SITUATED AT A DISTANCE: A FRAMEWORK FOR TEACHING REFLEXIVE INQUIRY THROUGH DIGITAL GAMES

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SITUATING AT A DISTANCE:

PROBLEMS AND POSSIBILITIES FOR TEACHING REFLEXIVITY THROUGH DIGITAL GAMES

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[To my wife, Swantika, the shining light in my times of trouble]

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LIST OF SYMBOLS AND ABBREVIATIONS

CM	Classical Mechanics
NPC	Non-Playable Character
NRC	National Research Council
QM	Quantum Mechanics
STS	Science and Technology Studies

SUMMARY

As science and technology (technoscience) grow increasingly complicit in systemic injustice, there is an urgent need for practitioners to conduct scientific inquiry as a reflexive process. Reflexivity in technoscience entails critically examining how one's position in material, political, and cultural structures of practice relates to their process of scientific inquiry. For example, it can involve examining how one's position as a researcher at a large for-profit corporation affects their framing of research problems. Teaching scientific inquiry as a reflexive process is necessary as it enables one to understand how values and assumptions permeate inquiry, and how one's positionality can embody or transform them. However, teaching it is also a paradoxical challenge: it requires students to be positioned in the structures of practice, while also at a distance from them. Being positioned in practice is necessary because the structures of practice differ significantly from those of education. Simultaneously, being at a distance is also necessary because those structures can bind one's understanding of a problem according to shared cultural norms. This raises two research problems: How do we design educational environments that position students in practice, at a distance? How can these environments support inquiry as a reflexive process?

This dissertation makes two primary contributions towards addressing these research problems. First, I draw upon feminist STS and pragmatist scholarship to propose a framework that brings one's positionality in structures of distribution, power, and culture into relation with the process of inquiry. The framework explores positionality in four ways: as one's *means*, *status*, *culture*, and *experience* and brings them into relation to three interdependent processes of inquiry: *problematizing*, *hypothesizing-experimenting*, and

resolving. By providing a systematic means of examining positionality and inquiry, the framework lays the grounds to analyze and develop responses to each question. This, I hypothesize, allows it to function both as an analytical tool to examine educational environments as well as a design space for educational environments that aim to teach scientific inquiry. Second, I hypothesize that digital games can approach these research questions because they can simulate the structures of practice, one's position in them, and the processes of inquiry as they relate to those positions, all at a distance from real practice. I investigate this potential of digital games by using the framework to conduct case studies and design-based inquiry into multiple digital games. This process demonstrated how the framework can be a source of design possibilities for approaching the two research questions. Simultaneously, it also surfaced key strengths and constraints of digital games as environments to support inquiry as a reflexive process. Particularly, I highlight how the procedural, evaluative, and artificial affordances of digital games can support but also constrain them from teaching scientific inquiry as a reflexive process (as stand-alone environments), and how such games can be complemented.

CHAPTER 1. PROBLEM AND SIGNIFICANCE

Summary: This chapter introduces three key aspects: the goal that inspires this dissertation, why that goal is important, and two key problems in the quest for this goal. The primary goal that this dissertation aims to support is teaching science and engineering students how to do scientific inquiry as reflexive process. Reflexivity entails critically examine how one's process of inquiry is situated, i.e., how it affects and is affected by societal structures such as structures of distribution, power, and culture, as well as one's position in them. There is an urgent need for practitioners to be reflexive due to the continuing complicity of technoscience in social injustice that has perpetuated systemic oppression and environmental destruction at both local and global scales. However, teaching scientific inquiry as a reflexive practice is a paradoxical challenge as it requires students to be positioned in technoscientific practice, at a distance from it. Being positioned in practice is necessary because the structures of practice differ significantly from those of education. Simultaneously, being at a distance from practice is also necessary because it allows one to critically examine its ways of thinking and doing which can be difficult to escape as a practitioner. Investigating this paradox, I develop the primary research questions of this dissertation: Can we design educational environments that position students in technoscientific practice, at a distance from it? Can those environments support inquiry as a reflexive process? If so, how?

1.1 Introduction

Scientific inquiry is a *situated* practice (Haraway 1988). This means that the processes of scientific inquiry, such as problem-framing, hypothesizing, experimenting, and problem-resolving, are always entangled with the position of the inquirers in social structures, such as structures of distribution, power, culture, and knowledge. These structures and one's positions in them imbue inquiry with values and assumptions that often escape critical examination. For instance, non-disabled researchers, by virtue of their position as non-disabled people in an ableist society, often implicitly assume that the goal of assistive technologies should be to help the disabled conform to the able norm, as opposed to helping them have more autonomy *as* disabled people (Williams and Gilbert 2019). Similarly, electrical engineers in large companies, by virtue of the need to elevate or sustain their own position in the company, often prioritize designing devices that maximize the company's profit, even if those devices have detrimental impacts on society—especially on workers in other countries—and the environment. These examples illustrate that disregarding the entanglement of one's positionality and inquiry (knowingly or unknowingly), has and will continue to make technoscience complicit in perpetuating social and environmental injustice.

Consequently, there is an urgent need for current and future technoscientific practitioners to do scientific inquiry as reflexive process. Reflexivity in technoscience entails critically examining how inquiry is situated, i.e., how it affects and is affected by societal structures and one's position in them (Harding 1992, 1991). Understanding how inquiry is situated can support just and democratic technoscientific practice in two key ways. First, it foregrounds the role of structural values and assumptions in inquiry. Explicitly deliberating over such values and assumptions as part of inquiry can help practitioners develop research methods and/or design artifacts that are more aligned with social justice and democracy. Second, reflexivity can help practitioners reason about how their positionality can be employed to advance structural change. This is especially relevant in cases where practitioners are aware of, but disregard the causes and consequences of their work—"that is not my job", "we only focus on the technical matters", "we have no choice but to do what we are told"—due to their position in the very structures that need to be changed.

However, teaching reflexivity is a paradoxical challenge: it requires that students have a position in technoscientific practice, at a distance from it.

Being positioned in technoscientific practice is necessary because one's position as a practitioner differs significantly from their position as a student. For example, doing scientific inquiry as scientist in a industry research lab is significantly different from doing it as part of an academic course. This is because of multiple reasons: the practitioner has access to more resources, people, and places; they occupy a position of power and responsibility as their work has social implications beyond their lab, and the culture of practice is built around developing new knowledge as opposed to learning what is known.

At the same time, being at a distance from practice is also necessary for learning reflexivity for two reasons. First, as a practitioner, it can be difficult to step away from or *unlearn* the ways of thinking, being, and doing cultivated by the structures of practice. For example, until Copernicus' proposition of the Heliocentric model, most scholars assumed that the Earth was the center of the universe and did not critically examine other possibilities for hundreds of years, despite increasingly contradictory evidence (Kuhn 1970). Second, being at a distance frees one from the constraints of the position in practice. For example, an outsider does not need to worry about jeopardizing their job for questioning the way inquiry is done in practice as real technoscientific practice often resists critical self-examination (Metz and Wakabayashi 2020; Wakabayashi 2020, 2019).

This paradox raises two primary research questions:

- Can we design educational environments that position students in technoscientific practice, at a distance from it? If so, how?
- Can these environments be designed to support inquiry as a reflexive process? If so, how?

It is important to note that these questions are exploratory in nature. The goal of this dissertation is to explore design possibilities for educational environments, not formally evaluate them. I will discuss this further at the end of the chapter.

1.2 What is scientific inquiry and how is it "situated"?

Dewey (1938) defines inquiry as the "controlled and directed transformation of an indeterminate situation to one that...determinate." Drawing upon this definition, inquiry involves at least three key inter-dependent non-linear processes: problematization, hypothesizing-experimenting, and resolving. Problematizing involves determining the indeterminacy of a situation so that one can begin to transform it. This occurs when one unsettles assumptions about the situation, i.e., finds out what makes a situation doubtful. Once doubtfulness has been raised and problems framed, the subsequent processes involve finding facts (such as by experimenting) and developing ideas (hypothesizing) in iteration until a suitable resolution has been reached.

Feminist and STS scholars have demonstrated how these processes of inquiry are always “situated”, i.e., intertwined with one’s position in social structures of practice. Consequently, to understand how inquiry is “situated” we need to explore what is meant by “structures of practice.”

Iris Marion Young explores such structures in her work on the Five Faces of Oppression (Young 1990). In it, she described oppression as being “structural”:

“...oppression designates the disadvantage and injustice some people suffer not because a tyrannical power coerces them, but because of the everyday practices of a well-intentioned liberal society...Oppression in this sense is structural, rather than the result of a few people's choices or policies. Its causes are embedded in unquestioned norms, habits, and symbols, in the assumptions underlying institutional rules and the collective consequences of following those rules.”

In in its use here, “structural” refers to an assemblage of a wide variety of things: norms, habits, symbols, assumptions about rules, and consequences of rules, that collectively govern the actions and practices of people in a society. What is notable in Young’s description is that the effect of these structures can be different from the intentions of the people who constitute them. Individual people may not be racist, but the system that they collectively form still might be. For example, standardized college entrance exams such as the SAT keep poorer people—who can’t afford to prepare for these exams—stuck in poverty at a time when more and more jobs require a college degree. Given that due to historical factors, several poorer people are also Black and Latinx, such a system becomes racist as it inhibits their upward mobility as individuals and as a community. It is possible that no single individual carrying out or making the rules of the system *intends* to be racist. They may be simply following the system and continuing to believe in the spirit 'meritocracy' without knowing how it can be systematically racist. This discrepancy between the effect of the system and the intention of the people who enact it is central to why there is an urgent need to critically examine what these structures are, how they affect society, and how our positions in them affects our inquiry.

On the basis of this definition, Young outlined three key societal structures that she argues play a central role in perpetuating oppression:

- division of labor (the range, nature, meaning, and value of tasks across occupations),
- decision-making procedures: (the rules and procedures according to which decisions are made)
- culture (symbolic meanings through which people express and share experiences)

While these three structures are defined in relation to "oppression," and are not specifically about scientific inquiry, the fact that technoscience is complicit in several forms of oppression makes them useful for understanding the situatedness of scientific inquiry as well. In fact, as scientific inquiry often operates within oppressive societal structures, a key reason for learning scientific inquiry as a reflexive practice is to understand how it embodies the values and assumptions of these oppressive structures and conversely, to learn how it can be employed to transform those structures for social justice.

Extending this discussion into the domain of STS, scholarship on the Social Construction of Technology (SCOT) frames “structures” as:

“Specific formal and informal, explicit and implicit ‘rules of play,’ which establish distinctive resource distributions, capacities, and incapacities and define specific constraints and opportunities for actors depending on their structural location.” (Klein and Kleinman 2002)

Drawing upon this definition, Klein and Kleinman outlined multiple structures underlying technological development, such as the structure of: relevant social groups (who participates?), interpretation (how meaning is made), closure (how research concludes), the technological frame (the values underlying technoscientific development), concentration (how different groups are organized), and resource accessibility.

Such “rules of play” can operate in ways that make seemingly benign technologies made by well-intentioned people into racist, sexist, and oppressive artifacts. This has been shown repeatedly in the domain of AI technologies such as automated resume-filtering tools and recommendation systems that mimic and amplify underlying systemic biases against women and black people (Benjamin 2019). More generally, such “rules of play” often have a significant impact on how scientific inquiry is conducted. For example, the pressure to publish papers that show new, positive, and sensationalist results has been shown to be detrimental to the reproducibility of science because of approaches such as p-hacking and lower reproducibility studies (Head et al. 2015). Such a pressure to publish is not brought about by individual scientists wanting more positive results, but because technoscience often rests atop financial structures that perpetuate social and economic inequalities. For example, funding for research is given primarily by private or military organizations, often with expectations of financial/material returns on their investment in the future. Since reproducing other's studies does not usually generate such returns, most research focuses on new research and technologies, and therefore fewer reproducibility studies are done. This is only amplified by social norms about the role of technoscience as a tool for "innovation" or "disruption" rather than as a medium for inclusive and democratic societal growth.

1.3 What does it mean to do scientific inquiry as a "reflexive" practice?

In one sentence, doing inquiry as a reflexive process entails critically examining how it is situated in societal structures.

More specifically, reflexivity entails "placing the subject of knowledge on the same critical plane as the subject of knowledge" (Harding 1991). The subjects of knowledge according to Harding, are "the individual and the historically located social community whose unexamined beliefs its members are likely to hold "unknowingly". The objects of inquiry are the subject-matters of technoscience. Consequently, reflexivity entails examining one's "cultural agendas and assumptions [that] are part of the background assumptions and auxiliary hypotheses" and are difficult to detect, but significantly shape our approach to inquiry. In other words, doing reflexivity entails critically examining one's social position as a practitioner. This is further reified by JafariNaimi, Nathan, and Hargraves (2015) in the idea of employing values as hypotheses, which requires inquirers to explore and investigate values just as they would investigate subject-matter.

Further, feminist scholars such as Haraway (1988) argue that all knowledge is situated, i.e., our positions matter in determining what knowledge is and how it comes to be. Consequently, it is not enough to critically examine one's social position as a practitioner. It is also necessary examine the relationship of that position to the knowledge and knowledge development process. This is echoed by JafariNaimi et al. (2015) and Schön (1983), who outline the need for a dialectic process, where the inquirers and the situation mutually re-shape each other. The actions of the inquirer transform the situation and knowledge about it, while the situation in turn transforms the actions of the inquirer.

Drawing on this dialectic, what actions constitute reflexivity? Leydens and Lucena (2018) outlined six such actions (core criteria) to keep in mind when doing engineering for social justice: Listening contextually, identifying structural conditions, acknowledging political agency and mobilizing power, increasing opportunities and resources, reducing imposed risks and harms, and enhancing human capabilities. Being reflexive means understanding the situation that one is a part of as an inquirer i.e., how the situation affects you and you affect the situation. Engaging in the activities outlined by Leydens and Lucena, such as identifying structural conditions and acknowledging political agency are examples of ways that one can do inquiry reflexively.

1.4 Why is it necessary to learn scientific inquiry as a reflexive practice?

Reflexivity is important because it is necessary for two key goals: systemic reform and strong objectivity in technoscience.

First, systemic reform requires changing the structures that give rise to injustice as opposed to treating the symptoms of injustice. Reflexivity, by critically examining such structures aims to problematize them and suggest directions for systemic reform. For example, it can help us see that worker exploitation in the production of iPhones is not the result of individuals, but the result of a system where there is little to no safety net for unemployment, low regulatory oversight (which itself can be a result of lobbying power), and lack of alternative options for workers.

Second, reflexivity can help make science "strongly" objective by requiring practitioners to examine the underlying values embodied in the structures of their practice. This does not mean making technoscience "value-free", as that is impossible. Rather, it entails being more deliberate and cognizant of the role that values play in one's work. For example, the design of the mobile phones is often examined in terms of values such as efficiency, speed, and size, which are considered to be purely technical in the design process. However, critically examining the structures through which these designs translate into development reveals the political nature of these values. For instance, smaller phones may be more efficient in speed, but have thinner parts that are more difficult to assemble and can increase headaches and eyestrain in workers, further stressing them in their already overworked conditions (Chan, Selden, and Pun 2020). Consequently, a reflexive approach can incorporate such considerations to reframe the structures of the design process to not only strive for technical innovation but also justice.

1.5 The challenge of teaching scientific inquiry as a reflexive practice

The paradox of teaching reflexivity in a nutshell is that it requires students to be positioned in practice, at a distance from practice.

1.5.1 Why do students need to be positioned in practice?

Being positioned in technoscientific practice is necessary because scientific inquiry is a situated practice and one's position as a practitioner differs significantly from their position as a student.

First, scientific inquiry is a situated practice, even when its "situatedness" is not explicitly engaged with. This means that learning to do scientific inquiry like those in practice requires not just learning how to enact processes such as designing experiments or analyzing data, but to do so while entangled in the material, sociopolitical, and cultural structures of practice. For example, designing an experiment to test some electronic hardware requires not just deliberation about the theory underlying electronics, but also deliberation over how to acquire the resources needed to do the experiment while also under pressure from a manager to deliver results in a culture that promotes quick turnover rather than steady, deep investigation.

Second, recreating such structures in an educational setting—where the goal is to support learning technoscience rather than conducting original research—is difficult, if not impossible to do as the structures of education are significantly different from the structures of technoscientific practice (Abd-el-khalick, 2008). For example, doing scientific inquiry as scientist in a industry research lab is significantly different from doing it as part of an academic course. The practitioner in the lab has access to more resources, people, and places; they occupy a position of power and responsibility as their work has social implications beyond their lab, and the culture of practice is built around developing new knowledge as opposed to learning what is known. Consequently, it is important that students have a position in practice to learn how inquiry in practice is situated.

1.5.2 Why do students need to be at a distance from practice?

Being at a distance from practice is necessary for learning reflexivity for two reasons. First, as a practitioner, it can be difficult to step away from or *unlearn* the ways of thinking, being, and doing cultivated by the structures of practice. Second, being at a distance frees one from the constraints of the position in practice.

First, the culture of practice can become the default lens through which one examines problems. Being at a distance enables one to examine practice more holistically. For example, AI researchers in a large tech company often examine AI ethics primarily as a computational problem involving the optimization of "fairness" and "bias" which are themselves defined mathematically (see Keyes et al., 2019 for a satirical take on this). Feminist STS scholars however, point out how such a framing is reductive as it ignores several social, political, and cultural issues such as social roles, power structures, and history that cannot be quantified but play a significant role in making algorithms "fair" (Benjamin, 2019; Parvin 2019). The culture of practice can become the default lens with which to view non-computational problems as well.

Second, the structures of practice are often antithetical to strong reflexivity. This is partly because critically investigating the relationship between one's positionality and inquiry can jeopardize the position of the inquirers (Metz and Wakabayashi, 2020), especially since it often involves surfacing and challenging the core values and assumptions embedded in the structures of practice, such as that of maximizing profit or improving efficiency. For example, researchers in university or industrial settings who learn that their work will be used for militaristic purposes cannot challenge the organization they work for without risking their job. Such an environment is not ideal for learning inquiry as a reflexive practice.

1.6 Research Questions

Drawing on the above discussion, I outline two primary research questions explored by this dissertation:

- Can we design educational environments that position students in technoscientific practice, at a distance from it? If so, how?
- Can these environments be designed to support inquiry as a reflexive process? If so, how?

Now, there are three important considerations to note in relation to these questions.

First, and most importantly, these questions are exploratory in nature. The goal of this dissertation is to explore design possibilities for educational environments, not formally evaluate them. In this sense, while the question of how *effective* such educational environments can be for teaching inquiry as a reflexive process is important, it is secondary to this dissertation. Understanding the effectiveness of such environments would require a formal evaluation of a variety of designs with control groups in a variety of educational settings, which is beyond the scope of this dissertation. Instead, by outlining design possibilities through these questions, I aim to highlight directions for future work that can draw upon these possibilities for development and testing. Consequently, the primary contribution of this dissertation lies in its surfacing of new design possibilities for science/engineering education that can potentially be meaningful to the teaching of scientific inquiry.

Second, “distance” is used not just in the physical sense, but also in the critical sense. While the goal is to help students experience what it is like to be positioned as a practitioner, it is also necessary for students to be critical of such positions. For example, a culture of societal disengagement is common in scientific practice due to which practitioners often isolate the technical aspects of a problem from its social aspects. It is necessary that students learn not to simply accept this culture and participate in it, but rather learn to critically examine its limitations.

Finally, these questions are interdependent. Specifically, approaching the second presupposes the first. If one’s position in the educational environment does not resemble that of practice, then learning to be reflexive of that position may not be a useful exercise. Instead, the more a students’ position as an inquirer is like that of a practitioner, the more meaningfully they can explore the relationships between positionality and scientific inquiry as they manifest in practice and critically reason about them. This helps better ensure that what students learn within the educational environment can translate beyond it into practical situations.

CHAPTER 2. LITERATURE REVIEW

Summary: In this chapter I explore prior research in education in relation to the two research problems outlined previously and identify their key strengths and limitations. Specifically, I examine four foundational philosophical traditions of education: instructionism/behaviorism, constructivism, communitarianism, and pragmatism/ feminism. I analyze how the principles of learning outlined by each, frame the ways in which they have (or can) position students in technoscientific practice at a distance and teach students scientific inquiry as a reflexive practice. Grounding this analysis in digital educational games about scientific inquiry from each of these five traditions, I illustrate how the strengths and limitations of these philosophies can translate to educational approaches that employ them. In doing so, I illustrate key gaps between science education and science studies pertaining to their framing of science and scientific inquiry.

2.1 Introduction

To situate my research, in this chapter I analyze how five dominant philosophical traditions of education—instructionism/behaviorism, constructivism, communitarianism, and pragmatism/feminism—have aimed (or can aim) to teach scientific inquiry as a reflexive practice. These traditions were selected as they form the foundations of most theories of learning/education and by extension, most pedagogical techniques for teaching inquiry as a reflexive process, such as case-based learning (Fleddermann 2000; R. Howard 1996), problem-based learning (Savery 2006; Boud and Feletti 1998), and project-based learning (Blumenfeld et al. 1991). Consequently, a comprehensive review of all individual theories and techniques for teaching inquiry as a reflexive process is beyond the scope of this thesis as a critical analysis of their foundational philosophies is sufficient to surface their core assumptions about learning and teaching inquiry as a process.

To anchor my analysis, I examine key texts underlying each philosophical tradition. These primary texts include:

- Instructionism/Behaviorism: Shannon (1948), Weaver (1949), and Skinner (1953)
- Constructivism: Piaget (1964), von Glasersfeld (1995), and Vygotsky 1978)
- Communitarianism: Lave and Wenger (1991), Brown, Collins, and Duguid (1989)
- Pragmatism/Feminism: (Dewey 1916; Freire 2000; hooks 2010) Dewey (1916), Freire (1970), and hooks (1994)

Drawing upon the research questions outlined in Chapter 1, my analysis of these foundational philosophies/texts involves asking four key questions.

- What are their core principles about learning?
- How do/can they aim to position students in technoscientific practice, at a distance?
- How do/can they aim to teach scientific inquiry as a reflexive practice?
- What are their limitations?

To summarize my analysis, I briefly describe my analysis for each philosophy.

Instructionism and Behaviorism understand learning as information-acquisition and skill development. Learning is successful when a student knows what the teacher knows and can do what the teacher can do. This framing of learning harbors the assumption that being positioned in practice entails remembering important technoscientific facts and procedures.

Consequently, instructionist/behaviorist approaches aim to position students in practice at a distance by facilitating the memorization, drill, and practice of those facts and procedures. Instructionist approaches do this in a teacher or information-centric manner, focusing on information is presented to the students. Behaviorist approaches do this in a student-centered manner through operant conditioning, where positive and negative reinforcement gradually help students learn to "get it right." Both these approaches teach students scientific inquiry as a set of terms and procedures. This limits their teaching of inquiry as reflexive process to eliciting student reflection on their memory and skills related to experimental terms and procedures.

Constructivism frames learning as a process of assimilation where students construct mental models that strive to be consistent with their past experiences. Learning is successful when students are able to construct such mental models. This framing of learning understands doing the *practices* of inquiry as a key part of learning inquiry. Consequently, constructivist approaches aim to position students in practice by providing experiences and environments where students can learn inquiry by doing the practices inquiry. This approach is limited in teaching reflexivity as it does not engage students with how those practices are situated.

Communitarian approaches frame learning as a process of enculturation into communities of practice. Learning is successful when students have become effective contributing members of a community of practice. This framing of learning understands being positioned in practice as direct participation in practice or in environments that are culturally similar. Consequently, communitarian approaches aim to position students in practice and teach them inquiry by involving them with real practitioners or creating an equivalent community of technoscientific practice within the educational environment. This approach limits their teaching of reflexivity in scientific inquiry to eliciting reflections of one's position within a community of practice, i.e., their status as a community member. However, it does not give students the agency to critically investigate their positionality in relation to the culture of practice without jeopardizing their position as community members.

Finally, pragmatist/feminist approaches frame learning as a liberatory practice. Learning is a continuous dialectic process between the learner and the societal structures they are entangled in, with each continually (re)shaping the other towards liberation. It has no definite metric of success aside from staying continuous, liberatory, and dialectic. This framing of learning understands that being positioned in technoscientific practice entails conducting, critically examining, and reshaping practice to align with values of democracy and justice. Consequently, they aim to position students at a distance and teach them inquiry by engaging them in inquiry into their own local environments. If possible, such an approach is inherently reflexive as students to have examine their position in the local distributive, sociopolitical, and cultural structures as part of the process of inquiry. This approach becomes limited when it is impractical or unsafe for students to engage in real-world inquiry.

To anchor my analysis of these philosophies, I examine educational games that were designed to teach inquiry drawing upon these philosophies. The rationale for this is threefold. First, digital games are increasingly being used to teach scientific inquiry due to their affordances such as being able to simulate of virtual worlds where students can be positioned as practitioners. Second, a key hypothesis of my dissertation is that digital games are well-suited to teaching scientific inquiry as a reflexive process. Examining other games designed to teach scientific inquiry is therefore necessary to inform and substantiate this hypothesis. Finally, there are only a few games explicitly designed to teach scientific inquiry as a reflexive process. Consequently, to expand the scope of my literature review, I included games that were designed to teach inquiry more generally. These include games such as: *Operation ARIES!*, *Legends of Alkhimia*, *Martian Boneyards, Quest Atlantis,* and *The Mystery of Taiga River*.

Based on this analysis, the primary gap that we see between science studies and science education (aside from practically feasible pragmatist/feminist approaches) is the lack of focus on the *situatedness* of inquiry in science education. Despite years of feminist science studies and STS, major educational approaches and standards such as the National Research Council's framework for science education, (National Research Council (U.S.) 2012), which are the basis for the Next Generation Science Standards, focus primarily on the *practices* of scientific inquiry, such as modeling and data analysis as opposed to teaching students how to critically examine the situated nature of scientific inquiry.

2.2 Instructionism/Behaviorism

2.2.1 What is Instructionism/Behaviorism? How do they frame learning?

Instructionist approaches to education frame learning as a process of *acquiring* information and skills that have been transmitted by an experienced instructor. Such a framing is anchored in Shannon and Weaver's mathematical model of communication which involves a transmitter (instructor), channel (verbal/textual), receptor (student), and a feedback mechanism (student response) (Shannon 1948; Weaver 1949). Learning occurs when each of these elements of communication function properly. This approach is predominantly teacher-led as they are the source of information and skill demonstration. A common example of this approach is the traditional lecture, where an instructor disseminates information to a group of students through speech and text on a board. Consequently, learning inquiry through an instructionist approach involves acquiring and repeating the facts and procedures of inquiry transmitted by the teacher. For example, teachers may demonstrate experiments and experimental procedures that students are expected to learn through observation. An effective demonstration will have qualities such as clear visibility and be error-free for effective transmission.

Behaviorism builds on this approach by determining how instruction should condition and be informed by student feedback. It frames learning as a process of operant conditioning where students acquire target information and skills through positive and negative reinforcement (Skinner 1953). For example, rewarding students for a correct answer to a question is a form of positive reinforcement, while punishing them for incorrect answers is negative reinforcement. Consequently, learning inquiry through a behaviorist approach involves acquiring and repeating the facts and procedures of inquiry through operant conditioning. This can be seen in lab courses in school where students are graded based on how well they can reproduce experiments demonstrated by the teacher. Better imitation yields a higher score (positive reinforcement) and poorer imitation yields a lower score (negative reinforcement).

In this way, both approaches frame inquiry as a set of facts and procedures to be acquired and applied.

Almost all digital educational games, including those designed to support the learning of scientific inquiry, involve some features of instructionism and behaviorism. The former can be seen when students are told what they are supposed to know or do in the game such as in a tutorial or an in-game explanation of a concept. The latter can be observed when games reward/punish player's actions in the game. However, not all games treat inquiry as a set of facts and procedures as instructionism and behaviorism do.

Given this ubiquity, I anchor my analysis of these philosophies in the game Operation ARIES! (Millis et al. 2011). The primary rationale for selecting this game, aside from the fact that the game is designed to teach scientific inquiry, is that it not only aligns with these philosophies in terms of using tutorials and reward/punishments but also frames scientific inquiry as a set of concepts to be memorized and applied.

Operation ARIES! is a digital game that aims to teach high school seniors, college students, and the public about the scientific method, which it understands as collection of concepts/procedures such as "Dependent and Independent Variables", "Control and Experimental Group", and "Conflict of Interest." The goal of the game is that players must use these concepts to identify "flawed research" reports sent by aliens to confuse people on the Earth.

To support students in learning inquiry as a set of concepts, the game engages them in three modes: a training mode, a case study mode, and an interrogation mode. Gameplay in the training mode involves reading an eBook with multiple-choice questions and tutorials about the concepts of scientific inquiry. Gameplay in the case study mode involves students reading research reports in the form of news articles and typing in what they think makes the research "flawed" (if at all) such as "premature generalization of results" or "insufficient sample size." This response is evaluated by the virtual AI tutor who tells them if their observations are correct or wrong and gives them a more detailed explanation of why. The student can chat with the AI tutor during this process to explain their answers and ask questions as well. Finally, gameplay in the interrogation mode requires students to do the same thing as the case-study mode without assistance from the AI tutor. Here, whether students' observations of the flawed research are correct or not has an impact on the game's state as students can fail the mission here or succeed and ward off the aliens.

Given that the game's core mechanics involve multiple choice questions in the training mode and positive/negative reinforcement by the AI tutor/game-state in the case study and interrogation mode, *Operation ARIES!* is a good example of how both the instructionist and behaviorist philosophies can manifest in a digital game about teaching scientific inquiry.

2.2.2 How can/do these philosophies aim to position students in technoscientific practice, at a distance?

Both philosophies limit their understanding of learning to the acquisition of facts and procedures. A student's position as a technoscientific practitioner is therefore also understood in terms of the facts and procedures of practice. The better that one is able to remember and apply these facts and procedures of inquiry, the better positioned they are as a technoscientific practitioner in the class. Consequently, both approaches aim to position students in practice at a distance by placing them in environments that support the acquisition and application of relevant facts and procedures about inquiry.

Instructionist approaches aim to do this by creating environments that optimize the transmission and reception of information by students. For example, the form of the lecture hall has the teacher on an elevated stage, visible and audible to all students for unobstructed transmission/broadcasting of information. The students' role is to be good recipients of that information, taking notes, memorizing them, asking relevant questions and so on. *Operation ARIES* creates such an environment digitally in the form of a training mode where students can, without distraction, peruse an eBook with the relevant facts and procedures about inquiry.

Behaviorist approaches aim to do this by creating environments that positively or negatively reinforce student learning, with the student functioning as the operant to be conditioned. For example, having a class with strict disciplinary rules that punishes "bad" behavior in the classroom such as by sending the student away or deducting their grade is a form of negative reinforcement that teaches students what *not* to do. In *Operation ARIES* such an environment manifests digitally in the case-study and interrogation modes, with the student operant taking the role of a research reviewer. In the case-study mode, students, as reviewers, are rewarded with a smiley face, a high score, and an affirmative response from the AI tutor, for correctly spotting research flaws (and vice-versa for incorrectly doing so). In the interrogation mode, the stakes are higher, as the success of the mission depends on getting a high score on finding flawed research.

2.2.3 How can/does it aim to teach scientific inquiry as a reflexive practice?

Based on an understanding of scientific inquiry as a fixed set of facts/procedures to be learned, and of positionality as one's ability to remember and apply those facts/procedures, both approaches can teach inquiry as a reflexive process by inviting students to find connections between the two: How much about inquiry do students know and not know? How does what students know make it easy or difficult to learn the remaining facts/procedures? Can the set of facts/procedures be reorganized in a way to address what students are finding difficult to learn?

Instructionist approaches to teaching scientific inquiry aim to support reflexivity by evaluating students' understanding of inquiry and sharing the results with them. For example, by letting students know what they got right or wrong about inquiry, they make students aware of their position (what they know) and bring it into relation with inquiry (the whole set of facts/procedures about it). *Operation ARIES* does this in the training mode through a series of multiple-choice questions that test student's understanding of the concepts of inquiry and letting them know their scores. It also does this in the case-study mode through a smiley face and scoreboard that keeps track of how many research flaws students correctly or incorrectly identified. Both these scores and feedback help students understand their current position (understanding of inquiry) and to adjust their approach accordingly.

