Epistemic Agency in Lab: When, Why, and How Introductory College Biology Students Direct their Own Science Investigations

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Abstract

As college biology educators we want students learning how to conduct their own scientific investigations. This means designing laboratory curricula in which students exercise control and responsibility over the knowledge building actions of an investigation—that is, in which they exercise *epistemic agency*. Our current understanding of epistemic agency in college biology labs is limited—we lack evidence for when, why, or how students contribute to knowledge building when conducting their own investigations, and what is the role of the curriculum in facilitating students' investigative decision making. In this dissertation I begin to fill this gap through three case studies of students in an introductory college biology lab course that employed a *hybrid lab* design—in which students controlled the production of data through experimentation with organisms and simulation with computer models. With each study I unpack when, why, or how students exercised epistemic agency in the lab, and examine the role of the lab design in facilitating these dynamics. Through accounting for student activity in these empirical studies I build theory for studying student agency, and develop design ideas for supporting students carrying out their own scientific investigations in introductory college biology labs.

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Chapter 1—Introduction

1.1 Motivation for the dissertation

> "There was an extreme sense of curiosity. What is going on? I want to understand this, but I have no idea what's going on. I wanna know what's going on. So I guess in that sense. At the end of the day, even in the simulations we don't completely understand what's going on, so you're trying to come up with an explanation that is able to explain not just the result of one simulation, but the result of every single simulation that you're trying to do. I guess it was a bit challenging, but it made the experiment much more worth doing." (Alaad, 2018)

I am writing this dissertation to tell the stories of students who engaged in doing science in an introductory biology laboratory course—these students were, at one point or another, hooked by curiosity, they felt empowered to pursue it, and they took opportunities to shape the knowledge building actions of their scientific investigations. I seek to understand what hooked them, why they felt like they could and should work to figure something out, and how they went about setting and pursuing their investigative aims. That is, I am interested in understanding the process by which these students exercised *epistemic agency* in conducting their own lab science investigations, and in determining how curriculum design features played a role in supporting that.

1.1.1 Why I care about epistemic agency in lab science

I am interested in studying students' epistemic agency in lab science investigations because I want to support students to feel motivated and empowered to pursue their own curiosity to do science (in the lab and also in life). I believe there is a strong link between creating opportunities for

students to shape knowledge building work, and supporting their development in thinking, acting, and feeling like a scientist.

Thinking like a scientist

> "I think the most challenging parts of the labs so far have been coming up with our own procedures. Especially coming up with our own questions to pursue. … It's kind of like thinking out of the box a little bit. Trying to come up with something that's interesting, something that's interesting to see the results in. You have to think through not only what question you want to answer, but what results are you going to be measuring, specifically to answer this part of the question. You have to think it through a lot." (Damien, 2017)

When I refer to thinking like a scientist, I don't mean knowing the most relevant concepts or proper techniques for pursuing a scientific question (though I also want students to refine their understanding in those ways), but rather I mean being in a state of mind to pursue scientific curiosity—what many authors refer to as sensemaking (Odden & Russ, 2019; Kapon, 2017). I see the motivations for sensemaking as differing from "doing the lesson" in school (Holmes & Bonn, 2014; Jiménez-Aleixandre, Rodríguez, & Duschl, 2000)—that is, acting to achieve goals of schooling, such as getting a good grade—and I would like to develop lab science curricula which inspire students to make sense of phenomena rather than simply getting through lab. Furthermore, I believe that by engaging in sensemaking, students activate and develop resources for learning (Conlin, Gupta, & Hammer, 2010) that they will be able to utilize for pursuing their own scientific interests in other contexts (Hammer et al., 2005). For example, in Damien's quote above, he refers to the challenge in thinking not just about posing a research question, but about how to configure materials to answer that question. Or, as another student put it, "it was weird because like we had to **predict** ahead of time what was going to happen in an experiment that we were doing to try to figure out what happened." This consideration is not familiar to most students who take our labs

(I would posit, to most students in any introductory-level college lab science course), it requires cultivating a new way of thinking about scientific investigations, and it emerges in the context of students being positioned as in charge of designing their own experiments.

Acting like a scientist

> "Then I went online and searched plant, umm, like what different ways plants use sugar in their leaves. … I found two possible reasons for why basically a leaf can be heavier but not necessarily mean, like that the plant is using all its ATP for growth. And I think one was like, I think it was too much CO2 kind of like makes- this was me (g – points to self) like making a prediction too much CO2 kind of like prevents, sugar being used for ATP and it kind of makes all your sugar go, into like structure mode and like kind of like grow leaves but not necessarily grow like taller." (Alice, 2016)

By acting like a scientist, I'm referring to the "grasp of practice" through which scientists learn when, why, and how to act to pursue investigations (Ford, 2008, 2012). This involves not only gaining expertise in practices which are "authoritative for knowing" in the discipline (Ford & Forman, 2006; Manz, 2012)—such as modeling or argumentation—but also developing a sense of why these practices are valuable for constructing scientific knowledge (Russ, 2014), and learning how to adapt them to the context of one's own investigation (Forman & Ford, 2014; Manz, 2015a). For example, in Alice's quote above she describes turning to the literature to help her make sense of a puzzling observation from her experiment. She was not directed to research biological mechanisms for this lab—she saw identifying how plants allocate resources as valuable for explaining experimental data that didn't match her expectations of how plants should grow, and adapted the practice of reading scholarly papers to meet that aim.

Feeling like a scientist

> "I think you can tell, I am a little bit frustrated and trying, like I still don't know for sure, that's the thing, I don't know what the right answer- like what we should have gotten and, I don't really know how to explain what I got yet. So, that makes it frustrating but at the same time that's, what you're actually supposed to be doing when you're doing science like you're supposed to be, trying to find things that are unknown- not known and like, whatever your results are you figure it out from there. So like, I don't know, I think that that element has made me really like the lab. Like I wanna go do it again if I could." (Nick, 2017)

In Nick's quote above, we see a frustration with not knowing as both inherent to his sense of what science is "actually supposed to be like", and connected to his motivation to continue to pursue his scientific curiosity—to "go do it again". This *epistemic affect*—a feeling inextricably connected to the process of learning—is an example of what I mean by supporting students feeling like a scientist (Jaber & Hammer, 2016). Not only does Nick see being frustrated with not knowing as a part of doing science, it's what he *likes* about the lab course, a meta-affective stance (Radoff, Jaber, & Hammer, 2019). I see motivation to pursue scientific curiosity as deeply connected to experiencing excitement, frustration, confusion, and other feelings about doing science; and I believe that cultivating opportunities for students to shape knowledge-building entails not just supporting sensemaking or adaptive practice, but also epistemic affect.

Throughout this dissertation, underlying my efforts to understand the dynamics of students being positioned with, perceiving, and acting on opportunities to shape knowledge building, is an attention to the ways that students think, act, and feel like scientists. I will bring connections between epistemic agency and these motivating ideas to the foreground in the closing chapter (Chapter 8).

1.1.2 Designing for agency in lab science

> "Yeah I remember, feeling like "oh", like pretty satisfied with what we came up with or, our ideas about it. The fact that it actually made sense and it was like, not that we were just kind of reaching for an explanation. … 'Cause I feel like that doesn't always happen in like, college labs. You're like, "Oh, like I need to write about something. Maybe this makes sense in explanation, but it doesn't **really** fit my results. Like something else weird is probably going on, that's like, beyond the scope of this class or something."" (Mary, student, Bio14L 2017, Unit 1)

In addition to *studying* epistemic agency, I am also motivated to design lab science spaces which support students exercising epistemic agency. There is general consensus that "traditional" lab structures restrict students' opportunities to shape knowledge building work (Brownell & Kloser, 2015), motivating a trend towards designs for introductory college biology lab courses which expand students' participation in doing science. While some design efforts attempt to create opportunity through "authenticity" (Indorf et al., 2019) or "broad relevance to the discipline" (Auchincloss et al, 2014), they rarely factor in the dynamics by which students exercise agency (see Hester et al., 2018, for one design study that does center student agency). I see building an understanding of how large-scale introductory curricula facilitate student agency as especially important, since these courses have potential to reach broad audiences of students. I believe this gap in design is owing in part to a lack of theorizing about when, why, & how epistemic agency is exercised in introductory college lab spaces (Holmes, 2020), coupled with issues in facilitating heterogeneous investigations at large scales. It is my intention within this dissertation to build theoretical and design ideas together, with introductory college lab contexts in mind, to help address this gap.

1.1.3 What I'd like the reader to take away from this dissertation

> "One gives examples and intends them to be taken in a particular way. – I do not mean by this expression, however, that he is supposed to see in those examples that common feature which I – for some reason – was unable to formulate, but that he is now to employ those examples in a particular way. Here giving examples is not an indirect way of explaining – in default of a better one." (Wittgenstein, 2009/1953, p. 38e; #71)

With this dissertation I have two interconnected goals: building theory on epistemic agency in lab science investigations, and developing design ideas to support student agency in lab science learning spaces. I work towards meeting these goals through three empirical case studies.

Each of the empirical cases I present illustrates a phenomenon related to students being positioned with, perceiving, and acting on opportunities to shape knowledge building in our intro biology lab science course. In developing analytical frameworks to explain these cases, I treat (and hope for the reader to see) the enactment of epistemic agency as *complex*, *contextual*, and *dynamic*. By complex I mean that opportunities for students to shape knowledge building emerge and play out in relation to many factors simultaneously—in this dissertation I'll explore student framing, the configuration of curricular materials, and social positioning, for example—and as researchers (and designers) we need to consider the roles of all of these factors, in interaction with one another, to build an account of students exercising epistemic agency. By contextual I mean that when, why, and how students (or teachers, for that matter) exercise agency is inextricably connected to the socio-material context of the classroom—for example, what is perceived as an opportunity to shape knowledge building in one learning space might not be in another. By dynamic I mean that the process of positioning, perceiving, and acting on opportunity changes over time—for example, what is perceived as an opportunity to shape knowledge building at one moment might not be in the next.

The elaboration of these cases, and synthesis in the final chapter in the dissertation, is not meant to prove that epistemic agency works one way or another, nor to develop "best practices" for supporting it. I believe that the features elaborated above (complexity, contextuality, and dynamics) render such targets impossible. Instead I aim for *usefulness* (Cobb et al., 2001) and *generativity* (Hammer, Gouvea, & Watkins, 2018; Roschelle, 1992). That is, I hope for the reader to come away from this work with an understanding of dynamics by which students exercise epistemic agency in lab science investigations, grounded in empirical examples, that is useful for their own practice (be that research, design, instruction, or anything else). And I hope that the ideas developed in linking epistemic agency to other analytical constructs (framing, the mangle, and participatory inequity) serve to inspire new imaginings of how to think about and support students' epistemic agency.

1.2 Organization of the dissertation (Chapter summary)

In the next three chapters of this dissertation, I will establish the theory, design, and methodology which cut across the empirical studies to be presented. In the theory chapter I will first introduce the definition of epistemic agency I'm using throughout the dissertation—"students being positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community" (Miller et al., 2018)—and situate that definition within the education literature. I'll then motivate how I approach the study of epistemic agency through and in relation to three analytic constructs—framing, navigating uncertainty, and participatory inequity. In the design chapter I will briefly introduce the Bio14L curriculum, emphasizing those design and implementation features that are relevant to all three studies. In the methodology chapter I will first motivate my use of case study for my empirical chapters. Then I will situate the focal cases within the full context of data collection and selection across the three years represented in this

study, and describe the iterative analytical approach applied in each study. Finally, I will motivate a cross-case analysis employed in the final chapter of the dissertation.

The following three chapters are stand-alone empirical studies in which I investigate student agency in lab science investigations. In study 1 I account for a shift in one student's perception of her own epistemic agency across the semester, in 2016, using *framing*. I demonstrate how the design of the curriculum acted at various times to either stabilize or destabilize her confirmatory framing of science lab courses, which imposed (or lifted) a barrier on the kinds of knowledge building contributions she saw as appropriate to make in accounting for unexpected phenomena encountered in lab experiments. In study 2 I employ a framework of *navigating uncertainty* to detail the ways that two student groups exercised agency in authoring the aims and moves of their own investigations in the first unit of the lab course, in 2017. I foreground the role of coupled experimentation and simulation in facilitating this authorship through material agency in resisting student aims and affording means to pursue new aims. In study 3 I examine the role of intra-group dynamics, in positioning individual students with the agency to contribute to directing investigations, through an analysis of *participatory inequity* across one group's investigation in the first unit of the lab course, in 2018. I first characterize shifts in participatory inequity across two weeks of conducting an investigation; then I detail the role of investigative materials, in conjunction with instructor facilitation and student framing, in amplifying and attenuating participatory inequity throughout the case.

In the final chapter I begin to unpack the relationships between the analytical ideas developed in the standalone empirical chapters. I first extend the analyses of each of the three empirical chapters by considering how their analyses apply to the broader data corpus. I then revisit

my initial conceptualization of epistemic agency, and consider how that has shifted in light of the analyses presented throughout the dissertation.

Chapter 2—Theory

In this dissertation I seek to broaden an understanding of students exercising epistemic agency in lab science investigations. Here I will establish the theoretical framework that informs my use of epistemic agency. I will then overview a conceptual framework for this dissertation by foregrounding how I will build upon this conceptualization of epistemic agency in each of the chapters through analysis of student framing, student groups' navigation of uncertainty, and participatory inequity within student peer groups.

2.1 Theoretical framework—Epistemic Agency in Lab Science

Throughout this dissertation I start from the definition of epistemic agency provided by Miller et al. (2018, p. 1058): "students being positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community." In this section I'll situate this definition within the literature on epistemic agency by splitting it into two themes and unpacking each—first, shaping knowledge building work in a classroom community, and second, positioning with, perceiving, and acting on opportunities.

2.1.1 Shaping knowledge building work in a classroom community

> "**EPISTEMIC AGENCY**
>
> **Socio-cognitive dynamics:** Participants set forth their ideas and negotiate a fit between personal ideas and ideas of others, using contrasts to spark and sustain knowledge advancement rather than depending on others to chart that course for them. They deal with problems of goals, motivation, evaluation, and long-range planning that are normally left to teachers or managers." (Scardamalia, 2002, p. 10)

By naming agency as an analytical construct, education researchers call attention to who gets to do what in science learning spaces. In specifying *epistemic* agency, we're identifying that the

salient "what" should be related to how knowledge is constructed (Ko & Krist, 2019). So, for example, we might ask of a discussion in a science classroom, who gets to propose new ideas, and who decides the criteria by which ideas are evaluated? Or of a scientific investigation within a lab course, who gets to name problems, or make methodological decisions? (Stroupe, Caballero, & White, 2018) Supporting student epistemic agency means, in part, that students are the "who" making these sorts of knowledge building contributions.

Knowledge building work is embedded within disciplines (within this dissertation, biology lab science), and empirical research on epistemic agency tends to be organized around practices which are recognized as conveying authority for knowing within the discipline (Ford & Forman, 2006; Manz, 2012), such as argumentation (Manz, 2015b; Ford, 2012; Chen, Benus, & Hernandez, 2019) and modeling (Manz, 2012; Gouvea & Passmore, 2017; Metz et al., 2019; Kapon, 2016). Within the context of science lab classrooms, we also value disciplinary practices of shaping how and why to manipulate *materials* used to conduct investigations, which researchers have referred to as "physical agency" (Hester et al., 2018) or "decision-making agency" (Holmes, 2020).

In classrooms, as in disciplinary communities, knowledge building work is not individual, but instead "emerge(s) out of a dialectic interaction between individuals—and their individual backgrounds—and the classroom community, as a whole" (Berland et al., 2015, p. 6). That is to say, in studying epistemic agency, researchers situate *what* counts as knowledge building work within a community of practice (Engle & Conant, 2002; Brown & Campione, 1994), which may establish local norms for what are valued ideas (Ball, 1993) or practices (Manz, 2015a). This embeddedness has inspired some authors to refer to epistemic agency as a group, rather than individual, phenomenon (Damşa et al., 2010).

In sum, attending to epistemic agency in learning spaces means asking who is shaping knowledge building work within a learning community. Here "knowledge building work" is embedded both within a broad disciplinary context—with certain practices recognized as authoritative for knowing within science—and within a local classroom context, which may dynamically come to value different forms and functions of contributions in response to the learning goals of the group.

In addition to considering who is shaping knowledge building work in a classroom community, and what the work entails, research on epistemic agency is also concerned with *when*, *why*, and *how* students contribute to building knowledge.

2.1.2 Positioning, perceiving, & acting on opportunities

> "...the challenge of positioning students with epistemic agency—when should students be given the answer to a scientific question (provided it is known), and when should they be encouraged to proceed down a road with a predictable outcome?" (Stroupe et al., 2018, p. 1190)

In learning settings there is a power differential between instructor (or curriculum) and student (Stroupe, 2014; Keifert et al, 2018). Implicit in the goal of supporting students exercising agency is a redistribution of power to students (Ko & Krist, 2019). It is tempting to characterize this redistribution in terms of *giving* students more agency (Scardamalia & Bereiter, 1991; Erkunt, 2010). More recent scholarship has pushed back on characterizing agency as something that is had, or can be given, opting instead to characterize agency as something that is *enacted* (a process, rather than a property) (Ko & Krist, 2019). Within this framework researchers focus on the *opportunities* students perceive and act on to shape knowledge building work (Miller et al., 2018; Stroupe, Caballero, & White, 2018), and on when, how, and by whom students are positioned with such opportunities.

What constitutes an opportunity to contribute to knowledge building involves a complex interlinking of curricular, individual, and social factors. For example, a lab science curriculum designer might intend positioning students with authority to direct elements of an investigation that are often specified by external authorities, such as posing research questions and specifying research methods (see, e.g. Indorf et al., 2019 Table 1; Auchincloss et al., 2014 Table 2), as presenting opportunities to shape the purpose for an investigation. If students perceive the lab as having a predetermined purpose, they may instead see this curricular structure as presenting an opportunity to demonstrate their competence (Holmes, 2020) or to simply complete a new kind of task (Koretsky et al., 2015). Even if students' perception of an opportunity aligns with the intentions of the curriculum designer and instructor, other factors like social risk may impact whether and how they take up pursuing knowledge building (Watkins et al., 2018; Conlin & Scherr, 2018).

Experiencing scientific *uncertainty*—a sense of not knowing about how to account for or investigate a phenomenon—can play a role in how opportunity is co-constructed through a process of positioning, perceiving, and acting, particularly in science learning. Students perceiving problems as not having a known solution can motivate a need for practice (Berland & Reiser, 2011; Gouvea et al., 2022a). By contrast, even when ostensibly positioned with the authority to exercise epistemic agency, when students see a problem as pointing to a single, known solution, they are unlikely to see themselves as having opportunities to shape how to solve that problem (Holmes, 2020; Engle, 2012). Students' sense of what is uncertain in an investigation can inform not just when students perceive but *how students act on* opportunities to shape knowledge building work in science classrooms (Manz, 2015a; Hardy et al., 2020).

This dissertation is organized around explicating this process of positioning, perceiving, and acting on opportunities to contribute to knowledge building, through detailed empirical case examples in a lab course. Next, I will overview the conceptual framework (Luft et al., 2021; Maxwell, 2005, Chapter 3) which underpins my efforts to make sense of epistemic agency in our lab science course.

2.2 Conceptual framework for the dissertation

2.2.1 Characterizing the co-construction of opportunities to shape knowledge building

Within this dissertation I unpack the process by which opportunities to shape knowledge building work in lab science investigations are co-constructed. This spans two kinds of knowledge building work—generating explanations for phenomena, and setting aims and moves to direct investigations—and three processes, perceiving, acting, and positioning with opportunity. In my first empirical chapter (Chapter 5), knowledge building work is located in what kinds of explanations the focal student sees herself as enabled to make when accounting for unexpected experimental data. Through this analysis I aim to explicate the role of student perception in constructing opportunity. In my second empirical chapter (Chapter 6), I focus on how student groups set the aims and moves of their investigation in designing an experiment and making sense of data. Through this analysis I aim to show how the configuration of curricular materials can guide when knowledge building opportunities arise and how they are taken up. In my final empirical chapter (Chapter 7), knowledge building work is negotiated between individual students striving to set the aims and moves for their group's investigation. Through this analysis I aim to unpack the relationship between opportunity to shape knowledge building and opportunity to participate in group work.

2.2.2 Analytical constructs for making sense of positioning, perceiving, and acting

For each of my empirical chapters I leverage a different analytical construct for making sense of the process by which students' opportunities to shape knowledge building are co-constructed. Here I will name these constructs, in the order they appear within the dissertation, and review their relationship to epistemic agency. More detail on the theoretical and analytical use of each construct can be found in their respective empirical chapters.

Perception of opportunity, and framing (Chapter 5)

Framing describes the process by which individuals interpret meaning in activity. It is shaped by in-the-moment cues (Scherr & Hammer, 2009) as well as prior experience (Tannen, 1979), and it shapes what we notice and how we act in a particular interaction (Tannen & Wallat, 1987). In the context of epistemic agency, framing is useful for characterizing how and why students perceive varying opportunities for knowledge building in different learning contexts.

For example, researchers have characterized a general distinction in student framing between "doing science" and "doing school" (Jiménez-Aleixandre, Rodríguez, & Duschl, 2000), each of which entails different noticings and purposes guiding action. In this vein, Holmes & Bonn (2014) share how one student reports trying to be "safe" rather than "accurate" in reporting measurements in a physical lab, which they associate with doing school, (Holmes & Bonn, 2014, p. 187). A specific kind of framing relevant to science labs is *confirmation*—in which students see science labs as about confirming a predetermined conceptual idea (Holmes, 2020). This can shape student actions in carrying out a lab, particularly in interpreting and reporting data that doesn't match their expectations (Smith, Stein, & Holmes, 2020), which I will explore in depth in chapter 5.

Acting on opportunity, and navigating material uncertainty (Chapter 6)

In science, uncertainty is often grounded in and about material phenomena (Phillips, Watkins, & Hammer, 2017). One framework for unpacking how scientists experience and act on uncertainty about material phenomena is *the mangle of practice*, which characterizes human agency as in conversation with disciplinary and material agency (Pickering, 1995). When studying students' epistemic agency, the mangle provides a way to think about when and how students encounter and act on opportunities to shape knowledge building work in carrying out their own investigations, which I will illustrate in chapter 6.

Within the mangle, opportunities to shape knowledge building emerge through material *resistances* to scientists' (or students') investigative aims, and exercising agency entails accommodating ideas and practices to those resistances (Manz, 2015). Knowledge building contributions are held in some way accountable to material behavior. This mirrors dialogic accounts of scientific practice which view student authority to shape practices as accountable to the norms of a disciplinary or classroom community (Ford, 2008; 2012). This accountability should be viewed not as constraining, but rather informing the contours of opportunity. For example, Pickering (1995) describes how scientists can leverage disciplinary or material *forced moves* to orient to where to go next in an investigation.

Positioning with opportunity, and inequity (Chapter 7)

Power differences within a classroom are not limited to teacher-student; they also exist between students, and this can affect when and how some students are positioned with opportunities to shape knowledge building. Most commonly this imbalance is described as a *relational inequity* (Boaler, 2008), which can impact whose contributions are taken up by their peers through processes such as privileging some students' contributions and not others (Kurth et al, 2002).

Relational inequity is associated with a perceived difference in epistemic status, which also intersects with racial and gender biases (Cohen & Lotan, 1995). Power differentials can also disproportionately impact students' opportunities to participate in group work, which is described as *participatory inequity* (Shah & Lewis, 2019; Deitrick, Shapiro, & Gravel, 2016; Kurth et al, 2002). In the context of epistemic agency, reduced opportunity to participate in group work means fewer opportunities to shape the knowledge building work of small group investigations, which I will unpack in chapter 7.

Positioning, Perceiving, & Acting—connections between framing, uncertainty, and inequity

Through this dissertation I will explore the process by which opportunities to shape knowledge building are co-constructed by curricula, instructors, peer groups, and individual students. Each empirical chapter foregrounds *one part* of the chain of positioning with, perceiving, and acting on opportunity, by leveraging participatory inequity, framing, and the mangle of practice, respectively, to describe when, why, and how opportunities to shape knowledge building emerge and are taken up.

In the final chapter of the dissertation, I will look across cases to consider how these constructs interlink in the process of co-constructing knowledge building opportunities. Through this cross-case analysis, I will extend my characterization of how students frame lab spaces, consider how this informs (and is informed by) where students turn to navigate investigative uncertainty, and finally explore how both framing and uncertainty navigation are socially negotiated within small groups.

Chapter 3—Overview of the Curricular Design

The cases from this dissertation come from a multi-year design-based research initiative situated within an introductory college biology lab course at Tufts University titled Bio 14L (Gouvea et al., 2022b). In this chapter I will orient readers to three general features of the curricular design, to provide context for the studies to follow: centering uncertainty in inquiry, hybrid data production modalities, and responsive teaching. More specific implementation details for each year of the curriculum are provided within their corresponding empirical chapter.

3.1 Design features of Bio14 Labs

3.1.1 Centering uncertainty in inquiry

The Bio 14L curriculum leverages uncertainty to motivate students contributing to knowledge building and engaging in scientific practice. This informs three major design features of the labs: positioning students with authority to pose research questions and make methodological decisions; orienting labs around open-ended framing questions; and selecting complex study systems that generate messy data.

A design strategy for supporting student agency in inquiry-based lab science courses is to position them the authority to pose research questions, to make methodological decisions, and to propose biological explanations for observed phenomena (Auchincloss et al., 2014, Table 2; Indorf et al., 2019, Table 1). Exercising this authority entails grappling with uncertainty around how to engage these disciplinary practices (What counts as a good research question? Will this design address my research question? Does this explanation make sense?). We embed this authority within extended investigations that span three weeks. In the first week, students orient to a study

system, in the second week students design and conduct experiments, and in the third week students analyze data from their experiments.

Each unit (three-week investigation) is introduced as addressing a broad orienting question in evolutionary biology. For example, the first unit (which features prominently in Chapters 6 & 7), starts with the question "is it better for a population (of an organism) to mutate a lot or a little, and under what conditions?" This question is intentionally ambiguous, in part for students to identify and grapple with the uncertainty inherent in that ambiguity, and in part to leave room for students to pose more specific, testable research questions (Hester et al., 2018).

For our labs we have selected complex study systems which are likely to produce messy data that *resist* simple hypotheses about an organisms' behavior (Manz, 2015; Hardy et al., 2020). This is intended to increase the chance that students will encounter and grapple with uncertainties in the form of unexpected data (Bolger et al., 2021), which will motivate a need for novel explanations and practices (Berland & Reiser, 2011). The study system for each unit comprises both an organism (for instance, *E. coli* bacteria strains of varying mutation rates) and a computational model in NetLogo (Wilensky, 1999). In the next section I will describe how students investigate both components of the study system through coupled experimentation and simulation.

3.1.2 Coupled data production modalities

Student-led investigations entail student groups producing data (Hardy et al., 2020) using experimentation on a model organism coupled with simulation on a computational model, which we refer to as a "hybrid labs" model. This dual design is inspired by research in systems biology (MacLeod & Nersessian, 2013) and biology education research (Blikstein, Fuhrmann, & Salehi, 2016) that has shown affordances of coupling experimentation and computational modeling in

helping researchers to make progress on investigations when stuck, and in helping students to uncover discrepancies between modalities that expand and refine their conceptualization of the system as a whole.

As noted in the prior section, students design and conduct their own experiments in the second week of each unit. Prior to generating their own experiment, students work through an instructor-generated protocol with the model organism in week 1 of the unit, to orient them to how to manipulate materials—for example, in the bacteria unit, students practice intubating, growing, and plating bacterial strains from an initial culture. While students are encouraged to pursue their own research aims, their experiments are constrained by material limitations that are given to them before they start their own experimental design—for example, in the bacteria unit student groups are limited in the number and type of indicator plates they can use, which bounds what kinds of investigations are possible.

In the second week of each unit students are introduced to a computer model of the study system in NetLogo. "The Simulation" is designed to model salient features of the organismal system, as an alternative means for students to produce data. The simulation affords two features which complement data production in the experiment: students can run trials rapidly (on the order of minutes, rather than hours or days with experiments using live organisms) allowing for iteration and refinement of ideas within the time-frame of a lab section; students can manipulate parameters that are static within the organismal model—for example, in the bacteria lab students can change the frequency of certain kinds of mutations. In week 3 of each unit students are required to revisit the simulation after analyzing their experimental data, to supplement their experiment in addressing their investigative research question.

Specific details of the experimental design and simulation implementation in the bacteria unit can be found in Chapter 6.5—Hybrid Lab Curriculum Implementation.

3.1.3 Responsive teaching

Each section of the course, comprising 20-30 students, is facilitated by a graduate student teaching assistant (TA) and an undergraduate student learning assistants (LA). Since students are encouraged to name and pursue their own investigative aims, instruction needs to be able to adapt to the heterogeneity of students' interests and ideas. To this end we train our TAs and LAs in responsive teaching pedagogy, which focuses on noticing and eliciting students' ideas (Simon, 2022; Hammer, 1997). This training is carried out through a weekly lab prep with all TAs and LAs, facilitated by the lab coordinator and designer of the curriculum, Julia Gouvea. Lab prep consists of TAs and LAs carrying out investigations in the role of students, discussing ideas, experiences, and questions with peer instructors, and for TAs practice grading assignments (Hill, 2018). In 2018 we also offered an elective professional development course for instructors of the lab (Simon, 2022) which further emphasized the discussion elements of prep. All of this training is aimed at preparing instructors to facilitate student groups' independent investigations. In each of the empirical chapters in this dissertation, instructor facilitation plays a role in understanding the dynamics of students being positioned with, perceiving, and acting on opportunities to shape knowledge building.

Chapter 4—Methodology

As mentioned in Chapter 1, a primary intention for this dissertation is to build theory on epistemic agency in lab science investigations. In this chapter I will overview the affordances of case study methodology and why it's useful for achieving this aim. I will then situate the focal cases within a broad corpus of qualitative data, by overviewing the various sources of data and defining the criteria by which cases were selected. Lastly, I will overview the analytical approach employed broadly across the three empirical chapters, how that results in three very different analyses, and motivate a cross-case analysis for Chapter 8.

4.1 Methodology

4.1.1 Case study

> "Believing, with Max Weber, that man is an animal suspended in webs of significance he himself has spun, I take culture to be those webs, and the analysis of it to be therefore not an experimental science in search of law but an interpretive one in search of meaning. It is explication I am after, construing social expressions on their surface enigmatical." (Geertz, 1973, p. 5)

Case study is a qualitative research approach which centers a bounded phenomenon embedded in a real-life context, called a case (Yin, 2002; Merriam, 1998). Three features of case study make it particularly suitable for achieving the aims of this dissertation: that it is Descriptive, Holistic, & Heuristic (Yazan, 2015).

Through case studies researchers seek to generate a "thick description" of a phenomenon (Yazan, 2015; Corbin & Strauss, 2008). A description is thick when it goes beyond just a literal accounting of what is observable action and attends to implication, or the meaning behind action (Geertz, 1973). This feature is important to achieve the objectives of this dissertation for two

reasons. First, as we will see with the framing analysis in Chapter 5, theoretical constructs, such as the way students make meaning in classroom settings, may not correspond in a one-to-one way with their actions or with curricular context—two students may do the same thing for different reasons, or may see the same thing and make different meaning out of it (and that goes as well for the same student at different times). Second, two researchers can see the same data and glean different meanings. So in trying to account, for example, for student perception of opportunities to shape knowledge building, it is important to go beyond just listing what students do or what is done around them, to include a researchers' interpretation of the meaning behind observations. This can draw the attention of the reader to important details that might be below the surface of what is observable, and creates more opportunity for the reader to evaluate the validity of what is being claimed.

Cases are embedded within real contexts (such as learning within a classroom), and case study is holistic in the sense that it "consider(s) the interrelationship between the phenomenon and its contexts" (Yazan, 2015). This feature is important to achieving the aims of this dissertation for two reasons. First, I take it as an assumption that meaning making is context-sensitive (Robertson, McKagan, & Scherr, 2015; Hammer et al., 2005), and any accounting for how and why students exercise epistemic agency is incomplete without accounting for the role of context. Second, through explicitly reporting my interpretation of the role of the particular curricular context of Bio14 in facilitating students exercising agency, I hope to highlight connections that the reader can use (for example through comparison and contrast) in structuring their own learning spaces, which are likely to differ in many ways from the specifics of this lab course.

Finally, case study is heuristic in the sense that it is motivated towards "illuminating the reader's understanding of the phenomenon under study" (Merriam, 1998). Education researchers

have specifically identified “relevance to practice” (Gutierrez & Penuel, 2014) or “usefulness” (Cobb et al., 2001) as the criteria by which we should judge the rigor of qualitative research. One such use is in the development and refinement of theoretical ideas (Creswell, 2014; Hammer, Gouvea, & Watkins, 2018; Gouvea, 2017). With each empirical chapter I seek to build connections between theoretical constructs, as well as between student activity and the learning context, and in so doing to develop and refine theory in a way that is useful for the reader and the discipline.

4.2. Data collection and selection

Cases for these studies are situated within the context of Bio14L, an introductory college biology lab course which enrolls between 300-400 students per year across 12-15 sections. Data collected include semi-structured interviews with students, in-class audio/video data of focal groups within focal sections, and lab reports. A summary of enrollment and data collection numbers can be found in Table 4.1. Next I will elaborate on the sources of data, and criteria by which cases were selected for this dissertation.

