“WITHOUT FAILURE, IT’S JUST NOT RESEARCH”: INVESTIGATING UNDERGRADUATE STUDENTS’ EXPERIENCES OF SCIENTIFIC FAILURE IN RESEARCH SETTINGS

by

SANDHYA KRISHNAN

(Under the Direction of Georgia W. Hodges and Julie M. Kittleson)

ABSTRACT

Failure seems to have various meanings and manifestations in diverse contexts. Students hope to avoid failure because of the potential consequences towards their aspirations, yet scientists speak of failure as a typical part of the scientific experience. Because of its consequential impact for students, particularly for undergraduate STEM attrition, the experience of failure needs to be better understood in its different contexts. Situated learning experiences like undergraduate research offer students the opportunity to learn through participation in the scientific community of practice. This dissertation explores how undergraduate students define and understand the experience of scientific failure in the context of natural sciences research settings. Students were recruited through surveys to undergraduate researchers, where respondents could opt to participate in an interview. The study was guided by hermeneutic methodology. Hermeneutic analysis revealed that students saw failure as particular outcomes, responses, or as a process. These were not mutually exclusive definitions as students sustained multiple conceptions of failure simultaneously. Students also rationalized failure methodically, by admitting their inexperience in the research setting, experiencing some emotional distress, recognizing specific skills for managing failure, and finding an opportunity for learning. Students responded to failure with begrudging acceptance, based on their perception of failure as a part of the scientific process. Hermeneutic analysis through the community of practice (CoP) framework demonstrated that scientific failure could involve student participation within the facets of (1) domain through epistemic engagement, (2) membership through mentorship, and (3) practice through critical reflection of the process. This work supports arguments for allowing broader participation of students in undergraduate research and highlights the key role of mentorship in these spaces in facilitating students' sense-making of the failure experience. While this work cannot make any conclusions about students' experiences of failure in the undergraduate science classroom settings, it establishes that this meaning-making experience can be valuable to students as a means of achieving a science epistemology. Translating this learning into the classroom will require investigating how metacognitive training utilizes reflection as an epistemic practice and how students' identities impact their perception and experience of failure.

INDEX WORDS: Failure, Science Education, Undergraduate Research Experience, Hermeneutic Phenomenology, Community of Practice framework

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DEDICATION

I dedicate this dissertation research to both my grandfathers, Ramaswamy Santhanam and Santhanam Krishnamachari who, among everything else they were known for, were also known as the best of teachers and are remembered for their teachings. Ramaswamy Thatha who lives life exuberantly; who continues to find joy in everything he does and is the very definition of a lifelong learner; who has a better grasp of digital technologies in his 80s than I do. Santhanam Thatha, our mischievous yet saintly grandfather whose imparted wisdom were as precious as pearls in the sea; who read constantly to improve himself; who found such immense joy in sharing stories and in listening to them.

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I dedicate this to all those who fail and make that failure a journey of discovery.

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detailed work that scholarship entailed, but how to delegate equitably. I learned what it looks like to carry yourself as a powerful and confident female and to lead with humility. You also knew my style of working before I did – that I would get lost in the weeds of hermeneutic work, and firmly pulled me back from the precipice of many an investigative abyss.

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CHAPTER 1

EMBARKING ON A DISCOVERY OF FAILURE

Forward

"Failure" is a complex concept, with connotations that seem to differ based on the settings and situations that the word is used to describe. While this can be dismissed as a question of semantics, the reality of failure is deeply consequential to those who experience it. Understanding how students experience failure and the meaning they make of their experiences can provide educators the tools to support students in managing such experiences. By examining failure within scientific research settings, we can learn what students understand as failure in this context and how they process scientific failure as an experience. This dissertation explores the undergraduate failure experience in the scientific setting and the implications of that experience for student learning. In this introductory chapter, I share my rationale for studying this phenomenon and the questions I was driven to ask in my work.

A defining feature of qualitative research is the recognition of personal investment in the author's investigative journey. I begin this chapter by recognizing that my desire to study failure stemmed from both personal and professional reasons. Through my formative educational experiences which culminated in an undergraduate degree in Neuroscience, I considered myself both a student and a prospective scientist. During the years I spent in medical school, I experienced many assessment-oriented failures which forced me to recognize the debilitating nature of my identification as a "good" student. I saw that my entire sense of self was very heavily tied to my identity as a student, whilst my aspiring ambitions in science were a negligible aspect of my identity. As I struggled to reconcile my failure experiences with future aspirations, I began work in a laboratory that focused on cardiac neurophysiology, led by esteemed researchers who were passionate about medical education. Engaged in the practices of that lab, I began to associate myself more with the scientific community. Through that work and the thinking that the professors mentored me through, I began to reconsider how my academic failures impacted me and how the experiences of failure in the lab setting renegotiated what it meant to fail.

As a graduate student, I saw undergraduate students struggle with academic failure as well. When working on a research project in an undergraduate chemistry course that was designed as a preparatory course for general chemistry, I saw male and female students disproportionately represented in the preparatory course as opposed to the general chemistry course. While enrolled in the general chemistry course, students had the option to switch to the preparatory course if they performed poorly on the first exam of the semester. In the semesters that I studied the course, I observed that after the first exam, approximately four times as many females chose to switch to the preparatory course as males, though the course instructor indicated that both genders performed similarly on the exam (by looking at the grade distribution by gender). I recognized students' experiences with academic failure were similar to mine in how they could destabilize perceptions of oneself and one's capabilities and considered pursuing study on the gendered disparity in responses to academic failure and its impact of identity. As I read into the literature however, I realized that the reason I found responses to failure fascinating was because I considered the academic failure experience as inherently a learning process. It took further reflection to realize this belief was inextricably tied to my understanding of and background in science. As I was able to re-conceptualize what it means to fail after engaging in authentic scientific practice in a laboratory setting, I wondered if the same was true for other undergraduate students. This was the moment I decided to shift from a study of failure and identity in science classrooms to instead exploring the scientific failure experience.

I recognize that my drive to explore this research topic is rooted in a personal curiosity of the subject as well as a personal history with failure. Any work I do in this area is also driven by a desire to transform undergraduate science education to allow more affordances for academic failure such that it does not negatively impact students (i.e. emotional, psychological, aspirational repercussions), perhaps by transforming experiences of academic failure to look more like what I conceived of as being an experience unique to scientific settings. I had understood the former as being personally devastating, and the latter to be enlightening both personally and professionally. To bridge that change in experience, I needed to first explore what it is that uniquely characterizes the scientific failure experience. I aimed to study undergraduate science students' experiences with failure in the research setting through a hermeneutic phenomenology lens. In the following paragraphs, I explain why I believed this topic of study imperative and why a hermeneutics perspective fit this inquiry.

In becoming and being a scientist, the experience of failure is one well-recognized as part of the learning and investigative process (e.g. Simpson & Maltese, 2017; opinion pieces from Akinwande, 2018; Parkes, 2019; Mehta, 2019). While scientists have acknowledged experiences of failure as critical to the profession (e.g. Firestein, 2015; Kuhn, 2012), science education literature has yet to grapple with how that understanding develops. Exploring individual experiences of failure can yield rich descriptions of the phenomenon such that we can better utilize failure to inform how we approach students' learning. Because undergraduate students (pursuing undergraduate study in STEM disciplines) hover in the space between learning science and being scientists, their understanding of the failure experience in science can provide unique insight into whether failure has a role in the scientific process. Though they would be stepping into settings particular to the communities of science, they come from the assessment culture entrenched in educational systems and so their associations with failure may require them to reflect more deeply on how to separate scientific failure from academic failure. As such, studying undergraduate students situated in the scientific setting who have experienced failure in that setting allows us to fully and distinctly comprehend the phenomenon that is scientific failure. A detailed study of experience falls under the purview of hermeneutic phenomenology, requiring analysis of the phenomenon in a way that does not essentialize or boil down the experience, but conveys the complexity of it. Through the descriptions that the participants provide, I planned to (1) categorize the experiences described by undergraduate students; (2) examine the experiences of scientific failure through hermeneutic analysis; and (3) examine how these experiences of scientific failure relate to understanding of science practices.

Problem Statement

In science education at the undergraduate level, we aim for both scientific literacy and to better equip students to enter into the spaces of scientific disciplines. Recent standards for both K-12 and undergraduate science education document this vision for science education to reflect the ideals and practices of the scientific communities (e.g., American Association for the Advancement of Science [AAAS], 2011; National Research Council [NRC], 2003; NRC, 2012; Organisation for Economic Cooperation and Development [OECD], 2017). These guidelines call for more student-centered learning experiences rather than the didactic transmission of information. *Vision & Change* (AAAS, 2011), a guiding document for undergraduate life sciences curriculum, states that undergraduate biology education should incorporate authentic activity such that students can experience knowledge generation in science. As such, students' science education experiences should include those that encourage epistemic thinking – activities and thinking that scientists engage in in the process of generating scientific knowledge and then incorporating that knowledge into existing frameworks of thinking. Undergraduate science education has attempted to address this through the introduction of laboratory experiences that allow for different levels of instructor facilitation – from guided inquiry experiences to more open inquiry. Researchers debate on the extent to which these experiences reflect authentic scientific activity (e.g., Brownell et al., 2012; Auchincloss et al., 2014), but on the whole, undergraduate science education moves slowly towards a more student-centered model of instruction that attempts to engage in more authentic scientific activity, both within the classroom and laboratory settings (Freeman et al., 2014; Wieman, 2014).

Though student experiences are moving towards the inclusion of authentic, evidence-based practices in science education, STEM undergraduate education continues to face a problem of attrition. STEM students, even high-performing ones, leave prospective majors in STEM disciplines for various reasons: poor grades, failing courses, the perceived quality of instruction in the introductory courses, feeling a lack of belonging or an unwelcome atmosphere (Chen, 2013; Chen, 2015; President's Council of Advisors on Science and Technology [PCAST], 2012). The PCAST report called this "a national crisis in STEM teaching" (2012, p. 6) stating that unless we found new ways of encouraging students in STEM, we would be facing a critical dearth of graduates to populate the STEM workforce in the United States. In response, educational research has turned to new ways of tackling learning and instruction so as to improve retention of students in the sciences (Watkins & Mazur, 2013; Freeman et al., 2014).

I would like to propose an alternate route to addressing this problem – one that takes a deeper look at science at its most fundamental level through the purpose and philosophy of science functioning as a human endeavor. Science education is not science – a distinction that is critically important for the case I would like to make. Years of science education across primary, secondary, and undergraduate science education attempt to inculcate novices into the modes of practice, thinking, and values of the community that is science. But embedded as it is within the system of education, science education has particular practices that may not translate well to science. In particular, the culture of assessment means that students spend an inordinate amount of their time in science education demonstrating their grasp of the products of scientific knowledge, and when students experience failure, consequences are often severe, both motivationally and academically (Layton, 2015; Nelson et al., 2013; Labaree, 2005; Busato et al., 2000; Weiner, 1976). Yet those who become scientists (not necessarily those who do well academically in science courses) tout experiences with failure as an expected part of the discovery process in generating scientific knowledge (Firestein, 2015), asserting that failure is essential to developing a creative mindset (DeHaan, 2009; Estabrooks & Crouch, 2018) and integral to their development as scientists (Simpson & Maltese, 2017). These discordant depictions of failure in the literature call for a deeper study of the experience.

Hermeneutic phenomenological inquiry allows us to deeply investigate lived experience, to examine all of *what* makes a phenomenon a uniquely human experience, and yet that contains common elements to which we can relate. It "orients to the meanings that arise in experience" (van Manen, 2016, p. 38) and "aims to express, in rigorous and rich language, phenomena and events as they give themselves" (p.61). While a broad analysis of undergraduates' failure experiences could yield detailed descriptions of failures that look to be of all shapes and sizes, a hermeneutic phenomenological approach could provide a more incisive interpretation of the scientific failure experience for undergraduate science students. Exploratory as this investigation is, *how* an experience is described will only be an initial step to detailing *what* that experience is. Through hermeneutic phenomenology, I hope to take the first steps to understanding the failure experience such that future studies can examine its role in classroom settings. Experiences with failure – at least, scientific failure – can be considered a form of epistemic reflection on the scientific process. As a disciplinary view of epistemology deals with the nature of knowledge within scientific communities (Kelly et al., 2012), reflection on the experiences of failure may generate epistemic understandings of science unique to the experience. If so, this could aid further attempts to utilize epistemic thinking in science education.

In order to learn about the potential role of the failure experience in developing student understanding and learning of science, I propose investigating undergraduate students' failure experiences in authentic scientific contexts. As undergraduate science students straddle the line between the scientific communities of practice and formal education, they are often expected to gain experience in actual research settings, not just participation in laboratory courses. This makes them well-placed to experience scientific failure, while the notion of assessment-oriented failure remains a concern as it can serve as barriers to them entering scientific careers. As such, I expect this population of students to demonstrate some level of tension in teasing apart their experiences of scientific failure from their experiences of academic failure. Investigating undergraduate science students should thus yield a wealth of knowledge about how experiences of scientific failure allow for epistemic engagement.

Research Questions

After reflecting on the aims described above, I developed the following research questions:

RQ1. How do undergraduate students engaged in scientific research describe their experiences of scientific failure?

RQ2a. How do undergraduate students make meaning of their scientific failure experiences?

RQ2b. How do the experiences of failure described aid the students in constructing their understanding of the scientific enterprise?

Purpose

The purpose of this study was to characterize the experiences of scientific failure as described by undergraduate students participating in scientific research. These students were uniquely positioned to render their experiences within an educational context and could thus demonstrate how scientific failure experiences allow students to achieve the educational goals laid out for science education (see Duschl, 2008). This study also hoped to capture the common threads of the undergraduate experience so that the process of sense-making around scientific failure can be made accessible to students in broader settings and so that we can better understand failure's role in the scientific enterprise. Were this revealed to be a constructive role, we could argue for the incorporation of more scientific failure experiences in other science education contexts (undergraduate courses, secondary and primary science classrooms, and perhaps even informal science learning environments). By normalizing the experience of scientific failure, we may be able to influence how students see failure in science education, and perhaps make a dent in the STEM attrition problem!

Through reading this work, I hope it becomes clear wherefrom my fascination with this phenomenon stems. I have made transparent each step of the investigative process so that readers may follow the analytical process. The next chapters explain more in depth the literature and the methodology upon which this study builds. Chapter 2 defines the terms that will be important to this study, situates this work in relevant literature, and explains the theoretical framework that underlies my thinking about the study of failure in research contexts. Chapter 3 shares the methodological framework and the types of analyses that guides the study. Chapters 4 and 5 discuss the results of the different analyses applied to answer the different research questions: Chapter 4 organizes the results to RQ1 as themes that emerged from iterative analysis of student survey responses while Chapter 5 addresses RQ2a and RQ2b through hermeneutic analysis of student interviews. Chapter 6 discusses the findings in the context of current literature and imagines the possibilities for future directions of this work.

CHAPTER 2

REVIEW OF RELEVANT LITERATURE

Introduction

This chapter outlines the thought processes that guided me towards the study of scientific failure in the authentic context of science research. Initial attempts searching for literature on failure brought up only studies that looked at work studying performance or gaps in achievement in classrooms and work in educational psychology on constructs like fear of failure, mindset, persistence, and productive struggle. While these constructs explore why failure may impact student experiences, they did not explore how students experienced failure. Thus, the literature explored in this chapter turn instead to the context within which I study failure, to provide some justification for why I begin a career's worth of studying failure with an exploratory study in undergraduate research experiences.

This chapter begins by clarifying my use of epistemological terms in the context of more thorough research of the subject so as to orient the reader. Then, I define what I mean by "failure" and the literature that directly discusses failure in education research. I will continue by problematizing what it means to be "authentic" and the impact this term has had on areas of undergraduate science education. I will then describe relevant literature of the context that I have chosen as my area of study – in undergraduate science research experiences. This leads to a discussion on what researchers and philosophers consider to be "science" and how that has influenced what it means to *do* science – in other words, we will review what is said about the values and ideologies of science practice. Considering science as a community of practice will lead to the discussion of my theoretical framework. We will end the chapter with a model that integrates all of these ideas, outlining what I hope to capture through my study. The organization of this chapter is meant to take the reader through a rationalization for the study of failure in this context of undergraduate science research, by understanding what each of those spaces and terms mean.

On My Use of Epistemology

In the introductory chapter of this dissertation, I was very liberal with my use of the "epistem-" terminology. Epistemology is a composite of the Greek term *episteme* (knowledge) and the suffix *-ology* (derived from *-logy* or Greek *logos*). The suffix is commonly understood as "the study of", so epistemology broadly translates to "the study of knowledge". Understanding this will become important because of the role I believe the failure experience plays in developing thinking about knowledge construction in science. But before I go further, I should clarify what I mean by epistemology, epistemic practice, epistemic thinking, epistemic understanding, etc. – so that I may be free to use the terms without defining them at every time in future passages. For the purposes and scope of episteme-related discussions in this review, some of the terms will be used interchangeably – I will specifically identify those.

Kelly (2008) describes epistemology (as pertaining to scientific disciplines) as the study that "typically examines issues such as the growth of knowledge, the nature of evidence, criteria for theory choice, and the structure of disciplinary knowledge" (p. 99). This offers a disciplinary perspective of science epistemology– that which regards the construction of scientific knowledge as an activity in which members of the scientific community participate. The members of the community are those who are united on "common purposes and expectations, with shared cultural values, tools, and meanings" (Kelly, 2008, p. 99). This leads to the idea of epistemic practices – “the *specific ways* members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary practice” (p. 99, italics added for emphasis). In essence, epistemic practices in science are those activities in which members of the scientific community engage aimed at developing, arguing, and communicating how we know what we know in science (compiled definition from Kelly, 2008; Kelly & Licona, 2018; Jiménez-Aleixandre & Crujeiras, 2017). Epistemic engagement then is the active participation of people either in epistemic thinking or epistemic practice as it “involves students’ understanding and practices of why and how scientific knowledge develops” (Hand et al., 2016, p. 234).

Epistemic thinking and epistemic understanding are used interchangeably – as the latter is the manifestation of the former. Epistemic understanding can be evidenced and evaluated as the knowledge people display about how knowledge is generated (Hofer, 2004), and is the tangible expression of thinking. I use the word “understanding” deliberately as a vague term to cover the umbrella of theories regarding epistemological development and beliefs (Hofer, 2004; Sandoval, 2005) as the purpose of this project is not to delve into the development of epistemological thinking, but to see what evidence there is for students’ epistemological thinking in science. In science education, we see the use of the terms “epistemic understanding” and “epistemic engagement” in reference to goals for students’ science learning (see Rudolph, 2003; Duschl, 2008). According to Kelly and colleagues (2012), these goals call for helping students gain personal epistemologies of science that comes closer to a disciplinary epistemology – that is, developing one’s own knowledge about how science knowledge is constructed in the process of considering the philosophical basis of science (Kelly et al., 2012). To that end, when discussing epistemology, use of the term in the context of science as a community of practice (later on in this literature review) takes a disciplinary perspective, whereas my discussion of students’ epistemologies (in later chapters) will reflect a personal perspective. In the next section I define failure so as to bound my study of the phenomenon.

Failure – A Definition

Before examining the role of failure, we have to elucidate on the term's meaning. In common parlance, "fail-" is a ubiquitous term that has many meanings when used as a noun, verb, or adjective, but always negative in connotation. A search of online dictionaries including Merriam Webster (2020) and the Oxford English Dictionary (1989) defined failure most commonly by its opposite, as a lack of success. For the purposes of this study, I consider failure as a happening, an event, or an experience. This allows failure to be studied as a phenomenon rather than as a semantic curiosity.

In developing a theoretical construct to examine the failure experience, Henry and colleagues (2019) define failure as "the inability to meet the demands of an achievement context, with the result of not achieving a specific goal. Achievement contexts 1) consist of some task(s) to be performed, 2) involve evaluating the performance of said task(s) against standards or expectations that indicate goal achievement, and 3) require certain competencies to carry out the task(s) to defined standards" (p. 2). Their definition is situated in the context of and in opposition to success, as they continue by stating that:

> "When an individual does not successfully carry out the task, they have *failed*. For example, not getting meaningful results from a scientific experiment when the expectation is that the results will have meaning constitutes a failure of that experiment, even if future experiments can be performed to rectify that failure." (p. 2, italics from original)

They continue to distinguish their conception of failure from inability to succeed due to a lack of effort and as distinct from the concept of errors, "in that failures are marked by not accomplishing a goal within an achievement context, while errors do not necessarily preclude accomplishment of a goal (i.e., errors can be corrected relatively quickly without failing)" (p. 2). Theirs is a comprehensive definition, from which I derived a simpler one to describe the entire experience of failure: *an unexpected outcome and the response to that outcome*. Failure is not an endpoint, nor does the outcome stand on its own. It is an experience that begins with an unanticipated event and is judged by the response to that event. The next section takes a look at how the topic of failure has been made a part of learning in the classroom space.

Failure in Education

According to many scientists, failure is necessary to learning and doing science (e.g. Firestein, 2015; Simpson & Maltese, 2017). Whilst failure in science drives scientists forward, failure in science education drives many students to back away from science. Especially in higher education, where assessment-defined failure in science education has high stakes, negative experiences with failure turns students away from science (Chen, 2013; Nelson et al., 2013) and what we end up with are students who have developed skills to tackle assessment, but not necessarily students who have cultivated scientific habits of mind (a term coined by Dewey, 1910). Because of the seemingly inherent value of failure in science, some researchers look to incorporate experiences of failure into educational settings, described here as failure-centered learning.

Failure-centered learning accomplishes two worthwhile goals of education – first, it removes the negative connotations associated with the assessment-oriented conception of the term and second, it allows for engagement in epistemic thinking that is independent of scientific practice. Different methodologies are discussed here to delineate how this type of learning can achieve both objectives. Tawfik and colleagues (2013) summarized it best when they explained that:

> "…the theories posit that failure generates an additional inquiry process at the point of failure that may not exist during a successful experience... The inquiry process is a critical component of any ill-structured problem-solving because it engages the learner to ask additional questions; ascertain potential causes for a breakdown; hypothesize the reasons for why they happened; and find evidence to justify the reasons." (p.977)

In developing a unified framework that incorporated failure-centered methods of learning, Tawfik and colleagues worked through earlier models in the literature before concluding with a cognitive model that demonstrates how explicitly confronting and overcoming failures as part of learning improved learning gains. While this pedagogical approach assumes failure as central to the learning process, the assumption for why this is the case in learning and in science is not questioned. While I could envision myself using failure-centered approaches in the classroom, the question of what students experience as failure remained.

In addition, though incorporating failure-based learning in educational settings (outside of authentic environments) has demonstrated some success with student learning, the consequence for the student is one that needs to be addressed. Along with the sociocultural consequence of failure, there is an emotional one that educators could address.

> "Failure and success are complicated constructs that are not simply determined by red checkmarks, comments boxes, and grades: they are messages imbued with significance that students appraise according to their educational goals and, as a result, generate emotional responses that can have a strong impact on their future learning, educational decisions, and even health." (Jarrell et al., 2017, p. 1264)

Jarrell and colleagues make the case that confronting failure in learning is not enough. Especially in the case of academic failure (as opposed to failure in the context of science), the role of performance feedback on emotions has to be considered. Other constructs in motivational and educational psychology attempted to address student experiences by looking at how students responded to failure and developing theories about the cognitive and non-cognitive constructs that informed such decisions.

In studying school children, Dweck & Legett (1988) made a landmark distinction between thinking that regarding the outcomes of ability and effort, differentiating between an entity theory of intelligence and an incremental theory of intelligence. The former identified thought processes that viewed intelligence as a fixed construct, whilst the latter viewed intelligence as a continually developing construct. These implicit theories of intelligence were also found to relate to the goals people set for themselves. Indeed, "conceiving of one's intelligence as a fixed entity was associated with adopting the performance goal of documenting that entity, whereas conceiving of intelligence as a malleable quality was associated with the learning goal of developing that quality" (p. 256). Relating behavior to goal-setting meant that individual response to success and failure could be predicted based one's thinking about intelligence. As such, Dweck (2006) framed these two polarities of thought in terms of students' mindsets – those with fixed mindsets and those with growth mindsets. In essence,

> "…students with growth mindsets seek to learn and develop their abilities, and thus pursue challenges, value effort, and are resilient to setbacks; in contrast, students with fixed mindsets avoid challenges (which could reveal 'permanent' deficiencies), dislike effort (which they think signals low ability), and give up more easily when facing setbacks (which they view as evidence of low ability." (Rattan, Savani, Chugh, & Dweck, 2015, p. 722)

In defining these distinct modes of thought, these educational psychologists are well-positioned to address the development of mindsets (sociocultural influences, parental impact, relationship to prior performance or achievement, etc. – Dweck, 2006) quantitatively. Early work by Limeri and colleagues (2020) has demonstrated that mindset is a far more complex construct in undergraduate students than in elementary school children, as their ideas about what intelligence is seems to factor into what kind of mindset they orient towards. This work begs us to critically examine the validity of interpretations in studies that measure undergraduate mindset, graduate, and instructor mindset as Dweck's initial work to establish this construct was only tested for validity in elementary school students. Findings from various studies, particularly meta-analyses, have shown inconsistent results from either studying mindsets directly through the use of surveys or through interventions, which Limeri and colleagues attribute to not taking measures to establish validity. Still, the concept of mindset is an appealing construct to understand as it may inform the tools students utilize to address and rationalize failure. Working to shift undergraduate student thinking to reflect a growth orientation may be a worthwhile instructional approach to mediating emotional responses to failure. Another approach considers how students persist in spite of failure.

In reporting that academic performance, especially in higher levels of education, did not correlate with ability (Duckworth, Peterson, Michaels, & Kelly, 2007), researchers believed that non-cognitive concepts (see West et al., 2016 for clarification) could perhaps better predict achievement. In this way, they developed the measurable concept of grit, originally defined by Duckworth and colleagues (2007) as "passion and perseverance for long term goals", which is now understood as the persistence to achieve goals, driven by underlying non-cognitive processes. Grit describes the quality that pushes students to strive to attain their goals, and survey items used to measure its constructs reflect both these ideas. Persistence is also usually described as the staying power of students in a discipline (Graham et al., 2013; Maltese & Tai, 2011) but is often the term *de riguer* for describing the paths navigated by gender and ethnic minorities in the STEM disciplines (Carlone & Johnson, 2007; Talley & Ortiz, 2017; Toven-Lindsey et al., 2015) or in alternative collegiate paths to STEM majors (Fong et al., 2017; Bazelais, Lemay, & Doleck, 2016), as a simple search of the term in science education literature indicates. Grit as a non-cognitive construct has been understood as having multiple facets – going beyond simple effort to achieve a goal, but also the drive to pursue that goal. Quantitative studies looking at measures of grit, have studied it as a predictor of performance but have yet to make a definitive argument for that relationship (Credé et al., 2016; Credé, 2018). This concept has so captured the interest of education researchers that scientists are also looking for neuronal correlates of the constructs of grit. Myers and colleagues (2016) found striatal projections between the notion of grit and that of growth mindsets (described below) differed significantly – though there are a few caveats which concern this study given its limitations (age of participants, given the original presumption of the constructs, number of participants, etc.). Still, these studies only capture ideas that surround the failure experience.

In beginning to address what is so often a sensitive topic to most students, care must be taken to facilitate constructive experiences with failure. By setting out to understand the failure experience, this dissertation might elucidate those components of the failure experience that can serve to advance student learning without causing emotional harm, or at least aid instructors and students in developing strategies to manage emotional responses productively. But thus far, we have only discussed what has been studied in the classroom setting through using failure, in response to failure, and in spite of failure. The next sections articulate why we might consider more authentic settings for study and why we need to understand what it is science is in order to then study failure in the context of that setting.

Authenticity and Inquiry

In the call to improve undergraduate biology education, *Vision & Change* (AAAS, 2011) urged that "authentic" research experiences become accessible to all students – with the implication that engaging in experiences that allow students to participate in what scientists do and how they think qualifies as authentic science. Conceptually, this is a static notion of authenticity – science as scientists practice it – and can lead to an other-ing of students who do not see themselves and their experiences within science, thus de-legitimizing those students as prospective scientists. Instead, emergent conceptions of authenticity, developing out of students' experiences and using those to ask questions about local natural phenomena positively influences students' ownership of learning and makes science learning meaningful (Rahm et al., 2003). Authenticity then is not just epistemic engagement of science practices, but also contextualizing epistemic thinking in the experiences of students. I bring this up to recognize that authentic science activity can be considered as student-centered authenticity or science-centered authenticity.

The practical implementation of "authentic" activity is synonymous and interchangeable with scientific inquiry (e.g., Brownell et al., 2012; Spell et al., 2014; McLaughlin & Coyle, 2016). However, asking instructors and researchers for a definition of inquiry is entering a lexical quagmire. Pedaste and colleagues (2015), in looking at other researchers' frameworks of inquiry-based learning, found there to be epistemological differences based on whether researchers conceptualized the initial phase of inquiry as an inductive or deductive process. These authors developed a general framework of the phases of inquiry learning by synthesizing other frameworks that looked at inquiry as a series of steps involving separate forms of thinking and practice. Analyzing 32 studies, the authors found 109 terms that described the inquiry process, and by grouping similar terms, pared these to 34 inquiry activities, from which emerged five general phases (with sub-phases that elaborated upon these): orientation, conceptualization, exploration, conclusion, and discussion. These process-oriented phases also emphasize scientific thinking, consonant with the science practices promoted by the Next Generation Science Standards (NRC, 2012). McLaughlin and Coyle's (2016) stepwise progression through a similar process included a review of scientific literature as part of the inquiry process to better position students as participants of scientific research. At its essence then, inquiry as emphasized in undergraduate curriculum encompasses the practices by which scientists develop scientific knowledge and the critical thinking scientists use to analyze and interpret that knowledge in the context of existing frameworks of scientific thought, activities that engenders epistemic understanding. But including these aspects of inquiry – or inquiry methods – in courses could look quite different from fully engaging in inquiry as scientists do.

Because of the variety in definitions for inquiry, attempts to incorporate it in the undergraduate biology curriculum result in a variety of implementations. In their study of the implementation of inquiry-based labs, Beck and colleagues (2014) categorized inquiry learning as guided, open-ended, and research-type, based on student activity in those labs. Brownell & Kloser (2015) adapted a gradation of types of inquiry based on the degree of autonomy students demonstrated, from cookbook to authentic. Both studies considered more research-like experiences to involve a greater amount of independent work from the students. The latter also specified that the learning should be appropriate to the level of understanding students were expected to achieve - that a topic-oriented guided inquiry experience would be more beneficial to students in early science courses, whereas upper level students could more reasonably be expected to engage in a greater scope of inquiry activities in the course of an investigation independently, from considering the research questions to the experimental design to the analysis of the results. As such, from course-based undergraduate research experiences (CUREs), to problem-based learning, inquiry methods most often reflect what instructors and researchers view as most authentic practices to science and what they deem students capable of handling.

Inquiry experiences at the collegiate level have been studied extensively in undergraduate life sciences. This is particularly true within the biological science courses given their nature as gateways to other science degrees and disciplines. As *Vision & Change* (AAAS, 2011) advocated for the transformation of traditional lab instruction to more inquiry-oriented practices, laboratory courses were initially targeted to revise their curriculums. Incorporating inquiry in lab courses of biology education have involved such different strategies that inquiry learning has taken many forms. At the introductory level, most instructors and researchers believe that the introductory level seems to require some measure of guidance for students as it is currently practiced (Brown et al., 2006; Brownell & Kloser, 2015). Guided inquiry differs from problem-based inquiry as the latter allow students to critically evaluate methods and experimental design, while the goal of the former is more to integrate skills with content, where the application of the content is addressed in greater depth through in-lab and post-lab discussions (Basey et al., 2011). Unlike a complete (ideal) research experience where researcher and student would work more collaboratively through the discovery process, guided inquiry begins with instructors offering students a question (traditionally) or predicament (in labs that focus on socioscientific issues) to investigate. Open inquiry differs from both of these - compared to guided, there is less scaffolding, and students develop their own questions and compared to authentic/research practices, there is less equivalent dynamics between the instructor and student (again, ideally). Based on evidence that the few students who took the initiative to find research opportunities for themselves often were disproportionately advantaged, Wei and Woodlin (2011) compiled a list of projects in undergraduate biology education research that embedded inquiry experiences into their curricula. They grouped these efforts by their goals, from introducing students to research and "demystifying" science processes to allowing students to participate or contribute to ongoing faculty projects (the first type of guided) to service-learning projects that connected students to local communities (the second type of guided: problem-based). A few of the projects described involved introductory students participating in course-based undergraduate research experiences (CUREs) - a form of authentic inquiry that was situated in a question or problem, as yet unanswered, "of interest to the scientific community" (Auchincloss et al., 2014, p. 30).