Behaviorist approaches to teaching scientific inquiry aim to support reflexivity through positive and negative reinforcement. Positive reinforcement affirms a student's position and pushes them to continue doing what they are doing. For example, in *Operation ARIES*, if a student correctly identifies the research flaws in an article, they receive an affirmation and can proceed to the next article. Negative reinforcement, on the other hand, repudiates their current position, prompting them to reflect on it and correct their response. For example, in *Operation ARIES,* if a student incorrectly identifies research flaws during the case-study mode, they are informed accordingly and have to keep trying again until they get it right.

2.2.4 What are its limitations?

There are three key limitations of instructionist/behaviorist approaches to teaching inquiry as a reflexive process: a reductive framing of positionality as one's knowledge of facts and procedures, a reductive framing of inquiry as a set of facts/procedures, resulting in a reductive framing of reflexivity.

First, a student's position as understood within the instructionist/behaviorist tradition is quite different from that of a scientist or engineer in practice. This is because what facts/procedures a practitioner knows is not the only factor that matters to their positionality. There are several other interdependent matters such as their social status, power, culture, experiences, and their entanglement with societal structures that collectively constitute one's position as a practitioner. While a focus on the foundational facts/procedures of inquiry is necessary, it is by no means sufficient. Consequently, Instructionist/Behaviorist approaches are limited in their capacity to engage students' positionality as practitioners.

Second, learning *about* inquiry is not the same as learning how to do inquiry. One may understand matters relevant to inquiry such as what counts as a hypothesis or a control group, or when data is invalid, or a sample size is insufficient, but knowing them is not the same as knowing how to problematize, hypothesize, experiment, and resolve problem-situations. Given that doing inquiry is essential to learning it, Instructionism and Behaviorism cannot, on their own, teach students inquiry.

Finally, drawing on both the above limitations, if teaching students reflexivity entails teaching them how to critically examine their positionality in relation to their inquiry, then the most that Instructionist/Behaviorist approaches can do is to help student's reflect on their memorization and application of the facts/procedures of inquiry. In other words, a reductive framing of positionality coupled with a reductive framing of inquiry, yields a reductive framing of reflexivity.

2.3 Constructivism/Cognitivism

2.3.1 What is constructivism? How do they frame learning?

Constructivist approaches to education frame learning as a process of constructing mental models that strive to be consistent in explaining one's experiences. Such a framing derives from cognitive theories such as that of Piaget's (1964) which frames learning as the assimilation of reality into mental operational structures; von Glasersfeld's (1995) radical constructivism which frames learning as a process of constructing viable explanations of experiences, and Vygotsky's (1978) social constructivism which frames learning as a process of knowledge construction that happens individually but is mediated socially with experienced members of a community through the zone of proximal development (ZPD). Several different approaches fall under the umbrella of constructivism such as problem-based learning, project-based learning, discovery learning, inquiry-based learning, collaborative learning, and reciprocal learning.

Despite the diversity of constructivist approaches, there are at least two primary assumptions made by all of them. First, knowledge does not exist independent of knowers. Rather, it is constructed by them. In this sense, knowledge is not "transmitted" but "re-constructed" when one shares knowledge with another. Second, knowledge is not constructed on a blank slate. Instead, it is constructed by students as they make sense of new knowledge in relation to their prior knowledge and experiences. These assumptions about knowledge differ significantly from Instructionist/Behaviorist approaches which treat knowledge as an independent transmissible entity to be acquired by a passive recipient (students) during teaching.

Given that constructivist approaches aim to support students in constructing knowledge, their approach to teaching inquiry usually involves learning by doing, with an explicit focus on the *practices* of inquiry such as asking questions, modeling, conducting experiments, and analyzing data.

For example, consider this high school unit on static electricity that aims to help students answer the question, "why do clothes stick when they come out of the dryer?" (Create for STEM Institute 2018). The unit is composed of three phases: discussion, demonstration, and modeling. The first phase begins with a driving question asked by the teacher to the students: "Why do some things stick together and other things don't?" The class engages in a discussion where students suggest different hypotheses such as "magnetism" and "static," while the teacher prompts reflection with probing questions such as "what do you mean by ‘static’?” without confirming or rejecting any of their suggestions. In the second phase, the teacher sets up an experiment involving the Van de Graff generator. They place a pile of aluminum plates on top of the generator and ask students to predict what will happen when the generator is switched on. Third, students observe the demonstration and are asked to develop and communicate a model that explains their observations using a diagram. Eventually, students are given two apparatuses to conduct similar experiments with: two strips of tape and a simulation tool containing particles of different charges. They are then asked to conduct specific experiments such as “adjust the charges on the spheres to make them behave like the two strips of tape.”

There are several frameworks that outline key practices of inquiry for students to participate in. Notably, the National Research Council (2012) in their *Framework for K-12 Science Education* (the basis for the Next Generation Science Standards) proposed eight practices of scientific inquiry that students should engage with:

- Asking questions
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Constructing explanations
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

Similarly, Chinn and Malhotra (Chinn and Malhotra 2002) developed an extensive framework that highlighted several processes of scientific inquiry in practice and compared them inquiry in the classroom. To summarize, they argued that: scientists generate their own research questions; design and conduct their own study (e.g., selecting/creating/controlling several variables and the methods of observation based on the research question); develop theories/models based on unobservable entities (such as energy, wavefunction) and research done by others, having to frequently resolve inconsistencies between their work and those of others, and communicate their findings keeping in mind potential flaws/generalizations/limitations.

Consequently, the primary difference between constructivist approaches to teaching scientific inquiry and Instructionist/Behaviorist approaches is constructivist approaches aim to teach inquiry by having students *do* inquiry, while instructionist approaches teach it as a set of facts/procedures to be memorized. For example, a constructivist approach may invite students to explore a dataset and frame their own questions for further investigation, while an instructionist/behaviorist approach may show students how to do an investigation and ask them to follow along (Maor and Taylor 1995).

Most educational science games follow a constructivist approach to teaching inquiry where students learn by engaging in the practices of inquiry and constructing models as they solve in-game challenges. This includes games such as *Legends of Alkhimia*, *Kerbal Space Program*, *Motion Force*, and *SURGE Symbolic* (Sengupta and Clark 2016).

I explore *Legends of Alkhimia* (Chee and Tan 2012) in more detail here as it was specifically designed to teach scientific inquiry and has published research supporting it.

Legends of Alkhimia is designed for middle-school students and aims to foster the learning of chemistry through inquiry. It is a multiplayer game that supports up to four players over a local network. As the authors describe it: “The game embeds students in problem solving challenges related to the use of chemistry in realistic contexts. In attempting to solve these problems, students must engage in individual laboratory work using an in- game virtual chemistry lab.”

Legends of Alkhimia adopts a constructivist approach to teaching inquiry as it gives students the freedom to lead their own investigations. To support them, it gives them access to a set of laboratory tools such as a distiller, bunsen burner, and liquids that they can use to construct, test, and refine their hypotheses about the miscibility and purity of liquids. Most problems in the game have multiple acceptable solutions (though not equally effective). This invites students to explore different ways of approaching problems, constructing and test multiple hypotheses along the way, all of which help them learn inquiry by doing inquiry (understood as a set of practices).

2.3.2 How does it aim to position students in technoscientific practice, at a distance?

Constructivist approaches assess students’ position on the basis of their (pre)conceptions, i.e., what are their mental models and past experiences of technoscience? For example, a common student preconception about electric current is that it starts with electrons moving from one part of the circuit to another, when in fact electrons in all parts of the circuit always flow together. Comparing student’s conceptions with those of established technoscience helps constructivist approaches gauge where students stand in terms of their understanding of technoscience. The more aligned their mental models are with those of established technoscience, the better positioned they are (or will be) as practitioners. Consequently, they aim to position students in technoscientific practice at a distance by giving them the experiences and environment that lets them build upon their preconceptions/past experiences and change their conceptions to be more aligned with practice.

For example, in one of the levels of the game *Legends of Alkhimia*, students learn inquiry in relation to the reactivity of pure substances vs impure ones. Before entering the level, students have their own mental models about how different liquids at different purity levels react with metals. This game level invites students to explore and refine those mental models through practices such as designing and conducting experiments with chemistry apparatus in the following scenario. Players have to escape a lab room that is filling up quickly with toxic gas. To do this, they need to puncture a hole in the lab's metal door by firing bullets at it loaded with liquid chemical substances. Different liquids react differently with the door. Highly impure liquids will not cause much damage to the door, and not all pure liquids will react either. Students can use the virtual lab equipment to distill and explore different liquid mixtures, allowing them to change their purity level and/or try combinations of them. Providing students with an environment and experience like this where they can construct hypotheses using virtual lab equipment and test them by firing the bullets at the door enables students to refine their mental models about reactivity until it aligns with the established knowledge.

2.3.3 How does it aim to teach scientific inquiry as a reflexive practice?

Drawing on cognitive science, constructivist approaches understand reflexivity as a form of "metacognition" which refers to the "knowledge of one's knowledge, processes, and cognitive and affective states; and the ability to consciously and deliberately monitor and regulate one's knowledge, processes, and cognitive and affective states" (Hacker, Dunlosky, and Graesser 1998). Based on an understanding of scientific inquiry as a set of practices, and of positionality as one's mental models and past experiences, doing inquiry reflexively entails reflecting on one's practices in relation to their past/current mental models: What are my current mental models about this topic? Are they assisting or constraining my ability to engage in inquiry? In turn, how have the practices of inquiry affected my mental models?

Legends of Alkhimia aims to support reflexivity through incremental progression. The game contains six levels, each of which builds atop what students have learned in the previous. Students need to continually draw upon their past experiences in earlier levels to strategize their current and future actions. This induces continuous reflection about what they have learned and puts it in dialogue with their current process of inquiry: "This approach worked for the previous problem, could it work for the new one?"

2.3.4 What are its limitations?

There are three key limitations to constructivism in relation to teaching scientific inquiry as a reflexive process, all of which pertain to the lack of consideration for societal factors in relation to positionality, inquiry, and reflexivity.

First, one's positionality extends beyond their mental models and associated past experiences. While both are integral to one's position as a practitioner in practice, they are also entangled in larger material, sociopolitical, and cultural structures that are not considered by constructivism. To some extent, social constructivism does attempt to correct this as it also considers one's relationship to a community as a key factor, but this too often disregards matters such as power dynamics, cultural background, and history. For example, *Legends of Alkhimia* does position players as part of a team with an overarching goal (such as to escape a lab) and constraints (time-limit) that affects their process of inquiry. But their purpose in the game is simply to direct and lend meaning to the gameplay, not replicate the structures of practice, which is why they are unlike real goals and structures of practice.

Second, inquiry is more than a set of abstract practices. In fact, focusing on these practices too much can draw attention away from the actual process (Tang et al. 2009). Further, all these practices are entangled with each other and in larger societal structures that are not considered by constructivism. For example, the politics of modeling are especially evident when there are multiple models that can explain the same phenomenon or when a new model radically challenges the assumptions of the former. The history of science has shown time and time again the resistance of scholars to accepting new models (Kuhn 1970), such as in the case of Wagner's theory of tectonic plates which cost him his career and reputation, but was ultimately accepted later after decades. Developing a new model is entangled with one's social, political, and cultural position which all collectively shape the modeling process.

Finally, reflexivity in constructivism is limited to metacognition. Metacognition is integral to reflexivity as it involves identifying the gaps between what one knows and what one should know. At the same time, its focus inwards on the self and not on the position of the self in society limits its ability to help surface the underlying societal structures and their values/assumptions that permeate inquiry.

2.4 Communitarianism

2.4.1 What is communitarianism? How does it frame the learning?

Communitarian theories of education frame learning as a process of enculturation by and into communities of practice. This is reflected in Lave and Wenger's (1991) understanding of learning as legitimate peripheral participation where individuals learn how to become more integral members of a community of practice, and Brown, Collins, and Holum’s (1991) framing of teaching/learning as cognitive apprenticeship which highlights the importance of learning in real-life contexts with tutors as opposed to breaking it down to an abstract set of skills independent of the situation.

These approaches understand inquiry as socially constructed processes, which differs significantly from the instructionist/behaviorist and constructivist approaches as it includes a sociocultural dimension. For example, learning how to do inquiry as an electrical engineer requires not just learning the foundational concepts or using/developing models, but to do so and more as part of a community of practice that also comprises expert electrical engineers. As there is no universal scientific method, the ways in which a community of practices engages in inquiry are particular to them—inquiry is what the community deems inquiry to be. Consequently, teaching students scientific inquiry requires placing them in a community of practice that does inquiry such as through an internship, a job, or a team project comprising of both experts and novices.

A notable example of an educational approach involving a community of practice is Hanauer et al. (2006) who collaborated with a genomics program in their university to allow undergraduate and high school students to work in their research group for discovering new bacteriophages and sequencing their genomes. Such a collaboration was possible because isolating phages from the environment do not require advanced knowledge and technical expertise, and can be done even by middle school. Over 75% of the students who participated in the program achieved the isolation and purification of phages and more than 18% contributed to a real research paper on their findings.

Others have attempted to recreate scientific communities of practice within the classroom. For example, Messina (2001), employed the software Knowledge Forum—an online collaborative note-making tool for education (Scardamalia, 2002), to create a community of practice within a fourth grade classroom as students explored the properties of light. They collectively came up with six areas of interest—Sources of Light, Images, Angles and Reflection, Colors of Light, Colors of Opaque, Objects, Mirrors—and divided into groups to investigate them using the experimental equipment available in the lab. The teacher's role here was only to support students and not direct them. Students used Knowledge Forum to document and share their findings and eventually came up with a peer review system of their own to verify their findings similar to real communities of scientific practice.

One example of digital game that uses this approach is *Martian Boneyards* (Asbell-Clarke et al. 2021). It is an online 3-D multiplayer game that invites players to learn how to identify and distinguish between human and animal bones by attempting to uncover a mystery about human remains on an island. Players control virtual avatars on this island and can explore it, pick up and inspect objects, use scientific tools to gather and analyze data about bones, and communicate with each other using a chat system, all asynchronously.

2.4.2 How does it aim to position students in technoscientific practice, at a distance?

Positionality in communitarian approaches is understood in terms of their social position, such as their status in the community—novice, expert, newcomer, veteran, junior, senior, principal etc—or their role—engineer, manager, lead, financial advistor etc. For example, in a student team attempting to build a formula one style racing car, some students will be more senior (usually those who have done it before), and others more junior. The senior students may take on more design-related tasks while juniors may be tasks with implementing those designs. While some communitarian approaches advocate for placing students directly in practice, (Hanauer et al. 2006), others aim to create their own communities of practice within the educational environment.

In *Martian Boneyards*, this kind of community of practice is constructed in two ways. First, there are two kinds of characters: those played by players and those by designers. The role of the player characters is to solve the mystery, while that of the explorers (designers) is to support the onboarding of new players into the game, support and gauge how players are conducting inquiry by asking them questions such as "how did you figure that out?" and building/refining the game narrative in response to the players. Second, long-time players are more experienced than new ones and so automatically assume the role of experts in the game, leading to a social stratification that forms a community of practice.

2.4.3 How does it aim to teach scientific inquiry as a reflexive practice?

Based on an understanding of scientific inquiry as a cultural process determined by the community, and of positionality as one's social position in that community, constructivist approaches can aim to teach inquiry as reflexive process by inviting students to relate the two: How does the community engage in inquiry? How does it define roles? How does my social position in the community affect my contribution to inquiry? How does the process of inquiry in the community determine what my role is?

While *Martian Boneyards* does not explicitly focus on supporting inquiry as a reflexive process, it does support a communal approach to inquiry in the form of data gathering, analysis, and theory building, all of which are interdependent and require collaboration. For example, each artifact that players find pertinent to the mystery has to verified and approved by at least 20 others before it can be used as evidence in claims and theory-building, which supports consensus building similar to professional scientific practice.

2.4.4 What are its limitations?

There are four primary limitations of this approach:

The primary limitations of this approach is that by situating students as members of a community, this approach also risks acclimatizing students to the community's norms, rendering them invisible (or less visible) to reflexive examination as students become "used to" the culture of practice. For example, students interning in big electronic companies may not learn to question and challenge the company's policy on labor as that could be discouraged by the norms of that company.

Second, while communitarian approaches give students the opportunity to experience the entanglements of technoscience and society, they do not give them the agency to critically investigate and challenge them without jeopardizing their position as community members. For example, if a company notices that an intern is a potential troublemaker or may whistleblow on their work, it may fire them without notice. Consequently, even though students may be able to act on real situations as community members, that action is constrained and dictated by the norms of the community which limits reflexivity.

Third, students engaging in professional environments rarely have the opportunity to problematize situations. Instead, they are usually given ready-made problems by an industry or academic research organization and have to develop solutions or follow procedures for them. In this sense, their inquiry is limited to what their community assigns them.

Finally, it is difficult to find research environments that that meaningfully accommodate students in real research given their limited experience. Students (especially those still in school) simply do not have the technical knowledge and skills to participate meaningfully in most communities of practice.

2.5 Pragmatism/Feminism

2.5.1 What is pragmatism/feminism in education? How do they frame learning?

Finally, pragmatism and feminism, despite their different historical origins, are philosophically united in their framing of learning as liberatory practice that aims to foster citizens who actively participate in the advancement of democracy. Learning as a process here manifests as a dialectic between the learner and the societal structures they are entangled in, with each continually (re)shaping the other. Students learn by attempting to transform their local environment and are, in the process, transformed as well. This framing of learning is reflected in Dewey's (1916) framing of education as a practice of freedom that liberates us from our impulses and cultivates the knowledge and virtues to participate meaningfully in a democracy, and Freire's (1970) framing of education as a process of liberation that works to overcome systemic hierarchies of power and oppression, and hooks' (1994) approach to education as engaged pedagogy where students and teachers aim to understand and work *with* each other rather than *for* each other as a means to their empowerment and social change. Consequently, these traditions are concerned not just with assimilating students into a community or society but nurturing them to act in and on society and further its democratic cause (Riley 2008, 2013, 2008; Huff, Zoltowski, and Oakes 2016; Leydens and Lucena 2018). Unlike the other approaches where learning has an achievable end goal in the acquisition of facts/procedures, development of mental models, or assimilation to a community, learning here has no definite metric of success aside from staying as a liberatory and dialectic process.

To support the teaching of scientific inquiry as a dialectic and liberatory practice, scholars in science and engineering education have developed a variety of educational approaches, especially in relation to social justice.

Riley developed six principles for a critical/feminist/liberatory pedagogy for engineering education:

- “The point is not only to understand the world, but also to change it”

- Technoscientific theories must lead to action in relation to real needs of people and at the same time, be informed by them.

- "No education is politically neutral."
    - We need to ask "Who benefits? Who loses? Who isn't even at the table?" both in the content of the education as well as its approach.
- "Power relations are everywhere"
    - Power dynamics are always present in every form of practice and education and should be critically engaged with and challenged when unjust or undemocratic
- "Student responsibility for learning"
    - Giving students more responsibility to undertake real world projects that matter, where the situation is more open-ended than the class, can help them learn to be more responsible as inquirers.
- "Centrality of relationships"
    - Understanding one's relationships to and in a community of practitioners, even within school such as with teachers and staff. is at the heart of critical practice.

Drawing on these principles, Riley outlined a four-step critical and iterative pedagogical process that requires students to engage, analyze, reflect, and change situations. For example, when teaching thermodynamics, students may first engage with thermodynamics by identifying and reading about their local energy resources such as coal, hydro, solar, and biomass. Next, students analyze these energy resources such as by calculating their efficiency. Students then reflect on their analysis such as by exploring how their equations changed for each resource. Finally, students explore how such analysis can be changed, such as by exploring and suggesting other factors beyond "efficiency" that matter to critically examining energy resources. They can then conduct a new investigation with the new factors in mind. This iterative approach helps students systematically and critically inquire into technology as opposed to simply learning what they are told.

A practical example of feminist pedagogy in action is illustrated by Barton and Roth (2004) in the approach a fifth-grade teacher, Shagufta (pseudonym), who worked in a Pakistani school that was afflicted by a lack of resources, a shortage of adequately prepared teachers, and systemic pressure to teach for exams. To challenge this situation, Shagufta aspired to situate students' learning in their particular circumstances and use their education as a means to evoke action. For example, she engaged students with building tools and gauges that measured levels of noise, air, and water pollution in the neighborhood and to use their findings to understand and communicate the health and environmental risks of pollution to their families so that together they may improve the situation of the community.

Most digital games are not designed with this dialectic feminist/pragmatist approach in mind when teaching inquiry. However, there are games do engage students with the sociopolitics of inquiry, such as *Quest Atlantis*, *The Mystery of Taiga River*, *River City*, and *Crystal Island*. I analyze *Quest Atlantis* in this section and will go into more detail with *The Mystery of the Taiga River* (its successor) when I examine it using my own framework in Chapter 5.

Quest Atlantis was a digital game designed to situate scientific inquiry in a broader social context as opposed to purely technical and conceptual approaches (Barab, Zuiker, et al. 2007; Barab, Sadler, et al. 2007b). The premise of the game is to find out why fish in a park river are dying. The game is unique in the educational science games space as it aimed to explicitly engage students in socioscientific inquiry, i.e., "the process of using scientific methods to interrogate rich narratives about societal issues that have a scientific basis." It does this by incorporates socioscientific issues into its design such as by encouraging students to think about scientific solutions in relation to economic and ethical solutions to the same problem. For example, students have to critically think about the high revenue that logging companies provide in conjunction with scientific evidence that implicates logging for reducing the fish population.

2.5.2 How does it aim to position students in technoscientific practice, at a distance?

Position in pragmatist/feminist approaches is understood as one's entanglement in societal structures. For example, capitalist power structures often condition what kind of research can be done and who it can benefit. The more students are able to learn how to act on and in response to these structures, the better positioned they can be as practitioners. Consequently, these approaches aim to position students at a distance and teach them inquiry by engaging them in inquiry into their own local environments

In *Quest Atlantis*, one's position as a park ranger is given meaning by their relationship to the other members of the park community such as the fishers, the loggers, and the farmers. For example, given that the loggers provide a significant source of income essential to the running of the park, players must make a more informed judgement about how each group could be contributing to the dying fish population and what should be done about it.

2.5.3 How does it aim to teach scientific inquiry as a reflexive practice?

If feasible, such an approach is inherently reflexive as students to have examine their position in the local distributive, sociopolitical, and cultural structures as part of the process of inquiry. For example, in the Cheche Konnen Project (Warren, Rosebery, and Conant 1989), high school and middle school students identified the problem of poorer water quality in one of their school's fountains. In response, they designed experiments to verify and test the water, talked to other students and staff about their experiences, and examined possible sources of pollution. Each of these actions further transformed the situation, encompassing multiple classes and eventually included the school and local municipal community.

Quest Atlantis supports several processes of inquiry, such as hypothesizing about why the fish are dying, gathering evidence to find its possible causes, interviewing the local social groups to understand how they might be complicit in accelerate the decline of fishes, conducting experiments with a virtual fish tank where they can explore the effects of different factors such as acidity, temperature, and salinity on the health of fishes over time. The process is dialectic to some extent as students have to help decide the policies of the park—such as increasing fishing limits, or reducing logging—to curb the decline of the fish. These different policies have different implications on the situation of the park, supporting some groups and limiting others. However, this transformation only occurs at the end once students give their final recommendations. Throughout the process of doing inquiry, it is only the students and teachers who are transformed, not the other NPC characters as their processes continue as they were, without changing until the end.

2.5.4 What are its limitations?

There are two primary limitations of this approach: it is not always feasible or safe, and it may not conform to the requirements of the educational system.

First, given that this approach involves conducting real local investigations into one's community, it may not be feasible to use it as a means of teaching students subject-matter that is not pertinent to their community such as quantum physics and thermodynamics. Further, there may be safety concerns because critically examining and challenging the societal norms as that could lead to social division and political backlash in the community. For example, involving students in the fight for reproductive rights (such as for pro-choice) can put students in a precarious position between school and their family. Games such as *Quest Atlantis* can help overcome this problem by situating inquiry virtually. However, most games do not engage students critically with the relationship between societal norms and inquiry.

Second, anchoring technoscience education in such problem situations may leave students without the necessary knowledge to pass the systemic educational requirements and barriers. This is evident in the example of Shagufta outlined earlier in this section. Her school's prevalent social norms proved prohibitive to her feminist approach for three key reasons. First, the headmistress reprimanded Shagufta for taking students off-campus as female teachers were prohibited from doing so given the social values of the society. Second, she was discouraged from engaging students with concepts outside the state curricula such as noise pollution as they would not be asked on the exam. Finally, by encouraging students to ask questions, challenge the existing conditions, and speak up against their injustices Shagufta was cultivating behaviors that were frowned upon by the school administration who instead supported a teaching culture that demanded silence, obedience, and adherence to hierarchies of power so as to maintain discipline. For students as well as for Shagufta, this experience highlighted their limited position as technoscientific practitioners in their community and the challenges that come with it. This limitation can be addressed to some extent by aligning the subject-matter of inquiry with state/federal educational standards, but it will still involve going beyond the syllabus.

Despite these limitations, pragmatism/feminism offers a meaningful way of approaching the challenge of teaching reflexivity for three key reasons. First, teaching reflexivity as a means to liberation and democracy can help students learn technoscience as an emancipatory and societally entangled practice rather than as a politically "neutral" activity isolated from society. Second, teaching reflexivity through dialectic inquiry enables students to learn how to *be* responsible citizens by identifying, acting on, and transforming important problem situations and by critically reflecting on their individual, historical, social, and political position as technoscientific practitioners in their communities and society. For example, in attempting to find ways of depolluting local groundwater students may run into bureaucratic inertia, financial constraints, and delegitimization by local authority figures on account of their status as students. Reflecting on these issues in the process of trying to formulate and resolve such technoscientific problems is both valuable practical experience and is instrumental to learning democratic citizenship. Finally, designing learning environments to support teaching reflexivity in the pragmatism/feminist tradition requires a pluralistic approach to education that addresses learning at multiple levels: subject-matter, individual, communal, and societal. This is because designing a learning environment for teaching reflexivity that is aimed at fostering democratic citizenship requires helping students learn how to critically engage with technoscientific concepts and methods, build on their individual experiences, participate as active members of multiple communities such as school, home, and their township, and critical reflect and act on their positions as citizens and practitioners in society. Consequently, pragmatist/feminist approaches encompass the core principles of other philosophies while repurposing them for cultivating democratic citizenship.

2.6 Research Gaps

There are two general gaps outlined by this literature review that this dissertation seeks to explore in relation to teaching scientific inquiry as a reflexive process.

First, most educational philosophies do not consider the situated nature of scientific inquiry when teaching it, focusing instead on framing it as a set of abstract concepts or processes, or not engaging students critically with the structures underlying inquiry in practice. This is reflective of a larger gap between science studies and science education. Pragmatist/Feminist approaches do stress on the important of reflexive inquiry but are limited by practical constraints and systemic educational pressures.

Second, while digital games have been used to teach scientific inquiry they have not been designed to teach scientific inquiry as a reflexive process. In fact, most digital games that aim to teach scientific inquiry do not consider its situated nature, focus primarily on the practices of inquiry. The few that do consider it, such as *The Mystery of Taiga River*, do not critically engage students with how social structures are entangled in the processes of inquiry. They choose instead to complement or use inquiry to support/diminish political claims rather than integrate politics into the process of inquiry itself. Further, these games often present students with predetermined problems as opposed to letting students problematize the situation on their own.

CHAPTER 3. HYPOTHESIS

Summary: In this chapter, I develop two hypotheses that collectively aim to approach my research questions. First, I propose a framework of reflexivity to help analyze and design approaches to both research questions. The framework brings the processes of inquiry into relation with the structures of distribution, power, and culture, and one's position in them. This approach, I hypothesize, enables us to examine how students can be situated in practice at a distance, by providing us with the grounds to compare positionality in science education to scientific practice. Further, it also lets us examine if and how inquiry is being conducted reflexively. For example, the framework directs us to ask questions such as: how do students/scientists' position in structures of power different from students' position of power in educational environments? How are scientists/students examining the role of power in relationship their inquiry? Second, I hypothesize that digital games, can draw upon the framework to both position students in practice at a distance and teach them inquiry as a reflexive practice. This is because they can simulate the above structures of practice as rules of play using the grounds laid down by the framework, position students as practitioners in them, and engage students in reflexive inquiry by requiring players to strategize about positionality as they conduct virtual investigations.

3.1 Introduction

With the research gaps highlighted by my literature review in mind, I revisit the two research questions framed earlier:

- Can we design educational environments that position students in technoscientific practice, at a distance from it? If so, how?
- Can these environments be designed to support inquiry as a reflexive process? If so, how?

To approach these questions, I propose a two-part hypothesis.

3.1.1 Hypothesis

First, I develop a framework that I hypothesize can support the analysis and design of educational environments that aim to position students in practice at a distance and teach them how to do scientific inquiry, reflexively. To summarize, the framework defines and relates one's positionality to scientific inquiry. It frames the positionality of inquirers in four ways—as their *means, status, culture*, and *experience* each of which embody their position in structures of distribution, power, culture, and all three, respectively. Briefly, *means* refers to one's position of access to materials, information, people, and places in distributive structures of society. *Status* refers to one's position of responsibilities in structures of power. *Culture* refers to one's ways of thinking, being, and doing embedded in the social fabric of their communities and their history. *Experience* refers to one's collective knowledge and expertise built up over time, including from their past experiences of *means*, *status*, and *culture.*

The framework places these positions in relation to scientific inquiry which is understood as the three interrelated processes of *problematizing*, *hypothesizing-experimenting*, and *resolving.* All of these processes are instrumental in defining and transforming situations between indeterminacy and determinacy. *Problematizing* involves unsettling what has been established and framing questions that capture the ensuing uncertainty. *Hypothesizing* and *experimenting* involve developing ideas and collecting facts by testing those ideas. Finally, *resolving* involves synthesizing one's findings of inquiry and deciding when the constituent parts of a situation "hang together" as opposed to being indeterminate and disconnected (Dewey 1938).

Second, I propose that by drawing on this framework, digital games can be well-suited as educational environments to position students in scientific practice at a distance from it, as well as teach students to do scientific inquiry reflexively. It is important to note that my hypothesis is that digital games as *stand-alone* environments can support this kind of simulation. That means that I will be exploring specifically the worlds simulated within digital games and their capacity to position students in practice at a distance and support inquiry as a reflexive process. How digital games are themselves employed and situated within the educational environment will no doubt significantly impact their ability to do this. However, I reason solely about the game environment in itself for two reasons:

- First, digital games are highly scalable. Consequently, if games could teach inquiry as a reflexive process on their own, then that could help spread this approach to teaching far more quickly than if they could only do so with the external pedagogical support.
- Second, examining digital games alone enables us to isolate and identify their strengths and limitations, thereby allowing us to both complement them accordingly and design them to their strengths.

I will now discuss the rationale for proposing the framework and digital games as my hypotheses for addressing the two research questions.

3.1.2 Rationale

The rationale for developing the framework is that it provides us the grounds to analyze responses to both research questions. In turn, the rationale for employing digital games is that they can be designed as educational environments that crystallize those grounds for teaching scientific inquiry as a reflexive practice.

Approaching the first research question—can we position students in technoscientific practice at a distance—requires developing grounds for comparing positionality in practice to that in education. The framework provides these grounds with its focus on the distributive, power, and cultural structures of practice, and in its framings of one's "position" in them as one's *means, status,* and *culture,* respectively. By employing these structures and positions as grounds for comparison, we can begin to inquire into the nature of positionality in both practice and education. For example, focusing on structures of power and one's status we can ask: How do the structures of power in the classroom differ from those in practice? How does one's position within these power structures affect inquiry in each environment? How can we design educational environments that engage students in more democratic power structures of practice, or critically engage them with the limitations of authoritative power structures of practice? Such questions invite us to examine if and how educational environments should position students like real practitioners and suggests directions for designing such environments.

Digital games, I propose, are one possible candidate for such an educational environment. They can be designed to draw upon the grounds described by the framework (and the questions those grounds raise) to position students in practice, at a distance. This is in part because they can *simulate* the distributive, power, and cultural structures of practice, contextualize them through a narrative, position students virtually in them, and give appropriate feedback to them as they do inquiry promote learning. Consequently, these qualities can allow students to experience and explore the structures of scientific practice, at a distance from them. Such a design is made possible because of the many affordances of digital games, especially as procedural, artificial, and evaluative media. These affordances will be discussed later in the chapter.