4.2.1 Data sources

Each year we collected audio-video data of student activity within the lab. In 2016, this was limited to one single camera capturing video of one focal lab section. In 2017 and 2018, this expanded to include video and audio recordings of focal group activity, from a camera placed facing individual groups’ work areas and an audio recorder sitting on the work bench in front of (and facing) focal groups. The distribution of focal groups across focal lab sections is indicated in parentheses next to the total number of focal groups, in Table 4.1. Additionally, when working on computers focal groups’ screens were recorded along with synced webcam video, using Camtasia software. Our intention behind collecting focal group data was to capture student activity *in-situ*, including verbal, paraverbal, and non-verbal (i.e. gestural) information. In the context of this dissertation, I

use audio-video data to understand when and how students were *positioned* with and *acted on* opportunities to shape knowledge building in the lab.

Year	2016	2017	2018
Enrollment	306	311	340
# Sections	12	14	13
# Focal Sections (A/V)	1	2	2
# Focal Groups (A/V)	-	6 (3, 3)	9 (5, 4)
# Students interviewed	5	9 (5, 4)	6 (1, 5)

Table 4.1 *Summary of data collection across three years.*

In collecting video data (Hall, 2000) we initially assumed that most investigative activity happens within a confined work-area at a bench. In reviewing data from 2017 we found this to not be the case, as students would move around the lab space to view data from other groups (or share data with other groups), to talk to instructors, or to utilize lab equipment not present at the bench. As a result, in 2018 we upgraded recording equipment to capture wide angle video, positioned our whole-class cameras to cover space omitted by focal group cameras, provided instructors with lapel mics and portable audio recorders to capture their dialog as they moved around the room, and implemented a two-researcher memoing protocol to annotate activity as it was happening throughout the lab (at 10 minute intervals).

In addition to in-class audio/video data, each year we recruited students to participate in semi-structured interviews with a member of the research team. In 2016, this recruitment was extended to any student in the lab course, while in 2017 and 2018 only students in focal lab sections (in which we also collected audio and video data) were recruited for interviews—the distribution of interview participants within each of the focal lab sections is indicated in parentheses next to the total number of students interviewed, in Table 4.1. Interviews typically lasted about an hour,

organized primarily around recall questions related to affectively charged moments from the lab—for instance, "were there any moments in lab when you felt surprised?"—and students were compensated monetarily for their time. Details on the interview questions, and rationale behind them, can be found in Chapter 5.5. Through conducting interviews we intended to get an *emic* account of student experience within the lab—that is, one from the students' perspective (Jordan & Henderson, 1995; Fink, 2022). Within the context of this dissertation I use interviews to understand students' *perception* of opportunities to shape knowledge building.

My final source of data in this dissertation comes from student lab reports. Consent to collect lab reports was collected across the entirety of the course, in all three years. Lab report data has been used within the broader research project as a primary data source (Fu, 2018; Jiang et al., 2020). Within the context of this dissertation lab reports serve as a secondary data source, supplementing claims made from analysis of interview or in-class audio/video data.

4.2.2 Case identification and selection

In this section I will describe the process by which our research group identified potential cases from among the full corpus of data outlined in Table 4.1. For reference, I summarize this case selection in Table 4.2, below.

Case identification

Each of the cases in this dissertation illustrates part of the complex, dynamic process by which students are positioned with, perceive, and act with epistemic agency. Our research group initially identified prospective cases from among the entire corpus of data through two data reduction techniques—examining interviews, and memoing (Corbin & Strauss, 2008).

For the 2016 data, I constructed analytic memos of every interview, with the intention of uncovering themes around students' experience of uncertainty in the lab. This led me to identify

Alice and Caleigh as focal cases—the former for her productive response to uncertainty in the second unit of the course (Hayes & Gouvea, 2017); the latter for a shift in how she approached accounting for unexpected data between units (Chapter 5).

For the 2017 data, a researcher managing recording equipment for the lab section identified Gp A as a focal case owing to their adaptive use of the simulation in conducting their experimental design in the first unit of the course. I identified Gp B and Gp C as focal cases from interviews with members of those groups. In Gp B, one member, Mary, described adaptive employment of scientific practice (Forman & Ford, 2014; Manz, 2015a) in overcoming emergent uncertainties her group encountered while using the simulation in the first unit of the course. In Gp C, Jennifer described adaptive scientific practice in how her group used the computer simulation to complement, rather than reduplicate, the data from their experiment in the second unit of the course.

For the 2018 data, I identified Group 1 as a focal case through memoing focal group activity in the lab—I flagged adaptive scientific practice in their unique use of multiple computers to explore an unexpected simulation pattern in the first unit of the lab (Gouvea & Parker, 2020). Another researcher identified Group 9 as a focal case through memoing focal group activity in the lab—he flagged sensemaking activity and argumentation practices in their use of the simulation in the first unit of the lab. Lastly, I identified Group 8 as a focal case from an interview with one member, Marcia, who articulated her sense of the epistemic value of the simulation for overcoming uncertainty within their groups' investigation.

Through memoing and interviews I identified eight potential cases across the three years of study (see Table 4.2). Next I will outline exclusion criteria which resulted in the four focal cases studied within this dissertation.

In	from among __ potential focal groups	__ were identified as potential cases.	From these __ were excluded for context or triangulation	resulting in __ focal groups	within chapter __.
2016	5	2	0	1	5
2017	6	3	1	2	6
2018	9	3	2	1	7

Table 4.2 *Summary of case selection.*

Case selection

Of the eight potential cases identified, I excluded two of them—group 8 and group 9 in 2018—from consideration for further analysis on the basis of *triangulation*. Our data collection in 2017 and 2018 was organized around collecting both in-class audio-video data and interviews from the same groups, in order to draw comparisons between student activity and student experience. Since group 9 had no members who participated in interviews, and for group 8 we were missing in-class video data of their experimental design, neither of these groups were considered for further analysis in this dissertation.

Of the remaining six cases, one (Alice) did not fit the emerging analytical focus of perception of agency, which is illustrated by Caleigh's case in Chapter 5. Notably, Alice's case is referenced as an example multiple times throughout the dissertation, despite not being a focal case for any chapter.

The remaining four cases (Gp A, Gp B, Gp C, in 2017, and Gp 1 in 2018) had all been identified as exemplars of adaptive scientific practice. Of these, three took place in unit 1, while one (Gp C) took place in unit 3. In order to focus on the role of the curricular *context* in facilitating student groups navigating uncertainty, I excluded Gp C from the analysis presented in Chapter 6. Below I describe how Gp 1 came to be part of a separate analysis in Chapter 7.

4.3 Analytical approach

4.3.1 Iterative theory building

> "Third, distinct from this theoretical orientation are qualitative studies in which theory (or some other broad explanation) becomes the *end point*. It is an inductive process of building from the data to broad themes to a generalized model or theory." (Creswell, 2014, p. 65)

As noted above, theory building and refinement is a primary objective of this dissertation. The process by which I develop theory involves an iterative negotiation of fit between the phenomena illustrated by the case and constructs grounded in education literature (Engle, Langer-Osuna, & McKinney de Royston, 2014). For each case this starts with an open coding of the data, to uncover patterns and themes about the phenomenon of interest (Corbin & Strauss, 2008). From this initial thematic analysis, I explore the literature for existing theory which might have explanatory power in describing the case. I then seek to explain the case using the identified theoretical framework or constructs, noting places where the theory does not fit the phenomenon. To account for these misfits, I revisit the literature to identify alternative or supplementary frameworks or explanations. I iterate this process until I have a description of the phenomenon connected to existing theory.

Analytical trajectory for each chapter

This iterative process is most evident in my first empirical study (Chapter 5). After identifying Caleigh as a prospective case, I transcribed her interviews, and a round of open coding on this text led me to identify her sense of "purpose" for the lab as a central theme (Hayes, Gouvea, & Wagh, 2017). From the literature I identified *framing* as an explanatory framework for describing what I was calling purpose. In coding for framing, I saw that this explained but did not capture fully the phenomenon of interest—the shift in the *kinds* of knowledge building contributions Caleigh made (or saw herself as able to make) between the second and third unit of the course. In revisiting the

literature I identified epistemic agency, and particularly Miller et al.'s, (2018) characterization of *perception of epistemic agency,* as potentially useful for filling this gap. I then re-coded the transcripts for both framing and for perception of epistemic agency, leading to the final argument presented in Chapter 5.

For my second empirical study (Chapter 6), I decided upon a multi-case analysis initially organized around adaptive employment of scientific practice, that was to include Gp A, Gp B (the two focal groups for Chapter 6) *and* Gp 1 (the focal group for Chapter 7). I transcribed all three groups' investigations across week 2 and week 3 of unit 1. I initially characterized the moments where these groups appeared to generate their own local scientific practices in response to uncertainty encountered in their investigations. I then turned to the literature, and identified the *Mangle* as a theoretical framework which could describe what our research group started to call "navigating uncertainty" (Gouvea & Wagh, 2018). From this point I determined that the story Gp 1 was telling needed to include social dynamics of exclusion that did not fit the framework built for Gps A & B, and so that case branched to start the analysis for Chapter 7. I attempted to use Gp A & Gp B to extend the Mangle into a new theoretical description of a *trajectory of practice*, highlighting both the interconnected, local emergence of their practice over the course of an investigation (Hayes, Gouvea, & Wagh, 2022a), and the role of the curriculum in supporting practice (Hayes & Gouvea, 2019; Hayes, Gouvea, & Wagh, 2022b). In aligning this chapter with the dissertation I chose to focus on students' epistemic agency as conceptualized by *free moves* (Pickering, 1995; Koretsky et al., 2022) in conducting an investigation. This resulted in the analysis found in Chapter 6.

After branching from the previous case study, I sought to identify a theoretical framework which could capture the group dynamics which seemed to contribute to when and how Alaad was

enabled to shape knowledge building work within Gp 1. I identified the analysis of *participatory inequity* in Shah & Lewis (2019) as potentially explanatory of those dynamics. After coding the case for discursive markers of inequity in access to the conversational floor (# of turns, length of talk), I determined that 1) there was non-verbal evidence which contributed to how I was making meaning of students' opportunities to contribute to the group's investigation, and 2) I needed a way to identify more directly when and how much students were contributing to shaping knowledge building in their group. Returning to the literature, I adapted Engle, Langer-Osuna, and McKinney de Royston's (2014) notion of "access to interactional space" into my non-verbal evidence. Additionally, inspired by Wang et al.'s (2023) notion of a *technological conversational floor*, I developed my evidence for an *investigative conversational floor* which included bids to contribute to shaping the aims and moves of an investigation, along with engagement with those bids. Taking all these together led to the analysis presented in Chapter 7.

4.3.2 Cross-case supplemental

> Qualitative researchers must adopt a "strategy of addressing particular validity threats after a tentative account has been developed... this approach requires you to develop the specific threat in question, and to develop ways to attempt to rule out that particular threat." (Maxwell, 2005, p. 107)

In defending the prospectus to this dissertation, the committee raised what I would refer to as two validity threats (Maxwell, 2005) for the theory building of this dissertation. The first is, how generalizable is the analysis outside the scope of the particular cases for which the analytical tools were developed? The second, related, is how much do the cases chosen represent "golden moments", and within our own dataset are there either additional supportive instances that were not presented, or potentially complicating cases which do not fully support these analyses?

My first effort to address these questions is through detailing the analytical trajectory for each chapter above, explicitly contextualized by the theory-building intention of this paper. Additionally, in Chapter 8 of this dissertation I will make an initial pass at applying the analyses from Chapters 5-7 to each of the other cases presented in this dissertation. This cross-case analysis will show how the ideas developed within each empirical chapter can be applied to familiar cases. In doing so I mean not just to generalize but to deepen the theoretical ideas I've developed throughout this dissertation, revealing new considerations that can serve as starting points for future research.

Chapter 5—Attending to Student Perception of Agency in the Design of Science Lab Curricula

5.1 Abstract

In this chapter, I examine a gap between *curricula positioning* students with the agency to construct knowledge (epistemic agency) and *students perceiving* themselves as enabled to exercise epistemic agency, through a case study of one student in an inquiry-based biology laboratory course. This course is designed to engage students in contributing ideas to make sense of complex biological phenomena. The focal student, Caleigh (ps), expands the kinds of explanations she provides when encountering unexpected experimental data—from seeking mistakes with how she carried out the protocol in the first two units, to providing ideas about how the biological study system might be behaving in the final unit. Drawing on interview data, I show that this expansion can be accounted for in terms of *a shift in Caleigh's perception of her own epistemic agency in the lab*. I then illustrate, using framing theory, ways in which the curriculum influenced Caleigh's perception of constrained agency in the first two lab units. Lastly I zoom out to consider how we as curriculum designers can factor student perception of agency into the design of learning spaces.

5.2 Introduction

5.2.1 Curricula for Doing Science

There is a push in science education to support students to be "doers of science" rather than "receivers of facts" (Miller et. al. 2018). The linguistic shift from a passive to an active role reflects a broad pedagogical interest in students taking on a more agentive role in their learning. Through exercising agency over how scientific investigations are carried out educators hope students will "learn to think like a scientist, (and) find research exciting" (Auchincloss et al., 2014, p. 29).

Curriculum designers support students' exercising agency by positioning[1] students to contribute, and have valued, ideas (Engle & Conant, 2002, p. 404; Ko & Krist, 2019, p. 4). Inquiry (Lehrer, et. al., 2000; Ward, 2002) and discovery (Brown & Campione, 1994; Hammer, 1997) curricula, for example, position students to construct[2] questions about phenomena—an activity typically reserved for authorities such as instructors and textbooks—and to investigate answers to those questions using their existing knowledge and the knowledge of their peer community.

Building from the inquiry literature (Indorf et. al. 2019), college biology lab curriculum reform has promoted the development of authentic research experiences, most recently through initiatives intended to reach large groups of students like Course-Based Undergraduate Research Experiences (CUREs) (Ballen et. al., 2017), ALLUREs (Rowland et. al. 2016), & AIM-Bio (Hester et. al., 2018). These reformed lab curricula are viewed as extending a spectrum of traditional (or "cookbook") labs and inquiry labs, in the degree to which they position students to exercise agency in the discovery of new ideas *and* in the use of scientific practices (Auchincloss et. al., 2014, p. 32; Brownell & Kloser, 2015, p. 528).

For the last 30 years educators and researchers have grappled with a major challenge of implementing curricula for doing science—helping students to *take up* the agency to construct knowledge when, from prior schooling, they've learned that science ideas come from authorities such as the textbook (Redish, Saul, & Steinberg, 1998), and that the way to engage in problem solving is superficial and prescribed (Schoenfeld, 1988). Positioning students with agency to conduct investigations in a lab course could contrast with students' prior expectations of "doing

[1] I use positioning in the informal way found in Engle & Conant, 2002, p. 404 or Ko & Krist, 2019, p. 4. This is distinct from the formal discourse analysis construct found in Davies & Harré, 1990, or Watkins, et. al., 2018.
[2] I use *construct* following Phillips, Watkins, & Hammer (2017; 2018), to foreground the effort in generating research questions. Other researchers have likewise valued students *asking* questions (Bransford & Schwarz, 1999) and *posing* questions (Manz & Suarez, 2018; Karelina & Etkina, 2007).

lab" (Holmes & Bonn, 2014; Duschl, Jimenez-Aleixandre, & Rodriguez, 2000)—they might come in with the expectation that in lab there is a "right answer" that they are meant to confirm, and so tailor their experimental design and data interpretations to demonstrating that answer (Smith et. al., 2020; Holmes, 2020).

In this chapter I present a case study which illustrates this challenge; in which one student saw a curriculum not as positioning her with agency to contribute new ideas about the biological systems she was studying, but instead as *limiting* the kinds of contributions she was able to make early in the course. In unpacking what happened for this student, and why, I consider implications for how curricula impact when and why students might take up epistemic agency in doing science.

5.2.2 A Case Study in Agency

The case is situated within an inquiry-oriented, introductory-level biology lab course. A primary objective of the course was supporting students' exercising epistemic[3] agency in reasoning about biological systems—that is, contributing their own ideas about how study organisms might be behaving. One place where we positioned students to contribute to knowledge building was in accounting for unexpected experimental data. We designed experimental protocols that were not "amenable to a (simple) target conceptual interpretation" (Hardy, Dixon, & Hsi, 2020), and reinforced the expectation that students reason about the complexity of the biological system. For example, the first lab report prompted students "not to get to some particular "answer," but rather to make some sense of the data" (see Appendix 5.1). We planned that having an unanticipated phenomenon would provide space for and motivate students to contribute ideas about the behavior of the biological systems they were studying.

[3] Epistemic meaning related to students contributes to *knowledge building* - I elaborate on this in the theory section

Over the span of the course, the focal student of this case study, Caleigh[4], expanded the *kinds of ideas* she contributed to account for unexpected experimental data. In the first two units Caleigh explained unexpected data solely in terms of mistakes in how she carried out the experimental protocol. Only in the final unit did she additionally contribute ideas about how the biological system might be behaving. Interviews with Caleigh reveal that this expansion was tied to Caleigh's **perception** of her epistemic agency (Miller et. al., 2018)—that is, what kinds of explanations she saw herself enabled to contribute (or not).

In this chapter I address the question of why Caleigh felt that she couldn't contribute biological explanations in the first two units of the course, and why that perceived constraint was lifted in the third unit. Through a lens of *framing* (Hammer & Scherr, 2009), I show that this constraint is entwined with a familiar expectation of lab courses as about confirming a predetermined target idea. I then unpack how the structure of the early curriculum stabilized this expectation **for Caleigh** even while prompts within the curriculum were explicitly messaging students to engage in sensemaking rather than to get to a "right answer". Lastly, I present specific revisions that we've made in later iterations of the curriculum which address the dynamics explored in unpacking this case.

5.3 Agency & Framing in Education Theory

In order to understand Caleigh's participation in the course, what changes for her, and how that is connected to the structure of the curriculum, we first need to unpack agency and framing in education contexts.

[4] All research participant names are pseudonyms.

5.3.1 Agency

Epistemic Agency & Decision-making Agency

The term agency as I'm using it in this chapter comes from a conception in the education literature of agency as learners' ability to contribute to the knowledge building work of the classroom community (Stroupe, Caballero, & White, 2018; Miller et al, 2018; Scardamalia, 2002; Ko & Krist, 2019; Damşa et al., 2010). This emphasis on knowledge production (or a shared knowledge object) leads education researchers to refer to students' exercising *epistemic agency*.

Another kind of contribution that is specific to science lab courses is making decisions about how to conduct an investigation (for instance, how to design an experiment). In the chapter I find it useful to distinguish *decision-making agency*[5] (Holmes, Keep, & Wieman, 2020) for considerations of curriculum design and analysis of student activity in the lab.

"Ability to contribute" is contingent on many factors and (powered) dynamics between (and among) students, instructors, and curricula[6]. I will focus on one particular dynamic identified by Miller et. al. when they define epistemic agency as "students being positioned with, perceiving, and acting on opportunities to shape knowledge building work in their classroom community" (Miller et. al. 2018, p. 1058).

Positioning with Agency ↔ Perceiving Agency ↔ Acting with Agency

In the design of curricula for doing science—that is, from the perspective of a curriculum designer—one may think about providing students opportunities to exercise "more agency" (Scardamalia & Bereiter, 1991) over various elements of learning—for example, "the agency

[5] Calling out decision-making agency as separate from epistemic agency is unique to this chapter, in part because the curricular design for 2016 was unique in how it separated them (see 5.4 Study Context for details). Throughout the rest of the dissertation I include decisions about how to conduct an investigation as a part of epistemic agency, on the grounds that they contribute to building knowledge (just through actions rather than ideas).
[6] And beyond the context of the classroom, though my attention is restricted to the classroom here.

afforded students in how they chose to test their models was a key element of our AIM-Bio curriculum design" (Hester et al, 2018). I say that a curriculum *positions* students with agency[7] when it provides students opportunities to contribute ideas or decisions about an investigation.

Curricula positioning students with agency is in service of students taking up, or *acting* with agency. Ko & Krist define agency as "**the way in which** [a student] acts, or refrains from acting, and the way in which her or his action contributes to the joint action of the group in which he or she is participating (Gresalfi, Martin, Hand, & Greeno, 2009)" (taken from Ko & Krist, 2019, p. 4, emphasis added). This definition does not identify *whether or not* students take up agency. The presumption is that students always act with some form of agency (Gresalfi, 2009; Stroupe et. al., 2018; Miller et. al., 2018), and instead puts focus on characterizing what students do with the opportunities afforded them, and how those actions contribute to knowledge building.

Miller et. al. (2018) identify students' *perception* of their own agency as an important (and underexplored) bridge between curricular intentions in positioning with agency and the ways in which students actually act. If 'positioning with agency' prompts us to ask "where in the curriculum can we provide students opportunities to contribute ideas?", and 'acting with agency' prompts us to ask "what sorts of ideational contributions do students make?", then 'perceiving agency' prompts us to ask "what sorts of ideational contributions do students *see themselves as able to make within the context of this curriculum*?"

The central focus of this chapter is on unpacking one student's, Caleigh's, perception of agency, and how it was informed by the design of the curriculum. This requires examining places

[7] This phrasing is something of a shorthand for "curriculum designers, through the structure of a curriculum, position students with opportunities to exercise agency." Though it's also worth noting that opportunities may arise in the implementation of curricula that were not intended in the design.

in the curriculum where students were positioned with the opportunity to contribute explanations[8], characterizing the types of explanations Caleigh did contribute, and identifying when she perceived herself as enabled (or not enabled) to contribute certain types of explanations. In particular we're interested in when and why there is (mis)alignment between curriculum positioning with agency and student perception of agency. To understand this we first need to consider the dynamics of how students *frame* learning spaces.

5.3.2 Framing

Framing describes how people **interpret**, and **act** within, social context (Bateson, 1987/1972; Goffman, 1974; Tannen & Wallat, 1987). The central idea behind framing is that there are many ways to understand and act in a setting such as a classroom. For example, students could interpret a classroom discussion as a space for argumentation, or as a space for sharing ideas (Berland & Hammer, 2012). In a space for argumentation student action might include noticing inconsistencies in a claim and raising those to peers, while in a space for sharing ideas student action might include generating new explanations and offering those to the instructor.

Using framing we characterize this automatic interpretation of the setting as an answer to the tacit question of "what's going on here" (Scherr & Hammer, 2009, p. 149). This is important in the context of student agency because a student's sense of what's going on in the classroom—how they interpret lectures, materials, questions, assignments, feedback, discussions—will impact the contributions they will see themselves as enabled to make.

[8] As noted in the introduction the curriculum positioned students to exercise epistemic agency in accounting for unexpected experimental data. The focal knowledge building contributions in this paper are Caleigh's explanations that do this accounting.

Structures of Expectation

> *"To frame an event, utterance, or situation in a particular way is to interpret it based on previous experience: to bring to bear a structure of expectations about a situation regarding what could happen, what portions of the information available to the senses require attention, and what might be appropriate action." (Scherr & Hammer, 2009, p. 149)*

In the above example, "a space for argumentation" and "idea-sharing" describe two *structures of expectation* (Tannen, 1979) that students could bring to understand and act in a classroom discussion. The term structure of expectation points our attention to a consistency in framing carried to the present from prior experience. When education researchers refer to "confirmation" as a feature of traditional labs (Smith, Stein, & Holmes, 2020; Hester et. al., 2018; Brownell & Kloser, 2015), they are invoking a structure of expectation—that experiments yield data which illustrate a previously known concept—borne out of prior experience—having engaged in lab courses which are structured in a certain way.

The Dynamics & Stability of Framing

This begs the questions of where do structures of expectation come from, when are they applied, and how do they change? If we want to support new forms of student engagement with doing science (for example discovering new ideas rather than confirming known ideas) we need language for discussing the dynamics of framing.

Education researchers have found that framing can shift over the course of a single tutorial session (Scherr & Hammer, 2009) or classroom discussion (Berland & Hammer, 2012). Many factors can contribute to such shifts, from change in audience (see TA Frame in Scherr & Hammer, 2009; or the juggling of audience in Tannen & Wallet, 1987) to bids by classmates, instructors, and curricular materials (e.g. a worksheet prompt).

These factors are referred to in the language of dynamics (Thelen & Smith, 1994) as *perturbations* because they push on structures of expectation. In the Berland & Hammer (2012) paper students started in an idea-sharing discussion, and during that discussion one student perturbed that framing by challenging another students' idea (p. 77). This bid was *destabilizing* in that it acted to change the idea-sharing frame to something new. As the conversation evolved into one of argumentation, students made bids that *stabilized* the new frame when they directly addressed one another over the directive of the instructor to "shh" (p. 81). Perturbations of students' expectation structures (frames) are the conceptual tools we use for understanding how students learn new ways to interpret, and act in, the classroom.

In short, framing describes a process by which students actively interpret and decide how to act in learning environments—that is, what they perceive is going on and what they should be doing in a classroom. Experience in classrooms leads students to develop structures of expectation through which they frame their participation. Designing with framing in mind requires us to consider both what structures of expectation students might bring in, and how curricula might destabilize *or reinforce* those structures of expectation.

5.4 Study Context - Designing for Agency

This case study is situated within a large—about 400 students across 14 sections—introductory biology laboratory course, taught by graduate student Teaching Assistants (TAs) paired with undergraduate student Learning Assistants (LAs). The design trajectory described in this section was our first attempt at reforming a pre-existing curriculum with the intention of positioning students with epistemic and decision-making agency in conducting biology investigations. For the former we planned that engaging with unexpected data would be a strong motivator for

contributing explanations. For the latter we planned that designing experiments would be a locus of decision-making.

We anticipated that students would have previously experienced highly structured confirmatory lab courses—that is, labs in which experimentation functioned solely to generate data that demonstrated a concept previously discussed in lecture (Hardy, Dixon, & Hsi, 2020). In addition to positioning students with epistemic and decision-making agency, we saw it important to destabilize that "target idea" framing of lab courses, and set the expectation that this lab course was a place to explore and reason about biological phenomena. This was especially important to embed within the design of the curriculum, given the large, distributed nature of the lab course.

Unit	Weeks	Study System	Focal Idea	Design Emphasis[9]
1	1-3	*E. coli* Bacteria	Mutation rate	**Framing** : Exploratory rather than Confirmatory lab
2	4-6	C3 / C4 plants	Energy allocation	**Epistemic Agency** : Making sense of unexpected data
3	7-9	Bean Beetles	Oviposition behavior	**Decision-making agency** : Designing an experiment

Table 5.1 *Study systems & design emphases for each lab unit, 2016.*

The course design consisted of three units spanning three weeks each (Table 5.1), connected by a broad theme of evolutionary trade-offs. Each unit centered around a study system, chosen specifically for their complex behavior which tends to resist simple confirmatory conjectures. The enactment of the course was broken into four activity structures: Experiment, Simulation, Discussion, and Lab Report. In this section I

[9] Each of these design intentions is present, to varying degrees, throughout the course.

1. Present an overview of the biological study systems for each unit to ground our interpretation of Caleigh's reasoning in the findings and
2. Describe how and why the aforementioned activity structures were enacted in each lab unit to open space for students to exercise epistemic and decision-making agency.

5.4.1 Summary of Course Design

Unit 1 - Mutation Rate Variability via E. coli bacteria

In unit 1 students investigated trade-offs of varying mutation rate through studying two strains of *E. coli* bacteria grown in different kinds of environments. One strain (E939) was a 'wild-type' bacteria strain, while the other (E938) had a defective DNA repair mechanism, causing it to accumulate mutations at approximately ten times the rate of the E939. The focal trade-off was between the advantage conferred from more readily acquiring a "beneficial" mutation—for instance gaining resistance to a particular antibiotic—and the disadvantage of harmful mutations, such as might kill a replicate bacterium.

This tradeoff was posed as a question in the opening Discussion of the lab—"Is it better to mutate a lot or a little?" This is deliberately ambiguous. The intention was to leave space for students to locate the ambiguities themselves—for instance, in individual versus population level units of analysis, or in one environmental context versus another. In order to establish a classroom norm of students exercising epistemic agency, TA instructors were trained to attend and respond to students' reasoning in classroom discussion and in their written reports (Hill, 2018). This responsive pedagogy (Hammer, 1997) was meant to facilitate students exploring the conceptual space of the study system, rather than honing in on a single conceptual target for the unit, and valuing and critically engaging with the knowledge contributions of their peers. The weekly,

facilitator led, class-wide Discussion was typically structured around orienting to the system in week 1 of a unit, and interpreting wet-lab data in weeks 2 and 3 of a unit.

In the *E. coli* bacteria unit, the Experimental Design protocols and sequencing were entirely structured a priori, leaving no room for students to exercise decision-making agency in the experimental design. This design was in part pragmatic, given the scope of the lab course (400 students across 14 sections), and also enabled us to design a protocol we knew was likely to result in multiple experimental outcomes (messy data). Having multiple experimental outcomes can resist alignment with simple confirmatory hypotheses, and provide space for students to *problematize* the system under investigation (Phillips, Watkins, & Hammer, 2018; Phillips, Watkins, & Hammer, 2017), a point I will elaborate on below in outlining unit 2. This, we hoped, would destabilize students' expectations of confirmation.

As students were making sense of their wet-lab experimental results (Week 3) they were introduced to an agent-based computer Simulation in NetLogo (Wilensky, 1999). In this environment (see Figure 5.1) students could manipulate parameters inaccessible to them in the experimental design, such as the frequency of certain kinds of mutations and the mutation rates of the bacterial strains. The primary intention of introducing the simulation at this time was to further downplay the expectation of confirmation by reinforcing the *exploratory* nature of their investigations. This intention was built into: the design of the simulation, which foregrounds novel patterns such as those which occur over time; the sequencing of the simulation, which was introduced immediately after seeing their (likely unexpected) experimental results; and was also made explicit in a handout accompanying their introduction to the simulation, which prompted that it was "meant to help you explore.... If you notice any strange or puzzling patterns be sure to make note of those here to share with your TA/LA" (Lab 1 Handout 5_Sim).

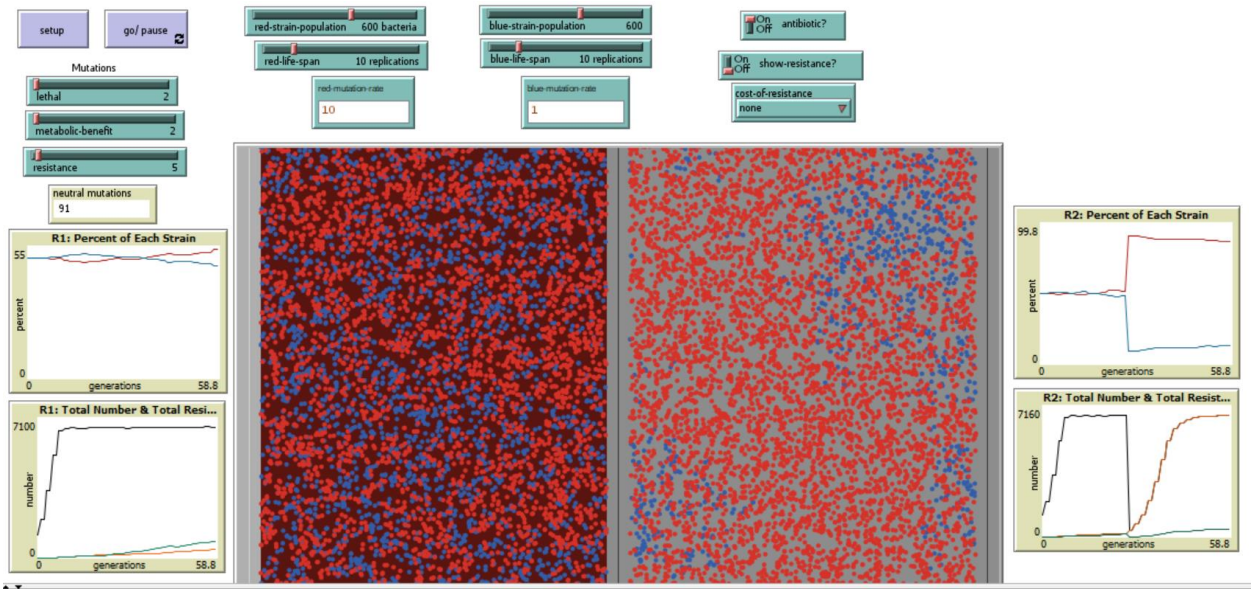

Figure 5.1 *Screenshot of simulation for bacteria lab in 2016 (Unit 1). Mutation rates are adjustable input boxes at top of environment. Mutation phenotype frequencies are adjustable sliders to top left of environment. Simulation outputs are split into two regions, R1 to the left and R2 to the right, which always run simultaneously. Only R2 can have antibiotics introduced when the "antibiotic?" switch (top right) is set to "on".*

After making sense of experimental results and exploring in the simulation, students were expected to synthesize their findings in a final Lab Report. As with the other elements of the lab this came with explicit messaging against confirmation expectations, such as "The purpose is not to get to some particular 'answer,' but rather to make some sense of the data and support your ideas with logic and evidence". At the same time it included a degree of structure, outlining expectations for what to include in an Introduction, Methods, Results, and Conclusion sections, as well as Formatting Guidelines. In each section we encouraged clarity and reasoning over conventions and jargon (see Appendix 5.1—Mutation Lab Report Guidelines, 2016).