CUREs and UREs

To put it simply, CUREs put the study of science in the context of science. CUREs developed out of collaborations amongst faculty, as researchers found ways to provide students access to research experiences that also gave the students opportunities to contribute to scientific knowledge. The distinguishing elements between CUREs and using inquiry methods in laboratories was made clear by Auchincloss and colleagues (2014), who specifically address that the "motivation for the inquiry [method] is to challenge the students, rather than contribute to a larger body of knowledge" (p. 31) – thus characterizing the inquiry methods in lab courses as engaging students as a facsimile of practice, as opposed to CUREs, which engaged students in the actuality of practice. The unique features of CUREs went beyond just that of its motivation, but in that all five of its described dimensions had to be present: (1) practices of science; (2) element of discovery in outcome (or question); (3) importance/impact beyond the scope of the course; (4) collaboration amongst all levels of participants – students, teaching assistants, faculty; and (5) iteration that is understood as inherent (Auchincloss et al., 2014). While research on the impact of CUREs on student outcomes is still in a nascent stage (see Brownell & Kloser, 2015; Corwin et al., 2015), initial work has shown that students do perceive gains in attitude, persistence, and motivation. This suggests that these learning experiences become an integral part of the undergraduate biology curriculum (Russell et al., 2015; Rodenbusch et al., 2016). Simply for the reason that they allow more equitable access to scientific research (Bangera & Brownell, 2014), they should be considered a required aspect to *introductory* science courses. Of all the ways in which literature has described incorporating inquiry into classrooms, CUREs seem to encompass all aspects of "authentic" practice.

Several researchers of CUREs have made incidental findings about students' perception of failures in those settings, which also begs further direct study of the failure experience. Kazempour and colleagues (2012) found that through inquiry, students came to realize that failure experiences were expected in science, and this led to the understanding that science is not a linear process, but iterative. Russell and colleagues (2015) share a prime example of this with their discussion of the Ecology student who, after correctly identifying their organism, received from their biology partner a completely different identification based on DNA analysis. Instead of washing their hands off the project by deeming it a failure due to experimental error, the investigative nature of the project allowed the student to use the tools they had learnt to discover that their organism had been infested by another - leading to other ecological concepts of complex species interaction (going beyond just the goal of the project as identification of local organisms). Goodwin and colleagues (2021) made the clearest argument for student perception of failure as part of authentic science activity in their recent study of a CURE module. In surveying participating students about their CURE module, students were asked what experiences made the course more like authentic science. Coding the reflections, the researchers found that 59% of respondents mentioned that failures supported this perception of authenticity, far outstripping other codes, including participation in actual scientific practices.

To a certain extent, undergraduate research experiences (UREs) can be argued to offer similar learning experiences to science students, without the structure provided by the experience given a "course" designation (i.e. time commitments subject to the researcher's expectations rather than student choice; the start and end of the experience not subject to the academic calendar). The most comprehensive sampling of science students to date found that of those students intending to graduate with a science degree, over half of the respondents participated in some kind of undergraduate scientific research experience (Russell, 2007). UREs also offer more individual mentoring opportunities in scientific research than CUREs, but the potential positive impact would depend on the researchers' ability to mentor undergraduates most effectively (Linn et al., 2015). Like with CUREs, the evaluation of UREs on the basis of student learning outcomes has been limited, but generally shows positive affective impact (Linn et al., 2015) and positive perception of learning gains (Stanford et al., 2017). The literature in this area has further to go in the evaluation of these experiences but suit my purposes very well in the demonstration of their "authenticity." CUREs and UREs in particular can be implemented to attend to the more dynamic, student-centered definition of authenticity. Indeed, Wei and Woodin (2011) describe several examples of UREs that develop as collaborative efforts between students and scientists.

Having described now what authentic science activity might look like in undergraduate science education, I would like to define what it is I mean by "science" using literature from philosophies of science, which will better situate us for a discussion on what it means to know in science.

An Understanding of Science

I choose to understand and engage with science as a way of thinking about the world – a process of accumulating knowledge and then of generating meaning using that knowledge and within which that knowledge is situated. This conception of science aligns most closely with the views of the philosophers Helen Longino (1990) and Thomas Kuhn (2012). Longino wrote that the purpose of science is "the systematic and unifying treatment of phenomena [that] enables us to interact with the natural world with reliable expectations. A methodology that legitimates the stabilization of inquiry thus serves some constitutive ends of knowledge seeking" (p. 224). Kuhn's development of the concept of "paradigms" explains the latter half of my definition – how meaning derived from the knowledge produced by scientific processes is fit into frameworks of knowledge, frameworks developed by knowledge pursued in a particular way and furthered by study founded on that knowledge (2012).

That is not to say, however, that the rigorous process of observing, cataloguing, and making sense of the world is all that is science. The values that underlie these processes are equally as important. Lederman and colleagues (2002), known for their work on the nature of science, make clear that many "often conflate [nature of science, or NOS,] with science processes… we consider scientific processes to be activities related to the collection and interpretation of data, and the derivation of conclusions. NOS, by comparison, is concerned with the values and epistemological assumptions underlying these activities" (p. 499). Longino (1990) separated those set of values, defining one set as the constitutive values of science, or "the values generated from an understanding of the goals of science…; the source of the rules determining what constitutes acceptable scientific practice or scientific method" (p. 4). Longino's constitutive values reflect those ideals to which science is commonly described as aspiring to. These values stand opposed to what Longino defines as contextual – those determined by society's landscape or zeitgeist. Lederman (2002) also acknowledged the role of society and culture in science, writing that "science as a human enterprise is practiced in the context of a larger culture and its practitioners are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion" (p. 501). In short, these authors agree that of the values that govern science, those defining knowledge production remain outside human influence, but those defining the integration and utilization of that knowledge into the accumulated wealth of human knowledge, are influenced by human subjectivities.

It follows, then, that the practice of science today has evolved from the science of the past due to the evolution of the society of practitioners. From the days when science was used to reinforce the horrific practices of slavery and the gross injustices of racism, to today where we see more inclusion of diversely-identifying peoples in science, we moved from scientific frameworks dominated by the colonial and paternalistic white male culture to scientific frameworks more accommodating of feminist science ideologies that aimed to include alternative frameworks of understanding the world. Science as a sociocultural practice becomes, like any other human endeavor, part of the cultural way of understanding the world, and the story that scientific knowledge is used to tell depends on the interpretations of the current community of science practitioners. But what continues to distinguish science from other narrative or explanatory human disciplines are the values that remain outside the influence of human morality or judgement – its constitutive values – and the rigorous standards to which the community holds its practitioners to uphold those values.

It would be nearsighted to consider science as a wholly rational, logic-oriented activity. Given the nature of inductive reasoning and its centrality to current scientific practices (Okasha, 2012) – a large part of constructing phenomenological explanations in science – we know that science involves an element of creativity. Lederman and colleagues (2002) also recognized this attribute, that “generating scientific knowledge also involves human imagination and creativity. Science, contrary to common belief, is not a lifeless, entirely rational, and orderly activity. Science involves the invention of explanations and theoretical entities, which requires a great deal of creativity on the part of scientists" (p. 500). But this is not only true for the generation of meaning and explanations. Even in the generation of questions to ask about the workings of the world does creativity show its hand, as with the ways in which to investigate those questions. The beauty of science lies in its flexibility to address the world, as long as one remains true to its constitutive values. Longino (1990) believed this was grounded in the understanding of scientific processes and a depth of knowledge from which to draw. "The demand for information about a phenomenon, which originates in the particular context in which research is done means that choices must be made about what sorts of effects to test for and what sorts of methods will be used in those tests. When ignorance about the phenomenon frees those choices from the constraints imposed by constitutive norms, they are left vulnerable to other contextual pressures such as beliefs…" (p. 92). This makes a case for the development of scientific content knowledge before engaging in the practices of inquiry – so as to not purport the practices of science through ignorance of the knowledge frameworks that drive a scientific community. Though this is not often problematic with the community of practicing scientists, bringing newcomers into that community as participants without the requisite knowledge becomes an issue. This will be explored more in my discussion of this study's underlying theoretical framework.

Integrating these conceptions of science generates my understanding of science as a way of thinking about the world – a process of accumulating knowledge and then of generating meaning using that knowledge and within which that knowledge is situated. It ties the values of science to the process of science and inherent to that is the belief that "science" is not complete without both constructs. Thus, I define science as a human enterprise characterized by practices, critical thought, and ideals (that are reflective of the society in which it is experienced), with the goal of developing understanding of the natural world, and of communicating that knowledge (compiled definition from: Dewey, 1910; Longino, 1990; Kuhn, 2012; Firestein, 2015). How this definition relates to the actual implementation of science both within its own disciplines and within science education will be discussed in the next sections.

An (Epistemic) Understanding of Science

Whilst the ideals of scientific endeavor to steer the enterprise into the realm of the unknown, the practice of science remains firmly in human hands, subject to human influences – the difference again between its constitutive and contextual values as posited by Longino (1990). Developing this comprehension involves developing an understanding of the epistemology of science, a venture into “the origins, scope, nature, and limitations of knowledge” (Boyd, 1991 as cited in Kelly, 2012, p. 281). The communities of science have been investigated by sociologists (e.g. Traweek, 1988; Latour & Woolgar, 1986), and more recently by educational researchers under the banner of “science studies” (e.g. Wong & Hodson, 2009; 2010). Through the lens of ethnography, Traweek (1988) explored the different aspects of interaction, of knowing, and of valuing in science particular to a small, physically disparate, global community of high-energy physicists: from the manner of dress to cafeteria positioning, from the language to the explicit and implicit expectations, from the roles of the community members to the intellectual hierarchy.

The philosopher of science Latour, alongside sociologist Woolgar (1986) conducted an anthropological study of practice, investigating the messy reality of scientific practice – how knowledge generation was far more constructed than simply discovered. Their depiction of the scientific enterprise is gritty and raw, stating that “scientific activity is not “about nature,” it is a fierce fight to *construct* reality. The *laboratory* is the workplace and the set of productive forces, which makes construction possible. Every time a statement stabilizes, it is reintroduced into the laboratory… and it is used to increase the difference between statements. The cost of challenging the reified statement is impossibly high. Reality is secreted" (p. 243, italics in original source). This notion is underscored by Kuhn's (2012) own depiction of the normal state of affairs of science in feeding its own paradigm. Whilst all these researchers adopt a disciplinary epistemology, Traweek (1988) and Latour and Woolgar (1986) address it through the ethnographic and anthropologic study of science. Kuhn's (2012) treatise is largely holistic, charting movements in scientific thought.

The chaotic nature of scientific practice was also made evident in interviews with scientists conducted by Wong and Hodson (2009; 2010), where scientists were asked to share their views about authenticity of practice and the nature of science in order to refute common misconceptions educators have about those concepts. Scientists shared their experiences of different aspects of scientific practice and knowledge generation similar to the statements above – that "knowledge generation requires scientists to "stretch their imagination and creativity" to construct explanations and theories to fit with existing observations. [The participating scientists] noted that imagination is guided or even bounded by one's disciplinary training and experience" 2009, p. 120). Though all the scientists involved in the study subscribed to the universality of scientific knowledge (considered a naïve view under the NOS framework by Lederman et al., 2002), they acknowledged the social context of science practice as affecting the interpretation of that knowledge in social, political, and economic spaces.

All of this leads us to consider the epistemological underpinnings of science. Epistemology, as the field of philosophy which considers how we develop an understanding of our reality (whatever we consider that reality to be – that falls under the realm of ontology), describes how we know what we know (Okasha, 2012). Thus, what is important about the practice of science as it relates to the philosophy of knowing in science is the nature of practice to: (1) knowing how to justify explanations of phenomena; (2) critically evaluate information; (3) recognize the social context in communicating science (summarized from Duschl, 2008 as cited in Jiménez-Aleixandre & Crujeiras, 2017). These criteria make up the definition of the epistemic practices of science, what Popper (1959) described as the "context of discovery". This is not to be conflated with the actual practices of science – the planning and carrying out of investigations, analyzing and interpreting data, communicating results, etc. (what Popper, 1959, would consider the "context of justification"). Instead, epistemic practices are embedded within the broader category of scientific practices – that in order to be able to effectively communicate results, one needs to recognize that science is situated in a social context and translate those results into meaningful statements that can then be acted upon in the social, political, and economic space. Epistemic practices can be unique to disciplines in science or universal to science. Kelly & Licona (2018) define them as "the socially organized and interactionally accomplished ways that members of a group propose, communicate, evaluate, and legitimize knowledge claims" (p. 140). The members are those participating in the community of practice that is science – and it is these communities of practice where epistemic practice is made apparent – which then trickles out to education through authentic practice.

Samarapungavan and colleagues (2006) studied the differences in epistemic understandings amongst groups at succeeding levels of education entering into the scientific community – from high school students to scientists (chemists), with undergraduates, research undergraduate research assistants, and graduate students making up the middle. By organizing their interviews around five epistemic themes, the researchers found variety in the depth and quality of responses that indicated differing levels of epistemic understandings across the groups.

They found that epistemic beliefs varied by expertise between scientists and all the other groups and also varied by research experience between the undergraduate researchers compared to the undergraduate lab students. The latter finding helped determine my study population.

In engaging students in research-oriented settings as participants who are situated in the authentic experiences of science, I believe the experience of failure will convey essential aspects of epistemic understanding through epistemic practice. In the next sections, I envision the relationships between science, learning, and failure within my personal ontology through the frameworks that guide my approach to the study of failure.

Theoretical Framework

The framework that guides this study integrates theories of learning in science with the philosophy of science, bounded within the researcher's worldview, and all circumscribing the communities of science and education. I acknowledge my subscription to a relativist and interpretivist ontology – that knowledge of the world is limited to what we observe of it, and that meaning is found and created within, rather than placed from without (Okasha, 2012). My ontological standpoint allows for multiple ways of knowing, and so acknowledges my own way of knowing as ascribable to scientific ideologies – or knowing the world through scientific inquiry. Whilst a scientific worldview has been known to be aligned with positivist epistemologies (Longino, 1990; Duschl, 2008), given my ontological stance, it naturally follows that my epistemological approach takes on an interpretivist stance (Erickson, 1986), within which constructivism addresses the sense-making processes (Schwandt, 1994) whereby undergraduate students develop an understanding of what it means to fail in science.

Constructivism, borne out of the work of Piaget and Vygotsky thus describes the process of meaning-making that students develop around failure and their experiences both as students and as practitioners of science at the fringes of the scientific communities of practice. The inclusion of the research setting is underscored by the knowledge that science learning is also situated (Lave & Wenger, 1991). Scientific communities of practice call for novices to enter into their spheres through participation in the specific practices authentic to that community. Undergraduate research experiences (course-based or otherwise) provide the most legitimate method of engaging that community, situating learners in the practices and contexts of scientists. The intersection of practices of science and education is the space within which undergraduate science students find themselves as they grow as learners and participants in the community of education but make their way into scientific communities from the periphery. This is the space in which I hope to study the experience of "scientific failure".

The concept of a community of practice arises from the notion that learning must be situated in the context of that being learnt (Brown et al., 1989; Lave & Wenger, 1991). A community of practice is one that negotiates shared meaning through shared practice (Wenger, 1998). If science is the encapsulation of the processes of thought enacted upon to generate knowledge about the physical world, practitioners of science participate in the negotiation of what thought and activity count towards knowledge generation. Membership within the scientific community of practice (within which one can find disciplinary communities of practices) is not a card-carrying one, but "translates into an identity as a form of competence" (Wenger, 1998, p. 153). As such, entering the scientific community of practice does not have to be the physical transplantation of students into the contexts of disciplines (for example, it does not have to mean learning about planning scientific investigations in a laboratory settings), but must simulate the cognitive and physical tasks that scientists engage in (for example, discussing and debating examples of scientific writing to judge more effectively the quality of the research). In essence, by engaging in epistemic thinking and practice of a community of practice as a member (peripheral or otherwise), participants come closer to developing expert understandings of the community of practice. Undergraduate students after experiencing scientific failure in a research setting may demonstrate a more nuanced understanding of science because of failure's function to elicit epistemic understanding of science – one of the aims of this study. The notion of authenticity is also closely tied to this theory of situated learning, as those epistemic practices determined as authentic are legitimized because of the communities of practice in which they are accepted as practices to generate knowledge (Edelson, 1998; Kelly & Licona, 2018).

A Model Summary

The framework described above is best understood by the model depicted in Figure 2.1. Students first learn to navigate the formalized system for learning – engaging in the practices that are central to the "doing" of education. Through their interaction with science in the context of education (through science education), they engage with scientific knowledge, but the focus whilst a student is still to succeed in the practices of education, and they do so by demonstrating mastery of the knowledge that are the products of that community of practice. Being good at education can thus be considered a gateway to the community of practice that is science. Students who can begin to make steps towards the scientific community are those who can demonstrate they have acquired scientific knowledge. Inquiry – particularly the more authentic context of undergraduate research experiences – which is still situated within the community of practice of education, theoretically allows students to legitimately participate in the practices of the scientific community. Students are expected to develop the skills and the thinking through engagement in authentic scientific inquiry. This model suggests that whilst education allows students to enter the community of science through legitimate peripheral participation, experiences eliciting epistemic understanding, particularly those surrounding experiences of scientific failure are what move students from novice to expert understandings of science. In the discussion about students' learning within the scientific community of practice, I use epistemological learning as equivalent to domain-specific learning (Wenger et al., 2002). Some aspects of the model represent thinking that has not yet been elucidated – because it is not the focus of this study, it is not addressed here. Future studies will incorporate the results of this study through revisions of the ideas relevant to this study and expand upon the model through investigation of aspects not touched upon here.

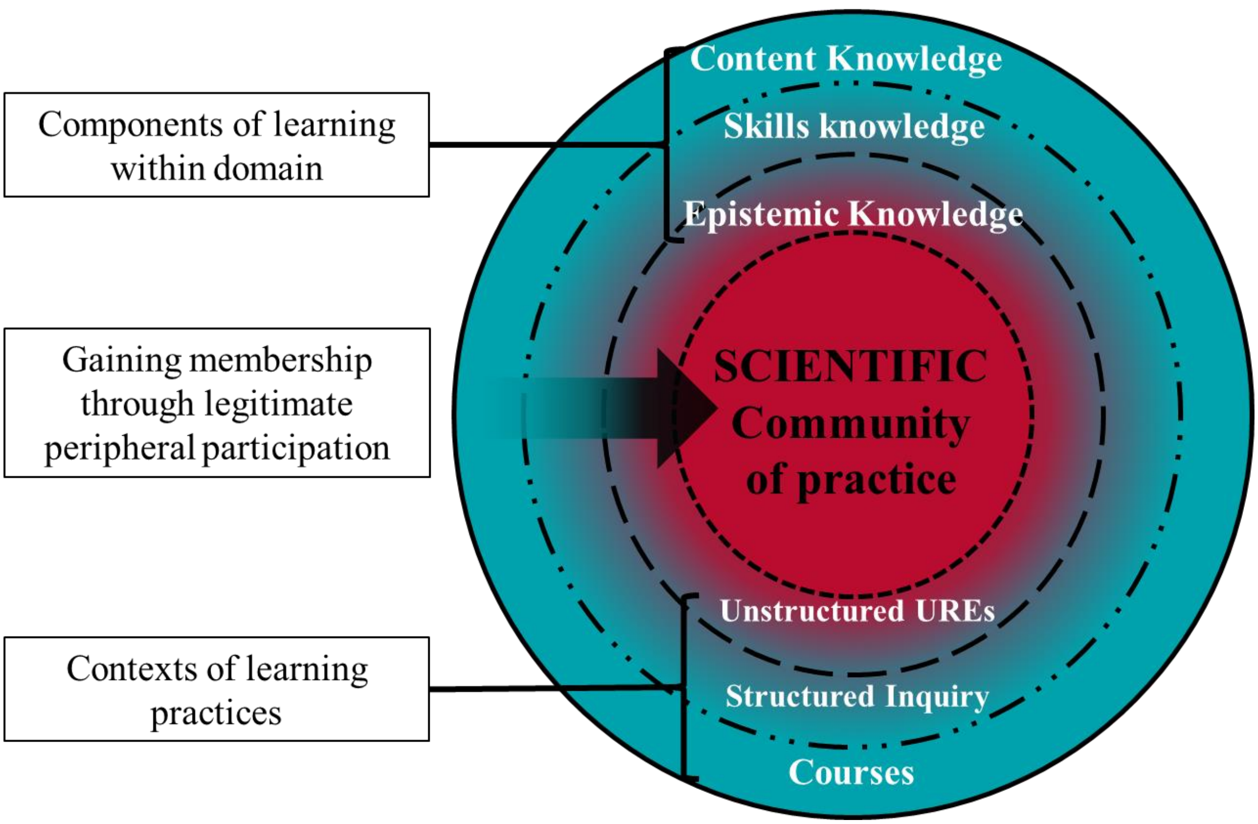


Figure 2.1. An initial model of the components of legitimate peripheral participation: how students enter into the scientific community of practice through participation in learning and contexts that gain more authenticity as they resemble the practices and learning of the community.

Chapter Summary

This chapter walked through the rationalization for this work and the philosophical basis that drives this work. In doing so, I also touched upon the gap in the literature that I identified and will attempt to fill. The literature on the topic of failure took me into articles in peer reviewed journals in middle school math education, all the way through texts on the philosophy of science. What I found was that while failure as described by scientists was almost universally positive (Simpson & Maltese, 2017) and deemed necessary for progress in the various disciplines of science (Kuhn, 2012), failure in undergraduate science classrooms are perceived as almost universally negative experiences. While studies of students participating in activities designed to elicit productive struggle, like problem-based learning, show some increased engagement and learning, perception of such experiences is still often more negative than positive (Holmes et al., 2014; Allen & Tanner, 2017). However, one step removed from the classroom, studies in laboratory spaces show that when students experience failure in the most authentic of lab settings – the course-based undergraduate research experiences (or CUREs) – they feel that the science that they engage in is more authentic (Goodwin et al., 2021), that failure is expected in science, and that science is not a linear process, but iterative (Kazempour et al., 2012; Russell et al., 2015). The gap I found that I think is critical to address is the lack of studies on students' experiences of failure in undergraduate science research. By bridging the gap between what scientists experience as failure and what students in courses experience as failure, we can figure out what supports students need in the classroom setting to feel like they engaged in constructive authentic practice in the face of failure. While that may be the overarching goal of my work in failure, the research questions brought up in Chapter 1, and revisited in the next chapter will help narrow the scope to something more answerable for the purposes of a dissertation.

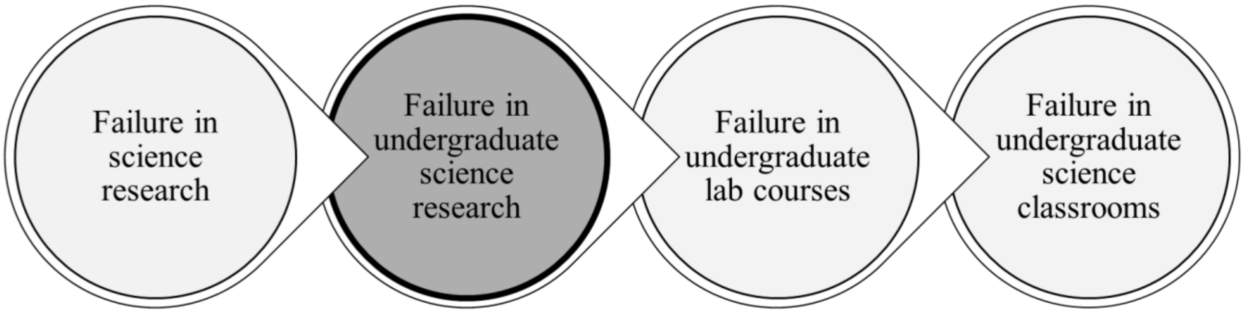


Figure 2.2. An identified gap in the literature around failure.

CHAPTER 3

METHODOLOGY and METHODS

Overview of Research Design

This work explores undergraduate students' experiences of scientific failure through in-depth investigation of their experiences, guided by the following questions:

RQ1. How do undergraduate students engaged in scientific research describe their experiences of scientific failure?

RQ2a. How do undergraduate students make meaning of their scientific failure experiences?

RQ2b. How do the experiences of failure described aid the students in constructing their understanding of the scientific enterprise?

This chapter describes the methodological tradition that guides this study as well as the design of this study. It begins with a description of the broader approach that underscores the philosophy upon which hermeneutic study is built, starting with its interpretivist roots, followed by its phenomenological stem, to finally arrive at hermeneutic (or interpretive) phenomenology. Then, I rationalize why hermeneutics suits the purposes of studying scientific failure experiences in particular. The rest of the chapter communicates the design of the study. This is separated into a section on a description of the data collection and followed by a section on the analysis. Where relevant, I also include how planned actions changed on actual implementation. Whilst a published article might not necessitate documenting my intended actions, I felt it appropriate to do so through the medium of a dissertation as it highlights how deliberate engagement with hermeneutic methodology led to a far richer analysis.

METHODOLOGICAL FRAMING

Interpretive Qualitative Research Traditions

In harmony with my own worldview, I judged that an interpretive approach to qualitative research best suited my purposes for the study of undergraduate students' experiences of scientific failure in scientific research. This could include a variety of approaches – symbolic interactionism, ethnography, or hermeneutic phenomenology. The central tenet binding these approaches is the epistemological stance that all experience is filtered through one's own interpretation, such that meaning is not an inherent property of something but is attached through social construction and agreement (Prasad, 2008). These are based on the understanding that our knowledge of our reality is also arrived at through social and contextualized means of learning. The social and subjective meanings made of the world reflect how external reality is processed, and it is the interpretivist researcher in all these approaches who attempts to make visible the process of meaning-making. This is the principle of *verstehen* (Weber, 1949 as cited in Prasad, 2008), "whereby understanding, meaning and intentionality is emphasized over and above causal explanations" (p. 14). I chose to proceed with the hermeneutic phenomenological framework as it focused on the meaning-making of *the experience* situated in a broader societal context. Symbolic interactionism focuses on *the self* in relation to meaning-making, whilst ethnography focuses on *the culture* wherein meaning is made.

A Brief History of Phenomenology

I bring up phenomenology to give a nod to the methodological tradition that hermeneutics grew out of and in response to. Phenomenology as a research methodology emerged out of the philosophical work of Edmund Husserl (1859-1938), whose work understood reality as a function of human consciousness. All reality was subject to interpretations of that consciousness, and meaning was made in the interaction between the unique aspects of an object and human consciousness. By asking “what is this experience?”, Husserl’s work drove this approach on returning to “the thing itself” (Marton, 1988; Laverty, 2003; Wertz et al., 2011). He argued that any human experience could be reduced to essential components that comprised every instance of that experience. In essentializing experiences, a researcher could get to the “truth” of that experience. Though this philosophical basis first rankled of more realist, objectivist ontology, empirical work soon moved in more interpretive directions (e.g., van Manen, 1990; Laverty, 2003; Sandberg, 2005), especially under the auspices of Martin Heidegger’s (1889-1976) hermeneutic or interpretive phenomenology.

Interpretive Phenomenological Approach – Hermeneutics

Hermeneutics evolved as a field that studied meaning in texts, recognizing that many historical texts (classics and religious texts alike) could be subject to multiple interpretations (Ricoeur, 1976). The root of the word “hermeneutics” comes from Greek, as “the process of explaining and clarifying with the intent of making the obscure more obvious” (Bauman, 1978 as paraphrased in Prasad, 2008). Heidegger (1962) and Gadamer (1960) turned the focus of hermeneutics to consider the act of interpretation itself – regardless of its context within or without text. They asked what it was that shaped interpretations – what aspects of the experiences that shaped the interpreter to make the interpretations that they did (Prasad, 2008). Hermeneutics under their auspices became a more reflective practice that gave due consideration to the context of the experiencer as well as the parts of the experience, a central concept of hermeneutics: the hermeneutic circle. This concept conveyed that meaning evolved out of an “iterative spiral of understanding” (Prasad, 2008, p. 34) – that to understand a text/phenomenon, one had to take into account the societal and cultural context, but that the context was also mediated in turn by the text/phenomenon. This translates very well to my theoretical framework that situates the experience of scientific failure within the context of the scientific community of practice, and the considerations of how to understand one through the context of the other.

Certain principles characterize interpretive phenomenological study: (1) the experiences studied are often common place or taken for granted, but made visible through study; (2) the experiences are explicated on by individuals who are or have experienced the phenomenon in question; (3) the individuals explicate the phenomenon as it is brought to consciousness, without reflection; (4) the experiences are described with "depth and richness"; (5) phenomenological questions investigate meaning – they do not solve problems (comprehensively described by van Manen, 1990; various concepts present in all papers on phenomenology).

This leads to a more complex and perhaps fundamental reason to distinguish phenomenology from hermeneutics, which is ultimately the philosophical distinction in the questions they ask. Whilst Husserl's descriptive approach answers ontological questions about the characteristics of an experience that is known to the experiencer, Heidegger's interpretive approach addresses more epistemological questions – that the nature of an experience that emerges from knowing/being is a reflection on how it is known – because according to Heidegger, separating the experience from the conscious knowing of the experience was not possible (Laverty, 2003; van Manen, 1990). In the case of my topic, a descriptive approach might look at uncovering constructs of the failure experience universal to scientific communities without being influenced by my worldviews and experiences of failure, whereas an interpretive approach would focus on the participants' experiencing and interpreting of their experiences of failure with the addition of my own interpretations of both the experience and the participants' meaning-making.

Rationalizing Hermeneutics as Methodology

Because of my interest in understanding students' experiences and their meaning-making through those experiences, the hermeneutic perspective championed by Heidegger, Gadamer, and van Manen best suits my purposes. I hope to know how students describe failure and what meaning-making occurs through "scientific failure" but cannot guarantee that what I find can characterize more than my immediate population of undergraduate student research experiences. Hermeneutics, unlike pure phenomenology, makes explicit the researcher bias and standpoint and allows for the researcher to be a part of the interpretive process along with the participant. This approach essentially elevates the lived experience of individuals as a way of knowing, conveying that there is more to reality than just an external reality, but gives weight to the meanings of the experience co-constructed in the interactions between the researcher and participant (Laverty, 2003; van Manen, 2016). This methodology is grounded in the principle that meaning is a result of experiencing a phenomenon and interpreting it whilst embedded in the context of one's prior experiences. Hermeneutic phenomenology suits the study of sense-making within a community of practice as the methodology is founded on the idea the meaning is developed, shared, and situated within a context without which it cannot be understood (Prasad, 2008; Laverty, 2003; McCaffrey et al., 2012). Indeed, epistemic practices are also based on the same interpretivist approach to knowing (Kelly & Licona, 2018).

My foray into the literature of hermeneutics has led me to believe that this lens would best suit the study of the experience of scientific failure. This may sound contradictory to some scholars as both established (e.g., Gadamer, 1968; as cited in Moules et al. 2017) and newer scholars (e.g., Caputo, 2007) made a point to distinguish the lofty search for universal truths and objectivity of scientific pursuit from the nuanced finitude (the limits to understanding inherent to any study) and uncertainties of hermeneutic work. I want to address these concerns in concert with why I believe hermeneutics particularly well suited for this study.

First, the emergence of hermeneutics as a study of philosophical and theological texts to elicit deeper meaning led to later scholars translating that methodology into the study of additional mediums of language, such as discourse (e.g. Ricoeur, 1976; Merleau-Ponty, 1982). This allows for the study of meaning that emerges from the descriptions of experience that participants share through interviews. Particularly in the context of such rich experiences as scientific failure, the dialogue between the researcher and the participant allows for reflective meaning-making. Here, it is not the idealized pursuit of truth that comes under the scope of hermeneutics, but the reflection on the experience of pursuing scientific truths. What meaning is grasped from this very human experience certainly falls under the auspices of hermeneutic study.

Second, one of the arguments that I would like to make is that scientific failure is a rather unique phenomenon in comparison with "failure" in general. Hermeneutics allows me that given its preoccupation with context as necessary to understand language. Schleiermacher (1768-1834) in particular "saw understanding in language as made up of two elements: the expression of thought by one person, and in its reception and comprehension by another" (Moules et al., 2017, p.11). Why is it that when someone says failure in terms of academics, we immediately attach a negative connotation, but when a scientist talks about failure, it can have more positive associations (as described in popular science books – e.g. Firestein, 2015; or in peer-reviewed publications – e.g. Simpson & Maltese, 2017)? This study allows for us to investigate how the context of a scientific community of practice may reframe how an experience is understood.

Third, hermeneutics takes issue with the terms "subjective" and "objective", as Heidegger (1889-1976) was clear to point out that what is important is what meaning is made internally when humans interact with the external world, what Dilthey (1833-1911) coined as "lived experience" (Dilthey, 1900/1901). Because existence is experienced through the senses, all interpretation is filtered through thought and communicated through language. Thus, to study the natural world, one is still constrained by the very means by which we study and express our understanding. In studying a phenomenon such as scientific failure, this notion allows us to examine all that is human about the scientific enterprise. How we define the act of failure, how we encounter it, and how we respond to it all can be rooted in the historicity of the disciplines of science as well as the experiences that make us who we are.