Approaching the second question—can such environments teach inquiry as a reflexive process—requires developing grounds for deciding if and how students are actually learning scientific inquiry as a reflexive process. The framework supports this endeavor by outlining key relationships between positionality and inquiry that are important to consider when engaging in reflexive inquiry and can therefore serve as possible indications of it. For example, using the framework, we can ask: are students examining the potential consequences of the *resolutions* of their inquiry on the *means* of others? How are students critically examining the effect of their *culture* on the *problems* they frame? Can we engage students more meaningfully with the relationship between power structures, their *status* in them, and the scientific *hypotheses* those positions tend to support? By inviting such questions, the framework enables us to examine how a learning environment is able to engage students with these relationships and also suggests directions for transforming them to better teach inquiry as a reflexive practice. This focus on the relationships between inquiry and positionality is what makes the framework unique. Other frameworks designed to teach students scientific inquiry often focus primarily on enabling comparison between the processes of inquiry in practice and those in education without consideration of the broader context of practice such as its distributive, power, and cultural structures and one's position in them.

Digital games, I propose, are well-suited to teaching students to do scientific inquiry reflexively as they can be designed to invite critical engagement with these relationships through their game mechanics and narrative. For example, having a core mechanic where a student's *status* as an engineer in the game impacts the kinds of devices they can *experiment* with (and vice-versa) can invite students to strategize about how best to act on or transform this relationship to advance their game state. Such strategizing in the game is a form of reflexivity as it requires understanding the relationship between their position and their process of doing inquiry.

With these rationales in mind, let us examine the framework and digital games in more detail in relation to the two research questions.

3.2 The Framework of Reflexivity

The premise of the framework are the feminist notions of "situated knowledges" (Haraway 1988) and "strong objectivity/reflexivity" (Harding 1991, 1992). The former argues that scientific knowledge, and by extension scientific inquiry, is always developed by practitioners who are positioned ("situated") in material, social, political, cultural, and historical structures of practice. The latter argues that because of this situated nature, scientific inquiry, in order to be "strongly" objective, must be "strongly" reflexive of its positionality, i.e., critically examine the relationships between its positionality and inquiry. Based on these notions, the framework has two dimensions: one focusing on positionality and the other on inquiry (Figure 1).

In this section, I will draw upon a range of examples in scientific practice across different fields to reify these two dimensions and their relationships. I aim to especially highlight practice in the electronics industry. The rationale for this is threefold. First, the electronics industry perpetuates oppression and environmental injustice at multiple points in the lifecycle of electronic devices—in the mining of raw materials, the manufacture and assembly of devices, their daily use, and final disposal. Given the scale and dependency of society on electronics, there is an urgent need to critically examine the practices of this industry. Second, given this import, the educational environments I was seeking to develop focused on teaching inquiry into the design of electronic devices such as computer chips and solar cells. This allows us to compare positionality in real scientific practice to educational environments that were aimed at preparing students for that practice. Finally, the science and engineering of electronics are often seen as being value-neutral and political. By examining how the societal structures affect and are affected by the technoscience of electronics, I aim to show how it too is situated and therefore value-laden and political. Where necessary, however, I will also use examples from other industry/university environments to illustrate my point.

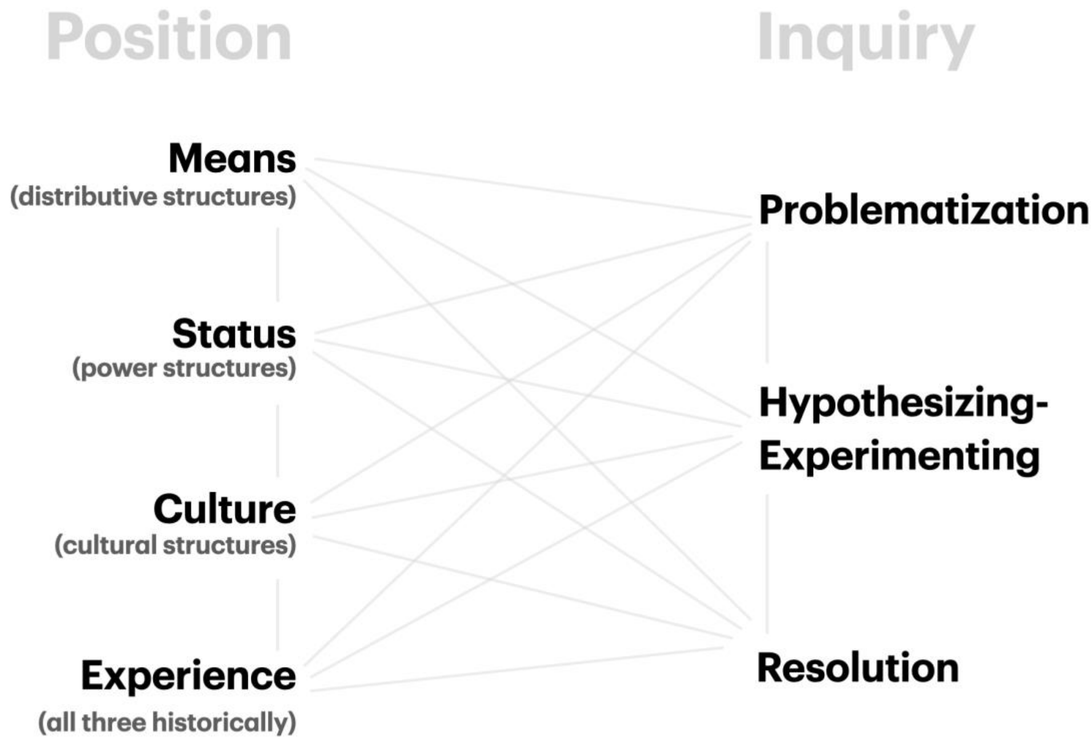

Figure 1 – The Framework of Reflexivity. It relates positionality in societal structures to the processes of inquiry.

This chapter will focus on using these relationships to analyze scientific practice and in doing so, aim demonstrate the capacity of the framework as an analytical tool for it. I will build on this approach in the next two chapters to analyze and (re)design educational environments with the framework.

3.2.1 Positionality

Positionality forms the first arm of the framework and refers to one's location in structures of society and practice. To understand positionality therefore, we need to also understand the structures which it exists in relation with. Drawing upon the typologies of Young (1990) and Klein and Kleinman (2002) discussed in Chapter 1, I outline three structures within which one is positioned as an inquirer: structures of distribution, power, and culture. I discuss these structures in conjunction with one's positionality in each of them as: *means*, *status*, and *culture*, respectively.

3.2.1.1 Position as Means (Structures of Distribution)

I define the *means* of a practitioner/community as their position in structures of distribution, i.e., systems that govern people's access to resources (both physical and conceptual) and places. Structures of distribution includes the structures of resource-access outlined by Klein and Kleinman. Examples of such structures include: the budget that can be spent on resources, the system of sharing and distributing resources among researchers, the logistics of supplying and replacing resources, or the state of the market.

Distributive structures affect one's means both as a practitioner and beyond it. Resource related issues include matters such as obtaining access to relevant resources (including funding, equipment), planning inquiry with limited resources, working with unreliable equipment, distributing/ sharing resources equitably, and maintaining those resources, all of which significantly impact how inquiry is done. For example, in a competitive market, an electronics company with a tight budget will have to prioritize its spending and therefore not be able to spend well on apparatuses. So electrical engineers may need to share resources such as circuit boards, voltmeters, and ammeters. A tight budget also means that it may not be able to pay engineers well, which affects their means beyond practice.

Conversely, one's means can also affect the distributive structures. This happens more frequently for those with excessive means. For example, rich executives and CEOs commonly lobby politicians to subside their industry and keep taxes low for them, thereby enhancing their wealth and means. Yet, those with lesser means can still affect the system when they band together, such as through revolutionary protests in order to ensure more democratic and equitable distribution of resources. This was seen in protests against FoxConn factory workers who worked long hours with low wages to assemble iPhones (Chan, Selden, and Pun 2020). While the protest helped improve their wages and hours to some extent, it did not change the fundamental system which produced a surplus of workers and not enough jobs.

Distributive structures can also affect who becomes a practitioner. Rising tuition costs in college, expensive tutoring classes for standardized tests, and a lack of sufficient funding for schools in poorer neighbourhoods are all part of a system that keeps those with less means out of education, and therefore out of contention for getting a degree needed to be a practitioner. Predatory student loans further exploit those students who aim to seek the means necessary to get a college education, which can either drag them down a rabbit hole of debt or lead them to pursue the highest paying jobs (which may not necessarily the most rewarding ones), affecting if and where they become practitioners.

Understanding one's position as their *means* in such distributive structures entails asking questions such as "what resources do they have? What places can they go to?", or "Who can they network with?" Linguistically, this framing of position as means can be seen in phrases such as "they were not in a position to go there" or "their position granted them access to better healthcare than others." It is also be used to refer to communities as a whole: "the position of people below the poverty line is appalling" with "position" referring to one's basic means such as food and shelter.

3.2.1.2 Position as Status

I define the *status* of a practitioner or community as their position in structures of power. These structures comprise the systems of rules, procedures, and norms that determine people's agency over their own-lives and those of others. They include Young's structures of labor division and decision-making procedures, the structures of relevant social groups, interpretation, and closure highlighted by Klein and Kleinman.

One's status enacts relations of power between them and others, dictating what they should do, what they can do, and for whom. People/communities with a "higher" status, such as high ranking-executives, have more power to define tasks and make decisions, while those with a "lower" status, such as company employees, are often responsible for executing tasks and implementing decisions made by others and have limited agency to do the former.

Status can manifest in several different ways depending on the specific structural configuration. For example, in a place of occupation, one's status can be understood in terms of their designation, such as an electrical engineer, manager, principal investigator, field researcher. Each of these positions have their own scope of action and are accountable to those in higher positions—an electrical engineer may only work on issues of electronics (not management) and is accountable to their manager. Similarly, in a familial setting, one's status can be understood as their role in the family such as a parent, child, or guardian. In a civic setting, status can refer to one's political position such as a citizen, immigrant, and non-resident. Linguistically, this framing of position as status can be observed in phrases such as "their position as a president makes them less immune to litigation" or "they occupy a lower position at the institution."

One's status, both within and beyond technoscientific practice, plays a significant role in how they engage in practice. Within practice, it is integral to how scientific responsibilities are defined and assigned. For example, in a traditional hierarchical lab structure, principal investigators are responsible for more administrative and high-level tasks such as getting funding, deciding what problems to investigate, and assessing the research group's progress. In turn, experimental researchers in this lab would be responsible for more on-the-ground tasks such as designing, conducting, and analyzing experiments. Further, one's statuses (responsibilities) beyond practice also shape and are shaped by their status in practice. For example, a parent may not be able to take on the responsibility of field research if it meant leaving their young child behind for extended periods of time. Conversely, a researcher looking to do field research that requires extended periods of travel may re-consider having a child until they are more settled.

3.2.1.3 Position as Culture

Culture can be understood as both a structure as well as one's position in it.

As a structure, culture can be understood as "the water that we fish swim in,", i.e., the shared norms, rules, and assumptions that situate our ways of thinking, being, and doing. Culture, as a structure, expresses itself in several ways, such as in the fabric a community—Indian culture, Black culture, tech culture—or as a school of thought such as positivism, neo-liberalism, and feminism. It includes culture as conceptualized by Young as well as the technological frame by Klein and Kleinman as discussed in Chapter 1.

Structures of culture extend their influence at all scales, from day-to-day activities to systemic decisions. For example, feminist scholars have long discussed how research labs can have sexist cultures where women, trans, and non-binary scholars are not cited or credited for their work, not accommodated for their needs, and continually sexualized by their male peers and authorities. At a societal level, cultural stereotypes about BIPOC and LGBTQ people often hinder them from being considered or supported for participation in STEM fields. This is worsened by a cultural mindset that favors "meritocracy" without considering the inherently unjust social structures that determined who becomes "meritorious" in the first place as well as the normative criteria of "merit" set by those in power. Given that the presence of non-male and non-White or non-Asian scholars is necessary for changing the very system that excludes them, a culture of bigotry in science systematically maintains an oppressive status quo.

Structures of culture are also exhibited in the paradigms/disciplinary matrices of research as scholars assimilate to different schools of thought and the associated "isms." Affiliation in these schools of thought can inhibit one from examining problems in novel ways. For example, when scientists in the 18th century discovered evidence that the orbit of Mercury did not align with predictions made by Newton's laws of motion, they developed several different theories to explain the discrepancy, all of which assumed that Newton's laws were true. Some posited that there was a missing object between Mercury and the Sun, while others posited that the sun's shape was not as spherical as assumed. Each of these theories played with the possibilities enabled by a culture of science that was characterized by its overarching acceptance of Newton's laws of motion and rejection of scientists who sought to challenge those laws. This observation however, was ultimately explained by Einstein's theory of relativity which fundamentally challenged Newtonian laws about gravity and motion (Lakatos, 1970).

As a position, culture refers to our entanglements in cultural structures. However, we are not an aggregate of the cultures that we belong to. Rather, our cultural position manifests in the mutual reshaping of these cultures. For example, black feminist culture arose partly out of black disillusionment with white feminism (hooks, 1984) and in the process, reshaped both black and feminist culture. Linguistically, this framing of position as culture can be seen in phrases such as "his position as a white man has given him many privileges" or "their position as a determinist precluded them from understanding the universe probabilistically."

3.2.1.4 Position as Experience

Finally, while the other three framings of positionality focus on the present situation of the practitioner/community, *experience* accounts for their past, including their past *means*, *status*, and *culture*, as well as the expertise or knowledge they have built up over time.

One's prior means, status, and cultural experiences have epistemic value. This is true especially for those from marginalized backgrounds. As Harding argues, those who have been historically marginalized are in a more epistemically advantageous position as their experience navigating oppressive situations helps them identify problems and resolutions that may otherwise be overlooked. For example, workers in an oppressive electronic factory know the problems faced by them and their peers—such as the difficulty of managing and assembling small pieces (Chan, Selden, and Pun 2020) and the lack of protective equipment for handling toxic substances like benzene (Jang et al. 2019)—better than the designers and executives who developed the factory. If such a worker ever becomes a manager or designer in the future, they can design the factory or devices to improve such a work environment accordingly.

3.2.1.5 Caveats of "Positionality"

It is important to note that these different ways of understanding positionality are intertwined and not mutually exclusive. One's *means* of access in an organization can be a function of their *status* in it. Further, there may also be overlap between these framings depending on the broader context. For example, systemic racism collates *access* and *culture* as it often restricts black, indigenous, and people of color from accessing vital resources such as a good education or healthcare. Given this entanglement, the rationale for framing them separately is that each framing is useful for a different kind of situation. *Means* is useful when talking about material or spatial conditions, *status* is useful when talking about one's responsibilities in the functioning of communities and institutions, and *culture* is useful when talking about one's underlying ways of thinking, being, and doing. Their interrelationships do not detract from our analysis as the purpose is not to use them for categorization, but to employ them to enrich our understanding of the situation as a whole.

Similarly, these framings of positionality may not be exhaustive, as they were defined with an understanding of reflexivity that places one's position in systems of oppression as integral to scientific inquiry. This focus on systems of oppression limits their scope accordingly. The rationale for focusing on oppression itself has been discussed in detail in Chapter One, but briefly, it allows inquiry to be more "strongly" objective by drawing upon the epistemically advantageous situations of the oppressed. Changing this focus to examine other matters such as the relationship of inquiry to modernity will likely change how positionality is defined to better suit that purpose.

3.2.2 Inquiry

The second arm of the framework focuses on the processes of inquiry. Drawing upon Dewey's pattern of inquiry (Dewey 1938), I outline four interconnected processes that are integral to conducting scientific inquiry: *problematizing*, *hypothesizing-experimenting*, and *resolving*, each of which is grounded in and given direction by the positionality of the inquirers in distributive, political, cultural, and knowledge structures.

3.2.2.1 Problematizing and Positionality

Problematization is the initial stage of inquiry where one creates or finds a situation of doubt. Problems in practice are usually not "given" as well-defined and solvable questions, but must be developed, and are often ill-defined, unbounded, and unknown to be resolvable.

Let us examine the problem of designing a solar cell in relation to these three qualities. First, the problems are developed, in that the research team has to consciously decide what counts as a meaningful problem. Should we design a new solar cell? Who will it benefit? Second, this problem is ill-defined because the constraints have to be set or determined over time by the designers such as the desired efficiency of the solar cell, its reliability, the budget, the timeframe, and the materials. The research team has to define the problem in conversation with several other parties such as their managers, consumers, manufacturers, and suppliers. Further, the problem can change as inquiry proceeds. For example, it might be decided that an efficiency of 27% is too high given the budget and that one of the two should be revised. Third, the problem is unbounded. It requires not just electrical engineers but also mechanical engineers to address issues of heating on the board, financial experts to calculate and minimize the costs of making the device, and managers to distribute the project load in a manner that supports a high turnover. Each of these "different" problems is part of the same problem of designing the solar cell and requires extensive communication across experts in different domains to resolve. Finally, it is not known whether the problem can indeed be solved. *Is* it possible to design a solar cell with 27% efficiency given the budget we have? Consequently, until the problem is actually resolved either as initially framed or after reframing, there is no guarantee of resolution.

One's means determine the scope of problems by physically limiting what research can be done. For example, a research group that only has the apparatus to design, develop, and test silicon solar cells, will be limited to problems about silicon solar cells. They may not be able investigate other types of solar cells, such as multi-junction, GaAs, and organic cells unless they have the means to access the resources needed to do so. This is a significant limitation because once a research group (say at a company or university lab) has committed to a certain project and acquired all the necessary funding and apparatus needed to do their investigation, they may be unable to change direction until the project is complete, without bearing significant material, financial, and professional losses. Instead, the situation may coerce them to keep finding newer and ever narrower problems that can be investigated with the access to resources and places they already have.

Conversely the way problems are defined can affect one's means and those of others. For example, framing problems in ways aligned with the vision of the funders can help sustain funding into the future. It can also affect the means of others. For example, how a research group frames or prioritizes problems impacts their own position of access, as well as those of others. For example, framing the problem of designing computer chips without factoring their social and environmental effects has helped electronic companies such as Apple and Intel extend their means through higher profits (due to factors such as cheap labor), and subsequently, more research opportunities. At the same time, it has robbed access to higher wages and better working conditions for the several miners and factory workers that help make those devices (Frankel, 2016).

Status can affect problematization by constraining one's agency to define problems. For example, hardware testing-engineers in a company are often assigned hardware-testing related problems by their managers, such as deciding on the number of tests, running tests efficiently, analyzing test results, and identifying sources of and digression from the expected results. The scope of problematization is bounded by the engineer's position *as* an engineer. For example, the engineer may identify a problem with the traditionally inefficient and manual way of gathering test data and attempt to replace it with an automated system. Beyond this limited ability to problematize however, there is little scope for defining and developing new problems, as that would take away time and resources from the responsibilities already assigned. Further, if such specializations are part of a rigid hierarchical power structure, then practitioners may not even have the agency to negotiate with management about the nature and scope of their problems.

Conversely, the problems one works on affects their status. For example, working on a lead project with high visibility for a company may promote one to a higher position and more agency to problematize. At the same time, in a competitive power structure, it can also inhibit the advancement of status for another practitioner competing for the same position.

The culture of practice also has a significant impact on the framing, development, and prioritization of research problems. For example, electrical engineering teams that develop computer chips often solely examine design in technical terms due to a culture of societal disengagement. Issues such as the environmental impact, exploitative sourcing and manufacturing of devices, and access to the device are usually not considered in the design phase by the team.

Conversely, what research goals one sets can also affect the culture of work. For example, tech culture often begets more tech culture as it often allows teams to produce highly profitable products (even when they have a detrimental impact in several area). This can expand beyond individual research groups as other research groups and companies seek to imitate a culture that has proven economically successful such AGILE or Waterfall cycles of work.

Finally, one's experience and more specifically, their expertise in the area of focus shapes the kinds of problems they frame. For example, inexperienced or newly promoted technical team leaders can often struggle to frame deadlines, targets, and team goals well initially. There are several invisible factors that become more visible as the project proceeds that cannot easily be anticipated, especially for new team leaders, such as handling unpredicted budgetary constraints, assigning responsibilities between team members, handling sexist/racist incidents and procedures, and improving diversity and inclusivity. Often times, these are not considered as part of the problem that is framed and are learned over time through experience. This is inherently an iterative and cyclical process as new experiences condition problem-framing and vice-versa.

3.2.2.2 Hypothesizing-Experimenting and Positionality

Hypothesizing involves ideating possible resolutions to the problems raised based on what is known. This involves actions such as developing hypotheses/models for explaining what is currently known, making predictions using them, and designing studies or experiments to test them.

Experimenting involves conducting studies to test hypotheses and/or find evidence for or against them. It comprises of tasks such as acquiring equipment, collecting samples, performing tests, and analyzing test results. It also extends beyond the lab room. For example, releasing a new device can be seen as a social/economic experiment, which helps practitioners improve their designs for the next iteration. What studies are performed depend on the hypotheses developed and selecting for testing and inform future hypotheses.

Both these processes go hand-in-hand and are difficult to separate. Practitioners are continually hypothesizing as they experiment and experimenting with different hypotheses. Is the experiment working? If not, is there a problem with the hypothesis or the experimental design? What factors are not being considered by the hypothesis and how could they be affecting the experiment and its results? Can the experimental findings be explained by multiple different hypotheses? Such problems entangle the processes of hypothesizing and experimentation as hypotheses inform experiments and experiments inform hypotheses.

In practice, a researcher's means affects their ability to develop hypotheses and conduct experiments. For example, hypothesizing (or designing) and testing an electronic circuit board requires acquiring specific hardware apparatus such as wires, circuit components, voltmeters, ammeters, soldering stations and so on. As an engineer, being able to get and keep these resources long enough is essential to completing the test. However, when these resources run in short supply or are being shared between other engineers, then one has to improvise and develop a research plan that allows them to do the tests on time keeping the resource constraints in mind: "If I test the board in this way, then I won't need the voltmeter later on and so it won't be an issue if someone else takes it"

Conversely, what hypotheses a researcher chooses to investigate and experiment they run can also significantly impact their means. For example, using up one's allocated resources or time slot in a research group when testing a hypothesis can mean that the researcher may have to find other means of continuing testing. This extends to resource constraints of the whole research group, whereby failed experiments may deplete resources to a point that they can no longer be conducted without external means and support.

The status of a researcher (and the research group) and both indirectly and directly affect their hypotheses and experiments. Indirectly, it can affect their means which, as discussed above, plays a key role in hypothesizing and experimentation. For example, more prestigious research groups can draw upon their reputation to get access to people, equipment, and funding that is not easily accessible. Top research groups attract the best talent, which helps them sustain funding, and continue experimentation. New research groups however, may not be in a same position to do so. Directly, one’s hypotheses may be conditioned by their desire to maintain or preserve their status. This was partly the case in the Mercury example discussed earlier in the chapter where researchers did not dare hypothesize that Newton’s laws may be wrong for fear of losing their position. History has shown that scientists who radically challenge the dominant view often lose their positions such as with Galileo, and more recently, with Wagner and his theory of plate tectonics.

This ties into the role of culture in hypothesizing and experimentation. Different research groups and communities have their own acceptable methods for hypotheses and experimentation. For example, technical journals such as those by IEEE often require quantitative analyses, even for sociological problems such as electrical engineering education. Consequently, the technical focus of electrical engineering research extends into the electrical engineering education research, even though the latter may demand a different approach as quantifiable data are hard to generate due to the plurality of social factors involved in education. In turn, journals such as *Science Education*, which is rooted more in the social studies of education is far more willing to accept a wide variety of methods and experiments.

The effect of culture on research is also visible at a systemic level, such as with the culture of capitalism. For example, white American companies often exploited indigenous women in the name of their culture. Many indigenous women within the US were supposedly chosen to work on semiconductor devices in the 1970s because of the “nimble fingers.” The designs of the circuits were even seen as an extension of existing cultural weaving practices. Yet, these were just marketing and PR moves as these women did not really have much of a choice to sustain themselves even as the companies employing and exploiting their labor gained tax incentives on native American land. The situated was even worse in Malaysia where state sponsored capitalism resulted in widespread forced labor for electronic manufacturing. Migrants' travel documents were seized and they were forced to work and undergo severe human-rights abuses. The lack of action against these forced labor practices highlights the willful negligence by governments who fail to curb such practices even when they have the power to do so, highlighting the systemic nature of the issue.

Finally, the role of experience is inherent to the cyclical nature of hypothesizing and experimentation. Failed experiments inform new hypotheses which inform new experiments and so on. Each iteration is conditioned by the means, status, and culture of the research group, the research communities, and society more broadly as highlighted in the above examples. At a broader level, more experienced research groups can engage in these cycles more effectively, especially when the new problems they tackle are similar to the old ones, as they learn from their mistakes.

3.2.2.3 Resolving and Positionality

Resolution consists of the processes that synthesize the facts and ideas generated during inquiry and employs them to make the situation more coherent and determinate. This occurs usually after multiple iterations of problematizing, hypothesizing, and experimenting to understand how the parts underlying the initial indeterminate situation of doubt "hang together" in a manner that settles confusion. Resolution is similar to the notion of “closure” highlighted by Klein and Kleinman. Several questions can permeate this process: What counts as evidence? What makes the evidence “sufficient”? How do we know if the problem has a meaningful solution? Who decides these matters and how?

One example of this can be found in solar cell research that has been aspiring to increase the efficiency of the silicon solar cell to its theoretical maximum of around 30%. Every research group that aims to get closer to this value is faced with the same question: “is it possible to go closer to this value?” Every time the process fails there are several uncertainties that emerge: was there a theoretical problem? a practical problem? an implementation problem? or something else entirely? Deciding whether to try again or conclude the research at this point is contingent on the positions of the research group and inquirers.

One’s means can significantly affect their ability to resolve the above situation. For example, if the budget for the project has dwindled or the group does not have access to more precise measurements, it may take a call to end the project where they are. Or, if they believe there are several other possibilities they can explore with their current means, then they may decide to continue researching the problem.

Conversely, repeating the problem again and again may exhaust the research group’s resources. This can be seen by the group as an unresolved problem, or they can take what they learned from the process and conclude that their approach does not work, which is a resolution and contribution to the research in its own way.

The status of the research group also matters to resolution in this situation. For example, if the research group has a reputation for outstanding research and a history of significant contributions towards improving cell efficiency, then they may persist longer until they can improve some marginal gains. Their elevated status may also enable them to get funds to conduct more accurate experiments and analysis which can accelerate the resolution of the problem. Failure may not be seen as an option to preserve the status of the group. This can create a high-pressure environment, exacerbating inequalities in the group. For example, those who were already finding it difficult to manage their time due to external roles they play, say as parents or caregivers, may leave the lab in order to be able to fulfil their external responsibilities. Further, the status of the individual researchers also matters to the resolution process. Junior researchers may have less say about concluding the research, especially for a negative result than senior or principal investigators.

Conversely, resolving the problem (or a variation of it) can further elevate the status of the group, while keeping it unresolved can lower it within the research community. It can also affect the status of those who helped resolve the problem within the research group.

Building on this, the culture of the lab and the research community as a whole significantly impacts the resolution process. When competing for funds (from a company or government organization) is the primary goal, there is an added incentive to continue working on the problem even when all methods have failed. This pressure for a positive result is also reflected in the present culture of academic publishing which prizes positive results far more than negative ones or those that reproduce results. The culture can impact the culture of the lab turning it into a high-pressure environment, even if none of the researchers individually intended for that to happen.

Conversely, if several research groups in the community fail to increase the cell's efficiency beyond a point, the lack of resolution may become acceptable. This could make some research groups more relaxed while motivating others to try even harder in order to make a name for themselves.

Finally, past experiences are intertwined at every stage of this problem because of its inherently iterative and cyclical nature. Past successes can motivate the group to build and maintain that success. Past failures can help the group get closer to resolving the problem by either reaching the higher efficiency or concluding that it is not possible due to some theoretical/practical constraints. New success and failures then add to one's experiences and inform the resolution process in the future.

In practice, every resolution is arrived at with a sense of uncertainty or a degree of confidence in the results. No resolution can be known to be the "right" one *a priori*. Even when a higher efficiency has been achieved, it may not be reproducible easily and therefore take longer to verify. The verification process in turn may find that the result was incorrect, thereby resetting the resolution. Learning to live with this uncertainty is an important learning experience for real scientists and engineers.

3.2.3 Caveats of Inquiry

Now, it is important to note that the framework is meant to function as tool to support the analysis and design of educational environments for teaching inquiry and not to evaluate inquiry. Inquiry in practice is messy and entangled and all its processes and contexts cannot be separated from each other. Consequently, the way to use this framework is to use it as a starting point for investigating the dialectic of position and inquiry in educational environments and to explore possibilities for (re)designing educational environments to teach inquiry as a reflexive process. Using the framework, one can examine a given educational environment and ask questions such as: "What relationships can we see between the process of designing experiments and the status of the student here? What potential relationships *could* there be between them? How can we help students reflect on these relationships?" Consequently, the framework is not meant to be an end point for categorization, but as an approach for design critique and a source for sparking new design ideas. Such ideas can originate in either the "position" arm or the "inquiry" and examine its affect on the other. For example, we can ask "how can student experiences as black girls be shown to be valuable to problematizing the research literature or designing an artifact? In turn, we can also ask: "how might the experiences of analyzing scientific data be fruitful for improving the position of black women students as an underrepresented community?"

3.3 Digital Games

Designing digital games to support inquiry in a manner that builds on pragmatist/feminist practices entails designing to simulate the social structures and situations of real scientific practice, not just the technical matters. Now, it is important to note that my hypothesis is that digital games as *stand-alone* environments can support this kind of simulation. That means that I will be exploring specifically the worlds simulated within digital games and their capacity to position students in practice at a distance and support inquiry as a reflexive process.

Keeping this in mind, I discuss how the affordances of digital games can support them in approaching the two research questions.

3.3.1 Key Affordances

Overall, the key reason digital games can support the learning of scientific inquiry as a reflexive process is that they enable the simulation of virtual worlds and students as virtual practitioners. As Barab et al (2007) argue, games can enable "situative embodiment":

"Situative embodiment involves more than seeing a concept or even a context of use; it involves *being* in the context and recognizing the value of concepts as tools useful for understanding and solving problems central to the context in which one is embodied...It is just such socio-material embodiment that others have argued videogames can afford."

While digital games have several affordances in support of this endeavor, I argue that three are especially useful when attempting to teaching inquiry as a reflexive process: they are their procedural, evaluative, and artificial affordances.

3.3.1.1 Procedural

Procedurality refers to the ability of digital games to "represent and execute conditional behaviors" (Murray 2012, Bogost 2010). Procedurality enables the dynamic simulation of "real and hypothetical worlds as complex systems of parameterized objects and behaviors" (Murray 2012). This includes scientific models that can be described by mathematical equations, dynamic visualizations, graphs and charts, interactive diagrams etc. Non-digital media such as analog/physical games are also procedural as they too involve executing procedures (such as different game phases). The same can be said of mechanical devices such as Rube-Goldberg machine where a ball is “programmed” to move along a predetermined trajectory by strategically placing different objects in its path.

However, digital media can process, render, and store information about such systems at a speed and scale far greater than analog/media, all without requiring player intervention or action. For example, in the game WIRED (2016), players must create electrical circuits to solve in-game challenges. The mathematical circuit-solving model programmed into the game automatically and quickly calculates the current flowing through different wire segments. In contrast, to calculate the current flowing in such circuits in a physical/analog setting would take significantly more time, effort, and/or resources as players must either calculate the currents manually or attach and re-attach sensors (ammeters, voltmeters, multimeters) at different points to know how much current is flowing in each wire segment. If the goal of the game is to enable inquiry through experimentation, then allowing players to explore a wide range of configurations quickly is advantageous. On the other hand, if the goal is familiarize and accustom players with the hardware, then the physical/analog option may be more suitable. Consequently, digital media are conducive for engaging students with several practices of inquiry such as modeling, data analysis, and experimentation as they can simulate a wider range of scenarios that physical/analog media may take significantly more time and resources to do.

3.3.1.2 Evaluative

Digital games are evaluative in that they assess or judge a player’s performance based on a set of predetermined criteria or parameters (Karhulahti, 2015). This is made possible by their procedural nature which allows them to programmatically check the state of different parameters against a predetermined "success" or "fail" state. Consequently, repeatedly checking the state of the players' parameters in a virtual world enables digital games to simultaneously enable inquiry in the simulated environment and also evaluate it, and to guide (or challenge) players accordingly.