In summary, the main curricular focus of Unit 1—the Mutation Rates or Bacteria Unit—was on disrupting students' expectations of Lab as a place to confirm a target idea, and setting up an expectation of it being a place to explore ideas about biological phenomena. This was designed

through ambiguity in the orienting question of the unit, TA training in responsive pedagogy aimed at eliciting students' ideas, an experimental protocol with multiple likely outcomes to make sense of, a simulation built and sequenced to promote exploration over confirmation, and a lab report with explicit messaging to reason rather than get to a particular 'answer'. This structure, we intended, positioned students with space to exercise epistemic agency—that is, to contribute (and have valued) explanations about the biology of the study systems under investigation. Each of the following units followed a similar structure, with adjustments being made primarily to provide space for students to exercise **decision-making agency**—that is, to contribute (and have valued) ideas and actions about how to conduct the investigation.

Unit 2 - Environmental conditions for success via C3/C4 plants

In unit 2 of the course students investigated environmentally mediated trade-offs between the C3 & C4 cycles of photosynthesis. This unit aligned with a section of the lecture course on plant physiology, and explored a similar evolutionary question to the first unit—under what conditions are certain traits favored—in a more complex organismal system. This trade-off was explicitly contextualized by global warming—what changes might we expect in relative C3 & C4 plant abundance as the atmospheric temperature, CO2 concentration, ambient humidity, and other factors change?

The primary structural difference in Unit 2 from Unit 1 was in the Experimental Design. To provide space to exercise decision-making agency, student groups[10] were given control over which of two conditions they would like to vary in their main experimental protocol—ambient CO2 concentrations, and ambient water vapor. They may adjust one or both conditions. This small change introduced students to making experimental design decisions while preserving the

[10] Across all units of the course students work in groups of 2-4 students, depending on lab section size.

scalability of data collection—as with the first unit, the organisms needed to be kept in controlled conditions for extended time outside of the lab. Additionally, two measurements—plant height and plant weight—served as proxies for success, in contrast to the singular "number of colonies" from the first Unit.

This 2x2 experimental condition, with multiple metrics of success, expanded the space of possible experimental outcomes. This was intended to afford more opportunities for students to encounter messy data through *material resistance* (Manz, 2015; Pickering, 1993). Stated roughly, this framework locates the motivation for scientific investigation and innovation in the material world "pushing back" against our understandings of how things work. Notably this includes considerations of the interpretive assumptions being made, in addition to the hypotheses about the study system behavior. For example, a simple interpretive framework could be that successful plants grow taller AND heavier. Under certain conditions, like low light, this is not necessarily the case[11], and such resistance of the plants to conform to our expectations can direct the flow of student inquiry (Manz, 2012). In fact, we have reported (Hayes & Gouvea, 2017) on the knowledge building contributions of Alice, a contemporary of Caleigh, who encountered this exact resistance—C3 plants grew taller while C4 plants grew heavier in one condition —problematized it, researched the literature, and generated her own hypothesis as to why the two plant types were allocating their carbon differently to one another.

In short, in Unit 2 we opened some space for students to make decisions about the conditions under investigation in the Experimental Design. In order to increase the likelihood of multiple outcomes, we designed multiple measures into the protocol. This opened up the possibility for students to encounter material resistance when both measures were taken as simple

[11] Plants starved of light will grow taller.

proportional proxies for success. We have evidence of students in Caleigh's year responding to this resistance by contributing their own biological explanations for the observed phenomena.

Unit 3 - Behavior, synergies and trade-offs in reproductive success via bean beetles

In unit 3 of the course students investigated trade-offs in oviposition behavior and population growth of two sub-strains of *C. Maculatus*, more commonly known as bean beetles—both of which are agricultural pests which parasitize beans to grow their larvae. One strain, named SI for its original location in Southern India, grows in mung beans, and their larvae tend to fight for space in their host beans, cannibalizing competitors. The other, named BF (Burkina Faso), grows in cowpeas, and their larvae tend to share space in host beans, so that a single bean can support multiple larvae. As with the prior units, students investigated the conditions which might select for variegated oviposition strategies, though notably there was a much larger space of factors affecting oviposition presented to investigate.

The curriculum design in Unit 3 opened considerably more space for students to exercise **decision-making agency,** through the design and execution of their own experiments. In week 1 the class collectively carried out a predetermined experimental protocol to familiarize themselves with the system (what sorts of data can one expect to collect?), and generated multiple models of beetle oviposition. They engaged with a simulation at this point (rather than at the end of the Unit) to explore the plausibility of these models being selected under a variety of conditions. In week 2 student groups generated a research question to test a model, and devised and carried out their own experimental designs using provided materials (e.g. multiple types of host bean). This structure explicitly foregrounded novel physical/material explanation (Hester et. al., 2018), and provided a new space for material resistance, in the form of limited material, space, and time. At the same

time, any given class had many different experiments being run, drastically *reducing* the opportunity to see multiple outcomes from an experiment.

To summarize, Unit 3 employed student design of experiments as a means of opening space for them to exercise decision-making agency, though materials selection and study system were still chosen a priori (out of necessity, this being a large scale lab course). How this impacted students' opportunities to exercise epistemic agency seemed much less predictable, though in principle by this point they would have had 6 weeks of practice generating biological ideas and explanations in efforts to make sense of the earlier biological systems.

5.5 Methods & Analytical Coding

5.5.1 Data collection

Data for this study come primarily from hour-long, semi-structured interviews, conducted at the start, middle, and end of the semester[12]. The first interview, a pre-interview, is not included in this analysis, as it does not capture how students acted within or interpreted the lab. The second interview occurred after Unit 2, and covers student experience in Units 1 & 2. The third interview occurred after Unit 3 and covers student experience in Unit 3, as well as the class as a whole.

Each interview is one-on-one between a student and researcher, each student was interviewed by the same researcher across all three interviews. Accounts from interviews are triangulated with students' written lab reports. The interview protocol was created to get a sense of how students were experiencing doing science in the lab course. To elicit this we asked them to describe what they did in lab (general recall), to recall specific moments in lab associated with a feeling, such as "moments that were challenging" or "moments that were exciting," (stimulated

[12] See Appendix 5.2 and Appendix 5.3 for full transcripts of the second and third interviews respectively.

recall), and to report on when in lab they most felt like they were doing science. Below I describe what we see as evidence for perceived epistemic agency, and for framing, in the interview data.

5.5.2 Interpretation of analytical evidence

Perceived Epistemic Agency

The central question guiding our interpretation of perceived epistemic agency is, "What kinds of explanatory contributions, both ideational and material, do students *see themselves as able to make* about the study systems they are investigating in our lab course?"

Ideally, perception of epistemic agency would be evidenced by explicit self attribution of an explanatory contribution, as in "This was *my* idea." Such attributions are rare, and usually appear as a hedge (i.e., "I'm not saying this is the right idea, it's just what I thought.").

More commonly, we mark perception of epistemic agency in students' descriptions of what they **actually do**, or **habitually would do**, or **feel they cannot do** in moments of uncertainty about what to contribute. For instance, when Caleigh notes "if we got, results that showed our C3 plants did better, um like, we can't really write a lab report saying C3 plants do better" we see this as evidence that she did not see herself as having the agency to contribute a certain kind of explanation when interpreting her data. This evidence is elicited in our interview protocol by questions about moments which were surprising, challenging, frustrating, or uncertain.

Framing

Framing characterizes students' sense of "what's going on" in the lab—both their interpretation of what curricular elements mean, and of what actions they should take.

We mark framing in student **justifications for their actions**, particularly when informed explicitly by an **expectation**—as in "I analyzed data that would have been more, correct and (laughs) like I don't want to say/ that data is correct just like um, what the lab instructor expected

us to see"—and in students' **interpretations of what they should do in lab**—as in "I am pretty sure that we were given the question we were supposed to answer… we weren't expected to like incorporate all the other stuff."

5.6 Analysis

In this section I first describe the kinds of explanations our focal student, Caleigh, makes to account for unexpected experimental data—from attributing it to human error in carrying out the protocol, to contributing new ideas about the behavior of the biological system. Second, I provide evidence that this is best accounted for by a shift in how Caleigh *perceived* her own epistemic agency—that is, that she saw providing her own explanatory contributions about the system as not appropriate in the first two lab units, but expected in the third unit. Third, I explain this shift in terms of her framing the first two lab units as about confirming a target idea, and the destabilization of her framing lab in this way in the third lab unit. Lastly, I discuss those elements of the curriculum enactment which contribute to the stability of her confirmatory framing in units 1 & 2, and those which contribute to the destabilizing of that framing in unit 3.

5.6.1 Caleigh's accounting for unexpected experimental data across the lab course

Units 1 & 2 - "take into account everything that could have gone wrong"

In this chapter I examine Caleigh's contributions when she accounts for unexpected data—that is, what she does when, as she puts it, "After analyzing the results from our lab section, we noticed that our results did not support our hypotheses." (Lab Report 2) In unit 2, for instance, the hypothesis was "that the C4 plants…would experience more growth than the C3 plants in environments with low carbon dioxide and low water levels." (Lab Report 2) The unexpected data was that C3 plants grew taller than C4 plants in that condition.

Caleigh recalls accounting for unexpected results in the first two units by "tak(ing) into account everything that could have gone wrong and just like lay(ing) it all out there." (I2, 41:45) That is, she "look(s) for places we made mistakes" when "our results (don't) match what we expect to happen." (I2, 35:54) This is corroborated by her lab report discussions, in one of which she notes "Our results contradict what we know about C3 and C4 photosynthesis" followed by a lengthy paragraph about "various potential sources of error that could have led to the results that we got" (Lab Report 2). For units 1 & 2, any deviation of data from expectation is characterized as a *mistake* in carrying out a protocol, a point on which she is very specific during her third interview, noting "everyone's given that same piece of paper, so our results should more or less be the same as those of our classmates. So it was really obvious if one group did something wrong." (I3, 17:20)

In short, Caleigh accounts for unexpected data in Units 1 & 2 by searching for and identifying possible errors that her group made in carrying out the experimental protocol. This contrasts with unit 3, where she additionally seeks biological mechanisms and factors which might account for generating unexpected data.

Caleigh, Unit 3 - "try to figure out what factor, was making certain beans more appealing."

In unit 3, students designed their own experiments. Caleigh's group partnered with another group and hypothesized that bean color might be an important factor determining beetle oviposition. The two groups ran identical experiments in which beetles had access to two types of beans with contrasting colors—they even set up beans in an alternating grid configuration, to control for spatial organization of the beans, and massed beans to a tight band of 0.11-0.14 grams, to control for mass preferences (Lab Report 2). Both groups found a trend of preference for the darker bean, but her group's results were not statistically significant while the other group's were (I3, 1:42).

Caleigh views this ultimately as a negative result, as they were not both able to significantly support the hypothesis that color is an important factor in oviposition.

In response to this discrepant data, Caleigh notes that "with lab three… it was more of like- figuring out, what each group found from the results, like from th- **doing** the experiment, and not like whether or not each group did it correctly." (I3, 17:20) In the interview she describes *wondering* (about the biological system behavior), and "trying to figure out what **factor**, was making certain beans more appealing." (I3, 1:16, her emphasis)

This is strongly corroborated in her lab report, where she introduces the possibility of alternative factors to color—e.g., smell, and presence of previously lain eggs—which might affect beetles' egg-laying behavior. She still considers areas in which the experimental protocol could have been lacking—for instance, in small sample size undermining interpretations of statistical significance, or in potentially insufficient control for mass. Additionally, she now accounts for unexpected data with explanations *about the biological system*.

For us as curriculum designers the question is, what contributed to this expansion in Caleigh's ideational contributions in the third unit?

5.6.2 Perception of Epistemic Agency affects the scope of Caleigh's explanatory contributions

In the third interview, Caleigh herself presents her experience in unit 3 *in contrast to* her experience in units 1 & 2. In a summary, provided near the end of the interview, Caleigh reveals a sense of *constraint* she felt in writing her lab report in the first two units that was absent in the third.

> "So, I feel like, umm, that- at the beginning of (the course) I thought there are very specific pieces that we need to use in order for our TA to give us a good grade. But, towards the third lab I felt more like, um, they were letting us use our best judgement for what pieces we needed to include." (I3, 45:11)

Going back in the third interview we see in more detail this constraint that Caleigh felt, in her description of how she engaged with writing her earlier lab reports, and her rationale for the choices she made.

> "I feel like, like we were comparing C3 and C4 plants and like every bio textbook out there will tell you that like C4 plants, do better in hot, environments. And if we got, results that showed our C3 plants did better, um like, we can't really write a lab report saying C3 plants do better. Because like everyon- like every scientist will tell you that C4 would do better. So I feel like, because they were very specific results that, they were looking for in the first two labs, like we had to write our report and analyze our data like around those. Around what was expected." (I3, 21:10)

Caleigh says plainly that she feels she *cannot* write a lab report which validates the interpretation that the C3 plants did better. This is because the idea that C4 plants do better than C3 plants in a particular type of environment is, for her, a scientific fact backed up by textbooks—she cannot change that. In the second interview Caleigh expresses a very similar feeling in the first unit, identifying results that she is "supposed to see" because they support "an accepted fact in the field." When her experimental data doesn't align with that she figures something went wrong with how she carried out the experiment, because her "tiny little experiment probably didn't like **disprove** this whole thing that's been accepted." (I2, 24:37, her emphasis)

This evidence indicates that Caleigh perceived a constraint on the *kinds* of knowledge contributions she could make during the first two units—she did not see herself enabled to revise the biological ideas central to those units. This perceived constraint seems absent in the third unit. The question we ask ourselves is, why did Caleigh see herself as not enabled to contribute certain ideas in the first two units, and what changed in the third unit?

5.6.3 Caleigh's framing the lab course

Units 1 & 2 - framing lab as about confirming a target idea

In explaining why she couldn't write that C3 plants did better than C4 plants, Caleigh stated that "they were very specific results that, they were looking for in the first two labs." Across both interviews we see evidence that her perception of which kinds of knowledge contributions she can make, or not, is informed by a felt expectation of what the instructors of the course (the TAs) are looking for, which she characterizes as the correct answer for the lab.

> "I analyzed data that would have been more, correct and (laughs) like I don't want to say that data is correct just like um, what the lab instructor expected us to see… we used, data that the lab instructor told us we were **supposed** to see, just like based off of what we know in like real life situations... the results we got were definitely **not** correct. Or I don't know I am hesitant to say the word "correct" in experiments. ... Yeah so I feel like just because we did something different doesn't necessarily mean they're wrong even though like, for the purpose of **learning** from the experiment, and learning about bacteria and how they mutate, um that data would not have helped us like come to the conclusions that we came to." (I2, 23:03, her emphasis)

In this excerpt Caleigh hedges a bit when characterizing *data* as correct because she is trying to tease apart a subtle distinction between the behavior of the system (what the bacteria are doing) and the learning outcomes of the lab course (the idea the bacteria are illustrating)[13]. It's not that the bacteria behave wrongly, it's that data that are worth analyzing are those which support the idea we're supposed to learn for the unit.

In other words, the point of being in this lab is learning a target idea in each unit—for example that C4 plants outperform C3 plants in hot environments. The thing one does in lab is demonstrate that they've learned that idea by generating particular data which confirm it. At the

[13] This is a sophisticated epistemological distinction. Caleigh's framing of the lab is not a naïve view of science, but a well-adapted view of doing school science.

time of the second interview (end of Unit 2), Caleigh frames the lab as about confirming these target ideas.

When I say that Caleigh frames the lab as about confirming these target ideas I mean that she *interprets* the curriculum to this purpose. So in analyzing data for her lab report she is actively "looking for ... whether or not our results match what we expect to happen," (I2, 35:54) with the understanding that "what we expect to happen" should confirm the target idea for the unit. This objective directs and constrains her attention (i.e. identifying correct data) and activity (analyzing said data). This is most clearly illustrated in her engagement with the simulation.

Confirmatory framing impacts Caleigh's interpretation and use of the simulation in lab units 1 & 2

Recall that we had students use an agent-based computer simulation in each unit with the intention of emphasizing exploration, rather than confirmation, of ideas. In units 1 & 2 Caleigh takes up the simulation, and how it fits into the broader unit, in ways coherent with the confirmatory framing of the class (and thus contrary to the design intention).

In the first unit Caleigh does describe *exploring* population growth trends using the simulation, including some which don't align with her experimental results. She then goes on to characterize this exploration as "beyond the scope" of what she's expected to analyze and write about in her lab report, because "we were given the question we were supposed to answer and … I feel like that question was specific enough that we weren't- we weren't expected to like incorporate all the other stuff." (I2, 32:39) In a way the simulation pushed her into an exploratory frame for a little while, but the need to write a lab report restabilized confirming an idea (from the wet-lab experiment), and the simulation data was seen as just something extra.

In the second unit, Caliegh takes up the simulation not as an exploratory tool, but as an epistemic authority against which to compare her experimental data, precisely because it is less error prone than students are.

> "at least my group we, we trusted, that we did the experiment right if that reflected what we saw in the computer simulation... Just because I feel like when we are doing something there's a lot more room for error than if a computer is doing something." (I2, 58:24)

Caliegh's not saying here that simulations are more real than wet-lab experiments. She's saying that they're more likely to reliably produce results which confirm the target idea that the lab instructors want students to learn in this unit, than are students at the bench.

Both responses to the simulation—rejecting it as beyond the scope of what's needed to write about in the lab report, and treating it as a less error prone data generator—are coherent epistemic activities when the lab course is framed as about confirming target ideas. These examples suggest that Caleigh's confirmatory framing is stable enough not only to resist perturbation by curricular elements, but to re-interpret them through the lens of the confirmatory frame.

Unit 3 - destabilizing confirmation framing and replacing it with something new

I've argued that in units 1 & 2 Caleigh frames the lab as about confirming a target idea. This influences her interpretation of curricular elements like the simulation, constrains how she perceives her own epistemic agency, and so impacts the kinds of knowledge building contributions she makes. We **don't** see this same interpretive lens applied to the third unit. Caleigh is very explicit on this point in the third interview, contrasting the third unit from the first two.

> I think it was our lab instructor wasn't looking for like specific results (in the third unit). It was just kind of whatever, results we got we were supposed to analyze that to the best of our ability. So it was more of like the process and the analysis, in lab three. Versus like, I feel like in labs one and

> two, part of doing the lab was making sure that we could follow like a procedure or protocol. (I3, 16:37)

It's difficult to characterize Caleigh's emergent framing of the lab in unit 3. In describing the process of designing her experiments, and of interpreting her data, she invokes a "path" metaphor:

> ...if we were intereste- more interested in one thing **after** realizing like we did something, then we would go down that path. Like there was just so much more, like flexibility within the third lab so, we didn't feel like we were doing anything wrong, even if like i- it deviated from our original plan. (I3, 14:40)

"Pursuing what's interesting" is maybe the simplest way to characterize Caleigh's framing of unit three. Notably, this is something she feels like she's *meant* to be doing, that the instructors "were letting us use our best judgement for what pieces we needed to include" (I3, 45:11).

For her the agency she takes up in unit 3 is an intended part of the journey, a destination after going over the basics in the first two units, "Kinda like, how, the difference between grammar and usage like once you learn proper grammar you could like kinda bend the rules a little bit to make your writing better..." (I3, 18:23). She sees this as a natural part of the progression of science education, noting that "for upper level classes like later on there's going to be more of, students using their own judgement on what's best to include (I3, 45:59).

Given our design aims for students to exercise epistemic agency throughout the course, the question then is, what (in the enactment of the curriculum) contributed to Caleigh's shift in how she was framing the lab course (and so expanding the kinds of explanatory contributions she saw herself as enabled to make), and why didn't it happen sooner?

5.6.4 Dynamic interaction between curriculum and framing

I investigated the dynamic stability of Caleigh's framing of the lab to identify how and why a shift might occur in the middle of the course. This involved characterizing elements of the curricular

enactment that perturbed—that is acted to destabilize *or to stabilize*—certain ways of framing the lab, and Caleigh's response to these perturbations. For example, above I noted that using the simulation in the first unit cued Caleigh to explore ideas (i.e. destabilized confirmation), and that it was writing her lab report which seemed to pull her back into (stabilized) a confirmation framing.

I have consolidated these elements into two lists: those parts of the curricular enactment that acted to *stabilize* Caleigh's framing the lab as about confirming a target idea, and those which acted to *destabilize* this framing and contribute to her emergent "pursue what's interesting" framing. My intention in presenting these lists is in part to identify specific places in the curriculum that had an impact on Caleigh's framing (and so which might be worth revisiting in later iterations of the lab course), and in part to identify underlying factors that could inform how we restructure labs for students exercising agency.

Curricular elements which stabilized confirmation

Instructors as origin of the experimental protocol

Recall that Caleigh identified a reason for *why* it was easy to spot errors in the first two units, stating "everyone's given that same piece of paper, so our results should more or less be the same as those of our classmates. So it was really obvious if one group did something wrong." (I3, 17:20) This provision of a protocol by the lab coordinators acts as a stabilizing factor for framing lab as about confirming a target idea, because it supports a sense that "our TAs know exactly what we did and (are) looking for very, specific, like results inside our lab re*port*." (I3, 11:41)

In short, if the instructor defines the protocol then they know what sorts of results should come out of it; this coheres strongly with there being a specific conceptual idea that those results illustrate. I'll revisit this momentarily when investigating *destabilizing* factors.

Instructor moves stabilize the "wrong results"/"right answer" interpretation

In moments of making sense of her unexpected data, Caleigh attributes to the instructor frequent reinforcement of a 'wrong results' paradigm, stating "our instructor even told us (our data) was a little messy" and "we were told some of stuff we saw isn't- isn't what was expected." (I2, 37:30) Similarly she identifies moves that reinforced a 'right answer paradigm,' as when her group generated a hypothesis about the bacteria system and "we were told by our instructor at that end that like we were correct." (I2, 14:32)

Calling attention to these moves is not an indictment of the graduate TA of her lab section. The data from the labs was meant to be messy, and the latter move could even characterize the TA noticing and affirming her group's ideas. Rather, I'm calling attention to something that *stuck* for Caleigh, in how it supported her framing the lab as about confirming a target idea.

Alignment of lab conceptual material with lecture material

Part of what sets up an expectation of a target idea for Caleigh is that the study systems chosen for the first two units line up considerably with material covered in lecture. This overlap relegates the overall role of the lab to the *application* of conceptual material—"we got like the background knowledge from our instructor and then we got to somehow apply it to, the, lab we were doing." (I2, 21:30)

This is coupled with that sense that the instructor is the mediator of canon—"we, learn something in lecture and we expect that to happen in our labs but like when we don't- like we're not sure if our understanding is incorrect or if like the lab just didn't go as expected. So it's definitely helpful to have like, our lab instructor there telling us, or like keeping us on track." (I2, 38:44)

Curricular elements which destabilized confirmation and supported an emergent framing

Students as the origin of the experiment, and the impossibility of a checklist

Recall that the stabilizing effect of the instructor provided protocol was that the instructor could design the protocol with a specific outcome in mind—one which demonstrates the target idea for the unit. We specifically intended the opposite, designing in multiple experimental outcomes, but that curricular structure leant itself to the familiar expectation of confirmation. This interpretation is further corroborated by the *destabilizing* effect of a student generated protocol, because "it would be impossible (for the instructor) to have, a checklist for like what each group needs to include." (I3, 45:59) That is, the instructor couldn't have a specific experimental outcome in mind for every student designed experiment, which strongly perturbs framing lab as being about confirming a target idea.

This also appears to influence Caleigh's emergent "pursue what's interesting" framing. She sees that the instructor trusts her and her classmates to design their own experiments, and seeing this suggests to her that they're being positioned as more advanced doers of science.

Comparison of experimental results with peers - equal epistemic authority

Caleigh's framing lab in units 1 & 2 involves her comparing her results to what she expects should be the "right" results. The "right" results are inferred from various authoritative sources, such as the lecture and her lab instructor. By contrast, in unit 3 Caleigh compares her experimental outcomes to those of her peers. This destabilizes the interpretation that she's done something wrong, because "we don't know if their results were due to chance, or our results were due to chance." (I3, 3:23) Caleigh can't immediately assume error when comparing with her peers, because "they're in the same class as us, they like in theory don't know much more than we do…" (I3, 30:57)—that is, her and her peers have *equal epistemic authority*.

Instructor feedback on prior work - destabilizing the safety impulse

The lab being a graded course has a stabilizing effect on students framing lab as about confirming ideas. Ultimately students are assessed, and their grade is carried on into their broader schooling trajectory. We have evidence that this embeddedness may have encouraged Caleigh to initially play it safe when things didn't go as expected—"after the first lab when we got completely random **results**, I was like 'oh no, this lab report is going to be so bad, like our TA is going to give me such a bad grade'." (I3, 39:33) Over time, feedback from the TA seems to have had a role in destabilizing this safety impulse and making Caleigh "feel, like more comfortable taking more risks" (I3, 11:41).

Taking these stabilizing and destabilizing elements as a whole, Caleigh's framing of the lab appears intertwined with a sense of who is the epistemic authority for the unit, and an attention to the safest course of action for achieving a good grade in the course. I unpack how those factors influence our own design thinking in the discussion.

5.7 Discussion

In this chapter I presented a case study examining a shift in the kinds of explanatory contributions one student, Caleigh saw herself as enabled to make in a biology lab course—from identifying where she made mistakes in carrying out a protocol, to proposing ideas about how the biological study systems might be behaving. I showed that this was connected to how she was framing the labs, first as about confirming a target idea and later as about pursuing what's interesting. Lastly, I identified elements of the curriculum that influenced this framing shift, and noted some underlying factors that were central to the dynamics of her framing.

On the one hand, we see Caleigh's engagement throughout the course as scientific, and are happy with the shift she experiences towards the end of the course, which appears connected to

her own sense of being more like a scientist. On the other hand, we would like to support such a shift in engagement earlier in the course, so that students have more time to practice the work of learning to think like a scientist. In the remainder of this section I discuss how we're reconceptualizing designing labs for students exercising agency, and present specific design revisions that we've implemented in later iterations of the course.

5.7.1 Design thinking with student perception of learning spaces in mind

In this chapter much of the theoretical machinery was identified post hoc out of a desire to make sense of what had quite clearly changed for Caleigh, and how this intersected with the design intentions and implementation of the lab course. As such we do not have the data to confidently characterize Caleigh's emergent framing in the third unit. Is the motivation to "pursue what's interesting" aligned with the more well studied sensemaking framing (Odden & Russ, 2019, p. 192)? Is this new framing stable, as with the emergent argumentation framing in Berland & Hammer (2012)? Does it extend beyond Caleigh to other students? While I cannot answer these questions, the underlying dynamics of Caleigh's framing shift offer more traction for design of learning spaces.

Examining the factors that influenced Caleigh's framing shift, we see it involves a "'Dance' of conceptual, epistemic, social, & affective dynamics" (Conlin & Scherr, 2018). Her sense of lab having a right idea is tied up in how the curricular structure and instructor moves position epistemic authority of data, and in the affective sense of risk associated with being graded on performance in lab. Across interview data with contemporary students in the lab we see consideration of epistemic authority and of affective risk, and we have attempted to design later iterations of the lab course bearing in mind the impact of the design of the lab on student perception. I will outline the larger changes here.

5.7.2 Curricular enactment with student perception of learning spaces in mind

One lesson we've taken from this is that it's useful, when thinking about agency and framing, to expand the space of curriculum-student to curriculum-student-instructor. Caleigh (and other students) attended to the (perceived) expectations of the instructor, even when curricular materials were signaling different expectations. We had trained Graduate Teaching Assistant instructors of this course with a weekly lab prep, particularly with respect to grading lab reports (Hill, 2018), and lab report feedback may have played a role in communicating to students that they could (and should) share their ideas without fear of being punished through getting points taken off. In future iterations of the course we expanded training to include a separate (voluntary, for credit) course on responsive teaching pedagogy, for both GTAs and Undergraduate Learning Assistants (Simon, 2022).

As noted above, Caleigh felt enabled to contribute ideas for interpreting data when those data were being compared against her peers' data rather than to expectations set by the instructor or textbooks—that is, Caleigh shared ideas when she saw herself as having epistemic authority over deciding how to interpret data. This connection between epistemic authority and perceived agency (Holmes, 2020) highlights a tension in science education between student agency and disciplinary agency (Hardy, Dixon, & Hsi, 2020). One strategy for addressing this tension has been to shift emphasis from replicating broad Disciplinary practices (i.e. those things Biologists do) to constructing locally emergent disciplinary practices (i.e. those things which help our classroom community to do biology) (Manz, 2012; Scardamalia, 2002; Engle & Conant, 2002, Cobb et. al., 2001). In later iterations of our lab course we have attempted to enact this by 1) having students design experiments from the start of the course, to remove the possibility that data interpretations

are fixed ahead of time by an authority; and 2) encouraging students to use peer and/or simulation data in constructing (and critiquing) their arguments (Gouvea & Parker, 2020).

Accompanying Caleigh's shift in perceived agency was a shift in her feeling that she could take risks without being punished (with poor grades). Researchers have discussed how students mitigate affective risk through epistemic distancing (Conlin & Scherr, 2018) and meta-affective learning (Radoff, Jaber, & Hammer, 2019). In our lab course we have sought to reduce risk by breaking up lab reports into parts that can be done across a unit. This means that any one assignment carries with it less weight, so taking risks is made easier. It also means that students receive feedback (and grades!) from instructors earlier and more often, which communicates expectations of reasoning and contributing ideas in a tangible way.

5.8 Concluding Remarks

In the context of designing educational spaces for students doing science, Caleigh's case puts a spotlight on *how* a student takes up agency when positioned with it, and foregrounds student *perception* of learning spaces as a critical consideration for how we structure and teach in those spaces. Designing learning spaces with student perception of agency in mind involves a shift from considering what students are positioned to do, to what students may think to do. This involves taking into account the structures of expectation students have for framing a learning space, and thinking carefully about the ways in which the enactment of a curriculum might push on those expectation structures (either to destabilize *or to stabilize* them).

5.9 Acknowledgements

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Chapter 6—How Hybrid Labs Support Students to Navigate Uncertainty in Scientific Investigations

6.1 Abstract

This chapter contributes to an emerging goal in college biology laboratory design of supporting students' agency over setting research aims of scientific investigations and authoring study designs to pursue those aims. I explore the potential for coupled experimental and simulation data production modalities to support students to author research moves and aims through a process of encountering and navigating uncertainty. Using the "mangle of practice" to characterize uncertainty navigation, I illustrate this potential through two case studies of student groups in an introductory college bio lab course encountering and taking actions to resolve investigative uncertainties. I then consider both cases together to draw broader implications for the design of biology labs.

6.2 Agency & navigating uncertainty in college science lab design

> "We didn't know exactly what was gonna happen. We had ideas based on the discussions of mutation rates and how they affect population and stuff. We had ideas about what might happen, but it was just the unexpectedness of it that appealed to me." (Damien, a first-year biology student)

Recent undergraduate science laboratory course design efforts have aimed to facilitate students exercising agency over setting the research goals of investigations, and authoring study designs to pursue those goals, contrasting explicitly with traditional lab course structures in which these are decided ahead of time by an instructor or by the curriculum (Hester et al., 2018; Indorf et al., 2019; Auchincloss et al., 2014; Brownell & Kloser, 2015). A prerequisite for students authoring research

aims and moves[14], is a real sense for students that the outcome of an investigation, as well as the steps to reach an outcome, are unknown at the outset (Holmes, 2020; Hayes, 2021). Part of exercising epistemic agency over science investigations involves navigating uncertainties that arise from addressing these unknowns (Hardy, Dixon, & Hsi, 2020; Miller et al., 2018; Pickering, 1995). In this chapter, I add to a body of undergraduate biology education research that seeks to describe students' navigation of uncertainty (Gouvea, & Wagh, 2018; Bolger et. al., 2021), with the goal of designing labs which facilitate students exercising agency over setting aims and making moves in conducting science investigations.

To meet this design goal we implemented a *hybrid lab curriculum*—in which students produce data for their biology investigations using experimentation on organismal study systems coupled with simulation on computational study systems (Gouvea et al., 2022b). Based on prior research with similar lab science structures we conjectured (Sandoval, 2014) that coupling two modalities for producing data

1) would structure a complex space for students to author moves by choosing how and when to use each modality to pursue research aims (MacLeod & Nersessian, 2013), and
2) would support the authorship of new research aims and moves by coordinating mismatches in data produced by the two modalities (Blikstein, Fuhrmann, & Salehi, 2016).

In this chapter I illustrate and extend these conjectures through a case study of two student groups conducting their own investigations in an introductory college biology laboratory course. I describe their activity using a modified version of the mangle of practice, which characterizes

[14] I use the term *moves* to highlight the dynamic, adaptive nature of student activity in authoring both study designs and interpretations.

navigating uncertainty as a dialectic process of encountering resistances to investigative aims, and adapting investigations to overcome those resistances (Manz, 2015a; Pickering, 1995).

The first episode is centered on students in Group A navigating how to develop a meaningful research question and experimental design when they're not sure how the biological study system might behave—with this episode I will foreground how Group A authoring moves using both data production modalities to make progress when stuck (Design Conjecture 1). The second episode is centered on students in Group B navigating how to make sense of two confusing patterns in their experimental data by replicating the design within a computer simulation—with this episode I will foreground how through coordinating experimental inputs and outputs with simulation inputs and outputs Group B encounters scientific uncertainties which shape new research aims and moves (Design Conjecture 2).