Finally, the most convincing arguments for a hermeneutics lens are found in the writings of Kockelmans (1997) and Heelan (1998), philosophers of science who argued that science itself utilizes and is built upon hermeneutic concepts. Take the necessary act of referencing prior work! In the very act of contextualizing one's findings in the larger body of knowledge, both present and historical, scientists engage in a hermeneutic circle of interpreting their work. In addition, "all forms of scientific description, explanation, and understanding are sophisticated forms of interpretation. A scientist does not state what a thing is, but merely how it will appear under a given number of assumptions... From the preceding historical observation, it is clear that scientists… always project the phenomena they are dealing with upon a framework of meaning that is accepted in advance, and to some degree at least accepted independently of the observed phenomena… The important thing to note here is that all scientific work is done within a hermeneutic circle, which no science can ever overcome" (Kockelmans, 1993b, p. 35). Kockelmans' description of the scientific process as making sense of data, working from a body of existing knowledge and an embedded in an established community of practice, reads as hermeneutic practice. The accompanying figure summarizes how certain tenets of the philosophy of science parallel hermeneutic philosophy as described in the text above.

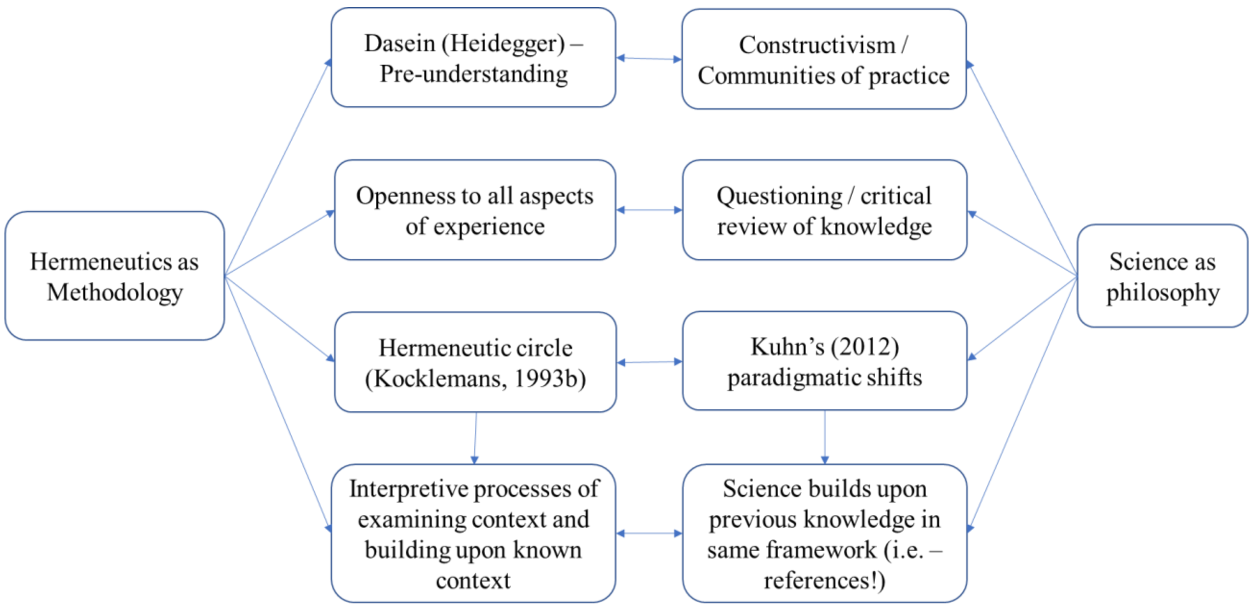


Figure 3.1. Principles of hermeneutic methodology as paralleling tenets of science philosophy

While the above sections brought up hermeneutic principles in broad, sweeping strokes, the remaining sections in this methods chapter will touch upon further principles as relevant to the data and the analysis. These sections communicate the approach taken to investigate undergraduates' experience of scientific failure in research settings, built upon principles of hermeneutic phenomenology.

Reflection on Sense-making as Central to Understanding

As hermeneutic philosophy involves making transparent the processes of interpretation (Ricoeur, 1976; Gadamer, 1988), a key question in every hermeneutic endeavor concerns understanding how an experience is experienced, i.e., how participants make sense of the experience. In Ricoeur's *Interpretation Theory* (1976), a treatise on meaning, he summarized that "It is not the event insofar as it is transient that we want to understand, but its meaning – the intertwining of noun and verb, to speak like Plato – insofar as it endures" (p. 12). He communicated that meaning endures beyond the experience itself and is what makes an experience relatable across individuals. Dialogue then becomes a way to communicate shared meanings. Hermeneutic analysis offers an additional layer of meaning-making through the interaction of text (interview transcripts and analytic memos) and researcher in the investigation of what meaning was wrought within dialogue (interview). As such, hermeneutics is the process of interpretation made transparent and analysis makes clear how experiencers understand or make meaning of a phenomenon. The nature of understanding is made clear in Riceour's distinction between explanation and understanding, that "in explanation, we ex-plicate or unfold the range of propositions and meanings, whereas in understanding, we comprehend or grasp as a whole the chain of partial meanings in one act of synthesis" (p. 72). We generate meanings through cognitive engagement with a phenomenon and understanding that phenomenon in full comes from the act of synthesizing those meanings. Accordingly, the act of translating students' understanding of scientific failure comes from breaking down what meanings emerged in their making sense of the experience.

The literature in science education also makes clear the importance of sense-making to conceptual learning. Odden and Russ (2019) generated a comprehensive definition of sense-making based on the literature on the topic, writing that "sensemaking is a dynamic process of building or revising an explanation in order to "figure something out"—to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's understanding. One builds this explanation out of a mix of everyday knowledge and formal knowledge by iteratively proposing and connecting up different ideas on the subject. One also simultaneously checks that those connections and ideas are coherent, both with one another and with other ideas in one's knowledge system" (p.192-193). This builds upon constructivist theories of learning and resonates with the core of Posner and colleagues' conceptual change theory (1982) by starting the sense-making process with a perceived inconsistency in understanding. If inconsistencies or gaps provide the impetus for sense-making, then the experience of scientific failure seems a logical focus for the study of sense-making processes. Using hermeneutical methods to understand how students experienced failure in scientific settings meant establishing what meaning they made within the experience and the process whereby they made meaning. The core of this investigation captured what meaning was made through nine students' experiences. Additionally, survey responses indicated that sense-making could have a more universal basis even when students' actual experiences diverged.

RESEARCH DESIGN

Study Context

This study takes place at the level of undergraduate study and through the selection of experiences that fit the criteria of natural science research activities. The study was entirely based in one doctoral institution of highest research activity that can also be categorized as a predominantly white institution. This institution identifies as a public land-grant university in the south-east region of the United States. During the time that data collection began, an international pandemic had necessitated drastic changes to university attendance and subsequently, undergraduate research participation. Students engaged with each other and with faculty remotely and virtually.

Participants

I anticipated that data collection would rely solely on survey responses and interviews with select participants, the latter being central to hermeneutic study. I gathered participants through an organization within the university which held an annual symposium showcasing the results of students' research experiences. From their publicly available synopses of student presentations, I identified students who had participated in this symposium and presented on research in the natural sciences in 2019 and 2020. I tracked down the e-mail addresses of the students and determined if they were still undergraduate students. A total of 357 students were e-mailed a link to a Qualtrics survey in April 2020. Initial survey participation was very poor, potentially as this took place only weeks after pandemic restrictions had taken effect. I incentivized student participation in June 2020 by offering to donate $10 to a charitable organization of their choice (out of a list of six options – list and breakdown of charity donations attached at the end of Appendix A). By the time the survey was closed in October 2020, 91 students had participated, but only 68 participants had completed the survey. The survey sent to the identified students asked for descriptions of their failure experiences. I characterized their responses to answer RQ1. Due to the focus of my study being the experience of scientific failure, the survey was meant to elicit those students who had extensive research experience (two or more semesters in the same research setting, a recommendation that comes out of Sadler & McKinney, 2010) and those who believed they had experienced scientific failure. Though I had initially hoped to have enough participants willing to participate in interview that I could selectively include based on pre-determined criteria, I realized quickly that would not be the case. In the end, those students who indicated that they were amenable to being interviewed were contacted about participating in one. The interview data thus incorporates the analysis of 9 students' experiences. I conducted one-on-one interviews to provide rich descriptions to answer the remaining research questions focused on participants' meaning-making around the failure experience and any connections made to scientific epistemologies. Interviews ranged from 55-90 minutes. The undergraduate students who participated in this study ranged in demographics: from age to racial or ethnic backgrounds, to background experiences bringing them to this experience, to the intended majors.

DATA AND ANALYSIS – RQ1

RQ1. How do undergraduate students engaged in scientific research describe their experiences of scientific failure?

Data – Description and Examples

This section describes the data gathered for the purposes of answering this research question and the methods used to gather that data. Whilst the previous section mentioned the survey, this section provides further detail about the development of the survey and the questions asked.

The survey used in this study underwent several revisions prior to distribution. An initial version was created for a broader population of undergraduate students and after feedback from a group of education researchers about some of the questions used, revised for use in that context. After finalizing a population of study in my prospectus for this project, the survey questions were tailored for this study, and underwent final revisions based on feedback from my faculty committee. The questions in the survey serve multiple purposes. Table 3.1 provides these goals, some examples of the questions in the survey, and some examples of student responses to those questions.

Table 3.1

Example of survey questions

Purpose: *To gather a brief description of…*	**Example Questions**	**Example Responses from Participants**
The participant's research and potentially an indication of their role	Please describe your research experience briefly (no more than 3 sentences about the project and your role in it).	"I conducted plant genomic research where we exposed different cultivars of a crop to different environmental conditions. From that point we took note of their survivability under those conditions and performed transcriptome analysis on tissues collected from the plants after the treatment, while collecting the same information from control groups. By doing this we could find differences in gene expression under the given conditions."
Their failure in that context	What did the failure experience look like? (Please describe the scenario in which you experienced this scientific failure) How did you respond to the scientific failure experience?	"Inability to move on in a research project because of something. In my case, this was a lack of time from an advisor to help me move on and learn in my project."
Their definition of scientific failure	Based on your response to the questions above, how do you define failure in science? Please give a few synonyms for failure in science - a word you might use to talk about the experience without using the word "failure":	"Now I define failure as giving up or not learning from what you're doing in the lab. I don't define failure by the outcomes of my experiments." "Failure in science is when you receive an unexpected outcome that's not part of normal results" "Failure is what you learn from. It bring about better techniques and skills." "negligence; carelessness; ill-planned; doomed" "Unexpected. Mistake. Overlooked. Underwhelming. Repetition." "Misstep, obstacle, challenge, setback."
How they perceived	How is failure in science	"I do not think the experiences are at all

failure in scientific research relating to failure in science learning	related to failure you could experience in learning science? (If they are the same or different, please describe why.)	similar. Learning science in a classroom setting has no novelty or discovery aspect to it; you are learning already established facts and your performance has more to do with effort than anything else. Conducting science often does not have clearly defined end goals and has failure is very often unavoidable in the lab. Its somewhat paradoxical; if you knew your experiment would not fail, then it wouldn't be very novel."
How their identities affected their perception of failure	Which identities are personally important to you? Do you believe any of your identities has an impact on how you view or experience failure in science? If "yes" selected: How do you believe your identities impact your experience of failure in science?	"I think as a female there is a lot of pressure to "make it" in the sciences. I haven't felt that pressure from anyone in my lab, but I take that pressure with me wherever I go because I know that it is both difficult and a privilege to be a woman in STEM." "I think the culture I was raised in was one with a reverence for the seeking of truth and fact as well as a respect for the discoveries of the past as well as the institution of teaching but these values may be more familial than cultural"

Additional questions (not displayed here) allowed me more insight into students' definitions of failure through creative uses of language (synonyms and similes/metaphors) that students could use to describe the scientific failure experience. The final version of the survey is attached as Appendix A. The following section walks through the analysis of student responses and how they were used to answer question RQ1.

RQ1 Analysis

I characterized the open-ended survey responses from participants through thematic analysis (Braun & Clarke, 2006). Thematic analysis serves "to theorize the sociocultural contexts, and structural conditions, that enable the individual accounts that are provided" (Braun & Clarke, 2006, p. 85). As this method of analysis is not tied to any methodological framework, it has the flexibility to work across them to develop some understanding of the underlying structures that facilitate student descriptions of the failure experience. While van Manen (1990) and Freeman (2016) describe a hermeneutic approach to thematic analysis – developing rich textural descriptions of experience interwoven with reflective statements – in this case, I chose to operate with an atheoretical lens to simply categorize how students depicted failure in their research settings. After familiarizing myself with the data by reading and rereading the survey responses across all the questions and across each individual participant, I began the coding process. Figure 3.2 below provides an overview of the process.

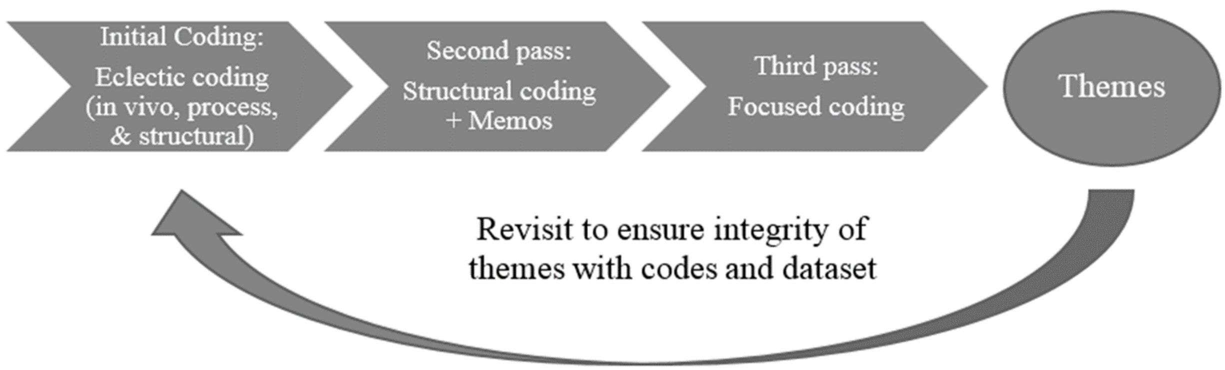


Figure 3.2. Visualizing the thematic analysis process

Initial Coding. Responses were downloaded from Qualtrics as a Microsoft Excel document, then separated into sheets based on the purpose of the questions. One sheet preserved individual participant responses grouped by the individual, so that I could also conduct a more holistic coding of participants. The first step involved reading and rereading the survey responses and briefly noting codes. Initial coding followed Saldaña's (2015) conception of Eclectic coding, a term to describe the intentional combination of different coding processes. In this case, I coded the dataset with In Vivo coding, Process coding, and Structural coding in mind.

In Vivo coding respects the participant voice by using words or phrases from the participant's response to code a segment of data. I chose this coding process as I did not want to stray too far from the participants' actual responses given the already succinct nature of survey responses. Process coding captures "action/interaction and consequences, and the documentation of routines and rituals" (Saldana, 2015, p. 296). I found this type of coding essential to capture how students described their actions in the laboratory space, their roles in research projects, and their responses to failure. Structural coding describes the application of general codes to segments that directly relates to the research question. I used this code as a categorization code in the first pass analysis. Below is an example of how I used this coding process.

Quotation	Structural Code
"I think failure in science would be not learning from the experience. Because at the end of the day whether or not research or a particular project even goes till completion, you still gain valuable experience in the research process, which to me is what it's all about to begin with. "	Failure as not learning

Initial coding began as the responses were received, without waiting for the closure of the survey. This meant that as I received and included new responses, I coded these with an understanding built from previous responses, and that I revisited previous codes with any insights gained from the new responses. This continuous revisiting of the codes drew from the hermeneutic circle described earlier as one of the founding tenets of this methodology.

Second-pass coding. According to Braun & Clarke (2006), a key element to the analytic procedure is that equal attention is paid to all aspects of the data in order to maintain a systematic approach. I first organized the codes into categories that broadly tied the codes based on either similarity – defined as commonalities of constructs – or contiguity – defined as the relationship between or influence of one text and/on another slice of text (Maxwell & Miller, 2008). I attempted to keep true to the language of the participants, which meant using direct quotations from student responses as group codes. Structural codes from the earlier pass were reconsidered in light of the entire data set and, if possible, re-named with participant language. At this point, I re-assessed the entire dataset of survey responses with the complete list of codes, with any additions/changes made in the second pass – including adding new codes, changing the text of prior codes, or reshuffling the codes in their categories. I also began developing analytic memos (as described by Saldaña, 2015) to keep track of my reflections on the data. Any patterns that emerged in the process of memoing were made into codes that had not been identified in the first or second pass analysis that were then used deductively in the third pass of the analysis. The combination of a structured analysis (thematic analysis) and an unstructured tool (memoing) allows me to systematically consolidate ideas in the data, but also allows me to be reflective.

Third-pass coding. A final pass of the data utilized focused coding to develop the themes present in the data. Focused coding brought together coded sections of the data based on conceptual similarity and looked for ideas prevalent most often in the data to give a robust basis for the themes. I also coded the analytic memos for any patterns found. At this point in the process, I developed a concept map of codes and did a final reorganization of the codes using this interactive visual format. Through the visual emerged four themes of scientific failure as experienced by undergraduate students engaged in scientific research. The initial concept map (prior to reorganization) is included in Figure 3.3. A final concept map that led to the themes is included in the next chapter.

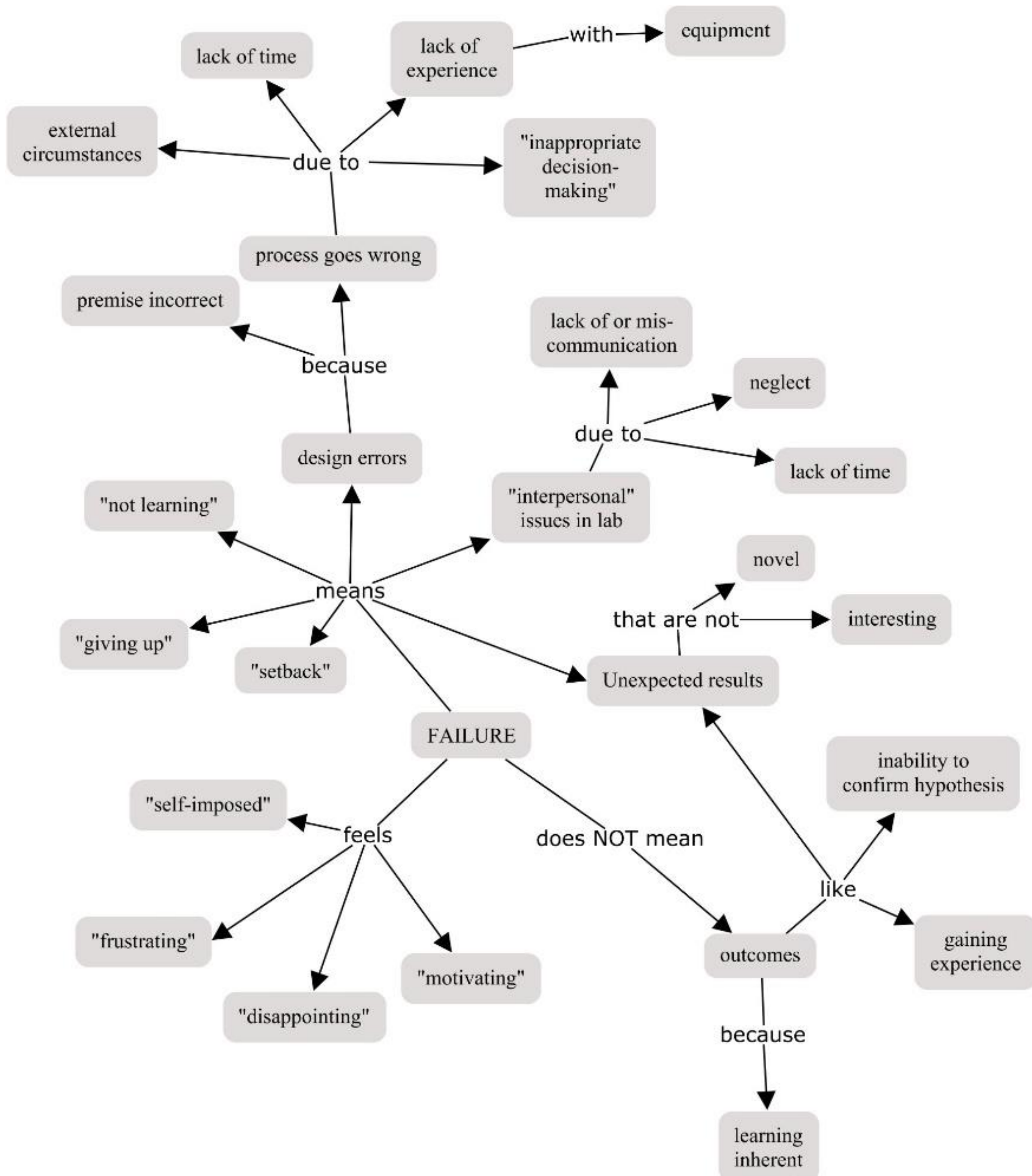


Figure 3.3. Initial concept map of codes developed from survey responses to categorize failure

DATA AND ANALYSIS – RQ2a & RQ2b

RQ2a. How do undergraduate students make meaning of their scientific failure experiences?
RQ2b. How do the experiences of failure described aid the students in constructing their understanding of the scientific enterprise?

Data – Description and Examples

This section describes the data gathered for the purposes of answering these research questions and provides more detail about the interview structure meant to elicit a full picture of the student experience.

I developed an initial interview protocol to follow phenomenological principles (see, Bevan, 2014; Høffding & Martiny, 2016) of interviewing, which championed an open or semi-structured interview design. What results is more of a dialogue, where the participant is treated as the expert on the phenomenon being investigated and the interview meant to gently nudge them into lines of conversation to produce maximum detail about the phenomenon. The rationale for this puts a greater burden on the interviewer-in-the-moment, to follow certain threads of dialogue and to be so closely attuned to the phenomenon as to recognize and deepen conversations at key points. I realized that my level of experience with phenomenological research (zero) did not qualify me to be an experienced interviewer under this framework, so the next revision included guiding questions to help me approach certain aspects of the failure experience in case the participant did not bring it up themselves. Further reading on structuring interviews for hermeneutic study led me to revise my interview protocol further to add questions to develop context for the experience as well as to understand what about a participant's prior experiences may have influenced their experience of failure. The next iteration of the interview protocol also included questions to establish students' epistemological thinking prior to their failure experience and to whatever changes may have occurred because of the failure experience.

I piloted this interview protocol with two volunteer students, a first-year graduate student and a matriculated undergraduate student in the sciences and made minor revisions to the protocol at that point. Final revisions were made after presenting this protocol to a group of researchers, who provided additional minor feedback. The final version of the protocol, with the rationale behind the inclusion of each of the questions, is attached in Appendix B.

The interviews themselves ranged from 55-90 minutes. Interviewing through the lens of hermeneutic phenomenology can be equated to engaging with the participant in reflecting on the experience. Together, the participant and researcher construct and clarify their understanding of the experience and through that the phenomenon, through Socratic-like questioning (Dinkins, 2005; as cited in Roulston, 2010). A volunteer for one of the pilot interviews actually recommended that I be explicit about the reflective process, so that the actual participants understood that they could take time to silently reflect. My interviews began with students telling me of their work in the research setting, then describing what they experienced as scientific failure, and how they responded to that. This part of the interview was left as open as possible to allow the dialogue freedom to explore the topic in depth. Here, I engaged all the participants in explaining how they approached and experienced their failures, and how that led to their definition of failure. We played with what may have made that experience not a failure and imagined what skills or abilities might have changed their response to failure. I listened to their explanations and challenged contradictions and welcomed their insights. The hermeneutic aspect of the interviews also came through in the way some students came to some new realizations about their experience through the interview, and I came away with more questions than answers!

Having conducted the interviews, I transcribed them, also including time for pauses and any articulations that expressed pauses (for example: "uh…", "um"). The audio files were then uploaded to the Temi transcription service because of the platform's ability to link audio files with the text file. I replaced the automatically generated transcripts with my own transcripts, and then downloaded the linked file into MAXQDA. As mentioned earlier, I invited students to participate in the interviews if they demonstrated a willingness to do so in the survey. Only then were they able to share personal identification so that I could contact them. Because they opted to be identified in the survey, I was also able to bring up their survey responses during the interview to clarify their survey statements further. I added any details that the students provided in the surveys that were not brought up in the interview to the end of the transcript so that I could have all of data related to any one interview participant on one document. These transcripts were then used for hermeneutic analysis. The following section walks through the analysis of participant interviews and how they were used to answer question RQ1.

RQ2a & RQ2b Analysis

To answer RQ2a and RQ2b, the strategies for analysis relied on the philosophical underpinnings of hermeneutics. As said earlier, hermeneutics highlights the subjective experience, making the interpretation of the experience more valuable than the particulars that make up the experience. Thus, hermeneutic analysis does not seek to find an essential Truth but uses dialogue and reflection to uncover the full reality of an experience. In order to make clear the obscure, the interview transcript undergoes multiple iterations of analysis looking at elements of language, and of meaning. Analysis in hermeneutics resembles interpretation in other contexts, because of the centrality of reflexive writing (McCaffrey et al., 2012). van Manen describes this experience further, writing that through reflective analysis, we "attempt to grasp the pedagogical essence of a certain experience" (1990, p. 78) – that by orienting reflection towards the experience under study, the goal of analysis is to experience that phenomenon as though it is the researcher's own lived experience.

The overall analysis can be described as following Moules and colleagues' (2015) guidelines for hermeneutic analysis, specifically that "it is divergent rather than convergent: it involves carefully opening up associations that strengthen understanding of the topic rather than focusing in on a single governing theme… analysis is interpretation" (p. 116). Suddick et al. (2020) brought this concept home through their detailed depiction of a hermeneutical study. They explicitly laid out the steps involved in each step of hermeneutical analysis. In concert with the principles of hermeneutics, these steps were not necessarily practical ones, but conceptual ways by which to engage with the interview data.

To be clear about the analytical process, I have to admit that I did not analyze the data with Suddick and colleagues (2020) framework guiding me from the beginning. Their work would have been the Virgil to my Dante, providing a check to my thinking on this analytic journey. But unlike Dante, whose journey through the perils of Inferno was directed by the epitome of wisdom and rational thinking, I let myself learn through trial and error and let failure develop my wisdom around hermeneutics. Instead, I found their work particularly comforting as it echoed my own process of learning how to conduct hermeneutic work and provided an excellent graphic synopsis of the entire process (Figure 1, p. 10), that I adapted to describe my process further below. The following paragraphs explains my initial attempts and subsequently, how this led me nowhere with analysis.

Initial Attempts. The first step I took involved careful reading and rereading the interview transcript and writing memos (Lempert, 2007; Saldaña, 2015) about any aspect of the responses that caught my attention in each of the transcripts, using the framework as a guide to thinking about the responses. The second step involved grouping together similar ideas that were present across the data. Identifying themes was not a goal of this analysis, but emerging themes from the data helped group or separate participant responses such that the complexity and richness of the failure experience could be more wholly elaborated upon. The third step to analysis involved deliberate engagement with the concept of the hermeneutic circle. This concept conveyed that meaning evolved out of an "iterative spiral of understanding" (Prasad, 2008, p. 34) – that to understand a text/phenomenon, one had to take into account the societal and cultural context, but that the context was also mediated in turn by the text/phenomenon. At an analytical level, this also included thinking about particular pieces of data in the context of the individual experiencer and the whole experience.

Initial attempts at analysis met with dead-ends as I did not synthesize the experiences that participants described to obtain a coherent and complete picture, nor did I engage with the data meaningfully. My analysis looked and felt superficial, and I grappled with both insecurities about my research as well as with my framework. Upon re-reading Moules and colleagues' (2015) suggestions on hermeneutic analysis, one line stood out as being the precise error I had made, that:

> "…the purpose in hermeneutic research is to bring understanding around the topic; the participants in the study are not the topic but are chose to bring their knowledge about, and to, the topic. Therefore, the *goal is not to describe the participants fully, nor to conserve their stories and experiences intact, but rather to listen* to what participants have to say for that which will cast *new light* on the topic and expand our understanding of the phenomenon we are attending to in the conversation." (p.123, italics added for emphasis)

My errors had included trying to center my analysis on the participants, rather than their experiences, and to try to fit their experiences into the conceptual framework of failure that I had constructed, rather than build understanding from their experiences *before* seeing if the framework was at all useful. My final point of tension was with the hermeneutic circle, as my mind just seemed to regard it as mental acrobatics, juggling between granular details and macroscopic thinking about segments of data. Instead, I came to regard it as a cycle by which understanding an experience is made richer through the constant re-engaging with that experience. In articulating it as a cycle and seeing my own learning of hermeneutics as part of that cycle, I cleared this hurdle to a more coherent analysis.

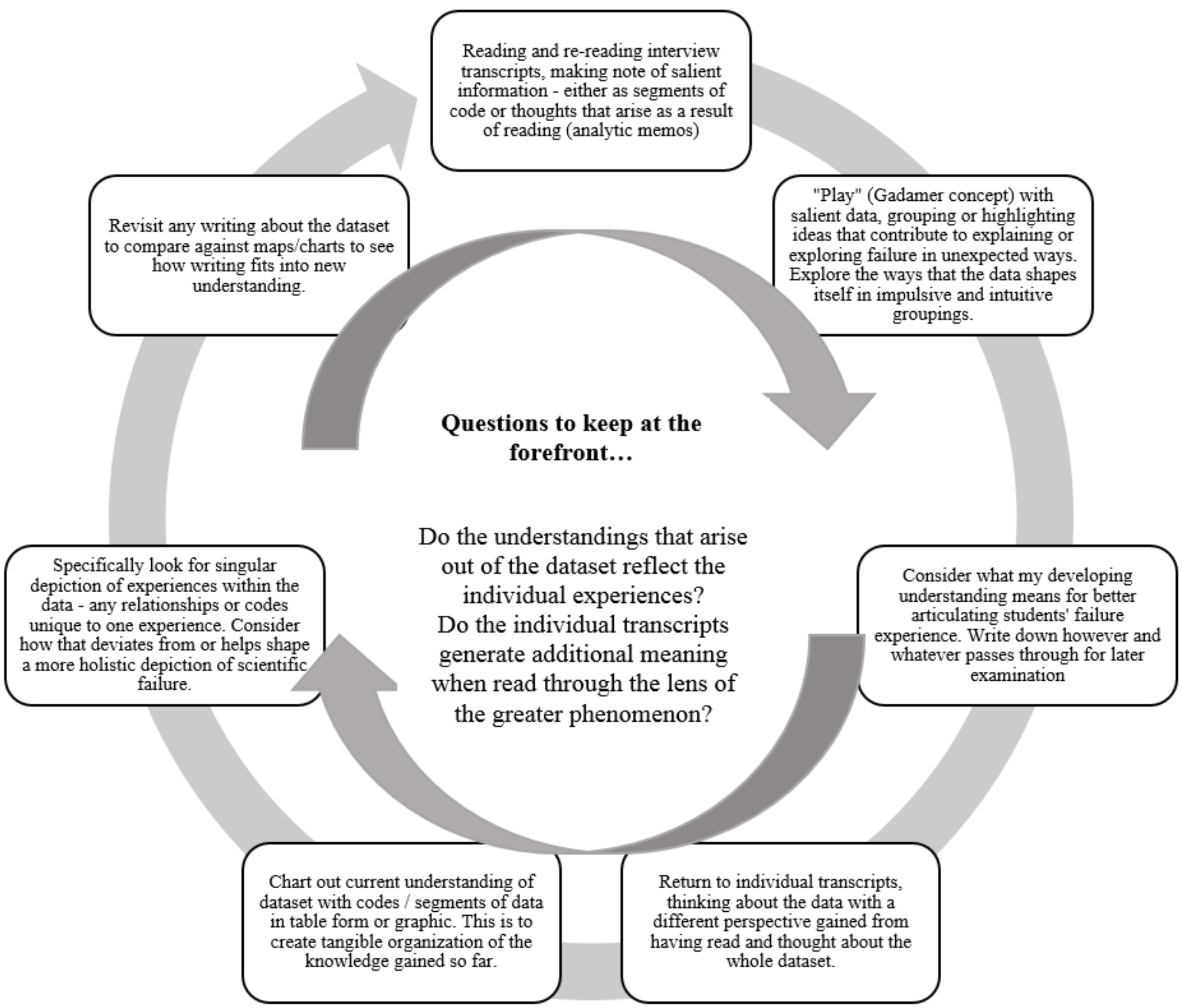
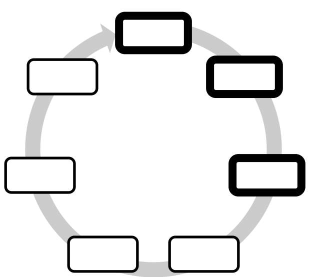


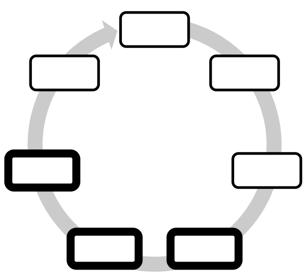
Figure 3.4. Visualizing the hermeneutic analysis process, adapted from Suddick and colleagues (2020)

A Deeper Analysis. Now, I describe my next attempts at analysis, undertaken with a burgeoning understanding of hermeneutics methods and principles, and using an adaptation of the figure initially developed by Suddick and colleagues (2020) to better visualize how each part of the process contributed to the whole.