This evaluative quality of games often takes the form of goals or quests that players complete. It is most evident in games with clear win/lose states such as *Super Mario Bros*, where the main character dies or loses when they come in contact with the enemy or wins when they defeat the boss character. It is also present in games that do not have clear win/lose state such as *SimCity* where the game "unlocks" new technologies for players when their income or population parameters cross a predetermined threshold. In both cases, there is an in-built progression that the game is programmed to follow which allows or disallows the player from accessing different in-game features depending on the player's performance measured against a set of predetermined states.

Evaluating players in this way is essential for teaching inquiry as it enables games to teach students how to monitor and assess the effectiveness of their inquiry. For example, the game *Poly-Bridge* is able to teach players how to design bridges by setting quests that require them to work within tight constraints. These quests guide players through an increasingly complex trajectory of scenarios, each with a clear goal and criteria for "success." For example, one level may require that players design a bridge that costs less than $1000, while another may require them to build a bridge using only wood as a material. Each level helps shape students understanding of different strategies for bridge design and to gradually learn which strategies suit which scenario. This helps students learn how to inquire into the design of new bridges in new landscapes. Without such a level-by-level approach and well-defined goals in each level, students may get overwhelmed by the diversity of materials, designs, and landscapes available and subsequently disengage from learning inquiry.

This evaluative quality of digital games serves to distinguish them from other procedural digital media such as software and simulations as the latter usually do not have in-built goals and systems of evaluating them. Further, it adds an additional layer of difference from physical/analog games as the latter require an external agent such as the players or a referee to evaluate their performance, based on a given set of criteria. For example, in a physical jigsaw puzzle, a player must do the work of evaluation themselves by checking if they have met the winning criteria, i.e., if the configuration of their jigsaw pieces resembles the jigsaw image. In contrast, a digital jigsaw puzzle may do the evaluation on its own to determine if the player wins or loses and correspondingly communicate that result to the player. However, this evaluative nature does not help differentiate digital games from digital "gamified" applications such as fitness trackers, car performance indicators, and AI tutors which also automatically evaluate students (or users) based on a set of predetermined criteria.

3.3.1.3 Artificial

The artificial affordance of games refers to their constructed nature as "separate" from the real-world. One of the historically consistent affordances that scholars have outlined as being a central quality of games (both digital and non-digital) and play in general, is their ability to distance players from the "real-world" by immersing them in "magic-circles" with their own rules and events. Salen and Zimmerman embody this in their definition of a game as "a system in which players engage in an *artificial* conflict, defined by rules, that results in a quantifiable outcome" [emphasis added].

This artificial quality of games is essential for supporting the teaching of inquiry. This is because it allows games to distance students from the risks and responsibilities of real-world inquiry while still allowing them to participate in its practices. For example, in the game *Poly-Bridge*, students can design different structures of a fictional bridge under fictional budgetary and material constraints and observe when and how its fails, without compromising the lives of any real people. This is especially important for learning inquiry, as it allows students to prepare for practical problems of science and engineers without being professional practitioners, i.e., to fail "safely" (Barab, Gresalfi, and Ingram-Goble 2010). Further, well-designed fictional worlds can give students the confidence that what they learn through their fictional experiences can also translate into real-world experiences. For example, flight simulators have shown to be useful environments for learning how to fly real planes (Hays et al. 1992).

In digital games, this fictional quality is made possible by their procedurality, which allows for the simulation of imagined and imaginary worlds with characters who play out roles and narratives. This quality is shared with physical/analog games and even non-games such as videos and books that are able to "immerse" audiences in their stories, i.e., give them "a sense of being contained within a space or state of mind that is separate from ordinary experience" (Murray, 2012). It separates digital games from digitally "gamified" applications which do not engage students with artificial worlds, but rather respond to and augment their real world experiences and events.

3.3.2 Play: A Key Rationale for Designing Digital Games

Based on these affordances, I argue that digital games are especially useful for supporting inquiry as a reflexive process because they enable play. Drawing upon Salen and Zimmerman's (2004) definition, play can be understood as "free movement within a more rigid *structure*." This definition resonates well with Klein and Kleinman's definition of the "structures" of technoscience as "rules of play" reinforcing how one can be understood as the other. Understanding the rules of play in terms of structures of scientific inquiry allow us to examine play as a form of inquiry and vice-versa. Digital games can capitalize on this resonance by embedding structures of practice into their rules to *simulate* inquiry as play and play as inquiry. For example, one can imagine a digital game that aims to recreate the structures of real civil engineering practice such as budgetary constraints, design specifications, and political pressure, as rules within which students "play" by conducting inquiry virtually into bridge design. Indeed, the game *Poly-Bridge* does include some of these constraints such as budget, materials, and design specifications. This allows digital games to be a powerful medium for engaging in inquiry at a distance and it builds upon their procedural, evaluative, and artificial affordances.

Further, this analogy can be extended to compare strategizing in play to reflexivity in inquiry. Strategizing requires critically examining one's position as a player in relation to the structures of play and the spaces of possibility they afford. This is also a central quality of reflexivity which involves examining one's position as a practitioner in relation to the structures of practice and the spaces of possibility *they* afford. For example, in a football game, players must continually examine their own position (where they are) in relation to the space of possibility (how they and others can move) keeping in mind the structures of play (its rules) in order to score a goal. Similarly, if we take the case of bridge design, engineers need to understand their own positions (what resources they and others have available) in relation to the space of possibility (what different dam designs are possible, should a dam even be built, what different ways can the project be financed, and so on) keeping in mind the structures of practice (budget, materials, design specifications).

In this way strategizing links positionality to play just as reflexivity links positionality to inquiry. While this does not mean they are the same process, it does mean that their similarities can be employed by digital games to teach reflexivity through strategizing. For example, a game where players can be fired for designing over-budget bridges requires them to strategize about how best to preserve their position while also producing the best quality bridge within the in-game budget.

CHAPTER 4. METHODS

Summary: In this chapter, I discuss my approach to investigating my two hypotheses in relation to the research questions of this paper. To investigate how the framework and digital games can support the positioning of students in practice at a distance and the teaching of scientific inquiry as a reflexive practice, I took a two-fold approach. First, I performed *case studies* using the framework to examine three digital games that aimed to teach scientific inquiry. This surfaced key limitations in their design and illustrated how the framework can be employed as an analytical tool. Second, I employed the framework to design possibilities for a new digital game to support scientific inquiry as a reflexive process, which I recorded in the form of a *design case*. This process explored the capacity of the framework as a design space for digital games and also surfaced key constraints of digital games as media for supporting reflexive scientific inquiry.

4.1 Case Studies and Design Case

4.1.1 Case Studies

To explore the framework as a tool for design critique and analysis, I employ it to conduct a case study into the game *The Mystery of Taiga River* (Chapter 5), *Particle in a Box* (Chapter 6), and *Psi and Delta* (also Chapter 6). The first of the three was explicitly designed to teach scientific inquiry as a situated practice. This makes it ideal for analysis using the framework. The latter two are games I made that while designed to support scientific inquiry, were not explicitly designed to support it as a reflexive process. This makes them ideal for exploring possibilities for re-design using the framework.

Employing the framework to conduct case studies into these games was a two-step process. First, I examined how the games were designed to simulate structures of practice and position students in them, specifically in the structures of distribution, power, and culture. To inform my understanding of the structures of practice, I drew upon multiple sources:

- Informal interviews with practicing engineers
- My own experiences in engineering research as a master's and bachelor's student in electrical engineering
- Books, papers, and news articles on technoscientific practice such as: Parvin and Pollock 2020; Parvin 2018; Barad 2007; Mills 2011; Latour 1987; Knorr-Cetina 1999; Kuhn 1970; Fan 2019; Vinck 2003; Hossenfelder 2018; Traweek 1988; Nakamura 2014; Whitten 1996; Sormani 2014; Defazio and Larsen 2020;
- Books, papers, and news sources on the societal implications of technoscience such as: Smith, Sonnenfeld, and Pellow 2006; Gabrys 2013; Grossman 2006; GoodElectronics and MVO Platform 2009; Simpson 2017; "Criteria for Accrediting Engineering Programs, 2020 – 2021 | ABET" 2021; Whitbeck 2011; Riley and Lambrinidou 2015; White 2016; Whitbeck 2011

Second, I examined how the games simulated inquiry in relation to students' positionality, identifying potential gaps and alternative design possibilities that could theoretically better support inquiry as a reflexive process for each of them.

The process of doing these case studies helped surface key gaps in the designs of those digital games. I then attempt to design a new digital game, *Solaria*, by drawing upon the framework to build on these gaps and better support inquiry as a reflexive process. To document my design process and the key challenges associated with designing such a game, I employed the method of a design case (Chapter 7).

4.1.2 Design Case

Design cases are "rich descriptions of the design and a narrative of how it came to be as it is." Particularly, they "must expose patterns or relationships between tensions and/or features in such a way as the knowledge can be exploited by those who might look to the design case for precedent." Producing them requires employing techniques such as investigating "multiple data sources, peer debriefing, member checks, thick descriptions and a negative case analysis–reflection on what was not done" (Boling 2010; C. D. Howard et al. 2012).

The design case is split into two parts. In Chapter 7, I highlight the core design features of the game *Solaria* using the framework. In Chapter 8 I examine tensions associated with the design due to the affordances of digital games. Collectively, the goal of this design case is to serve as a precedent whose strategies, failures, and limitations other designers may learn from when designing digital games or digital game-based environments to teach scientific inquiry as a reflexive process.

The rationale for developing a design case is twofold. First, the game (*Solaria*) was never developed, and consequently the design case serves as a means of discussing the design features and challenges of designing the game in a cohesive and systematic manner. Second, the goal of a design case is to serve as a precedent to future designers. By outlining the design and design challenges for my game in relation to some of the key affordances of all digital games, I aim to provide a blueprint of the strengths and limitations of those affordances that other instructional designers can learn from when developing digital games or game-based learning environments for teaching scientific inquiry. Particularly, the limitations of digital games I highlight can serve as starting points for future investigations into instructional strategies that can best supplement or complement them, so as to ensure that students have opportunities to learn how scientific inquiry in a manner that is more aligned with and reflexive of practice.

Why was the game not developed and evaluated? There are three reasons for this. First, the goal of this dissertation (as mentioned in Chapter 1) was to explore and support the exploration of design possibilities to teach scientific inquiry as a reflexive process, especially for digital games, and not to develop and evaluate them. Second, in order to explore the full range of possibilities afforded by the framework, the game I designed aimed to draw upon all of the dimensions and inter-relationships between positionality and inquiry which led to a design that was difficult to implement as a Ph.D. student. Finally, these practical constraints were compounded by theoretical constraints due to the affordances of digital games that I discuss in Chapter 8, which limited the design possibilities of the game.

CHAPTER 5. CRITIQUING WITH THE FRAMEWORK (THE MYSTERY OF TAIGA RIVER)

Summary: In this chapter, I employ the framework as an analytical tool to conduct a case study into the digital game: *The Mystery of Taiga River*, which was designed to help middle and high school students learn scientific inquiry as a situated practice in relation to ecology. The game positions students as park rangers who have to figure out why the local fish population in the park river is declining, who might be responsible for the decline, and what policy decisions should be taken to help curb the decline. Key gaps surfaced through this analysis include:

5.1 Introduction

The Mystery of Taiga River is part of a series of games of the *Atlantis Remixed* project (http://atlantisremixed.org/) that itself is an iteration on a previous project called *Quest Atlantis* (Barab, Sadler, et al. 2007). Images, videos, and other supplementary material for the game can be found at https://gamesandimpact.org/taiga_river/. The game is set in a fictional environment called Taiga National Park. The primary challenge in game is discovering why the fish population in the local river (called Taiga river) is declining. The suspects involve three key groups: the farmers, the fishers, and the loggers.

To help resolve this mystery students are hired by the park as water quality scientists. Their job is to work with the Head Ranger Bartle (the role that the teacher takes on) to investigate why the fish population is declining and how the park policies on fishing, farming, and logging should be changed to curb it.

The game as a whole is organized into seven missions. Four of these missions require students to investigate different hypotheses about why the fish are dying: acid rain, rise in turbidity of water caused loggers, overfishing by fishers, and eutrophication because of farmers. The remaining missions require students to explore the park and talk to its different groups, explore the effect of policy changes using simulator tool to “see the future”, and finally, to actually time travel into the future in the game to see the final results of their policy suggestions.

The rationale for selecting this game is that students in the game have to engage critically with not just scientific, but also social, political, and economic factors in a difficult situation involving multiple stakeholders with different viewpoints. In this sense, the game aimed to simulate the challenges of doing inquiry that come with having real stakeholders in technoscientific practice. Such an approach for a digital game was unique, and therefore made the game well-suited as a candidate to address the challenge of situating students at a distance.

5.1.1 Critique and Possible Redesign Strategies

Drawing upon this analysis, I examine *The Mystery of the Taiga River* in relation to the two key questions (based on the key research questions of this dissertation):

- Can *The Mystery of the Taiga River* position students in technoscientific practice, at a distance from it? If so, how?
- Can *The Mystery of the Taiga River* support inquiry as a reflexive process? If so, how?

To summarize, I draw upon my framework argue that while the game does position students in a virtual community of practice and engages them in processes of inquiry, it can do more in both respects.

For the first question, while the game does position students as virtual water scientists such as by giving them access to many of the tools used by real scientists such as a simulator, sample collection tools, and analysis tools, there is also room to better simulate the means, status, culture, and experience of practice in it.

In relation to *means*, the game gives players indefinite and free access to resources, which is not the case in practice, and so it can limit those resources and also make them unreliable to better recreate practice. In relation to *status*, the game can experiment with more un-democratic structures to help students understand how power dynamics unfold in real practice and how it can affect and be affected by inquiry. In relation to *culture*, students' characters' cultural backgrounds in the game environment have no bearing on the actual investigation or the narrative. To approach this problem, the game can have the characters be from the same social groups as the in-game communities such as the fishers, loggers, and farmers to enrich the conversations players have with them and subsequently the processes of inquiry. This can also give the characters a "prior" *experience* to draw upon when beginning the game.

For the second question, while the game there are several ways in which the game engages students inquiry such as by allowing them to generate hypotheses and run experiments in related to the science of fishes and pollution, it can do more to promote other processes of inquiry such as problematization and resolution and to relate all of them to player's means, status, culture, and experience.

The game does not promote *problematization* as it presents students with a ready-made problem: to find out why the fish in the local river are dying. To initiate problematization in relation to a players *means*, the game can give students access to different resources such as news articles that have different degrees of reliability and perspectives on the problem and allow students to decide what the problem is. To relate problematization to *status*, the game can give students multiple roles beyond that of a water-quality scientist—say as a local business- owner who benefits financially from the decline of fishes—and allowing them to frame the problem in their own terms, thereby bringing a conflict of interest into the process of problematization. The game can further relate problematization to status by instituting a hierarchy between players of different roles that only allows one or two leader students to make the final decision on what the problem is. To relate problematization to *culture*, by giving all the characters a cultural background and history (including the student's character), customizing interactions between people of different backgrounds, and allowing students to frame the problem together as the community, rather than telling them what the problem is. This also brings the character's *experiences* into relation with problematization.

The game provides three ready-made *hypotheses* to students about why the fish population is declining and ready-made or predetermined *experiments* to test them such as through the fishtank and its fixed set of variables. This limits their capacity to engage in open-ended hypothesizing-experimentation and also does not relate much to their means, status, culture, and experience. Relating hypothesizing-experimentation to *means* could be done in several ways such as by enabling students to program their own simulator in the game as opposed to using a predetermined one. The game can relate hypothesizing-experimentation to *status* such as by assigning them as representatives of the fishing, farming, and logging communities, thereby introducing a deliberate conflict of interest. To relate hypothesizing-experimentation to *culture*, the game could be designed in a way that each student character could initially only engage with in-game characters and content who belong to a single discipline such as climatology, geology, and ecology. This would give them time to be encultured into a certain disciplinary tradition which then differentiates the way they hypothesize about the problem. All of these tie into students' characters' *experiences* and backgrounds as well by giving them a history with different social groups.

The game limits scientific resolution by having "correct" answer about why the fish are dying. It limits creative political resolution by outlining policies to choose from. It can improve upon both and connect it to positionality in the following ways. To relate resolution to means, the game can reduce access to tools that tell players what the right answer is such as the 'Simulator' and 'Chain of Reasoning' tool and replace it with real discussion in the game with players and NPC characters. To relate resolution to *status*, the game can prevent students from actually making policy decisions themselves and instead require them to convince political leaders to make policy decisions they believe are right. To relate resolution to *culture*, the game can require players and NPCs from different cultural backgrounds to work together, as opposed to having the players interview each social group separately, in order to find a viable political solution as well as to build a consensus on the scientific resolution. Students' characters' *experience* can also matter to resolution by requiring players to draw upon the scientific and political opinions of their own respective social groups.

5.2 Positionality

5.2.1 Position as Means

There are multiple structures of distribution relevant to students within T*he Mystery of Taiga River* game world. For example, the leveling up scheme gives student more tools and rewards as they complete the early tutorial missions and the structure of missions is such that students can access at any time and do them interchangeably. At the same time, the game's design and virtual nature itself acts as a structure of access as it limits students to only those tools and places that are provided by the game. Any other options are simply not in the game and therefore cannot be accessed.

The means of students in the game include access to a variety of research tools such as:

- a 'Fishtank' that lets students experiment with the effects of water quality parameters such as the pH level or turbidity on fish
- a 'Chain of Reasoning' tool where students can build models using data gathered from the fishtank, interviews, and evidence such as photos
- a 'Simulator' which can allow students to propose policy changes and 'see' the future implications of those changes on the park.
- a camera to take photos of the environment (for collecting evidence) and a notebook to record them (digitally and physically)

In addition to these tools, students within the game also have access to visit places such as the river bank, the scientific lab, and the respective residences/offices of each of the communities—farmers, fishers, loggers—that live and work there.

While tools such as the 'Simulator'—which allows players to see the future based on their policy decisions—do not exist in real life, they play an important role in helping students *learn* to be reflexive as they allow them to examine the consequences of their choices without any implications to their gameplay experience. This encourages experimentation as students don't need to worry about making the "wrong" choice. This experimentation is supported further by simulation tools like the 'Fishtank' which allows players to simulate the effects of several different factors on the health of fish. Such simulation tools are common in real scientific practice as well and so including them in the game helps position students in practice at a distance.

However, this can habituate students to indefinite and free access to resources, which is not the case in practice. To avert this, the game could potentially add elements that bring the virtual environment closer to real practice without significantly impacting learning. Particularly, features such as requiring students to share resources, making some tools unreliable, and requiring a protocol for accessing the farming, fishing, and logging communities could all have enhanced the fidelity of the game to practice, positioning students more as practitioners at a distance, while still supporting the *learning* of inquiry.

5.2.2 Position as Status

The structures of power within *The Mystery of Taiga River* replicate, to a limited extent, the structures of power in the classroom. This is because both students and teachers have a status/role in the game. The students are water-quality scientists and the teacher is the head ranger they report to. For example, students (as water quality scientists) can develop hypotheses about why the fish are dying and send them to the teacher (as head ranger), who can then give them feedback and guide them accordingly. However, the teacher does not participate in the inquiry beyond this limited role and do not have say over students' actions within the game environment such as by assigning them projects/problems or deadlines.

Aside from the student-teacher power dynamic, there is also a minor power struggle between the three suspected groups: fishers, farmers, and loggers who each defend themselves while blaming the others for causing the fish to die. These groups do not interact with each other directly in the game but can communicate their feelings about the other to the students when talking to them. In this sense, students function as the medium for the power struggle, as each group aims to convince students to pass policies that favor themselves.

These power structures offer a more democratic glimpse of how power dynamics could be in scientific practice. Even though the teacher is the head ranger, students (as water quality scientists) lead the investigation and have autonomy over their actions within the game environment. This is in contrast to practice where some authority such as the principal investigator or manager dictates matters such as what the researchers should be working on, how they should be working on them, and when they should complete the work by. Such authority is respected in practice as employees/researchers often depend on their work for the livelihood and may not be able to afford losing their jobs, even if they wanted to leave. Technically, this is also true between students and teachers outside the game environment. For example, a teacher may ask a student to leave the classroom if they misbehave while playing the game. However, the game itself does not contain any means of exercising control by the head ranger over the water quality scientist.

While having a democratic power structure in the game is desirable for students, especially when they are learning, the game can also experiment with more un-democratic structures to help students understand how power dynamics unfold in real practice and how it can affect and be affected by inquiry. For example, the game could have an optional feature of job security or salary that the water-quality scientists need to maintain to win the game. Failing experiments, not doing them on time, or producing findings that others have already made could be reasons for their job security to be lowered within the game environment.

5.2.3 Position as Culture

The primary structure of culture in *The Mystery of Taiga River* is its setting as a predominantly White, North American park. This is embodied in the ways that people in the game look, talk, and act. The game does not explicitly give the player's characters a background in a culture that they can draw upon within the game environment. At most, it lets them modify the look of their characters, although this has no effect on gameplay. Overall, student's characters do not have their own culture, history, or heritage to draw upon within the game. Instead, the ways in which their character can act and talk to other characters, such as through the options in dialogue choices, defaults them as part of the same White, North American culture.

The fact the culture of the student's *characters* in the game environment has no bearing on the actual investigation or the narrative might seem like a desirable outcome. However, it can be problematic in two ways. First, it does not engage students with how social injustices such as racism and sexism can manifest in practice. This paints an idealistic but false picture of science as being free of discrimination. Second, this problem in compounded by the fact the dominant culture of practice in the game is of White, North American science. In this sense, by erasing cultural differences in an attempt to be non-discriminatory, the game may instead promote the image of science as belonging by default to a White, North American culture. At the same time however, making the game experience be different for characters of different cultural backgrounds can also be discriminatory.

This is a challenging problem due to the need for games to evaluate characters' actions in the game in order to respond to them. For example, NPC characters from the fishing community must respond to questions asked by the player in some way to progress the game state. If the players' race *does* make a difference to their response, then it can seem racist. Simultaneously, if the player's race *does not* make a difference to this interaction, then it can seem whitewashed (assuming the default response is what it would be for a white researcher). I return to this paradoxical problem in Chapter 8 when discussing the constraints of digital games for teaching scientific inquiry as a reflexive process.

5.2.4 Position as Experience

Finally, students' experiences in the game evolves as they play and replay the game. For example, as students become more knowledgeable about both the science and the policy issues, they can become more confident in their hypothesis about why the fish population are declining and implicate the different communities in the park for it.

In practice, one's *prior* experiences of means, status, and cultural positions all collectively affect their inquiry. However, the game does not give the player's characters a "prior" experience to draw upon when beginning the game. All characters start off the same way and improve the same way as they gain more knowledge about the game and its underlying ecological concepts. Now, students can still draw upon their prior experiences *as* students which will affect their experience within the game. For example, some students may start the game knowing more about ecological concepts than others, which in turn affects their gameplay experience. But the character's past is still nonexistent. In this sense, the game can enhance the role of the *character's* experience to gameplay and inquiry by giving them cultural backstories, different statuses in the game's past, and/or different means in the beginning, all of which can change the experience of students, allowing experience to play a more prominent role in inquiry for the class as a whole. For example, a character could have a past status as a logger, which could influence their interviews with loggers and provide them with valuable information that other characters may not have access to. This, in turn could promote more collaboration between students as they share their differing experiences with others.

Given that experience is so deeply tied to these other positions, I will not be discussing it separately in the following sections.

5.3 Inquiry and Positionality

5.3.1 Problematization and Positionality

The game places students in a situation of doubt with the question of why the fish population is declining. However, by predetermining this doubt and presenting it to students as a ready-made problem, the game constraints their ability to problematize the situation themselves. Telling students what the doubt is, is different from *them* discovering, developing, and justifying that doubt. At the same time, limiting problematization in this way can be seen as necessary because it allows the game to have a coherent goal. Without a clear goal, students may lose a sense of purpose or motivation for playing the game, and not be engaged with it.

5.3.1.1 Problematization and Means

The game is not designed to engage students in the relationships between their means and problematization as it presents students with ready-made research problems and goals. In this light, the relationship between means and problematization is limited to the game's narrative. Notably, the problem of fish population decline affects students' means in the game, narratively speaking, as it motivates the in-game community to hire them as water-quality scientists and give them access to tools, places, and people they wouldn't have otherwise.

In contrast to the game, a researcher's position of access in practice significantly affects their ability to problematize their situation. For example, without access to reliable news and journal articles, interviews with park rangers, proper scientific equipment, and the river itself, researchers may not be able to ascertain whether fish population in an area are indeed declining or why.

Based on this analysis, we can suggest multiple directions for redesigning the game. For example, the game may give students access to different resources such as news articles that have different degrees of reliability and perspectives on the problem, without explicitly defining the problem for the students. This would lead each student to come up with a different formulation of what the problem is and produce productive disagreements between them about the severity of the issue, thereby producing a rich space for problematization.

5.3.1.2 Problematization and Status

Like the access-problematizing relationship, the relationship between *status* and problematizing is also not a feature of the game due to the ready-made problem provided to students.

In practice, the status of the researcher significantly affects their ability to problematize. Principle investigators have significantly more power in deciding the research goals and problems than junior researchers. Furthermore, a researcher’s role outside the lab can also affect how they frame their research problems. For example, researchers who are also leaders of the local river community may frame the problem not only in terms of declining fish populations, but also in terms on its detrimental affect on the employment status of their community. This can expand the scope of the research goals to including finding alternative forms of employment for locals as part of the official process of inquiry. Conversely, what research goals one sets can also affect their role within and beyond the lab. For example, setting the research agenda to include the local community problems may elevate one’s position as a community member or leader.

Drawing upon the role of ‘status’ in practice, the game can enable a richer relationship between a player’s role and problematizing in multiple ways. For example, giving students multiple roles beyond that of a water-quality scientist—say as a local business- owner who benefits financially from the decline of fishes—and allowing them to frame the “problem” in their own terms can help students better explore this relationship. Further, the game can institute a hierarchy between players of different roles that only allows one or two leader students to make the final decision on what the problem is. For example, some students’ characters can be more “senior” than others, giving them the final call on what problem as a whole is. The problem itself can go beyond doubts about if and why the fish are dying to include matters such as what the budget, role-assignments, and deadlines should be. Such a hierarchy can invite discussions about the role of power in inquiry.

5.3.1.3 Problematization and Culture

The relationship between *culture* and problematizing is also not a feature of the game due to the ready-made problem presented to students in the game.

In practice, however, one’s culture as researcher has a significant impact on what research goals they set and how they frame their research problems, especially when considering the culture of others who are involved. For example, if the local community near the river predominantly involves native people (including the researcher), then the researcher may see the decline in fish population not simply as a scientific or political problem, i.e., in terms of policy, but as a cultural one that signifies a loss of connection with the land. Consequently, they may frame the problem in cultural terms such as: how can we draw upon native knowledges of the river to preserve both the fishes in it and our culture? In turn, if the researchers are not native to the region and have a different background from the local community, then they may inadvertently frame the problem purely as a scientific or political one instead of a cultural one (as is the case in the game), unless they make an effort to form meaningful relationships with the native people.

Drawing upon this example, the game can enrich the relationship between culture and problematization by giving all the characters a cultural background and history (including the student's character), customizing interactions between people of different backgrounds, and allowing students to frame the problem together as the community, rather than telling them what the problem is. At the same time, this has to be done carefully to prevent discrimination and stereotyping of people with different backgrounds as discussed earlier.

5.3.2 Hypothesizing-Experimentation and Positionality

5.3.2.1 Hypothesizing-Experimentation and Means

The game provides three ready-made hypotheses to students about why the fish population is declining, each implicating one of the three communities for causing the problem. Initially, the game also provides a "red herring" (acid rain hypothesis, which students learn quickly is false) as a tutorial for learning the game's mechanics. However, by outlining these hypotheses for students, the game reduces students' ability to hypothesize for themselves. For example, students do not have to hypothesize about *whether* one of these communities is indeed responsible, only which among them are. That being said, the game does allow students to hypothesize about specific casual relationships as part of these broader hypotheses: can logging near the river cause a rise in turbidity in the river? Can a rise in turbidity of the river affect the fish population? It also allows students to decide what experiments best test these hypotheses.

Students access to resources plays a more prominent role in their ability to hypothesize and do experiments than for problematization. For example, having access to the fishtank where one can see all the relevant parameters such as pH level, oxygen levels, and temperature can help students generate hypotheses about the relationships between these parameters. However, this can also constrain hypothesizing because if students did not have access to the fishtank and its parameters, then they would need to hypothesize about what the parameters themselves should be. This could be done by requiring students to program their own simulator in the game as opposed to using a predetermined one.

Another example that links means to experimentation are the “powercells” without which students cannot collect water samples. Powercells are restricted in the game. However, gaining access to them is as simple as passing a pre-programmed in-game test that evaluates their knowledge about relevant topics such as the science of marine biology. Limiting powercells more stringently, such as by requiring students to share them or access them only for short durations, could invite students to better explore the relationship between one’s means and experimentation as students try to optimize the best way to make use of their limited time with the powercells to collect data.

Drawing upon practice, if the game and educational environment gave different students access to different study equipment and places, students would likely conduct studies/experiments in different ways or have to get creative with what they have. This could help elicit reflection into how one’s access to resources relates to performing experiments and also promote collaborative inquiry.

5.3.2.2 Hypothesizing-Experimentation and Status

The status of students in the game as water-quality scientists does not significantly impact their ability to develop hypotheses because the primary three hypotheses which implicates each of the three communities for contributing to the decline in fishes have already been laid out for them. Nor does it affect their ability to conduct experiments apart from their ability to conduct interviews. This is because the game enables them to talk to the farmers, fishers, and loggers through a variety of dialog choices. Selecting some choices may offend the characters and others may make them more open to sharing information. Ultimately however, since the dialog trees are designed such that no matter what students ask or say, they will always get the desired information, their status as an interviewer does not affect the data they collect from the interviews, even though it affects how they perform the study. There is no other status that students can adopt beyond their position as a water-quality scientist.

In practice, a researcher's status does affect their hypotheses, especially when they have to decide between multiple equally effective hypotheses. For example, a research group that wants to elevate its status in the broader community may choose to develop and investigate more high-profile hypotheses first, such as hypotheses that implicate the big for-profit logging company, as opposed to the local community of farmers. Conversely, what hypotheses a researcher develops can also affect their role. If the logging company learns that they are being implicated in the hypotheses by the researchers, they may use their position of power to lobby against their investigation. This can affect the status of the researchers, especially if the logging company can get or prevent access to their records and operations.

Further, a researcher's status in practice as an interviewer is markedly different from a students' position as interviewer in the game, as the researcher must actively strive to develop a relationship with their subjects in the process of asking them questions. If they offend their subjects in real life they might not get the information they need, unlike the game. Further, researchers often have roles beyond research which can significantly affect how they perform experiments. For example, if a researcher also has the role of a single parent and needs to pick up their child from school every day in the afternoon, then they may prioritize visiting the river in the mornings to collect water samples, which can affect the quality of data they get. Simultaneously however, if they are a senior and respected member of the team, then other team members might be willing to collect water samples in the evening on their behalf. Conversely, how well one performs their experiments can affect their role. For example, if researchers make repeated mistakes while conducting an experiment, then they might be given a diminished role within the lab in the future.

Drawing on this example of practice, one way that the game can engage students more critically in the status-hypothesizing relationship is by assigning them as representatives of the fishing, farming, and logging communities, thereby introducing a deliberate conflict of interest that requires critically reflecting on this relationship. Further, the game can implement multiple strategies to make one's role matter more to their performing of experiments, such as by having a permanent impact of interviews on non-playing characters. That way, if they feel offended they will also stop sharing what they know with students. Further, students can be given additional roles within the game say as parents which can affect their ability to perform experiments as compared to those who do not.

5.3.2.3 Hypothesizing-Experimentation and Culture

In practice there is a large possibility space of hypotheses to explore (unlike the game which is limited to three hypotheses), especially early on in the inquiry process. This gives significant room for a researcher's culture such as their discipline, their culture, and their social group to have an influence on their hypothesis. For example, a researcher trained in climatology may initially hypothesize that the fish population is dying because of climate change. Similarly, a researcher trained in geology may to hypothesize that subterranean features of the landscape, such its volcanic history may be worth investigating. Notably , the same data can be seen as evidence justifying multiple different hypotheses by researchers from such different disciplinary backgrounds. Say the data indicates that an increase in temperature of the river water correlates strongly with the declining fish population. A researcher with a background in climatology may see this as evidence that global warming is to be held responsible while a geologist may see it as evidence in favor of rising local magma levels, both of which can increase the temperature of the river water.