6.3 Theory—Agency, navigating uncertainty, & hybrid labs

Here I build from K-12 science education literature on student agency to motivate navigating uncertainty as a focal analytical construct. I then show how researchers characterize uncertainty navigation in science using *the mangle*. Finally, I motivate the hybrid structure of our lab for supporting students exercising agency in investigations through navigating uncertainty.

6.3.1 Navigating uncertainty as a construct for characterizing epistemic agency

> "...both goals and the practices developed to meet those goals are emergent from participants' interactions with uncertain and resistant phenomena." (Manz, 2015a, p. 91)

I take from Miller et al. in defining epistemic agency as "students being positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community" (Miller et al., 2018). In this chapter, I am focused on two specific kinds of knowledge building work important to lab science investigations: the setting of research *aims*, and the

authoring of *moves* to accomplish those aims. These two knowledge building activities are central to anthropological accounts of scientists exercising agency over investigations (see, e.g. Pickering, 1993 or Gooding, 1990), and align strongly with design goals for reformed biology lab courses (see, e.g. how researchers distinguish lab types in Auchincloss et al., 2014, Table 2; Indorf et al., 2019, Table 1; Brownell & Kloser, 2015, Table 1).

A prerequisite for students to *shape* this knowledge building work is that it is not provided for them, that a path to the answer is not certain ahead of time (Holmes, 2020). Researchers have shown how articulating and grappling with this uncertainty connects to and constitutes important knowledge building work in science (Phillips, Watkins, & Hammer, 2018; Engle, 2012; Bolger et al., 2021; Ford, 2012; Hardy, Dixon, & Hsi, 2020; Manz, 2015b; Berland & Reiser, 2011; Chen, Benus, & Hernandez, 2019; Watkins, et al., 2018). In lab science contexts theoretical and methodological decision-making can be characterized by a process of *navigating uncertainties* both present at the start of an investigation and emergent from conducting it (Gouvea & Wagh, 2018; Hayes, Gouvea, & Wagh, 2022). Next, I will review a framework for describing navigating uncertainty that forms the foundation of my analysis in this chapter, the mangle of practice (Manz, 2015a; Pickering, 1993).

6.3.2 The mangle of practice for describing navigating scientific uncertainty

> "It wasn't this big ahaa moment ... We'd come up with a plan and then go through like, what we expected at each stage but then if something didn't make sense we'd be like ok we have to change whatever it was before that, that caused this problem." (Nick, a first-year student in biology)

Manz (2015a) has described the process of navigating scientific uncertainty using a framework from anthropology of science called the mangle of practice ("the mangle" for short) (Pickering, 1993). The mangle characterizes progress in science investigations by a dialectic process of encountering *resistances*—stalls to progress in an investigation (i.e. uncertainty)—and making

accommodations—decisions made to adapt to and overcome the uncertainty (Pickering, 1993). For example, Manz shows how the changing morphology of plants as they grow constituted a resistance to a class of fourth graders attempting to draw conclusions about plant life-cycles (Manz, 2015a, p. 104). Students accommodated this resistance by engaging in practices of defining—including identifying function (in addition to form) as important to definitions for parts of plants—which enabled them to develop a shared language around how plants grow and die.

The mangle is a useful analytical framework for characterizing students exercising agency through navigating uncertainty because it was developed with epistemic agency of scientists in mind (Pickering, 1993). The mangle explicitly attends to establishing, evaluating, and adjusting scientific aims, which aligns with our conceptualization of epistemic agency in scientific investigations. And the mangle incorporates a notion of "free and forced moves" (Pickering, 1995) which addresses the tensions between student authorship—students constructing ideas and employing practices—and accountability—evaluating ideas and practices as useful according to classroom and disciplinary norms—raised by Ford (2008; 2012), a point which I will return to in discussing design implications.

6.3.3 Hybridity for supporting student agency through navigating uncertainty

> "She was able to efficiently coordinate her modeling and experimental activities… The result of this coordination was that it gave her the ability to run experimentation and modeling as an effective coupled system." (MacLeod & Nersessian, 2013, p. 8)

Our laboratory course employs a hybrid structure, in which students study biological systems using both "wet-lab" experimentation on model organisms with "dry-lab" computer simulation on computer models (Gouvea, Wagh, Hayes, & Simon, 2022). In prior work I have shown how positioning both experimentation and simulation as tools for *data production*, rather than data collection (Hardy, Dixon, & Hsi, 2020) can communicate to students that they are in charge of

authoring solutions to an unknown problem (Hayes, 2021). When students see themselves as epistemic agents, laboratory materials take on a new role in communicating to students *how* to address uncertainties they encounter when conducting their own investigations (Jordan et al., 2011). Here I will draw from prior work to articulate the role we initially saw a hybrid lab structure having in supporting students navigating uncertainty. In the next two sections I will detail how hybridity is implemented in our introductory lab course.

MacLeod & Nersessian (2013) unpack an anthropological account of one graduate student researcher conducting an investigation using what they refer to as a bimodal system of computational simulation and experimental design. The main thrust of their description is showing how this researcher bounces back and forth between the two modalities in order to make progress on her investigation when she is stuck (MacLeod & Nersessian, 2013, Fig 5, p. 9). From this, we conjecture that coupling experimentation and simulation as data production tools can provide student researchers multiple opportunities to author moves to make progress when encountering an uncertainty that is impeding their investigation.

In their work with high school biology students Blikstein, Fuhrmann, & Salehi (2016) show how bifocal modeling—coordinating physical experimentation and virtual models in real time to investigate natural phenomena—can support students encountering uncertainties in how to effectively model the phenomenon, which they label discrepant events. These discrepancies "motivated (students) to reach beyond physical experimentation and begin a process of inquiry that included questions, group discussion, and exploration to seek an explanation of the discrepancy" (Blikstein, Fuhrmann, & Salehi, 2016, p. 524). From this, we conjecture that mismatches in data produced by experimental and simulation modalities can serve as a kind of uncertainty that supports students' authorship of new research aims and moves.

6.4 Study Context

This study takes place in a large (~400 student) introductory biology laboratory course at Tufts University, organized conceptually around broad questions in evolutionary biology. Each lab section comprises between 20 and 30 students, split into groups of 3-4 students, taught by two instructors—a graduate student Teaching Assistant (TA) and an undergraduate Learning Assistant (LA) who has taken the course before.

The course is broken into units in which students investigate complex organismal study systems that resist simple mechanistic explanations (Manz, 2015a). In the focal unit of this chapter, the first unit of the course, students investigate the concept of mutation rate variation in nature. This is oriented around a framing question for the unit, "is it better for a population (of an organism) to mutate a lot or a little, and under what conditions?" This question is deliberately ambiguous to leave space for students to propose and explore more specific parameters, but it points to a conditional trade-off in the phenotype of mutation rate. The framing question is examined through experimentation on a study system comprising two strains of *E. coli* bacteria. The E939 strain is a "wild-type" strain. The E938 strain has a damaged DNA repair mechanism which results in it acquiring mutations at roughly 10x the rate of the LM strain—that is to say, a population of E938 can be expected to acquire ten times as many random mutations per generation as one of its wild-type E939 counterparts. For this reason E938 are dubbed "high mutators" (HM) and E939 are dubbed "low mutators" (LM), which is how they'll be referred to in the remainder of this chapter.

6.5 Hybrid Lab Curriculum Implementation

Here I will describe the two data production modalities as they are implemented in the bacteria unit, first with an overview of what students can manipulate with each modality, and then with a summary of how they are structured throughout the three weeks of the unit.

6.5.1 Experimental design with *E. Coli* bacteria

In the experimental design, student groups develop their own research question and experimental protocol which address the framing question of the unit—"is it better for a population (of an organism) to mutate a lot or a little, and under what conditions?"—using the model organism—the HM (high mutator) and LM (low mutator) strains of *E. coli* bacteria.

Groups have access to three kinds of growth media (LB; LB+Rif, an antibiotic; and LB+Lactose, a novel nutrient), and three indicator plate types (agar; agar+Rif; and MacConkey media, which indicates lactose digestion) to use for their experiments. Groups are restricted to six total plates per group, owing to the scale of the lab (~400 students). Furthermore, they can choose to grow HM and LM strains which are made to fluoresce different colors under UV light, so that the strains can be distinguished if grown together in competition.

6.5.2 Computational simulation in NetLogo

The simulation (Sim) models the *E. coli* study system using an agent-based simulation in NetLogo (see Figure 6.1). The model "co-cultures" (up to) two strains of bacteria. Strains acquire mutation phenotypes according to their mutation rates (input boxes, top right) and phenotype frequencies (sliders, top left). Phenotypes are limited to 4 categories: lethal phenotypes kill individuals (these model deleterious mutations); metabolic benefit phenotypes allow individual bacteria to produce more replicates over the span of their lifetime; resistance phenotypes confer complete immunity to an antibiotic, which can be introduced into Region 2 of the model via a switch (top middle);

neutral mutations do nothing. Region 1 of the model can never have antibiotics, allowing for a control comparison when introducing antibiotics (or a replicate if not). Outputs include a color-coded visual representation of the bacterial growth in each region (bottom right), and time-dependent graphs indicating the relative proportions of each strain in each environment, and the proportion of individuals of each strain that have developed metabolic benefit or resistance mutations.

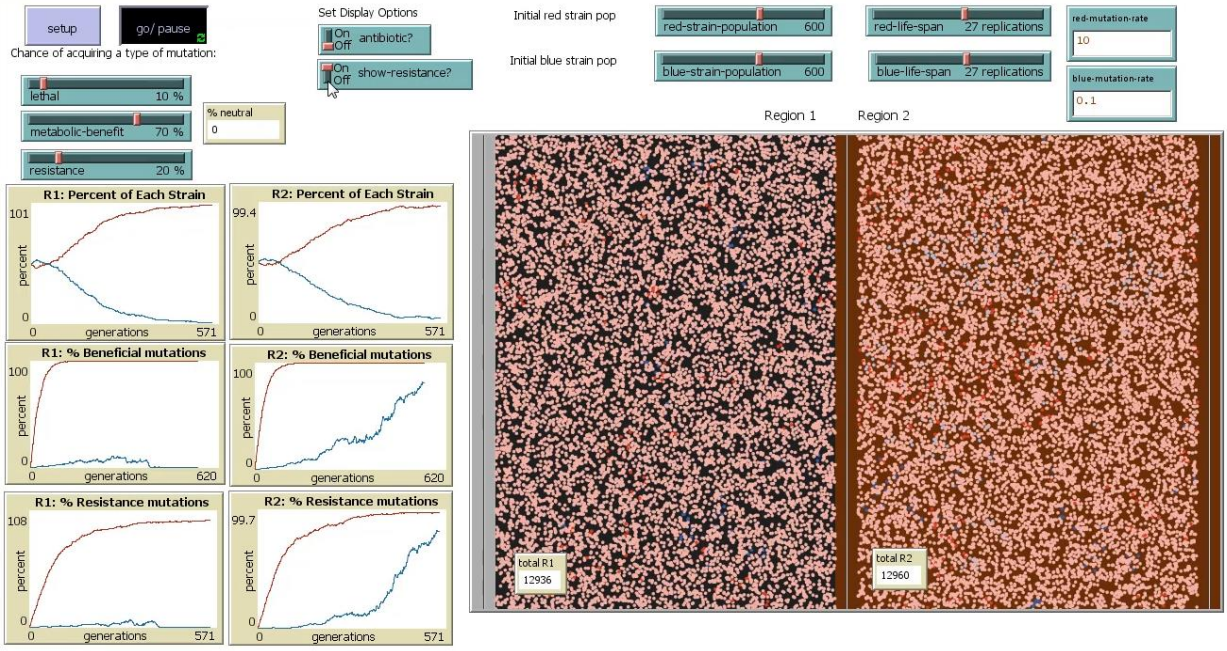


Figure 6.1 *Interface of the computer simulation for the bacteria unit, 2017.*

6.5.3 Overview of the unit structure—Bacteria Unit

The intention of hybrid labs is for students to use both experimentation and simulation as joint tools for producing data to investigate a research question. In order to support students in taking up the modalities in this way, units span three weeks, providing time to orient students to these tools before carrying out their own investigations.

Week 1 is structured around orienting to the framing question, and to the study system. Students engage in whole class[15] discussion about selection for mutation rate, then carry out a predefined protocol in which they empirically identify the relative mutation rate of the HM strain to the LM strain, using phenotypic resistance to the antibiotic Rifampicin (Rif) as a proxy for mutation frequency. This protocol orients students to the materials and methods they can use for conducting their own experimental design.

Students start week 2 by analyzing their plates from week 1 and discussing them as a class. They are then introduced to the agent-based computer model in NetLogo and given some prompts for exploring trends through simulation. This initial simulation activity orients students to how they can manipulate the computer model to conduct simulations as part of their investigation. The remainder of week 2 is dedicated to student-directed data production, centered on experimental design using the *E. coli* study organisms. Student groups generate their own research question, design a protocol for addressing that question, and carry out their experimental protocol, which requires a minimum of 72 hours to grow bacteria first within a culture tube, then on an indicator plate.

Week 3 is organized around data analysis and presentation. Groups are told at the start of the week that they will be presenting their findings to their peers in a poster session. Students start by analyzing their plates from their experiments with *E. coli* (this typically involves counting many colonies of bacteria), and generating a summary representation of their results. Next, they revisit the Sim, with the prompt to "providing insight on (their) research question." This gives them a second opportunity to produce data, with the context of their experimental data guiding them.

[15] Throughout this chapter "class" refers to the lab section of 20-30 students, not the entire course of 400 students

Finally, groups share their findings in a poster session. This expands the pool of data, trends, or arguments available to them in constructing an argument for their final lab report.

Students present their investigations in a distributed lab report—they share their initial ideas about mutation rate selection after week 1, describe their research question and experimental design after week 2, and report on their findings (at least their own experimental results, but also potentially simulation or those of their peers) and how those inform their understanding of mutation rate selection after week 3.

6.6 Data Sources and Selection

The data for this chapter focuses on two groups, labeled Group A (Gp A) and Group B (Gp B), both from the same lab section, taught by a (doctoral student) member of our research group. Here I'll quickly overview each group's members, why the groups were selected for analysis, and what data sources were collected and analyzed.

Group A is composed of four members, all first-year students, pseudonyms Abram, Damien, Nick, and Walt. Group B is composed of three members, two of whom are second-year students and the third a first-year student, pseudonyms Karl, Mary, & Sujan. Both groups were chosen as a focal group for in-class data collection in part because one or more students in the group consented to participate in interviews conducted after each unit. Gp A and Gp B were selected for further analysis from among six focal groups across two lab sections because in interviews, members of those groups express feeling agency over their investigations and describe engaging with and overcoming uncertainty in conducting them.

Analysis for this chapter comes from four data sources: in-class video & audio, lab reports, interview data, and curricular materials. In-class video & audio was recorded of the focal groups and of the whole classroom, for the entire lab each week (totaling about 9 hours across the three

weeks of unit 1). Computer activity was recorded using Camtasia software. Interviews were semi-structured, lasted about an hour (between 40 and 75 minutes), and students were paid for their participation.

Descriptions of student groups navigating uncertainty come primarily from analysis of in-class video and audio (see Appendix 6.1 & Appendix 6.2 for transcripts of each episode). This is triangulated with lab reports and interview data to better understand the conceptual terrain students were engaging with (for instance, to clarify the use of relational terms that come naturally in speech production like "those" or "over here"); and with curricular materials both to clarify student actions (for instance by reference to these materials) and to identify potential contributions these materials may have had on student activity.

6.7 Analytical Methods

I use a modified version of the mangle (Pickering, 1995; Manz, 2015a) to characterize students encountering and acting to resolve uncertainties in how to carry out their investigations. I code these as "Resistances to Aims" and as "Generative Moves & Evaluation", respectively. Here I'll define these constructs, exemplify how they are coded, and outline how I will use them to describe the activity of Gp A and Gp B.

6.7.1 Resistances to Aims

Resistances to Aim(s) characterize students' experience of uncertainty as stalls to their own investigative progress. While this aligns strongly with Manz's use of resistances, I make the choice here to always (and only) ground resistances in the context of students' investigative aims. This affects what gets coded as a resistance *to aims*. For example, "the changing nature of plants" (Manz, 2015a, p. 106) is not a resistance to aims as stated. "(The plants were) changing in ways that (students) weren't entirely sure of (as they) attempted to draw conclusions about them" (Manz,

2015a, p. 104) *is* a resistance to aims—it includes both an investigative intention (to draw conclusions about plants) and an uncertainty in meeting that intention (uncertainty about how the plants were changing). This stricter criterion centers student agency by focusing our view on *their* experience of uncertainty ("plants changing" might constitute a different resistance for students pursuing a different aim—for instance, the changing plants could pose a barrier to carrying out an experimental protocol, for students aiming to confirm a concept by running an experiment).

6.7.2 Generative Moves & Evaluation

Generative Moves & Evaluation characterize student reorientation of activity in the face of uncertainty. Naming both moves and evaluation as relevant accommodations acknowledges that exercising epistemic agency in scientific investigations entails both employing practices and ideas, **and** deciding to what extent progress has been made and where to proceed next in an investigation.

This elaboration on accommodation is intended to foreground two central components of decision making—actions made to overcome uncertainty, and re-orientations of aims for deciding how to make future progress. The former is coded when students introduce an idea (e.g. an explanation) (see, for instance, Engle & Conant, 2002, p. 428), or a scheme for resolving an uncertainty. By scheme I mean the development of tools for ultimately (not immediately and directly) overcoming uncertainty, like Glaser's' inclusion of a triggering strategy for a bubble chamber to resolve an uncertainty in the timing of detecting cosmic rays (Pickering, 1993, p. 571), or Hamilton's appeal to algebraic manipulations to resolve an uncertainty in the conceptual meaning of quaternions (Pickering, 1995, p. 123). Re-orientations of aims are coded when students adjust their investigative intentions, for example by refining investigative research questions and goals (Gooding, 1990, p. 147), or deciding whether and how to develop a particular model (MacLeod & Nersessian, 2013, p. 7).

6.7.3 Case study structure

Each case is bounded by a single, continuous **episode** of student groups navigating uncertainty in their scientific investigations, consisting of **moments** in which student groups encounter a *resistance to aims* and make a *generative move and evaluation* to overcome that resistance. For each episode, moments are grouped to illustrate the two design conjectures of the chapter.

6.8 Illustration of Design Conjectures

6.8.1 Group A navigating uncertainty in experimental design

Gp A's episode centers on their striving to author a research question and experimental design, when uncertain about how the study system might behave. To situate the episode, I will start by describing the resistance they encounter to their design aims. Then I will illustrate Design Conjecture 1 by describing two sequential moves they make to overcome this resistance—first, by generating hypothetical experimental data; second, when this does not enable them to make progress, by turning to the simulation to produce data, which does enable them to navigate this uncertainty and finalize an experimental design. Finally, I will illustrate Design Conjecture 2 through a moment in which they encounter a resistance when coordinating the simulation inputs with their experimental design, resulting in their developing a research question that incorporates data from both modalities.

Gp A's Resistance to Aims

This episode takes place in week 2 of the bacteria unit, which is organized around designing an experiment that addresses the orienting question of the lab—"is it better to mutate a lot or a little, and under what conditions?"—using the *E. coli* study system and available materials (growth media and indicator plates). Gp A decides that they want to design an experiment using a new

material—a growth medium containing the novel nutrient lactose—because it's "more interesting" than using the same antibiotic they used in week 1. Designing an experiment using the lactose medium becomes an investigative aim.

A worksheet provided to the students breaks the experimental design task (roughly) into two parts: 1. articulate a research question (RQ) and 2. specify an experimental protocol (see Appendix 6.3). In the span of about 5 minutes Gp A constructs the RQ "Does the presence of a secondary source of energy, like lactose, benefit growth of the strain that mutates more (the HM strain)?" Gp A hypothesizes that the HM bacterial strain will grow more in the lactose environment.

The expectation that a higher mutation rate can be advantageous in changing environments emerged during discussions in the first week of the unit. In an experiment conducted in week 1, the HM strain of *E. coli* grew more colonies than the LM strain when introduced to an antibiotic environment, which corroborated this expectation. Gp A models their lactose experiment hypothesis on this known trend in one growth medium (Rif, an antibiotic), with the assumption the same trend would apply in a different kind of growth medium (Lac, a novel nutrient). Satisfied with their research question, Gp A sketches a rough experimental design, modeled off of the protocol they had carried out in week 1.

Gp A checks in with the TA to validate their research question and design. The TA replies "interesting, so what do you expect to see?" In addressing this question, the Gp A members start to articulate an uncertainty. They initially expected that the HM strain would grow more than the LM strain, because that's the trend they saw in the antibiotic. Now they are not so sure this will be the case because there is no "negative force" acting to reduce population growth of the LM strain—in the antibiotic environment not gaining a resistance mutation meant death, but in the lactose

environment if individuals don't develop a lactose digesting mutation there is plenty of normal metabolite to get energy from. The TA does not resolve this uncertainty, but instead prompts them to "think in terms of your expected results."

The outcome from talking to the TA is visibly frustrating for the students in Gp A—they entered that conversation with a pretty clear plan of action for designing their experiment, and left it with this big conceptual uncertainty impeding that aim.

Design Conjecture 1—Hybridity facilitates making progress when stuck

Damien's hypothetical—How one data production modality can be insufficient to make progress

After a brief moment of collective composure gathering ("Oh god." "Okay." "Alright. Here we go.") Damien pulls up a piece of paper and starts to draw out some hypothetical experimental results, in the form of potential colony counts on their final indicator plates (Figure 6.2). This paper model starts with only one salient difference between the two strains—the HM strain has more lactose digesting colonies than the LM (total colony counts are assumed to be equal). After writing this down he asks simply, "So what does that mean?"

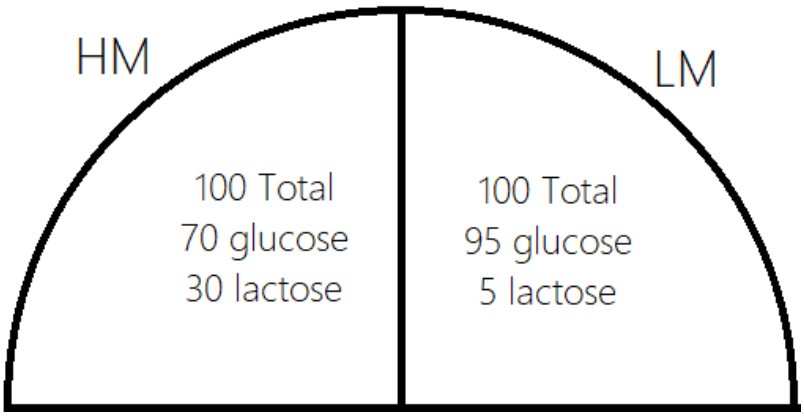


Figure 6.2 *Recreation of "Damien's hypothetical" paper model.*

Damien's move to author a paper model initiates a conversation which orients their articulation of uncertainty around three salient concepts—competition, advantage, and scarcity.

While it provides some theoretical traction as to the mechanisms at play, ultimately Group A evaluates that they do not know the relative impacts that those mechanisms will have, and so have not resolved their uncertainty around determining whether the HM strain will outcompete the LM strain in a lactose + LB environment enough to proceed with their experimental design aims.

Turning to the simulation—A second data production modality enable progress

Gp A's inability to overcome resistance leads to further frustration. They feel stuck with their experimental design. At one point Damien proposes abandoning the aim of using lactose for something that's easier. The students are visibly uncomfortable, and fill the space with nervous laughter. Damien tentatively proposes that they "use the thing, the computer program? Just to see what happens." He is referring to the computer simulation they had explored earlier that class, after analyzing their week 1 experimental data. Damien proposes a way to manipulate parameters in the computational model that might address if a difference in growth between HM and LM is at all plausible in Lac+LB medium. Initially taken aback by this suggestion ("Wait, could we? Actually, just try it. Is this the plan?"), the Gp A members decide to go for it ("Why not? It'd be fun.") To their excitement this move works—the HM strain in the simulation consistently grows more than the LM strain, when metabolic benefit mutations occur frequently (Figure 6.3).

When Gp A is stuck on a conceptual uncertainty, having access to both the experimental modality and the simulation modality as tools for producing data sets up opportunities for them to author moves to make progress on their aim of designing an experiment using a lactose growth medium. In the discussion I will expand upon this by considering why the move to turn to the simulation is successful for Gp A in this moment, and why the move to create a paper model is not. Next, I will show how Gp A authors new research questions when the data output by the simulation do not provide a perfect one-to-one resolution to their experimental uncertainty.

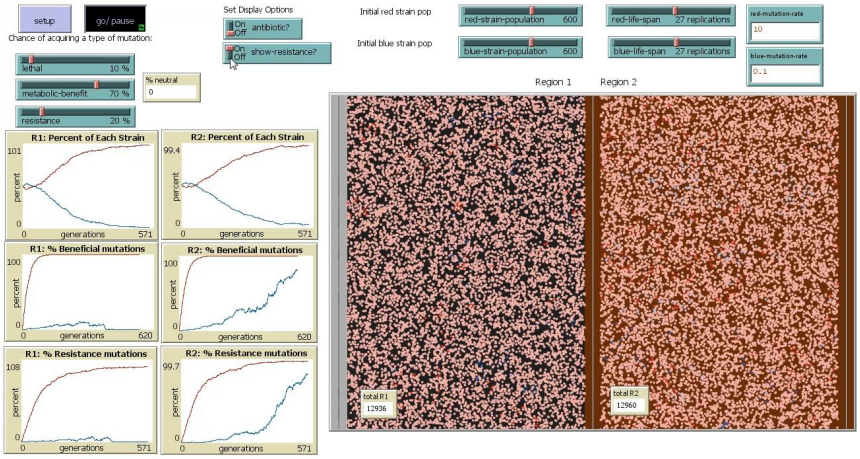


Figure 6.3 *Gp A simulation results showing HM (the red strain) outcompeting LM (the blue strain) with metabolic benefit mutation frequency turned to 70%. In this trial the blue (LM) strain is extinct in region 1, and nearly extinct in region 2.*

Design Conjecture 2—Coordinating modality mismatches facilitates authoring research aims

Metabolic benefit vs Lactose—Uncertainty coordinating representations leads to refined RQ

In evaluating what the simulation data has to say about whether or not an HM strain of *E. coli* can plausibly outcompete an LM strain in a novel nutrient environment, Gp A notices a subtlety that needs accounting for—the simulation doesn't model a lactose environment directly, but instead models a mutation phenotype that confers a "metabolic benefit." This misalignment constitutes another resistance to their experimental design aims—it is uncertain whether the HM outcompeting LM in the simulation environment, with metabolic benefit mutations, implies they will also outcompete in the experimental environment, with lactose growth media.

The group bridges this gap by adjusting their research question to "would being able to metabolize lactose as a secondary resource be beneficial to E-Coli survival?" There's a logic of transitivity to how this addresses their initial aim— they know from the simulation that metabolic benefit mutations support more growth of the HM population (as compared to the LM population), so if they can experimentally confirm that lactose metabolism is beneficial, then they can show

that the presence of lactose will support growth of the HM over the LM (what they initially sought to show).

Gp A's research question ultimately hinges on data produced in *both* the experimental and the computational modalities, in part because it emerges from coordinating a mismatch in how each models the study system. In the discussion I'll consider the kinds of mismatch coordination that supports both groups in authoring new research aims and moves.

6.8.2 Group B navigating uncertainty in making sense of experimental data

Gp B's episode centers on their using the simulation to make sense of two unexpected data patterns from their experiment. To situate the episode, I will start by describing how these two patterns resist their aim to understand the study system. I will briefly illustrate Design Conjecture 1 through showing how they take up the computational modality to overcome these resistances. With most of the episode I will illustrate Design Conjecture 2 through unpacking three moments in which they encounter, and make moves to overcome, further resistances. First, through coordinating experimental and computational *outputs* they author a modified experimental protocol which incorporates a new dimension of the study system—how populations evolve over time. Second, through coordinating *inputs* they develop a simulation protocol to preserve "representativeness" between the two modalities. Third, through attempting to simultaneously coordinate both inputs and outputs, they identify sensitivity to input conditions as a relevant parameter of the system.

Gp B's Resistance to Aims

The episode for Gp B takes place in week 3 of the unit. This week is oriented around student groups analyzing and reporting on the data generated from their experiments. Gp B designed an experiment in which HM and LM strains were grown together in three conditions with increasing levels of exposure to antibiotics (Figure 6.4)—no exposure (control condition); exposure on plates

only (“single exposure” condition); exposure in growth tube and on plates (“double exposure” condition). In their week 2 design reports, Gp B members broadly indicated the expectation that conditions with more antibiotic exposure would have fewer colonies overall, and would have a higher proportion of HM to LM bacteria—the control condition would show a lot of growth of both strains, in “roughly equal” proportion (maybe some more LM than HM due to deleterious mutations); the single exposure would show a lot of HM and few LM; and the double exposure would show some HM and no LM.

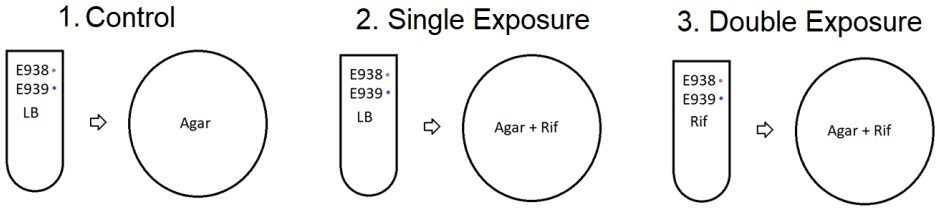


Figure 6.4 *Depiction of Gp B’s three experimental conditions.*

Group B sees two unexpected trends in their results (Figure 6.5). First, the control condition has almost no growth of the HM strain. Second, the single exposure condition has *no* growth of the LM strain, but the double exposure condition shows *some* growth of the LM strain. That their replicate plates show nearly identical results indicates to Gp B that these two outcomes are real phenomena (i.e., not an error in carrying out the protocol), but why these patterns emerged resists Gp B’s aim to understand the study system.

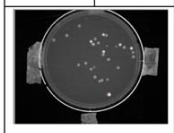
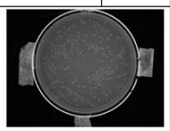
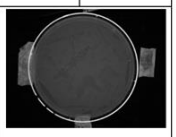
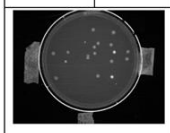
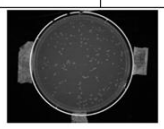
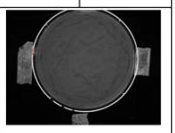
Growth Medium / Plate	LB / Agar (Control)		LB / Agar + Rif (Single exposure)		LB + Rif / Agar + Rif (Double exposure)	
Strain	E939	E938	E939	E938	E939	E938
Plate #1	27	2	0	452	11	Lawn
						
Plate #2	19	0	0	232	14	Lawn
						
Average	23	1	0	342	12.5	Lawn

Figure 6.5 *Table of Gp B's experimental results from one student's lab report. In the left (control) condition there is an average of 1 colony of the HM (E938) bacteria. In the middle (single exposure) condition there are 0 colonies of the LM (E939) bacteria, while in the right (double exposure) condition there are an average of 12.5 colonies of the LM (E939) bacteria.*

Design Conjecture 1—Hybridity facilitates making progress when stuck

Replicating the experiment—Using the simulation to make sense of experimental data

As with Gp A, Gp B's initial instinct is to discuss data solely within the experimental modality. Unlike Gp A, Gp B does arrive at a tentative resolution to their uncertainty over why more LM grew in the double exposure condition than in the single exposure condition. They conjecture that the concentration of Rif may differ between the growth medium and the indicator plate, and in particular may be weaker in the tube, allowing more time for some individuals to develop antibiotic resistance. This materials-oriented explanation seems satisfactory to them, though it does not account for the first unexpected pattern (in which no HM grew in the control condition).

After some time, the TA prompts all groups in the class to "model something that helps (each group) get at the question (they) asked, using the simulation." Gp B takes this as an opportunity to overcome the tentatively resolved conceptual resistance. After some discussion they move to replicate each of their experimental conditions within the computer model, to see if they can also replicate the experimental outcomes, and identify what might be contributing to those

outcomes. Notably this move re-opens the uncertainty in their understanding of the pattern with the LM bacteria in single- and double-exposure conditions.

It's worth noting that Gp B doesn't choose *when* to use the simulation here; its use is prompted by the instructor and the curriculum, a point I'll revisit in the discussion. However, Gp B does author *how* to use the simulation, and this move is grounded in their own investigative aims and uncertainties. In the following section I elaborate on the details of how they carry out this experiment replication within the simulation, the resistances that emerge, and the research moves they make in response to those resistances.

Design Conjecture 2—Coordinating modality mismatches facilitates authoring research moves

Population inversion—Coordinating outputs leads to authoring a new experimental design

Gp B starts their work on the simulation by setting the computer model to compete a high mutator and low mutator in an environment with no antibiotic (as with their control condition) (Figure 6.6, left). They see an initial advantage for the HM strain, and as time passes the population graphs converge and the LM strain becomes dominant, until they get to a point when there are no HM bacteria left (Figure 6.6, top right). Sujan notes that lethal mutations might disproportionately affect the HM bacteria, which may account for the long-term trend of the HM strain dying out.