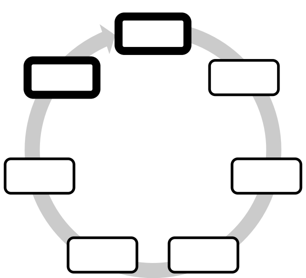
Figure 3.4 depicts how analysis of the interview transcripts began and progressed through repeated cycles of engagement with the data. It reads as a physical exercise, an active dialogue between the researcher and the data. In essence, this takes hermeneutic methods back to its inception as a form of deep textual analysis. This communicates how in hermeneutic analysis, the interview participants become part of a narrative bigger than themselves; how they, as individuals, become secondary to the description of their experiences, all of which are woven into the tapestry of the phenomenon of scientific failure. This conversation with the data becomes central to the analytic process, a back-and-forth dialogue from which emerges an understanding of students' experiences as it answers my research questions.



Developing an Initial Understanding. In redoing my analysis, I started at the beginning. I read and reread, one transcript at a time, annotating the transcripts with comments and questions that arose in my mind, referring to participants' previous statements or comments. I reread my own annotations, exploring patterns in students' thinking or anomalies in their statements. I "played" with the data, a concept that Gadamer espoused in *Truth and Method* as central to engagement with the experience filtered as it was through the data. Playing with the data meant fully absorbing oneself in the data as a medium of expression for the experience and being responsive to the ebb and flow of information in that zone. In practice, that meant engaging for days at a time in thinking about the data, allowing it to percolate at the back of my mind at all times, and jotting down thoughts as they arose, examining salient data points from perspectives present and imagined. Moules and colleagues (2015) make a great analogy, comparing this process to that of examining works of art. All observers of art come away with different feelings and thoughts and perspectives about the art, but in engaging with that work, share an external experience with the artist and others who have engaged with that work, and are themselves changed (p. 43). Playing with the experiences of scientific failure as experienced by my participants meant approaching a shared mental space with them, and in doing so, developing understandings that were perhaps unique because of my own prior experiences with failure. This then led to my writing any musings that this process elicited and reflecting upon the reflections to see what understandings particular to that research question this process developed. It was in engaging in this step that I realized how deeply extensive the reflection in the hermeneutics process had to be.



Contextualizing Findings. Once I conceived an initial understanding of the data, both as individual experiences and as a narrative of a larger phenomenon, I returned to the transcripts to further develop my thinking. At this time, I did engage in coding the document again. The first time through this process, I used Structural coding (as defined by Saldaña, 2015 and earlier in this chapter in the analysis section for RQ1) in order to target those responses I thought addressed my research questions. However, though this coding method worked to group survey responses, in this instance, I found myself scanning for the questions asked by me in the role of the interviewer and coding only the responses to those, and not reading the rest of the interview transcript in full. I returned to the beginning of this phase, this time using a combination of Process coding and Versus coding. Process coding let me focus more on the actions involved about and around failure, and Versus coding caught instances where students juxtaposed descriptions of failure against other ideas. This combination coding led to a development of a map to sort out all the ideas developed thus far. In my first iteration of this process, the map was more of a visual jumble of shapes, with no organizing principles or thoughts. Though daunting, it accurately reflected the overwhelming tumble of thoughts and codes that a first pass of the data generated. Without trying to make sense of that, I returned to the individual transcripts to see if anything stood out as particularly unique, an outlier of experience that could contribute further to an understanding of scientific failure in undergraduate research. In particular, I looked for what could further broaden or bound what Gadamer (2004) calls the researcher's horizon of understanding, the limit to which I could *see* the phenomenon in the data.



Writing and Re-turning. The next phase took me back to the writing and mapping that I had compiled of the data with the lens of my extended horizon of understanding. I added to my reflections on the data, writing and mapping where relevant and organizing my thoughts if possible. This was not an end, but a bridge back to the individual transcripts. In returning to the data, transcript by transcript, I added the lens of the research questions, one at a time. More comfortable in embedding myself in the data, I could now add a filter to the reading of the data as to how, if at all, the data answered the study's driving questions. I re-engaged in this process from the beginning, re-turning the hermeneutic circle adding new angles for thought. Through this, I added and rejected some conceptions of meaning-making in the failure experience or the presence of epistemological thinking through failure. As this continued, I reached a point where my writing and mapping gained coherence and clarity. Once I did not have anything left to add, remove, or change, I ended the analytic process.

To conclude, I have to state that this figure does not fully capture how my process culminated in my results, as it implies a never-ending engagement with the data. I did indeed engage iteratively with the dataset, analytical steps, and my own understandings, but in order to complete the dissertation, I had to decide on stopping somewhere! Had I the creativity to generate such an image, the one that would most accurately capture the process would be a spiral that would show the multiple occasions of revisiting data but also come to a definitive end at my results. A spiral would also more accurately depict how the iterative loops did not necessarily tread the same ground at each revisiting, and also how the loops led to a tighter conclusion towards those end results, as less changed with the data available to me. Hermeneutic principles convey that one can never truly come to an end in this circle of being, as one is constantly experiencing, and thus constantly revisiting the meaning of prior and present experiences. While that makes for sound philosophy, again, it does not a finished dissertation make. So, though I will continue to use this depiction in the discussion of my analysis, I have to be clear about having arrived at an end point!

Anticipated Limitations due to Methods

Before the project began, I recognized that there were limitations to the study that would provide checks on the extent to which I will be able to generalize my results. Generalization is not the goal of the current investigation, but thus far I have talked about scientific failure in largely general terms (and with no specificity to any particular discipline). The rationale for this stems from the lack of knowledge on failure. As there is no theoretical or empirical work that directly establishes failure as an epistemologically valuable experience in science, I decided to discuss scientific failure as a general term to be able to draw upon a larger literature base in developing the theoretical basis of and justifications for this study. This also allows me to draw from a larger student population, but the value (and constraints) of this may only become evident through data collection.

I have earlier provided justification for my choice of participants – undergraduate students who enrolled in research experiences and can describe having experienced (what I have earlier described as) scientific failure in that setting. Given the nature of the university setting, I expected that the students' research experiences to be limited to the laboratory setting, and their responses about the experience to be limited to lab-based scientific activities. This severely limits the breadth of what scientific activity and potentially scientific failure can encompass, but as the phenomenon I aim to investigate in this project is the *undergraduate* experience of scientific failure, the context of the phenomenon and the interpretations that can be made is already bound.

In addition, given hermeneutic phenomenological study's reliance on participants' descriptors and explanations, I recognize that language is another limitation of this work. This could affect how students respond to the survey, in the selection of interviews participants, and in analyzing and interpreting the responses collected through both survey and interviews. Failure is a term that is used in a variety of contexts and requires context to be made sense of. I have attempted to constrain students' responses to failure in the scientific setting by selecting students who participated in natural science research, by indicating "scientific failure" in the survey, and in using my definition of scientific failure (found on p. 24) to choose interview participants. I hope to mitigate any effect of language on my understanding of students' interview responses by being as thorough as possible in the interview in capturing students' experiences.

CHAPTER 4

THEMES OF FAILURE IN SCIENCE

Overview of Chapter

This chapter explores the results of the analysis for the following questions:

RQ1. How do undergraduate students engaged in scientific research describe their experiences of scientific failure?

First, I offer a brief summary of the survey data, and then proceed with the results of the analyses. Then, I describe the results of analysis guided by the question asked of the survey responses. In alignment with the principles of hermeneutic phenomenology, I have centered my discussion on the failure experience and not the students, going so far as to refer to responses as "one student", "another student", etc.. This is done at the suggestion of Moules and colleagues (2014).

Descriptive Summary of Survey Data

The methods section briefly described the purposes of the survey to (1) gather students' descriptions of failure experiences and (2) to solicit participation in the interview. Table 4.1 provides the exact number of responses to the survey. Because of the attrition in survey completion, I share this to be transparent about the number of responses per question that the thematic analysis drew upon.

Table 4.1

Descriptive Survey Data

Queries	Numbers
Total respondents	91
Completed surveys	74
Descriptions of research experiences	80
Description of failure experiences?	68
Students who did not experience failure but provided a definition	6
Total definitions of failure	68
Responses to failure in science as related to learning	64
Demographics information (prospective major, post-graduation plans, race/ethnicity, gender identity, etc.)	68

The literature on students' experiences provides strong evidence for the impact of their identities (and the intersection of multiple identities) on how students perceive and understand those experiences. However, because this study takes a hermeneutic phenomenological approach, the focus here is not on the multitude of students' identities, but how those identities provided context for their experience. Because the format of the survey did not allow for a deeper analysis of the nuances of identity interaction with failure, and thus could not do justice to this topic in the context of this dissertation, I did not attempt to draw any correlations between responses about students' experiences and any part of their identity.

Furthermore, providing additional demographic information through descriptive summary serves little purpose in the context of this study, other than to provide a general idea of the population of undergraduate students who participated in natural science research. I nevertheless present a brief synopsis of my survey participants, recognizing that no summary could do justice to these individuals as composite beings of myriad experiences and intersecting identities. On average, participants (who responded to the demographics questions, n = 68) had been full-time students for over 3.65 years. All but 2 participating students considered themselves domestic, United States-based students. Participants included 26 male students, 42 female students, and 1 student who identified as non-binary. Thirty-six students described themselves as white, 18 as being of Asian descent; 4 students as Latinx, 4 students as African American, and 4 additional students as having multiple racial/ethnic identities. Post-graduation plans showed that 38 students planned for graduate careers in science, 16 for medical or dental school, 6 for industry, and 3 for other professions. Students primarily identified by their career aspirations, then by their educational level, and then by traditional demographic qualifiers, like race/ethnicity and gender identity. Forty-four students remarked that their identities potentially influenced their views of failure, 10 did not believe there was a relationship, and 4 preferred not to respond to that question. This suggests a need for a further follow up on students' perception of the impact of identity on the experience of failure – a whole dissertation or study in itself!

The following section details the results of the thematic analysis that characterized the survey responses. As described in the previous chapter, the analysis went through iterative coding processes until themes emerged from code groupings.

RQ1 THEMATIC ANALYSIS RESULTS: CATEGORIZING FAILURES

Here, I present the results of the initial analysis conducted of the survey responses. In the previous chapter, I reviewed some of the questions asked of students in the survey, and examples of codes created in the sequential passes made of the data. Themes, as defined by Braun and Clarke (2006; Clarke & Braun, 2014), encapsulate semantic and latent ideas that present as patterns in the dataset. These patterns are codified based on the theoretical and/or methodological framework and guided by the research question. Through the process explained in Chapter 3, I arrived at four categories of failure experiences, presented here as emergent themes: (1) Failure as consequence; (2) Failure as expected; (3) Failure as lack of learning; and (4) Failure as intellectual and emotional dissonance. Once generated, I returned to the codes and to the data itself to confirm that the themes accurately captured the dataset.

This section presents the finalized themes, definitions and elaboration of those themes, and examples of quotations that best represent those themes. The presentation of the themes is organized by the salience in relation to the research question, which sought to categorize the experiences of failure as described by students. The themes most prevalent in the data is discussed first, followed by themes that, while less common in the data, provide unique insight into how students also described failure. Quotations are presented exactly as written by the students, with no changes made for grammatical considerations. One caveat to consider through the reading of this section is that due to the limitations of short-text survey responses, the elicited themes could not demonstrate the same level of complexity that emerged from the interview data. Figure 4.1 shows how the themes emerged out of a final grouping of codes in concept map form.

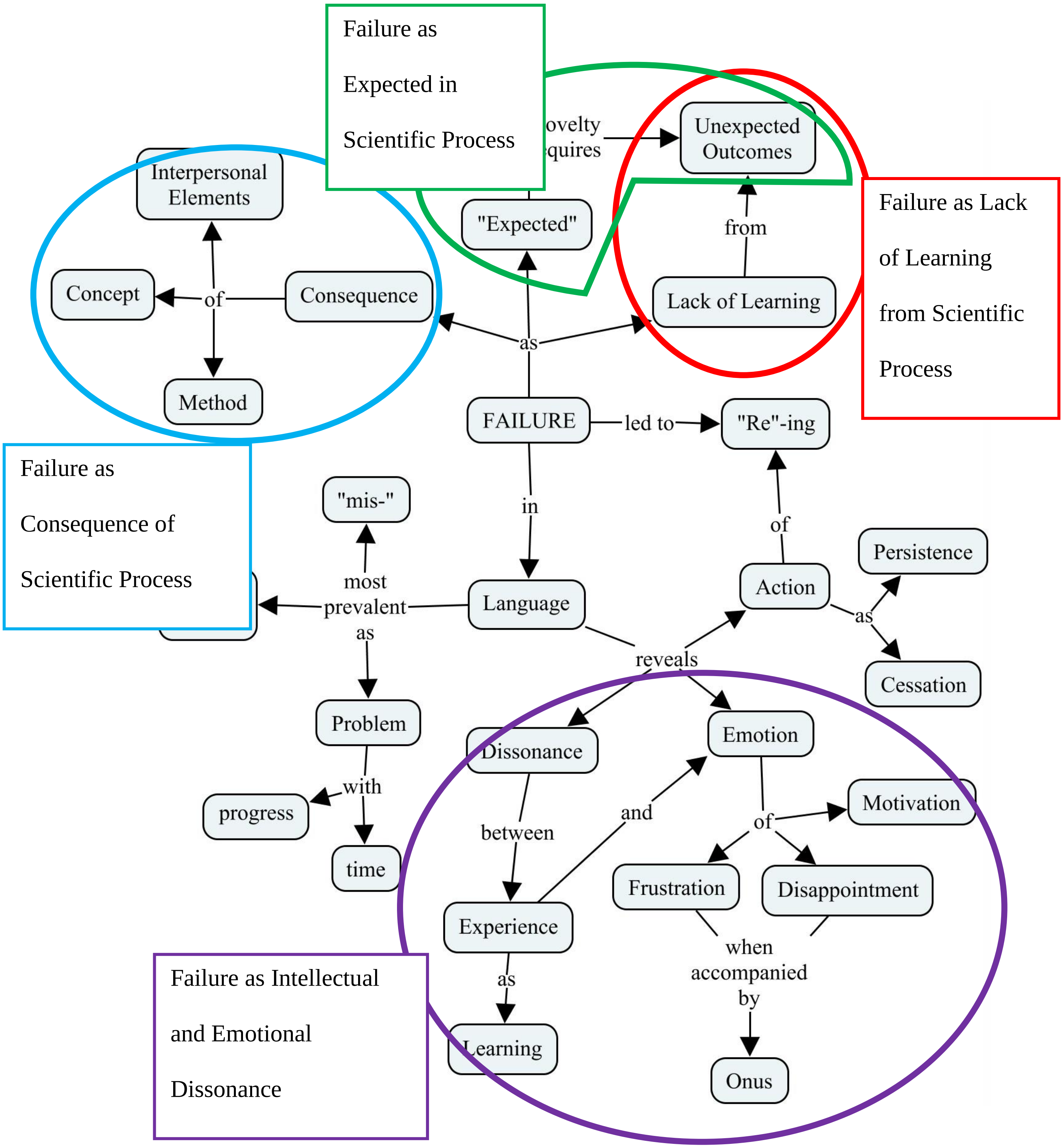


Figure 4.1. Final concept map of codes developed from survey responses to categorize failure. Reorganization led to the themes that emerged.

Theme 1: Failure as Consequence of the Scientific Process

In describing their experiences, most participants communicated the idea of consequence in their responses to queries about their experience and in defining scientific failure. "Consequence" communicated the (often) explicit meaning of an outcome preceded by three dimensions of action, thought, or behavior. Students described situations that arose as a result of actions taken in the laboratory space (consequence of method). Students also described failure in research design or limitations in how their research was conceptualized (consequence of concept). A final piece emerged from student descriptions of unproductive relationships through lack of mentorship or structure (consequence of interpersonal elements). All of these dimensions were specifically bound within the research space, either involved in the process of conducting research, or in the context of the lab environment.

Consequence of Method. Failures of method involved problems that respondents had to solve often attributed to a lack of technical knowledge and experience. This code often included explicit mention of scientific procedures that students conducted when they assumed responsibility for failure. When respondents spoke generally of the outcome they describe as failure, no sense of responsibility was present. Some examples are provided here:

"Sectioned and stained muscle cells and it turned out incorrect. Spent multiple days working on it and tried again but messed up in a different way"
"The most substantial failure was a serious struggle to collect usable RNA samples from the plant tissues, as the procedure we tried to refine did not work for weeks."
"For months I could not get my PCR gel to work. It seemed that no matter what I tried, the gel never showed any bands."
"In my instance, I would say scientific failure is when experiments don't go to plan. However, it could also include doing protocols incorrectly, accidents in the lab, and other mistakes that could ruin an experiment."
"When something goes not as you expected so you redo your whole entire scientific method (start from the hypothesis again) or redo the experiment (to confirm if the result is the same again)."

Consequence of Concept. Failures of concept was not as frequently described in the data but revealed increased engagement with the scientific process. These responses demonstrated the thinking involved in developing scientific study, rather than simply the procedures carrying out the study. Student thinking was evident either in their explicit mention of proposing research questions or in reference to study design, which indicated a level of reflection about more than just method or protocol implementation. The following quotations represent this dimension in the data:

"My question for my CURO independent research wasn't succinct enough. The question I was asking wasn't going to provide scientific results that would be considered complete. "
"The first project I worked on for the first year in the lab led to no productive output. Hours of work in an especially demanding behavior task with rodents did not lead to any useful data or fruitful conclusions, due to a combination of poor study design and missing data.
"Failure in science is when you follow through on a project where the premise of your experimentation is incorrect"
"The point of failure I like to focus on in science is inappropriate decision-making or intellectual lapses that caused an experiment to fail; things like failing to design an experiment properly to account for all variables"

Consequence of Interpersonal Elements. This dimension was used to capture where students described failure as challenging situations caused by human interactions or as the human interactions themselves. Though the rarest of the three types of consequences, this category highlights how the lab environment extends beyond the actions and thinking that predominates characterizations of science as objective, rational, and neutral spaces. In the five responses that shared this categorization, failures led to feelings of inadequacy. One response (the last of the quotations shared below) actually denied the interpersonal focus to espouse that the notion of failure was "self-imposed". While that seems to negate the interaction element of this code, the addition of the second sentence of the quotation acknowledges a socialized construction to notions of failure.

In addition, one of the quoted students characterized failure as a “great learning experience” due to the atmosphere of the laboratory space. Given that positive and negative elements of human interaction can influence the research experience of a student to the extent that students can denote opposite meanings for failure means that interpersonal elements as part of laboratory culture are a potential area for targeted retention efforts.

“Inability to move on in a research project because of something. In my case, this was a lack of time from an advisor to help me move on and learn in my project.”
“I received a lack of support in the development of my thesis that resulted in an undesirable performance in the presentation of my project. It made me feel as if I failed in my effort as a scientist when in reality I was neglected.”
“I was part of a great lab, so failure in research was always a great learning experience and I felt like people really knew and cared about me and my success- without too much pressure.”
“Failure in science I think is a self perceived shortcoming or lack of proficiency in the accomplishment of an objective. More often than not it’s usually self-imposed rather than extending from peers or a third-party.”

Theme 2: Failure as Expected in the Scientific Process

This theme captured students’ descriptions of failure as an expected outcome, in that they came to understand that the scientific process potentially yielded the non-significant or unexpected. This idea most strongly communicated how students incorporated failure into the routine of the scientific process. One student wrote about discovering this through her research, saying “At first I was frustrated because it was taking so long to get a simple result. However, my mentor seemed like they were expecting failure, and that made me realize that failure is completely normal in a scientific setting.” The student also shares how proximity to a practitioner’s response calibrated her own response to failure, demonstrating the meaningful ways by which participation in the practices of a community can influence learning.

Another student, in comparing classroom learning to research learning, wrote

> “Learning science in a classroom setting has no novelty or discovery aspect to it; you are learning already established facts and your performance has more to do with effort than anything else. Conducting science often does not have clearly defined end goals and has failure is very often unavoidable in the lab. Its

> somewhat paradoxical; if you knew your experiment would not fail, then it wouldn't be very novel."

This quotation was representative of a motif in the data about failure as related to the constructs of novelty and discovery, sometimes even necessary for these constructs. The student also refers to the nature of science construct of uncertainty, indicating that working towards uncertain and potentially novel outcomes necessitates leaving room for failure. This reflects a notion present in a saying made popular by physicist Enrico Fermi to his students, that "if you experiments succeed in proving the hypothesis, you have made a measurement. If your experiment fails to prove the hypothesis, you have made a discovery" (as quoted in Firestein, 2015, p. 19). For students to engage in scientific research to espouse similar ideas, this further highlights the importance of bringing more burgeoning scientists into the spaces of authentic science.

One student wrote, "I think failure in science is normal and almost necessary to really understand research and develop as a researcher and a scientist… Failure in science cements concepts". This quotation shows how students can perceive failure as involved in the establishment (not necessarily in the construction) of knowledge frameworks related to the discipline of study. In writing about failure as an expected part of the process, students often declared the scientific process to be about failure. One student remarked that "I typically view it as part of the process because science is about finding out things that are not known yet. If it were supposed to be easy nothing would ever fail." While this communicates the notion of uncertainty as intertwined with failure, this quotation also highlights the endeavor as inherently challenging. The thread running through all these quotations represents this prolific notion that whatever is defined as failure, it is an expected component of the scientific process.

Theme 3: Failure as Lack of Learning

This theme almost always referenced methods or outcomes that students faced, but they did not agree with the use of "failure" to describe the situation. Instead, students defined failure as what they extracted (or did not extract) from the situation. While "learning" was the outcome students mentioned as not having gained, this theme also captured instances of "no information gained" or, as this student said, "Failure sounds harsh because any data is data but I guess failure is when the data does not result in the way you had hoped or in a helpful way." Some students defined learning in the research space, describing learning through failure as being procedural learning, gaining experience, or an appreciation for the scientific process. A lack of learning then was defined as students facing a challenge or problem but not changing their approach to the situation or not learning how to troubleshoot about the problem. Students also described "giving up", explicitly addressing a lack of learning along with a loss of time and effort. One student shared that:

> "Failure could mean that an experiment did not support a hypothesis or did not work as expected for any of a multitude of reasons, which I do not think is failure as it still taught you something and generated useful data to inform future directions, even if not novel or especially publishable."

Students were quick to point out that unexpected outcomes were not failures, because learning still occurred. But if learning was not the outcome, as another student describes, failure is "when the inevitable happens and something goes wrong but you don't work through it to come up with a better solution". A final quotation for this theme exemplifies the ideas brought up in this section and parallels it to learning in a class setting, with this student writing,

> "Id say if you never even realize that what you did was wrong that would constitute failing. Even if you do poorly on the test at least you learned that you dont have a good understanding of the material. If the test is flawed in a way that makes it so someone without good knowledge can still pass and feel like they understand the topic then that is failure. Similarly to how a correctly done

> experiment in which your hypothesis is disproven is better than a flawed experiment in which you learn nothing or the draw the wrong conclusion."

This quotation captures the student thinking about design elements important to true learning in research and classrooms, but also warns of a false perception of learning in both environments.

Theme 4: Failure as Intellectual and Emotional Dissonance

This theme emerged out of comparing students' descriptions of their failure experiences against their definitions of failure and the synonyms and phrases they used to describe scientific failure more colloquially. In their descriptions of their specific experiences, many students ascribed emotional components of frustration, disappointment, irritation. One student wrote that:

> "it was frustrating when my problems were at the very start - even creating a good question to ask. Figuring out the variables and predicted data was very hard to wrap my head around at the beginning. I was discouraged but I got help from my professors to come up with a question that was answerable."

These initial emotional responses juxtaposed against the more positive definitions of failure that the same students provided. The same students who described disappointment during their experience defined failure as intellectually stimulating experiences. When students were asked to define failure (based on their experiences), a quarter of all responses included not only what failure was to students, but also what failure was not and a rationale for why that was not failure. According to the students, failure was not the outcome, and was not the process, but was exemplified by a lack of learning or progress, as exemplified by the previous theme. One student captured this in writing,

> "I define failure in science as when a procedure gives no result. I don't think failure is when you see no change in your variable, because you still learn something from this. I think that failure occurs when you perform a procedure but no information can be gained from it."

These quotations represent the incongruous nature of failure as learning experiences, yet emotionally difficult experiences. While seemingly dissonant, this result actually parallels work studying active learning outcomes in undergraduate science education (Walker et al., 2008), where students perceived that their learning did not equal that of lecture settings, and yet students demonstrated better learning outcomes in the former environment. In the research setting, however, students seem to recognize that intellectual struggle and negative emotional responses do not preclude intellectual growth. One student captured this idea well, writing of how the emotional response changed in the process of responding to the failure, writing that she "was irritated at first but eventually enjoyed perfecting [her technique]."

Summary

The nature of survey responses as short statements that cannot possibly encapsulate the richness of an entire experience, means that any analysis of this data is limited in scope and depth. Yet hermeneutics as a framework for thinking about data considers the importance of the language that participants use to describe lived experience (Ricoeur, 1976). As such, I believed it necessary to share this analysis because the common aspects of language used across students' experiences with failure allowed for distinct characterizations of the failure experience.

Thematic analysis of the survey responses showed failure to be synonymous with a broad array of activities in students' research experiences. This led me to understand that "failure" as a concept may perhaps be too broad a term to facilitate study of an experience. That perhaps even "scientific failure" may not provide enough specificity for what all students can define under this term. The next part of this study, the analysis of interview responses, investigated if this was indeed the case – whether meaning made from failure converged into a new understanding about the experience. Failure captured as consequence, as expected, as lack of learning, and as dissonant through the experiences shared by the participants primed my thinking about how students could potentially and more richly describe the experience. While some of these themes repeat in the next chapter as ideas also present in the interviews, hermeneutic analysis placed these within broader conceptual contexts.

CHAPTER 5

MEANING OF AND IN SCIENTIFIC FAILURE

Overview of Chapter Structure

The previous chapter provided a summary of understandings about failure gained from the analysis of responses to survey items. The brevity of responses and the lack of ability to follow up meant that such categorization was inevitably superficial. The interviews thus became an opportunity to elicit more detail and potentially uncover more depth. The interviews, analyzed as described in Chapter Three, yielded a richer, more nuanced depiction of scientific failure experiences, contexts, and lessons. This chapter explores the results of analysis for the following questions:

RQ2a. How do students make meaning of their scientific failure experiences?

RQ2b. How do the experiences of failure described aid the students in constructing their understanding of the scientific enterprise?

The chapter is organized to first answer what meaning students made of their failure experience and then to answer what meanings students found in scientific failure as it related to scientific endeavors. The sections are divided by ideas that emerged from analysis. Again, this is where the tenets of hermeneutic phenomenology stand opposed to pure phenomenology – offering elaboration as interpretation rather than reduction. While the circular nature of hermeneutic analysis yielded a consolidated understanding of the failure experience that led to the creation of particular section headings in this chapter, the goal was not a result that reduced the essence of the experience to a pithy phrase. The titles of the sections offer a succinct glimpse into the salient ideas that emerged, but not as a reduction of those ideas. Instead, the titles provide a starting point for the elaboration of ideas necessary to communicate the threads of common experience tying together various descriptions of scientific failure.

The purpose of using a hermeneutic phenomenology framework is to attain new insights into an experience, by assembling together accounts of that experience through the individual and particular lenses of the experiencers. It is not to explain or develop an insight into the individuals themselves. Instead, by investigating the processes of thought that the experiencers engage in, we learn how they make sense of the experience and what supports they use in making sense of that experience. In this case, the experience of scientific failure is the subject of study, not the nine interview participants who provide context to phenomenon. As such, in the sections below, I highlight segments of interview transcripts to help make sense of scientific failure as experienced by the students, not to make sense of the students who experienced it.

Interview Participant Summaries

To reconcile the need to contextualize the phenomenon of scientific failure within the students' own experience of research with the need to prioritize the experience, I provide in Table 5.1 a brief glimpse of the students through the data they provided in the survey.

Table 5.1

Interviewed Students and Initial Survey Responses

Pseudonym (demographic self-identifier)	Brief description of research	Brief description of failure (and response) in research context	Definition of scientific failure
Jayd -Asian Female -Biology major -Medical track	I completed experiments, wrote papers, and presented my work at symposiums. My work investigated hypothiocyanite and its antimicrobial properties against bacteria and viruses.	I was doing an experiment using hypothiocyanite involving mice cells that had been infected with influenza. We had expected mice cells in hypothiocyanite would have a lower antibody count but we found no correlation whatsoever. We moved on to other studies using streptococcus pneumonniae.	In my instance, I would say scientific failure is when experiments don't go to plan. However, it could also include doing protocols incorrectly, accidents in the lab, and other mistakes that could ruin an experiment.
Leia -White Female -Biology major -Medical track	Drosophila melanogaster dissection and attempted expansion microscopy.	Drosophila tissue did not expand upon completion of protocol Changed protocol/chemicals used to attempt expansion	Not achieving a quantitative or qualitative change
Eoin -White Male -Biology major -MD/PhD track	Multiple project including determining the role of sex in endocrine mediated stress responses to severe traumatic brain injuries, role of transcranial direct current stimulation in changing TBI recovery trajectory, use of chondroitin sulfate hydrogels to aid in chronic recovery following TBI, novel development and validation of forelimb motor task. I have been involved in all aspects of research, including study design, animal surgery and behavior, histology and microscopy, electrophysiology, data quantification and analysis, and manuscript preparation.	The first project I worked on for the first year in the lab led to no productive output. Hours of work in an especially demanding behavior task with rodents did not lead to any useful data or fruitful conclusions, due to a combination of poor study design and missing data. The project was attempted to be revamped and revised multiple times, but ultimately, the decision was made to cut our losses and move on to other projects instead of trying to pick up the broken pieces of this project. Lessons were taken away about why this project failed and how to avoid these sorts of mistakes in the future.	There are 2 definitions of failure that are common parlance, in my opinion. Failure could mean that an experiment did not support a hypothesis or did not work as expected for any of a multitude of reasons, which I do not think is failure as it still taught you something and generated useful data to inform future directions, even if not novel or especially publishable. The point of failure I like to focus on in science is inappropriate decision-making or intellectual lapses that caused an experiment to fail; things like failing to design an experiment properly to account for all variables or include an appropriate control group or failing to plan to prepare all needed behavior tasks prior to sacrificing animals.

Table 5.1 (continued)

Pseudonym (demographic self-identifier)	Brief description of research	Brief description of failure (and response) in research context	Definition of scientific failure
Cera -White Female -Cellular Biology major -MD/PhD track	I carried on with a project idea that stemmed from previous work by a PhD student, where I was investigating some of the host response changes seen during viral infection with a genetic mutation background.	Multiple experiments have failed due to old media, PCR machines crashing, software not being updated, etc. There isn't much an undergraduate student can do when the failures are due to lab maintenance issues, so beyond frustration I just had to repeat the experiments on another lab's machines.	I would define failure as something occurring to where you get no data suitable for analysis. A lot of times, we saw no significance when we were hoping for some, but a strong data set is a success in my opinion even if the results are not what you wanted.
Leon -Asian Male -Biochemistry major - Medical track	3 years working in a biochemistry lab. First two years on an independent mouse project next year RNA sequencing. Also conducting public health systematic review.	Sectioned and stained muscle cells and it turned out incorrect. Spent multiple days working on it and tried again but messed up in a different way I tried again but failed again. Covid ended up interrupting my project so I didn't get a chance to try again	Failure in science is when you receive an unexpected outcome that's not part of normal results
Saul -White Male -Biochemistry major -Medical track	I was an undergraduate research assistant in a biochemistry lab. I assisted a graduate student in her project investigating the effect of mutations on the stability and activity of an ER bound glycosylating enzyme, B3GLCT.	About halfway through my first year, I discovered that the primers I was using weren't working because there was a mutation in our gene construct. My graduate student mentor and I sat down with my PI and figured out the best way to fix the constructs. I obviously saw a lot of my work washed away, but I wasn't too discouraged, because failure in science is part of science.	Failure in science for me is when your project experiences a setback. The setback can be because of the scientist (human error) or just bad luck. Regardless, keeping your head up and learning (most importantly) from the failure is part of the scientific experience.