A researcher's cultural background can also significantly affect how they perform studies/experiments. For example, let us examine how one's culture can relate to performing interviews in practice. While the game simplifies conversations to a series of binary choices as part of a dialog tree, conversations in real life have significantly more possible trajectories, particularly if one had a shared background with the other participants. For example, if both the researcher and the farmer shared a common heritage, say as Jews or Vietnamese people, then their conversations could draw upon their shared cultural experiences and possibly lead to a more personal relationship between them. Such a relationship could greatly impact what the researcher learns about the farmer and the history of the farming in the area, and consequently, affect future inquiry. Conversely, this interview study experience could also add to the researcher's background in farming by teaching them more about other farming techniques.

Drawing on practice, the game can enrich the relationship between culture and hypothesizing-experimentation by *not* providing students with pre-given hypotheses to explore and experiments to perform, while also critically engaging the student character's cultural backgrounds. For example, the game could be designed in a way that each student character could initially only engage with in-game characters and content who belong to a single discipline such as climatology, geology, and ecology. Groups of students could be allocated to different disciplines. This would give them time to be encultured into a certain disciplinary tradition. Then, after they have developed some background in their discipline, they could be given the chance to explore the park, learn about the fishes, and generate their own hypotheses. In-game discussion then could draw upon different students' disciplinary backgrounds to produce novel and creative hypotheses for further investigation in the game. Further, to make culture matter for interviews, dialog trees in the game could be programmed to incorporate differences in backgrounds of the people involves, as well as their shared conversational history.

5.3.3 Resolution and Positionality

There are two kinds of resolutions within the game: one that pertains to the problem of why the fish are dying and the other to what policy changes should be made to prevent their decline in the future.

The former has a “correct” answer once students have drawn upon scientific evidence: the fish are dying because all three of the groups have collectively reduced the water-quality of the river by raising its turbidity (dumping of silt into river by loggers), reducing the oxygen levels (algal blooms caused by agricultural runoff from farmers), and overfishing by the fishers. While having a “correct” answer is necessary in the game as it gives a sense of closure to the scientific “mystery” it may also instill an incorrect picture about scientific inquiry in the minds of students about inquiry as a process that results in a clear, definite, and determinate answer to real-life scientific problems when in fact, research can only ever talk about degrees of confidence as there will always be uncertainty even in seemingly unequivocal scientific findings.

The latter allows students to explore the role of science in informing policy. Here the game gives more leeway to students’ exploration as there can be multiple possible futures based on what policies students select. At the same time however, by giving students a fixed set of policy choices, the game in itself can limit creative political thinking. Consequently, discussions about policy and possible futures need to take place outside the game environment through in-class discussions to offer more depth.

5.3.3.1 Resolution and Means

Student’s access to tools such as the ‘Simulator’ tool and ‘Chain of Reasoning’ tool is significant to their process of resolution in the game. The former allows students to change policy regulations (such as “ban fishing completely” or “limit fishing to x amount/day”) and observe the effect of these changes in the future, immediately. This enables students to instantly explore several different possible future outcomes. The Chain of Reasoning tool analyzes students' models, evidence, and claims through a pre-determined scoring system which lets students know how "correct" their models and evidence are in light of the three predetermined hypotheses. This helps students be more confident of their scientific models and to use them to inform their policy-level resolution.

In practice, researchers do not have access to tools like the 'Simulator' or the CoR. Consequently, and every resolution is arrived at with a sense of uncertainty or a degree of confidence in the results. No resolution can be known to be the "right" one *a priori*. Learning to live with this uncertainty is an important learning experience for real scientists and engineers.

Drawing on this comparison, keeping students in a position of uncertainty can be done by reducing their access to tools that tell them what the right answer is such as the 'Simulator' and 'Chain of Reasoning' tool and replacing it with real discussion in the game with players and NPC characters.

5.3.3.2 Resolution and Role

Students' status as water-quality scientists has no bearing on how they decide what their final resolution about the hypothesis or policy-level proposal will be. This is partly because of the aforementioned simulator tool which allows students to explore all possible future outcomes at any time.

In practice, however, the process of arriving at a resolution is a combined group effort which depends significantly on the organizational structure and power dynamics of the research group. For example, researchers in a company may have less say in finalizing the resolution of the problem compared to their manager. Further, in practice, scientists and engineers can usually only suggest policy recommendations to their political leaders. They rarely have any political agency themselves.

Drawing upon this example, the game could enrich the relationship between status and resolution by adding unequal power structures. For example, the game can prevent students from actually making policy decisions themselves and instead require them to convince political leaders to make policy decisions they believe are right. This could help them better understand the limitations of their role as scientists, help them explore the political climate and its relationship to science, and learn how to make scientific arguments.

5.3.3.3 Resolution and Culture

In practice, how a problem is resolved depends significantly on the culture of all those involved. For instance, decisions about the best policy for tackling the decline of fishes should ideally be made with the involvement and consideration of those from different backgrounds who hold a stake in the outcome. Excluding say, the native population from the conversation, can lead to policies that inadvertently harm them. For example, banning fertilizers for farming may harm the local farmers who have no other recourse for their crops. While the game does allow students to test different resolutions before actually making a final decision (by "seeing the future" using the simulator tool), this is not a luxury that real practitioners have. Consequently, there should be opportunities to learn how to actively involve people from different backgrounds when developing resolutions.

Drawing on this example, the game can enrich the relationship between background and resolving by requiring multiple groups to be present when the policies are submitted and decided. Currently, the game lets individual students pick from a selection of pre-given policy decisions and implement it. Instead, if the class as a whole was virtually involved in making a decision together about the best policy in conjunction with the non-playing characters with all of them gathered together in the same virtual room, then a rich space for resolution could be created that engages everyone's backgrounds. Of course, this approach would have to be mindful of the local power and cultural dynamics among students and characters, but even this could be an asset if different strategies of decision-making were employed.

CHAPTER 6. STUDY 2: REDESIGNING WITH THE FRAMEWORK (PARTICLE IN A BOX & PSI AND DELTA)

Summary: In this chapter, I employ the framework to conduct a case study into two digital games: *Particle in a Box* and *Psi and Delta*, which were designed to help students learn scientific inquiry into quantum physics. This process allows us to critically examine how they embodied and promoted inquiry. At the same time, it allows us to explore opportunities for redesigning both games to better position students in practice at a distance and support them doing inquiry as reflexive process.

6.1 Introduction

Particle in a Box and *Psi and Delta* are digital games designed to support high school and undergraduate students in conducting inquiry into quantum physics. I designed and developed both games as part of interdisciplinary team of electrical engineers, media and STS scholars, and HCI researchers comprising undergraduate and graduate students as well as faculty at Georgia Tech. *Particle in a Box* aims to support inquiry by allowing students to virtually explore, compare, and experiment with worlds that follow the laws of classical and quantum physics (Anupam et al. 2018, 2020; Peng et al. 2014; Tople et al. 2015). Building upon *Particle in a Box*, *Psi and Delta* aims to teach inquiry as a social process by requiring two players to cooperate, develop, and employ concepts of quantum mechanics together in order to resolve the challenges of the quantum world (Anupam et al. 2019). Both games can be downloaded and played at https://learnqm.gatech.edu. In this chapter, I employ the framework to analyze these games for the purpose of redesigning them to support inquiry as a reflexive process.

The rationale for examining the games using the framework is three-fold. First, while both games were developed to engage students in scientific inquiry, they were not designed explicitly to teach it as a reflexive practice. This allows us to employ the framework as a means of critique, highlighting potential areas where the games can be redesigned to support inquiry as a reflexive process. Second, it allows us to explore the framework as a design space to suggest design possibilities based on the critique. Finally, by examining these games through the framework and highlighting ways in which positionality can potentially matter to the formulation of quantum physics in them, the framework can invite critical examination into the social structures underpinning real scientific environments about quantum physics as well. Given that quantum physics seems (at the surface) to be immune from social structures, showing how even *it* can be affected by social values and assumptions can further demonstrate the situated nature of scientific knowledges beyond the life sciences.

6.1.1 Critiquing their framing of Inquiry

The framework helps us identify key limitations of how both games frame inquiry by examining their ability to support problematization, hypothesizing-experimentation, and resolution of technoscientific problems.

A key limitation of problematization in both games is that, unlike practice, the problems in them are predetermined, well-defined, strictly-bounded, and known to be solvable. In contrast, the most pressing problems in practice are often open-ended, ill-defined, unbounded, and unknown to be resolvable.

Further, both games can be completed through trial-and-error which diminishes the role of educated and informed hypothesizing and experimentation. Trial-and-error is possible partly because there are no significant consequences to failure in the games and partly because the game has a small enough possibility space that allows students to explore different options quickly without necessarily learning the core concepts. This is different from practice where the decision to test hypotheses has significant real-world consequences and requires navigating a vast possibility space involving the underlying concepts and theories.

Resolution in both games is also predetermined, i.e., there is a well-defined condition that needs to be met in order to advance the game state that helps conclude the inquiry for each game level. In contrast, there is always a lingering uncertainty about whether a problem has been resolved in practice. Consequently, there is the challenge of deciding what counts as an acceptable solution: when is evidence "enough"? what counts as evidence? When can we be confident of our predictions? What counts as a suitable error/confidence rate? Such questions play a pivotal role in determining when a problem has been resolved and are entangled with social, political, technical, and cultural issues at the heart of communities of practice.

Finally, as both games were not intended to specifically position students as virtual practitioners, they are not designed to relate inquiry to positionality. This is a major area of improvement for redesign.

6.1.2 Possible Redesign Strategies

Drawing upon these limitations, I explore two questions for *Particle in a Box* and *Psi and Delta* in relation to redesigning them (based on the key research questions of this dissertation):

- Can these games be redesigned to position students in technoscientific practice, at a distance from it? If so, how?
- Can these redesigns support inquiry as a reflexive process? If so, how?

For the first question, redesign possibilities for simulating position as *means* in the games can be to have unreliable resources, limited resources, and an in-game economy. For simulating *status,* they can involve having a cooperative/competitive mode, introducing power dynamics between players, giving players multiple roles. For simulating *culture* better, the games can have more diverse/customizable characters, tie different character cultures to gameplay, and narrativize gameplay. Finally, to incorporate students' *experience* into the game they can relate the game to real-world QM devices and use QM to generate a personal artifact for each player.

For the second question, the games can support inquiry as a reflexive process better by relating the processes of inquiry to positionality as follows:

Problematization can be related to positionality by introducing unsolvable problems (means), adding individual and collaborative achievements (status), tying different character backgrounds to gameplay (culture), and allowing students to create/modding game levels as part of the game (experience).

Hypothesizing-experimentation can be related to positionality by introducing unreliable and limited resources (means), introducing power dynamics between players (status), narrativizing the game (culture), and connecting gameplay experiences to real experiences (experience).

Resolution can be related to positionality by depleting resources for each experiment (means), connecting resolution to reputation (status), introducing competing NPC groups (culture), and changing initial conditions (experience).

These are just some of the possibilities afforded by the framework and are by no means exhaustive. There may be several more options that I have not explored that can further support both positioning students in practice at a distance and supporting inquiry as a reflexive process.

6.2 Two Games for Supporting Inquiry into Quantum Mechanics

Quantum mechanics (QM) is a branch of physics that focuses on the science of the very small, such as atoms and electrons. It is significantly different from classical mechanics (CM), that was developed by scientists such as Galileo and Newton and was able to describe the motion of several macroscopic objects from balls to planets. While QM involves many of the same fundamental properties of CM such as energy, position, and momentum, it radically challenges the classical interpretations of these properties. For example, in a quantum system, we can never know a particle's precise position and momentum at the same time. We can also never predict with certainty where a particle will be at a future time. We can only calculate the *probability* of finding the particle at various positions. Further, particles exhibit wavelike properties similar to light, where they can "spread out" over an area. Counterintuitive quantum phenomena like these require students to fundamentally re-envision assumptions and concepts that they know from classical mechanics.

To help students learn these phenomena, most introductory QM courses and books use a quantum system known as particle-in-a-box (also known as the square well). This system is concerned with the behavior of a confined quantum particle and it used widely because it highlights the fundamentally unique nature of quantum mechanics and can be solved and understood analytically, i.e., without computational or algorithmic calculations. The 'particle' (in this case, an electron) is confined by two walls of infinite or high potential energy (the 'box'). Due to this configuration and the laws of quantum physics, the system produces two unique quantum phenomena that both games particularly focus on: superposition and energy quantization. I discuss these briefly below to assist the reader in better understanding the design of the games. However, it is important to note that it is neither intended nor possible for this description to serve as the basis for understanding quantum mechanics. I reference these concepts only to the extent that is required for demonstrating the design of the games. Interested readers are directed to (Griffiths 2005) and (Ananthaswamy 2019) for an excellent introduction to quantum physics.

First, within the particle-in-a-box system, the position of the electron is not definite. Rather, the electron can be understood to be in a state of multiple positions at the same time, which is called a ‘superposition.’ However, when we try to ‘observe’ the electron through measurements, this superposition collapses and the electron is found temporarily in one location. This location cannot be predicted as it is probabilistic, i.e., the likelihood of finding it in some location is more than in others, but no location is certain. After the measurement is taken, the electron gradually ‘spreads out’ and moves into superposition again. Superposition is the foundational concept on which new technologies such as quantum computing are built on.

Second, the energy of the electron in the particle-in-a-box system is *quantized* (that is how ‘quantum’ mechanics got its name). This means that the electron has discrete energy levels that it can move between. It can only move from a lower energy level to a higher one if it is provided *exactly* the amount of energy needed to make the transition, usually in the form of a photon of light. For example, to go from an energy level that has 2 eV of energy to one that has 3 eV, the electron must be provided exactly 1 eV of energy. No more, no less. Similarly, when an electron moves from a higher energy level to a lower one, it releases energy corresponding to the difference between the two energy levels, again in the form of a photon of light. Many practical devices such as solar cells (which converts light to electricity) and lasers (which converts electricity to light) are based on these quantum phenomena.

6.2.1 Particle in a Box

Particle in a Box is a single player 2-D platformer game that is based on the particle-in-a-box system. It was designed to support undergraduate and high school students in conducting inquiry into the concepts of introductory quantum mechanics. The player in the game assumes the role of a virtual avatar who travels through a two-dimensional rendition of the classical and quantum worlds. Experiencing both worlds affords students the opportunity to compare their similarities and differences–an approach that has shown to be effective in learning quantum physics.

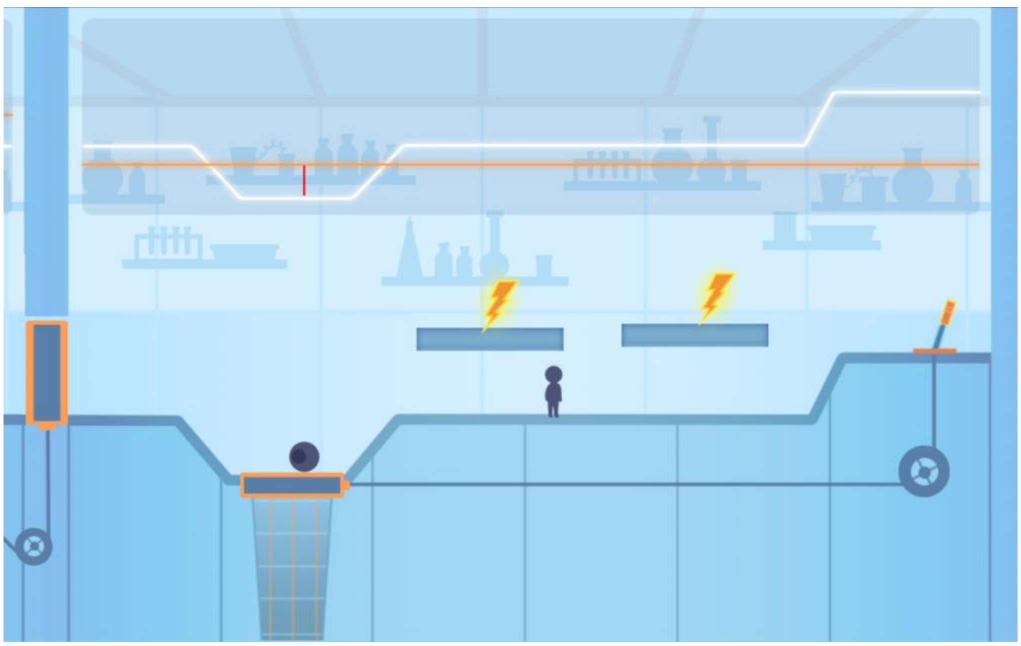

Figure 2 – The classical world in *Particle in a Box*. The player must reach the energy bolts, carry them, and place them in the path of the moving ball.

In the classical world (Figure 2) the objective is to raise the energy of a rolling ball, so that it pushes a lever located higher up, which opens the door to the next level. The ball initially does not have enough energy to do this and rolls back and forth at a lower height. It can increase its energy by absorbing an energy bolt. The player has to pick up and place the energy bolts in the path of the ball. As the ball rolls through the bolt, it absorbs it, increases its energy, and can travel further and higher. If the player touches the ball, they 'faint' and return to the starting position. To avoid this, the player must predict the ball's motion and try to jump over it. The rationale for having a classical world is that it helps students compare how concepts such as energy and position compare across both worlds and learn from the similarities and differences.

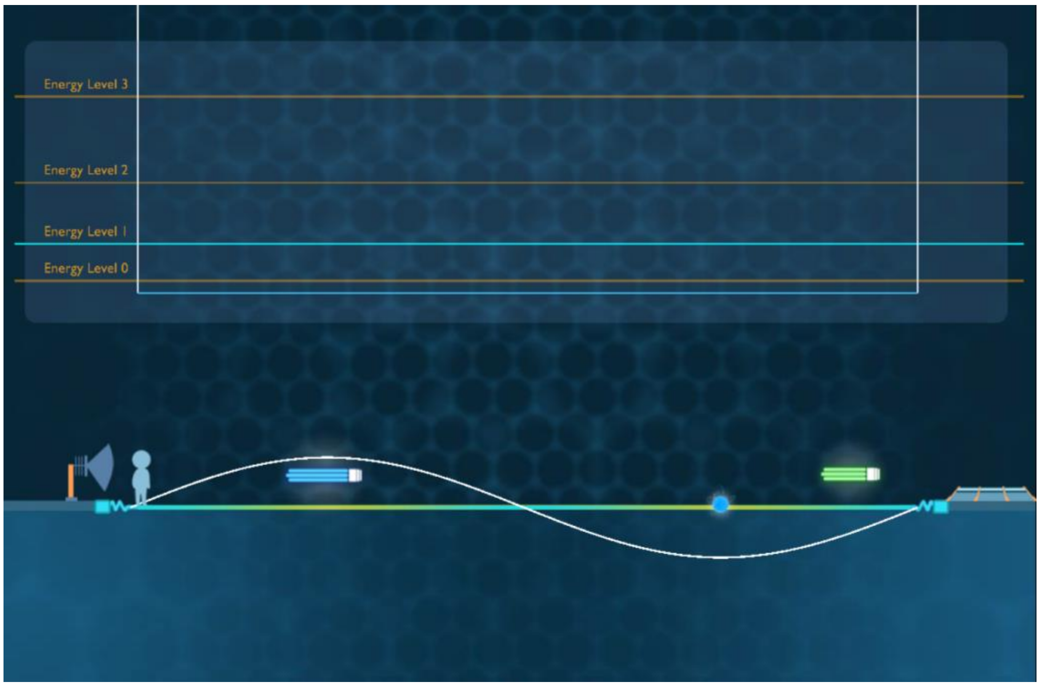

Figure 3 – The quantum world in *Particle in a Box*. The player must carry the colored bulbs to the lamp (left) that will shine light and increase the electron's energy level (top). The blue dot is the electron and the bright line it is on, is the wire.

In the quantum world (Figure 3), the objective is similar to that in the classical world, i.e., to increase the electron's energy. The electron is confined to a horizontal wire in an infinite square well (particle-in-a-box) and players are located on top of the wire. Unlike the ball in the classical world, the electron can only increase its energy in discrete amounts by absorbing light. Different colors of light provide different amounts of energy, so the electron will only absorb light when the correct color is shined on it. To shine light, players must bring a lightbulb to a lamp. The color of the light shined depends on the color of lightbulb brought to it. If the bulb color is correct, the lamp shines with the corresponding light and increases the electron's energy; if not, the bulb returns to its original position.

In the process of getting the right bulb, the player risks getting hit by the electron. The electron's position changes as it is automatically and periodically measured. When a measurement is made, a blue dot (representing the electron) temporarily 'appears' at the measured location on a wire. This location is random but follows a probability distribution (curved white line in Figure 3), with some locations being more likely than others. The taller the probability distribution is above or below a spot on the wire, the more likely it is that an electron will be measured at the spot on the wire. After each measurement, the system resets and the dot disappears. Since players faint if they are hit by the electron when it is measured, and must continue from their starting position, they need to observe the electron's probability distribution (i.e., the probability of where it will appear if measured), determine the likelihood of appearance of the electron, and use that knowledge to better navigate the level.

Now, if the electron's energy level changes, so does its probability distribution. Higher energy levels produce more nodes in the probability distribution – points where an electron can never be measured. This makes it easier to move across the wire as by standing on a node, a player cannot be hit by the electron. A node can be seen in Figure 3 where the probability distribution (curved white line) intersects the wire.

Through this gameplay, students can formulate and test hypothesis (e.g., standing at different points on the wire), examine its outcomes (fainting if hit by the electron), and modify their behavior (stand at nodes to be safe). They can manipulate the system parameters (e.g., the energy level) through in-game activities (e.g., transporting light bulbs) as they try to move towards an end goal (the electron reaching the third energy level). The game mechanics (transportation of bulbs, getting hit by an electron) are designed to help students formulate such strategies and thereby understand the concepts of superposition and energy quantization. Through repeated measurements, the game simulates an ‘experience’ of probability as the player learns to identify the locations where they are more likely to be hit, by being hit by the electron an experiencing its connection to the probability distribution. In this way, Particle in a box aimed to support inquiry by promoting cycles of hypothesizing and experimentation as students explored and compared classical and quantum physics.

6.2.2 Psi and Delta

In *Psi and Delta*, students adopt the role of two robots, with the aim of defeating opposing robots in a world governed by the laws of QM. Students accomplish this task by using QM concepts to lure and “shock” the opposing bot. If a student’s bot touches the opposing bot or gets “shocked”, it loses part of its health. If any player’s bot loses all their health, the level restarts.

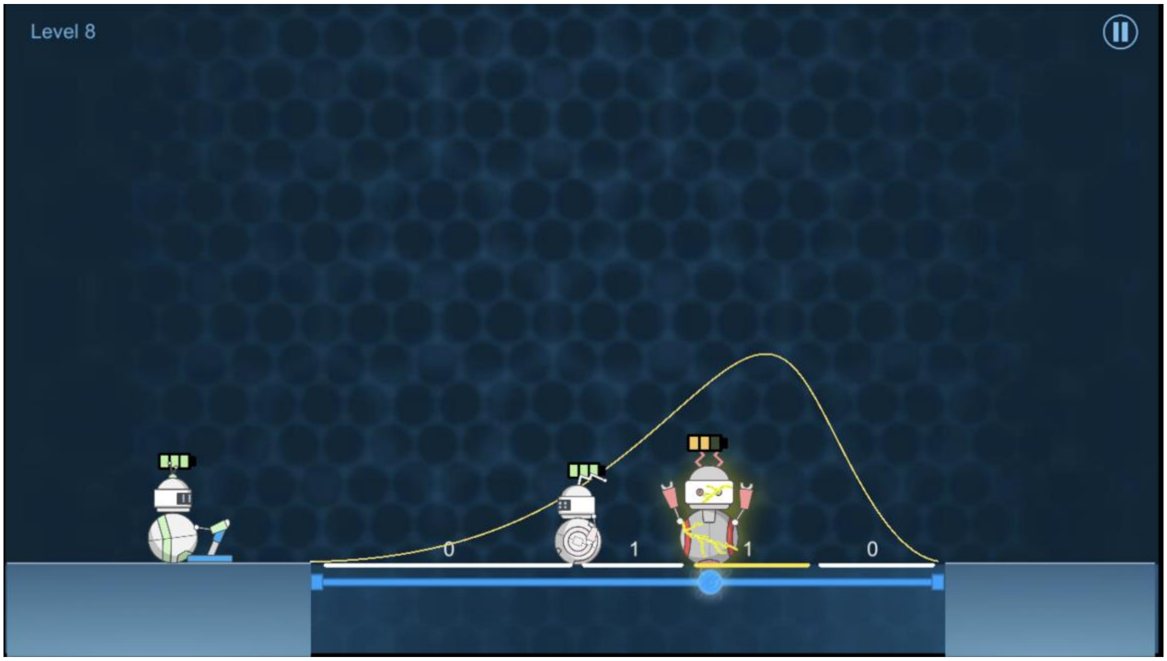

Figure 4 – Taking a measurement in Psi and Delta. One player (left) takes the measurement by pulling a lever, while the other (middle) lures the enemy bot a higher probability area. Here, the enemy bot is getting shocked by the measured electron.

The game is divided into two parts. In part one, students develop models of the concepts of superposition and probability. As discussed earlier, when an electron is confined in a small area, it will enter a superposition, i.e., it will exist in multiple positions simultaneously. To break this superposition, one needs to take a "measurement." In the game, the electron is confined in a small blue quantum wire. In contrast to the automatic measurements in Particle in a Box, it is the students here who take measurements by pulling a lever, Each time a player pulls the lever, a measurement is taken which collapses the electron from its superpositions state to an unpredictable position on the wire for a brief moment. Any robot (player or enemy) standing on a platform directly above the collapsed electron will get "shocked" and lose some health (see Figure 4) . The position where the electron collapses is probabilistic, i.e., some positions are more likely than others. The relative probability of these positions is illustrated by the electron's probability distribution, the orange curve in Figure 4. The longer the platform and the higher the curve above it, the more likely the electron will be measured under it. After each measurement, the electron returns to superposition.

Figure 5 – Shining light to increase the electron's energy level in *Psi and Delta*. The horizontal lines on top indicate the electron's energy levels. The spectrum (bottom-left) lets players change the color of light shined.

In part two, students develop models of energy levels. Here, the opposing bot has a shield which protects it from getting shocked. To break the shield, the electron needs more energy. Electrons can only have a discrete amount of energy such as 1 eV (electron-volt) or 3 eV in the case shown in Fig. 2, but nothing in between. Energy can be supplied to an electron in the form of light, which consists of discrete energy packets (photons) whose energy depends on their color. To excite an electron from a lower energy (say 1 eV) to a higher energy (3 eV), one must shine photons with the exact energy as the gap (2 eV). In the game, students can shine light using a lamp and also change its color using a spectrum.

Psi and Delta aims to promote inquiry by withholding information from the players. In the early levels, the game guides learners through basic QM concepts using signboards, pacing complexity gradually. Subsequently, however, students face unguided situations which feature new concepts that build on the basic concepts. For example, after learning how to operate the lamp light, students face a situation where they need to understand how to an increase the electron's energy without guidance (Figure 5). Students initially attempt to shine the default colored light and notice no change in the electron's energy level. This spurs a discussion that brings out their assumptions about the electron's energy levels. For example, students often draw on their daily experiences and assume that if an object does not react when given energy, then more energy is needed (such as pushing a heavy boulder harder). Based on this assumption, they attempt to increase the energy of the lamp light to its maximum value and shine light again. However, this experiment too produces no change and makes the situation more uncertain. Does light need to be shined multiple times to increase the electron's energy? What color of the light will be absorbed by the electron? Ad- hoc trial and error is possible here, but is arduous as there are several possible colors of light provided by the lamp and changing the color requires both players to coordinate their actions to move the slider on the spectrum (one player has to activate it by standing on a button, while the other moves the slider on the spectrum to change the color of light). This makes changing the color of the light and shining it each time, difficult to execute quickly. By not describing the problem situation and making it difficult to proceed by ad-hoc trial-and-error the game encourages students to reflect on their beliefs and on how those beliefs shaped their experiments. Through inquiry and with support from an energy diagram (Figure 5, top), students gradually develop the notion that matter can possess discrete levels of energy in which case it will only absorb light of specific colors/energies.

6.3 Positionality

Both games were not designed using the framework and therefore do not explicitly aim to simulate positions of practice in terms of their means, status, culture, and experience. However, the design of these games does capture some features of the positions of practice implicitly. These can become building blocks for redesigning both games to support positioning students in practice at a distance.

6.3.1 Position as Means

In *Particle in a Box*, students can access virtual worlds that embody rules of classical and quantum physics, respectively. Each of these virtual worlds is composed of multiple game levels and access to a game level is contingent on completing previous game levels. Each level in turn provides students access to particles (ball and electron) that obey different rules of physics. To interact with these objects without colliding with them, players have access to a repertoire of in-game resources such as energy bolts that they can carry and place in the path of the ball, a lamp that can shine light on the electron, and light bulbs of different colors that can be picked up and brought to the lamp.

Players also have access to a tutorial level in each world, which gradually introduces the game environment to the students to ensure they are able to make sense of the system. The tutorials introduce the formal representations of the system such as energy level diagrams and their effect in the game. They teach students the importance of these representations and strategies for their manipulation. Students can control the pace of the tutorial and move back and forth between each step until they finish. Once past the tutorial level, students play a more complex level without guidance that builds on the tutorial.

Psi and Delta builds on *Particle in a Box* by giving students access to new features such as a lever that lets them take measurements of the electron's position, a spectrum-slider system that lets them change the color of light in the lamp more precisely, the ability to jump and stun the "enemy" bot, and to cooperate in a multi-player mode with other students. It also allows students to access any level they wish to play without completing prior levels, through the level-select screen.

While students' means in the game involves access to highly fictional tools and places that are clearly not possible in practice (such as pulling levers in a quantum world), it is still possible to emulate and critically examine real practice in the game by focusing on the *distributive structures* of practice that govern access to tools and places. I suggest three possibilities for redesigning these games that draw upon the distributive/material structures of practice: unreliable/imperfect tools, limited resources, and costs to inquiry.

Not all tools in practice are equally reliable. Over time most tools tend to become error prone. Educational science games, including *Particle in a Box* and *Psi and Delta* generally treat the equipment they give students access to as ideal tools: the lamp always functions correctly, the bulbs are exactly the color they are supposed to be, the lever always works. For example, a red bulb in the game may not always give the specific red color that has the exact energy needed to change the electron's energy. It could be slightly higher sometimes, slightly lower another time, and exactly at some other time. By making these tools *unreliable*, the games can add an additional element of uncertainty that nuances inquiry—did my strategy fail or was the tool problematic? How can this discrepancy be resolved? Such uncertainties often permeate real technoscientific practice. Consequently, engaging students with them in the game can position them in such uncertainties at a distance.

Building on this idea of unreliability, the games could also limit access to more reliable tools. This is often the case in practice as the more reliable tools are usually more expensive and limited. The games could be redesigned such that students have to *earn* the right to use those tools over time, as opposed to being simply given them by crossing the game's levels. This could not only make gameplay more engaging by encouraging students by adding a progression system but also teach students to value and understand the tools they have and get. Further, in a multiplayer setting, students may also be required to share resources (such as more reliable bulbs) with other player and non-player characters due to their limited supply. This can be implemented structurally through a distributive system in the game that limits the time that each character can use a particular resource before sharing it with others.

Finally, and to add further to the previous suggestion, the games could also involve a budget/economy system, where there are several available tools, but one's access to them is limited by their budget. Students' would therefore have to learn to work with a limited budget to optimize their inquiry. For example, students could be given the choice of spending the funds on more reliable bulbs, a lever that lets them take measurements faster, or an electric charge that allows them to change the shape of the probability distribution of the electron. These choices will have a bearing both on players' gameplay actions but also their process of inquiry—should I buy the electric charge and just reshape the probability distribution to make my easier, or should I buy a more reliable lamp so that I don't have to keep switching it on/off or repairing it?

Now, it is possible that such adding such difficulties/obfuscations/uncertainties may seem like a counterproductive strategy for engaging students and lead to more frustrating experiences for them. However, learning to live with these frustrations and draw strength from that frustration is essential to effective scientific inquiry in practice. The goal here is to cultivate in students the *character* to be effective and reflexive inquirers, not only to help them simply memorize and apply certain scientific concepts.