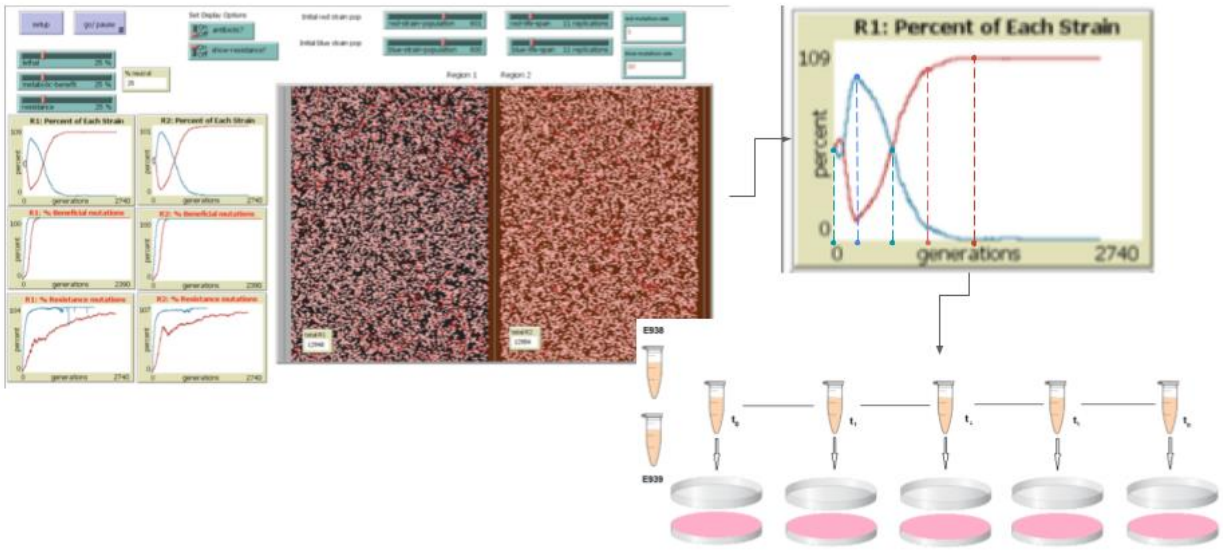


Figure 6.6. Left - Results from Gp B's control-condition trial. Top-right - HM (blue) bacteria starts off with higher population, then dies out leaving only LM (red). Bottom-right - Karl's proposed experimental setup for tracking populations over time.

The long-term outcome is what they wanted to replicate and account for, and Sujan's explanation serves to resolve their initial resistance to understanding the control condition data. However, now they are confused as to why, in the Sim, the HM *initially* got an advantage before dying out. To overcome this new resistance, Gp B moves to run a repeat trial. During this trial, Karl notices that the increase in population for each strain coincides with an increase in metabolic benefit mutations, which may account for the HM strain's initial advantage (it acquires more metabolic mutations earlier, and so grows faster than the LM at the start). Gp B evaluates this to be a reasonable explanation, but Mary proposes they test it again using just metabolic benefit mutations and lethal mutations "fifty-fifty"[16]. The pattern plays out similar to before, with HM both peaking and dying out faster (which appears to corroborate the mechanisms they identified). Satisfied that they have accounted for the control condition, they take a screenshot of their results.

[16] Gp B chose initially to make all four mutation phenotypes equally likely, since mutations are random and they had no basis for assuming one was more prevalent than any other.

As they're doing this procedural work Karl opines "Wouldn't it be pretty cool if we took like samples from- like renewed the plate every however many hours or so, just to see the distribution of which-?" Sujan is so excited by this proposal that she interjects "Just to see! Yeah. Because maybe like the high mutator was doing well in the beginning, and they just died." Karl is authoring a future experimental design in which one samples bacteria from the tube onto plates at regular intervals (Figure 6.6, bottom-right), to identify a more continuous growth pattern of the two strains that might detect non-linear population trends like they saw in the simulation.

Karl's proposed design iteration, while utilizing the same materials as their first design, has an entirely new research aim—to understand the evolution of patterns over time, rather than to see which strain does better in which environment. This aim emerges from coordinating a mismatch in the outputs of the two modalities, one of which (the simulation) is continuous in time and the other of which (the experiment) is discrete.

Representing an experiment—Coordinating inputs leads to a new protocol

Gp B next moves to replicate their 'single-exposure' and 'double-exposure' outcome in the simulation, with the intention of overcoming the other resistance to understanding their experimental data. They start with the single exposure condition, and immediately hit an uncertainty that was not present in replicating the control condition—how, within the simulation, do they differentiate growth in the LB tube versus on the Agar+Rif plate? They need a way to represent growing bacteria *first* in a neutral environment and *then* on an antibiotic-laden one.

The simulation measures time in terms of generations, so Mary makes a move to identify how many generations of bacteria replicated in the LB tube, and to use that number as the time to grow the bacteria with antibiotic turned off, after which they will turn antibiotic on to represent plating on Agar+Rif. They deem that this will make the simulation "representative" of their

experiment. A generation time of twenty minutes had been provided in week 1, so Sujan is able to quickly identify that there were roughly 51 generations of growth in the tube during the 17 hour incubation. Gp B also works out how to adjust the initial populations of bacteria both at the start (in the tube) and later when they introduce the antibiotic (on the plate), to account for the sampling protocol in their experiment—they convert the numbers of bacteria present at each of those times, bearing in mind any dilutions made when sampling bacteria.

This mapping move emerges to overcome a resistance in coordinating inputs in the simulation and the experiment. The newly authored protocol sets the groundwork for exploring both the single-exposure and double-exposure conditions within the simulation.

Making sense through failure—Coordinating inputs and outputs leads to noticing system sensitivity

With a well-defined procedure for replicating experimental inputs in the simulation, Gp B moves to replicate the unexpected results they saw with the "single exposure" and "double exposure" conditions.

In carrying out simulation procedures they encounter a new resistance—they cannot reproduce the unexpected results from their experiment with the *E. coli* bacterial strains. For the single exposure condition trial, they observe that the populations trend in the expected direction (much fewer LM bacteria after they introduce the antibiotic) but the LM bacteria don't die out in the time frame that the experiment took place (i.e. within the number of generations the bacteria incubated for). For the double exposure condition, they encounter the opposite problem—the LM bacteria die out before "plating" (51 generations). They iterate each condition a few times, but the simulation trends are consistently misaligned with what they saw with the organismal model. They evaluate that they cannot replicate the experimental outcome using "representative" inputs, and

decide they want to identify what it would take to get the same results in the simulation as they did in their experiment.

They start manipulating the mutation rate of each strain, noting that this may no longer be representative of the experimental condition. First, they increase mutation rates of both strains, so mutations are more frequent for both LM and HM strains, though proportionally the same as in their earlier trials. This results in too many LM bacteria *surviving* in the double exposure condition. So, they begin a process of calibrating mutation rates until they get the desired result—and they never quite get there. They work right into the TA introducing the next activity, a poster session. While manipulating parameters, they observe that some values work once but fail on subsequent trials. They characterize the system as sensitive to a number of input parameters, and *extend* this to possibly include the organismal system—as Mary puts it in her lab report, "Repetition of our experiment using strains with slightly different mutation rates could yield very different results."

Gp B encounters resistance at the intersection of coordinating *both* inputs *and* outputs of the two modalities; this is expressed as a balancing of "representativeness" (of the simulation with respect to the experiment) and explanatory power (of the simulation to illustrate the pattern observed in the experiment). This resistance leads to them shifting their aims for how to use the simulation, from it being a representative replication of the experiment to it having explanatory power. Ultimately, they re-evaluate their own experimental results in light of the lingering uncertainties from working on the simulation.

6.9 Looking Across Cases to Refine and Expand Design Conjectures

At the start of this chapter I conjectured that a hybrid lab curriculum—coupling student control over data production both with experimentation using organisms and with simulation using computer models—can support students to exercise agency over setting research aims and making

moves to achieve those aims. I illustrated these design conjectures through two episodes of student groups navigating uncertainty in conducting their own scientific investigations in an introductory college biology lab course employing a hybrid design.

With the rest of this chapter I will look at commonalities and differences across both episodes, to refine and expand my initial design conjectures. I will end by naming an additional design consideration connected to instruction which emerged from this analysis.

6.9.1 Design implications for students exercising epistemic agency over science investigations

Flexible, authoritative data production modalities facilitate students making progress

In both episodes presented in this chapter, we saw student groups producing data using a simulation in order to make progress when stuck either producing or analyzing data produced using an experiment. This directionality—stuck in experiment so turn to simulation to make progress—is natural because the simulation affords a much more rapid means of producing (and reproducing) data than the wet-lab experiment, and has a lower material cost. The other direction—stuck in simulation so turn to experiment to make progress—also occurs within our broader data corpus. We see students proposing novel experiments to validate ideas discovered within the simulation, for example Karl's time-series sampling protocol. In later iterations of the course, we also see students leveraging experimental data from *other groups* to amplify or temper arguments made from their own investigations. In these instances, experimenting with 'real' organisms tends to afford an epistemic authority greater than that of the simulation.

In turning to either modality to produce data that helps one resolve an uncertainty in the other, we see evidence of what Pickering (1995) referred to as "free and forced moves." This dynamic involves a ceding of agency by a researcher to some external (material, disciplinary) authority in order to make progress. In the case of Gp A, for instance, part of what enabled the

simulation to validate their ideas was that the outcome of the simulation was not up to them, but was instead decided by the material behavior (in this case agent based model behavior) of the simulation—where they ended up was the result of a forced move. The way that Gp A initialized and ran the trials, and how they later interpreted the data, *were* up to them and so constitute free moves. It is this balancing of researcher discretion and material or disciplinary authority—a dance of agencies, as Pickering puts it—that drives forward scientific research. We have observed this dynamic leveraging disciplinary forced moves. In an earlier design of the lab one student encountered a resistance in how to interpret what seemed to her contradictory trends in plant growth (an inverse relationship between height and weight). This student turned to the literature to study mechanisms of plant resource allocation, and leveraged this in constructing her own explanation for why the plants grew how she observed (Hayes, 2017).

For the design of biology labs, it appears that an affordance of data production tools is the combination of their manipulability (ability to facilitate a broad scope of free moves) and material authority (ability to generate forced moves). A design consideration, then, is how such tools can be shaped by students to achieve investigative aims, while behaving in ways that can generate useful information. Additionally, it is important in designing data production tools to consider how they might enable students *to circumvent limitations* they may encounter in producing and interpreting data in other available modalities, which may become sticking points for their investigations.

Coordinating modality outputs and inputs facilitates students authoring research aims and moves

Looking across both episodes we see a diverse range of uncertainties that arise from coordinating experimental and simulation modalities. This heterogeneity is to be expected when students are in control over setting research aims, and makes it challenging to separate idiosyncrasies from usable

design implications. We see coordination of *outputs* and *inputs* between data production modalities as a useful design consideration, which I'll elaborate here starting with Gp B.

Gp B first encounters a resistance when the time-continuous output of the simulation diverges from the time-discrete output of the experiment, a sort of "discrepant event" (Blikstein, Fuhrmann, & Salehi, 2016). Rate and scale of measurement, then, are potential considerations in the design and coupling of data production modalities—for this unit the affordance of the simulation to provide real-time feedback, as well as feedback for longer "time-scales" (in the sense of generations of bacterial growth) reveals a gap in experimentation that might otherwise be invisible.

The next resistance Gp B encounters is in how to match the inputs of the simulation to ensure it is "representative" of the experiment. This is similar to the kind of resistance Gp A encounters, except they are concerned with how "metabolic benefit" mutations represent a lactose growth environment. In each case, the degree to which students trust that both data production modalities are aligned in representing the study system, serves as a location for encountering productive uncertainties that result in authoring new or modified research aims.

Finally, Gp B finds coordinating outputs in tension with coordinating inputs, resulting in their identifying parametric sensitivity as a consideration for the study system. It is my contention that this tension was facilitated by the selection of both organismal and computational models which resist simple explanations (Manz, 2015a). The *E. coli* study system proved complex enough to resist Gp B's simple "more antibiotic leads to fewer colonies" prediction. Similarly, the stochastic nature of the agent-based computational model produced non-linear trends in population survival, resisting simple explanations for why the simulation results didn't match the experimental results.

Regardless of whether students encountered uncertainty in coordinating inputs, outputs, or both, these mismatches provided opportunities "to see data as contingent on material and technological origins" (Hardy, Dixon, & Hsi, 2020, p. 109), and drew their attention to specific material considerations for how they were measuring the system (Ford, 2005).

Design Implication—Motivating aims and moves without over specifying solutions

> "I feel like normally you are just used to giving an easy answer and moving on from there, but (here) they try and pull a little bit more out of you so you can kind of like think through the whole process, of, how you came to that." (Nick, a first-year biology student)

While the design conjectures of this chapter center the coupling of experiment and simulation for supporting students exercising agency over investigations, here I would like to draw attention to how *responsive instruction* appeared to contribute to student navigation of uncertainty—in particular, the utility of moves by the instructor and curriculum which motivated student aims and moves without over-specifying solutions to overcoming resistances.

Structuring in opportunities to encounter and navigate uncertainty does not guarantee that students will take up this form of engagement. I have written on the importance of attending to student perception of their own agency in curricular design, and drawn the connection to student framing of lab spaces (Hayes, 2021). One pattern we observed in both Gp A and Gp B was that these groups *took up* navigating uncertainty for themselves when instructors and curriculum provided direction without over specifying solutions. In fact, both episodes start with a form of this move.

For Gp A, they start to articulate their first uncertainty when the TA, rather than simply signing off on their initial experimental design, positions them as evaluators of their own design by asking them "what do (they) expect to see?" He reinforces this orientation to self-evaluation by prompting them to "think in terms of their expected results." This move communicates to the

students that they are expected to do the intellectual work of authoring their investigations, and it provides an initial direction for doing so that we see directly reflected in the group's first move to resolve their uncertainty (Damien's hypothetical).

Recall that Gp B does not choose *when* to use the simulation—in fact, in the design week, Gp B had a bad experience using the simulation, and likely would not have opted to use it on their own (this is supported by their own criticism of the Sim at the start of the episode). They are directed by the curriculum to "model something that helps (each group) get at the question (they) asked, using the simulation." This prompt provides some direction for how to use the simulation (to get at the research question they asked in week 2). *How* they are to go about that is unspecified. This leaves room for Gp B to establish their own aim to replicate the two unexpected outcomes from their experiment within the simulation.

This pedagogical move has a dual purpose: it supports a framing of the lab as a space where students are primary contributors to the investigation, and it helps students orient themselves within that investigative space. We see this move as connected to our implementation of responsive teaching in our labs (Simon, 2022).

6.10 Concluding Remarks

There is some consensus that college biology labs should facilitate students exercising agency over setting research aims of, and making decisions about how to carry out, investigations. In this chapter I presented hybrid labs as one kind of design that might support students' exercising epistemic agency in lab science investigations, and proposed navigating uncertainty as an analytical lens to unpack how students author research aims and moves. This approach is nascent, and open to improvement; for instance, I am currently using it as a starting point to address issues of equity in small-group decision-making over the direction of investigations.

Chapter 7—Participatory Equity and Epistemic Agency in Small Group Lab Science Investigations

7.1 Abstract

My focus in this dissertation is on unpacking the role of our hybrid labs curriculum—defined by students conducting their own investigations using experimentation on organismal study systems coupled with simulation on computational study systems—in supporting student's epistemic agency—"students being positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community" (Miller et al., 2018). In this chapter I approach this through a case study exploring how the curriculum impacts intra-group dynamics to expand or restrict individual students' opportunities to contribute to knowledge building work. Through an analysis of *participatory inequity* (Shah & Lewis, 2019) in a group of three students conducting their own investigation in 2018, I identify moments in which students' opportunities to contribute to setting the aims and moves of their investigation are restricted or expanded. I then unpack how the investigative materials of the hybrid labs curriculum, in interaction with student's negotiated framing of the lab, and instructor facilitation, serve in these moments to amplify or attenuate participatory inequity. Finally, I explore how this analysis of participatory inequity informs an understanding of epistemic agency in lab science investigations.

7.2 Introduction

> "When people come together for joint work, power relations will organize that work. In learning settings, these power relations entail negotiations over learning resources. As students vie for access to learning resources, tensions will arise. These tensions will occur regardless of how equitable the collaboration appears." (Shah & Lewis, 2019, p. 446)

In joint investigations (as with the small groups in our labs), power relations between peers become relevant to individual students' opportunities to contribute to knowledge building (Wang, et al., 2023; Stroupe, 2014), as decisions about how to set the aims and moves of the investigation are negotiated amongst group members (Engle, Langer-Osuna, & McKinney de Royston, 2014; Bolger et al., 2021). Ideally, every student in a group would have as much opportunity to participate in this decision-making as is needed to support their learning, a condition known as participatory equity (Shah & Lewis, 2019; Fink, 2022). In reality, intra-group power dynamics always have the potential to restrict opportunities to participate for some students relative to others, resulting in participatory *inequity*. Researchers have identified how factors such as social status (Cohen & Lotan, 1995), affective risk (Conlin & Scherr, 2018), perception of competence (Johnson, Franke, & Turrou, 2022), and task structure (Shah & Lewis, 2019) can amplify or attenuate participatory inequity—that is, build up or break down barriers to equitable participation. Less attention has been paid to the role of curricular materials themselves in shaping the dynamics of participation in small groups (Wang, et al., 2023).

In this chapter I explore the relationship between participation and epistemic agency through a case study of one group of three students conducting their own science investigation in 2018. This group, labeled group 1, exhibits social dynamics that impact one group member's opportunities to contribute to directing the aims and moves of their investigation. In week 2 of their investigation, the focal group member's design proposal is not taken up by his peers, limiting his contributions to their experimental design. In the following week his work with a computer simulation is taken up as meaningful and significantly contributes to directing their analysis of the study system. I explicate this apparent barrier to epistemic agency through an analysis of participatory inequity (Shah & Lewis, 2019).

In order to unpack the role of the hybrid labs curriculum in facilitating these dynamics I conduct two analyses. With the first analysis I address the question "How can I characterize shifts in participatory inequity within this small group biology investigation?" (RQ1). I construct a scheme by which I evidence participatory inequity according to three components, two from the literature—access to the conversational floor (Shah & Lewis, 2019), and access to the interactional space (Engle, Langer-Osuna, & McKinney de Royston, 2014)—and one emerging from a need to describe a form of participation specific to the context of our lab science course—the ability to set the aims and moves of an investigation which I call access to the investigative conversational floor. I use this scheme to describe shifts in participatory inequity across group 1's investigation. With the second analysis I address the question "How does the hybrid labs curriculum contribute to attenuating or amplifying participatory inequity in this group's investigation?" (RQ2). I identify seven factors—three related to investigative materials, one to lab materials (worksheets), two to instructor facilitation, and one to student framing—which appear impactful in shifting inequity. Given the central role of investigative materials (biological and computational data production modalities) in our hybrid lab design, and their prevalence in impacting student inequity, I illustrate through detailed description of four impactful interactions, how investigative materials interact with instructor facilitation and student framing to amplify or attenuate participatory inequity.

Through unpacking how hybrid labs impacts opportunities for individual students to participate in authoring decisions within their group, I extend theoretical and design considerations for structuring a lab space in which all students can exercise agency over science investigations.

7.3 Theory—Epistemic Agency & Participatory Equity in Groups

Here I outline ways in which education researchers have conceptualized epistemic agency in the context of social dynamics, and use this thread of research to motivate participatory inequity (Shah

& Lewis, 2019) as an analytical construct for interrogating opportunities for individual students to exercise epistemic agency in group investigations. Then I overview how researchers in education have approached the study of participatory equity and inequity, to ground the first analysis. Lastly, I review how researchers in lab science have conceptualized the role of investigative materials in guiding student activity, to ground the second analysis.

7.3.1 Epistemic agency and power

> "We view the epistemic agency as a dynamic and multidimensional construct negotiated through interaction… "redistribution" of epistemic agency means more dynamic negotiations, such that students are increasingly involved in guiding the construction of knowledge in their classrooms." (Ko & Krist, 2019, p. 4)

Some education researchers have called attention to the social embeddedness of opportunities to contribute to knowledge building by defining epistemic agency as "the power for individuals and groups to shape the knowledge production and practices in a setting" (Stroupe, 2014). Power describes a relational imbalance that is present in any social interaction. In school settings, for example, it is common for an imbalance to exist between teachers and students; the former's contributions are privileged relative to the latter by virtue of their status (Kurth, Anderson, & Palinscar, 2002). Framed this way, the goal of supporting student agency can occur through 'redistributing' agency by challenging those power dynamics (Ko & Krist, 2019). One such strategy for mitigating this common power imbalance is by positioning students as authorities over their investigations, and so shifting agency from instructors to students (Eriksson & Lindberg, 2016; Holmes, 2020; Johnson, Franke, & Turrou, 2022; Bolger et al., 2021). However, this still does not take into account how power differentials emerge and shift *within* peer groups, and the impact that has on individual student's opportunities to contribute to knowledge building (Engle, Langer-Osuna, & McKinney de Royston, 2014).

In the context of collective construction of a shared knowledge object, epistemic agency takes on a regulative, or interpersonal, dimension (Damşa et al., 2010; Stroupe, 2014). Members of the group not only contribute ideas and actions for building knowledge, but also "develop, test, and revise" norms for how contributions are introduced, valued, and taken up (Stroupe, Caballero, & White, 2018, p. 1195). Whose ideas are privileged within a space, and how the conversational floor is defined and maintained, has an impact on what opportunities individual students have to contribute to group knowledge building (Engle, Langer-Osuna, & McKinney de Royston, 2014). Understanding how norms develop, and how power is negotiated among peer groups, can be described through analysis of *equity* in group activity.

7.3.2 Participatory (in)equity

> "We argue that attending to negotiations across moments and pathways sensitizes us to issues of power and equity as we wrestle with how to productively support students' agentive participation in science knowledge building." (Keifert et al., 2018, p. 192)

Participatory equity describes the fair distribution of *opportunities* to participate and learn among students (Shah & Lewis, 2019, p. 428; Fink, 2022, p. 9). Participatory equity is an ideal, something to strive towards in classrooms. In reality there is always the potential for powered social dynamics to restrict some students' opportunities to participate and privilege others, creating participatory *inequity* (Shah & Lewis, 2019). Higher participatory inequity means fewer opportunities for marginalized[17] students to contribute to shaping knowledge building in small (or large) group joint activity. So understanding the factors which *amplify* or *attenuate* inequity is impactful for designing learning spaces in which all students can exercise epistemic agency.

[17] Marginalization can occur at many intersecting scales of social participation and identity. Throughout my analysis in this chapter I use marginalized to refer to dynamics of participation within the group—that is, students whose contributions are being treated as marginal within the group, within a moment of activity.

Most prominent in research on what amplifies participatory inequity is the role of *relational inequity* (Shah & Lewis, 2019; Boaler, 2008). Referred to variously as social status (Cohen & Lotan, 1995), "socially negotiated authority" (Engle, Langer-Osuna, & McKinney de Royston, 2014), or cognitive authority (Stroupe, 2014), this refers to a relational imbalance where the contributions of some individuals are *de facto* valued more highly than others, much the same as the common power imbalance between teachers and students described above. Strategies to mitigate relational inequity include positioning marginalized students as competent (Johnson, Franke, & Turrou, 2022), establishing a classroom norm of valuing multiple abilities (Cohen & Lotan, 1995), and framing "who knows" scientific knowledge as public (collective) rather than private (individual) (Stroupe, 2014). Another social factor which can act as a barrier to certain kinds of participation, such as sensemaking, is affective risk. This risk can be mitigated by social-discursive strategies such as epistemic distancing (Conlin & Scherr, 2018). Cutting across all of these factors are intersectional factors of race and gender (Fink, 2022; Cohen & Lotan, 1995; Shah & Lewis, 2019).

Additionally, researchers have identified curricular features such as participant structure, task structure (Shah & Lewis, 2019), and distance learning (Fink, 2022) as impactful to both amplifying and attenuating participatory inequity, in intersection with the social factors described above. One curricular feature that has been underexplored in its impact on equity is the role of curricular materials (Wang et al., 2023).

7.3.3 Role of Investigative Materials in Facilitating and Constraining Student Participation

Central to this dissertation is unpacking the role of student control over two coupled sets of investigative materials—experiments with organismal systems & simulations with computational systems—in facilitating students' carrying out their own investigations. In Chapter 6 I emphasized

the role of material agency in *affording* students opportunities to set the aims of their experiment, and to make progress on their investigations when stuck. In prior work, researchers have identified how investigative materials can also *constrain* student agency in conducting experiments (Jordan et al., 2014). They point out how materials can cue confirmation framings of a lab (Smith, Stein, & Holmes, 2020), cuing students to focus on procedural competence rather than creativity (Jordan et al., 2014). Each of these cases focus on exploring how curricular materials directly impact student group activity, and do not factor in intra-group dynamics.

When considering how materials affect *individual* student participation within groups, researchers tend to focus on *negotiation* of whose ideas will be taken up (Bolger et al., 2021), who will get to utilize materials (Kurth, Anderson, & Palinscar, 2002), or how materials will be used (Wang, 2023). All of these cases describe a complex interplay between access to materials, access to participation, relational equity, framing of joint activity, and intersectional factors such as race and gender. Consequently, we might expect that the role of material in either affording or constraining individual student's opportunities to contribute to knowledge building will be highly contextualized by intra-group dynamics and other features of the curricular enactment (e.g. how the investigative activity is framed, or when, how, and to whom investigative materials are made available).

7.4 Data Sources and Selection

This case study centers a group of three students, pseudonyms Alaad, Jackie, and Kyle, working on their own investigation in unit 1 of our Bio 14 Lab course in 2018[18]. This group, dubbed Gp 1

[18] See Chapter 6.5 for more details on the design and implementation of the bacteria lab in 2017. In 2018 there were two salient changes from 2017: first, both the TA and LA participated in an elective professional development course run by two members of the research team (Simon, 2022); second, for the experimental design students had access to both transformed and untransformed bacteria strains (compare the design worksheet from 2018 to that from 2017).

throughout this chapter, was initially selected for analysis from amongst nine focal groups to unpack sensemaking activity prompted by Alaad's use of the computer simulations in week 3 of the unit (Parker, Wagh, & Gouvea, 2019). I chose to focus on Gp 1's activity for this analysis because I observed a difference in the way Jackie and Kyle attended to and took up Alaad's bids to contribute to the investigation in week 2 and in week 3, and I wanted to understand what about the curriculum supported these opposite dynamics.

For this study I analyzed in-class audio and video of the focal group, supplemented by student lab reports. Details on how this data was collected can be found in Chapter 4.2. This is to establish a *researcher perspective* on participatory inequity. Ideally, this would be triangulated with a *student perspective* on participatory inequity (Fink, 2022). While we do have interview data with Alaad, our interview protocol[19] was not designed to elicit student's perspectives on equity in the class, and so I limit my characterization of participatory inequity in this chapter to analysis of audio-video data.

7.4.1 Episode bounding

With this analysis I sought to characterize shifts in participatory inequity during each week of Gp 1's investigation. Consequently, I bounded the data to just the time in unit 1 where they are carrying out their own investigation. This resulted in two episodes, comprising thirty minutes of experimental design activity in week 2, and sixty minutes of data analysis and simulation activity in week 3. I transcribed all turns of talk by the three group members, as well as those by outside participants in interaction with Gp 1 (see Appendix 7.1 and Appendix 7.2 for a full transcript of both episodes).

[19] See Chapter 5.5.1 for a description of the form and function of our interview protocol.

Since the analytical focus was on *shifts* in participatory inequity, I further divided the data-set into moments based on changes in activity (for example, examining data versus working on a worksheet) and participant structure (for example, when a TA or LA joins the conversation). This resulted in seven moments for week 2, each spanning two to seven minutes, and fifteen moments for week 3, each spanning one to eighteen minutes.

7.5 Analytical Methods

7.5.1 Coding for participatory inequity

With the first analysis in this study, I aimed to address RQ1: "How can I characterize shifts in participatory inequity within this small group biology investigation?" This involved marshaling evidence for imbalances in Gp 1 members' relative opportunities to participate throughout their investigation.

Opportunity to participate is most commonly evidenced by student's access to the conversational floor (Shah & Lewis, 2019). I coded for general access to the conversational floor by measuring the distribution of talk from each of the three members of Gp 1 (Shah, Lewis, & Caires, 2014; Lewis & Shah, 2015; Deitrick, Shapiro, & Gravel, 2016). This is evidenced by counting the number of turns each student made in a moment, as well as the number of words they spoke across those turns (to capture moments where one student held the floor for a long time within a single turn).

What constitutes the conversational floor is dependent on the context of a joint endeavor (Wang et al., 2023), and as such I sought to supplement the general evidence above with evidence of access to the *investigative conversational floor*. This involved coding for student's access to authoring the investigation, as evidenced by bids to direct the group's investigative aims and moves, as well as engagement with peers' bids.

To code for authoring the investigation, I identified turns of talk in the transcript in which students introduced new bids for *actions* the group should take, or *interpretations* for constructing a joint understanding of the study system. Actions included suggestions for how to carry out their experimental design ("We could do one with like a lot of lactose and one with not a lot of lactose"), data analysis ("Put 'em on the, put 'em against the white (paper for contrast)"), or presentations ("We'll probably draw the two plates on the whiteboard and explain, why we got we got"), as well as task-oriented proposals such as soliciting information from an instructor, generating artifacts, and filling in the worksheet. Interpretations included observations of data ("these are like **ob**viously have like no pigment to them"), evaluations of data ("Oh I think we got it (the pattern we expected in relative success between a high and low mutator) though"), proposal of factors affecting patterns in data ("Maybe red picked up lethal"), and questions soliciting of any of the above ("But why would the red go extinct?"). For each moment I totaled the number of bids each student in Gp 1 made. In characterizing who made bids I prioritized who *first* made a suggestion, and did not count repetitions by the same student or another student towards bid totals.

To code for engagement with peers' bids, I identified turns of talk in the transcript in which students either accept, clarify, elaborate on, restate, or modify bids from themselves or peers. This included statements as well as questions. For each moment I totaled the number of times a bid a student made was engaged with. For example, Alaad made a bid to use "one (treatment) with a lot of lactose and one with not a lot of lactose" in their experimental design. Each time that a student (Kyle, Jackie, or Alaad himself) engaged with that design idea counted towards the total engagement with Alaad's bids for that moment of W2. Unless a bid was outright ignored it was likely to be engaged with at least once, and could be many more times than once if students

continued to reference and build off of it, so engagement with bids typically was larger than the number of bids made.

Lastly, I supplemented my quantitative characterization of access to the conversational floor with a qualitative characterization of "socially negotiated access to interactional space" (Engle, Langer-Osuna, & McKinney de Royston, 2014). This involved coding for qualitative markers of students sharing, hogging, or avoiding the conversational floor, as well as inviting or rejecting participation in directing aims and moves from their peers. Evidence in this category included verbal cues such as explicitly inviting others to contribute new ideas ("And what's your idea in mind?"), to evaluate ideas ("Does that work for you too?), or rejecting ideas ("no we're not gonna dilute the agar"); gestures which indicate inviting participation (looking towards someone after asking a question) or ignoring participation (looking away from someone during speech, while they look at and listen to you); the degree to which access to artifacts and physical space is shared/open to all group members (everyone manipulating and standing around plates) or closed to some members (TA physically positioned toward some members of the group at the exclusion of others).

These three forms of evidence—access to the conversational floor through quantitative markers of turns and words, access to the investigative conversational floor through quantitative markers of bids and engagement with bids, and access to the interactional space through qualitative markers of physical positioning, gesture, and verbal invitation or rejection to participate—were taken together to characterize each moment in the case as evidencing: *low inequity* when there was rough parity in quantitative markers between group members, and agreement from qualitative markers, *high inequity* when there was disparity in quantitative markers between group members, and agreement from qualitative markers, and *mixed inequity* when there was disagreement between

different forms of evidence. To draw attention to *shifts* in participatory inequity may have been attenuated or amplified, I consolidated adjacent moments in which participatory inequity did not change, reducing seven moments in Week 2 to four periods of activity, summarized in Table 7.1 below, and reducing fifteen moments in Week 3 to eight periods of activity, summarized in Table 7.2 below.

7.5.2 Coding for factors that amplify and attenuate participatory inequity

In the second analysis I aimed to address RQ2: "How does the hybrid labs curriculum contribute to attenuating or amplifying participatory inequity in this group's investigation?"

In my initial analysis I sought to unpack ways in which the learning context affected the dynamics of inequity. Following Shah & Lewis' (2019) approach, I made two additional passes through the data. First, I flagged interactions which seemed consequential for amplifying or attenuating inequity, yielding four interactions in W2, and seven interactions in W3 (see Table 7.3). Second, I identified factors in the curricular enactment which might have been contributing to those consequential moments, with a focus on components of the *curricular structure* and *student enactment*, as described by Shah & Lewis. I found four factors from the curricular structure that were impactful in amplifying or attenuating inequity, three related to investigative materials, and one related to worksheet and presentation artifacts; I found one impactful student enactment, a negotiated group framing of the lab activity; finally I found that a third category, *instructor facilitation*, contributed two factors necessary to describe the shifts in inequity observed in the data (see Table 7.4).