Table 5.1 (continued)

Pseudonym (demographic self-identifier)	Brief description of research	Brief description of failure (and response) in research context	Definition of scientific failure
Tate -White Male -PharmD major -Pharmacy track	Analyzing neurotransmitters in human urine using HPLC w/ UV/VIS. - Lead the team, analysis, etc.	Received a CURO grant to conduct a prospective cohort study evaluating medication adherence in veterans with heart failure. The project fell to the wayside due to changes in a memorandum of understanding with the medical institution that we partnered with historical for clinical research, due to the institution changes hands/names etc. By the time the MOU got sorted out I was beyond my window for conducting the research. So while the study did not go to completion, I did get to be involved with the IRB submission, write up, proposal, design, etc, and presented my research, absent of any data at the CURO symposium in 2019. It was a good learning experience, there will always be barriers to research that may beyond a students control especially. The experience motivated me even more to be involved with research and seek out opportunities to publish.	I think failure in science would be not learning from the experience. Because at the end of the day whether or not research or a particular project even goes till completion, you still gain valuable experience in the research process, which to me is what it's all about to begin with.
Mera -White Female -Agriculture major -Graduate science track	My first project was using phylogenetics to determine a new pathogen of pecan trees. My current study is determining the epidemiology of latent infections of Brown Rot in peaches. In between, I have completed extension research for peach, apple and grapes growers in Georgia.	*(In survey, indicated that she had not experienced failure in the research setting, but that failure may look like:)* Not double checking your gels and using incorrect PCR results or using your last sample of something and it going wrong. Or for qualitative research, not doing hard and electronic copies of interviews.	Failure is something going wrong to the point of no return.
Evie -White Female -Ecology major -Graduate science track	I was hired as a student research assistant in a pollinator biodiversity project. I pinned and identified almost 3,000 bees and butterflies. Now, my responsibilities have expanded to creating student manuals and assisting on other projects.	*(In survey, indicated that she had not experienced failure in the research setting, but that failure may look like:)* not having a study examine the intended variables or ending up not being feasible	failure in science is about quitting a project without analyzing results garnered from the experience

Where necessary to understand either the process of meaning making or to add insight into students' epistemological thinking, I provide any additional detail about the research experience that students shared in interview. No claims about failure as it relates to identity are made in this chapter, as the interviewed students did not represent the breadth of identities represented in the survey. Though Tate self-identified as a student with veteran status and Cera self-identified as disabled, and did remark on how those identities influenced their view of general failure in the survey, I did not include it as a component of analysis if it did not come up in the interview as part of their understanding of scientific failure. All students who participated in the interviews had at least three years of experience in the collegiate setting and had completed at least two semesters of undergraduate research. Segments of interview transcript are made available throughout this chapter to help make the argument for the results derived from analysis. While each segment offers a wealth of data to wade through, the **bolded sections of text** are what are immediately relevant to the neighboring sections of analysis. The rest provides context for the bolded sections. Some of the same interview segments may crop up in different places with different aspects of those segments highlighted for purpose of analysis.

RQ2A – Making Meaning of Scientific Failure

Here, I examine what meanings emerged from the failure experience within the student interviews. Analysis revealed three major concepts: (a) distinct groupings of failure, (b) a process of rationalization, and (c) coming to a begrudging acceptance.

Failures as outcome-oriented, response-oriented, or process-oriented

The elaboration of student understandings of failure revealed three distinct conceptions of failure – defined by an outcome, by the response to that outcome, or as a part of a process. This was particularly interesting to me as my definition of the experience incorporated both the outcome and the response to that outcome but had not attended to process connecting the two. When defined as an outcome, failure was an event with no recourse: “a dead end”, “a missed opportunity”, or an “unresolved ending” and no way to respond to it productively but to “abandon the project” and “move on”. When defined as a response, failure was a lack of action taken about an expected or unexpected situation – most often as “when you don’t learn” or when what you learn is not communicated. When students defined failure as process-oriented however, the experience had a role as part of something larger than the failure itself. Saul spun it in a positive light, as “an integral part of the scientific experience”. Students’ definitions often shifted between these three categories between initial definitions that evolved into others upon elaboration or upon reflection of the experience within the duration of the interview. These categorizations of failure revealed what students thought the failure experience entailed, or sense-making *about* the phenomenon. This was particularly clear in the cases of Mera, Evie, Eoin, and Tate. Mera and Evie were unique amongst the interview participants as they initially indicated that they had not experienced failure in the research setting in their survey responses but could elaborate on examples they could identify as examples of failure from their experience in research.

Evie realized early in our conversation that she had indeed experienced outcome-oriented failures where she had lost out on opportunities. She initially described failure as the abandonment of a project:

> “Well, see, like, in that situation, in my first research experience and kind of with my second, that was ended by COVID, it just kind of felt- I, like am almost embarrassed because I kind of gave up on the- both situations. 'Cause I kind of was like, I just don't know how to pursue from here. I'd let too much time pass and I'm like, I just feel like I can't reach back out [to rejoin a lab following a semester away from school]. And so that's kind of what I interpreted the failure as, because it's just like, **not completing a project to, not like doing a project to completion and just like kind of abandoning it felt like a failure because I**

> **never really got like any kind of result out of it**… So it's just kind of like, by like, **by not giving yourself the opportunity to see what's actually gonna happen, um, is a failure by not fully engaging and like following proper methods to completing a scientific experiment**…I think it's made me a lot more stubborn in this situation where I'm like, "Nope, I'm gonna, I'm gonna finish these projects to completion now." I'm like**, I want, I want to see a project come to an end and like, just get the full experience out of it**. I mean, I, I just, I want, I just want to see all of it happen and just kind of just, I don't know that- you, when you complete a task, it just feels so good. And just like, I want that with research and I want that with, um, all these projects that I'm working on. **So it just has kind of made me a lot more, um, um, more headstrong in these situations are like, okay, we're going to, we're going to get through this.** Like, whatever happens, you know, I'm in, I'm in this project way too deep to leave it now."

Evie, who had experienced multiple setbacks due to an accident which removed her from school, and subsequently her initial lab, felt that failure there was having worked for a time in a space and not seeing it through due to her having left the lab, quitting halfway through a project. But additional research experience afforded her the opportunity to respond to future situations in a productive way. With the perspective she now had after working in several labs, she recognized (elsewhere in the narrative) that she had skills with which to deal with such a situation, something she felt lacking in and embarrassed by earlier. This led to developing an understanding of a measure for success in her scientific efforts: becoming "headstrong" and persisting in her work. As the conversation continued, she recognized that failure was not just missing out on a potential project. Instead, she remarked that that ending came about due to loss of communication, both with the lab and with the content of the lab work. No longer being involved in the processes of the lab environment as a result of what occurred was the failure.

> "'Cause like, I guess like as a whole, um, it was like a matter of **like losing communication with those people, but then it's also a matter of like losing the communication of the research I was doing**. So it kind of was just like all, like, everything was just kind of, um, I don't know. It just like, just felt like a dead end on a lot of, in a lot of ways."

From an outcome-oriented understanding of failure as an "abandoned project," her thinking shifted to reveal the real tragedy was the "loss in communication" to both the context and the content of the lab. After being disconnected physically and intellectually, she no longer felt like she could return to that environment, and thus she recognized that her inability to re-engage with that space was her actual experience of failure, not actually leaving the project behind. Thus, an outcome-orientation shifted to a response-oriented failure.

Mera's thinking of failure shifted from an outcome-oriented definition in her survey definition (above) to a response-oriented definition with an outcome-oriented explanation of failure. When explaining how she thought about failure, she could conceptualize the experience as two types of outcome-oriented failures, one based on personal error and one for the greater scientific community. But her initial reaction was to define failure as response-oriented:

> "So if you're doing a harsh failure, like absolute failure, I would imagine it **being something that you can't turn away from**. So I'm trying to think of an instance where ultimate failure, um, like there is no other option and so scientific failure… Personally, I think there's two avenues for that. So you have failure because of, uh, you know, something that happened, you know, whether it, you know, you're doing environmental research, whether you lost all your data, what have you, then you have this other kind of failure that is more futuristic and I kind of hint on this I remember in my survey in- I remember I took an animal biotechnology class and we learned about this publication that was published and the results were revolutionary, people were teaching in their classrooms. Turns out the guy falsified, everything knowingly. And so while of course he himself does it as a failure. It's a failure for the future generations that were using that research for their own research for, you know, medical things. And so there's, this is going on, but in a different tangent, but like there's two different guardrails for failure. **There's one, that's just basically, um, ignorance on the part of the researcher and not upholding the code of research and what it means to be, do very good peer reviewed studies. And on the other hand, you have the failure of, you know, maybe it's a mistake you did**. Maybe it was not having hard copies when you, like I said, all your data just gone into the abyss."

The initial description as "something that you can't turn away from" offers a very physical description of response-oriented failure that Mera repeated later in the interview. The physicality of the description manifests an image of failure as a thing one faces head on but cannot get beyond. This imagery is repeated when she said "… in that moment, I cannot imagine like, if you would take that moment in and of itself and not- and just mull on it and just sit in that circumstance, it's definitely going to be failure." Failure is a lack of action, whether out of unwillingness or inability, a response to an unexpected outcome. Through her expansion on the topic, Mera also described failure as outcome-oriented. For the individual researcher, it is a dead end because of potential personal error. For the scientific community, it is the wasted efforts of future generations of researchers due to wrongdoing. She separated this from her own experience as she did not believe her experiences harsh enough to constitute failure. "…Like, basically you put all this time and effort in and nothing's going to happen. Like you're done, I guess, is how I would describe failure. And then my answers have been more hiccups or kind of like bumps in the road." From an outcome-oriented failure, however, she transitioned to thinking about failure as a process. By incorporate reflection as a piece that made failures a natural "pivot" point, she crafted an understanding of failures as process-oriented. A detailed analogy of science as a journey served as a mechanism to convey this point.

> "I was imagining research is basically: you're on a road and you take different exits, but then you end up getting back on the main road. The main road is what your research is. Then you have to go off the road for like your literature review and go off the road for this. **And I guess a failure, it would be, you know, getting rear-ended.** And in that moment, you're going to freak out. I remember I rear-ended at a red light. Um, I started crying and freaking out and calling my dad, you know, basically you're questioning probably questioning your life decisions… Um, you know, you sit down, you pull over, you call the police, you know, probably your family, uh, to console you and then you have the insurance come. And I think that insurance would be your research mentor and granted there's different kinds of mentors, but all the ones that I've experienced, they're like, "Hey, it's okay. We will work on this." And you know, the insurance handles you, you know, they kind of, they take you and your car away, um, and you get fixed, you know, you, maybe you get a new bumper or something. Um, and **so I guess failure is, if that metaphor works, it's something that there's a lot of variables in. Um, but you do end up getting back out on the road…**So I

> think what you learn is when you're having to detail the incident to the police officers and the insurance company, know your parents, you know, your, your, your support system, um, and de- detailed to your insurance company, your mentor, you're able to evaluate it from different perspectives. And, you know, in that moment, of course, you're like emotional, you're crazy, you're beside yourself. Um, but then after that, you're able to kind of take a step back and look at, okay, well, what led up to that? Um, and you know, vice versa, if it's something that you did, you know, it could have been, you rear-ending someone else. And that takes on a lot more responsibility than someone else rear-ended me. So for example, if I rear-ended into someone else and it was my fault, the insurance company, the police officer are going to be a little upset, but you're still able to do an evaluation of, well, how did this happen? Oh, I got too close to the car. Okay. So maybe I should have done X, Y, or Z, and you learn from it. And like I said you get back out on the road."

Though the analogy seems to start with failure as outcome-oriented ("getting rear-ended"), the expansion of her analogy reveals how this jarring occurrence is only the initiating event for a process. As per Mera's analogy, in the case of an accident – even as minor as a fender-bender – drivers are expected to follow the established protocol of calling police officers to explain the accident, take on whatever responsibility, and then take the necessary actions to return their vehicle to road-safe conditions. Following through with that analogy, Mera explained how failure initiates a reflective and evaluative process that serves to understand the phenomenon of failure in the research context and then use that understanding to return to research armed with more knowledge. After sharing this analogy, Mera revisited the experiences she described as "bumps in the road" as failures that she had indeed experienced and underwent this same process with. Though an outcome-oriented definition did not suit her experience, reimagining failure as process neatly encapsulated her experience within that definition, to the extent that she felt that process-oriented failures added to the story of scientific research so as to make research more compelling.

Eoin's experience of failure demonstrated all three types of failure, though he explicitly identified only two – one that was outcome-oriented and one that was response-oriented. He saw that though contextual factors often mediated the impact of both the outcome and the response to that outcome, that defining failure in outcome did not preclude defining failure in response. Indeed, after recounting his experience of failure, he concluded that the most severe failure that occurred was not necessarily the ending of the project but the mishandling of it.

> "It was kind of a project that I think the first- so myself and my grad student at the time, [mentor name], um, we both started in the lab in August of 2017 and we, that was the project that [mentor] was given. And so I was given, um, and I think, kind of the **first kind of piece of it was we were, he, he didn't have a good idea of what, what the end goal of the project was.** We were given kind of this vague idea, and we were, we were given these rats that we were given from our collaborators that were preconditioned with these endocrine-disrupting chemicals. And the idea was, how does this affect TBI**? But I don't think we ever clear had an end goal of what the hypothesis is or what the kind of what the, what the end result should look like** beyond we have these rats, they're going to get a TBI and then something's going to happen to them. We're not sure what, um, and so I think that just led to a lot of like bumbling around and there was never a clear direction per se. And then the kind of **the second issue was along with that, we, we were, we were doing experiments and then we weren't analyzing our data as we were going.** And so one of the big problems that came up was we ended up losing data, um, from our experiments that there were behavioral experiments… And the videos went missing at some point, and we didn't figure it out until after the project had been completed. And we then started trying to analyze the data and the data was missing and it was unrecoverable. And that was kind of the second big issue of what do we do with it now. Um, and then even the, and then I think the **third part was... It just kind of, we had tissue, um, we had the brains and so what do we do with this?** What are we staining for? What are we doing PCR and HPLC for? And I, there was just never a, never a clear direction until kind of the end. And, you know, the end being, once we started kind of trying to analyze the data, we figured out data was missing. And then we were scrambling to make something out of it. And that's when I think the initial direction emerged at that point. But at that point, then the data had gone missing and it kinda got too late to, um, do anything with it… **I think there were multiple failures that led up to a big failure.** I think if there was probably any, any one of those that was isolated, you could probably work around it and still get something productive. But no, I think each, I mean, each step at a point, I mean, there are other things I didn't mention. Um, but there were, there were multiple strings of failures that led to the project overall being a failure… **I think [failure is] just bad decision-making.** It's not, you know, an experiment fails and that's, that's okay. As long as it's not, it's not due to...[pause]. **I mean, you, you have a hypothesis and if your data doesn't come out and doesn't support the hypothesis, that's not a failure… Because that's the whole point of doing the experiment. If you already know the answer to the**

> **experiment, then you won't have to do it.** That's not, that's not a failure. Um, but if you, if your experiment doesn't work because you didn't put it in the right reagents, or because you calculated the wrong concentration of solution, or because you didn't run the right experiment, **you use the wrong technique or something, then I think that's more so a failure. I mean, that's a small sense**. I think, I think the **larger example of scientific failure is kind of what happened in the first project is you, you spend a year on something and you don't recognize at any point that what you're doing isn't right.** Not because of, I mean, who knows if you analyze the data who knows what it would show, but you never even got to, we never got to a point where really you could even analyze the data in a meaningful way. **I think the failure comes in, in not recognizing when something's not going to work.** And you keep on doing the same thing over and over and over again. Or you keep on, you know, you can do an experiment once that fails due to some reason, but if you don't recognize that it's failed or why it's failed and you keep doing it over and over and over again, I think that's, that's a problem.

Through the first half of the narrative, it is clear that Eoin considers the experience of failure to lie in something larger – the lack of structure in research design which did not gain any clarity until the end of the project. In this way, failure in process actually sustained the project as a vague conception or potential end results. To Eoin and his first-year graduate mentor, their inexperience with scientific work kept them from recognizing that lack of clarity could cause potential problems. Upon reflection with a new mentor (elsewhere in the narrative), Eoin recognized the missteps due to design mismanagement, thus the contributing role that failure played in the greater scope of the project. As stated earlier though, this did not preclude failure as response, because apart from the vague approach to the experiment, Eoin also stated that failure is that "you don't recognize at any point that what you're doing isn't right." Along with Eoin's declaration of failure as "not recognizing when something's not going to work", these statements echoed a response-oriented failure as an unexpected outcome that does not generate the thinking needed to move work in a productive direction. Here, persisting without re-evaluating action is labelled the greater failure. Thus, in Eoin's case, failure in process along with failure in response led to failure in outcome. Eoin also explicitly stated what failure was not. An unexpected outcome at the conclusion of the experiment could not be a failure because that instead reflected how he understood the nature of scientific inquiry. He reiterates the point by stating it in an alternate way – that knowing the outcome of the experiment defeats the purpose of scientific inquiry. Eoin thus walks through different conceptions of failure within the narrative, each highlighting a different way he makes sense of what failure is within science.

Tate, whose research experience was far more extensive than the other students due to the unconventional path his studies had taken, first identified failure as an impossible event in research setting, but followed that up with a response-oriented definition.

> "…but then, you know, after a while you kind of realize, well, that's just kind of, that's just sometimes how [science research] works. And, um, you know, you, you have to kind of take from it what you can. Uh, and that's kind of really what I refer to in terms of, I think that in this, you know, in these endeavors, you always, you know, uh, that's why failure really the way, uh, in terms of a word or a, what I think is just not there because that's, **you can't fail at anything. No one's testing you**…Well, right? Because at the end of the day, you don't know what you're going to see. That's the point of research. You make a, you make an assumption, you have a hypothesis and you evaluate it through observations and data, and it may be something that you, you thought, maybe something different. Um, and that's just, you know, the thing, um, with scientific inquiry again, is that, um, you're evaluating what you think based off of previous literature, science, um, expert opinion, et cetera.

His initial conception of failure reflected it as antithetical to the scientific process because of its implications as an outcome of assessment rather than research. Though outcome-oriented, the definition did not suit scientific research because the nature of research meant that while research evaluated knowledge, it was philosophically incompatible with the assessment of knowledge, under whose umbrella the term "failure" was housed. However, Tate's elaboration of failure which grew from his own experiences, confirmed a more response-oriented definition which also reflected how he thought about science.

> “Um, we went live for enrollment, you know, at the hospital for patients into the study, and then sh- very shortly after that, um, there was a change in the memorandum of understanding. And so what that means is you basically have to stop whatever you're doing. And, um, we, we basically went on hiatus, um, and then it just took forever to get that worked out. Um, we're talking over a year…So, you know, I fulfilled my obligation in the CURO grant, as per the, uh, the CURO advisors and administrators, um, for who run CURO. But in terms of my overall objectives with the research definitely didn't happen. Um, you know, completing the whole research process and getting good data and getting to analyze it and, um, you know, hopefully publish, um, you know, ultimately was really what I wanted to do, having been through the process of a different type of research before. Um, and that's kind of really how it ended…Personally, **I think failure would be, if you, you did go through these experiences and you didn't understand, you didn't take away I think what most people would conclude after, after putting that much time and understanding that this is how science works**. You don't, you don't always, um, you know, get your data. You don't always publish, you don't always make a discovery or change the world. Um, you know, it's an incremental experience. You just keep plugging away… I think the general premise is not unique to science. I think **failure would, would be the absence of understanding, um, in any, any arena**.”

This extension of Tate’s definition communicates an unexpected outcome and a lack of intellectual growth from engaging with that outcome. Tate’s failure came about due to factors out of his control, but he was able to salvage from that experience an understanding about the incremental nature of scientific progress. He credited his perspective about failure and its role in the scientific process to the emotional maturity gained from his diverse life experiences and to prior research experiences that ended in a similar fashion.

Sense-making through categorization revealed that students made sense about failure either by defining it within the bounds of the event of the outcome and response to it, or by contextualizing its role in the greater scope of scientific research. Through these three ways of understanding *about* failure, students could then begin to tackle the experience of failure itself.

Rationalizing Failure

As seen above, the students experienced a range of events that they described as failures in the scientific setting, shifting between definitions of failure as they gained depth to their thinking through the course of the interview. Yet, sense-making *within* the experience was similar across all the participants. All detailed failure sequentially as: (1) couched in inexperience, (2) involving emotional distress, (3) often, but not always, recognizing certain skills or knowledge to act in response, and (4) creating opportunity to gain new insight. Through this process of rationalizing failure, students incorporated the experience into their knowledge frameworks as flavor to the experience of research – as Mera noted, "[failure] makes research sweeter."

Rationalizing failure integrates what the previous chapter identified as this incongruous event because of the dissonance caused between its emotional and intellectual impact. Students found failure to be jarring precisely because the experience elicited negative emotional consequences and yet promised to be intellectually valuable. This process enabled them to acknowledge their emotional distress and reconcile it with the opportunity failure inspired. Inexperience paved the way for the unfolding of the failure experience, followed by an immediate and negative visceral reaction. Then, the failure experience went from an individual one to a collective one as mentors and PIs engaged in thinking about the failure with the undergraduate student. In the process of watching the more experienced researchers navigate the experience, emotional distress became alleviated and critical thinking became engaged. The efforts resulted in insights into the general research process or more specifically, the practices and knowledge of the specific discipline in which the students worked. The narratives of Leia, Leon, and Saul highlight the process of rationalization that occurred to make sense within the experience of failure.

Leia's work with fruit flies felt to her like a series of failures, to the point that she felt inured to the experience. She was new to research and initially felt that her inexperience caused the errors, but watching her mentor and PI walk through the process led her to recognize the inability to get workable results did not rest solely on her shoulders and could also be due to external factors.

> "Um, **I was new to research**, so being in a wet lab where we were actually dissecting *Drosophila* was really exciting. I didn't think that, uh, I could ac- actually participate in the hands-on part of the work. I, I thought I'd be, you know, doing little stuff, clearing up the lab space, you know. But my mentor showed me, you know, the ropes, and all of a sudden I was expected to participate in this like hardcore part, uh, of the research and I, I- It was cool… The whole point of my work was to make it easier for the lab to be able to se- to visualize embryonic structures and I couldn't, um, get it to, to, uh, work. Basically, the protocol we'd created didn't work. But I didn't know that the first time. I went into this like thinking "I'm doing some- something to help the lab, we're going to, you know, advance the field of neuroscience" and it didn't work and **I freaked out** because I must have messed up. I didn't want to tell my mentor at first, but like, because the whole point of this was to, uh, to fig- to access enlarged um, structures, there was no, no way I couldn't tell him**… I remember being like scared** to say anything, but when I showed him the results, he, he wasn't disappointed or, or anything. He was, you know, just like "ok, let's figure this out" and that, **that attitude was exactly what I needed to hear to, uh, know that "oh, it's ok to mess up".** But it wasn't even me messing up, you know, it was just that we needed to adjust the uh, protocol. But I didn't know that. Uh, until, until it didn't work… **Then, I saw what kinda, kind of work went into putting the protocol together.** Because [the mentor and PI] had to go back and read, you know, how other labs had done it, what chemicals were used in what amount, right? And they talked about why like our protocol turned out like it did. Then they adjusted it and, and had me try again. And I did. And it didn't work. **But now I knew how to deal with it. And that it was ok.** And the more this happened, **the more I got to be, to be, um, involved in thinking** about why this happened and uh, what to do next."

In walking through her experience, Leia went from describing her role in the research setting to how that role and her inexperience in that setting influenced her response to the initial experience of failure. While she initially attributed the failure to her own errors and "freaked out", the actions of the team showed her that her reaction need not be fear, but acceptance of the outcome so as to then begin investigating that outcome. The investigation revealed to her what background work went into developing the work she had more superficially engaged in, which led to her becoming more fully engaged in that work. Leia's sense-making within the failure experience walks through the four steps described earlier distinctly and sequentially.

Leon walked through this process as well through his experience in failure related to staining and sectioning slides for visualizing RNA strands. When this happened early on in his time in the lab, he excused it as natural during training as his efforts were still overseen by a mentor. Once he began his own project though, the same errors became his failures.

> "Basically I just shadowed the lab manager for a few weeks and watch like everything she did when I came in and she would like explain what she was doing, why she was doing it and like a little bit of the science behind it. So that was my, like, I guess orientation… I mean, it was, it was all very interesting when I first started it, like some of the, **some of the like protocols, were like very, very advanced for like a freshman coming in**… Once I stained, I looked at it under a microscope, it was pretty obvious to tell that, like, this was not, this is not what she showed me it should look like. And like, I'm not too sure. Like, I guess I thought I like meticulously wrote everything she did down and I had the protocol down, but I mean, there're always like a few minor things that she did that like, you didn't really notice. And those were like all parts, that like separated, uh, into good sections and bad sections… Uh, I do remember the first time I went home that day or like a few times? **I just, I would just go home and like, not tell anyone at first and like delay coming back to the lab for a little bit**. Like, just a few days I would like- not take off, 'cause like they didn't expect me to come every day, but I just wouldn't come for a few days. And when I eventually come came, I would like go in and talk to my, like the lab manager and explain what happened... her reaction usually depended on the, like, what I did wrong. If it was like something that sounded like something was wrong with the, maybe like there there's something that she didn't explain too well, she would like be very, very nice about it and like, explain it again, but definitely went more by fault. Uh, there was some, like, I don't know, I guess not disappointment, but like some like, like "you make sure you don't do this again", or like, uh, that kind of thing… I mean, these kinds of failures are honestly, like, just expected when you're starting off in a research and like, **if I was like extremely meticulous and like, I, I recorded her or something in doing the procedures and like, rewatched it** then, like, maybe I would have reduced the number of failures, but like, I don't think, like, I don't think there's like many practical things I could do to like, to not fail those first times… I learned that failures failure is like expected. It's not like it's only about the deal in this kind of research. Uh, I also **learned like how important every little small detail is and like, like, you need to be extremely meticulous with everything you do**."

Leon’s experience mirrored the inexperience that Leia also described. But here, he bore the burden of responsibility for the failure experienced, because of his autonomy with the project. That independence lent a measure of fear in how he thought failure would be received by his mentor. The mentor did not always alleviate this concern, which increased Leon’s wariness in returning to the mentor with later failure experiences. However, failure still generated thinking within the experience. When asked explicitly about skills to deal with failure, Leon said that he could not name any skills he gained from the process, but in the course of describing what he gained, he could identify how a more meticulous approach may have mitigated some of the experiences of failure and their potential impact on his work. Recording his mentor could have led to being able to pinpoint precisely what differences lay between their techniques and thus offer more to learn from. His musings on the experience also added to the understanding of how Leon viewed participation in the scientific process. Like this, Leon too showed how made sense of his failure experience through sequentially communication of (1) his inexperience, (2) emotional difficulties, (3) thinking skills that could potentially mitigate failures, and (4) being meticulous about detail in science.

Saul presented his experience of failure in the same way as the others, introducing how his work on introducing targeted mutations to plasmid genes gave him a scare. He too came into his project brand new to research, explaining that he had known little of the realities of research but that it was expected for his career plans to engage in some kind of scientific research.

> “I, I didn't, uh, **I didn't really understand how an undergraduate kind of fit into that, you know, the bigger scheme of a research project**, because it's, it's, you know, like, because it seems like a lot of the, you know, major work is done by the graduate students and, you know, the, the post-docs and people like that… so at the beginning, um, what, uh, my job was to do was to, uh, use site directed mutagenesis, to, uh, introduce mutations into these plasmids that we had that had the construct for a gene that we were, you know, eventually interested in expressing this protein… so the first, so what my, uh, my graduate student mentor

> would, would do was, would be to perform the technique first in front of me, and then I would observe it and then I would do it myself one time while she watched. And then eventually I got to the point where I wouldn't, I, I could do it by myself with complete independence. So it was kind of like, uh, there was, there were like, there was a training wheels period, I suppose. And then eventually I got to the point where I was able to do it by myself… I would send [the plasmid mutate] off for sequencing and, uh, you know, ha, that was a nightmare having to look at the forward and then the reverse sequence, and then, you know, figure out what, what it actually, you know, the actual sequences. But I was about five or six mutations done, and each mutation takes about a week, a week or two, you know, just include, you know, getting to the point where you have the purified DNA. **So like, it was about like half a semester's work or something, or close to a semester's work. But, um, you know, I was, I was looking at the- this, the, the, the pages, and I was like, "this isn't right.** There's like this, this is wrong on e- every single one of these pages". And **then, you know, uh, I was scared because I'm like, "Oh, maybe I did something wrong."** 'Cause I, you know, I, I, I hadn't, I wasn't aware of like, you know, the, the concept that, you know, they could just spontaneously, you know, generate mutations, you know. Uh, you know, I brought it to my, my, my graduate student mentor**, scared that I had done something wrong**, but, you know, I talked to her, talk about it with her, and then eventually we brought it up with our, with our PI, and then we had to, um, basically figure out a solution. I mean, she, she was the one who… **she was used to it because she, she, uh, she's, she has run thousands of more experiments than I have.** So to her, I mean, it's, it, it, it was frustrating of course, because I mean, her primary goal was to finish her PhD as quickly as possible. So, I mean, she, she was annoyed, but like, you know, she wasn't terrified, like I was. And then bringing up to the, **bringing it up to our, our PI, uh, you know, he was completely calm**… it definitely taught me that, I mean, I, I knew, I knew failure was a normal part of the scientific process. Uh, I mean, to a certain degree, it's part of the scientific method. Uh, but, um, uh, seeing them not be as, you know, destroyed as I was, I realized, uh, more concretely that, you know, failure is part of the scientific process."

Saul's introduction to the laboratory space also included being oriented to his role in the lab. He, like Leia, initially believed undergraduate roles to be that of "grunt work" but realized (elsewhere in the narrative) that the purpose of his presence was to learn about science and learn particular techniques that he could later list as having mastered. His failure experience occurred once he felt more established in the lab, following his "training wheels" period, similar to that of Leon. Saul too communicated a fear associated with reading through and recognizing unexpected results. His fear subsided upon seeing his mentor and the PI's reaction to the results. As the more experienced researcher, his mentor exhibited annoyance, which Leon perceived as due to a loss in time. As the most experienced researcher, the PI exhibited a calm acceptance, which highlighted to Saul that failure is “normal”, an understanding he repeats through the rest of the interview. Though he did not come away inspired by particular critical thinking skills, through the experience, Saul learnt a concept that he had not been introduced before, that of spontaneous plasmid mutations, something that stuck with him beyond the duration of the project.

In addition, Saul went so far as to distinguish between failure as normal in scientific process and failure recognized as part of scientific method. The former case drew from his experience in the laboratory space, that failure could be expected in the everyday activity of scientific research, in engaging with the practices of science. The latter he explained more thoroughly, had to do with the way scientists answered statistical hypotheses and the goals of scientific research. He explained that the very nature of answering statistical hypotheses – either by rejecting the null hypothesis or failing to reject the null hypothesis laid claim to the role of failure as integral to the progress of scientific work. In addition, “there's that way of looking at hypotheses and there's also just, you know, you, you test a hypothesis and you don't get what you expect and you modify your hypothesis and **then that's the crucial thing is modif- going back and modifying your hypothesis**”. Failure was incorporated into scientific method through the essential restructuring of hypotheses it engendered.

Sense-making through this sequential process occurred at the intersection of cognition and emotion. Considering that learning seems to be part of the failure process as students have thus described, failure becomes all the more unique because of the powerfully unsettling emotions described. Among fear, frustration, and helplessness that the students described, none are often associated with the process of learning, but often are with assessment of learning

(Henry et al., 2019; Nelson et al., 2013). As an experience, students still recall their emotional response, almost as a way of recognizing the dissonance of the learning that followed. The sense-making process that the interviewed students engaged in allowed them to transmute emotional distress of an unexpected outcome into cognitive reframing of knowledge and action around an unexpected outcome.

A Begrudging Acceptance

The last observed type of sense-making that students engaged in was justifying the scientific failure experience. This did not necessarily incorporate students' own failure experiences, but situated an abstract idea of failure within science, and thus justified their having experienced some measure of failure. This resulted in a reluctant acknowledgment of the failure experience as part of the scientific process. Like Tate said, "you've to get used to it in this career". Regardless of the insights that failure provided, failure was not something actively sought, but an experience to guard against repeating, often because of the loss of time involved. However, students agreed that though a failure may not be repeated, given the nature of research, one could not anticipate all the ways in which one could fail. And this circled back to the begrudging acceptance with which students made sense of failure's part in the scientific process and to their learning about the scientific process. To better illustrate this concept, I use examples from interviews with Tate, Mera, and Jayd.