6.3.2 Position as Status

Particle in a Box places students in the role of a virtual avatar who travels across gameworlds that follow the rules of classical and quantum physics. Notably, the avatar's status makes them immune to the rules of each world and instead follows a predetermined ruleset that allows them to walk, carry objects, jump (in the classical world), and faint when they hit the particle, i.e., the ball or electron. For example, the avatar does <u>not</u> exhibit quantum behavior such as occupying multiple positions at the same time or possessing discrete energy levels, even when they shrink down to the quantum world.

Psi and Delta is similar to *Particle in a Box* in that players control virtual avatars that can walk and jump as they traverse the quantum world while being immune to its rules. A primary difference between the two games however, is that *Psi and Delta* has a multiplayer mode that requires collaboration between players. This introduces roles between players. For example, in order switch on the lamp to shine light on the electron, one player must jump on top of the other to reach the light switch as it is at a height that no individual player can reach by themselves. Consequently, one player must be the "base" and the other the "jumper."

The nature of the gameplay is such that a wide variety of social dynamics can emerge. For instance, in cases when one of the players is more well-versed with gaming, they may naturally take up a "leader" position, planning out what tasks need to be done, and dividing them between the two players. Similarly, when one player has significantly more in-depth understanding of quantum phenomena, then they may be the ones coming up with hypotheses about the various concepts (such as how much energy is needed to increase the electron's energy) and the other might accept their word for it without critically thinking about it themselves. In this sense, *Psi and Delta* already has some of the seeds in place for simulating status as it manifests in practice.

Three possible ways of engaging status in the games are: having a cooperative/competitive mode, introducing power dynamics between players, giving players multiple roles.

While *Psi and Delta* has a cooperative multiplayer mode, it can benefit for a variety of additional modes of social engagement: cooperatively, competitively, or both. Cooperation can involve characters having complementary abilities instead of the same ones, requiring both players to contribute to progress in the game their own unique ways. For example, one character could move faster (helping them avoid the enemy bot) and the other could jump higher (reaching other inaccessible places). The game can also take a competitive turn, where players attempt to excite their respective electrons before the other or in the minimum number of steps.

In both the cooperative and competitive designs, the games can also introduce power dynamics between players by giving some players “better” abilities or more resources. For example, some players may have in-game currency, allowing them to “buy” more reliable bulbs earlier than others. Or some players may be able to move faster than others. A slower player may need to learn about energy levels so that they can increase the energy of the electron, which increases the number of safe spots (nodes) that they can reach before each measurement. In turn, a faster player may not need to even inquire into the concept of electron energy to avoid the electron. Such features can help students reflect on how their status affects their inquiry.

Finally, the games can give players multiple conflicting responsibilities. Scientists in practice have responsibilities outside their lab such as towards their partner, parents, children, that affect the amount and kind of responsibilities they can hold within their lab. Drawing on this theme, the games could have characters hold non-technical responsibilities as well, such as spending time to collect resources for home in addition to finding and collecting resources such as light bulbs for level-progression.

6.3.3 Position as Culture

Both games do not have mechanics that engage students with their sociocultural dimensions such as race, ethnicity, gender, age, sexual orientation, and disability, nor incorporate do they incorporate non-white non-western culture into their designs. The game setting and character design in both worlds is that of a western sci-fi, modernist style, research lab.

Further, even design of the character in *Particle in a Box* was interpreted as being male, despite our efforts to make it gender-fluid. The character was designed to be a minimalist abstract figure (like a silhouette) with no facial features or attire, so that students could project their own identity onto it. This, we believed, would make the students more attached to the character and invested in their success, while also avoiding the perpetuation of stereotypes in both games and science (i.e., as a field only meant for white/asian males). We named this character 'psi' after the Greek symbol 'ψ' which represents the electron wave function in quantum mechanics and is also not associated with any gendered names to the best of our knowledge.

Similarly, both lead characters and enemy characters in *Psi and Delta* are designed as robots. The rationale for this was that a robot was simpler to explain as a character that can move around in the quantum world (like a nanobot). We hypothesized that players would be more willing to suspend disbelief and accept a robot in the quantum world than any other character. This is because robots are frequently referenced in popular culture (e.g., in science fiction series like *Star Wars*), where they perform activities that humans usually cannot do. The game also planned to have customizations, but these retained the robot as the central theme. For example, players have the option of choosing from different colors and shapes for the robot. we posited that letting players design their own variation of the robot character would make it more relatable while avoiding the reinforcement of gender or racial stereotypes.

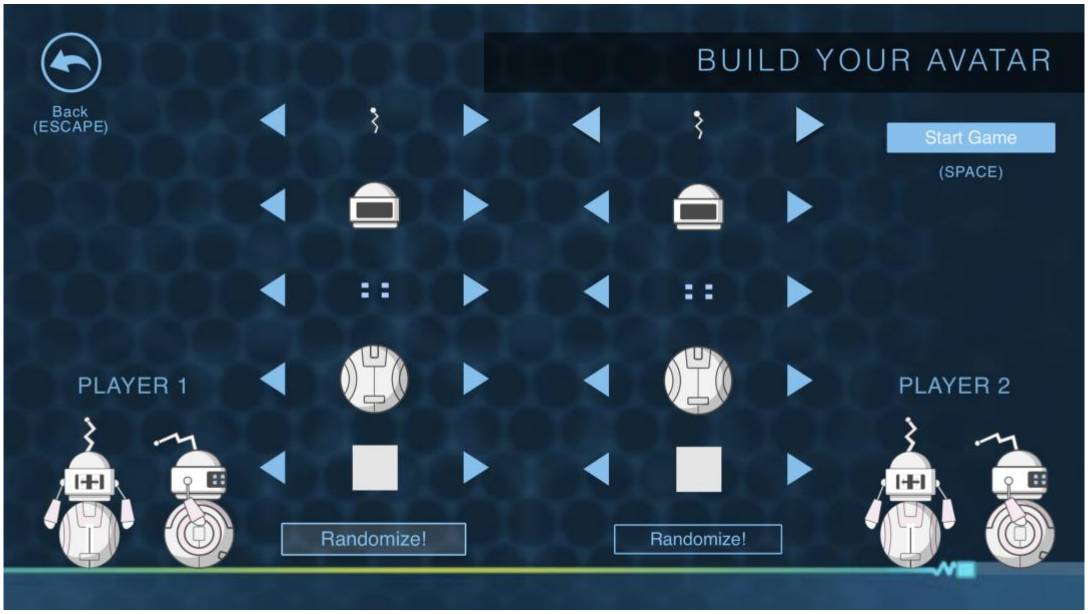

Figure 6 – Interface for character customization in *Psi and Delta* (planned).

Three possible approaches to engaging culture in the game are having diverse/customizable characters, tying different character cultures to gameplay, narrativizing gameplay.

Customization can involve giving students agency to change their character's appearance, their character's abilities, and the game-setting art. For example, players may be able to select from a pool of characters with different attributes from a variety of cultures. Some can move faster, but can't carry heavier equipment, while others may be able to jump higher but are slower. Customization can potentially increase players' engagement as they manipulate and evolve their characters over the course of the game. (Lankoski 2011)

Changing the character-type could also affect gameplay such as by giving access to the character to some areas (occupied by those similar to them or by a mixed group) and not to others areas. For example, characters that are big or medium in size may not be able to access a small-sized community that lives in an area with a small narrow entrance. This community of small-sized characters might have objects such as a low energy bulb that could be valuable to players but would be inaccessible to them if they didn't select a small-sized character to play with. Such an approach links both culture and means into gameplay, and can be an effective way of not only inviting players to explore different in-game cultures, but could also invite replayability as players choose different characters just to see where they get access to in the game.

Finally, narrativization can involve giving a backstory to the character. In the current games, the characters' intentions were not clearly understood. Why was it moving around in the quantum world? What did it want to do? Why are these robots attacking each other? The abstractness and the lack of any context or story associated with the character distanced it from cultural association. Narrativization can introduce culture into the game in such as by contextualizing *why* players are doing what they are doing and for who. For example, the rationale behind players collecting light bulbs to change the energy of the electron could be rooted in a historical backstory about how the electron is actually another character that was trapped in a square well and needs to be provided energy to escape. Such a backstory lends more purpose to the game and introduces a culture of camaraderie between the main characters and the electron character helping each other that could shape the dialogue ad responses by other NPCs as well.

6.3.4 Position as Experience

One of the key educational strategies of *Particle in a Box* was to foreground students' prior experiences about physics. Most students' prior conceptions of quantum mechanics are rooted in their prior experiences of classical mechanics (Johnston et al. 1998; Mashhadi 1995; Singh 2001). As novice students have little or no familiarity with quantum phenomena, their ideas of particle behavior are constrained to or adapted from classical mechanics. They find it difficult to understand that a particle's position can be inherently probabilistic and that the particle may not be in one definite position at a time. When confronted with information on the wavelike-nature of the electron, students often develop inconsistent synthetic models (Vosniadou 2001) in which they mix their prior understanding with the new information. For example, they may think of the electron as a particle that moves along a wave instead of itself behaving like one (Mashhadi 1995). Simply telling students about these phenomena may not be enough. Students may need to experiment with these concepts to better understand them (Vosniadou 2001).

Choosing the goal of the game to be that of raising the particle's energy in each of the worlds offered an effective way of illustrating the differences between particle behaviors in classical and quantum worlds. It aimed to help students break free of their prior conceptions of concepts such as energy that are rooted in their past education and daily experiences. This approach helped students critically examine their prior experiences of classical mechanics against their new experience with quantum mechanics.

However, the games did not engage with students' experiences other than classical physics. Two additional ways of incorporating students' experience into the game can be: connect the game to real-world devices and using QM to generate an artifact.

By engaging students with the quantum phenomena as part of real electronics devices such as LEDs, transistors, and solar cells, the game can help students connect their experience in the game better to their experience of QM outside it. This can help reinforce connections between the subject-matter and real-life which is especially important given the abstract and counterintuitive nature of QM.

Another approach these games can take is to enable students to produce an artifact within the game using the concepts of QM that they hold onto beyond the game. (Sullivan et al. 2018) research project *Loominary* did something just like this as players played an interactive narrative by weaving yarn of different colors together to make their in-game choices. The artifact they end up creating in this process serves as a physical embodiment of their journey through the narrative and became a memoir and a medium to share their experience of the narrative through with others. The two quantum games can accomplish something similar to this by allowing players to create visual art using the photons of different colors released by an electron when it moves from a higher state to a lower state. Given that the electron can move randomly down to almost any level below the level it is already at, there is a certain degree of uncertainty about what color it will release. Players can take advantage of this by drawing a shape that is then colored by the light the electron released. The final picture is something that can be saved as an image file or printed out. Using QM to produce art can help players form a personal relationship with its concepts that translates into their daily experience of both art and QM beyond the game.

6.4 Inquiry and Positionality

6.4.1 Problematizing and Positionality

In *Particle in a Box*, the goal is to increase the energy of a particle (ball or electron) to a given value. To do this, players must move around each gameworld (classical and quantum), gather units of energy, and supply them to the particle. During gameplay, students learn that colliding with the particle will make their character faint. A key problem therefore is to figure out where the particle is going to be in order to be able to avoid it. Avoiding the ball in the classical world requires observing where it is and to jumping over it when it comes nearby. In the quantum world, however, avoiding the electron is not always possible as it exists in a state of superposition until it is measured. Consequently, the problem of avoiding the electron in the quantum world involves interpreting the shape of its probability distribution and strategizing one's movements accordingly, such as by spending more time in low probability zones and less in high probability zones. While the game teaches players how to read the probability distribution through the tutorial, they must figure out how to best avoid it on their own. Until players learn to frame the problem in this way, they are likely to keep colliding with the electron and fainting.

In *Psi and Delta*, the goal is to defeat an "enemy" robot by "shocking" them. Shocking the bot is a team effort. It requires one player to lure the enemy bot onto platforms that have been laid on top a quantum wire that contains an electron. The other player takes measurements of the electron by pulling a lever stationed on the side. When an electron is measured under a platform it will cause anything on the platform to get shocked. Consequently, this problem is similar to *Particle in a Box*, i.e., the electron's position is probabilistic and where it will be measured cannot be exactly predicted, only estimated based on its probability distribution. However, there are additional problems on top of this depending on the level. For example, players have to figure out *which* platform is most likely to shock the enemy bot based on the length of the platform and the probability distribution of the electron under it. Further, when energy levels are introduced, the enemy bot returns with a shield of armor that can only be broken when shocked by an electron with a specific energy level. Players have to figure out how much energy to supply energy to the electron to get it to this specific energy level, based on the energy diagram. Then to supply that energy they have to solve the logistical problems of changing the color of light from a lamp and reaching the switch that activates the lamp, both of which require cooperation between players.

What makes such problems different from practice is that they are predetermined, well-defined, strictly-bounded, and known to be solvable. First, these problems are predetermined in that they are embedded into the design of the games. Within the game environment, there is no scope to question why these specific problems should be tackled and not others. Second, the problems are well-defined because they have specific constraints or goals that cannot be changed. For example, the problem of raising the energy level of an electron is specific and fixed. Players simply cannot progress in the game until they understand and solve this exact problem; nor can they redefine the problem within the game environment. Third, the problems are strictly-bounded in that the subject-matter that students need to learn to solve it is fixed. In the above case, it is knowledge of the discrete energy levels for an electron and the relationship between energy and light that is required to solve the problem. No other concepts or disciplines are needed. Finally, the problems are solvable because they have definite solutions. The very fact that the game has multiple game levels reinforces this idea as one can only get to higher game levels by solving the problems of the previous ones. Even if the problem seems unsolvable to students, for example if they believe the game has a bug when they are unable to solve it, other students or teachers can always tell them that it is indeed solvable and that they just have to try a different approach.

Redesigning the games to support problematization in relation to their positionality could include introducing unsolvable problems (means), adding individual and collaborative achievements (status), tying different character backgrounds to gameplay (culture), and allowing students to create/modding game levels as part of the game (experience).

Making some problems in the game unsolvable can make all problems inherently uncertain in terms of their resolvability (as is observed in practice). Students may not know *a priori* if the problem they are currently facing is resolvable, and thereby not sure what to make of their access to it. Consequently, students have to problematize each new game level or area as part of their in-game experience: is this solvable or not? Is it worth solving?

Adding both individual and collaborative goals to the game can help make player's statuses more integral to the gameplay experience, especially if they are oppositional. For example, if the game is such that players can collect coins as a common resource use them to purchase either upgrades to their characters (jumping higher, moving faster) or for the team (group abilities moving a positive/negative charge), there will be a tension between players about how to best use that resource in the game. If those upgrades pertain directly to the concepts of quantum mechanics, then this can bring status directly into relation with inquiry into QM—should we use QM to enhance individual status or that of the group's? This conflict could be exacerbated if the game rewarded individual achievements over collaborative ones at the end.

As discussed earlier, tying different character cultures into gameplay can be one strategy to relate inquiry in the game to culture. For example, if only certain characters can get players access to certain locations based on the character's culture, then the problems that players frame in the game will inevitably include the culture of character as well—should we pick the jumpers or the small-sized characters? This can further support inquiry into QM if the character's culture integrates elements of QM into it such as by having some character be able to shrink into quantum wires and be of different masses, leading to different energy levels or others having an inherent positive/negative charge that can distort the probability distribution of the electron.

Modding game levels can support problematization as players are put in charge of figuring out what needs to be changed and why. While modding the game may seem like overstepping the boundary of the game environment, modding can be done to some extent within the game's context as well. For example, the game's narrative could be framed such that there is a broken quantum simulator which the players have been transported into and have to fix. Fixing the simulator could entail programming in the established relationship between different quantum variables such as the relationship between light and energy levels. This considerably increases the space of possibilities for students to explore mathematically and therefore the problem space for inquiry.

6.4.2 Hypothesizing-Experimenting and Positionality

Particle in a Box engages students in cycles of hypothesizing and experimentation based on their experience through the sequence of gameplay. Playing the quantum world after the classical one encourages students to apply classical conceptions to quantum phenomena. This results in temporary failure which induces a recognition of the incompatibility of classical and quantum mechanics. For example, our evaluations indicated that students initially believed any color of light will increase the electron's energy. However, after observing that green light is ineffective and that red light is needed in the first game level, they learned that the electron's energy is unlike that of a ball and must be treated differently. Failure enabled them to break free from their prior understanding and build a more robust mental model of the behavior of the electron (Posner et al. 1982).

Psi and Delta builds on this as students initially believed that shining the maximum amount of energy should always work to increase the electron's energy. This belief has its root in classical physics. The harder we kick a ball the more likely it is move. Yet in QM, as discussed earlier, only an exact value of energy will work for transition between two energy levels. No more, no less. The electron simply will not absorb the energy if it is different from any of the values between two energy levels. This counterintuitive behavior invites students to rethink their fundamental assumptions and experiences about energy.

However, aside from linking it to students' past subject-matter related experience, the games do not relate their positionality of players with their hypothesizing-experimenting in other ways such as their means, status, culture, and other experiences. This can be done by building upon the suggestions in positionality, i.e., by introducing unreliable and limited resources, introducing power dynamics between players, narrativizing the game, and connecting gameplay experiences to real devices.

Having unreliable resources can significantly impact students' hypotheses. If the bulbs in the game were unreliable, it invites students to ask: "is it that the color of the bulb correct and it is simply unreliable or is the color of bulb itself wrong?" Further, if we consider the tutorial itself as a resource, then uncertain guidance, such as in the form of red-herrings (incorrect information), can direct their hypothesizing: does blue light have less energy than green? Is the electron really in multiple positions at the same time? Further, requiring students to carefully use their resources can invite them to learn how to design and prioritize experiments. For example, if the game scatters bulbs of each color differently (blue and green bulbs are more common than red bulbs), then students must optimize their strategy of experimentation, such as by trying different combinations blue and green bulbs before attempting to find and use low energy bulbs.

Similarly, introducing power dynamics, such as through an unequal competitive mode where some characters can afford more resources than others in a limited pool of resources, can help students learn about how power structures condition one's ability to hypothesize and experiment. For example, say the game had a mechanic where players had to catch electrons and were rewarded for it. Power dynamics can be introduced here if some players start off with better measuring tools than others. This allows them to make more measurements and find more electrons, which earns them more currency, which allows them access to even better measuring tools, in a positive feedback loop that leaves behind those who start off with lesser equipment and reiterates the systemically unjust nature of power and wealth in science.

Narrativizing the game can allow students to hypothesize not just in terms of technical concepts, but also sociocultural issues. For example, the game could have characters (player and NPC) that belong to different social groups each of which follows a different model of quantum mechanics such as: the Copenhagen model (the most popular one, which Particle in a Box already adopts), the Pilot-wave theory, and the many-worlds model. These three models are all commensurate, i.e., they make the same predictions about quantum phenomena but are radically different in their conceptualization of it. This could invite serious discussion between players belonging to different schools of thought, thereby reiterating the importance of epistemic cultures to inquiry.

Further, if the game allowed players to customize not only their character's appearance, but also their cultural background and connected it to their in-game strengths/limitations, it could echo Harding's notion of epistemic privilege. For example, characters coming from a poorer and more challenging backgrounds may have less currency to buy resources but may have unique abilities such as being able to resist being shocked by the electron better. This would invite students to think about the characters culture each time they develop a hypothesis or design an experiment. Further, as the game progresses, the character's ability could grow in response to their actions. For example, they could lose their ability to resist shocks if they haven't gotten shocked in a while due to better equipment. This integration of QM, culture, and experience in the game could help highlight some of the way that inquiry is entangled in culture.

Finally, while the game already conditions player's hypotheses by building on their prior experiences with classical mechanics, it can go further by drawing upon real devices that employ quantum physics such as computer chips, LEDs, and solar cells. For example, instead of having students change the energy level of an electron in an abstract 1-dimensional wire, the game can enable them to change the materials and form of a solar cell which can help them connect quantum physics back to their real-world experiences.

This can allow students to hypothesize about the application and real-life use of quantum physics in connected with their real life experiences.

6.4.3 Resolution and Positionality

Finally, the resolution to each problem in *Particle in a Box* and *Psi and Delta* is fixed and predetermined, i.e., there is only one correct solution for each game level. There is no ambiguity involved in resolution, students either pass the level or they don't. Further, while students do not initially know what that solution is, they do know that there *is* a right solution. Given that positionality affects resolution precisely when there is uncertainty, the current game designs do not engage resolution as a reflexive process.

Relating positionality to resolution can be supported in the games in several different ways such as: depleting resources for each experiment (means), connecting resolution to reputation (status), introducing competing NPC groups (culture), and changing initial conditions (experience).

If player's resources deplete each time they conduct an experiment in the game (e.g., using up bulbs each time a light is shined), and there are limited resources (bulbs) available, players must learn to optimize their use of the bulbs to maximize the electron's caught. Otherwise, a lack of resources will lead to a premature conclusion to their inquiry. Consequently, players have to plan their resolution given the resources they have and can find accordingly.

If the game attaches a certain level of prestige to catching more electrons, such as through an online leaderboard, this can make competitive players more inclined to find the best possible strategy for collecting electrons. Resolution then becomes a form of competition. Much like practice where competing groups strategize to make the most efficient cell, so do competing players strategize to collect the most electrons.

This can be also be done through an in-game capitalist culture that breeds competition between players and NPCs. For example, players could be part of one group and NPCs to another as they both aim to find the electrons to sell, buy better equipment, and find even more until they have captured the in-game market and ultimately, exhausted the electrons leading to an in-game collapse of the market and social order. This kind of approach can invite critical reflection into the detrimental effects of a hyper-capitalist culture that is often seen in practice where resources are mined and extracted without regard for sustainability and preservation, exacerbated by advancements in technologies such as for whaling/fishing and mining.

Finally, resolution can also be tied to a player's prior experience within the game by allowing players to select from a variety of scenarios to play from. Each new scenario produces new possibilities for resolution as prior resolutions may not work for similar problems in them. For example, collecting electrons by changing the probability distribution using only colors of light differs significantly from scenario to scenario if players don't always have access to all the possible colors.

CHAPTER 7. STUDY 3: DESIGNING WITH THE FRAMEWORK (SOLARIA)

Summary: Building upon the critique and redesign possibilities of *The Mystery of Taiga River*, *Particle in a Box*, and *Psi and Delta* discussed in the previous chapters, I employ the framework as a design space to explore design possibilities for a new game, *Solaria*. that aimed to position electrical engineering students in practice at a distance and support their learning of reflexive inquiry into issues surrounding semiconductor-based devices such as solar cells. Through the description of a design case of the game, I discuss how I designed the game's features to address each of the dimensions of the framework.

7.1 Introduction

Solaria is a digital multiplayer game that I designed (but never developed) that aims to situate students as electrical engineers in a virtual region which simulates the sociotechnical issues and relationships of the solar power industry. The game was not developed due to practical constraints as well as inherent constraints posed by the affordances of digital games. Instead, it serves as a thought experiment exploring the design possibilities afforded by the framework and to some extent, as a possible "theoretical maximum" of how digital games can be designed to position students in practice at a distance and support inquiry as a reflexive process.

7.1.1 Rationale for designing a game about solar cells

The rationale for focusing on solar cells is threefold: to invite critical examination into the utopianism underlying solar power so that they be developed and integrated more responsibly, to engage students with the politics of renewable energy technology, and to explore the rich space of possibilities for re-designing solar cells and their life cycles.

First, while solar cells are essential to the fight against climate change, their production, use, and disposal across the world also perpetuates social and environmental injustices. For example, the production of polysilicon in Xinjiang (which accounts for around half the world's total production), has been tainted by the use of forced labor of local the Uyghur population (Funaiole and Kurata 2021). Similarly, the mining of the raw materials for solar cells such as silicon and gold has caused thousands of cases of silicosis (a painful lung disease) in African miners (Sonke Gender Justice 2016). The disposal of solar cells is also becoming an increasingly problematic area of concern as they are toxic when left in landfills and are difficult to recycle (Atasu, Duran, and Wassenhove 2021).

Second, the rise of clean energy has coincided with (and contributed to) the decline of fossil fuel-based energy. This has resulted in the loss of several jobs and political backlash from the fossil-fuel sector. How can solar technology and policy be designed ensure that a transition to clean energy leaves no worker worse off or left behind?

Finally, there a wide range of responses to the injustices such as redesigning solar cells, enforcing regulation and labor policies, improving recycling technologies, each of which has its own social, political, ethical, and epistemic issues that collectively present a rich educational space for learning to do inquiry, reflexively. For example, students as electrical engineers in the game can explore how redesigning a solar cell can impact its social, economic, and political standing. These possibilities are rarely discussed in electrical engineering courses.

7.1.2 Summary of how Solaria aims to support inquiry as a reflexive process

Solaria was planned to be a multiplayer game that placed players as engineers in a solar power company called *SolarTron* as well as local representatives of their settlements in the region of *Solaria*. By placing players in this dual technical-societal position, the game aimed to invite critical examination into and dialogue between scientific and societal issues.

To promote problematization as a reflexive process, the goals of the game would be set by the players themselves at the beginning of each game-year. These goals would take the form of “pitches” for the design of a solar cell’s life-cycle to their company and “memorandums” about policies for their settlement community. Player’s *means* in the form of their access to resources such as a solar cell simulator, resources on solar cells, and conversations with NPCs would all play a role in the setting of these goals, as would having a *status* as both and engineer and a representative of the community, *culture* in the form of being part of a capitalist system as well as a local community with its own history, and *experience* in the form of prior successful and failed attempts. Conversely, the goals and problems that players define will affect their means, status, and experience in the future, as well as the culture of their settlements as they co-evolve with the changing landscape of renewable energy.

To support hypothesizing and experimenting as reflexive processes, the game invites players to explore different approaches to achieving the goals they set. For example, achieving goals for their company could entail exploring different solar cell designs, experimenting with different manufacturing processes, and strategizing about recycling/disposing solar panels at the end of their lifecycle. Similarly, achieving the goals for their settlements involves talking to people in each community, attempting to persuade them to support your cause (or oppose an antithetical cause), and finding a common ground such as: If coal-based jobs will be lost, can the community fund a training program for workers to get jobs in other sectors? If pollution from solar panel disposal is leaching toxic compounds into farmlands, can the landfill be moved elsewhere or more efficient barriers be installed? The process of inquiry here is deeply rooted in the player's *means* such as access to funds in the community or technologies to prevent leaching of toxic compounds, their *status* as a community member which allows them to be a leader/voice of authority when convincing people, the *culture* of their community (the values and assumptions about solar energy of the company and their settlement), and their past *experiences* with failed and successful hypotheses/ experiments.

Finally, to promote resolution as a reflexive process, the game involves problems that have no clear solution: How much more can we improve the efficiency of the solar cell? How much lower can its price go? Should work be automated? Resolving these problems requires players to make value judgements based on their position. For example, do they have time and money to explore these questions further? How far along are they in terms of reaching their deadlines and goals?

7.2 Solaria

Building on research in games for teaching inquiry and concepts of quantum and semiconductor physics [1–3, 41, 50], the educational goal of this platformer-style multiplayer game was to engage students in open-ended inquiry into the life-cycle of semiconductor devices, particularly solar cells.

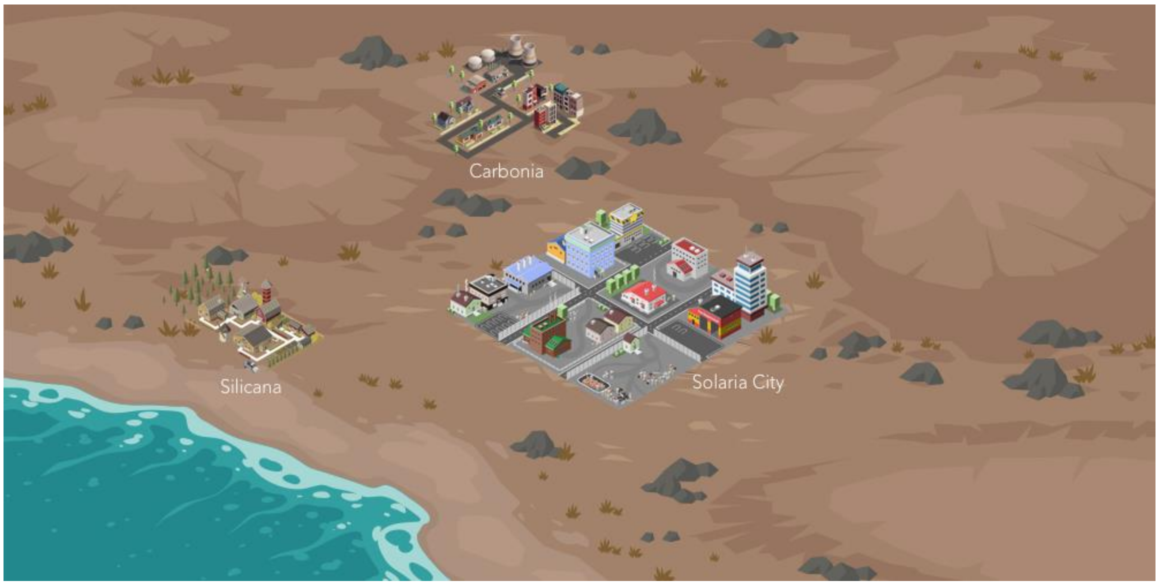

Figure 7 – Map of the Solaria region. It contains the settlements of Silicana and Carbonia, and the capital Solaria City where *SolarTron's* headquarters is housed.

There are multiple social issues that the game aims to focus on such as:

- Labor exploitation in the mining industry
- Forced labor in the development of polysilicon for solar cells
- Exploitative factory conditions for assembling electronic devices such as solar cells
- Leakage of chemicals during solar cell production (Hydrochloric Acid, Tetrachlorosilane, Hydrofluoric Acid, Cadmium)
- E-Waste and leaching of toxic chemicals after disposal of solar panels,
- Air pollution/climate change brought about by the fossil fuels sector,

- Loss of jobs in the fossil fuels sector/creation of jobs in renewable sector

The premise of the game is that each student would play as an electrical engineer as part of a team in a solar cell development company called *SolarTron* in a region called *Solaria* that is also populated with other solar cell companies. The players would also be representatives of different settlement in a large and variegated region. The goal of the game is to survive as both an engineer and as a representative by the end of 3 years.

As engineers, players work together and decide matters such as where the solar cell's materials come from, what its design is, how it will be manufactured, and how it will be disposed. The player also pitches the company targets of how much profit and market-share they will generate for them for each quarter and what the budget and timeline should be to achieve those targets.

As a representative of the settlement, the player can decide the local work policies for the citizens such as their minimum wage, maximum working hours, health insurance, and permissible automation levels. They can also talk to the local residents and gauge how they are feeling as they share their daily stories.

It was intended that the game would draw upon these actions by the players and simulate their relationship to the virtual society in the region. Consequently, each player's actions would have a ripple effect on the game due to the interdependency of the settlements, the company, and the market that constitute this virtual society of Solaria. For example, a mining silicon for solar cells can boost the player's position in Silicana, but may also lead to silicosis in several workers, leading to a hospital overload and protests by workers. Simultaneously, the higher efficiency of solar cells may endanger the viability of a local coal power plant and put workers out of jobs. Through such dynamics, the game aims to engage players in scientific inquiry into semiconductor physics and allow them to explore the entanglements of science and society.

