connect their product development and design processes through the lens of first-principle physics.

In practice, what REP aims to overcome is the post-hoc imposition of physics concepts within the problem-based design projects. In many of such multi-disciplinary assignments, students often tackle the problem from a high-level overview perspective, deriving ideas and solutions based own their own experiences and encounters. To associate the project with disciplinary domain knowledge, the assessment rubrics typically explicitly include components where students must consider incorporating such knowledge. Ironically, the need to assess the use of disciplinary knowledge often result in post-hoc imposition of the disciplinary domain knowledge *after* the problems and solutions to the project have been fully framed by the students. This therefore reduces the authenticity of design processes through the lens of first principles provided by the disciplinary subjects. This further signals at the students' inability to see the connections between the disciplinary subjects and their design process. As such, one could argue that a guided process to view the multi-disciplinary product development and design process via the lens of first-principle disciplinary subjects such as physics would be necessary to build up students' capacity to develop the connections.

DA^{3}D Framework in Guiding REP Activities

To guide the development of the REP activities, a framework which extends from the works of Ogot and Kremer (2006) is proposed. In the original framework, the reverse engineering process consists of 3 steps: dissemble, analyse, and assemble. The first three steps follow the physical steps of tearing down of a device, where the tasks aim to develop the students' manual dexterity and curiosity, and to expose them to functional products and processes in engineering. The proposed DA^{3}D framework therefore extends the current framework by introducing two more steps: augment and design. The last two steps serve as an extension of the in-class DAA activity where they would explore other objects that requires similar physical concepts to function, and then to elaborate on how the renewed understanding can help them in their design process.

More concretely, the key guiding questions within the DA^{3}D framework can be framed as follows:

1) *Dissemble*: What are the parts in the object?
2) *Analyze*: What are physical principles for the part to work? How are the parts related?
3) *Assemble*: How does the physical principles enhance or limit the device?
4) *Augment*: What are other objects that uses similar physical principles?
5) *Design*: What kind of insight can this relate to your own prototype/project?

What is noteworthy is that in the step 4, the students are expected to perform the tasks outside of classes as part of their self-directed exploration. In practice, such an activity can be performed in the form of a virtual dissection, where students find existing dissection videos that are available online and follow through the dissection and analysis process. The step has been deliberately designed to be an off-class activity to reinforce the experiences that they have learnt in class, and to be able to see the connection between the use of physics in product design in other contexts. Step 5 could be investigated through the students' engagement in their design projects or multi-disciplinary projects that they are concurrently undertaking in the term.

The framework has been implemented in the design of the REP activities in the physics classroom within the university, this will be further articulated in the next section.

Examples of REP Activities in Physics Classrooms

As a pilot study, the REP activities are implemented in the recent run of a 14-week compulsory introductory electromagnetism course, Technological World, for the undergraduate year 1 students in SUTD, which took place in Spring 2021. In consultation with two other faculty members who are instructors for the course, two dissection activities, aluminium electrolytic capacitor and induction cooker are designed. To balance between the need of delivering the course and the implementation of the REP activity, the activities are designed to last for approximately an hour long. In addition, the activities are introduced almost immediately after the relevant topics are covered in class, so that the concepts remain fresh in the mind of the students. Within the class the students are asked to complete a set of worksheets that guides them through the working principles and design of the product from the physics perspective. The activity is then followed up with a homework exercise related to the in-class activity.

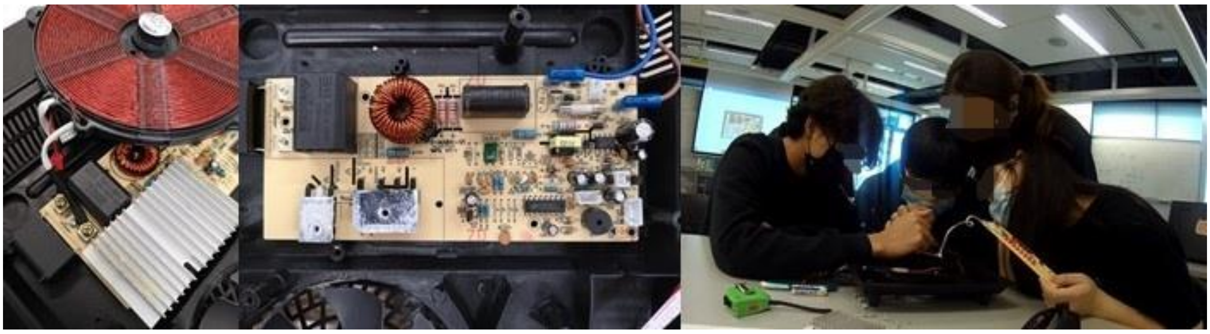

Figure 1 The dissection of induction cooker.