Notable from this list was the multiple, context-dependent ways that investigative materials impacted inequity across Gp 1's investigation, and how this intersected in mutually reinforcing or conflicting ways with the student enactments and instructor facilitation listed. Given this

complexity, and the overlap with the design emphasis hybrid labs puts on student control over coupled data production modalities in supporting agency (see Chapters 5 & 6), I conducted a final analysis in which I focused specifically on the role of investigative materials (from here on simply referred to as materials or material) on amplifying and attenuating participatory inequity in Gp 1's investigation. My goal in this analysis was to unpack the many ways that material can impact participation dynamics in small groups and to highlight how this plays out in interaction with student enactments and instructor facilitation.

7.6 Findings

7.6.1 Participatory inequity in week 2 and week 3

Week 2

Description of activity

The episode is preceded by a lengthy (~5 min) introduction of the experimental design task by the TA. During this overview each student is provided with a worksheet, and each group has a member grab a whiteboard to aid in diagramming their experimental designs.

(Moment 1) Gp 1 starts with a short (~4 min) but very active discussion in which they strive to develop their research goals & identify relevant experimental materials. Alaad proposes a research aim to test how mutation rate is selected for by resource scarcity or abundance; he also moves to test this with environments that contain "a lot of lactose" and "not a lot of lactose." This idea prompts two design proposals: Kyle suggests competing the (HM & LM) strains, while Jackie suggests growing them separately on plates with lactose and on plates with just agar, to see if the HM strain grows better than the LM strain in the lactose environment. Jackie and Kyle debate this,

while Alaad draws their design on the white board. Ultimately, Jackie's idea is taken up, and she gets up to check in with the TA.

(Moment 2) The TA comes over to the whole group to discuss their experimental design idea, leaning in to face all of them. After clarifying some of Gp 1's questions about the bacterial strains, Alaad shows the TA the whiteboard design he's drawn and asks "But do you think we could actually test this?" The TA has him clarify the design, and then draws their attention to which she sees as a potential confusion the students in Gp 1 might have about how materials are used to carry out an experiment—the difference between the growth medium (a nutrient broth in a tube) and the indicator used for measuring population size (a plate). After emphasizing this distinction, she prompts them to re-word their research question. Jackie takes this up directly, proposing growing the HM and LM strains separately in LB+Lac broth tubes (rather than on lactose rich plates). Alaad attempts to revisit the original research goal of testing resource scarcity, asking if "agar would be present in the broth" and following up by proposing that they "dilute the agar so that there would be less-." He is cut off by Jackie and Kyle both rejecting this idea of diluting agar, which they were just told by the TA is part of the indicator plates, not the growth medium.

(Moment 3) Alaad rolls his eyes, turns away, and puts on his beanie, while Jackie and Kyle pull out their worksheets. For the next 6 minutes they use the worksheet as a guide for articulating and refining their research question, experimental design, and hypothesis. They land on growing each strain separately in LB+Lac, then plating them each on MacConkey media (which indicate for lactose digestion) and agar as a control (setting a baseline for growth). During this discussion Alaad writes on the whiteboard, occasionally looking over to them. He talks just once, to check in with Jackie and Kyle that what he's drawn is what they expect to see.

(Moment 4) Satisfied, Gp 1 raises their hands to confirm their new design with the TA. As she is busy with another group, Jackie leaves to take care of something else for about four minutes. After an initial long pause, Kyle looks over to the whiteboard and asks Alaad if their research question is different from the one he initially wrote down. They discuss what the new research question is, and confirm that their design is represented on the whiteboard. When Jackie returns Kyle fills her in and they once more attempt to draw the attention of the TA.

(Moment 5) While awaiting the TA, Jackie and Kyle begin to discuss the logistics of carrying out their experiment, most notably when they can come into the lab to plate the bacteria. Jackie and Kyle both express difficulty with specific dates or times, before landing on a tentative time that works for both of them. At this point Kyle checks in with Alaad to see if that time would work for him too. As he's answering, Jackie suggests that not everyone has to be present. Kyle pushes back on this, insisting that more than one person ought to be present to make sure they're doing it right.

(Moment 6) At this time the LA walks over to check in with them, standing between Jackie and Kyle. Kyle summarizes their experimental design, ending by raising an uncertainty that "we're just not sure about diluting stuff and like setting it all up." The discussion, exclusively between Kyle, Jackie, and the LA, turns to what dilutions would be appropriate, as well as how long the bacteria will grow before they need to plate them. Gp 1 gets some clarity on these logistical considerations, and are told to check with the TA before coming to the LA for materials.

(Moment 7) Shortly after the TA walks over to check in with Gp 1, also positioning herself between Jackie and Kyle. This time Jackie moves to summarize their experimental design. The TA methodically steps through the process with them, confirming materials, dilutions, steps and timing of carrying out the protocol, all the while offering best practice suggestions for optimizing

their chance of success at measuring useful numbers of bacterial colonies. After confirming all the logistics, Gp 1 spends the rest of their lab time executing the first step in their protocol by diluting equal volumes of HM and LM bacteria separately into equal volumes of LB+Lac media.

Characterization of participatory inequity

Across moments 1 & 2 I have characterized participatory inequity in the investigation as low. All students demonstrated at least some access to the conversational floor, though Alaad spoke only about half as much as Kyle or Jackie. Alaad, Jackie, and Kyle made similar numbers of bids to direct the aims and moves of their investigations, and their ideas received similar amounts of engagement (see Table 7.1). There is evidence of keeping an inclusive, open conversational space through posture. For example, Kyle, who is situated in the middle of the three, regularly turns to face both Alaad and Jackie in discussing their ideas; similarly, the TA situates herself between all three members of Gp 1, and speaks to each of them (see Figure 7.1).

Moments	1-2	3	4	5-7
Par. Inequity	Low	High	Mixed	High
A # turns	12	1	4	1
J # turns	25	23	2	65
K # turns	28	21	8	53
A # Wds	125	15	35	3
J # Wds	332	470	7	855
K # Wds	245	180	132	576
A #bids	5	0	0	0
J #bids	3	3	0	4
K #bids	4	2	2	2
A Eng	10	1	0	0
J Eng	8	9	0	14
K Eng	4	0	4	16

Table 7.1 *Evidence for participatory inequity across week 2.*

In moment 3 participatory inequity in the investigation shifts to high; specifically, there appears to be less opportunity for Alaad to participate. Alaad is nearly absent from the conversational floor, speaking just once out of 45 turns, to confirm that what he's drawn on the whiteboard is aligned with what Jackie and Kyle are talking about. Correspondingly Jackie and Kyle each make a few bids to direct the aims and moves of their investigation, while Alaad makes none. Alaad also does not participate in filling out the worksheet along with Jackie and Kyle. At the start of the moment Alaad appears to physically withdraw after his bid to dilute agar is rejected, though he does resume participation as the one writing their experimental design on the whiteboard, and regularly glances over at Jackie and Kyle as they discuss their design.

After Jackie leaves, the participation structure changes. I have characterized participatory inequity in moment 4 as mixed. There is some evidence for access to the conversational floor between Kyle and Alaad based on their number of turns of talk, Kyle's opening the space for Alaad to contribute to restating their research question, and their talk centering on the whiteboard, an acknowledgement of Alaad's participation in synthesizing their design for presentation. On the flip side, the conversation appears largely directed by Kyle, who makes all the new bids to direct their investigation, and who also ends the conversation when Jackie returns.

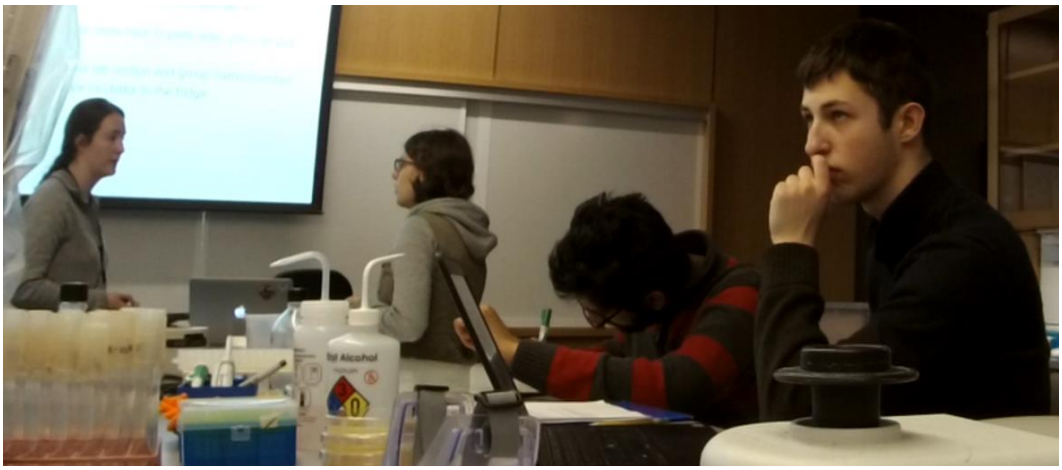


Figure 7.1 *Postural evidence of open participation. (Top) Jackie approaches TA at front of class to ask a question* on behalf of *the group. (Bottom) TA leans in to be near the whole group and addresses each member.*

Finally, I have characterized moments 5-7 as demonstrating high participatory inequity. The conversational floor is dominated by Jackie and Kyle, with Alaad saying just three words across fifteen minutes of dialogue—those three words in direct response to a question from Kyle, and interrupted by Jackie. Correspondingly Alaad contributes no bids to direct the investigation, and there is no engagement with any of his prior bids, while both Kyle and Jackie introduce a few bids and there is significant engagement with their bids. In moment 5, the conversation largely centers on difficulty in determining when to carry out their experimental protocol, and Alaad is conspicuously not included in this. In moments 6 and 7 both lab instructors position themselves closer to Jackie and Kyle, and Alaad can be seen at times to physically move his chair to be able to look at the instructor around Kyle (see Figure 7.2).

Figure 7.2 *Postural evidence of inequitable participation. TA is positioned closer to Jackie and Kyle. Alaad (left) slides his chair back to clearly see the TA as she talks.*

In summary, the evidence from week two points to a shift from an initial discussion in which all students in Gp 1 had opportunities to participate in directing their investigation, to an extended period of time in which one student, Alaad, was less able to participate than were his peers. The shift occurs around a moment where Jackie and Kyle reject a bid Alaad makes to modify the group's experimental design, and is reinforced throughout the episode, most notably by an apparent lack of access to the conversational floor (Jackie and Kyle appears to be talking exclusively with one another, and make few bids to include Alaad; similarly the TA and LA physically position themselves as talking with Jackie and Kyle but not Alaad). Later I will unpack how elements of the curricular structure worked with student and instructor enactments to amplify inequity in this episode. Before that, I will next detail a very different unfolding of participatory inequity that occurred in the following week of the same investigation.

Week 3

Description of activity

(Moment 1) Gp 1 starts week 3 by finding and unpacking the indicator plates from their experiment. Initial excitement at seeing results which seem to corroborate their experimental hypothesis turns to debate as Jackie makes a bid for them to clarify which colonies on the MacConkey media are digesting lactose. Jackie and Alaad each put forward a few ideas for how to interpret evidence of lactose digestion, before Kyle proposes that they ask the TA for help. While they wait for the TA, Kyle has them turn to a NetLogo computer simulation that the instructor has prompted them to use to help make sense of their experimental data.

(Moment 2) Alaad pulls up the computer model, and immediately makes a bid to replicate their experimental design on the simulation. He opens the space to his group mates as to how they might achieve that, physically rotating the computer to face them. Kyle takes over on the computer, with Jackie providing suggestions for how they could manipulate the parameters of the simulation to best model their experiment.

(Moment 3) With that set, Alaad takes back control of the computer, while Jackie and Kyle take pictures of their plates. As they're working on this they discuss frustration with the length of lab reports in this and other lab courses. Kyle invites Alaad to take pictures of the plates too.

(Moment 4) Finally, the TA comes over to check in on Gp 1. Kyle articulates their confusion in telling “like if they actually have lactose or not.” All three group members and the TA lean over the plates as Jackie explains some of the ideas that have come up. During this discussion, two ideas emerge. Jackie and Kyle’s initial impression is a very strict criterion for interpreting lactose digesting colonies based on the clear presence of a red dot, that would only include a couple colonies of HM as digesting lactose. Alaad introduces a different criterion, based

on more subtle differences in color between the colonies. Twice during this conversation the TA explicitly holds both ideas as valid in the space. The second time Jackie attends more closely to Alaad's suggestion, and begins to find evidence in support of it; holding the plate up to the ceiling lights, she invites others to see that there are in fact small, difficult to discern dots of red in the colonies Alaad has identified as lactose digesting. The TA builds off this to invite Kyle back into the collective construction of an interpretive criterion, then leaves to check on another group.

(Moment 5) Alaad turns back to the computer, and moves to interpret the output of the simulation as also supporting their hypothesis. Kyle asks for clarification, which Alaad provides, then affirms Alaad's interpretation. Kyle and Jackie take new pictures of the plates to capture this new, difficult to spot evidence of lactose digestion.

(Moment 6) Kyle and Jackie turn to filling in the worksheet, while Alaad continues to use the computer simulation. At one point Alaad joins in writing on the worksheet, though he does not join their conversation about it. He then turns to the TA as she's walking by and has a short side conversation (inaudible on the audio recorder) with her about the simulation while the other two continue on the worksheet.

(Moment 7) As they fill in worksheet items Kyle and Jackie start a short (~2min) discussion about lab report length, inviting Alaad into this conversation, before turning back to focusing on the worksheet.

(Moment 8) Jackie and Kyle come upon prompts about the simulation in this worksheet, and they turn to ask Alaad what he's been working on. Alaad notes that he's recording a trial of the simulation to use as an artifact, and affirms that the simulation output is corroborating their expectations. Jackie and Kyle then read out a few worksheet questions pertaining to simulation patterns, which prompts a short discussion about the parameter settings in the computer model.

(Moment 9) During this conversation, the TA displays the lab report prompt on a projector at the front of the class. Jackie and Kyle start to discuss what they'll include in their lab reports to meet the required length. During this conversation, Alaad is focused on the computer. Kyle shifts the discussion to group presentations, just as the LA walks over.

(Moment 10) The LA positions herself between Jackie and Kyle, and checks in about their experimental results. She then encourages them to work on their presentations, directing them to grab some whiteboards. Jackie moves to depicting their results on a whiteboard. Kyle bounces back and forth between discussing what gets put on the whiteboard with Jackie, and talking with Alaad who is sharing the recording from the simulation, which takes a considerable time.

(Moment 11) Recording shared, Alaad returns to the simulation to find that the pattern has changed—now the LM strain is outcompeting the HM strain, contrary to their expectations. He articulates this to the group, who are surprised. Alaad and Kyle affirm that the recording Alaad shared illustrates their hypothesis, and seem relieved to at least have the corroboration. Then Kyle introduces the aim of understanding "How did this happen?" They discuss briefly, opting to flag down the TA to get her opinion.

(Moment 12) While they wait for the TA, the conversation shifts to how they did on an exam, and how that compares to exams from other courses.

(Moment 13) The TA comes over, and Alaad explains why they're confused about the pattern they're seeing on the simulation. Kyle and Jackie participate as support in this explanation. The TA's first response is to point out a detail for interpreting the computer model, affirming that the HM strain is extinct. Alaad asks bluntly "But why would it go extinct?", which the TA reflects back to all group members. As they propose ideas the TA picks up and amplifies one suggestion by Kyle—that lethal mutations are responsible. Alaad initially rebuts this idea, and the

conversation shifts to another suggestion by Jackie, but after some time the TA brings it back into the space, saying “I don't want to discount Kyle's idea.” During this discussion the TA suggests running the simulation again, and Alaad moves to get a second computer so they can run simultaneous trials, which the TA is able to do.

(Moment 14) For about twenty minutes Gp 1 uses the simulation to see if they can reproduce and explain the unexpected pattern. First, they consider Kyle’s suggestion of lethal mutations. When the TA returns with a second computer they move to run two replicates, one with the exact same settings, and one with a lower lethal mutation frequency, a decision co-authored by all three students. During these simulation trials Alaad and Kyle propose many ideas for what’s going on, and identify some further discrepancies in the new outcome—most notably that some trails appear to have the HM go extinct, while others appear to have the LM go extinct! During this activity Jackie occasionally chimes in, but participates much less than the other two.

(Moment 15) Finally, Kyle proposes that their table begin group presentations. Jackie holds up their whiteboard, while Alaad turns the computer to face the other groups at their table. Jackie does nearly all the talking for the presentation, synthesizing a wide array of ideas from all group members. At one point she looks to Alaad to confirm a detail about the simulation, which he elaborates on briefly before Jackie takes back over to outline their working explanation.

Characterization of participatory inequity

Moments	1-3	4-5	6-7	8	9-10	11-13	14	15
Par. Inequity	Mixed	Low	Mixed	Low	Mixed	Low	Mixed	High
A # turns	8	12	4	8	5	28	55	3
J # turns	37	38	28	7	30	24	28	10
K # turns	41	22	30	10	24	21	60	10
A # Wds	41	107	58	64	33	261	467	25
J # Wds	418	412	339	59	281	179	225	406
K # Wds	336	166	312	112	186	170	397	42
A #bids	3	3	0	1	0	4	7	1
J #bids	8	4	0	0	3	3	4	3
K #bids	8	1	3	1	2	3	3	0
A Eng	8	14	1	3	1	25	31	5
J Eng	17	13	0	3	1	6	3	6
K Eng	15	5	9	3	4	19	17	2

Table 7.2 *Evidence for participatory inequity across week 3.*

Moments 1-3 I have characterized as exhibiting mixed evidence of participatory inequity. Jackie and Kyle take up significantly more of the conversational floor than Alaad, and make more bids to direct their investigation than he does. However, there is more equal engagement with everyone's ideas. Students appear to have equal access to looking at and manipulating the plates (see Figure 7.3), and in sharing their ideas about how to interpret lactose digestion they invite one another to notice features of the materials. Most of their bids build off of ideas from their group mates.

Figure 7.3 *All members of Gp 1 share access to materials (plates).*

When the TA arrives in moment 4 participatory inequity appears to decrease. Access to the conversational floor appears more equal, though Jackie still speaks more than either Alaad or Kyle. During this period Alaad and Jackie produce more bids than Kyle, and there is more engagement with their bids. As with moment 1, students appear to have equal access to the plates, and build their ideas off one another. Most notably, during moment 4 Alaad, whose participation in moments 1-3 was more marginalized, expresses disagreement about how to interpret the plates, and introduces his own idea into the space, suggesting the space is open for any participant to contribute to the interpretation of their data.

In moments 6-7 the quantitative evidence suggests unequal access to the conversational floor, with Jackie and Kyle doing nearly all the talking for this period. Furthermore all new bids to direct the investigation come from Kyle, and correspondingly nearly all engagement with bids is related to those Kyle has shared (the only exception being when Alaad briefly checks with this group that the simulation results confirm their expectation). The qualitative evidence complicates

an interpretation of high participatory inequity in this period, which is why I have opted to characterize inequity as mixed. The ambiguity comes from Alaad participating in a separate activity from the other two members of the group. Notably, while Jackie & Kyle engage in their conversation, Alaad has a side conversation with the TA (see Figure 7.4), which is not captured by the audio or included in the transcript (and so not counted towards the quantitative data about the conversational floor). Furthermore, at multiple times group members invite their peers into whatever activity they're working on: Kyle invites Alaad into their conversation about lab reports, and Alaad invites Kyle and Jackie to see his work on the simulation. In short, there is misalignment between the quantitative and qualitative evidence for participatory inequity in this period.

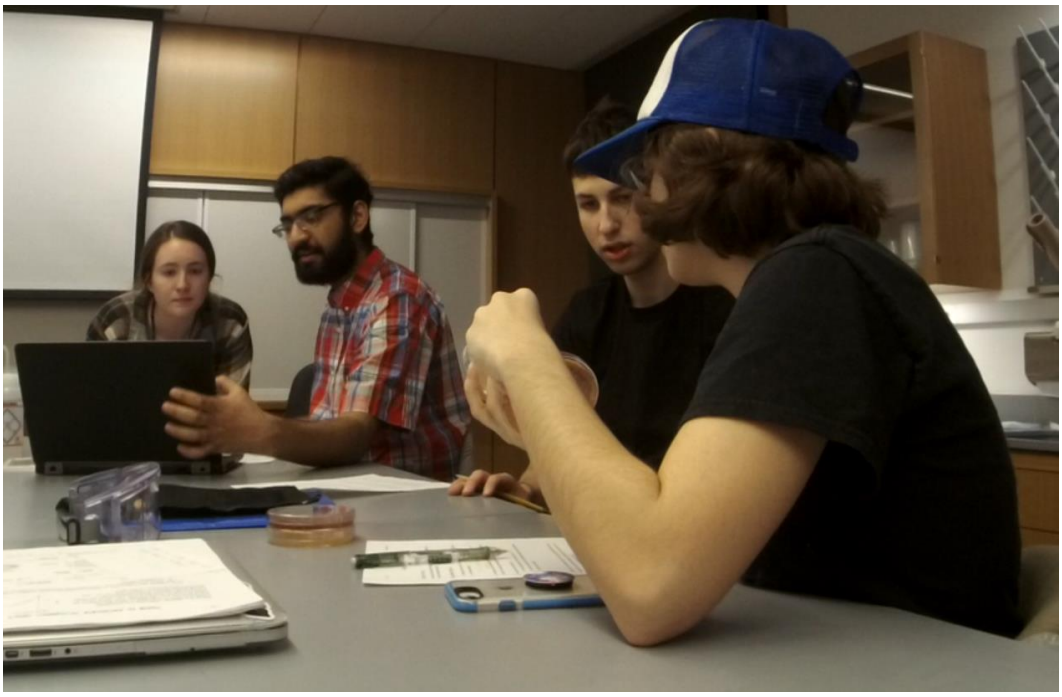


Figure 7.4 *Evidence of Alaad's participation. Alaad speaks with TA about computer simulation while Kyle and Jackie discuss plates and worksheet.*

In moment 8, as Alaad's simulation activity comes together with Kyle and Jackie's worksheet activity, the evidence for participatory inequity is low. There is nearly equal sharing of the conversational floor, bids to direct the investigation, and engagement with each members' bids.

As Jackie and Kyle shift their attention to the lab report and presentation, the evidence suggests a shift to higher participatory inequity, at least with regard to the in-the-moment directing of the investigation captured in this data. Jackie and Kyle take up more of the conversational floor than Alaad, and contribute many bids to direct the investigation while Alaad contributes none. Furthermore, in their conversation with the LA, she is once more positioned between Jackie and Kyle, and talking just with them, to the exclusion of Alaad. Once more, the qualitative evidence complicates an interpretation of high participatory inequity. Alaad remains in control of and working on the simulation, which is a separate form of participation; unlike in week 2, there is no evidence that Alaad is trying to participate in the groups' conversation with the LA. During this period Alaad shares a recording of the simulation as an artifact they can use for their lab reports.

Moments 11-13 show evidence of low participatory inequity, centered on making sense of the unexpected simulation pattern Alaad discovers at the start of moment 11. Students share nearly equal space in the conversational floor, and propose similar numbers of bids to direct their interpretation of the data, though Jackie's bids receive far less engagement than do Alaad's and Kyle's. In the video we see evidence of physical sharing of space, with Alaad turning the computer screen to face his peers, and Jackie and Kyle moving over from the whiteboard to crowd around the computer (see Figure 7.5). Along with shared physical space there is evidence of shared ideational space, with students building off of each other's ideas. Similar to moment 4, the TA holds and amplifies contributions from a member of the group who was less central to the simulation activity (Kyle), and there is evidence of expressing disagreement about how to interpret data and debating ideas.

Figure 7.5 *Gp 1 members crowd around the computer to discuss an unexpected pattern in the simulation data. TA amplifies an idea from Kyle.*

Moment 14 initially continues the trend of low participatory inequity, with all group members contributing bids for how to manipulate replication trials on the simulation. As the activity goes on, however, evidence supports an interpretation of mixed participatory inequity, with Jackie sharing less of the conversational floor than her peers, and there being significantly less engagement with Jackie's bids than with Alaad's or Kyle's. This shift is corroborated by video evidence, in which Jackie moves physically away from the computer, back to the whiteboard. Even though she talks less than her peers, Jackie regularly looks over to the computer and occasionally makes remarks that indicate she is following along with their activity.

In moment 15 the groups' activity shifts to presenting their data, and we see a corresponding shift to high participatory inequity. Jackie takes up a role as presenter, and dominates the conversational floor. Her presentation does synthesize contributions from both of her peers, and at one point she solicits additional information from Alaad. However, she also

frequently takes back the reins of the conversation, interrupting both Alaad and Kyle multiple times.

In summary, the evidence from week three points to a much more dynamic shifting of participatory inequity. Initial activity interpreting their experimental data shows a decrease in participatory inequity when the TA joins their conversation. After this the group bifurcates their activity, with Alaad taking control of a computer simulation, while Jackie and Kyle collaborate on filling in a worksheet. During this time evidence for participatory inequity vacillates between mixed and low, in part due to difficulty in characterizing "opportunities to participate, and participation itself" when the group is working on two activities in parallel. As a new uncertainty emerges in the simulation, the group converges on a single activity, and evidence suggests low participatory inequity, particularly when the TA joins the conversation. However, extended work on the simulation results in lower participation from one group member. Finally, when Gp 1 presents their data one student takes over the conversational floor entirely, indicating a shift to high participatory inequity.

7.6.2 How curricular enactment amplifies and attenuates participatory inequity

After characterizing participatory inequity in weeks 2 and 3 of Gp 1's activity, I looked across weeks to identify elements of the curricular enactment which contributed to amplifying or attenuating participatory inequity in their investigation. As noted in the methods, I first identified four interactions from W2 and seven interactions from W3 which seemed impactful for shifting inequity (Table 7.3). From these interactions I identified seven ways in which the curricular enactment contributed to these shifts, which I grouped under the categories of *curricular structure (4), instructor facilitation (2),* and *student framing (1)* (Table 7.4).

Week	Moment	Impact on Inequity	Description
2	2	Amplifying	Alaad's design idea rejected
2	4	Attenuating	Participation structure changes when Jackie leaves
2	6	Amplifying	LA positions self between Jackie and Kyle
2	7	Amplifying	TA positions self between Jackie and Kyle
3	4	Attenuating	TA invites ideas from all students, including previously marginalized student (Alaad)
3	6	Amplifying	Worksheet amplifies participation of Jackie and Kyle disproportionately to Alaad
3	8	Attenuating	Worksheet directs Jackie & Kyle to consider the simulation, amplifying Alaad's work
3	9	Amplifying	Emphasis on lab reports and later on whiteboard for presentation excludes Alaad from participating
3	11	Attenuating	Unexpected phenomenon on simulation gives a focus for everyone to participate in explaining
3	13	Attenuating	TA endorsement of unexpected phenomenon, and opening up space for non-central members (Jackie & Kyle) to provide explanations, and amplifying non-central member's (Kyle's) idea
3	15	Amplifying	Presentation task privileges fewer voices and provides opportunity for one student (Jackie) to dominate discourse

Table 7.3 *Interactions identified as impactful for shifts in inequity.*

In this section I unpack the role of materials, interacting with instructor facilitation and student framing, in amplifying and attenuating participatory inequity across the investigation. I found that materials had an amplifying effect on participatory inequity in week 2, but had an attenuating effect on participatory inequity in week 3. In both cases this effect was reinforced by instructor facilitation, and in week 2 it also reinforced by student framing, while in week 3 it conflicted with student framing. I will illustrate these dynamics through a detailed analysis of four interactions from the lab, two showcasing how materials amplify inequity and two showcasing

how materials attenuate inequity. My intention in presenting the analysis in this way is to point out how materials do not have a monotonic impact on inequity, and to illustrate how their impact shifts dynamically in interaction with student and instructor enactments in lab.

Category	Description
Curricular structure	Attention to material types & protocol logistics reduces space for discussing conceptual ideas
Curricular structure	Material (plates and simulation) offers a visual basis for introducing ideas into the space, and for defending them
Curricular structure	Material resists expectations (simulation) and invites opportunity for engagement from group members and instructors.
Curricular structure	Attention to worksheet and other presentation materials focus student attention and activity towards task-production, reducing opportunity for certain types of participation
Instructor facilitation	TA & LA posture in space positions students as included or excluded
Instructor facilitation	TA moves to invite and amplify ideas from marginalized (within the context of the activity) students
Student framing	Task production and confirmatory framings constrain valued forms of participation

Table 7.4 *Curricular factors that contributed to shifts in inequity.*

Materials amplify inequity

A feature of designing a wet-lab experiment in biology is in the construction and execution of a protocol— typically manipulating and measuring response in some focal organism (as is the case with the *E. coli* lab)—to "get at" the research question driving the investigation. *That* students are defining methods for their own experiments is, for us, a central component of their exercising epistemic agency in our lab. For Gp 1, I found that a focus on material logistics for setting up and carrying out a protocol had an amplifying effect on participatory inequity in week 2. Here I'll present two instances illustrating this effect, and in each will explore how this materials focus intersects with student framing and instructor facilitation.

Interaction 1—Rejecting Alaad's design proposal

The interaction where we see the most prominent shift in participatory inequity across the whole case occurs between moments 2 and 3 in week 2. Prior to this interaction participatory inequity is low, and after it is high for the remainder of the episode, with Alaad specifically taking less opportunity to participate in directing their experimental design. This shift appears initially prompted by Jackie and Kyle rejecting a proposal Alaad makes for how to use the materials in their experimental design.

Line	Speaker	Turn
64	J	Growth on- we were going to put them on, two- each strain on a regular agar, plate. So, just normal environment. And then we were going to put each strain on lactose and see, if the higher mutating one did better on the lactose than the lower mutating one. Because it had a resource it could tap into and potentially get a mutation that allows it to use it.
65	TA	So keep in mind that we're focusing on the fact that mutations happen in the tube and then when you plate them it's just a kind of way to look at what colonies are already in the tube. So how could you ask the same question, knowing that? And if you look on there you've got different types of treatments that you can include in your tube. You don't just have to grow them in LB- which is the sort of the growth medium. You can grow them in supplemented LB. So take a look at that, and see if that makes sense.
66	K	You can grow them with uh, lactose. Yeah.
67	J	Yeah, you can grow them in LB plus lactose and, see, if, that, would, yeah.
68	A	So the agar would be uh present in the broth, right?
69	K	Yeah.
70	J	What?
71	K	Wait.
72	A	So, is it possible that we dilute the agar?
73	J	No.
74	A	/Like so there's less.
75	K	/No we're not gonna dilute the agar.

Alaad's bid centers on how they could manipulate the available wet-lab materials to create growth environments for their bacteria with varying resource scarcity, by diluting the nutrients to different degrees between tubes. This addresses the group's initial research aim of seeing which of the HM and LM bacteria strains does better when resources are sparse or when resources are plentiful (W2, Line 7). Potentially impactful is that Alaad's proposal contains a slight error—the growth medium in the tube is an LB broth, while agar is the base medium of the indicator plate. The instructor had just highlighted that for their experiments growth will happen in the tube, with the LB, in response to Jackie's description of growing them on Agar, to make sure they knew how to use materials correctly when setting up their protocol. In this context of this correction, the *spirit* of Alaad's bid appears superseded by its inaccuracy—Jackie and Kyle dismiss the idea potentially because they hear "agar" immediately after being told that the relevant experimental materials are the tube with the LB broth, not the plates with the agar.

This barrier to taking up Alaad's bid seems to intersect a negotiated group norm to "choose something that's not a pain to do" (W2, Line 4). This negotiated norm is a component of what I refer to as a *task production* framing of activity in the lab—the organizing focus of their effort is directed towards completing the task at hand. Evidence for the centering of this framing at the instant Alaad's design proposal is rejected is that Jackie and Kyle both direct their attention towards their worksheets. The worksheet guides the broad activity of experimental design with specific questions about how and why students are conducting their specific experiment (see Appendix 7.3). Given how Jackie and Kyle specifically use the worksheet in both weeks, I see them taking up answering these questions as completing tasks towards finishing their required lab activity.

The instructors' move to draw attention to the specific differences in lab materials appears to have reinforced, for Jackie and Kyle, this task production framing, and with it the norm of choosing something simple for their design. This served to amplify inequity by constraining whether and how Alaad's ideas were considered by his group mates, and once they were rejected, the degree to which Alaad saw himself as able to participate and be heard within his group.

Interaction 2—Checking off task items with instructors

While the interaction described in the prior section can account for an *initial* shift in Alaad's participation in Gp 1's investigative decision-making, an attention to material logistics also appears to continually reinforce a task production framing, and by extension participatory inequity, a dynamic exacerbated by how the instructors facilitate the group's activity for the remainder of the episode. Moments 5-7 of week 2 are focused almost exclusively on logistics, particularly when to carry out plating bacteria, and which dilutions to use. Both of these considerations directly address questions provided on the worksheet, indicating a task production framing of the lab. In moments 6 and 7 first the LA and then the TA facilitate discussion about these logistics, and in both instances they position themselves *physically closer* to Kyle and Jackie than to Alaad, further exacerbating inequity by implicitly privileging their participation over that of Alaad.