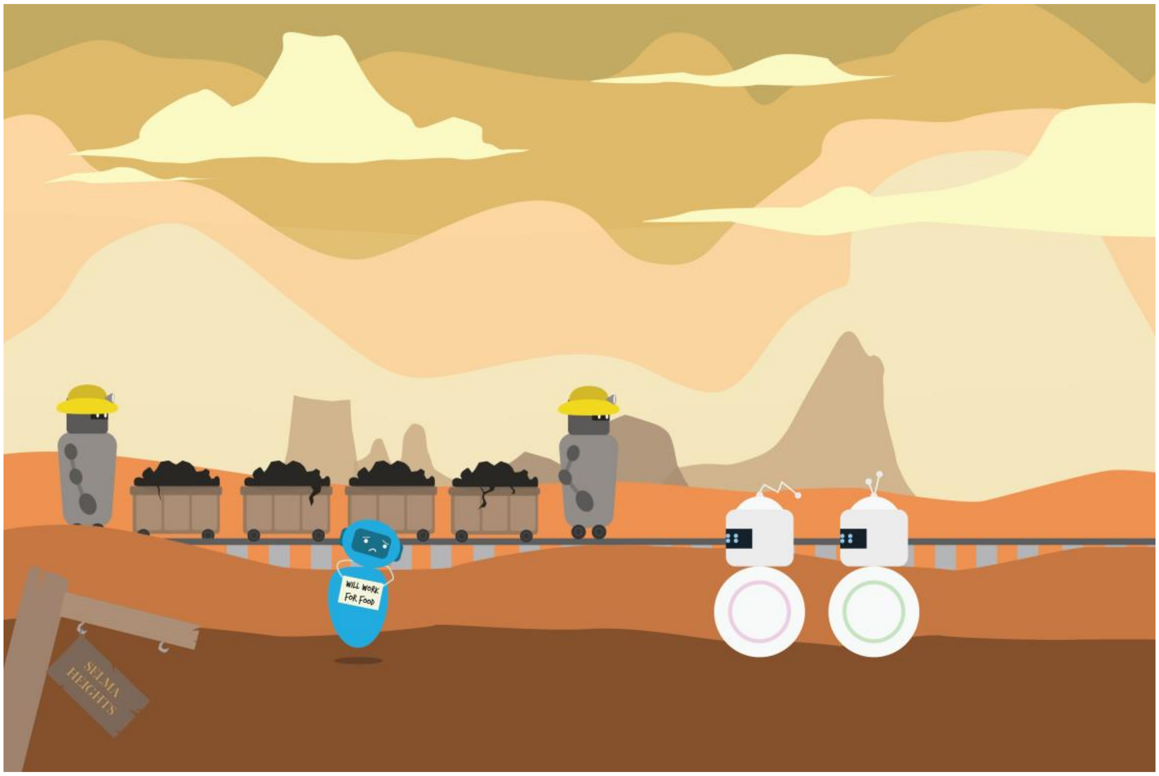

Figure 8 – Silicon Mine in Silicana. Players explore the poor working conditions here.

Now, there are two main challenges for players. First, the company can fire the player if they are not satisfied with the promises the players make such as about profits. Second, the settlement can choose not to re-elect the player as a representative if they feel that the player has not respected the wishes of its citizens, such as by not taking care of their minimum wage or working hours in factories. If one player loses any of these positions, they lose the game. In a multiplayer setting, if one player loses, then everyone loses.

With this basic description in mind, I explore the design of Solaria in more detail by describing it in terms of the framework.

7.2.1 Positionality in Solaria

7.2.1.1 <u>Status</u>

The game positions players in two concurrent roles: as an engineer working for a solar cell company, and as a representative of one's community. These positions are key to all actions that players perform in the game. If a player loses any of these positions, they lose the game. In a multiplayer setting, if one player loses, then everyone loses.

As an engineer of the solar cell company the player works as part of a team that is responsible for designing and testing solar cells. The team comprises solely of student players and they collectively have the freedom to decide what kind of solar cell they want to develop as long as it is profitable for the company and keeps them competitive in an increasingly tight market. Design is facilitated by the solar cell simulator which can be used to generate blueprints. These blueprints, once approved by the team as a whole, are sent to the manufacturing division of the company for building the actual solar cell prototypes. The team also selects how the cell is to be manufactured, i.e., what processes are to be used for each step. After the device has been built, it is sent back to the team for testing. If the team decides that the device works as intended, it is sent for commercialization and the company begins selling them to consumers or businesses in the region. If not, they redesign the device and try again. All of these processes cost the company time and/or money and must be completed within the budget decided by the team and the deadlines. If players realize that they might exceed the budget or the deadlines, they can negotiate with the project manager (an NPC character) and attempt to convince them to give them more money or time. However, if their rationale is not convincing or this happens too often, they can lose their employment. Players can also lose their jobs if their solar cell design and manufacturing process makes the company uncompetitive in the long term or causes them significant losses.

As a representative of their home settlement, the player's goal is to ensure the well-being of their community. The player is not alone as a representative but works alongside 2 other NPC characters on a council that must collectively decide what actions to take. To remain on the council players must be re-elected each year by the citizens of their settlement. There are three interrelated issues that the council is responsible for in the game: improving working conditions, keeping unemployment low, and preserving/promoting the quality of life. Improving working conditions means supporting worker unionization, supporting increased pay, lower working hours, and increased health insurance support from the companies. This informs conversations that players have with the company management such as about factory/mining policies as well as conversations with the locals such as for protests, strikes, and civil disobedience. Unemployment can be kept low in multiple ways as well, such as through a binding contract made with the worker union (if it is established) or by convincing the companies stay in their settlement and not outsourcing their work elsewhere. Finally, the quality of life in the settlement is a factor of both the previous two issues as well as environmental concerns such as air or land pollution and its health effects on the citizens of each settlement.

I discuss the interplay of this dual-status as employee and representative and its relationship to inquiry in a later section in this chapter.

7.2.1.2 Culture

Each character's culture is informed by the culture of the company and their settlement. Players live in different settlements, each of which were politically entangled, dependent on each other for resources, but have their own culture and community. While the initial version of the game planned to have several settlements with several players, the first step was to focus on two main settlements—Silicana and Carbonia—for a two-player version as well as a third called Solaria City where their company *SolarTron* is headquartered.

The culture of the company is that of a profit-driven, overworking, hierarchical organization. This culture manifests in multiple forms such as the costs and profits it is willing to accept, the working conditions of its employees, and the rewards/punishments for them. For example, the management decides how much the company can afford to be in loss. If players keep the company profitable, they may be rewarded with better job security and increased pay (which they can donate to their budget as a representative). If not, they become more at risk of losing their job. Further, the visual design of the company's logo, lab, and uniforms for workers, are all informed by corporate culture with a clean, modernistic/efficient, and standardized appearance. Dialogue between the players and NPC management characters is also informed by this culture as decisions must make sense to them financially to be approved, even if more socially just decisions require financial compromise.

This company culture is in part informed by the region's larger economic (capitalist) culture and in part by its political culture (which allows lobbying). The company has to prioritize profits and market-share over all else, otherwise it will lose the market to other solar cell companies in the region and go bankrupt because of losses. Similarly, the top executives of the company aspire for more personal wealth not only because of greed but also because their wealth gives them power to lobby the government for making decisions and passing laws in their favor. If they do not have that kind of wealth, executives from other companies and industries will lobby the region's government instead, which could threaten their own company's survival. These matters are not explicitly shown in the game, but are embedded in the conversations players have with different AI characters such as their manager, their local community lawyers, and other local representatives.

The settlements that players belong to—Silicana and Carbonia—are both small towns that are do not have much political standing in comparison to the capital city. They also have their own distinct cultures.

Silicana is a historically poorer settlement with a high unemployment rate, but is rich with silicon ore (quartz). Due to this, *SolarTron* has begun mining and refining operations there for silicon and has opened up a new solar cell manufacturing plant as well. These ventures have given the local population more employment opportunities and have begun to improve the economic health of the region. At the same time however, the working conditions in these mines and factories are appalling with low wages and long working hours. This is the case partly because the company knows that the citizens of Silicana have no alternative options for employment, and so it can leverage their situation to its own advantage. Such working conditions alongside historical poverty have led to a strong communal bond between the citizens of Silicana, and has also shaped their political stance as they support more centralized services such as power, health, and education. Consequently, the citizens here support a central solar power plant as opposed to each citizen buying their own solar panels for their roofs as the former is a cheaper and more communal option that supports everybody.

Carbonia, on the other hand, is historically richer due to its coal mines and coal power plant which supplies power to other towns such as Silicana and Solaria City, as well as an abundance of natural ores such of lithium, cadmium, cobalt, and lead, all of which are necessary for developing solar cells and supporting them through batteries and other electrical equipment. As a result, *SolarTron* has set up mining operations here to extract these elements. There is also a major landfill here. With the rise in production of solar panels across the region, more and more of the region's solar e-waste is ending up here and leaching toxic compounds into the local environment. Due to this as well as its historic dependence on coal, the citizens of Carbonia are generally anti-solar cells. Further, the culture of Carbonia is more individualistic, partly because its citizens are generally well off and have not needed to depend on each other due to the abundance of jobs. Consequently, they are not in favor of more central services which incurs higher taxes on them. Instead, they prefer that each citizen/family meet their own needs and therefore if they had to support solar cells, it would only be for smaller home solar power systems and not centralized solar power plants.

Finally, Solaria City is the region's capital and houses the headquarters of *SolarTron* where the players work. This city is primarily under the political control of the major corporations of the region such as other solar power companies and coal corporations. Players' only come to the city for work and return back to their respective settlements at night.

The game planned to have customizable robot characters just like *Psi and Delta*. Further, the player's robot design would set the base design for all the other characters in the respective settlement to give a sense of belonging there. For example, if a Silicana player's robot had two antennae, then most of the robots in Silicana would also have two antennae.

All of these settlements depend on each other and have material, political, and cultural strengths that can become weaknesses and vice-versa in the game. For example, Silicana depends on Carbonia for coal and carbon, while Carbonia depends on Silicana for technological devices. The effects on one can significantly affect the other. If disposed toxic waste in a landfill in Carbonia leaks into a nearby river, it can kill the fish and also spread to Silicana, affecting its local population.

7.2.1.3 Means

As an engineer, there are several kinds of resources/tools players can have access to in the game:

- Books/papers: players have access to an in-game database containing literature about different kinds of solar cells and how they work
- Solar cell blueprints: these are design templates for different solar cell types that can be sent off for monitoring. Players can either find these or make them using the

solar cell simulator, but they may not always be accurate or well-designed when found or given to players by others.

- A solar cell simulator: this allows players to model different kinds of solar cells and observe their electrical characteristics, material properties, and financial costs
- A financial forecaster: this allows players to estimate how well their solar cell is likely to do in the market given the current conditions
- Manufacturing process selection: players can select among a set of different processes for manufacturing solar cells such as diffusion vs ion implantation, chemical vapor deposition (CVD) vs molecular beam epitaxy (MBE), each of which have their own advantages/disadvantages
- Hardware for testing prototypes: players have to share common resources such as wires, voltmeters, ammeters, and other testing equipment with each other and other NPC groups in the company to test their physical solar cell prototypes

A notable feature of this game is the need for testing solar cell prototypes. How solar cells are simulated is not necessarily how they will behave as there is no model that can perfectly predict the behavior of real solar cells. Manufacturing processes and the variability of materials all contribute to the final solar cell behavior. Consequently, the game requires players to test the solar cell prototypes (which, for the purpose of simulating in the game, are simulated solar cell models but with randomly added variability). This recreates the process of professional practice where testing solar cell prototypes is a necessary step as simulations cannot perfectly capture the non-ideal behavior of each device.

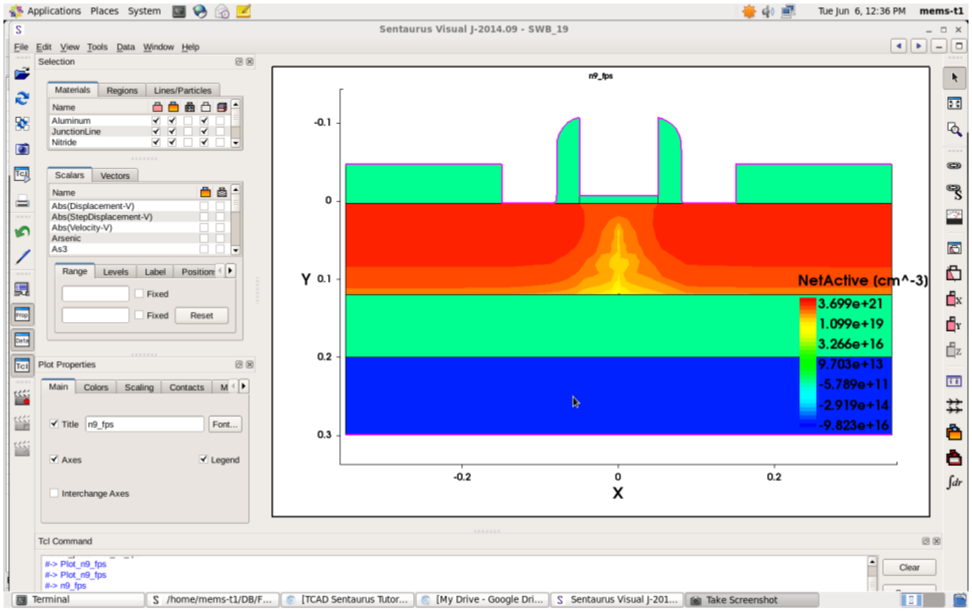

Figure 9 – Reference diagram for the Solar cell Simulator

As a representative of their settlement, players can use the funds collected through taxes and make policies for their settlement. The funds can be allocated yearly in the form of a budget for various purposes such as improving infrastructure, bettering healthcare/ education, and funding worker unions. Bills for new policies can be introduced and modified such as for mandating workplace regulations (work hours and minimum wages), giving/reducing subsidies to solar cell operations, and tightening/loosening of environmental requirements for company operations. For a bill or budget to pass, 2 out of the 3 council members (including the player) have to agree to it. Each bill/budget affects how the citizens of the settlement see their players and subsequently, their chances of being re-elected each year.

In both roles, players have access to conversations with NPCs such as their manager, other representatives, and citizens. These conversations are designed as branching-tree dialogs where players can select from a predetermined set of choices. It could also be done in the form of chat system with AI chatbots functioning as NPCs in the game. Conversations are key to gameplay as a significant portion of it involves persuading other characters to be on board with the player's plans such as: persuading their manager to consider the social/environmental implications of their solar cells, convincing the other council members to support worker unions, or rallying citizens to protest their working conditions.

Beyond these in-game features, the game also allows basic modding by allowing players to change the initial conditions of the game. This includes matters related to both the company and the settlement. In relation to the company, players can change four features: the maximum number of competing solar cell companies, the highest-possible level of market-share by any one company (to avoid monopolies), maximum permissible carbon-emissions in the region for each company, and the base-level support in the form of regional subsidies for solar cell development. In relation to the settlements, player can change four features: the starting unemployment/poverty rate, the base-level minimum wage, the maximum required working hours, and base-level support for healthcare. These features can invite multiple replays.

7.2.1.4 Experience

Finally, player's experience and knowledge about solar cells and the gameworld shapes their inquiry over time. As players meet or fail to achieve goals that they set in the beginning of each game-year, they become more accustomed to the practicalties of the game and adjust their expectations accordingly. Similarly, the more players understand how solar cells work, the better they can design them to meet different needs based on the goals they set. While the process of playing the game may not provide a clear answer about how solar cells *should* be designed and manufactured, it can help players experience the societal entanglements of what is normally considered a purely technical process, enriching their understanding not only specifically about solar energy but also more generally about the situatedness of technoscientific practice.

7.2.2 Inquiry in Solaria

By incorporating a player's social, political, historical, and cultural position as a core feature of gameplay, I aimed to help players experience how technoscientific inquiry is always a situated practice. Developing a technology or conducting research is not simply a matter of technical problem-solving but requires critically examining one's position in society as part of the problem- situation. In practice, who the scientist is and who they work with has a significant impact on the research that they (are able to) do. This section explores how the players' positionality in societal structures as discussed above can potentially affect and be affected by their process of inquiry in the game.

7.2.2.1 Problematizing and Positionality

Before the game allows the player to frame their own goals and problems, it first teaches players how to play the game through a tutorial. The tutorial has first time players begin the game in the middle of the year with predetermined goals for each role. It then helps players achieve these goals through hints and suggestions as players play through the weeks and get familiar with the game mechanics. The tutorial ends once the new year begins and players must draw upon their experiences and understanding of the game from the tutorial to set new goals each year for the remaining three years. These goals take the form of a "pitch" to their management in the company and a "memorandum" to their settlement at the beginning of each year.

For the company, the player has to decide four things as part of their pitch: the target market-share of the company, the intended total profits for the company they can generate, how much budget they need to accomplish their goals, and deadlines that break these yearly goals into monthly targets. For example, the player may target a market-share of 20% or a or budget of $25,000.

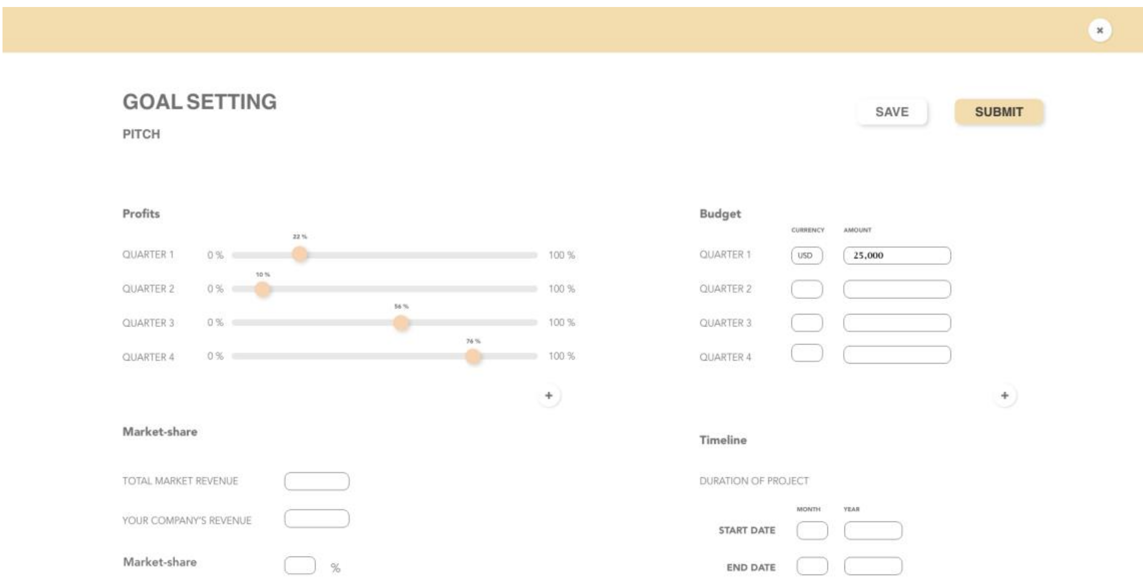

Figure 10 – Interface for setting the Pitch as an employee

For the community, the player has to decide their goals on three key issues as part of their memorandum: working conditions, employment, and quality of life. For example, players may aim to set the minimum wages and maximum work hours for employees, a 1% unemployment rate, and 10% less carbon emissions than the year before as well as increased coverage of healthcare for citizens for improving the quality of life.

Player's status as a common member to both groups plays a significant role in determining these goals while also being impacted by them. For example, as a representative they may aim to mandate higher minimum wages and lower working hours. However, this can drive up the costs and reduce turnover for the *SolarTron* factory/mines in their community, jeopardizing their position as an employee. Similarly, players may decide that a market-share of 20% is a feasible goal for the company and achieving it means increasing the production of solar cells, which requires longer working hours from citizens in the settlement and can therefore jeopardize their position as representatives in the next local election. Players therefore have to foresee these possibilities and judge what goals they can best achieve for each role every year.

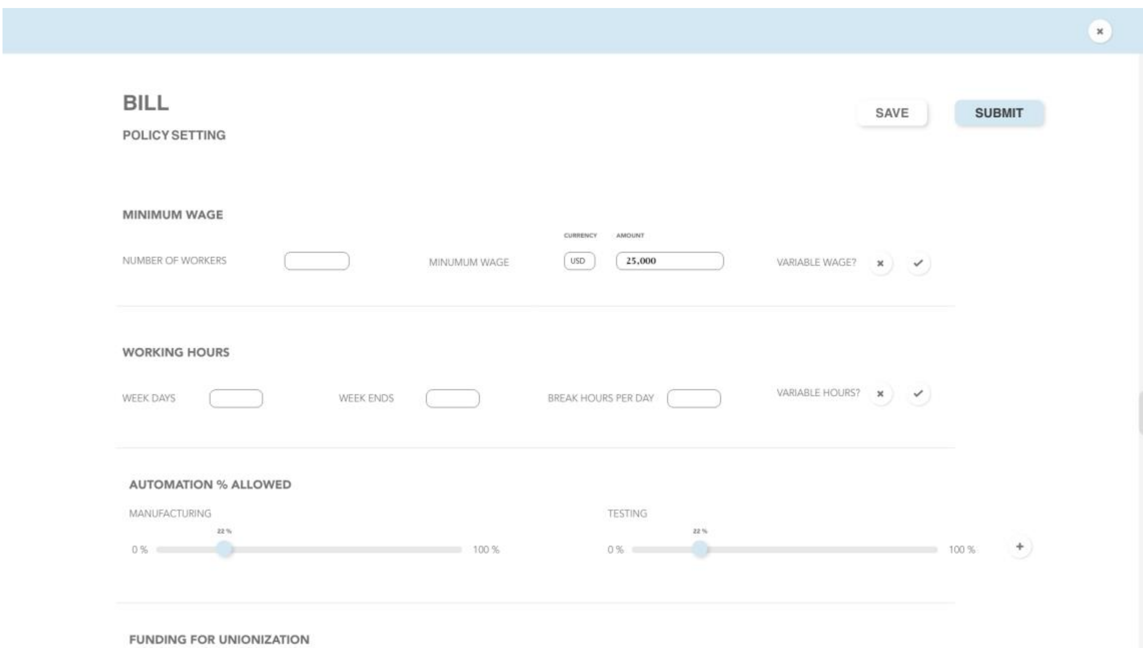

Figure 11 – Interface for setting the Policy Bill as a representative

Players' relative status to each other as representatives of their own local communities can further complicate problematization. All players have to work together as a team when deciding their goals for the company. However, since they come from different communities and have different communal goals, this goal setting process brings their communal problems into dialogue with one another. For example, a player from Silicana may be planning to improving working conditions in their community while the other from Carbonia may be more focused on increase employment. Now, aiming for a higher market-share in the company share may align well with increasing employment as the more workers there are, the more turnover the company can make. However, achieving higher market-share means that the influence of solar power can grow in the region as more people buy and use solar cells for energy, leading to a reduction of jobs in the coal-sector. Consequently, players have to understand each other's issues and find a common ground for sustaining their positions in the company as well as their respective communities. Failing to do so may lead one of the players to lose a position, in which case the game ends and everyone loses.

The culture of the economic and political system of the region also matters to problematization. Given that there are other NPC solar cell companies at play in the game as well, player's company goals have to be well thought out. Setting a market-share too low can leave the company vulnerable to competition. Setting it too high can be unachievable. Similarly, if the profits are targeted too low, the company may not have enough budget next year, and can subsequently be outcompeted by the market. Consequently, players must also consider the broader economic and political context when making decisions about the goals for the company.

Player's access to resources further complicates the problem-space. For example, access to a financial forecaster tool helps them evaluate feasible financial goals for their company such as their expected expenditure and profits (although it is not a perfect predictor). It draws upon the past price-fluctuations in solar cells (supply and demand) as well as the intended market-share to estimate how many solar cells would be added by the company and how that would affect the prices of solar cells. Further, access to books, papers, and blueprints about solar cells helps players make informed judgements about reasonable goals for the company and their community.

Finally, deciding what the goals should be is dependent on player's past in-game experiences as well as knowledge about solar cells, economics, and politics they may have gained outside of the game. The more they play and explore the ripple effects in the game, the more attuned they become to the nuances of the situation. For example, they may realize that achieving a market-share of over 50% is next to impossible in a highly competitive market and so lower their expectations accordingly. Similarly, they may learn that it is not possible to completely eradicate unemployment due to the volatility of the market and set their goals accordingly.

Going beyond the goals in the game, the larger question that animates in-game inquiry is what *should* be done about the situation. While the goals that player set in the game will change over time as they complete the game and replay it, players can explore this larger problem by changing the initial conditions in the game. For example, they can explore how the whole situation changes if there is a market-share cap or a higher base minimum wage overall. This expands the scope of problematization significantly as players explore the strengths and limitations of their strategies for different scenarios and initial conditions.

Through such a design, I aimed to engage students in open-ended problematization, where they decided their own problems, set constraints in accordance to their experiences in the system, modified the problem based on the response they received through their actions, and decided what counted as an acceptable resolution. This is a central tenet of inquiry in practice where problems are not "given," but rather must be framed and continually adapted to reflect new observations as inquiry proceeds.

7.2.2.2 Hypothesizing-Experimenting and Positionality

Players have to make hypotheses about several different issues in the game, both as employees as well as representatives. As employees, players have to generate hypotheses about what kind of solar cell to build, how to build it, how to test it, and when to release it. As representatives, players have to generate hypotheses about what policies should be passed and how the budget should be allocated. Further, players have to continually hypothesize about what to say in conversations with different people. For example, in conversations with the manager, the player may try to find ways to convince them on increasing the wages to the workers. Such persuasion could involve reasoning with them based on several different rationales such as on economic grounds (worker burnout will stall company turnover), emotional grounds (families are struggling to live this way), medical grounds (workers are falling sick or being injured), or political grounds (this can damage the company's reputation). Players have to hypothesize how the manager might respond to each of these approaches and then test them.

A player's dual status as employee and representative has significant impacts on what hypotheses they come up with and decide to execute. For example, as employees of the company, players may want to design solar cells that generate the maximum profit, such as polycrystalline silicon solar cells. But these require mining silicon which, without proper protection can cause silicosis in miners, a harmful lung disease which can compromise the health of the local citizens. Conversely, as representatives of their communities they may aspire to design solar cells that are more environmentally sustainable, such as organic solar cells. But these are not as efficient and can compromise profit for the company.

Players' relative status to each other also impacts their hypotheses, especially about values. The game aimed to invite players to think of values as a form of hypotheses (JafariNaimi et al). The process of designing solar cells requires making hypotheses not just about technical values such as efficiency and reliability, but also sociopolitical values such as justice and sustainability: What is a solar cell, "just"? What makes solar panels "sustainable"? The fact that players come from different settlements, each with different problems and cultures helps enact values as hypotheses as part of the game mechanic. For example, justice for an engineer in Silicana may mean doing what is best for the environment, i.e., reducing pollution levels in the region through solar cells. In turn, justice for an engineer in Carbonia may mean doing what is best for their community, i.e., keeping jobs safe, even fossil-fuel ones. This differences animates matters in the game such as the design of the solar cell that both players have to agree upon and the selection of manufacturing processes for it.

The culture of the game environment also impacts players' ability to hypothesize and experiment. For example, players may notice that all other companies have a similar kind of solar cell (polysilicion) and attempt to disrupt the market with a new kind of cell (organic) that is cheaper and faster to produce, but less efficient. Testing this hypothesis means examining its performance in the market. Similarly, as a representative of Silicana, players may prioritize getting everyone employment first over getting them better working conditions due to a history of high unemployment and poverty in the settlement. This approach may even work out in the short term as those who were unemployed may be willing to endure any conditions as long as it means they get a livable wage. However, over time as more employees get used to this new life, the culture of the settlement may change to favor better working conditions, which will be reflected in the conversations players have with the workers and the kinds of policies they support. In this way, culture and hypothesizing/experimentation co-evolve with each other.

Finally, the strengths and limitations of the tools that players have access to significantly shapes their hypotheses and experiments. For example, when using the solar cell simulator, players have to hypothesize about what mathematical model of solar cells and semiconductors to use. For rough estimates, players can choose simpler models such as the drift-diffusion model and simple recombination-generation equations. For more precise calculations, players may select models that incorporate more factors and points such as the density-of-states models, dangling bond equations, and device degradation equations, which collectively can take longer to simulate solar cells. Such decisions will be predicated on the player's current situation and experience: do they have the time and money to be more precise? Do they understand how much time it might take?

Overall, what hypotheses players generate and experiment with depends significantly on their position, i.e., their status, culture, means, and experience. Simultaneously, these hypotheses and experiments have consequences both on their own position and on how the virtual world evolves. This helps situate inquiry in multiple different ways in the game.

7.2.2.3 Resolution and Positionality

There are several problems that players can investigate in the game that do not have definitive answers: How much more efficient can solar cells be? How much lower can their price go? Should we automate production? The in-game solar cell simulator gives players a significant amount of freedom in designing the form and shape of the cell. Similarly, the market-simulator

Exploration of such problems in the game is constrained partly by the goals that players set at the beginning of each year and partly by the capabilities afforded by their position.

First, the extent to which players are in a position to achieve their goals and the periodical deadlines for the year affects how they resolve such problems discussed. For example, if they are in a comfortable position in terms of time and money then they may spend more time trying to make the solar cell more efficient or cost lesser.

Second, the capabilities of their position also affect their approach to resolving such problems.

The player's means have a direct impact on their ability to resolve problems. For example, if the solar cell simulator cannot simulate 3-D designs, then players are limited to exploring design possibilities for 2-D solar cells. Conversely, the smaller design space can limit player’s position in other ways. For example, not being able to improve efficiency because of a lack of a 3-D simulator can potentially hinder a player’s attempts to improve the market-share as an employee or reduce carbon emissions faster (more efficient cell).

A player’s status at the intersection of employee and representative also affects their decision to resolve the situation. For example, if automation can cause significant job losses then players as representatives may decide to pass policies that restrict or ban it. Conversely, players’ resolution to such problems will affect their status, such as by reducing their chances of being re-elected the next year.

The culture of the game also significantly impacts resolution. For example, players may decide that exploring lower costs of the solar cell is a necessary endeavor given the tight market competition. Conversely, implementing such a cell can significantly reduce market-competition allowing the player to explore other questions.

Finally, the player’s experience matters to resolution as past failures and successes are integral to deciding if or when a problem has been resolved. For example, if the player spent a significant portion of their time and effort in an attempt to increase the cell efficiency to 28% but could not do so, they may consider the problem resolved. Conversely, if players sense that efficiency could still be improved then that will condition their experience the next time they design the cell.

CHAPTER 8. DISCUSSION

Summary: Drawing on the design case for *Solaria* in the previous chapter, I return to the research questions outlined in Chapter 1: a) Can we design educational environments that position students in technoscientific practice, at a distance from it? If so, how? and b) Can these environments be designed to support inquiry as a reflexive process? If so, how? I argue that the framework and digital games can collectively support the design of educational environments for teaching scientific inquiry as a reflexive process, but digital games can be constrained in doing so due to their procedural, evaluative, and artificial affordances. In response, I suggest three educational strategies that can help complement digital games for approaching the constraints posed by their affordances: critiquing games, re-designing games, and creating/prototyping games.

8.1 Introduction

Drawing on the case studies/design cases explored in the previous three chapters we can now return to the research questions:

- Can we design educational environments that position students in technoscientific practice, at a distance from it? If so, how?
- Can these environments be designed to support inquiry as a reflexive process? If so, how?

In this chapter, I address both these questions in relation to the framework as a source of design possibilities for such educational environments and digital games as a possible instantiation of such an educational environment.

Briefly, I argue that the framework can be effective means of approaching both of these questions as part of a three-fold process: using the framework to identify and recreate the structures of practice in educational environments, positioning students in relation to those structures, and creating activities that require students to draw upon their position in those structures to do inquiry, which organically supports inquiry as reflexive process. By explicitly drawing attention to such societal structures and positionality, the framework gives educators a systematic way of keeping in mind the situatedness of inquiry as they design their educational environments. For example, it can help educators think of questions they may not have thought of before such as: how can I design the environment to involve power dynamics in relation to problematization? Or how can students' hypothesizing and experimentation affect their means of doing inquiry; or how can the culture of students be brought into relation with the culture of practice? In this sense, the framework functions as both an analytical tool for comparing practice and education as well as a source of design possibilities for educational environments.

Digital games, however, have both significant strengths and constraints in relation to the above questions, due to their affordances. Overall, I argue that they can be effective if they employ the framework for their design and/or are complemented by other educational strategies (that ideally also draw upon the framework in some way).

On one hand, their procedural, evaluative, and artificial affordances enable educators to manifest design possibilities for teaching inquiry as a reflexive process that may not be possible through other means. Procedurality enables students to pursue inquiry within complex socioeconomic systems (like capitalism). The evaluative affordance enables students to simulate the pressures of real practice such as job security and environmental risks. The artificial affordance enables students to explore extreme or fantastical scenarios without real-world consequences, thereby enabling them to get a deeper understanding of the structures underlying scientific practice.

On the other hand, these very affordances can also constrain the simulation of inquiry as a situated practice. Procedurality can constrain positionality and inquiry by trivializing/quantifying social and scientific issues such as by parameterizing exploitation. The evaluative affordance of digital games can constrain it by predetermining the means of doing inquiry such as focusing attention on only a few variables for design. The artificial affordance of digital games can constrain it by distancing students from the risks and responsibilities of real inquiry as there are no real-world consequences of in-game failure.