Tate documented his justification of failure with by how experience inures one to the process of failure in science. He noted that young researchers could get "jaded" or disappointed about unexpected outcomes because they do not necessarily have the emotional maturity to deal with the outcomes productively, but that this was the life of a professor.

> "You know, **as a student, um, I think in my case, I think I responded maybe a little bit more, uh, critically** having been through, um, the process of

> first, but after a little bit, you know, I just kind of thought about my, my previous experience and understanding that things in, there in the research process, um, like I said, they don't call it research for nothing. Um, I mean, you know, common joke among science people. Um, you know, I, **I thought, you know, I guess, um, I wouldn't necessarily say failure, but, uh, you know, I was really disappointed for sure**…When you're driving a project, when you put a lot of time in, um, before you even start collecting data, and then you get right there and, um, something else beyond your control stops it, it's, it's frustrating. It is because, uh, I think it's- **I think all of us who put that kind of effort into a project, um, we want to see it move forward. Especially the student. We, we don't have infinite amount of- I mean, we're not getting paid to conduct research, we're paying to conduct research.** And I think that, um, you know, **when you're a professor,… and things don't work out all the time. That's, that's your career. That's, that's what you do…** Um, I've known plenty of people who've done an extensive amount of, um, research and get data and the data just not be what they thought it would be at all. And not in a good way, you know, not, not in a, not to confirm some sort of bias, but there are, there are a lot of times where you're expecting to see something, especially in science and you don't see it at all. And, um, then it, then it becomes, "okay, well, did we do something that, you know, changed some outcome or is there something else you know?" We think of in terms of, you know, confounding variables or, I mean, there are a whole number of things, um, you know, that contributes… **And, you know, when, when you, um, so I think sometimes when things don't work out the way you want it, to use the- a euphemism, um, you do get, you get critical I think you get a little bit, um, you know, jaded about the experience**, because you're obviously excited to, to move forward with a project. Um, but then, you know, **after a while you kind of realize, well, that's just kind of, that's just sometimes how it works. And, um, you know, you, you have to kind of take from it what you can**."

Tate justified why failure for students elicited disappointment and frustration – not because of the failure itself, but what it means for the time and efforts wasted for people who are already time constrained. On the other hand, the repetition of work caused by failure is a regular function of professorial work. Failure becomes part and parcel of the research scientist's life, to the point where emotional distress is replaced by acceptance proceeded by an evaluation of the failure. Indicating that researchers have to "take from it what you can" conveys a weary resignation about what meaning is made of the experience and from the experience.

Both Mera and Tate had a lot of experience with research before coming into the context that they shared for their particular failure experiences. Mera and Tate's experiences communicate that observing mentors respond to failure and experiencing multiple failures in the research setting teaches students that negative emotional responses need not be a reaction to failure in these contexts. Mera also remarked that experience mitigates the emotional impact of failure, something young researchers build a tolerance towards.

> "And granted, like, while in high school [research], **like when things weren't happening or the timeline wasn't working**, what have you**, I would freak out. I would just, um, you know, go on tirades.** Why am I even doing this? Yada, yada, yada. But once, you know, maybe it took longer, maybe it was something happening it's- you still push through. And so maybe that's why defining failure is harder for me, because while failure might be something, **you know, for someone who just started doing research, it can be really detrimental and absolutely awful,** maybe it's just my very optimistic point of view of life, **but I just see them more as bumps or like, you know, maybe a little a blunder or mistake, something that just happens,** but they can be mediated in some way or form or fashion."

Here, Mera talked about the switch between her reaction to failure during her initial exposure to research and her current "optimistic" attitude, explicitly making the distinction between herself and "someone who just started doing research", and implicitly attaching experience to the diminished emotional impact of failure. Her immediate follow-up to failure as a "blunder or mistake" as something that "can be mediated" also recognized how prior experience with research leads to knowledge on what to do next. Mera expanded her analogy to account for how accidents, particularly the failure analogue of fender-benders, could not be accounted for. Instead, she recommended taking steps that attempted to avoid failure, but be resigned to experiencing it anyway.

> "I think we do try to avoid failure 100%, because when you do get in that fender bender instance, you'd have to call everybody hi, this happened. And then you look like an idiot or worse and you try to avoid it. **You, you know, you make checklists, you pack everything the night before you, you know, get things**

> **certified by the different organizations.** You have to get your survey certified by, but at some point it's just, it just happens. And you just can't avoid it because what's going to happen is going to happen. **You're not going to be able to, you know, anticipate "yes, I'm going to fall asleep at the wheel and I'm gonna run into somebody." You can't anticipate that.** You don't know what's going to happen. And so you can try to mediate that as much as possible, but if it's gonna happen, it's gonna happen…

Mera's analogy very neatly conveys that no matter the preparations you make, failure cannot be anticipated. That even with a vehicle certified to be in proper working condition, metaphorically reflecting the evidence-based protocols guiding the particulars of research being "certified" by the communities of scientific practice, internally and externally attributed variables can influence the outcome of the experience. In addition, the fatalism conveyed through the attitude that "[failure] just happens" reflects the notion of failure as a pre-determined outcome, suggesting that no matter what arrangements made, failure cannot be thwarted as part of the research experience. Mera once again followed that up with the notion to "mediate that as much as possible" which suggests that the researcher has more control over how to respond to the unanticipated event. Her repetition of failure as a foregone conclusion conveys a resignation to such experiences.

Jayd communicated this concept more implicitly than the other two, as she felt she had been more of a spectator in the failure experience. While she felt her work was valuable and that she was a contributing member of the lab, the particular context in which she experienced failure involved a project to which she was new and did not have as much ownership in, and thus she felt she was not as emotionally impacted by failure.

> "**But, I also think when you go into research, you are open to like, you can't just be like, "this is how it has to be", because that's not what research is**. I think, it was like, it could be doing this, it could not be doing this, it's, **it's going to do whatever it wants**. That's just how, the nature of research. So I think when I did, I was like, "this is fine", whatever, and I'd give it to him and he'd be like," Hmm, this is weird."

> And I'd be like, "Oh really? Like that's interesting." **And so when it didn't work out and we just kind of stopped the experiment, I was like, "okay, well this is just how it goes"…**I mean everyone could respond differently, I guess, **like if you were really invested in like your preconceived notion of it, you'd be really upset about how it was going.** But I think I was pretty fine with how it was turning out. 'Cause like I said, it wasn't like really impacting me that much."

Jayd, explained that one cannot anticipate research outcomes as that is the "nature" of scientific work. She, like Mera, felt that as research was wont to progress independently of scientists' predictions, as the phenomena of study would act according to their natures. In contrast to the previous statements about emotional response to failure as part of the failure process, she attributed a negative response to unexpected outcomes to an illusion of control over the process. Jayd seemed apathetic when her work did not yield the expected results, and her response to her mentor's statement suggested that the unexpected results sparked some curiosity. Later in the narrative, she described the work her mentor put in to figure out why the protocol did not work as expected and walking through potential explanations with him. Watching her mentor and PI decide to end the project after repeated attempts at a solution led her understanding that "this is just how it goes." She shrugged off the failure experience as just a part of the research experience, conceding that this attitude could be due to her lack of attachment to the project and its outcomes. Jayd's example considers whether the begrudging nature of acceptance displayed by the others grew out of a level of ownership of the project as perceived by the undergraduate researcher.

A Time to Fail. Tate and Mera's examples also suggests a temporal dimension to the experience of failure. All the interviewed students explicitly stated time as a factor of failure – whether it was a loss of time because of failure or a perceived lack of time in general that led to frustration with failure. Like grades in a classroom setting, time became the currency that students could not afford losing in the research setting. Tate's narrative above includes this sentiment, in which he stated that the frustration that came from losing time after putting in so much of that through his efforts in setting up his project, which did not even get to the data collection process. Mera communicates that as well through her discussion of failure not fitting into the "timeline" she envisioned for herself, and that it would take "longer" for such an experience to become acceptable. Cera's example provides an interesting contrast. While she clearly found time to be an issue as well, it also became the reason she could not accept failure in her context.

> "The problem was, **I didn't, um, you know, know how long I had.** I, I was only an undergraduate student, and I had things I needed, I wanted to do too, you know? And I loved the work, don't get me wrong [pause]… this was why I want to do a PhD even with medical- an MD. I- **But there, I would have time to fail**. Because I'd have, like, years to get fully into a project. **But I didn't, uh, I couldn't learn from that fully here. Because I didn't have time...** I know, it's funny, because I think in science, not getting the result you want is fine. I didn't necessarily get it, you know, but in the lab meetings, I could see that even- **like being frustrated by it was all fine. It's just a part of the process**. But I at least wanted to get to a point where we could, you know, figure out what we were seeing. What was going on with the viral vectors in the host. **But when little things got messed up and got in the way, like, that's even more frustrating. And I don't have time for that right now…** And, like, **I get that it's going to happen. Like, you can't always prepare for it. But I'm never going to like it. Not now."**

Cera's comments embody this concept well – that failure has a time and place where it can provide benefit to the researcher. And because of the constraints of undergraduate study, that time is not necessarily during undergraduate research, but starting with graduate studies. She could not, even begrudgingly, accept failure as a part of *her* research experience because the time to experience that would be when she could learn from it, and not when it was more of a hindrance to her understanding the results of her work. At the same time, she recognized that it was a part of research experiences in general.

Summary

Making sense of the failure experience involved students first trying to capture what they had experienced, then how they had experienced it, and then how they moved on from the experience by giving it some justification within the context within which they had experienced it. The totality of the experience can thus be captured by Figure 5.1.

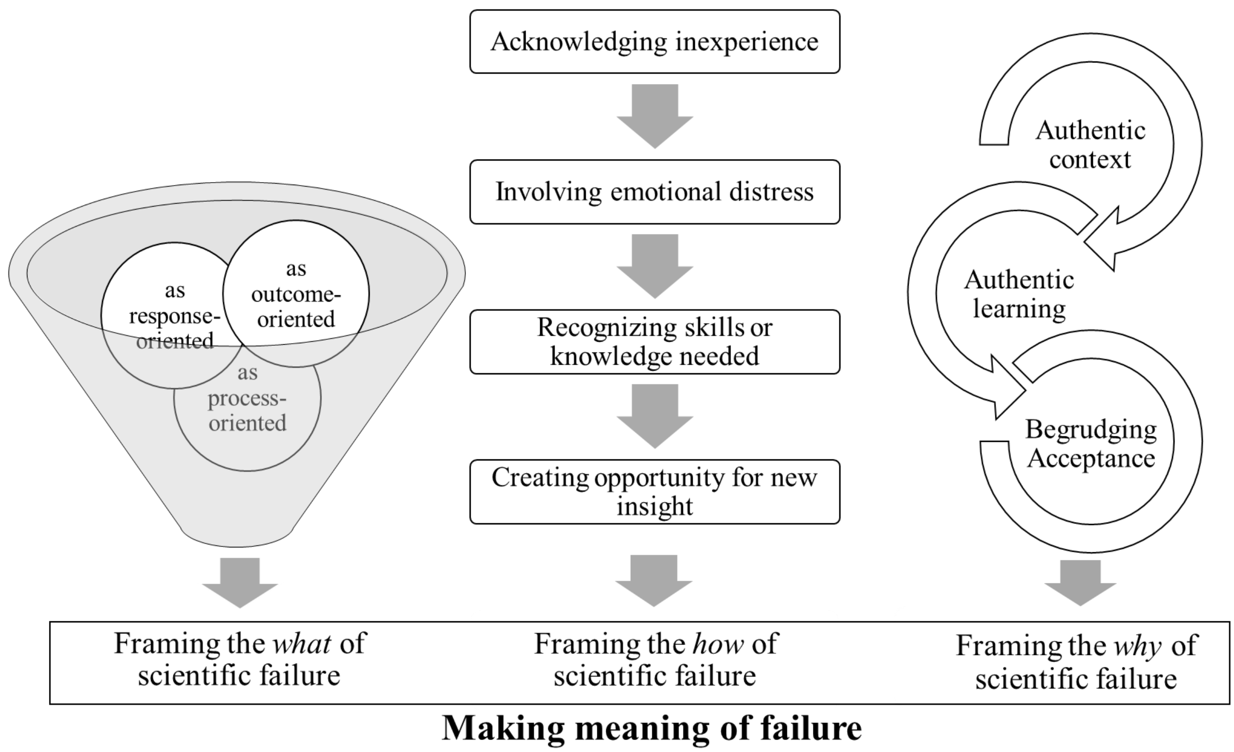


Figure 5.1. The processes involved in making meaning of scientific failure

Within a constructivist worldview, sense-making involves generating an explanation for the experiencing of phenomenon. In addressing this research question, I learned that the experience of failure is a fluid concept to students, one that vacillates between different categorizations even within the same experience. Within that vague idea of what scientific failure is, however, there seems to be an established process to describe how students experience it.

Having undergone an experience that involved some emotional and cognitive dissonance, students attempted to justify that through the context of their research experience. In the next section, I explore further how exactly students saw failure fit into this broader context of research.

RQ2B – Finding Meaning In Failure

Here, I explore how students situated their failure experience within the processes of science and whether that enabled their understanding of the scientific enterprise. While a separate analysis from the earlier question, some ideas overlapped just due to how centrally students situated failure in scientific processes. The framework that I derived from my understanding of learning in a community of practice (in Chapter Two) will be utilized here as a visual tool to help communicate how students saw failure as within science. This analysis drew from student commentary about their own experience of failure and research, but also from the observations they made about the disciplines of science from other sources.

My use of the Community of Practice (CoP) framework serves as a theoretical lens to situate students' learning through participation in research. Research using this framework spans educational contexts (i.e. student, faculty, and teacher learning communities, online learning, etc. – Sadler, 2009; Wesely, 2013), managerial contexts (i.e., Wenger, McDermott & Snyder, 2002) as well as the study of various professional fields (Lundgren, Crippen, & Bex, 2020). Investigations have also included work elucidating theoretical underpinnings of the framework as well as using the framework as a tool to understand and develop social learning environments. As the framework grew out of situated learning theory explicated by Lave and Wenger (1991), I returned to the descriptions of communities of practice by the original authors to develop my thinking about scientific research, and to orient how students described failure fitting into this context. Through this lens, unstructured undergraduate research experiences most closely resembling an apprenticeship model of learning, where newcomers gain knowledge specific to a discipline through participation within the contexts that generate knowledge about that discipline and at the side of people more experienced in the practices of that discipline. Lave and Wenger (1991) described this further, writing that "a community of practice is a set of relations among persons, activity, and world, over time and in relation with other tangential and overlapping communities of practice. A community of practice is an intrinsic condition for the existence of knowledge, not least because it provides the interpretive support for making sense of its heritage. Thus, participation in the cultural practice in which any knowledge exists is an epistemological principle of learning. The social structure of this practice, its power relations, and its conditions for legitimacy define possibilities for learning (i.e. for legitimate peripheral participation)" (p. 98). In essence, communities of practice develop by coalescing around a domain of interest, bringing together members who participate, and engaging and advancing practices those members identify as central to knowledge generation of that domain (Wenger et al., 2002). Communities of practice may even overlap, as Lave and Wenger point out with their example of physics students learning in a classroom being distinct from but overlapping in some aspects with the work in which physicists engage.

Failure and the Scientific Community of Practice

We can argue that with undergraduate research, where students physically and intellectually participate in aspects of knowledge generation, students are indeed participating as newcomers in the communities of science that legitimize knowledge through socially negotiated practices in their respective disciplines. Though the practices in which students engaged may be particular to specific disciplines, we can consider the scientific practices defined by the NGSS

(2012) to encompass the broad strokes of practices in which scientists engage. As such, the image derived in Chapter 2 (and revised here as Figure 5.2) to explain my theoretical approach to

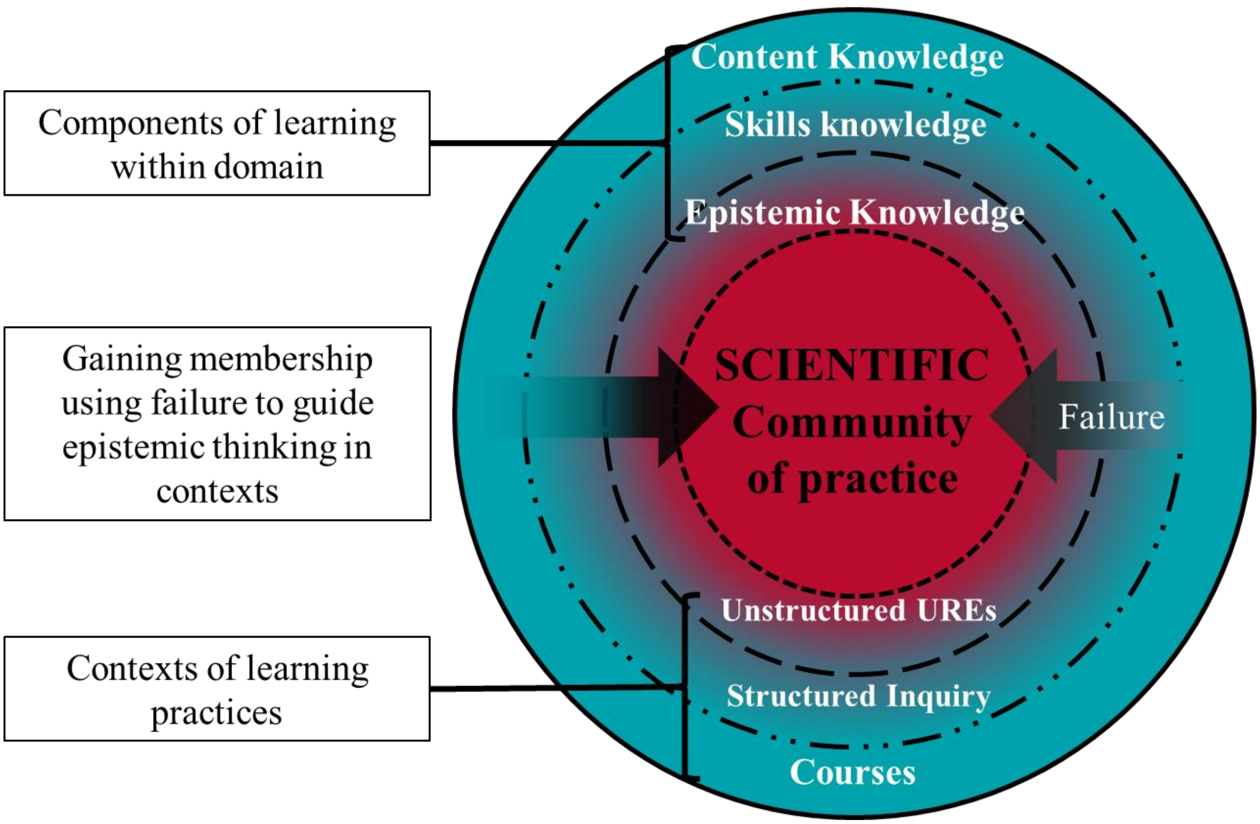


Figure 5.2. A revision to the framework developed in Figure 2.1, proposing failure as epistemic practice bringing undergraduate students closer to scientists

this work communicates how I view undergraduates approaching the scientific community of practice (CoP) from learners transitioning into more experienced researchers. Though Lave and Wenger (1991) distinguished between the community of learners in a class reproducing the work of a professional discipline of researchers, I saw the transition from education to practice to be more concentric, where education often acted as a gatekeeper to the community of practice. I believed that in the currently operating educational systems, students were required to demonstrate their grasp of content learning and practical skills before they could participate in the epistemological learning more closely aligned with the goals of professional discipline. Through the learning I gained from this analysis, I reworked the framework I had initially described to be more inclusive of how students described their learning in the research setting. In particular, how failure attended to epistemological learning within the community of practice through what it reveals of the nature of knowledge generation and the nature of shared histories, through its cultivation of membership, and through the practices provoked.

Failure and Domain: Epistemic Engagement in the Scientific CoP

All students interviewed revealed epistemological knowledge gained about membership and participation in the scientific community of practice through the experience of failure. Indeed, most mentioned that this knowledge could not have been gained without experiencing failure in their specific contexts. In particular, students understood through their experience or through justifying the nature of research that engaging in novel work required accepting uncertainty and expecting the unexpected. In addition, failure made discovery work more interesting and became a way for the researcher to feel more part of the community of researchers. These next sections explore these concepts in greater detail.

Novelty Requires Uncertainty – Failure as Expected.

Several of the students mentioned that the highlight to undergraduate research was participating in novel, discovery work. Often, they mentioned enjoying the opportunity to learn newly designed protocols and procedures or attempting to answer new questions in research. This was often juxtaposed against that of "cookbook" laboratory environments, rehashing established knowledge. Eoin addressed this early in his interview:

> "…research is- you're**, you're pursuing something novel.** Your, uh, lab courses, you have a procedure that you follow to the end, and it's not really, I

> mean, having done a lot of lab courses and having done a lot of research, I feel like doing lab courses does not prepare you to do research in the sense of things. I mean, **you're just following procedures** and you may have a technique or two that's applicable from one to the other, **but I don't think they're really comparable**. Um, I mean, I research is, I mean, I don't know. I don't know why I want to research, I guess it's just cool. **Um, I thought it would be cool and it'd be a good addition to my resume**…I got in there and I started and I, I thought I knew what to expect... And, um, I was able to- just kind of the way things worked out, **I was able to kind of take some role in leading and designing that project and kind of shaping it in some direction. And even though it didn't turn out the way we wanted, I, I enjoyed that. I liked being able to kind of design and experiment and think through things**. And so I think that kind of my first lab experience was a good one. Um, which may have, I mean, **even though the end result was not good, the process was good. It taught me a lot and I enjoyed going through the process and I wanted to keep doing it**."

The autonomy that Eoin was allowed in the lab space as a participant in novel work changed his perception of research as a means to an end for his career aspirations to becoming part of his career aspirations. Lab courses did not offer either novelty or opportunity for "leading and designing" and "shaping" of a project. Prior to participation, Eoin was unable to articulate any expectations for undergraduate research, but that it would add to his resume. But engaging in work where he was able to "design and experiment and think through things" even when the project ultimately came to an end because of mismanaged and incomplete data collection led to him shifting from an MD to an MD/PhD track. The act of participating in knowledge generation – engaging in the practices of scientists within the space of scientists, led this shift. Eoin was also able to recognize that failure did not take away from the discovery process, separating the unfulfilling product of the work from the process that he had enjoyed.

Cera, also someone who incorporated research into her career aspirations after her research experiences, communicated how her laboratory courses did not prepare her for the reality of research.

> "I mean, I didn't- I thought I knew what to expect, like obviously you're told "research means doing new things" not doing the same thing over and over

> and over. **I mean, like what's the point of the labs where- when we keep, when we already know the answer we'll get. The TAs already know what we're supposed to get and so you just look like an idiot, you know, if something goes wrong.** Because then it's just your fault. And, yeah, I get that you're supposed to learn about reproduction, uh, reproduc-, uh where science is more reliable because it can be reproduced over and over. **But even then, it's not new work.** So I didn't know what to expect. I worked on a project that the post-doc had already begun… we were trying new things all the time. I mean, not new infection procedures, but **we were exploring new ideas, we were in the unknown territory**. Like how cool is that? **And nobody knew what we'd get out of this.** I mean, like, my mentor had some idea, and obviously the PI knew, well, even more. **But still, nobody had an answer. And so if something went wrong, we'd have to sit down and troubleshoot it together, you know.** It wasn't- it wasn't like "you got this wrong, now do it all over again", but "let's figure out if this is what the cells will actually do, or like where did we go wrong." Ev- and then, even if it is because I used the PCR machine wrong, it's not the end of the world. I just learn how sensitive the mat- how to use it right. All, uh, part of the learning process."

Cera's learning about research and gaining enjoyment within research ties both the novel aspects of research with failure processes. Lab courses as places where the instructors already knew what to expect made her feel like something going wrong was belittling. In charting "unknown territory" however, failure became part of the investigation – to learn whether the unexpected element took the research in new directions, or to revisit the mechanisms of the discovery process. In doing so, the learning that occurred in this space benefitted Cera to such an extent that she saw the same potential issues in two different lights. In the less authentic space, "you [would] just look like an idiot" but in the authentic environment of the research space, "it's not the end of the world…[but] part of the learning process." In this way, the novel context changes the meaning of and the response to failure. Cera's experience translated to analogizing failure within science and then scientists' role connecting the two.

> "Well, **science is like, um, order… you know, things work in, in certain ways and when you do something based on what you know, you expect a, a certain result… Then, if it doesn't work uh, the way you expect, you get chaos, uh, failure.** So failure is disorder… But in science that's ok. **Because the scientist's job is to, to make sense out of that disorder.** That's what we did. Dr. [PI] had

> the whole lab sit down and figure out why our results looked so weird… Was it because we messed up with the equipment? Or did we use the wrong quantities of stuff? I, I can see now why writing everything you do is so important in the lab too you know… And even that discussion was chaos. Even though I, I couldn't really contribute, I got to watch it all go down. And uh, watch it all come back together. **Order out of chaos. Just, just the scientific process**."

This quotation was particularly powerful to me as it resonated with many concepts I thought was at the heart of the very nature of the human endeavor of sciences. Cera's experience with failure in research led her to a far deeper epistemic insights, one that resonated with scientists themselves.

In Leon's example, failing caught him off-guard as he was not used to failing prior to his college experience, but that he had become resigned to once in college. He too mentioned that failure in the laboratory space meant something different to him because of the context of research.

> "I mean, I definitely learned how to like, do the protocol better. 'Cause like, I mean, if you get it right the first time or like, **if you get it right, you don't like really realize what you did right**. But like when you get it wrong and you have to do it again, I guess you realize like, okay, so I messed up here, so I need to make sure I do this specific thing. **So by getting it wrong, I definitely learned like what to focus on and learn the protocol better. And then I guess I also like learned, like I got more appreciation for like how hard research is**…"

Leon specifically mentioned that what he learned from procedural errors in the laboratory space was something beyond what following correct procedure would get him. Failure within the authentic environments of the scientific community of practice meant an opportunity to be to learn more thoroughly about the processes of knowledge generation.

Tate went deeper into his thinking about these processes, revealing more epistemic gains from research about the nature of scientific work. His desire to participate in research came from epistemic understanding gained from prior research, and his experience of failure in the current setting – where the resubmission of memorandum of understanding allowing him to participate in clinical research stalled his efforts prior to data collection – led to becoming more aware of the protocols that provided structure and support for scientific work.

> "Um, so really the inquiry is how to make an observation, how to make an observation and measure it, um, using the scientific method and, you know, really how to evaluate that as well. I mean, that's a huge piece. There are a lot of things that people observe and measure, but what does it mean, um, in, in context? And I think that's, **that's really, the nuanced part is looking at data, looking at, um, what you happen to see in any, any, uh, experimental design is, you know, w how do we interpret that?** And that's a really tough thing to, to get at, um, because there are many individuals who can take the same research, same data and present it in a different way, different light, a different context. Um, **and so I think that that's really kind of at the heart of, uh, inquiry is, is kind of putting in context to what you're doing and what you're observing and what you measure**… Because at the end of the day**, you don't know what you're going to see. That's the point of research. You make a, you make an assumption, you have a hypothesis and you evaluate it through observations and data, and it may be something that you, you thought, maybe something different.** Um, and that's just, you know, the thing, um, with scientific inquiry again, is that, um, you're evaluating what you think based off of previous literature, science, um, expert opinion, et cetera. And you're just here observing it and you're testing it. And then you, you make your, your observation of what happens. **Um, and a lot of times it is what you thought or the outcome, the data, wasn't what you expected it to be**. Um, so I think in that alone, there are people who get disappointed in the research process because they thought something was going to maybe be a good drug or cure disease, or show that this intervention is incredibly beneficial and helpful. **Um, and so there, there are plenty of times where, um, I think that generally a lot of people would consider that a failure, but like I said, those of us who are involved, I think in, in science are critically evaluating, know that that's the story, that's the case from the very start you start any project, it might not work out the way you thought it would.**"

Tate's description of the processes, particularly the focus on "putting into context" the interpretations made through scientific inquiry communicated the depth of his epistemic understanding. He recognized several scientific practices that naturally allowed for unexpected outcomes as a part of the discovery process. Tate tied together what he thought about research to what people would commonly recognize as failure because of his identification as a member of the scientific community of practice. The next section explores a particular example of a student recognizing failure as a tool to communicate within the community.

Failure as a Token of Membership

Through the development and expansion of her analogy of failure as a fender-bender on the long road of research, Mera detailed how failure made for a more interesting scientist and how it facilitated acknowledgement as part of the scientific community. Mera instinctively associated science with communities of practice, and within that she found the community aspect of it to be the most appealing. She explained that:

> "And I think the role you know, when you're off the road after the accident. [The lab members] play such a role too. **Um, 'cause that community, you know they can offer- they can tell you the stories of all the times they failed**. You know, they might take you out for breakfast, or going out for drinks or something, to console you and **remind you of why you're here and why you're doing what you're doing**. And so, while, you know, the police officer and the insurance company is important, **there's other cars on the road with you. And those other drivers understand what you're going through and can offer direction as well**… and **so you foster that community more and so that way, when you hit a mistake, you can be vulnerable about it and you have a community to support you through that being in the shop phase.**"

Through this analogy, failure becomes part of the shared histories of the membership of the scientific community of practice – an experience that other members resonate with and can support newcomers into the community through. Adding to the collective histories of failure within the scientific community became a tool with which to identify with that membership, particularly when it also showcased the persistence that Mera believed characterized scientists.

> "Um, so when you have failure, I think first off it knocks you down. If you've been getting too arrogant about what you're doing. Um, but **I think it humbles you so that, and I guess in one instance, that community can be fostered more because you're being vulnerable about what's happening** and you're he-, and you're able to be humbled through that. Um, but I think you get to learn more just about life in general, the cause, the effect, the emotion, the things. And then, you know, when you get back out on that road, the sense of passion that reinvigorates in me, because you're back in the saddle, you're back doing it again.

> You know, it can push you in further in your research than without that, feeling, if you never have failure and you're just all of a sudden, you know, Mr. Too-cool-for-school and doing all these things, they don't mean as much because there was nothing to, there was no, uh, your emotion wasn't fueled, I guess is one way to think of it because you're not, ef- golden sails all the way through your like yes, like cool, whatever**, but it might not be as gratifying 'cause what's the story you tell?** You know**, failure to a certain extent can add more comedy, more emotion to what you do and give more purpose to your why**… **I don't think research could exist without failure because if everything was perfect, every single time, that's boring**, number one. No one likes someone who's perfect. You know, **we don't want to talk to someone who has it all figured out and it's just smooth sailing**. They're not fun to talk to. **They're not, they're not relatable.** And I think you have to have it. And without it, it's just honestly, probably just not research. It's just "cool. He found that." Yeah… **I think it makes you more of a scientist because you get to overcome those things and when you overcome them, it refines first off a skillset you gain, but also it gives you more - what's the word - clout as to how, like, why you're a scientist, like, oh yeah. I'm still here even though X, Y, and Z happened."**

Mera highlighted how failure opens an avenue of connection with the community of scientists, but through this, also how perfection is not a quality that she finds appealing in science. Her identification of "smooth sailing" in research as "not relatable" also conveyed an understanding of failure as a token of membership within this community, a social currency demonstrating vulnerability and persistence, something that also provides "clout" for members. Failure became both a tool for communication and a token of identification with a membership. She added to this idea with an often-used example of a persistent scientist to offer value to research that builds from failure and the passion present in doing the work without expectation about the outcome.

> "You know, you read about **these stories like Edison and the light bulb**, how many light bulbs it took him. **It wasn't just one time it was magical. And voila, he had a light bulb.** He had like hundreds of failures that never worked and he kept pushing through**. But then once he got that light bulb, like euphoria, you know, like absolutely amazing,** he accomplished it... And that, **there's that passion area of when you get to experience failure, it makes research sweeter.**"

Mera's remarks point to failure not only as a token of membership but as an experience that adds flavor to research. In the context of her own experience, Mera displayed a weary acceptance similar to that of the other participants, but through her reflection on failure's role in science, she demonstrated a far greater acceptance of the process.

Overall, students' representation of scientific failure revealed the multiple ways in which failure contributed to entering the scientific community of practice: (1) recognition of failure as a natural outcome of the practices characteristic of scientific research settings; (2) failure as a means of connecting with membership; (3) failure as a means of connecting with the shared history of the community; and (4) failure as a currency of membership.