Both instructors appear focused on helping Gp 1 (and all the groups) get to a place where they could carry out the first step of their protocol by the end of lab time that week, and in doing so reinforcing the task production framing of the lab. This is evidenced by both instructors attending primarily to the logistics of materials, and by the degree to which their responses have a checklist feel to them—"what kind of strains are you using?" "have you thought about your dilutions?" When the instructors approach Gp 1, they position themselves near the group members

who are actively discussing the design, which serves to amplify inequity by further excluding marginalized members from participation.

Materials attenuate inequity

While attention to material logistics in carrying out a protocol showed evidence of amplifying inequity during Gp1's experimental design work in week 2, I saw two ways in which material *attenuated* inequity during their data analysis work in week 3—by providing a visual grounds for introducing and defending competing ideas about the study system, and by destabilizing confirmatory framings of lab through resisting student expectations. Reinforcing this I found evidence of instructors leveraging these material affordances to further attenuate inequity, through inviting and strengthening contributions from marginalized group members. Here I'll illustrate these dynamics through two interactions from week 3.

Interaction 3—Discussing interpretations of lactose digestion on their plates

At the start of week 3 the evidence for participatory inequity is mixed as the three Gp 1 members discuss the results of their experimental design, with Kyle and Jackie generally taking up more space in the conversational floor. After the TA joins the conversation, participatory inequity appears to decrease, as space is created for Alaad to fully participate with his peers. This is most evident halfway through moment 4, when they are all discussing evidence for which colonies in their experimental treatment are digesting lactose.

Line	Speaker	Turn
152	K	I think those are lactose digesting and those are not.
153	J	Yeah. I think there's a couple in here because / there's like a couple-
154	TA	/You think all of these are, //or these two.
155	K	//No I think that- those two.
156	TA	Okay.
157	J	It's kind of strange because-

158	TA	Wait. Alaad, what do you think?
159	A	I thought that almost all of these are digesting lactose. Like that's what I thought.
160	TA	So yeah, you guys-
161	A	/These are like *ob*viously like that, these are //like obviously have like no pigment to them.
162	J	/Because there's a dis-
163	K	//I can't see any discernable difference between that and that.
164	J	There's a di- a lot of these aren't digesting *much* lactose it doesn't look. But there's a distinct difference between the ones with little red spots in the middle. Almost like zits or something weird like that. /And there's just a couple in here.
165	A	/I mean if it was just- if it was just the background then we would see almost the same thing over here, wouldn't we?
166	J	And there's just a couple in here that are different //from the rest of them.
167	TA	//That's true a lot of these have dots in them.
168	J	And /like only //like one- two three four five, six
169	A	/So that's- that's-
170	TA	//Do you see that Kyle?
171	K	Is that 938?
172	TA	This is 938, yeah. So like, if you look like that (holds plate up to light).
173	K	Oh yeah you're right.

Initially Kyle and Jackie have settled on an idea for characterizing lactose digestion, which only counts two colonies on one of the plates they are all looking at as digesting lactose. At line 158 the TA invites Alaad to share his interpretation, which differs pretty substantially from what has been suggested, characterizing "almost all of" the colonies on one plate as digesting lactose. To support his bid, he references an "**ob**vious" difference between the colonies he claims are digesting lactose and other colonies that everyone agrees are not (see W3, Lines 24-25). While Kyle objects that he doesn't see the difference, Jackie takes this up and begins to articulate another piece of evidence that supports Alaad's interpretation, noting "little red spots in the middle. Almost

like zits". The TA builds off this idea, and suggests after that they might hold the plates up to the light to better see.

In this moment the lab materials (in this case the plates) offered a visible basis for Alaad, who was previously marginalized relative to his peers, to raise and maintain his idea in the conversational floor—he could appeal to a feature of the materials that they could all at least inspect, if not necessarily agree on how to interpret. This material affordance was leveraged by the instructor, who used the discussion over materials to invite ideas from a marginalized participant (Alaad), and who then specifically cited and bolstered visual evidence as a way for members of Gp 1 to strengthen and evaluate their ideas. Taken together this material affordance, reinforced by TA moves to invite and maintain contributions from marginalized group members, served to attenuate participatory inequity.

Interaction 4—Destabilizing task production framing through material resistance

Later in this same week the students in Gp 1 enter a period of split activity—Alaad working on the simulation, Kyle and Jackie on a worksheet—in which evidence for participatory inequity is mixed. After initially using the simulation to confirm their experimental hypotheses, Alaad spends some time working on sharing a recording of this trial with his peers as an artifact. All three group members' activity indicates a confirmatory framing of the lab—they direct their activity towards demonstrating the correctness of their experimental hypothesis, both through presentation of experimental data and through replication of that hypothesis using the simulation.

When Alaad returns, at the start of moment 11, he discovers that the simulation output now contradicts their expectations. Kyle and Alaad's initial response is to affirm to themselves that they saved evidence of their earlier simulation pattern which corroborated their experimental hypothesis. Regardless of that earlier pattern, however, the current trend is visible to all, and Alaad

flags down the TA to get her opinion, while Kyle opens up the question to the group of "How did this happen?" (W3, Line 373). After the TA arrives, we see the strongest evidence of participation from all members, as she reflects Alaad's question "But why would it (the HM strain) go extinct?" back to the other members of Gp 1 "Umm... so, what do you guys think do you have any hypotheses?" (W3, Lines 407-408). In what follows the students share many ideas over each other, and the TA takes a moment to amplify a contribution by Kyle, whose participation in the simulation to this point has been marginal, relative to Alaad's. In a mirror to the earlier moment with the plates, Alaad contests Kyle's interpretation, and just as before the TA holds this contribution from a marginal participant in the space and encourages them to look for evidence in the simulation to support their ideas, including suggesting they "run it again" to see if the pattern is consistent.

The simulation output *resists* Gp 1's understanding of the study system, in a way that is immediately visible to everyone. This contradicts their confirmatory framing of the lab, and they are forced to resolve this contradiction. Their initial response is to make sure that they *could* ignore the contradiction if needed, but then they decide to instead address the contradiction, which makes space for introducing new ideas to make sense of the unexpected simulation phenomenon. The TA leverages this material affordance to invite all members of Gp 1 to participate in this space, and amplifies the contributions of marginalized (with respect to the simulation activity) members of the group, both moves serving to attenuate participatory inequity.

7.7 Discussion

In this chapter I have unpacked shifts in participatory inequity across two weeks of one group's investigation in our biology lab course. I have argued that investigative materials had an impact on attenuating and amplifying inequity throughout the investigation, in interaction with student

framing of the lab and instructor facilitation. Here I will zoom out to consider how this analysis contributes to our understanding of epistemic agency, and the design of biology labs.

7.7.1 Participatory inequity in conversation with epistemic agency

The motivation for analyzing participatory inequity in Gp 1's activity was to further our understanding of how epistemic agency is affected by social dynamics in small groups. In my first impression of the case I attended to whose knowledge building contributions were taken up and elevated by the group for guiding their investigation. I was interested in understanding why Alaad's design idea in week 2 was rejected (and why his contributions did not seem present in their final experimental design), and why this contrasted with his work on the simulation which featured prominently in the final lab reports of all three members of Gp 1. Analyzing the case through a lens of participatory inequity helped me to turn my focus from contributions to knowledge building to *opportunities for contributing* to knowledge building.

Alaad's agency in week 2 was not constrained in the sense that his initial design contribution wasn't taken up in their final design (even though that matters), but rather in the sense that for the remainder of week 2 he was a marginalized participant, who saw few opportunities to make *new* contributions to the decisions guiding their investigation. Likewise, exercising agency with the simulation in week 3 was not just about Alaad's contributions being taken up as important to Gp 1's investigation, but was also about the opportunities it presented to all members of Gp 1 to direct an inquiry into a shared knowledge object. Attention to how these opportunities were restricted or opened as participatory inequity was amplified or attenuated added a new dimension to three design considerations already present in this dissertation—student framing, investigative materials, and instructor facilitation.

How amplification and attenuation of participatory inequity informs design for epistemic agency

The analysis in this chapter illustrates how framing 1) shifts dynamically over shorter time-scales (e.g. between moments 10 and 11 in the third week), 2) is negotiated between the scale of the group and individual students, and 3) affects participatory inequity. The first two observations are consonant with prior research on student framing in science learning spaces (e.g. Scherr & Hammer, 2009). The latter observation aligns with Shah & Lewis's finding that computer programming tasks (which can be framed as having a 'correct answer') amplified inequity more than design tasks (which were viewed as more subjective decisions) (Shah & Lewis, 2019, p. 439). I do not claim that this relationship is one-to-one, which I will illustrate in the next chapter, and unpacking how framing negotiations interact with participatory inequity is an important direction for future research.

The role that student focus on materials had in reducing opportunities for contributing experimental designs in Gp 1 aligns with prior findings that laboratory materials can constrain the scope of students' experimental design ideas (Jordan et al., 2011). Jordan et al.'s analysis locates this reduction in a by-passing of a planning step in groups comprising novices. The analysis in this chapter illustrates that the process by which ideational opportunities are constrained involves a complex, dynamic interplay of negotiating framing of an activity, as well participation within that activity, as individual students work to construct a shared knowledge object with their group. In the next chapter, I will revisit the experimental design work of Gp A (Chapter 6), and show how a focus on investigative materials amplified participatory inequity within their group at the same time that it motivated their productive navigation of uncertainty, illustrating how materials can serve many roles as part of the dynamics that afford or constrain student agency.

In this analysis I identified an instructional move—inviting and holding in the space ideas *from marginalized participants*—as impactful for increasing opportunities for contributing to knowledge building in small groups. Inviting and holding ideas is not just verbal—we saw that the way the TA and LA stood with respect to the group members could close off or open up participation to marginalized members, a finding that has been explored in engineering design work with elementary school students (Miel, 2021). This extends our current conception of responsive teaching, which involves eliciting, noticing, and responding to the substance of individual student's ideas (Simon, 2022), to include consideration of how our instructors can notice, and amplify participation of marginalized students in the classroom.

7.7.2 Limitations of this analysis, and future research directions

The focus on participatory inequity, and the specific way I characterized it in this chapter, emerged from a process of moving "back and forth between the emerging theory and detailed analyses of data, making revisions of both until there is a close fit between them and also with relevant literature" (Engle, Langer-Osuna, & McKinney de Royston, 2014). From this came new tools that may contribute to theory on participatory inequity in lab science investigations, such as my characterization of the *investigative conversational floor*. At the same time this emergent, *post hoc* focus meant that I was limited in my ability to triangulate my researcher perspective on participation with students' perspectives (Fink, 2022), owing to a lack of data capturing student perspective on participatory inequity in the lab. Furthermore, my scheme for characterizing participatory inequity was ill-suited to describing moments when students were working on parallel tasks. In the next chapter I will explore Gp A's (Chapter 6) work in week 3 of their lab, when a similar parallel participation structure emerged; because Gp A had four members, who split two-two, I can use discursive evidence to more accurately characterize participatory inequity

in these moments, and begin to unpack the role of parallel participation structure in attenuating inequity.

Chapter 8—Cross-case considerations

In Chapter 4, I named two potential validity threats of the empirical work done within this dissertation: generalizability of the analyses beyond the immediate cases, and building theory around "golden moments" which may not fully represent the whole dataset. With this chapter I intend to address these threats through an initial pass at applying the analyses from each chapter to the other cases from this dissertation (with which the reader should be familiar). In examining these cross-case considerations, I intend both to identify methodological limitations and to deepen the theory-building I set out to do with this dissertation. This latter function is especially salient given my assumption, stated in Chapter 1, that epistemic agency is enacted both contextually and dynamically. Following cross-case analysis for each analytical framework, I will revisit my conceptualization of epistemic agency, consider what each case has brought to that, and identify potential directions for future theory-building.

8.1 Extending the Analyses Across Cases

Across chapters 5, 6, and 7 I have constructed three unique analytical frameworks to describe students perceiving, acting on, and being positioned with opportunities to shape knowledge building work in science investigations, and applied them to one (or two) of four cases. In this section I will take each framework in turn, and apply it to the cases from the other empirical chapters. I will organize each sub-section in two parts: first, I will review the evidence of the analytical construct (framing, authorship of aims and moves, and participatory inequity) from each of the applicable cases; second, I will extend the theory building started in each empirical chapter, considering interactions between constructs (e.g. framing and navigating uncertainty).

8.1.1 Framing

> "Other labs like you can kind of feel like you're kind of a robot and just like going through things but this like, I think you can tell, I am a little bit frustrated and like, trying, like I still don't know for sure, that's the thing, like I don't know what the right answer like what we should have gotten and, I don't really know how to explain what I got yet. So, like that makes it frustrating but at the same time that's, what you're actually supposed to be doing when you're doing science like you're supposed to be, trying to find things that are unknown- not known and like, whatever your results are you figure it out from there. So like, I don't know, I think that that element, has made me really like the lab. Like, like I wanna go do it again like if I could so." (Nick, 2017, Interview 1)

Evidence of framing from interview 1

In chapter 5 I characterized Caleigh as framing the lab as about *confirming a target idea* in the first two units of the lab—which influenced her perception of opportunities to shape knowledge building when accounting for unexpected experimental phenomena—and claimed that this framing appeared to be destabilized in the third unit of the lab. This contributed to a design shift in 2017 and onward, in which we positioned students to direct experimental design starting in unit 1 of the lab. In this section I'll present evidence of framing from students' first interviews in 2017 and 2018 (about unit 1), which shows them framing the lab as *not* about confirming target ideas even in the first unit. Instead, we see them framing the lab as about *making sense* of various aspects of the lab. In the following section I will characterize themes which tie this sensemaking framing to students' perception of epistemic agency in the lab.

Identifying the confirmation framing for Caleigh relied, in part, on a contrast between her experience in units 1 and 2 with her experience in unit 3, which indicated a shift in her sense of what lab was about. Because the evidence presented here comes from the first unit, I cannot identify shifts in student framings *within* the course. However, each of the students we interviewed

drew contrasts between their experience in Bio14 L and in *other* courses, as a way to illustrate that they saw what they're doing in this lab as different from what they'd experienced elsewhere. Both Alaad and Nick specifically characterize other lab courses (for Alaad, chem labs, for Nick, a prior biology lab) as involving more "step by step" procedural work (Alaad, interview 1). Nick connects this specifically to his sense of *thinking* in the lab, noting that in procedural labs "it's not like, we didn't know what was going on but you almost like didn't have to" contrasted with Bio14 Lab which involves "a lot more thinking that you have to do on your own for it" (Nick, interview 1). Mary is even more specific in her sense of what feels different about what she did in Bio14L, when she characterizes Gp B's explanation for unexpected data as "something that actually made sense" in contrast to "reaching for an explanation." She elaborates on a familiar expectation in lab courses, stating "a lot of times I feel like people don't know what to write about so they're like, "Oh", like "human error."" (Mary, interview 1) This identification of human error as being normal parallels closely what Caleigh shared about her sense of needing to identify what she did wrong in carrying out the experimental protocol, which I identified as evidencing a confirmation framing of the lab.

Through drawing contrasts with their experience of other lab courses, students name the kinds of expectations that comprise a confirmatory framing of the lab—step-by-step procedure, reaching for an explanation, limiting the scope of the kinds of explanations one can contribute to account for unexpected data. They also start to hint at how they framed Bio14 Lab, providing a starting point for connecting sensemaking and students' perception of opportunities to shape knowledge building..

A sensemaking frame of lab, and its relation to perception of epistemic agency

In Chapter 5, I drew a direct link between Caleigh framing the lab as about confirming a target idea, and barriers she perceived to the kinds of knowledge building contributions she could make

in the lab. I claimed that through *destabilizing* that confirmatory framing those barriers were lifted, and she saw herself as having more opportunities to shape knowledge building (through proposing biological explanations for unexpected phenomena). In the previous section I noted that students in 2017 and 2018 drew contrasts between a familiar expectation of confirmation and a new *sensemaking* framing (Odden & Russ, 2019b) of the lab. Here I will begin to address the gap in my Chapter 5 analysis by unpacking three themes from student interviews which link a sensemaking framing of the lab to student perception of opportunities to shape knowledge building in their investigations.

One major feature linking students' sensemaking in Bio14 Lab to their perception of epistemic agency is a sense of *ownership* over how to conduct parts of the investigation. Many students express ownership in relation to proposing their own explanations, as when Alice shares "this was me (g – points to self) like making a prediction" (Alice, 2016, interview 2). Alaad specifically identifies ownership of ideas with a sensemaking framing, noting "I *have* to come up with my own explanation here. Yeah, so I feel like that's what science is, coming up with a new answer that better fits what you see. And I saw something new here, so I *needed* to come up with an explanation that's somewhat outside my usual route of thinking." (Alaad, 2018, interview 1, emphasis added) Through cultivating this sense of ownership, students see themselves as needing to take up more opportunities to shape knowledge building, as when Nick shares "we kind of wanted to (get from the TA) "like ok what do we do" and (he) wouldn't really give us that, so like that's kind of what I was saying where there was no right answer like, and they are not really going to give it to you. You kind of gotta like figure things out on your own because it's your own experiment." (Nick, 2017, interview 1) In short, a sensemaking framing seems to entail students feeling that they are in charge (and meant to be in charge) of generating some kind of knowledge

for their investigations, and this sense of ownership means that they perceive new opportunities to shape knowledge building in their investigations.

In addition to a sense of ownership, students ascribe a sense of *importance related to uncertainty* experienced in carrying out their labs. Alaad shares, of his work in the simulation, "There was an extreme sense of curiosity. What is going on? I want to understand this, but I have no idea what's going on. I wanna know what's going on. ... So in a way, I'm kind of grateful we got results that we were not expecting. It made it a lot more worth doing." (Alaad, 2018, interview 1) For him, the work in the wet-lab experiment was pretty boring and straightforward, and the meaningful (sensemaking) work of the lab came when he encountered uncertainty in the simulation. Similarly, as Gp B's class is transitioning to white-board presentations, bringing their work on the simulation to a close, Mary quietly shares with her group, "(I) don't want them to make us stop, I want to keep doing this. This is important." (Gp B, Lines 624-626) Once more we see a sense of importance emerging from uncertainty in the simulation results. This feeling was not limited to just work on the simulation, as Damien shares of working on experimental design "We had ideas based on the discussions, of mutation rates and how they affect population and stuff. We had ideas about what might happen, but it was just the unexpectedness of it that was-appealed to me." (Damien, 2017, Interview 1) In each of these cases sensemaking is motivated by a sense of importance related to figuring out something uncertain, and this importance drives students to pursue new opportunities to shape knowledge building.

Damein's quote above points to the third and final theme I identified as connecting sensemaking to perception of agency: affect. Every student from these focal groups describes in their interviews, or expresses during their lab work, *feelings* of challenge, frustration, satisfaction, risk, or excitement connected to their engagement with uncertainty and ownership of ideas. These

are not isolated emotions, but an interconnected constellation of feelings associated with sensemaking. Take, for example, Gp B from 2017. In her interview, Mary describes feeling a sense of “running a risk here” in designing her experiment, because they had to choose dilutions which would give meaningful results (either too few bacteria on the plates or too many would make it difficult if not impossible to draw meaningful inferences). Attempting to account for unexpected results proved challenging but, “it wasn't like a **bad** challenging” (her emphasis). During their work on the simulation Gp B expresses frustration at multiple points with the inconsistency in results, for example in Line 682 when Sujan exclaims “this makes me so mad!”. Ultimately, though, Mary shares “feeling like "oh", like pretty satisfied with what we came up with or, our ideas about it. The fact that it actually made sense and it was like, not that we were just kind of reaching for an explanation.” (Mary, 2017, interview 1) Among other students I identified similar patterns of feeling challenge, risk, or frustration when pursuing new opportunities to shape knowledge building, coupled with a sense of satisfaction or excitement in making sense of the study system through their own actions.

Ownership, importance related to uncertainty, and affect appear to be interconnected themes connected to a *sensemaking* frame in lab, which motivate students to perceive and pursue new opportunities to shape many features of their investigations, from explanation-building to experimental design. Furthermore, the trajectory of affect described above hints at some of the dynamics underlying a shift into students framing lab as a sensemaking endeavor. In particular, multiple students identified that if they had had “no idea” what to do in the face of uncertainty, then their frustration might not have been felt as a “not bad” challenge that ended in satisfaction at what they accomplished. This points to precarity in how to structure uncertainty into science investigations.

8.1.2 Authorship of aims & moves

Evidence of free moves

In Chapter 6 I characterized moments in which two student groups set the aims and moves of their investigations, and showed how opportunities to do so emerged and were guided by the hybrid configuration of data production materials. Here I'll illustrate how a mismatch between the simulation outputs and experimental outputs contributed to Gp 1 in 2018 (Chapter 7) encountering a resistance to their investigative aims in week 3 of unit 1, resulting in their accommodating scientific practices and explanations to this resistance. Unlike with Gp A and Gp B, a potential tension with how Gp 1 framed the lab nearly created a barrier to their taking up the unexpected simulation pattern as a resistance, which I'll briefly explore as a starting point for unpacking the relationship between student framing and navigating uncertainty.

As overviewed in Chapter 7.6.1, Gp1's week three activity started with their confirming the hypothesis that a high mutating strain of *E. coli* bacteria would grow more lactose digesting colonies than a low mutating strain (when grown separately). They appear satisfied that their experimental results bear this out, as evidenced by Jackie's drawings on the whiteboard (which they share during group presentations at the end of the episode). Aiming to further support this hypothesis, they turn to the simulation to replicate their experiment within the computer model. This investigative aim is evidenced by their talk in moments 2 & 5, where they discuss how and why to use the simulation, and then confirm that the data they are producing with the simulation is helping them to achieve this aim. Up until this point in their data analysis, they have encountered only few minor resistances to this investigative aim.

At the start of moment 11 they encounter their first significant resistance to the aim of confirming their hypothesis. Alaad returns to the simulation (which has been running in the

background) to discover that the LM strain of bacteria is now dominating and the HM strain is nearly extinct. Alaad's first move is to observe that "That's alright, we got the important part" (W3, Line 360)—establishing that this does not constitute a resistance (presumably for the purpose of reporting their findings). Only after he and Kyle have satisfied themselves that their artifacts back up their hypothesis does Kyle move to ask, "How did this even happen?"; at the same time Alaad moves to hail the TA to solicit her opinion on what's going on. This move serves to negotiate a new group framing of their activity for the rest of the class period—one in which they aim to understand this new pattern, even though it might not confirm their hypothesis.

During discussion with the TA, Gp 1 raises multiple plausible explanations for what might be going on with the simulation. They decide that they should replicate the results, but don't want to end the current trial, in case the dynamics change again; Alaad moves to get a *second* computer to run multiple trials in parallel. With two computers they run a total of 6 trials, varying the lethal mutation frequency in two of them. Through these trials they encounter a new resistance—the results are inconsistent! They end up with four trials in which the LM strain outcompetes the HM strain, and two trials in which the HM outcompetes the LM. There appears to be a correlation between steady-state outcome and time to extinction—in the trials where the HM "wins", the LM strain goes extinct within 3000 generations, and in all other trials the LM wins but it takes much longer for the HM strain to go extinct.

As with Gp B in 2017, we see resistance to aims emerging from coordinating the outputs of the simulation and the experiment. This draws their attention to time, and to lethal mutation rate, as potentially important factors, and they aim to bring simulation and experimental data together under a single explanatory hypothesis that incorporates these factors. However, the

stochasticity of the simulation leads them to encounter a resistance to this new aim, from which they move to refine their explanatory model to include two steady-state outcomes.

Framing appears to play a role in when this opportunity to shape knowledge building arises for Gp1. They only acknowledge the resistance they encounter in the simulation after they evaluate that it does not threaten their ability to confirm their hypothesis with the data they had previously generated within their experiment and the simulation. Despite establishing this criterion as a prerequisite for shifting into sensemaking activity, all three group members spend significant time in their lab reports unpacking the resistance they encountered in the simulation. This suggests that the work they did in overcoming uncertainty had a strong destabilizing effect on their jointly negotiated confirmatory framing of the lab, at least in-so-far as it pertained to writing a lab report in which they confirmed their initial experimental hypothesis.

Disciplinary & material forced moves versus curricular forced moves

In the discussion of Chapter 6 I identified Pickering's notion of material and disciplinary *forced moves* as potentially useful for understanding how students navigate the contours of uncertainty in conducting their investigations. Here I would like to consider the notion of a *curricular forced move*—where students turn to the curriculum to guide what to do when stuck—illustrated through three examples from across each year. In doing so I hope to explore more of the complex relationship between the configuration of curricular materials, student framing, and opportunities for students to shape knowledge building work in their investigations.

Curricular forced moves act as barriers to knowledge building opportunities

In unpacking Gp 1's activity in designing an experiment (week 2), I identified the instance between moment 2 and moment 3—in which Kyle and Jackie reject Alaad's design proposal—as impactful for amplifying participatory inequity for the remainder of the episode, and thus reducing the

Alaad's opportunities for shaping their groups' investigation. While I centered my analysis of what contributed to that instant around the role of materials and instructor facilitation, I also noted that Jackie and Kyle turned to the worksheet at the same time, which I claimed as evidence for their reinforcing a task production framing of the lab.

We could also conceptualize Jackie and Kyle's action of turning to the worksheet as a free move in which they seek to leverage *curricular forced moves* to make progress on their investigation at a point where they are stuck. In this way they are navigating uncertainty along contours defined by their investigation as a task to be completed within the context of a lab course. This embeddedness is important to take into consideration because it appears that the way we've structured experimental design lends itself to following this particular contour, which aligns with a task production framing of the lab. In considering the "golden moments" validity threat, we have to acknowledge the uniqueness of Gp A's experimental design work as being so centered on sensemaking rather than task production. This does not invalidate the role of the hybrid material configuration in supporting student's authoring of aims and moves during experimental design, but rather calls attention to the complexity of group dynamics and of student framing in also contributing to opportunities to shape knowledge building. There are no easy answers to this—in the next section I will discuss ways in which curricular forced moves may have contributed to Gp A's productive work in experimental design, and in the following section I will unpack how that productive work coincided with inequitable participation amongst members of Gp A.

Curricular forced moves set the stage for knowledge building opportunities to emerge

In week 3 of their investigation, at the start of moment 6, Gp 1 splits into a parallel participation structure, with Kyle and Jackie turning to the worksheet, while Alaad turns to the simulation to guide his work. As noted in the previous section, these could be considered free moves which rely

on different types of forced moves to help guide their investigations. Turning to the simulation involves navigating uncertainty along the contours of material agency, which initially confirms their investigative aims, and later resists them. Turning to the worksheet follows the contours of curricular agency. Interestingly, in week 3 these contours intersect—the worksheet guides Kyle and Jackie to the simulation. This helps to position Alaad's participation as legitimate within their trajectory through the investigative space, and sets the stage for the knowledge building opportunities that we know follow later to emerge.

Similarly, in the early part of Gp A's experimental design work, we see a moment where leveraging curricular forced moves guides them towards the focal episode presented in Chapter 6. They arrive at a nearly identical initial experimental design idea to what Gp 1 will construct the following year—grow the two *E. coli* strains in lactose and see if the HM grows more than the LM. And like Gp 1 will do, they then become mired in consideration of when they will be able to carry out their experimental protocol, which is especially pressing because they are anticipating a snowstorm during the time they would have to come in to plate their bacterial strains. It is Walt who proposes that they first address the prompts from the worksheet, and first of which asks "What is the research question or questions that you are investigating?" (Appendix 6.3). This is what they are discussing when the TA approaches them, at the very start of the focal episode, during which conversation they start to uncover the initial resistance to their aims.

Taken together these two vignettes illustrate that curricular forced moves can serve to guide students towards opportunities to author the aims and moves of their investigations, as well as potentially contribute to attenuating inequity. While the observed dynamics appear complex, I hope the examples presented serve as initial proof of concept for the notion of curricular forced

moves as a contour students may choose to follow in conducting investigations within lab science classrooms.

8.1.3 Participatory inequity

Evidence of participatory inequity in other groups' work

My framework for characterizing participatory inequity in group investigations emerged after I conducted the analyses for the other chapters. Here I will apply a limited version of this analysis to both cases from 2017, uncovering a pattern of inequity for Gp A during their experimental design work, and considering what might have contributed to seemingly equitable participation for Gp B.

Characterizing participatory inequity in Gp A's experimental design work

Moment	**1**	**2**	**3**	**4**
Par. Inequity	High	High	High	Mixed
Abram turns	2	12	20	16
Damien turns	6	19	27	24
Nick turns	7	9	18	23
Walt turns	0	3	1	4
Abram wds	6	61	67	149
Damien wds	100	301	208	264
Nick wds	37	269	155	300
Walt wds	0	14	4	40
Abram bids	0	4	3	4
Damien bids	5	5	6	5
Nick bids	1	5	5	4
Walt bids	0	1	0	3

Table 8.1 *Evidence for participatory inequity in Gp A's work*

In coding for markers of participatory inequity across Gp A's experimental design work, I have chosen to bound moments the same as in Chapter 6—that is, moment 1 corresponds to their identifying an initial resistance, moment 2 to Damien's hypothetical, moment 3 to their turning to the simulation, and moment 4 to their encountering resistance in mapping the computational and organismal models. Each group members' number of turns, number of words spoken, and number of bids made in each moment are tabulated in Table 8.1.

In moment's 1-3 of Gp A's activity, I have characterized participatory inequity as high. Nick and Damien generally dominate the conversation, with Abram speaking some, while Walt appears to only occasionally access the conversational floor. Their pattern of bids mirrors this, with Walt making just one bid across all three moments (when he proposes the term "advantage" as applying to the HM bacteria compared to the LM when grown in Lactose, which Damien initially rejects and then comes to accept after Abram supports Walts suggestion). Qualitative evidence is slightly more mixed, but generally aligns with this interpretation. At many instances we see Nick interrupt either Abram or Walt, seemingly ignoring what they are saying to express his point. Within moment 2 the increase in Abram's and Walt's conversational turns corresponds to a decrease in Nick's—in this moment he appears to be contemplating something, and does not seem to be attending to the conversation between the other three group members (see Figure 8.1). On the other hand, at multiple moments Damien opens his contributions up to the group at large, turning to face Abram or looking across to Walt. The seating arrangement appears to privilege Damien and Nick's participation, as they are in the middle, though throughout we see evidence of them both sitting back in a way that creates a physically open conversational space.

In moment 4 I have characterized participatory inequity as mixed. Although Walt still speaks much less than his peers, he speaks more than in the other moments, and contributes a

similar number of bids (to the others) to direct their investigation. Qualitatively Abram is put in control of the simulation, and controls the mouse during all of moments 3 and 4. The way the group members stand centralizes Walt and Abram more than during moments 1 and 2 (see Figure 8.2).

Figure 8.1 *Nick withdrawing corresponds with Walt and Abram participating more*.

Figure 8.2 *Abram controls the simulation, and he and Walt are more physically centered*.

Characterizing participatory inequity in Gp B's simulation work

Moment	**1**	**2**	**3**	**4**	**5**
Par. Inequity	Low	Low	Mixed	Low	Mixed
Karl	19	24	6	53	3
Mary	43	49	27	133	58
Sujan	39	37	26	99	54
Karl wds	120	279	45	381	10
Mary wds	470	763	300	1658	520
Sujan wds	332	344	171	728	408
Karl bids	4	7	1	9	0
Mary bids	6	10	5	11	7
Sujan bids	4	7	4	16	6

Table 8.2 *Evidence for participatory inequity in Gp B's work*

As I did with Gp A, in coding for participatory inequity in Gp B's work I selected moments which correspond to their moments from Chapter 6 (so moment 1 corresponds to their replicating the control trial on the simulation, moment 2 to their encountering resistance coordinating simulation outputs, moment 3 to recreating an experimental protocol within the simulation, and moment 4 to their replicating the "double exposure" condition in the simulation). I made one modification, opting to split moment 4 into two parts on the basis of a shifting participation structure—moment 5 corresponds to when Karl leaves the simulation work to construct a whiteboard diagram for sharing Gp B's work (see Table 8.2).

I have characterized moments 1, 2 and 4 of Gp B's activity as evidencing low participatory inequity. During this time turns of talk and number of words are somewhat equal, with Karl talking a bit less than either Sujan or Mary. All three group members produce similar numbers of bids to direct their investigation, including Karl making the focal move centered in the analysis of moment

2 in Chapter 6. Qualitative evidence of the student's physical positioning indicates all three group members have similar access to viewing the simulation, while Mary is controlling the mouse throughout the episode.

I have characterized participatory inequity in moment 3 as mixed, on the grounds that Karl accesses the conversational floor AND contributes bids much less often than his peers. Still, the qualitative evidence supports all three students having equal access to the simulation, and we see evidence of Mary and Sujan listening to and engaging with Karl's few speaking turns.

I have characterized participatory inequity in moment 5 as mixed. During this time Karl has almost no access to the conversational floor, because he is engaged in a separate activity (preparing the whiteboard). As with Alaad's simulation work in week 3 (Chapter 7), it is difficult to characterize participatory inequity with this parallel participation structure—for example, when Gp B's simulation work ends, Karl's work on the whiteboard features prominently in the following presentation activity.