Drawing upon these constraints, I suggest three ways of complementing digital games while still using them as part of the process of teaching inquiry as a reflexive process: critiquing games, re-designing games, and creating/prototyping games.

Critiquing games can use their limitations as an opportunity as students critically reason about what positionality and the structures of practice mean, how they are conceptualized in the game, and how it can be limited in relation to practice. The framework can function as a starting point for critique as well. For example, students can use an existing game such as *Phone Story* and critique it.

Redesigning games can support learning inquiry as a reflexive practice as it requires students to repeatedly imagine how different relationships between positionality and inquiry could play out and if they make sense in relation to practice. In this sense, it converts the constrained space of possibilities afforded by digital games into an open one, as students imagine and reimagine how science is or could be done.

Finally, building on the possibility that there may not be an existing game in the field that students can draw upon, students can aim to design new games (digital or physical) from scratch. This requires considerable research both into real scientific practice but also into science communication so that students can adequately engage other players in their game. This process has the dual advantage of supporting learning for both the makers and players However, it could take more time than may be possible for a course, unless a course is especially designed around it.

8.2 Addressing the Research Questions in relation to the Framework

Given the design possibilities afforded by the framework, I argue that we can use it to design educational environments to position students in practice at a distance and support inquiry as a reflexive process in them. The framework outlined several different design possibilities for positioning students in practice at a distance by providing a systematic analysis of positionality in structures of distribution, power, and culture and for supporting inquiry as a reflexive process by relating those positions to the processes of inquiry understood as problematizing, hypothesizing-experimenting, and resolving. The framework can aid in the process of designing such educational environments as part of a three-fold approach:

- creating rules within the educational environment that draw upon the structures of real technoscientific practice (such as structures of distribution, power, and culture)
- creating/assigning students to positions in relationship to these structures (in terms of their means, status, culture, and experience)
- creating activities that relate the positionality of students to the processes of inquiry (for problematizing, hypothesizing-experimenting, and resolving)

The first process is necessary as it creates a complex socioscientific environment that aims to be similar to real environments of practice. To create such an environment, the framework suggests at least three structures of practice that would be useful to consider as references: *structures of distribution* which are systems that govern people's opportunities to get resources and to reach places; *structures of power* which are rules and systems that decide what responsibilities people have and who they are responsible to, and *structures of culture,* which are the shared norms and principles that govern one's way of life. The goal of this process is to examine how such structures unfold in practice and recreate them in the educational environment. For example, in a classroom, these structures could take the form of rules such as creating a budget for classroom experiments and finding ways to get funding for it, assigning roles for role-play that recreate power dynamics of practice, and engaging the culture of the educational system or local community the class is a part of.

The second process is necessary as it positions student as practitioners in these environments. To create/assign such positions, the framework suggests four ways of understanding positionality in relation to the three structures of practice: as *means* (structures of distribution), as *status* (structures of power), as culture (*structures of culture)*, and as *experience* (all three structures + knowledge). All students' roles characters could also be designed in relation to these structures with their own circumstances, roles, and backgrounds that affect the gameplay.

Finally, the third process is necessary at it makes the processes inquiry—understood as problematizing, hypothesizing-experimenting, and resolving—*situated*. This is the main focus of the whole process and is what makes design explorations made using this approach different from other approaches that treat inquiry as a set of concepts or practices or do not engage students critically with the situatedness of inquiry. In doing so, it helps bridge a key research gap between science studies and science education outlined in Chapter 2.

Focusing on situating inquiry in this way can help surface new design possibilities not only for digital games in science education as I discuss below, but also science/engineering education in general. It can do this in at least two ways.

First, the framework helps systematize the design and analysis of science education environments that draw attention to material, social, political, and cultural issues and relationships that can be explored. For example, efforts to help students explore their local environment, such as in the Cheche Konnen project (Warren, Rosebery, and Conant 1989) can be augmented with deliberate reflections and engagement with structures of distribution, power, and culture. For instance, a future project could involve students in efforts to convince their local municipal officials for improving water quality. This could involve exploring identifying and collecting relevant data and means to make an argument, understanding the power structures in place, and involving the local community such as teachers and parents in the investigation. Their ability/inability to institute change would help surface key dynamics of access, power, and culture in the local community and its relationship to inquiry, which the framework can help in analyzing.

The framework can also serve as an educational tool in its own right that students employ when engaging in inquiry, such as to develop case studies. For example, while developing a case study of an engineering disaster such as a levee failure or bridge collapse, students can employ the framework to ask questions such as: What power dynamics shaped the bridge’s design? What means did the builders have access to? What was the culture surrounding bridge development and crisis aversion in that time? Students can also be invited to modify or enrich the framework with their own terms, or explore its limitations, which can further support reflexive examination about the societal structures underlying inquiry.

Further, the framework also aims to bridge a research gap within science studies for the systematic analysis of positionality and inquiry outlined in Chapter 2. However, there is more research needed here that draws upon specific feminist STS examples to substantiate and further enrich the framework.

8.3 Addressing the Research Questions in relation to Digital Games

Digital games have both significant strengths over other pedagogical approaches and are also constrained by their affordances in relation to positioning students in practice at a distance and support inquiry as a reflexive process.

8.3.1 *Strengths of Digital Games*

Digital games can be useful to some extent for teaching inquiry as a reflexive process if they are designed with the above three-fold approach by:

- creating game rules that draw upon the three structures of technoscientific practice
- creating characters that are positioned in relationship to these structures
- creating game mechanics that relate the positionality of those characters to processes of inquiry

This approach helps surfaces new possibilities for educational science games that systematically consider the environments of real technoscientific practice. As discussed in Chapter 2 (Literature Review), most digital games do not consider inquiry as a situated practice, and those that do, do not engage students critically with the structures of practice. The framework explicitly draws attention to these structures as part of the process of designing educational science games and also explores problematization as a defining feature of scientific inquiry. Summarizing the design possibilities explored in the case studies/design cases, digital games afford several approaches for teaching scientific inquiry that are rare within the space of educational science games such as:

- assigning players multiple conflicting roles: as practitioners and citizens (or as negatively affected by practice), as practitioners and managers, as all three together
- giving students' virtual practitioners different communal backgrounds that have to cooperate with each other, but can also conflict with each other

- exploring the role of systemic power structures and culture in shaping inquiry through the lens of in-game job security
- allowing students to explore the same systems from the perspective of multiple different models (such as the three different models of quantum physics)
- allowing players to modify the game, within the game
- giving players unreliable and limited resources (simulates uncertainty of tools)
- introducing different power dynamics between players such as through un-equal distribution of abilities (helps to critically examine positive feedback loops in real practice such as in hyper-capitalist cultures)

There are likely several other design possibilities I have not explored that depend on factors such as the subject-matter, the degree of fidelity to practice desired, the structures of practices and society used as references, and so on. All these possibilities allow digital games to teach students scientific inquiry in ways that are not feasible or practical without them.

8.3.2 Constraints of Digital Games

Now, despite affording these possibilities, digital games are also have several constraints as educational environments for teaching scientific inquiry as a reflexive process. In the process of designing *Solaria*, I found myself constrained by the very possibilities that supported their case for teaching inquiry—procedural, evaluative, and artificial affordances. In attempting to model real life systems, these affordances required some level of trivialization, predetermination, and distance from real practice that hindered the degree to which *Solaria* could theoretically support the learning of inquiry as a reflexive process.

While the focus of *Solaria* was on the electronics industry and electrical engineering, I posit that the constraints I encountered will be relevant to digital games designed for most scientific/engineering fields. This does not mean we should not develop digital games for teaching inquiry. Rather, it highlights areas of potential research and improvement for educational science games and keeping them in mind can enable us to better design/ complement digital games.

It is important to note that what I will be discussing here are the constraints of digital games for teaching scientific *inquiry* and not scientific *concepts*. There have been several successful digital games for teaching scientific concepts to students as the procedural, evaluative, artificial, and playful affordances of digital games align well with the procedural and mathematical nature of established conceptual relationships, such as the relationships between force and mass or voltage and current. Inquiry, however, is concerned with the *development* of concepts and is situated in material, sociopolitical, cultural, and historical structures of practice and society. Creating an environment that simulates these structures and the process of developing concepts in them is what I argue can be challenging for digital games.

8.3.2.1 Constraining Means

The procedural, evaluative, and artificial affordances of digital games constrain students' means as virtual practitioners by parameterizing tools and devices, predetermining tools that are available to students, and substituting hands-on experiences, respectively.

Procedurality, by reducing tools and devices to a set of parameters for in-game manipulation, has to make several approximations about them. For example, while the basic behavior of a solar cell can be modeled by a set of differential equations, real life solar cells are far more complex. In fact, most of the uncertainties and problems in professional practice arise precisely because real hardware behaves in unpredictable ways. A model of a solar cell may work perfectly in a simulation, but the real thing is rarely likely to follow that behavior beyond a limited degree. This is because many factors such as the history of conditions that a device has been in, the precise arrangement of all the molecules and atoms in it, and the relationships between those two, among many others cannot be simulated or modeled in a practical manner. Yet, such factors often play a key role in producing erratic or unpredicted behavior that can only be caught when testing real devices. This is why modeling and simulation can never replace real life testing. Consequently, an idealized or simplified model of solar cells in *Solaria* cannot emulate the fine details that create real life practical challenges and therefore limits inquiry to dealing with reductive models of these devices. Further, having the ability to simulate experiments in a virtual space may discourage educational institutes from investing in real equipment, which can ultimately be detrimental to students' learning of inquiry.

The evaluative affordance of digital games can constrain students' means by predetermining the tools available to students in the virtual environment. This predetermination is necessary so that the game can evaluate how the player uses those tools and integrate it into the game's progression. For example, the solar cell simulator in the game allows students to design the solar cell in relation to predetermined criteria such as cell efficiency, cost, and toxicity. These matter to the game's progression as the game can use them to calculate important in-game matters such as the market price of the cell and its environmental damage. If players were to add a new parameter to the solar cell simulator, such as durability, the game would have no way of meaningfully incorporating it unless players could modify its underlying mathematical models. Consequently, the game has to fix what tools and criteria players can engage with *a priori*.

The artificial interactions in digital games cannot substitute hands-on experiences of working with real equipment. For example, while conducting inquiry in a virtual space is advantageous when considering safety, learning to deal with unsafe environments is also essential to doing inquiry in practice. This includes matters such as developing and following safety protocols, designing experiments to minimize unsafe consequences, and developing appropriate response strategies to emergencies. If the proper safety means cannot be acquired, inquiry must be redirected appropriately. This too, is part of learning how to do scientific inquiry.

8.3.2.2 Constraining Status

The procedural, evaluative, and artificial affordances of digital games constrain students' status in the virtual world by parameterizing roles, predetermining responsibilities, and lightening its weight on students, respectively.

Procedurality can constrain the simulation of status and power structures by parameterizing one's roles. Practitioners play multiple roles within and beyond the lab—as experimenters, analysts, friends, mentors/mentees, and caregivers. Parameterizing these roles entails reducing them down to quantifiable/discrete tasks that can be measured by game, such as moving objects from one location to another, making decisions on a dialogue tree, and spending game-time with another character. This can significantly diminish these roles and their effect on simulated practice.

The evaluative affordance of games can further constrain the simulation of status by predetermining the player's responsibilities and progression. For example, in *Solaria*, the game must predetermine conversations between players and NPCs. Consider the conversational options for a player when they talking to a factory manager to convince them to change their policies and improve worker conditions are: "How much will you pay workers?" and "What is your factory policy towards sick laborers?" Such choices may be necessary to make sure the game can evaluate the player's response. Without them, a player may enter whatever they think and the game may not know how to respond meaningfully. However, although these questions may help players understand the logistics of the company, they may not help them learn how much it "cares" about its workers. This is because students cannot ask more specific questions such as: "how are mothers paid in this facility when pregnant?" or "what would you do if a worker had cancer?" This problem persists even if pre- written dialogues were replaced by an AI-based chatbot where players could type in whatever they wanted. This is because an AI chatbot (at least currently) cannot understand the nuances hidden in the details of conversations. For example, asking a factory manager "how are mothers paid in this facility when pregnant?" is quite different from telling them a story about their own underpaid mother in another factory and waiting for their response. Both will likely elicit different responses and give different insights about the company's stance on "caring" for their employees. Predetermined interactions, whether scripted or algorithmic, cannot enable such nuanced inquiry into values

Artificiality constrains the simulations of status because power and responsibilities in virtual worlds do not hold the same weight as responsibilities in practice. All decisions in real life inquiry have an impact on and are affected by real-world risks and the responsibilities that one holds. For example, one may not risk challenging their principal investigator or their funder for fear of risking their own funding. Conversely, one's responsibility to a society as a citizen may give them the courage to stand up as a researcher against design practices that disregard the company's exploitative labor practices. However, being situated in fictional game-worlds is unlike any of these things as there are no real-world consequences. Players can easily break the illusion of being situated by doing things they may have never done in real life, such as intentionally designing a bad solar cell and sending it for manufacture, just to see what would happen, without any real-world consequences.

8.3.2.3 Constraining Culture

The procedural, evaluative, and artificial affordances of digital games constrain the simulation of culture and background in the virtual world by reducing it down to an aggregate, predetermining cultural relations, and distorting it by mediating it through the culture of game design, respectively.

Procedurality limits inquiry as a situated practice by trivializing the culture and background of inquirers as a sum of measurable characteristics. People are more than an aggregate of demographic qualities such as age, gender, and race. These qualities are defined by dynamic relationships with our social, political, cultural, and historical positions. Any attempt to model people as a set of characteristics, such as by deciding what parameters constitute a male and what constitutes female risks perpetuating stereotypes and being discriminatory in its own right. However, avoiding such decisions by removing issues such as gender and race from the picture entirely is also problematic as it can make it seem as if these are irrelevant to inquiry, which is false and disregards the situated nature of inquiry. A middle-solution may be to use analogous characteristics through different character designs that focus on qualities such as shape and size. This can help students understand that inquiry is situated. However, since it depends on a quantifiable relationship between these characteristics and the situations in the game, such as if person is X shape, then they will receive Y response for a given situation, it still trivializes how our situatedness relates to inquiry in the real-world.

Further, the evaluative quality of games can exacerbate or create such stereotypes by predetermining a player's progress in the game based on their parameterized culture and background. For example, if the game predetermines that a black character will face additional hardships than a white character, this can be problematic as it embodies a generalization of the struggles faced by black people, rather than engage students with a nuanced and situation-specific approach. In contrast, situatedness in real-world inquiry is a function of the complex social relations of the inquirers that cannot be predetermined or generalized as our experiences in the real world are not pre-determined on the basis of our culture and background.

Finally, the artificial affordance of games produces tensions between the culture that it is trying to simulate and the culture of conventions surrounding simulation itself. For instance, in the game *Solaria*, students do not experience the culture of scientific practice, they experience a representation of the culture of scientific practice mediated by the culture of games. This can be seen in the idea of job security in *Solaria*. The game needs to inform players of their job security in some way, such as through a meter or in-game dialogue with their manager. Not telling students such an important game parameter as not good game design practice as players can lose without knowing why. However, in practice, job security is not known to the employee as it is not a mathematical variable. It depends significantly on the culture of the company as well as the social, economic, and political situation. The ambiguity of job security shapes practice significantly as employees tend to tread more cautiously. In the game however, this is just a matter of gauging the meter or dialogue change. This cultural convention of using meters or discrete events in games does not therefore align with the culture surrounding job security in practice.

8.3.2.4 Constraining Experience

The procedural, evaluative, and artificial affordances of digital games constrain students' experience in the virtual world as in-game experiences by reinforcing quantification, binding progression, and being sensorially distant.

Procedurality constrains experience as by binding it to proceduralizable content. Framing social, emotional, and cultural issues as quantifiable problems can perpetuate capitalist, neoliberal, that seeks to treat people as resources and issues as equations, which is precisely what reflexivity seeks to challenge.

The evaluative affordance of digital games further constrains player's experiences as practitioners by binding their progression. There are only a predetermined set of outcomes that students can experience for every action they take in the game. For example, the effect that a solar cell has on society and players in the game has to be predetermined directly as cause-effects conditions or as equations. In either case, as there is no social/societal model that can predict the impact that such a device can have on society, there will be several consequences that the game inherently does not allow students to explore.

Building on this matter, the artificial affordance of digital games inherently distances students' experience in the game from that of the real-world. Hands-on experiences with tools, people, and cultures cannot be replaced (at least not yet) by virtual experiences. While there are ongoing claims about how "immersion" in virtual worlds can catch up to or even exceed real world experience in terms of our senses (Bailenson 2018), it remains to be seen. Currently, digital games cannot recreate the same sensory immersion as real life.

8.3.2.5 Constraining Problematization

The procedural, evaluative, and artificial affordances of digital games constrain problematization in the virtual world by quantifying social problems, predetermining criteria for those problems, and distancing students from the risks/responsibilities of those problems.

While procedurality is essential to simulating the game-world, it also trivializes problems in it by parameterizing and quantifying them. This constrained the ability of the game to support problematization. For example, semiconductor miners in Africa [54] and factory workers (especially women) in East Asia have to endure harsh labor conditions and often contract chronic illnesses that can destroy their lives [46]. No amount of parameterization or quantification can do justice to their lived experiences. Simulating their situation, such as by using meters to represent their mental health, inadvertently reduces problematization to a matter of trade-offs: How much of their mental health can I risk reducing in order to lower the cost of the device? What are the dialogues I need to say to them in order to get them to do what I want? Such parameterization and goals not only trivialize problematization as a process of inquiry, but also caricaturizes, or worse, dehumanizes those who have been exploited and marginalized in real life, further exploiting their condition in the name of education or entertainment. Yet, not involving the conditions of these workers at all when engaging with semiconductor devices such as solar cells risks reinforcing the notion that social issues and problems are irrelevant to the problems of scientific inquiry. Given that other digital media such as simulations as well as non-digital games also involve procedurality, this limitation can also be extended to them.

The evaluative nature of games further limits problematization by requiring inquirers to fulfil predetermined criteria in order to progress in the game. In contrast, inquiry in practice requires deciding what these criteria should be. While I attempted to make the game open and not "give" problems to students to solve, exploration and experimentation in digital games can never really be open-ended as it cannot capture the vast space of possibilities of the real-world. For example, the problem of persuading characters in another settlement to support you is limited by choices about such conversations that the designer has baked into the script or algorithm. These choices are only a small fraction of possible conversations that could be had in a similar real scenario, which constrains the problem space significantly. This greatly reduces the scope of what can be said in such conversations, limiting opportunities for students to learn how to conversations and discourse is integral to real world problematization and inquiry more generally.

Finally, while the artificial quality of games is necessary to distance students from the risks and responsibilities of real research before they are ready, that is also its key limitation. Distancing students from the risks and responsibilities of real-world problems can constrain learning problematization as those risks and responsibilities are a key part of what makes situations doubtful. For example, the game allows students to make radical decisions about the design of solar cells and see their effects on society for the sake of experimentation. Such experimentation would not be possible in real-life situations where even the smallest design decisions can have significant personal, social, political, economic, and ethical risks and implications. Consequently, those risks and responsibilities must become part of the limitations of experimentation when framing real-world problems. While the fictional quality of games can allow students to assume some of those risks virtually, those risks cannot bear the same weight of responsibility as risks in real life.

8.3.2.6 Constraining Hypothesizing-Experimenting

The procedural, evaluative, and artificial affordances of digital games constrain hypothesizing-experimenting in the virtual world by limiting hypothesizable variables, predetermining outcomes, and allowing students to "fail safely".

Procedurality constrains hypothesizing not just about technoscientific issues such as by limiting the variables that students can hypothesize about, but also about values in inquiry, by reducing values to a set of parameters. Values such as justice, equality, democracy, diversity, inclusion, and sustainability cannot be precisely and universally defined, let alone be reduced to quantifiable variables. Yet, digital games need to encode some definition of such values through their design, whether explicitly or implicitly, which limits opportunities to hypothesize about them. For example, the game needs to make some judgement about what it means for the environment to be considered "sustainable." How much does pollution need to go down before the people in the settlements start to think of the region as environmentally- friendly? How is pollution measured? Is being pollution-free the same as being sustainable? Designers need to answer these questions in some form or the other, whether it is encoded in the storyline of the game, the character dialogue, or the graphics. This is because the game must evaluate and respond to the player in a way that progresses the narrative or game experience, which requires observing and judging values in a predetermined fashion. This limits opportunities for students to hypothesize what values such as sustainability could mean as all that matters to gameplay is what it does mean within the game-world. For example, students may notice if the narrative plot moves away from the topic of sustainability, or if people in a settlement say certain things ("my asthmatic daughter hasn't coughed in months!") or the map looks greener, and accept that this is what sustainability is or should be. In this way, students may habituate themselves to a reductive understanding of values and their relationship to inquiry.

The shortcomings of the evaluative affordance in relation to both hypotheses and experiments are also evident as both can only have predetermined outcomes. For example, hypothesizing and experimenting with work policies of one's settlement in *Solaria*, say by increasing the minimum wage, will result in two specific outcomes: lowering of the company's profits, improvement in the worker's lives (increasing their likelihood to vote for the player). However, in practice, there would be far more possible outcomes: the company may lobby to change the policy back, some workers may argue that the increased wage is still not enough to sustain them, it may lead to inflation in the settlement's economy by raising prices and cancelling out the effect of increased wages, and so on. While it is possible to add more and more of these possibilities in some quantifiable way, these outcomes cannot capture the rich space of possibilities in the real world.

The artificial affordance of digital games constrains hypothesizing-experimentation by allowing them to "fail safely," i.e., to make mistakes without real-life consequences (Barab, Gresalfi, and Ingram-Goble 2010). This is a double-edged sword. On the one hand, failing safely is essential to learning the subject-matter and examining it critically. By exploring different hypotheses and experiments, students learn to think about situations in a wide variety of ways. For example, in *Solaria*, the possibility of designing several different kinds of solar cells and seeing their social, political, and economic consequences allows students to learn and reason about them in a way that is difficult to reproduce through other ways. At the same time, however, it may not be suitable for learning *inquiry* as it is done in practice. This is because real world inquiry has real world consequences, which (as discussed above) significantly impact the ways in which one conducts inquiry in the first place. Real engineers carefully need to explore which design of solar cells they can release before they release them, as opposed to students, who have more freedom to do so in the game. If students could not "fail safely" then this tension would not matter as they would always need to carefully consider all the consequences of their actions. Now, if in-game problems like job security mattered more in the real lives of students, such as by compromising their classroom grade, then it might encourage students to be more careful about the hypotheses they develop and experiment with. But that has requires stepping *beyond* the game's boundaries to work. Within the game environment, the consequences simply cannot be as serious as the real world.

8.3.2.7 Constraining Resolution

The procedural, evaluative, and artificial affordances of digital games constrain the process of resolution by parameterizing socioscientific problems, predetermining goals, and distancing students from real-world causes and consequences.

The procedural affordances of digital games constraints the process of resolution because of the same reason it constrains problematization—parameterization. If problems are considered only in parametric/quantitative terms, then so will their resolutions. For example, *Solaria* by framing the problem of worker exploitation as a problem of worker sentiment (i.e., their chances of voting for them in the next election), the resolution to the problem involves achieving a target vote count. The whole process therefore takes on a mathematical form where players aim to calculate how much they afford to exploit the workers without losing their votes. This is exactly the opposite of what inquiry as a reflexive process should aim to do.

The evaluative affordance of digital games can constrain the process of resolution by nudging students towards predetermined goals. For example, “surviving” is a key goal of *Solaria* and requires that students not getting fired in the game. This goal can affect how students decide when a problem is resolved. For instance, there might come up a point in the game where students calculate that they can afford to use toxic materials in their solar cell because the game will end before these toxic materials can leak into the environment within the game time. That will enable them to survive being a representative while still using toxic materials for solar cells. This is unlike practice as toxic materials in real life are not time-bound.

The artificial affordances of digital games constrain the process of resolution for the same reasons they constrain problematization—a lack of real-world factors. Students do not need to worry too much if their efforts at making a 29% efficient solar cell in the game fails as the only real-world resource that they spend on it (that matters to them) is their time. In practice however, this failure could represent significant sunk costs, both economically and politically. Consequently, students can afford to delay resolution in the game far longer than they can in practice. This is not helped by the fact that artificial nature of the game allows them to do things not possible in the real world such as speed up time which further differentiates how students engage in resolution in the game compared to practice.

With these constraints in mind, I discuss some possible strategies for supplementing digital games so in the following section.

8.4 Strategies to complement digital games for teaching scientific inquiry

While there may be several educational strategies to complement digital games such as class discussions about scientific practice, field trips, interviews with real practitioners, reading papers/books on the social studies of science, and participating in real scientific practice. However, I discuss strategies here that still involve games in some capacity as it allows us transform their constraints into opportunities for learning: critiquing games, redesigning games, and designing/creating games

8.4.1 Critiquing/Discussing Games

Critiquing educational science games can use their limitations as an opportunity to help students critically reason about what positionality and the structures of practice mean and how they are conceptualized. The framework can function as a starting point for critique as well.

For example, students can explore the game *Phone Story* (Molleindustria 2011) which is a satirical game that invites players to be the oppressor in all stages of the life-cycles of the iPhone: whipping slave mining laborers in Congo, catching factory workers in China who attempt suicide, throwing iPhones at mindless consumers for money, and disposing waste iPhones to release hazardous chemicals and gases in India/Pakistan.

8.4.2 Redesigning Digital Games (Digitally or Physically)

The process of (re)designing games involves changing or creating features of the game such as its game mechanics, game narratives, characters, goals, and rules. This can be done at a conceptual level (such as a design document), through physical paper prototypes, or even by "modding" the game.

What makes this approach particularly useful is that it requires students to repeatedly imagine how different relationships between positionality and inquiry could play out and if they make sense in relation to practice. In this sense, it converts the constrained space of possibilities afforded by digital games into an open one, as students imagine and reimagine how science is or could be done.

This approach can be implemented practically as students do not have to develop a new game from scratch and can simply re-conceptualize the game. At the same time, the primary challenge is that there may not be games on science or scientific inquiry in their field to serve as starting points. In that case, students could begin with other options such as documentaries, movies, science fiction, or publications (provided by the instructor) and attempt to craft *them* into games.

8.4.3 Designing New Games (Digital or Physical)

Finally, building on the possibility that there may not be an existing game in the field, students can also attempt to designing new games (digital or physical) from scratch. This requires a significant amount of research on how real scientific practice is done, how it is situated in the structures of practice, and how one's position in them. Such research could help students learn significantly about the situatedness of inquiry. At the same time, it could take more time than may be possible for a course, unless a course is especially designed around it.

CHAPTER 9. LIMITATIONS AND FUTURE WORK

Summary: In this chapter, I explore the primary limitations of this study as well as the framework and suggest directions for future work. The study has three key limitations: the game I designed using the framework was not formally developed and tested, the constraints of the affordances of digital games I outlined may not be generalizable, and the game's design did not incorporate the context of use in education. The framework has two key limitations: it is untested for educational effectiveness and its terms can be confusing Drawing on these limitations and the strategies of complementing games in the previous chapter, I outline three directions for future work in this area in relation to science games, science education, and science studies.

9.1 Key Limitations

9.1.1 Limitations of the Study

The primary limitation of this study is that I did not formally evaluate my framework, i.e., I did not develop an educational environment using the framework and evaluate students to see if they learned inquiry as a reflexive process. This is a limitation in terms of testing the effectiveness of the framework. However, I did explore the design space afforded by the framework, which surfaced new ideas for digital science games designed to teach inquiry.

Further, reflections on one game's design cannot be generalized. There may be game design techniques that I am unaware of or those that are yet to be developed that might be able to do more justice to the four dimensions of inquiry. Further, the choice of technical subject-matter makes a significant difference to our analysis. For example, the procedural affordances of games may not be as problematic an issue when designing games to teach "programming" as a situated, value-laden, unbounded process of problematization because programming is fundamentally about procedurality.

Third, my analysis focuses purely on the design of a digital game independent of the circumstances in which it may be used. Real games are not used in a vacuum but are instead designed to be used as part of classroom environments. However, I defend my decision to focus solely on the design of the digital game on the grounds that my goal was to highlight the limitations of digital games in a way that educators can be mindful of them when incorporating them into their curricula or lesson.

9.1.2 Limitations of Framework

There are two key limitations of the framework: it is untested as an evaluative tool, and the terms it uses are highly entangled with each other.

The primary limitation of the framework is that the design possibilities it helps generate have not yet been tested for educational effectiveness. The ultimate goal (beyond this dissertation) is to be able to *create* effective educational environments that actually support students in learning inquiry as a reflexive process, not simply to generate ideas for such environments. In this regard, the framework is still yet to be tested.

However, testing the framework is a difficult endeavour as there are several local factors that can complicate such studies such as the specific design features of the environment, the history of the class, the relationship between the educator and students, and systemic administrative pressure to perform on standardized tests. Consequently, even if an environment designed with the framework in mind “failed” to teach inquiry as a reflexive process, it would be difficult to point the cause for that failure on the framework. Conversely, if such an environment “succeeded” in teaching inquiry as a reflexive process, that too would be difficult to point to the framework for. The highly localized nature of education therefore makes it difficult to evaluate.

The second key limitation of the framework is that the terms it uses to describe positionality—means, status, culture, and experience are all highly entangled. For example, one’s status is intertwined with the culture of their workplace and their prior experiences while also affecting their means. These entanglements can make it difficult for educators to understand if they are using the framework well: “Isn’t simply focusing on means covering all the aspects?”

To this, I would respond by stating the framework is not meant to be used simply as a checklist to “cover” all the bases. While it can certainly help educators keep in mind different ways of understanding positionalities, it is meant more to be a source of design possibilities. In that sense, the way to use the framework is to ask questions such as: “If we are to focus on the status of practitioners, how can it inform the others?” or “How can resolution of inquiry affect the culture of the system” It is <u>not</u> to ask questions such as “Have we covered all possible combinations?”

9.2 Future Work

Building on the complementing strategies I outlined in the previous chapter and the limitations highlighted above, there are three key directions for future research that can build on my work: in science games, science education, and science studies.

9.2.1 Science Games

If we focus solely on the design affordances of digital science games, the constraints highlighted in the previous chapter can serve as staring points for exploring new designs. How can digital science games parameterize issues that are inherently difficult to parameterize without quantifying/trivializing them? How can science games be predetermined and yet open-ended at the same time? How can science games be more "real" while still being artificial?

A starting for exploring such paradoxical problems can be to observe games designed to highlight issues of social justice. Games are an increasingly used space for exploring issues of social justice. For example, games such as *The Coming Out Simulator* (Case 2014) and *Gone Home* (Fullbright 2013) explore LGBTQ issues, without arguably trivializing them. Can educational science games learn from their designs to promote effective inquiry that meaningfully incorporates issues of social justice? For example, some games such as *Phone Story* do engage students with social justice issues related to electronics, although they do not promote inquiry into them. Is there a more meaningful way to redesign the game to support inquiry?

Moreover, this process and dissertation highlights an important question that has often been taken for granted in the educational game space. *Should* we be designing digital games to teach scientific inquiry? Is it worth the effort to make a game with an extensive open-world for promoting inquiry, when other means such as those that utilize digital games in a more limited way but supplement them with additional activities can do the same job? If digital games are worth exploring for teaching scientific inquiry, then what kind of digital games should we be aiming to make?

9.2.2 Science Education

Building on that last point, the framework opens up a space in science education more generally, with or without games, as was explored in the discussion section.

As the framework can inform the design of any educational environment that aims to teach scientific inquiry, there is a vast space of research yet to explored in a variety of contexts: How can the framework inform design in mechanical engineering education compared to biology education? How can the framework inform the design of an educational environment in India compared to the US or Europe? How can the framework be employed to design informal educational spaces such as museums?

9.2.3 Science/Engineering Studies

Finally, the framework can augment current approaches to feminist science studies, STS, and engineering studies by providing a systematic means of analysing the structures of practice and their relationship to inquiry. For example, it can help researchers who study technoscientific practice keep in mind how both the practice that they are studying and their own process is entangled in material, sociopolitical, and cultural structures.

Further, the framework can be employed to help find gaps in research on technoscience. For example, while feminist science scholars have long demonstrated how sociopolitical values affect the life sciences and biology, they have yet to conclusively show how such values affect the subject-matter of physics, aside from the names and metaphors used to describe phenomena. The framework can be used as a starting point for such investigations, inviting explorations into the means, status, and culture of practice and in showing their connection to the development of subject-matter, surface the underlying values and assumptions of physics.

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