Failure and Membership: Mentorship

Early work in the CoP literature focuses on the transmission of knowledge in the apprenticeship model of learning (Lave and Wenger, 1991). In these settings, the mentors became the paramount font of knowledge for the entrants in the community. With the experience of failure, students mentioned the mentors as being crucial to the learning that followed the experience. As seen in the previous chapter, when the students did not have a nurturing relationship with their mentors, the relationship itself became the failure. In later works, the mentorship aspect became subsumed under what Wenger and colleagues (2002) described as membership. Membership encompassed interpersonal relationships within the community space, how new members interacted with each other, with more established members and with the most established members, some of whom may play a role in mentoring (Wenger et al., 2002; Dolan & Johnson, 2010). The grooming of future scientists through existing academic apprenticeship structures has been documented extensively in the literature of mentorship – both the benefits (e.g., Thiry & Larson, 2011; Lopatto, 2017; Dolan & Johnson, 2009) and its potentially devastating consequences (e.g., Aikins et al., 2017; Limeri et al., 2019). Instead of focusing on all interpersonal elements of membership in a community of practice, this section focuses on mentorship because of the ubiquitous mentions to mentors throughout the interview responses. Students talked about their graduate student and post-doctorate mentors primarily through their efforts in initially orienting the undergraduates into the research space and then through their instrumental role in reframing failure from an emotionally distressing event into an opportunity to learn.

Mentors can redefine and redraw the bounds of failure, as happened in Eoin's experience, where the mentor was not only a source of knowledge about practices, but an inspiration in handling what Eoin thought was failure.

> "So in a point where like, I'm at a point where I don't really know what to do with, you know, uh, you know, **let's say an experiment's not working and I'm not sure what to do with it. He usually does know what to do.** So I think it's, I mean, in his eyes, he knows how to fix it so it's not a failure. But because I'm, you know, I don't know how to do it then to me, it does. **So working with him, you know, he can rescue almost anything. So I, yeah, he always, there's always a way for him to, to fix it. So working with him, you know, we're always trying to find a way to fix it…**"

Eoin realized that failure was relative through observing his mentor "rescue" their efforts. He realized that the knowledge and experience gap between their respective places in the community of practice meant that failure had a different meaning and impact the more central in the community of practice one journeyed.

Saul's mentor helped him find a place within the research space. Though he did not initially feel like he belonged in the lab, through his mentor's teaching him how to participate in the procedural work and through participating in dialogue with her and the PI about the work, the lab did feel more inclusive. Like Leia and Eoin, he also learned how better to manage failure through the reactions of his mentor and the recognition that her experience meant she was more accustomed to and better equipped to handle failure.

> "But, um, you know, I was, I was looking at the- this, the, the, the pages, and I was like, "this isn't right. There's like this, this is wrong on e- every single one of these pages**". And then, you know, uh, I was scared** because I'm like, "Oh, maybe I did something wrong." 'Cause I, you know, I, I, I hadn't, I wasn't aware of like, you know, the, the concept that, you know, they could just spontaneously, you know, generate mutations, you know. Uh, you know, **I brought it to my, my, my graduate student mentor, scared that I had done something wrong, but, you know, I talked to her, talk about it with her, and then eventually we brought it up with our, with our PI**, and then we had to, um, basically figure out a solution…Um, [the mentor], I mean**, she was, she was used to it because she, she, uh, she's, she has run thousands of more experiments than I have. So to her, I mean, it's, it, it, it was frustrating of course, because I mean, her primary goal was to finish her PhD as quickly as possible. So, I mean, she, she was annoyed, but like, you know, she wasn't terrified, like I was. And then bringing up to the, bringing up to our, our PI, uh, you know, he was completely calm…** seeing them not be as, you know, destroyed as I was, I realized, uh, more concretely that, you know, failure is part of the scientific process…"

While this segment of narrative (shared also in the results to the previous research question) identifies how the levels of emotional distress experienced in failure changed based on seniority within the research space, it also demonstrates the times in which simple observation of a mentor may change the way students' experience science research. Failure in this setting provided Saul an opportunity to see how more experienced researchers dealt with and learned from challenging situations, leaving him with more confidence about handling the next failure.

Leon also described fear as a response to his failure as a response, being so avoidant of the mistakes with the sectioning and staining of slides that he did not return to the lab for a few days. He did not perceive his experience with the mentor as a positive rapport. He found her to be friendly when things proceeded according to plan, but less so when he made errors.

> "I do remember the first time I went home that day or like a few times? I just, **I would just go home and like, not tell anyone at first and like delay coming back to the lab for a little bit.** Like it just a few days I would like not

> take off 'cause like they didn't expect me to come every day, but I just wouldn't come for a few days. And when I eventually come came, I would like go in and talk to my, like the lab manager and explain what happened… I mean, I think it depended on, like, **her reaction usually depended on the, like what I did wrong**. If it was like something that **sounded like something was wrong with the, maybe like there there's something that she didn't explain too well, she would like be very, very nice about it** and like, explain it again. But definitely when it was more my fault, uh, there was some, like, I don't know, I guess not disappointment, but like some like, like you- "make sure you don't do this again", or like, uh, that kind of thing."

He admitted that her reprimand-like reaction to his incorrect sectioning made this feel more of a failure – because the responsibility for the error lay solely with him – and also made him more wary of approaching her about future issues. Leon's response to failure was mediated by how he anticipated his mentor reacting to the failure. Leon's lack of the kind of rapport that the others did with their mentors may have contributed to him being the sole person who did not communicate perceiving a difference in the way that the more experienced researchers around him responded to failure.

Jayd's experience of research was enriched by her perception of the lab as a supportive environment, a community in was an independent and contributing member. As a result of many semesters in this lab, she felt connected to the community of the lab, describing it as a "family".

> "I really liked my lab. **They really tried to like, make sure that you were an active part of the research** and that you understood what you were doing. Like every semester you'd have a lab presentation about the work you were doing, which I think I learned about, and then, like, I did CURO, and I did like all, all of this stuff that like really made me have to go deeper into my work. **So I think as I did more of it, I realized like my mentor's, like thought processes**. **Like we'd be doing an experiment and if it was working, we kind of keep going with it. If not, he'd explain, like why we shouldn't be doing this and what else we should maybe focus more on.** And so after a while, I kind of just started to see like, Oh, if I'm doing this, he'll probably want me to do this. **And then just kind of like taking more of a lead on it in the research work.** And that's, I think kind of where my expectations, like, not, I guess, expectations, but like, **I started to take a more leading part in it and thinking more like a researcher… I would just run all the experiments and collecting, compile the**

> **data. And then me and my mentor would kind of go together and interpret it.**"

Jayd and her mentor established a good working rapport, to the point where she felt like she could anticipate the directions he could provide. Her mentor provided her the opportunity to take the lead on some efforts as well and participate "like a researcher". When it came to her experience with failure, her role was bringing attention to the data, which she and her mentor could not make sense of. Going through the process that led up to the inexplicable data set, and then resolving the issue involved a lot of time spent in reflection on the project and working through the development of a different protocol.

> "I think just like kind of, uh, it was kind of interesting to be like, I understood why it should be what it should have been and then have it not be that was kind of confusing to me to be like, why, why wouldn't this be working? And then like, I just don't know what's going on, like beyond that. So it was like, I just don't know**. And so maybe if I had had like more background knowledge in that I could have come up with like more ideas** to like dive a little deeper and then maybe we could have gotten more from that experiment, but I didn't have those skills**. And then my mentor who probably did have those skills, he didn't seem like he came up with anything to keep going on that path. So I think there are skills that like maybe would have helped us, but it seems like, I feel like if neither of us had anything, it was the right choice to kind of go in a different**..."

In getting unexpected results, Jayd felt that both she and her mentor did not have the knowledge to continue that particular project with any confidence in getting different results. She first addresses these limitations within herself, but assures herself that their decision to abandon the project – her definition of failure – was the correct one. She does so based on her observation that if her mentor, with all his skills could not salvage the work, then this "was the right choice." Jayd found that the work she and her mentor did to learn from this experience and move onto a different viral strain led to more insights about their respective places in the community of practice of science.

> I guess just **like how much, like researching behind the scenes you would have to do to understand this [failure]**. Like I know I had to do just like a little work of my own to be able to write my own papers, which took a lot of effort, but I know like when **my mentor, anytime I was working, he was always in the back, like reading articles, just trying to figure out how everything was working together and to make sure that like, to make the protocols**…**it's a lot of effort to kind of create those protocols. And I don't think I realized that**. I think I thought it was definitely more already established than it was, but it's definitely not like there's a lot of things you can explore… Uh, I feel like I said, this wasn't super like detrimental to me personally. I think if there were any concerns of mine, it was like, maybe like, "if this ends, will I still have a role in this lab?" But I wasn't super worried. Like I had already worked with everyone else in the lab to like find which project I'd be working on. So I wasn't like that worried about that. And then also just like, "will I be able to like present this? Will I be able to get like a publication from this?" And so I guess, like, those were my worries as an undergrad. I feel like if I were a grad student, it might be more serious to where it's like, "is this detrimental to my work as like a potential PhD candidate?" Like, I feel like that would be a lot more stressful and a lot more weight on me. And then that's, excuse me, that's like a lot of work for you to kind of figure out what's going wrong and that's just a lot of additional load on you. **So I think that may have stressed out my mentor a bit more, but I didn't super see that.** So I'm not sure how he experienced it, but for me, I think it wasn't that bad, but I do, I do think it like did have some good takeaways for me of just like how I viewed the research process..."

Jayd's mentor served as her connection to the greater scientific community and through his efforts to include her in the work of the lab, made her feel a valuable member of that space. As a result, the failure experience was not his or hers, but a shared one, a decision rather than an outcome foisted upon them. As such, her response was far lighter and detached from the other interviewed students, as it was not her efforts that proved fruitless. But she could see that detachment was perhaps not an option for her mentor, gaining some insight into the thinking of a graduate student in science, even though he did not make clear to her his concerns about scientific failure in the graduate research context.

All students talked about the crucial role of mentorship through failure – either to describe the different ways each learned to see that failure did not necessitate a strong emotional response or to show how it reinformed negative perceptions of failure.

Failure and Practice: Reflection

The scientific practices as enumerated by the Next Generation Science Standards (NGSS) can be broadly recognized as the underlying practices that unite a scientific CoP because of their universal application across the scientific fields. What separates it from the educational context is also the practices that involve recognition and value around knowledge generation – such as the development, publication, peer review, and replication of novel protocols and ideas, but even this can be subsumed under NGSS scientific practice #8: obtain, evaluate, and communicate information. The undergraduate students interviewed in this project made clear that an additional practice needed to be added as shared by the scientific community, a practice all of them interacted with through failure: reflection.

Students made clear that when their research proceeded without obstacles, they did not spend too much time thinking about their work – the mechanisms, the concepts, or even the equipment. Failure however necessitated thinking critically about every step of their work, using the resources available to them to evaluate and interpret what meaning could be elicited from their outcomes or why attention to detail in a protocol was particularly necessary. In addition, reflection on the process also allowed for the experience to be put into perspective, so as to mitigate negative emotional responses. As such, reflection was the process that allowed failure to go from a discouraging experience to a learning one. In contrast, through the thoughts that some students shared, they clearly felt that if reflection was not paired with reflection, this led instead to cognitive stagnation and more severe emotional distress.

Leia shared a representative example of these thoughts, as she began her narrative in saying that she was "lucky enough" to experience failure.

> "So it wasn't like, ok, I went into this wanting to fail, you know. But if I think about it, I was actually like, lucky enough to fail in a way that uh, I, I could

> learn from. **Because how else could I really see what work scientists do- did behind the scenes?** When we needed to figure out a new protocol for the *Drosophila* CNS expansion, I got to know so, so much more about what we were doing to come up with a re- an explanation why it didn't work. I got assigned papers to read, I was able to talk about it more intelligently. **Before I was just mindlessly doing the work**, I wasn't thinking about "oh, now I'm going to stain it like this, because that is what it's gonna do and why it's doing it." It was more, um, mechanical – I think that's the word, ha – than that. So it didn't work, and now I could tell you why. But that also put me, uh, in a, a better position to think about wh- what to do next. And obviously, like, I didn't do all the readings that [mentor] did. And I wasn't the one, um, making the final decision about the protocol. But I got to be part of that, and to, to some- whatever extent, I got to play in that sandbox… **But now I knew how to deal with [failure]. And that it was ok.** And the more this happened, **the more I got to be, to be, um, involved in thinking** about why this happened and uh, what to do next."

Her experience made clear that had not failure with the protocol occurred, she would have had no urgent cause to think about the procedural work she conducted in the lab and to connect that work to concepts guiding the research. However, failure paved the way for that learning and understanding. Leia went on to describe what she assumes may have happened without that time and space to reflect in the lab setting.

> "I think we needed to go back through the whole thing. But say we didn't. Say, like, say hypothetically, we didn't go over uh, what went wrong. We would have been stuck. **We couldn't have known what to do, where to go, who to contact to find out more information, all that.** We would have just- we would have had to abandon our protocol and, and start a whole new project. Now, yeah, sure, we did have to figure out a new protocol anyway. **But, uh, we wouldn't have known what uh, what changes to make and why we were making 'em. In that case, what's the point of, of research? Aren't we like supposed to think about the why?**"

Leia's narration set reflection as central to scientific processes as it constantly brought to fore the purpose of scientific work, the question of "why" an experiment yielded the results it did. Without reflection, research became a series of "mindless" operations. The question of "why" became particularly relevant with unexpected outcomes, because attempting that went counter to the practices characteristic of science.

Mera shared how science comes to a grinding halt without reflection using her analogy. That in the moment and without the advantage of time to reflect and a supportive community, "you're just going to sit there. And you're never - you're just gonna sit in the shop. You're never going to get back on the road and you never looked at research again. You're just gonna be like, "you know what? This happened one time. I'm never gonna do it again.'" Not only does research progress come to a halt, but her personification of the driver also conveys that the researcher too loses motivation to continue with research. In addition, she saw failure as connected to learning, but without reflection, that connection was absent. She used an example she had heard from a scientist external to her lab to illustrate this point.

> "**I think hindsight is, is re-, is required only because, you know, without it, it's just this moment in time that you never connect to anything else is, is that, is that connectivity to, well, this happened, but then this, and it's that connected. And if you, if you're not, if you're not reflecting on it, you're never going to really try to comprehend and understand how these things happen**. And I think without hindsight, it's just a blip of a dot along the time span of your life, that you never connect to anything else. **And then you end up mulling on it for so long, you know, on "it could have been."** Um, so for example, one of, uh, Doc- doc- doctor [CURO scientist mentor]'s, um, she tried to get her PhD three times and the second one, a cow actually ate her peas that were her research study for her PhD, completely ate them**. And so in that moment, I cannot imagine like, if you would take that moment in of itself and not just mold in it and just sit in that circumstance, it's definitely going to be failure.** And it's definitely just going to be **something harder on your, on your spirit,** where on the other hand, she used it as hindsight now as wow, that cow did this, but then I got this even more amazing PhD and it led me here to the university of Georgia so that the hindsight, I think makes it sweeter and it doesn't make it so heavy on you for what, um, for what it did in your life."

Mera saw reflection as a tool that provided perspective and self-encouragement to foster persistence and as also connected failure to learning. In science, she related failure plus reflection as learning and persistence, but in the grander scope of life, she seemed to see the reflection on failure which provided perspective to view failures as serendipitous opportunities. Without reflection though, failure became a heavy weight on the spirit.

Tate summarized this point as well, sharing similar sentiments with both Leia and Mera on the activities that reflection upon failure generated.

> "I think that a lot of people, uh, I was- I used the term failure very loosely here – learn a lot more from, from failure. I think, I think, **'cause you analyze things far more deeply and critically than if you succeed, but you think that if you succeed, you did it, you did it correctly, you did it right. That it.** Not any other factor there. Right? Like, um, like coincidence. Um, and **I think failure, we look at it from many different ways and analyze it for a much longer period of time. I don't sit there and think about my successes every single day, but I think a lot of us would ruminate on our, our quote unquote failures for far longer and more frequently.** Um, so I think it has something inherent to that. I think **that's probably why people become better scientists and better researchers because they do reflect** on [failure]- Reflecting. I mean, that's, that's really what it is. Um, I think that that's a big part of this."

In the moment of sharing this, Tate came to the realize the centrality of reflection as a practice. Failure plus the critical evaluation of it that reflection provides becomes a vehicle for scientists to improve upon their practices and a tool to gain self-awareness as a researcher. Tate is almost dismissive of success – even attributing it to possible "coincidence", but it conveys the point that scientists often trust the paradigms of the past to build new structures for science above it, without questioning what our successes could be due to. He presented failure as a far more thoughtful and thought-provoking experience, paired as it has to be with reflection.

Summary

Trying to find meaning within the failure experience led to an investigation to what epistemological knowledge came from failure. The Community of Practice (CoP) framework most aligned with my thinking about epistemological knowledge in undergraduate research, and thus it framed how this section of the chapter was organized. From what students gained of the knowledge of science through failure, to the relationships that exemplified aspects of membership in failure, and finally to the practice that emerged as intrinsic to the community and the experience of failure, attending to the aspects of the CoP framework as defined by Wenger and colleagues (2002) captured what students understood of science through failure. Figure 5.3 conveys failure's role in each aspect of the CoP framework. Indeed, this section conveyed how failure better allowed students entry into the scientific community of practice by exposing them to learning in ways they did not anticipate to learn. As such, the framework originally describing my orientation to this research adds failure as an experience that influences undergraduate students' peripheral participation in a scientific community of practice by bringing them closer to the practices, interests, and members of that community.

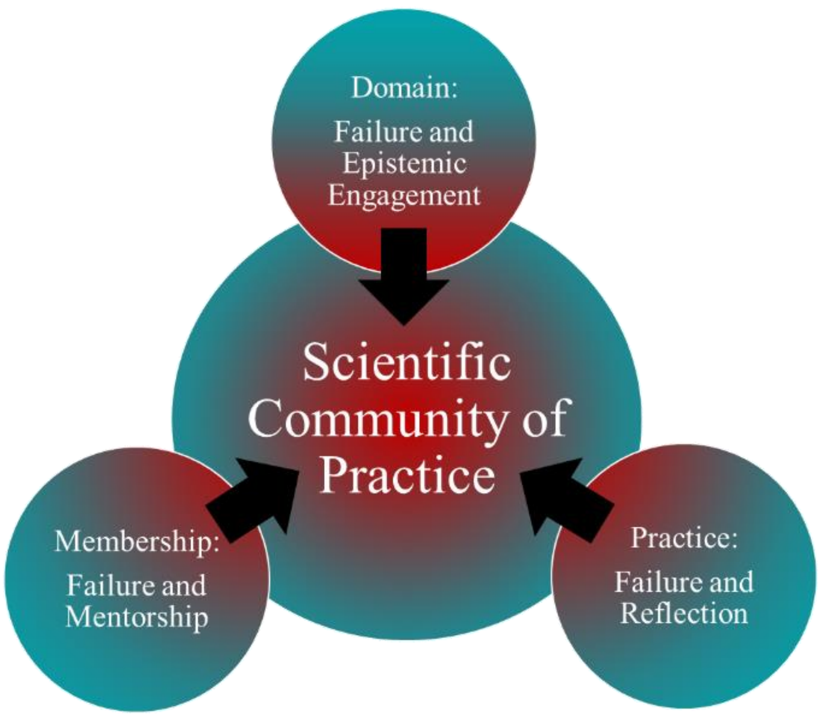


Figure 5.3. Framework to consider the specific ways failure allows students to enter the scientific community of practice

CHAPTER 6

DISCUSSION

Overview of Chapter

This chapter synthesizes the interpretations made in the previous chapter in the context of current literature in science education about students and their relationship with the different manifestations of failure they encounter. We begin the chapter with a brief summary of what was learnt from all the analyses, synthesizing the concepts that emerged in Chapters 4 and 5 where relevant. We continue with a discussion of these interpretations as they relate to literature on undergraduate science experiences and science studies. We then address some of the implications of this work and what additional questions this work generates. This is followed by the limitations of this study, to caution about the extent to which these interpretations have meaning to the greater student population. To wrap up, I will present a general reflection on the dissertation work that will offer some takeaways for this work as it relates to current work in the field of undergraduate science education. My personal reflections of this research journey will conclude this dissertation.

Summary of Findings

This study found that what students experience as scientific failure takes many forms, but that these varying manifestations can have common elements that unite students' understanding of those experiences as "failure". While the different experiences could be categorized as consequences of action, thought, or behavior within the scientific process, failures could also be organized by how students pinpointed failure within the experience – as the outcome, as the response, or as the process. The first type of categorization led to a fixed understanding of failure, in that students experienced failure in method and perhaps also a failure in interpersonal elements, but one looked quite different from the other. The latter categorization was far more dynamic, in that how students defined failure shifted between outcome, response, and process fluidly.

The theme of failure as intellectual and emotional dissonance developed from survey responses resonated with the rationalization process that emerged from the interviews. The rationalization process involved a level of emotional distress that was then attenuated by the acceptance of failure as an opportunity to gain new insight. The level of analysis possible with the survey responses did not allow us to see students make the transition from identifying an emotionally distressing event to the response and the learning that became possible, but the interviews captured how students mitigated the dissonant aspects though a recognition of failure as a normal part of the scientific process.

Students in both surveys and interviews saw failure as an expected part of the scientific process, though what led to this understanding was not clear. The interviews emphasized the role of the PI and mentor in communicating this through actions, as they were often the students' closest link to the scientific community of practice. The survey responses indicated that this could potentially be true for a larger population of students. For students to relay ideas similar to that of scientists (e.g. Simpson & Maltese, 2017; Firestein, 2015; Latour & Woolgar, 1986) underscores how scientific failure manages to communicate a level of acceptance about the experience which could potentially bolster their drive to persist in science. Whether this learning translates to failure in science courses is yet to be seen.

The Community of Practice framework enabled me to present what the students' experienced as failure in the context of their work and learning in the environment of scientific research. This context allowed for a more natural exploration of scientific practices and thinking, within which failure allowed students to see far more of the thinking that goes into developing process, making an argument for failure as a means of developing personal epistemologies. Failure allowed students to experience those domains that characterize involvement in a community of practice – (1) a domain of interest (the discipline) wherein students who experienced failure gained additional knowledge about the field through epistemic engagement; (2) membership as inculcation through the relationship between a knowing member central the community and a naïve participant which failure can foster through supervision through failure (failure can also dissipate this relationship based on the mentor's response – another study); and (3) the practice of critical reflection which leads to learning how to be critical of thinking and in planning a response to failure. The next section briefly summarizes these findings as they relate to relevant literature in undergraduate science education research.

Discussion of Findings

As described in Chapter 2, the literature on failure does not directly address experience of failure, but instead investigates failure as a potential pedagogical approach, how to mitigate negative responses to student failures, or what factors cause students to continue in the face of failure. So, situating these findings in the context of that literature becomes a challenge, as these findings are many steps removed from failure in the classroom. This is particularly so, given that the premise of RQ2b findings is on the situated experience of failure in research settings. Extending beyond this setting involves making too many assumptions about the relevance of these findings. Instead, this section addresses where in the literature of undergraduate education these findings have import.

The Practice of Reflection in Science as Metacognitive Practice in the Classroom

Critical reflection about the experience of failure in the research setting led students to deeper insights about the scientific process. Researchers *had* to reflect on failure because their evaluation of that failure directed their next efforts. In the classroom setting, students do not often experience structured reflection around challenges or failures. Recent work in the field of metacognition advises that students make critical reflection of their learning a priority and even emphasizes spending class time to teach students how to do so (Stanton et al., 2021). Tanner (2017) urges instructors to help students learn to reflect on their learning, writing "As researchers, we think metacognitively all the time, reflecting on our current understanding of our research system, what the burning questions are, and how our thinking has changed over the years with new data. Showing students explicitly how you, as a biologist, think procedurally in solving a problem—how you start, how you decide what to do first and then next, how you check your work, how you know when you are done—is one example of metacognitive modeling" (p. 117-118).

Based on work from developmental psychology, metacognition involves students actively planning, monitoring, and evaluating their learning regularly and across multiple facets of learning – from lessons, to activities, to assessments, and across the course level (Tanner, 2017). Just as the students in this study reported seeing a gradual acceptance of failure over time and repetition in the laboratory space and recognizing how better to respond to failure with repeated exposure, work in this field reports that students' metacognitive skills improve over time with regular application and knowledge about learning (Stanton et al., 2019). The reflective strategies employed by scientists through the failure process as observed and experienced by the participating students in the research setting best correlates with metacognitive strategies described to regulate students' own learning when facing unexpected challenges in learning (Dye & Stanton, 2017). Further investigation into this relationship can perhaps reveal the cognitive parallels between the four-step process that emerged of students' rationalization of failure in research and the metacognitive strategies they employ in the classroom as an avenue to reframe failure experiences in learning.

Mindset and Persistence

Within the research setting, students described failure such that the experience could be characterized as outcome-oriented, response-oriented, and process-oriented. Response-oriented failures, where students regard failure as a lack of action, seem to reflect that which mindset and grit interventions address. When students are provided tools to facilitate action in the face of an unexpected event, response-oriented failures may not be as debilitating to students as was described in Chapter 5. As we saw, emotion cannot be separated from the experience of failure. Learning to mitigate emotional distress may help students with the rationalization of failure. The shame that caused Leon to avoid the lab for several days may have not had as severe an impact if he had strategies to deal with that aspect of his experience. As such, it may be worthwhile to pursue how to reorient students towards a growth mindset. Rattan and colleagues (2015) argued that both growth and belonging should be targets for intervention. Students' rationalization process addresses why the former may work to aid students. Failure contextualized within the scientific experience, either through students entering research space or through students being made aware of scientists' own failures (e.g. Lin-Siegler et al., 2016) may foster a belonging mindset by normalizing failure in science.

The construct of grit as the driving force behind students' willingness to persist can also be used to provide students the tools to take action with response-oriented failure. Instead of providing students a reframing of the experience, as a change in mindset would do, grit considers the application of effort and in sustaining that effort (Duckworth et al., 2007). As the literature on grit does not show it to be a predictor of academic performance (e.g., Bazelais et al., 2016), it could perhaps shift what undergraduate researchers describe as failure. Grit and persistence are also inextricably tied to the element of time – that both interest and effort are sustained over a lengthy period; that the end objective requires stamina, a long-term investment (Duckworth et al., 2007). As time is also a component of how students come to accept failure in science setting, grit may be a factor in determining how students recognize what scientific endeavors are worth the investment to pursue. As undergraduate students, this may not be a broad range because of the limited time they have to offer in the research space. As Tate pointed out in his interview, scientists are hired to dedicate their time to research and can invest more time in persisting through failure. Grit, like mindset, represents another construct that may be of interest to pursue studying as a potential mediator for how students change shift their understanding of failures.

Situating the Failure Experience within the Scientific Community of Practice

In Chapter 2, I defined science as a human enterprise with particular values and practices that grounded the generation and dissemination of knowledge to shape understanding of social and natural phenomena. Here, I try to contextualize my findings in the literature that characterized those values and practices.

Simpson and Maltese (2017) studied the role of failure in scientists' professional development, and the authors found that the "participants rarely discussed failure as a final outcome, but instead framed it as an intrinsic part of innovation" (p. 228). Of the 99 scientists interviewed, 32% discussed failure as an opportunity for learning without prompting. When explicitly asked if failure leads to learning or growth, 88% of the 78 scientists who participated in a member-checking survey agreed. The students interviewed also concluded their rationalization of failure by reframing the experience as creating an opportunity for learning, which conveys that perhaps scientists also go through a similar process of rationalization that these undergraduate students did in making sense of the experience. This notion is further supported by the response to the following statement that Simpson and Maltese asked scientists to agree or disagree with: “There seems to be a transition from associating failure as a negative when I was a student to associating failure as a positive within my current position.” About 45% (of 78) of scientists agreed and said that this was due to (1) research experiences as students, (2) maturity, or (3) an environment that was not assessment driven and was supportive. The findings of this study corroborate all those statements as these students who discussed their failure experiences as providing insight into scientific practices believed this was possible because they participated in research. The idea of maturity translated in how students discussed learning to accept failure as something that came with time or like Saul said in considering how to respond to failure, “it's more of like a maturity thing, just, you know, devoting a lot of time and, you know, not being too upset afterwards.” Both the scientists in Simpson and Maltese’s work and the students in this study discussed the *why* of the failure experience by contextualizing it in the norms of the scientific enterprise. By framing failure as “matter of fact” (2017, p. 231), they discuss the epistemological gains of the experience.

On a macroscopic level, Simpson and Maltese’s (2017) study reflects how failure uncovers the traits that scientists value: of persistence, curiosity, and the desire to innovate. Science studies research uncovers the same. Traweek (1988) found that to be the case in her study of the community of high-energy physicists, commenting that "a detector that ran perfectly at all times would be considered either obsolete or not daring enough in conception" (p. 49). Failure in this case meant imaginative and resourceful exploration of the unknown, preferred over the dull certainty of the known.

Given my definition of science, failure in the macroscopic context of science can also be considered as a lack of coherence in the explanation of (natural) phenomena. Kuhn (2012) described this phenomenon in detail, writing that "…no theory ever solves all the puzzles with which it is confronted at a given time; nor are the solutions already achieved often perfect. On the contrary, it is just the incompleteness and imperfection of the existing data-theory fit that, at any time, define many of the puzzles that characterize normal science. If any and every failure to fit were ground for theory rejection, all theories ought to be rejected at all times." (p. 146). Firestein (2015) gives an example of this in the account of Ernst Haeckel, known as the "Father of Embryology", whose theories about embryonic development – captured succinctly in the phrase "ontogeny recapitulates phylogeny" – did not bear up to scrupulous examination. But given that his theories paved the way for the field of embryology, Haeckel's "failure" did not represent any lack in achievement, but a stepping point for further knowledge development, and he was still given recognition for his contributions to the field – a successful scientist by any definition! Kuhn's (2012) description of the nature of paradigm shifts is the basis for this conception of the role of failure in science:

> "In science… novelty emerges only with difficulty, manifested by resistance, against a background provided by expectation" (p. 64)..."Because it demands large-scale paradigm destruction and major shifts in the problems and techniques of normal science, the emergence of new theories is generally preceded by a period of pronounced professional insecurity. As one might expect, that insecurity is generated by the persistent failure of the puzzles of normal science to come out as they should. Failure of existing rules is the prelude to a search for new ones." (p. 68)

Kuhn's elucidation of the process of shifting frameworks within which we situate knowledge described the central importance of failure in science through the relationship between failure and the advancement of scientific thought.

This idea of failure as a lack of coherence for the explanation of natural phenomena is not only true for science at a macroscopic level, but within the laboratory setting. Cera's experience of watching her lab grapple with unexpected results led her to talk about failure as "disorder, chaos". She communicates the messiness of science, that however carefully we design our protocols and procedures to organize our knowledge and our expectations, the laws of the world, whether known or unknown, have a way of wreaking havoc. Latour and Woolgar (1986) also capture this in their anthropological study of the research setting, describing the practicalities of science as the creation of order out of disorder – the generation of "facts" from knowledge gained through the practice of science, as "between scientists and chaos, there is nothing but a wall of archives, labels, protocol books, figures, and papers" (p. 245). Indeed, neuroscientist Firestein (2015) makes similar statements about the reality of science, stating that science rests on the pillars of "failure and ignorance" (p. 3) as:

> "…it's not about facts and rules… it's groping and probing and poking, and some bumbling and bungling" looking for black cats in dark rooms without knowing for certain whether those cats exist "and then a switch is discovered, often by accident, and the light is lit, and everyone says "Oh, wow, so that's how it looks," and then it's off into the next dark room, looking for the next mysterious feline." (2012, p. 2)

In the scientific quest to further knowledge, failure also has another role – that of knowledge expansion. For example, if we consider experimental failure (for example, not yielding the hypothesized result), the knowledge gained from failing is still knowledge, as "knowing that something doesn't work can be as valuable as knowing that it does" (Firestein, 2015). Leon's example reflected this notion, when he said, "… by getting it wrong, I definitely learned like what to focus on and learn the protocol better." His experience added to the narrative that novel work requires a measure of uncertainty and failure. It is in the dissection of that failure where the virtues of creativity and curiosity and persistence (not blind effort but directed, towards the investigation of a question) also enter into the role of failure. The next investigation is inevitably: Why did the experiment fail? How does the experiment fail? Firestein (2015) describes this phenomenon further, writing:

> "…it's harder to design an experiment that will report narrowly on what isn't working. Harder it may be, but also probably more valuable… You will have to do experiments just to reveal the true nature of the failure… Tracking down failure is when you are most creative. Designing experiments to identify failure requires cleverness and cunning. You must be in the most critical state of mind. It is the closest a scientist comes to Sherlock Holmes. Nothing can be dismissed in the face of failure. The smallest clue could be the key element. What's missing is just as important as what's there. There is a universe of possibilities." (p. 43)

This mirrors, albeit in more colorful language, how students recognized reflection to be a critical aspect of the failure experience, and the mechanism by which learning occurs.