Figure 1 shows the REP activity of dissecting an induction cooker by the students in the class. Before the dissection, students are tasked to discuss and think about the components within the induction cooker that allows it to work. To guide the students, they are asked to consider the potential safety hazards, the types of circuits that are in place and the possible role of the parts that they have suggested in making the device to work. The expectation is for students to think about the inner workings of the induction cooker based on the knowledge of circuits that they have learnt earlier in the class. Once this pre-activity step is done, students are asked to open the induction cooker.

During the dissection activity, students are tasked to analyse the components that makes up the induction cooker, such as the induction coil, circuit board, fan etc. From the product design perspective, students are asked to identify ways in which the induction cooker prevents itself from overheating. Again, the question is deliberately framed such that students think about the ideas that they have learnt earlier, for example, the relationship between resistance and thermal loss. The result of this association is for students to relate the design of a thermal fuse with how it cuts off the current in the event of overheating. To relate the induction cooker to the physics concept of LC circuit that the students have learnt earlier in the class, they are also asked to figure out the capacitor that forms the LC circuit with the induction coil and then estimate the oscillating frequency. To relate this to product design, students are followed up with a question to consider why the oscillating frequency are designed to be at high frequencies. It is with this calculation and further investigation that students are made aware the ingenuity of such design decision based on physics, i.e., that such high frequency will significantly reduce the form factor due to the smaller inductance and capacitance values needed; and that the frequency is significantly above the audible frequency, to reduce the noise for the users.

A similar activity of the dissection of the aluminium electrolytic capacitor is introduced to the students as well (before the induction cooker activity). Given the significantly smaller form factor and cost of a single capacitor, the students are asked to perform the activity in pairs for this activity. Again, students are similarly tasked with the objective to understand how the physics concepts that they have learnt earlier in the class comes into play in the design of the capacitor.

Figure 2 The dissection of aluminium electrolytic capacitor.

Outlook and Future Works

In the previous section, two examples of REP activities are demonstrated, implemented in the classrooms, and integrated within the course. As highlighted earlier, the key aim of such activities is to go beyond how things work, and to create an opportunity for students to explore how the physics can influence product designs, and by extension, their own design process. This has been illustrated through a careful design of such form of guided reverse engineering process, as in the case of induction cookers and capacitors.

From the practitioner point of view, the immediate next step would be to design more of such activities given the initial success of the project. In the pilot, the designed REP activities are based on concepts in electromagnetism, but the repertoire of activities can be further expanded to include other areas of physics, such as mechanics and thermodynamics. Furthermore, while the current implementation is in physics (as the research team consists mainly of instructors who are teaching physics or with some form of physics or engineering background), the natural extension would be that if it is possible to perform similar REP activities to support the learning of other disciplinary subject and then relate the subject to the design process. As an illustration, a potential implementation would be for machine learning be undergo the same steps as prescribed in the DA^{3}D framework for students to appreciate the fundamentals of calculus, while at the same time, demonstrate how calculus influence the design or strategies in such application.

From the theoretical or research aspect, one could ask what sort of framework or theory could be derived to guide and further develop such activities? What sort of affordance does REP provides for the students' design iterations and processes through the lens of first-principle disciplinary subjects such as physics? For example, the affordance could be in terms of students' ability to connect physics in design thinking, their ability to perform engineering tasks, the shift in their class engagement, or skills development. The ability to answer these questions would inform researchers the overall experience of the students in terms of their cognitive development, affect and dexterity.

In addition, given the recent outbreak of the pandemic, much of the teaching activities has been brought online, including the activities within the university (Tan & Chen, 2020). A paradigm shift would be needed to continue to engage in these physical activities such as the REP activities in a sustainable manner. Furthermore, the pandemic has led to one to rethink how a classroom should be structured and transcend beyond physical spaces. While such idea has been explored in the context of hybrid or blended learning and widely studied in literature, the pandemic has inevitably catalysed the desire to implement these concepts into operations. As such, the question lies in how would one be able to conduct such activities online, if they could be done in the first place, and what kind of modifications would be needed? To what extent would the shift of such activities from physical to online changes students' perception in their learning and skills acquisition?

In this article, the concept of REP has been discussed and explored. Its implementation within the university physics classroom has been described. Given that this is an on-going study, it is expected that there will further outputs that will arise from this work. To conclude, while the activities described thus far has been implemented within the university physics setting, given the commonality of the physics across levels, the activities can be easily translated to pre-tertiary levels with light modifications.

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