Indeed, failure might even define what it means to succeed, as it can offer parameters for the success of inquiry. This phenomenon is of particular import to engineering disciplines where often the goal of an experiment is for a material or structure or design to fail – such that its limitations can be better understood. Failure of results to conform to expectations may even lead to the evaluation and acceptance of entirely new paradigms of knowledge. To consider failure an integral part in understanding science means to consider it an experience that furthers epistemic understanding. Kelly and Licona (2018) specifically mention "persisting and learning from failure" (p. 156) as an epistemic practice in STEM. Tate similarly said that failure "puts the re- in research". When asked what he meant by this, he explained that:

> "So, um, you know, re suggest when you put it in front of something that you're doing something, again, research the process is something you just do over and over and over and over, no matter the project, um, you do the research process over and over and over and every single time. And sometimes on any given project, you might do that process over and over and over and over again, um, trying to figure out your research project. Um, so I think that larger to supplying that saying to, to research, um, kind of, I guess, aligns the fact that research can be that process, which is something that you have to do continuously, um, try again."

Tate understood research to be an iterative process, and that every investigation followed the same guiding principles and values. Learning science and learning to do research meant repeatedly engaging in that practice. And failure, as one of the forces driving that repetition became a critical part of that process. Though Kelly and Licone (2018) placed this practice under the auspices of engineering disciplines instead of an epistemic practice of sciences generally, this study makes clear that failure is inherent to the values that drive scientific endeavor, as failure help give shape and/or define the boundaries of what is known and how it is known.

To conclude, components of the failure experience understood in this study may serve as targets for interventions for related constructs from educational psychology, such as mindsets and grit. This can perhaps even address some of the equity issues associated with STEM disciplines (e.g. Carlone & Johnson, 2007; Talley & Ortiz, 2017; Toven-Lindsey et al., 2015), as students can learn to confront failure in a constructive way – rather than the negative associations made with repeated exposure to academic failure. In understanding that failure in science can be constructive and enable learning, this could reverse findings like that of Fennema and colleagues (1990) who saw that young girls tended to attribute failures to internal more often than external sources, and attributed success to external sources – a finding that may have in part caused the predominance of female students I saw in the preparatory chemistry. Understanding that failure is also a central tenet of the processes of science and of learning can also be of benefit to diversely identifying minorities in STEM fields. All in all, scientific failure has immense value to science and allowing students to experience scientific failure either in wholly educational spaces or through legitimate participation in authentic science activities can only be of benefit to students.

Implications

While I cannot conclusively state that students' experiences of failure impact their learning in science research settings in any measurable way, we can suppose from the previous sections that in a welcoming environment, failure contributes to fostering learning within and about science, and that learning is contextualized to the spaces and practices of scientific research. As such, this work does offer – and reinforce – some practical suggestions for undergraduate student learning. First, that if these are the takeaways students have from simply failing in the authentic settings, that more students should be afforded the opportunity to participate in undergraduate research. Second, that more mentors should capitalize on failure in research to get students more involved in the thinking behind research design. And last, that even in the classroom, instructors structure time to reflect on scientist and student failures. The last point was made in the earlier section on reflection and metacognition. I explore the other two points in the section below.

The Experience of Failure in the Undergraduate Research Setting

As we explored in Chapter 2, Undergraduate Research Experiences (UREs) offer students the opportunities to learn in the very places that knowledge generation occurs. Students in these settings learn about the processes of science as well as the products of scientific work (Imafuku et al., 2015; Goodwin et al., 2021). In the research setting, there is little prior literature that ties the experience of failure to undergraduates. Goodwin and colleagues (2021) found almost incidentally that students found failure in the laboratory setting to add to the authenticity of their work, and the findings from this investigation provide some explanation for that – as failure more pronouncedly engages students in the processes and practices of science that might otherwise be hidden from them. By failing in these settings, students seem to gain even deeper insights into processes that underlie the day-to-day work of science and are encultured into the normative response to failure that scientists engage in.

A study of students' science epistemologies found that non-science majors and science majors had no significant difference in the views each group held about science (Liu & Tsai, 2008), but those undergraduate students engaged in scientific research were not identified and separated. Hunter and colleagues, on the other hand conducted their study into students' developing science identities in undergraduate research as grounded on the notion that epistemological development paralleled identity development (Hunter et al., 2005). More recent work assumes engagement with research automatically translates to undergraduate students' epistemic understanding of science (i.e., Brownell & Kloser 2015). As this dissertation highlights specific ways in which failure provides an impetus for epistemological development through the communities of practice framework, it offers insight into how failure can be utilized in the laboratory spaces as an opportunity for deeper learning.

For example, mentoring was emerged as crucial to epistemological development within failure in undergraduate research experiences. Research on mentoring in the undergraduate research settings strongly advocates for structured mentorship environments (e.g., Ceyhan & Tillotson, 2020; Estrada et al., 2018) and findings from both Chapter 4 (in the consequence of interpersonal elements) and Chapter 5 (how students are inculcated into the community of practice as members) consequence suggests further focus on how mentors approach failure experiences with undergraduate students. Just as mentorship can facilitate failure as epistemological learning, negative experiences with mentors can cause students to leave STEM altogether (Limeri et al., 2019; Aikens et al., 2017). Providing scientists and graduate student mentors with mentorship training that strategically targets how to respond to challenges and failures may have a significant impact on students' experiences in STEM research.

Exploring a New Framework

The original framework I developed in Chapter 2 meant to communicate how I conceptualized failure's place in science did help to make sense of students' experiences through the lens of science as a community of practice. In revisiting the original framework created prior to this work, we can add failure as a tool that facilitates entry into the community, whether it is response, outcome, or process-oriented, as through failure in the research setting, students gained epistemic understandings. Jayd, for example, communicated her recognition that research is steeped in uncertainty.

> "I think [failure] shaped my view of what a researcher is… someone that has a curiosity to find something new or find, just learn more about something that's already there. So, and by doing that, like I said, you're kind of, you're opening yourself up to both failures and succeeding and you're going to do a bunch of trial and errors to kind of find that."

But there was also a different way of building upon the framework that arose from Leia's experience. "It changes how I see scientists presented in class. Like all those experiments you hear about that led to new discoveries. How many times did they reach dead ends before they succeeded? And how many scientists are never mentioned?" This suggests that instead of looking at failure only as a construct of legitimate participation that allows students to more fully enter science, that the experiences of scientific failure and the associated learning described can be taken *back to* science courses. This could perhaps also serve as an entry point to reframe science learning. Student descriptions of failure reflect a deepening of their understanding of the nature of the scientific enterprise and that seems to be carried back to their learning science. Channeling their experience in this way changes the framework to incorporate the experiences of failure situated in the scientific community of practice back into science learning, as depicted in this figure. While the interviews were essential to eliciting how students experienced failure and what meaning they made from the experience, another aspect of this that I could not study based on the limited population of study was whether the degree of epistemic learning changed based on the context. Does this mean that the more central their participation in scientific research, the more sophisticated their understanding of failure's role in the scientific process?

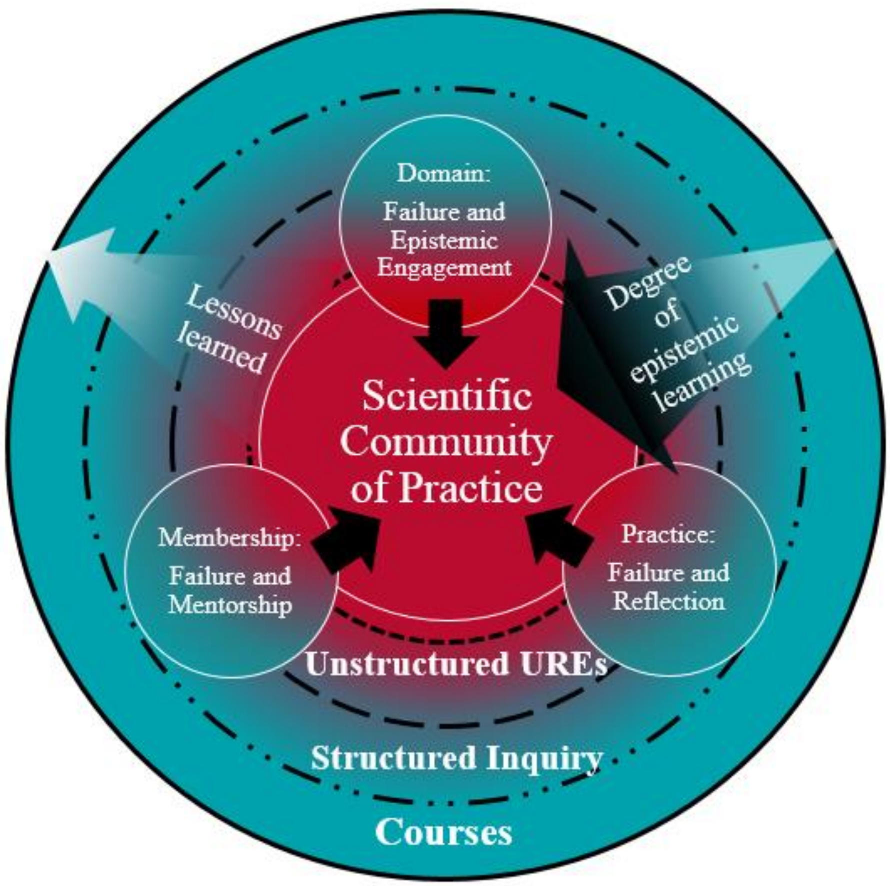


Figure 6.1. Potential framework to guide future studies: Using failure to guide epistemic thinking in all contexts.

This also suggests potential directions for continued work. For example, what specific lessons gained from experiences of failure in UREs do students bring back into science classrooms? How does their learning from failure impact learning in the classroom? Does epistemological learning from failure impact students' desire to persist in STEM education? And finally, how can more students benefit from failing in science? How can we translate an emotionally difficult experience to a learning opportunity? How can we better design authentic experiences in the classroom to look and feel like failure in the scientific research settings but help redefine failure in the academic setting? The next section describes an interesting find from this study that may also require further study to be understood.

The Language of Failure

Through the language used to communicate the experience of failure, it has been made evident that failure is an imperfect term to cover the breadth of experiences that students can experience under this umbrella. I believe this has more to do with the fluidity of the concept of failure, which may help with future reframing. The notion of failure is dynamic rather than static, contingent upon circumstance – setting, people, what knowledge students enter the experience with, and what knowledge they exit the experience with. It is not tethered to a concrete and universal concept but generates meaning unique to context. That untethered quality may be exactly what is necessary to influence how students experience failure in a constructive rather than destructive quality. This hearkens from the very nature of what we view as constructivism, as the cognitive act of creating building blocks for learning. Just as conceptual change theory builds upon a perturbance in students' assumed frameworks (Posner et al., 1972), we might come to consider the components of the failure experience explored in this study to be the explanatory mechanisms for learning through failure in a wider variety of settings.

The themes of failure generated from survey responses also suggests that there may be a continuum to how students experience failure based on continued laboratory work – that the language shifts to accommodate a broader set of experiences. Failure as consequence seems to be the most prevalent description of failure, perhaps because students new to the scientific process see errors as the closest parallel to failures in assessment/achievement-oriented settings. Failure as intellectual and emotional dissonance perhaps best describes the transition point for students as they move away from achievement-based understanding of learning to then seeing failure as expected in scientific communities. Failure as lack of learning perhaps best represents how students have shifted their definitions of failure to reflect a scientific mindset. Longitudinal study of students in research settings would help delineate this evolution of language to see if it is indeed tied to experience. The next section addresses the limitations of this work so as to caution how the interpretations of this work are extended beyond the contexts of this study.

Limitations

In Chapter 3, I presented some limitations I anticipated upon starting this work to communicate what might limit the scope of my interpretation of the data collected. In the following sections, I present limitations that became apparent following analysis, which impact to what extent the interpretations of this study can apply to a broader context.

Limitation to Thematic Analysis of Survey Responses

Survey responses collected in this study made for rich samples of data that made for an interesting attempt at thematic analysis. The issue with analyzing the survey responses was made clear throughout Chapter 4 – that the succinct responses students gave in response to questions made for easy coding but also made it more difficult to analyze in any more depth. To make more sense of the data, either more probing questions on the survey would have been necessary or more student responses should have been elicited. Though 91 students reportedly completed the survey, the final count of usable data was 68 student surveys out of 357 possible respondents, a completion rate of only 19%. Yet we cannot distinguish if this was because only a limited number of students felt they had enough knowledge about the phenomenon to respond to the survey or because students just did not want to participate (even given the incentive to do so).

An additional complication arose from students who initially responded that they had not experienced failure in scientific setting. These students were still able to connect an abstract notion of failure in science with science processes, indicating that they did not necessarily have to experience the phenomenon to make that connection. This begs the question of how they came to understand failure in science – one I did not ask of these students in the survey. In the unstructured space of the interviews however, even those students who initially felt that they had not experienced failure, were able to bring up and identify instances of failure experiences without prompting. This suggests that additional space and time for reflection on the research experience during interviews brought forth memories that students did not necessarily access in a quick survey. But it also highlights that the experiences of failure had differing degrees of impact on students that cannot be measured with the data available from this study.

Finally, a last caveat to the analysis of survey responses comes from the one piece of data I thought needed to be explored further but which I believe would take another dissertation to do justice to. At the end of the demographic section of the survey, I asked students if they believed their identities impacted their understanding and experience of failure. Out of the 68 students who answered this question, 48 students confirmed that their identities did indeed impact how they viewed failure, and 46 provided an explanation as to how they perceived this impact. As I had only this one data point about identity and failure, I could not do justice to an analysis of this area in my current dissertation work. The literature within the field of students' identities within and without science is remarkably complex, and I could not do justice to the nuances of students' associations of identity and failure with the approach I took in this dissertation. Thus I recognize my decision not to pursue this line of inquiry as a limitation of my work.

Limitations to Hermeneutic Analysis of Interview Responses

As described in Chapter Three, hermeneutic interviews involve an element of co-constructed meaning, as the interview provides the opportunity to reflect deeply on the experience. As described in hermeneutic research (e.g. Moules et al., 2015), both interviewer and interviewee gain new insights into the experience from the interview itself. Only three students explicitly mentioned gaining new insights while engaged in the interview, so I cannot claim that I performed the interviews as best as hermeneutic phenomenology necessitated. My process of meaning-making was documented through the writing of memos and the writing of this dissertation, but I also recognize that I did not include much of my own contributions to the interviews in the excerpts I provided, as I thought that may take away from the stories my participants shared.

From my readings on the topic of hermeneutics, the most impactful of hermeneutic analyses take place when interviews occur close in time to the participants experiencing the event or experience being studied, or the experience studied is an ongoing one (as in the studies of the experiences of post-traumatic stress disorder for example). In addition, the experience is usually of immense personal import for the participants. This was not the case with my study. Interview participants in this study were far removed from their experience in time, and the experiences shared demonstrated varying degrees of personal impact on students – more often, it was a professional impact.

In addition, phenomenological studies are often bound by the phenomena under study (for example, the nature of grief due to the loss of family members or the experiences of nursing students in a local, community-serving clinic). In this case, though there were boundaries set to define the experience of failure (like contextualizing the experience in undergraduate natural sciences research), the actual events students described varied – the unifying factor was bounded only by the language used to describe the phenomenon of failure. However, this perhaps lends more credence to the interpretations made through hermeneutic analysis, as common threads of language could still be woven to create a tapestry of what failure experiences look like and what meaning is made through such experiences.

Finally, hearkening back to the piece on identity in the earlier limitations section, sensemaking around science may be different based on student identifications with particular communities (Warren et al., 2001). So not attending to identity may fail to capture some aspects of how students attend to and respond to failure. While I did ask students whether and how they identified with the relation to the scientific community, I did not pursue this line of inquiry beyond connecting how students saw themselves as scientists to whether failure played a role in that. Further inquiry would be needed to make more sense of how sensemaking, identity, and failure interrelate.

I chose hermeneutics as a methodology as I believed the underlying philosophy to align with my philosophy of science, and I still believe that it offered the deepest analysis of the subject matter. However, I do recognize that my decision to use hermeneutics to study undergraduate students' experiences of failure in research settings through a communities of practice framework meant that certain limitations resulted. By identifying these limitations, I place bounds on what interpretations can be made from this study and add to the potential ways whereby future studies can improve and expand upon such interpretations.

The Success of Failure

This work led me to a revised definition of failure based on student experiences. I now define scientific failure as *an unexpected outcome (whether or not it is a tangible one) that may further knowledge in unexpected directions through reflection*. That in science, failure is a discovery of *how* and *why* to further learning, through: (1) the cognitive and emotional processes that develop a rationalization of that outcome, (2) the critical evaluation of that outcome and its impact on current knowledge frameworks, and (3) contextualizing the meaning of that experience in the greater conception of the scientific enterprise. The critical nature of science means that the experience of failure has to be explored and encouraged. If it is a failure of process, then the scientist learns the value of that process and makes a correction. If it is a failure in thinking, then one learns the limits of that thinking and makes a discovery. In all such gradations of failure in science, the scientist learns. Failure is thus inherent to and an implicit part of the scientific process. Essentially, the role of failure in science is that it creates opportunity to engage in the kind of critical thinking that is integral to scientific progress, not just engage in the procedural aspects of the practices, while cultivating the necessary virtues of curiosity and creativity integral to a scientist. Through this lens, failure has an incredibly positive association with learning. Understanding failure like this means that it can be made into a constructive experience in the classroom by reframing it as opportunity.

I hope that this dissertation has shed light on a topic I think is currently under-studied and ill-represented in the field of science education – under-studied often because it is ill-represented. Failure is a scary term even as a focus of study because even here, as I was once told in a proposal review, it evokes fears of a deficit orientation to student performance. I hoped that using a community of practice lens reshaped what it means for students to experience failure in the context of scientific research, and I look forward to finding out – whether it takes just reading this dissertation work or even ten or twenty years hence – if I succeeded! Embarking on this research journey taught me to value and be more critical of my own experiences of failure, both within and without science. More so than ever, I think the tools gained through failure matter to students' learning. My argument is that to understand science, one has to experience failure in science; to understand what it means to develop a scientific body of knowledge, one has to understand the role of failure in enriching the learning process; to engage in scientific thinking, one has to recognize the role of failure in developing that thinking.

Completing my dissertation through the global reckoning with a viral pandemic and a national reckoning with systemic racism was also illuminating in ways I did not expect. I was privileged in many ways to only by mildly impacted by the repercussions of a viral pandemic, but I had to confront my own part in perpetuating racist injustices in science and in our society through my careless use of language and through inaction. Like Mera asked in the middle of her interview, without failure, "what's the story you tell?" I wanted to ask that of my readers and of my own work going forward. With all my experiences of failure, what have I learned? What stories can I tell?

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APPENDIX A

Start of Block: Consent

Undergraduate Students' Experiences and Understanding of Failure in Science

Purpose of the Study
Thank you for participating in this research! This study looks at how students engage with failure experiences in their educational career in science. We are particularly interested in how failure experiences are perceived by and what failure in science means to undergraduate students, so that we, as educators, can develop ways to better support students in science courses. Students over the age of 18 are invited to share their perspectives of failure.

Study Procedures
If you agree to participate, you will be asked to answer questions related to the topic of failure. This survey should take between **15-20 minutes** of your time.

Privacy/Confidentiality
All of the data and records of your participation collected during the study are confidential. While this study may result in scientific presentations and publications, researchers will not release identifiable results of the study to anyone other than individuals working on the project without your written consent unless required by law.

Taking part is voluntary
Your involvement in the study is voluntary, and you may choose not to participate or to stop at any time without penalty or loss of benefits to which you are otherwise entitled. If you decide to stop or withdraw from the study, the information/data collected from or about you up to the point of your withdrawal will be kept as part of the study and may continue to be analyzed. Your decision about participation will have no bearing on your grades or class standing.

If you have questions
The main researcher conducting this study is Sandhya Krishnan (sandhya.krishnan25@uga.edu) in the Department of Math and Science Education at the University of Georgia. If you have questions later, you may also contact the Principal Investigator, Dr. Georgia Hodges (georgiahodges@uga.edu or 706-542-2257). If you have any questions or concerns regarding your rights as a research participant in this study, you may contact the Institutional Review Board (IRB) Chairperson at 706.542.3199 or irb@uga.edu.

Incentive to Participate
To thank you for your time, we will be donating $10 for every person that completes this survey (up to

$2000). At the end of the survey, you will be provided the option of choosing from a list of charities, and we will make a $10 donation on your behalf.

Participation

Please indicate your participation below to move forward!

Regards,

Sandhya Krishnan
Dept of Math and Science Education
University of Georgia

- ○ I agree to participate
- ○ I do not agree to participate

Skip To: End of Survey If Participation Please indicate your participation below to move forward! Regards, Sandhya Krishnan... = I do not agree to participate

End of Block: Consent

Start of Block: Research/Science Failure

Do you have any experience in science research outside of laboratory courses? (For example, BIOL 1107L or CHEM 1211L is a lab course, but independent research done for credit is NOT a lab course)

- ○ Yes
- ○ No

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = Yes

Was your science research experience for course credit?

- ○ Yes
- ○ No

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = Yes

Is the science research you did (or are doing) mandatory for your major?

- ○ Yes
- ○ No
- ○ I don't know

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = Yes

What is the longest amount of time you have spent in a science research experience at the university level? (If you have worked in different research labs, please indicate how long was the longest single experience)

- ○ Less than one semester
- ○ One semester
- ○ Two semesters
- ○ More than two semesters

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = Yes

Please describe your research experience briefly (no more than 3 sentences about the project and your role in it).Less than one semester

____

____

____

____

____

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = Yes

Have you experienced scientific failure in the research setting?

- ◯ Yes
- ◯ No

Display This Question:

If Have you experienced scientific failure in the research setting? = Yes

What did the failure experience look like? (Please describe the scenario in which you experienced this scientific failure)

____

____

____

____

____

Display This Question:

If Have you experienced scientific failure in the research setting? = Yes

How did you respond to the scientific failure experience?

____

____

____

____

____

Display This Question:

If Have you experienced scientific failure in the research setting? = No

What would scientific failure look like to you?

____

____

____

____

____

Display This Question:

If Do you have any experience in science research outside of laboratory courses? (For example, BIOL... = No

What would scientific failure look like to you?

____

____

____

____

____

Based on your response to the questions above, how do you define failure in science?

____

____

____

____

____

How is failure in science related to failure you could experience in learning science? (If they are the same or different, please describe why.)

____

____

____

____

____

End of Block: Research/Science Failure

Start of Block: Failure in Language

Please give a few synonyms for failure in science:

____

____

____

____

____

What are some common phrases (idioms, metaphors, etc.) that you have heard about the topic of failure?

____

____

____

____

____

End of Block: Failure in Language

Start of Block: Demographic Data

Demographics

In this section, we hope to collect demographic data in order to better understand how your identities might influence your experiences. Please answer the questions as it best describes your identities.

What is the major/degree you hope to graduate with? If you have unsure at this time, you can write "Undecided".

____

What are your plans after getting an undergraduate degree?

- ◯ Industry (Any employment)
- ◯ Graduate School in Science Discipline
- ◯ Graduate School in Engineering, Technology or Math Disciplines
- ◯ Graduate School - Non-STEM discipline (MBA, JD, etc.)
- ◯ Medical school or Dental school
- ◯ Undecided
- ◯ Other (not listed) ____

With which race(s) or ethnicity(ies) do you identify? Please check all that apply.

- ☐ African American or Black
- ☐ Asian (e.g., China, Indian subcontinent, Indonesia)
- ☐ Latinx or Hispanic or Spanish origin
- ☐ Middle Eastern or North African
- ☐ Native American or Alaskan Native
- ☐ Native Hawaiian or Other Pacific Islander
- ☐ White
- ☐ Prefer to self-describe: ____
- ☐ Prefer not to respond

What is your gender identity?

- ○ Female
- ○ Male
- ○ Non-binary
- ○ Prefer to self-describe: ____
- ○ Prefer not to respond

Would you describe yourself as transgender?

- ◯ Yes
- ◯ No
- ◯ Prefer not to respond

How many years have you been a full-time college student?

- ◯ I am in my first year
- ◯ 1 year
- ◯ 2 years
- ◯ 3 years
- ◯ 4 years
- ◯ More than 4 years
- ◯ I am a part-time student

Display This Question:

If How many years have you been a full-time college student? = I am a part-time student

If part-time, how many years do you identify as having been a college student?

- ○ In my first year
- ○ 1 year
- ○ 2 years
- ○ 3 years
- ○ 4 years
- ○ More than 4 years

How many collegiate institutions have you attended? (Do not include institutions you may have attended separately as a high-school student)

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ More than 4

With which designation as a student do you identify?

- ○ United States based
- ○ International student
- ○ Prefer to self-describe: ____
- ○ Prefer not to respond

Which identities are personally important to you? Please check all that apply.

- ☐ Career aspirations
- ☐ Collegiate institution(s)
- ☐ Educational level
- ☐ Gender identity(ies)
- ☐ Income
- ☐ Major in college
- ☐ Nationality
- ☐ Racial/ethnic identity
- ☐ Sexual orientation
- ☐ Socioeconomic status
- ☐ None of the above
- ☐ Other: ____
- ☐ Prefer not to respond

Do you believe any of your identities has an impact on how you view or experience failure in science?

- ◯ Yes
- ◯ No
- ◯ Prefer not to respond

Display This Question:

If Do you believe any of your identities has an impact on how you view or experience failure in scie... = Yes

How do you believe your identities impact your experience of failure in science?

____

____

____

____

____

If you are interested in participating in a 45-60 minute interview about this topic, please indicate so below and I will contact you soon about availability. The interview would be subject to confidentiality agreements as well. THANK YOU!

- ◯ I am willing to participate in an interview
- ◯ Please do not contact me for an interview

Display This Question:

If If you are interested in participating in a 45-60 minute interview about this topic, please indic... = I am willing to participate in an interview

Thank you for being willing to participate in an interview! In the spaces below, please provide your name and an e-mail address at which I can contact you. I will reach out to you in the next couple business days. I'm excited to continue the conversation that you started here!

○ Name ____

○ E-mail address ____

End of Block: Demographic Data

Start of Block: Donation

Donations

Choose where we will donate $10 on your behalf

Thank you again for participating in this survey! As a way of saying thanks for your time, we will be making $10 donations for every person who completes the survey (up to $2000 total). We have provided a list of charities below. **Please choose one charity where you would like my $10 to go towards**. We cannot offer more than the following charities, so if you do not want to donate to any of the ones listed, feel free to choose that option. If you are interested in knowing how much money finally ends up going to which charity, you can contact Sandhya Krishnan at sandhya.krishnan25@uga.edu.

Choose one option of the following:

○ ACLU - American Civil Liberties Union

○ Black Lives Matter Foundation

○ Meals on Wheels

○ Mercy for Animals

○ Save the Children

○ WWF - World Wildlife Fund

○ I do not want to donate to the organizations listed here

End of Block: Donation

APPENDIX B

Interview Protocol

As per the recommendations for phenomenological interviews (Bevan, 2014; Høffding & Martiny, 2016; Moules et al., 2015), interview protocols fall closer to unstructured interviews than to semi-structured. The structure present is meant to capture all aspects of the experience, but any further questions are led by participant responses and are meant to encourage as much detail about the experience as possible. As such, questions getting at the context of the participant's research have much more structure than the questions getting at the participant's scientific failure experience.

Structure aims

- Context of experience
- Description of experience
- Boundaries/limitations of experience through invariants
- Additional questions for RQ2

Research Questions:

RQ2a. How do undergraduate students make meaning of their scientific failure experiences?
RQ2b. How do the experiences of failure described aid the students in constructing their understanding of the scientific enterprise?

Key:

- *Italics* – Spoken text guiding progress of interview
- Numbered items during Interview – Main questions in interview. Sub-questions provide detail that answer that question
- *(**Italics)* – Additions to spoken text that I am not sure about (to bring up with research group)
- **Questions – Questions I don't know if I want to ask

To Prepare for Interview

1. E-mail participant day before the interview, confirming date and time (+ time zone)
    a. Share zoom link (SPECIFIC for each interview)
    b. Share consent form
2. Re-read participant's survey responses
    a. Note any questions I have about what is described
    b. Note down definition of failure
3. Re-read demographics data that may be of note (potentially bring up in interview)
    a. For example, transfer students may have had particular research/other science activity experience

4. Keep ready participant's description of failure experience to share with participant (on zoom chat)
    a. Can read out loud
5. RECORD INTERVIEW and SAVE CHAT

Preamble to Interview

Hello ________. Thank you for volunteering your time to participate in this interview today. The goal of this interview is for me to understand the details of your research experience, particularly in regards to how you experienced scientific failure in that setting. We will first discuss the consent form I shared with you by e-mail. Then, I will ask you questions about any prior science experiences you may have had, and then get into your current science research experience. After we establish this context, we'll get into what you described in the survey as your scientific failure experience. That will conclude the interview.

Do you have any questions before we begin?

*(**If at any point, you feel uncomfortable responding to a question, just say that you'd like to "pass" that question and move on to another.)*

Feel free to interrupt or ask me questions at any point in this interview.

Regarding consent form, while you can read the whole thing at your convenience, I wanted to highlight one detail that I think is most important. For, for the purposes of research, I will be recording this interview. No one other than myself and a few select research team members will have access to the video or audio file from this interview. Do you consent to participate?

Ok, let's begin!

Context Questions

1. Did you have any experience with scientific research before you came to UGA?
    a. Can you describe that research?
    b. What did you take away from those experiences? **(early epistemology)**
    c. Did you participate in any other science-related activities before this research – either at UGA or prior to UGA?

2. I saw that you plan on ______________ major in your survey response. What makes you interested in _______ major?
    a. What do you want to do with your degree? Why?

3. How did you get involved in research at UGA?
    a. Why did you choose to do research for credit instead of taking a lab course?
    b. What did you expect to gain from working in a lab that was different from a lab course or taking a class on the same subject? **(early epistemology)**
    c. What did you expect to take away **about science** from the entire research experience? **(early epistemology)**

   i. Did your expectations for the research experience change once you started working in the lab? How?

4. While I have read the abstract you provided in the CURO Book of Abstracts, can you describe for me your research again?
   a. In what department did you do research? What was the topic of study for the lab?
   b. How did you work in the lab with graduate student(s) and faculty member(s)?
   c. How did you work with peers in the lab?
   d. What was your role in the lab?
   e. How did the professor/graduate students initially orient you to the lab work?
   f. How involved did you feel in the lab and the lab work? Did you have/attend weekly lab meetings?
   g. What level of autonomy did you have in the lab work?
   h. How did you develop the project you presented at CURO?

Failure Questions

I would now like to ask you about the scientific failure you described in the survey. (Share participant's response from survey - place in Zoom chat). You wrote about a particular failure experience and I am very interested in the details of that experience. I would like to know everything you did and felt and understood during and after that situation.

5. First, can you please tell me everything that led up to that failure experience?

6. What did you do when …

7. How did you react to …

8. What did you do in response to …

9. Did you need to specific skills to respond to …

10. When during the experience did you know you had failed?
    a. How did you know?

11. What would have made this scientific failure not a failure? (Trying to **identify invariants** – how the experience might change)

12. What did you take away from the experience? **(late epistemology)**
    a. If you had not had this experience, would your understanding of scientific research have been different? How?
    b. What about this experience surprised you the most?
    c. What about this experience disappointed or upset you?
    d. What about this experience did you enjoy?

13. Having experienced all this, how do you define scientific failure?
    a. What makes this failure experience unique to science? (Does it have to be unique to science?)
    b. How can you see scientific failure being experienced outside of the setting you experienced it?
    c. (Check against the definition provided in survey)
14. Having experienced this, if you experience it again, would you call it a scientific failure?
    a. Would you do something to avoid experiencing this again?
    b. Why?

Closing Questions

15. Do you identify as a scientist, or a scientist-to-be?
    a. Did your experience of failure make you feel more or less of a scientist? If so, why?

16. What are the things you think make up a successful research experience for undergraduates?
    a. How did you experience that?
    b. Did your failure experience impact how you view a successful research experience? (How to phrase this in a way that is not leading???)

17. Is there anything else that you would like to share about your failure experience or overall research experience that we haven't discussed? Or anything you thought was very important to you and your learning that you would like to restate?

18. One last question before I open up the floor, so to speak. If I were to use quotes from this interview in my dissertation, is there a pseudonym that you would like me to use to represent you? If you don't have a preference on a pseudonym, I can either make one for you or I can refer to you with a generic Student number – which ever you would prefer.

19. Do you have any questions for me at this time?

Final Thoughts/Text

Thank you once again for participating in this interview. Your description of the failure experience provides a valuable insight that I am excited to investigate further. If I need to get more details about this experience, would it be ok for me to contact you with a few follow-up questions?

Alright, thank you. Once I get to writing about this interview and the insights I gained from it, would you be interested in reading that – just to check that I interpreted your thoughts accurately?

Once again, thank you for sharing your time and your thoughts!

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