Accounting for shifts in Participatory Inequity

Gp A starts with a pattern of high participatory inequity. Because there is no preceding moment to compare against, I cannot identify an *instant* that might have been impactful for setting up this dynamic. As noted in my description above, there are instances where inequity is amplified by Nick interrupting contributions from his peers, and similarly inequity appears temporarily attenuated when Nick withdraws from the conversation. Nick's interruptions appear to be in the service of re-articulating their groups' uncertainty in terms of glucose scarcity—that is, he seems to be engaging in *problematizing* (Phillips, Watkins, & Hammer, 2018), but in formulating his own ideas is not always attending to those of his peers.

The only shift in participatory inequity for Gp A comes between moments 3 and 4. For Abram, being in control of the computer appears to correspond to more opportunities for him to participate in the groups' conversation. For Walt, it appears that turning back to the worksheet contributes to attenuating inequity. Walt seems most involved in getting the group to properly fill in the worksheet. This raises for me the question of negotiating group *roles*, and how that could factor into characterizations of inequity in participation. In general, Gp A's pattern of equitable participation appears in direct tension with their pattern of sensemaking—during their sensemaking activity, one group member (Nick) appears to be less attentive to his peers contributions, actively interrupting to engage his own problematizing activity; by contrast, when the group moves back to working on the task (through filling in a worksheet) is when Walt seems most comfortable stepping in and contributing to directing their investigative activity.

By contrast to Gp A, Gp B never seems to exhibit high participatory inequity. As with Gp A, it is difficult to identify a consequential instant during which their equitable participation was established. It is potentially a continuation of a previously established group dynamic. In seeking contributing curricular factors to maintaining low participatory inequity more or less throughout the episode, I have identified two potential conjectures. The first is that the TA returns frequently to check in on Gp B's activity, and solicits all group members contributions in describing what it is they're doing. As with Gp 1 in 2018, he makes moves to open up the space to everyone in the group, and it is during the moments where he is present (moments 2 and 4) that we see the strongest evidence for low participatory inequity. The second is that no member of Gp B appears to be an expert in how to conduct the simulation relative to their peers. Recall that equal epistemic authority may have played a role in destabilizing Caleigh's confirmatory framing of the lab (Chapter 5.6.4).

It seems possible that this may also play a role in establishing relational equity between members of a group engaged in a joint task, and so contribute to attenuating participatory inequity.

Attenuating participatory inequity through parallel participation structure

In Chapter 7 I observed that in the moments of activity where Alaad worked on the simulation while his group mates worked on a worksheet, there was mixed evidence for characterizing participatory inequity—on the one hand, discursive evidence for accessing the conversational floor showed significantly unequal participation between Kyle & Jackie and Alaad; on the other hand, it was clear that Alaad was participating in setting aims and moves for Gp 1's investigation, just in conversation with the simulation. This same pattern re-emerged in applying an inequity analysis to Gp B's activity, when Karl broke away from the simulation activity to prepare for group presentations. As mentioned in the discussion of Chapter 7, I've identified a similar parallel participation structure in Gp A (2017) in *week 3* of their investigation. Here I'll consider all three cases (Gp 1, Gp B, and Gp A, all in week 3) together to explore the conditions under which parallel participation serves to attenuate participatory inequity.

First, to establish more concretely the discursive evidence of lowered participatory inequity during parallel participation structure in Gp A's work, I'll present rough comparisons in Walt and Abram's talk in the episode from week 2 (detailed in Table 8.1) and in their work on the simulation in week 3. This latter episode spanned 30 minutes, or roughly twice as long as the week 2 episode. In W2, when all four members of the group worked on the same design task, Abram spoke 50 total turns, or 283 words; Walt spoke only 8 total turns, or 56 words. By contrast, while working on the simulation in W3 (separately from Nick and Damien, who worked on examining experimental data) both Abram and Walt spoke approximately 200 total turns each, or ~1500 words for Abram and ~1800 words for Walt. Taking into consideration the difference in duration between the two

episodes, this represents approximately twice as much use of the conversational floor for Abram, and nearly fifteen times as much use of the conversational floor for Walt. All else not-withstanding, this represents a tremendous shift in participation for Walt.

And there is other evidence of lowered participatory inequity during this episode, from interview data. Abram was one of the students interviewed, and he notably recalls his participation in this simulation activity much more than in the experimental design activity. While factors such as recency bias may factor into this discrepancy, and while we did not explicitly design our protocol to gauge students' emic sense of participatory inequity, it is note-worthy that in response to general recall prompts Abram makes no reference to his participation in design, while his group mates Damien and Nick (both interview participants) spend significant amounts of time discussing their experimental design. Furthermore, there is evidence of Abram and Walt's simulation work playing a central role in how the whole group conceptualized the study system by the end of the unit (that is, that their bids to direct some aims and moves of the investigation were taken up by the group): both Nick and Damien refer to specific results from the simulation within their lab reports and interviews, and Nick specifically attributes this contribution to Walt and Abram during his interview.

Looking across this emergent parallel participation structure in Gp A, Gp B, and Gp 1's activity, there is a glaring commonality—one subgroup worked on the simulation, while the other worked on presenting experimental data using the whiteboard. Using language developed for navigating uncertainty, I would say that one subgroup is pursuing investigative aims along the contour of material agency within the simulation, while the other is doing so along a contour formed at the intersection of curricular agency (the need to present results to groups) and material agency of the experimental system. In two of these cases (Gp A and Gp 1) it is the more

marginalized participants who turn to the simulation, and in both instances they do work that is influential to the activity of the whole group. For Gp B, all three members work on the simulation, and then the most marginalized member splits off to work on the whiteboard. Across all of these instances it appears that providing an alternative means to contributing to the groups' investigation—a new contour to follow—creates room for marginalized participants to engage in work that contributes to the overall investigation. I should caution that this does not necessarily mean that multiple roles or tasks within small group investigations will guarantee more equitable participation opportunities. For one thing, I have not collected any emic evidence of participatory inequity—it's fully possible that students working on a parallel task might not have valued that task as highly as the work their peers got to do, or might have felt forced into that work (this seems especially plausible for Karl in Gp B). Still, the three cases taken together points to the start of a design idea for structuring small group investigations which increase individual students' opportunities to shape knowledge building work.

8.2 Revisiting conceptions of epistemic agency

With this dissertation I set out to build an account of when, why, and how introductory college biology students take up opportunities to shape knowledge building work in carrying out their own science investigations. My explicit goals were to build theory on epistemic agency in lab science, and to develop design ideas to support student agency in college biology lab courses (particularly at the introductory level, which has potential to reach a broad group of students). I will review my work to meet those goals here, and consider directions for future research.

8.2.1 Theory-building around epistemic agency

I started from Miller et al.'s (2018) definition of epistemic agency as "students being positioned with, perceiving, and acting on, opportunities to shape the knowledge building work in their classroom community." With each of my empirical cases, I sought to explore the dynamics by which positioning with, perceiving, and acting on opportunities is co-constructed in small group lab science investigations within an intro college biology classroom. In Chapter 5 I identified how a confirmatory *framing* of lab spaces can account for why a student might not perceive herself as having opportunities to shape knowledge building work, even with explicit positioning by the curriculum. In Chapter 6 I showed how the material configuration of hybrid labs could facilitate student groups authoring the aims and moves of their investigations, using *the mangle of practice* to describe how opportunities emerged and were taken up. In Chapter 7 I considered the role of group dynamics in limiting individual students' opportunities to shape knowledge building within their groups, through an analysis of shifts in *participatory inequity* across one group's investigation. Connecting each of these analytical constructs to the dynamics by which opportunities to shape knowledge building are co-constructed represents a first step in building theory on epistemic agency in college lab science investigations.

Beyond using these frameworks, I made context-specific modifications to characterizing the mangle and participatory inequity, in relation to epistemic agency in lab science. For the mangle, I reworked the analytical constructs of resistance and accommodation to *resistance to aims* and *generative moves and evaluation* (see Chapter 6.7). With the former, I intended to center the goal-oriented nature of agency in characterizing uncertainty that students encounter in doing investigations. With the latter, I intended to draw attention to the role of "deciding to what extent progress has been made and where to proceed next in an investigation" in exercising epistemic

agency in scientific investigations. For characterizing participatory inequity, I developed the notion of an *investigative conversational floor*, evidenced by students' contributions of and engagement with bids to direct the aims and moves of a group investigation. With this addition I meant to draw explicit connections between opportunities to participate and opportunities to shape knowledge building, appropriate to the context of small group investigations.

In the final chapter of this dissertation, I applied these analytical frameworks to other cases, and considered implications for further theory-building. Looking at interview data across five students I began to piece together themes for connecting a *sensemaking* frame of lab to students' perception of opportunities to shape knowledge building. These included a sense of ownership over how to conduct parts of the investigation, a sense of importance connected to experiencing uncertainty, and a trajectory of affect comprising challenge, frustration, satisfaction, risk, and excitement. This sensemaking characterization aligns with research around thinking and feeling like a scientist, referenced in Chapter 1.1.1. Through considering when and how students in Gp A, Gp B, and Gp 1 made free moves in conducting their investigations, I proposed the notion of a *curricular forced move* to supplement Pickering's *disciplinary* and *material* forced moves. I showed how curricular forced moves have the potential to obstruct or to create opportunities for student groups to shape knowledge building, and considered the role of framing in influencing those dynamics. Lastly, through characterizing participatory inequity for Gp A (across two episodes), and Gp B, I explored interconnections between equity, negotiated framing of lab, and navigating uncertainty. This revealed tensions between Gp A's productive sensemaking work and opportunities for some members of the group to participate, illustrating the complexity by which opportunities to exercise epistemic agency are co-constructed.

8.2.2 Design ideas for supporting student agency

For each case, I attended to the role of our curricular enactment in co-constructing opportunities to shape knowledge building. In Chapter 5, I identified a strong connection between student perception of epistemic agency (mediated by framing) and control over data production through setting research questions and methods for investigations. This directly challenged the idea that agency should be scaffolded in introductory college lab courses (Brownell & Kloser, 2015, p 527-529), and contributed to our changing the curriculum to position students to design their own experiments right from the start of the course. In Chapter 6, I supported a hybrid material configuration as a means of supporting students navigating uncertainty in their investigations, and pointed to a pedagogical move of orienting aims without over specifying solutions as potentially useful for supporting students seeing themselves as having the authority and means to engage with uncertainty. In Chapter 7, I explored the complex role of investigative materials, in interaction with students' negotiated framing of the lab and instructor facilitation, in amplifying or attenuating inequity in small group work. This foregrounded tension between task production and sensemaking framings of the lab, and their connection to the material configuration of a lab in which students are required to create their own experimental designs. In Chapter 8 I revisited this tension, exploring how students leverage curriculum to make progress in investigations, sometimes in ways that reduce opportunity to shape knowledge building and sometimes in ways which create it. Finally, I identified the potential for parallel participation structures to attenuate inequity in group investigations.

8.2.3 Directions for future research

> "I think that was really cool cause, it's more of like our interest, and like if we were curious about something like, we, got to find out about it but we also got to like figure out the steps that like, we

> have to do by ourselves to like get there. So, I think that that part was cool, 'cause it's cool when you're kind of like driving the ship." (Nick, 2017)

I stated at the start of this dissertation that my work herein would be evaluated on the basis of utility to the reader, and generativity to the field. While I can only hope that you have found this work useful, I believe that two of the ideas developed here can serve as especially generative launching points for future research: the contours of agency in navigating investigations, and the dynamics of participatory inequity in small group investigations.

In understanding how students set the aims and moves for their investigations I brought up Pickering's (1995) notion of *free* and *forced* moves as having some potential explanatory power. Within the context of the cases in Chapter 6 I focused on ways that students leveraged material agency (primarily the simulation) to guide them in their investigations. I also mentioned how students might leverage disciplinary agency (e.g. Alice's turning to the literature) in a similar way. In Chapter 8 I expanded on this to propose *curricular forced moves*, identifying moments when students turned to the curriculum to help them navigate uncertainty. I believe this notion of resources which students may turn to when stuck or uncertain—contours they may follow to navigate a terrain of investigative decision-making—has potential for unpacking how students enact agency in lab science investigations. This could be expanded further—for example, students often turn to their instructors to help them make progress when stuck, and we saw this as especially impactful for initiating Gp A's sensemaking activity. Accounting for how these agents (material, discipline, curricular, instructor, peers/peer groups) might guide students to navigate uncertainty, and when students might turn to them, would enable curriculum designers to construct holistic curricular systems to support students carrying out their own scientific investigations.

I mentioned in Chapter 4—Methodology that the participatory inequity analysis for Gp 1 emerged from an initial effort to characterize their navigating uncertainty, because of the role that social dynamics appeared to play in restricting some students' opportunities to shape knowledge building at points in their investigation. I believe that this microgenetic analysis has significant potential for uncovering the complex dynamics by which epistemic agency is enacted in real time. In particular, I found that this analysis enabled me to bring together a conceptualization of setting aims and moves in investigations, dynamics of power, and dynamics of framing. I see the "socially negotiated influence" model of Engle, Langer-Osuna, and McKinney de Royston (2014) as a potential starting point for extending my analysis in Chapter 7 to include other negotiated dynamics such as relational (in)equity. Unpacking specific examples by which negotiation of investigative decision-making plays out would better position instructors and designers to facilitate science lab courses in which every student has the opportunity to participate and learn.

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Appendices

Appendix 5.1—Mutation Lab Report Guidelines[20], 2016

Mutation Lab Report Guidelines

Mutation Rates Lab Report

Grading

- Discussion Draft Write-up & Peer Review (15 pts)
- Full Lab Report (20 pts)

Purpose of Lab Report

- The primary purpose of the lab report is for you to slow down and take time to think about what we have been doing and carefully write up your thoughts
- The purpose is not to get to some particular "answer," but rather to make some sense of the data and support your ideas with logic and evidence
- We want you to improve your skill in communicating scientific ideas clearly. Clean writing and formatting will help you communicate
- We will be primarily be grading for clear expression of your ideas and evidence (not particular formatting conventions)

Purpose of Peer Review Cycle

- We want you to practice noticing good scientific arguments so that you will get better at making your own
- You will have time in lab to discuss feedback from both a peer and your TA
- You will have time to ask questions/get clarification before the final lab report is due

Structure of Lab Report

Introduction

- Introduce the problem or question you will be writing about. What is known about the problem? What is unknown? What will you be writing about in this report?
- As you are writing, ask yourself, what is the overarching "story" here? Does this make sense? Could a reader follow and understand my train of thought?

Methods

- Explain what you did in a clear and concise manner.
- You don't need to recount every single detail, but you do need to give your reader a sense for what you did that will impact how they make sense of the results. What was the experimental setup? What was the data you were collecting? How did you collect it?

Results

- Report on what you found.
- Specifically, choose how you want to represent the data. Decide what data is appropriate to include and what data it may be appropriate to leave out.
- Describe in words what you see in the data and appropriately use figures to help you communicate and summarize what the data say.

[20] Parts of this document which could serve as identifying information, such as due dates, have been removed.

- You may add footnotes to explain or justify your choices.

Discussion

- Come back to the question/problem you posed in the introduction and help your reader make sense of the results. Do the results answer any of the questions posed in the introduction? Do they raise new questions? What does it all mean?

Formatting Guidelines:

- Include your name, the names of your lab group, your lab TA
- Decide on your title after the lab report is written so you can choose a title the clearly communicates to a reader what they can expect to read about (i.e. not just "Lab Report 1)
- Include page numbers and a running header that has your name
- Make section headings clear and double-space your report so it's more readable
- Include citations in your text (if appropriate) and a **References Cited** section at the end of the write-up
- Acknowledgements (if you want)

Additional Tips for Good Scientific Writing

- Use simple, precise language. If there is a vocabulary word that will help you communicate your idea, then use it. But avoid using excessive jargon (especially if you aren't sure
- what it means).
- Read your lab report aloud or to your roommates. It should flow and make logical sense.
- Revise your writing! (All writing gets better with revision)

Appendix 5.2—Transcript of Interview 2 with Caleigh

A note on notation:

, indicates a noticeable pause
/ns/ indicates an n second pause
- indicates interrupted speech
^ indicates a rising inflection
* indicates emphasis
[indicates student overlapping interviewer]
{indicates interviewer overlapping student}
(indicates a note, typically a paraverbal or gestural cue)

Line	Time	Speaker	Turn
1	00:02	Interviewer	Okay, so ^what, we're going to do, is like I said in my e-mail I'll just ask you some questions about, um, what your experiences with labs one and two were like, and umm, (clears throat) I just want you to tell me what you,- how you experienced them and, what you thought and, how they went for you. Okay? [Caleigh nods] And if you have and questions, um- if any of the questions are con^fusing, let me know and I'll try to rephrase. [Okay] Okay?

2	00:28	Interviewer	Umm. So, were there any- do you remember what you did in lab one generally? [Yeah.] Can you tell me a little bit about what you remember from what you did in lab one?
3	00:38	Caleigh	Ok so we had two strains of *E. coli* bacteria. There was the E-nine-thirty-nine strain which was a mutant strain like it would have a lot of mutations and it would develop those mutations really quickly. And then we had the E-nine-thirty-eight strain, which was like the normal wild type strain. {Ok} So that would just, it would have some mutations but it was not nearly as fast as the nine-thirty-eight strain. {OK.} So, we- we put both strains in a, like a normal environment- just like on a petri dish and and we also put them in an environment with rifampicin - it's an antibiotic. So we were trying to see like in which environment which bacteria would do better. {Mm} Um. So, we- we like plated both strains and we let them like grow like over the span of I'd say two or three weeks and we collected data from those. Um so *our* group actually like, something, Idon'tknow something happened with the (low?) cultures and our whole section like we weren't able to get good results from them so we actually used data from another lab section. {Ok} So yeah, like the process- the data analysis process was still really valuable and I learned from that. So basically what we learned was that, in um, in environments without bacteria, the wildtype strain did better because, um, they weren't developing like harmful mutations very quickly, cause the E-nine-thirty-eight one would be mutating really quickly and it would get like harmful mutations that would hurt it so it didn't grow as well. {Ok} But however in the, in the,- on the plates ^with antibiotics the mutant strain actually did better because, like because they were mutating faster they were also getting- there was a higher chance of developing mutations that had antibiotic resistance. {Ok} So like the- the benefits of getting antibiotic resistance were- like *outweighed* the cost of potentially developing harmful mutations. {Mm} So they actually, so like it kind of switched, like the, wildtype did better in a regular environment but, in a hostile environment the mutant ones did better.
4	02:41	Interviewer	Ok. Was that what you were expecting or?
5	02:44	Caleigh	Um well we weren't given very much like instruction at the beginning of the lab so we made a hypothesis and we kind of just- we just predicted that um the wildtype one would do better in the non-hostile environment, which was true, but we didn't see like the other side of it. How it would be switched in a, hostile environment.

6	03:03	Interviewer	Ok ok cool. So, um I am going to now ask you about some of your experiences with lab one. Maybe some moments that stood out to you in particular ways, and I just want to emphasize that this is not, it's not so much um about you know, the *content* itself, like don't think of this as an exam or as a- you know I'm testing how much did you *learn* about, you know the content. I, like, *really* what these interviews are ^for, is what trying to understand what your - Caleigh's - experiences were that, you know experiences that might have been ^good *or* negative or, both, you know? And *that's* what most useful for me. So, I just wanted to like put that out there. This is not a test so if you- if there's something you've forgotten like you can just say "I actually don't remember that" and that's okay. Okay? So, um were there ^any parts in lab one in your experience in those three weeks that you found, umm to be surprising in any way? Like any moments in your lab when you, you know foun- when you were 'doing the experiment' or you know 'analyzing data' or 'using the simulation' or the whole class discussion, or all of the things that you did. A-any thing that was surprising for you.
7	04:18	Caleigh	Uh, I feel like just because we were expected to figure out a lot of stuff on our own I realized like how many like, in the real world, how many different steps during which, like we could make a mistake or like, we could accidentally contaminate our data or something like that. So I just, I guess that's surprising because in high school most of our labs were very structured, we were told exactly what to do, so like there wasn't a lot of room for error in- in that- those situations. But like, here I feel like there were so many ways in which one person coulda- could have messed up and it would have like completely changed the results of our experiment. Um, so I guess it was a little surprising that, in a class like that big there's like,- I mean I know lab sections are smaller but in- with that many students they would give us like so, so much freedom in what we could do. Which I think is really important for our learning process but at the same time like our, our section like completely, did not get useful data. So I feel like, it would have been more, useful if we had been like told, just like given more, structure in the whole process.
8	05:20	Interviewer	But- And is there,- like in your experiment, in like when you were actually engaging in lab one, umm, can you talk a little bit more about the point when, the surprising thing happened?
9	05:33	Caleigh	Okay. Well, we /were-

10	05:35	Interviewer	/Do you know- is the question- does it make sense?
11	05:41	Caleigh	I think so, yeah. So like we were given, like a procedure like a handout that we would follow but if we had questions like we were told to ask our TA or lab assistant, but like often times they would tell us like (adopts deeper tone) "interpret this to the best of your ability" like we weren't - like when we weren't sure we weren't really given, direct instructions, it was more of like trying to figure it out. {Mm hmm} So, I feel like that was a little surprising because I- I think, in *my* experience before like, we were given instructions for a lab and then we would interpret the results on our own like *that* was the part that was more open-ended but like, in,- in (this class) in the first lab like I feel like the whole *process* was more open-ended. So like that surprised me.
12	06:20	Interviewer	That's interesting. Can you talk about - because this process was open-ended maybe some of the things that w- turned out to be challenging for you and your, partners or maybe specifically for you. Umm, that turned out to be challenging.
13	06:36	Caleigh	Yeah I just- I feel like especially because we are working in groups like one person might interpret it one way and another person might interpret it another way but like we just *have* to come to a consensus on, like how we're gonna, ^approach the problem because we're not like told which is the right way. So I feel like that was a little challenging just because we are working in groups. But, like just hearing people, like our lab partners reason through, like why they think it's that way and then we give our reasoning, like I think that was a really good learning process too.
14	07:05	Interviewer	So what- can you give me a more specific example of when that happened? D-d-d-did that ^happen in your, um lab experience in- in, the first time? /In lab one?

15	07:13	Caleigh	Yeah, /I would- I would say like, just, how- so we- part of the experiment was we had to dilute the cultures. Um so that- so like we were given a fixed amount of each bacteria and we were supposed to dilute it with I think it was just saline um, so that it wouldn't be as strong. Umm, and, I guess- we were just- we were told to dilute it and we- we- I think it was about like one tenth as much, or no maybe it was less, I don't remember the exact amount but, yeah we had to like *reduce* the amount of bacteria that were present in the cu- in the, like the ^cultures. And our group just- and we had a ^little, like trouble figuring out exactly how we were supposed to do that and like how- how diluted it was *supposed* to be. So like we followed the instructions the best we could but, like we weren't sure if that was *exactly* how we were supposed to do it. And our group actually turned out to have, more than, the lab instructors had expected. So I guess like we didn't, fully, dilute it {Mhm} as much as he wanted. {Mhm} Yeah.
16	08:13	Interviewer	Umm, and so then- like what- How did that- I know know, like how did that make you *feel*? Like what was that experience like in your first- this is your first bio lab, right?/ What was that like for you?
17	08:25	Caleigh	/Exactly. (Some emotional tones to "the second week" - maybe a quaver?) Well like the second week when we were all told to get our dishes and count them and like we have way more than some of the other groups that was a little frustrating. But like the lab instructors were really, like understanding they were like "you probably just made this mistake like, know that- like that's what you did *wrong* so that we could learn from it". But like they weren't upset with it- and we ended up like just taking data from like another group to analyze for that week.
18	08:46	Interviewer	So can you- so I'm going to really- I am going to really push hard to understand, what that frustration was like? And I know you've mentioned a few times that the lab instructors were super helpful and that's great. But I'm not- like I'm less interested in ^them. I am more interested in you. Okay? So I'm really going to push on that. Umm, so like, can you tell me a little more about what, like, and maybe it wasn't a big deal that you felt frustrated maybe it *was*. Umm, can you- can you tell me more about what that- what that, experience was like for you in a biology lab?

19	09:25	Caleigh	Okay. Yeah well, it was just- it was hard because like, other groups had done it correctly, and like we- we were really looking forward to like, *getting* the results of our experiment and seeing like what we did and like what we can learn from that information. So it was just- it was kind of frustrating to see that, like we were the ones who messed up. Like we *clearly* didn't do this the way it was supposed to be; there are way more bacteria than expected. {Uh huh} Um, so yeah, it was just- it was ^frustrating, to know that *we* did something wrong, um, especially when other groups had done it right. Like the following week a lot of people had like kind of messy data but, um, like the lab instructor said it was probably like something was wrong with the bacteria or they did something wrong it wasn't like, our procedure. But like the week before that it was clearly like we hadn't diluted it enough. So, I guess that was just- that was hard to hear especially because we couldn't go back and fix it or anything, we just had to use someone else's data. So like, I think- it's ^definitely valuable to ^learn that way, but at the same time I wish that we had had more instructions 'cause like we're the ones doing it, like we put in the time and the effort so I feel like I wish we could have known how to do it the correct way the first time. Especially because we're *not* going to get a second chance to redo it or anything.
20	10:32	Interviewer	So how did you- how did you guys go about resolving that, then? Like what happened next?
21	10:37	Caleigh	Umm, so, we kin- we looked at, another group's data, to like know what is was *supposed* to look like so we could learn from that. And then, at the end of the lab we actually like, we used FALCOR which is an- like an online simulation. {Ok} So, we took da- it basically like ran the, simulation like many times so we would have data from like a lot of trials and like, we took averages I think, is what we did. Um, so, l- from- for the *actual* like lab report and analyzing the data we- we analyzed a lot of the data that was, like computer ^generated. So like it didn't matter too much that our individual results weren't good. So yeah we, it w- it was ^okay. It didn't really impact our lab report that much but like it's just, as a student I- it was kind of frustrating.
22	11:23	Interviewer	Yeah, yeah, I can imagine. Um, can ^you- can you tell me about, umm, moments from your lab one that were maybe, that you felt like *you* were really engaged in the lab? And, that you were you know like ^super, into, what you were doing. And you felt like,- you know you were just, you weren't looking at the watch for instance maybe or

you were really excited and engaged about what you were doing. Was there any moment like that?

23	11:50	Caleigh	Yeah definitely. Umm, so like, when we *realized* that, the mutant strain, the nine-thirty-eight strain, did better in hostile environ- environments with bacteria, um, we thought that was really interesting because like we hadn't even thought about how that relationship would switch when you add bacteria. Um so like, it wasn't even that we, got our hypothesis wrong it was like we hadn't even thought about that so I feel like that was- that was just a really interesting, and like moment, yeah.
24	12:18	Interviewer	In *that* moment when you saw the results, what did you guys do?
25	12:21	Caleigh	Umm, well, we entered it, w-we like combined it with our class data so that we could see- we could make sure like "oh, this wasn't just something we got". So like when we compare it with our class we realized that like "oh, everyone saw this". So then, we went back and thought through like why,- why this would have happened. And like eventually we decided- I can't remember if like we came up with this or our instructor told us but like we tol- we, realized that it was because, um the mutant strain had the advantage because they could potentially develop antibiotic resistance. {Mm} Yeah so that was, that had *n:ot* been mentioned anywhere before so I guess that was really interesting to like see a- real live (life?) *data* and like come to that conclusion.
26	13:03	Interviewer	Interesting, so was that- so was that interesting to *you* personally? Or did you find that that was something that the whole class sort of found interesting as a thing that, you know came out from the lab.
27	13:15	Caleigh	Umm, ^I would say umm, probably just me personally. I'm not sure maybe other students had already thought about that. But like our group did *not* think about how- how the mutant strain would *ever* have the advantage, so like that was really interesting to like me personally and my group. But I feel like some people in the class might of- if they had, previous like experience with this kinda stuff, they might have known that already, or like hypothesized that already. {Mmm} Yeah, so I feel like- cause we- my group and I did not have

			as much experience with like mutant strains and that kind of stuff. Um, like we were pretty surprised and really interested by _that_.
28	13:50	Interviewer	Cool. So can you- ummm, how did you guys make sense of that? Because it was a- you're saying it was a finding that was surprising for you. [Yeah.] So how did you make sense of it?
29	14:03	Caleigh	Um well just like looking at the data and like running more simulations on the com- like the program. Um we realized that like that, well first like we had to determine that that would always happen, that wasn't just like an accident that happened in our lab.
30	14:14	Interviewer	Oh did you- did you- did the group do that, or how did you determine that?
31	14:17	Caleigh	So we looked at data from, a lot of grou- like all the groups in our lab section had, that, re^sult so we figure like it's probably not an accident and we also, did the simulations on the computer program. So,
32	14:30	Interviewer	W- wait tell me a /little bit more.
33	14:32	Caleigh	Um, it's called FAL,COR. It basically like, it does the lab a bunch of times so you can get results from multiple experiments. So yeah once we realized that the nine-thirty-eight actually had the advantage in antibiotic environments like we just- we tried to think through- like we thought back through the whole process of how bacteria reproduce and how, like how having a lot of mutations would help and we actually we did this worksheet- it wasn't- well, it was kind of a worksheet, it was just our lab instructor has us brainstorm like when having like a stable genome, like no mutations would be helpful and when having a lot of mutations would be helpful. {Mmm} So I think we decided that in a rapidly changing environment you would want mutations so you can keep up with your environment ^changing. Um, and- so that would be like the mutant strain having a lot of mutations. So we decided that that mutant strain would do, a lot better when the environment is rapidly changing, which is true in like the bacteria environment. So that's kind of how we got through it and then like we

were- we were told by our instructor at that end that like we were correct. Yeah.

34	15:40	Interviewer	Okay, cool. So, another thing I'm kind of curious about is, when you think about, your lab one right?- Are you comfortable? You can, like /(unclear) move around and lean back.
35	15:49	Caleigh	Oh I- (unclear) (laughs) I'm okay.
36	15:51	Interviewer	Um, so I'm curious about what you think about whether, everyone- so imagine all of the students in your lab, right? In your lab, um, section. So all of the twenty-five or whatever. Umm, do you think, if I were talk to each of them, which I- I haven't. I think you're the only one of them I've- I've spoken ^with. Do you think each of them would have, very similar things to ^say, in response to these questions about lab one? Or do you think it would be different? I mean I know it's a really broad question but I'm just curious.
37	16:24	Caleigh	I would ^say, they would definitely be different just because there's like- there's a whole, really, big range of variety of people like we- I'm a *freshman*, we have like, I'm pretty sure every grade like there's some seniors in the lab group too. And a lot of those upper classmen have taken like other bio classes with labs and I feel like, they're, just more experienced in that kind of s-situation. And like for me personally this is my first college lab so I was, especially when our data was, a little weird like I wasn't sure like, what, could have happened or like how, where we messed up until like we were told like what we probably did ^wrong. Um, so I- I feel like other students have had more experience in lab so they might have seen, like encountered similar situations before. Or just like, they have taken other bio classes so their knowledge of like, how bacteria, reproduce and mutate, could have just been, like better than mine.

38	17:18	Interviewer	Can you? I'm- so, can- can you explain more how more experience with bio labs would probably make,- I mean it sounds like you're saying they might have had fewer challenges um, than you guys did. Is that what you're saying?
39	17:30	Caleigh	I think- or just, even when they *did* make mistakes like they knew- 'cause I feel like in previous bio labs they probably made mistakes too and they probably learned from them. Umm, so just like having, more experience I feel like just do- doing the hands on stuff, will help with, like what they're doing in this lab right now.
40	17:48	Interviewer	Hmm. And *why* do you- what are the ways in which more experience will help you in, this bio fourteen lab? Like, /I'm trying to understand what you think about.
41	17:54	Caleigh	/I feel like- Yea, I jus- I feel like a lot of the, the procedures in bio labs are similar like pipetting stuff, and like plating, bacteria on dishes, like I feel like a lot of students have done that before. And that was just like- while it wasn't too challenging it was still like a step during which we could make a mistake or like, somehow mess up our results. So I feel like just having- even having something as simple having more experience, plating dishes, I feel like, umm definitely contributed to like some people doing better.
42	18:27	Interviewer	Okay. Okay. Are there other things that, more experience in bio labs might,(2s) like- fi- you know, ^impact, how these students are doing in bio fourteen?
43	18:35	Caleigh	Umm, well, one of my friends who actually took bio thirteen in the fall said that like lab was, kind of similar to this in the sense that, they weren't- it wasn't too structured. Like, like bio thirteen was definitely more similar to bio fourteen than like, high school labs ^were. And I feel like I was kind of at a disadvantage, 'cause I didn't take bio thirteen like this is my first college lab. Um, but, other than that I feel like it was- it wasn't too challenging. But I mean it was a little frustrating when we made mistakes but it wasn't, I don't know it wasn't like, a *shock* or anything.
44	19:11	Interviewer	Mm. Wait, tell me more, what do you mean? Like what was not very- was it the *content* that wasn't challenging/ or? Like, just the- yeah.

45	19:17	Caleigh	/No, I feel like. I think it's the whole like process of doing the lab, cause like, in high school it was like very strict. Like um, you'd put this amount of bacteria in your pipette, you put this much on this plate and like, we were just given very clear instructions, and then- in bio thir,teen, like my friends are saying that it was- it was definitely not as structured and bio fourteen apparently is even less structured. {Mhm} Um, so I guess like some people have had that transition. So it, like helps them a little in the process but, like for me it was straight from like *strict* instruction to like, the really flexible process. Yeah, so- I feel- like having- other students who've had more lab experience have had more of a transition than I have. (Looks at computer) _Is it..._
46	20:03	Interviewer	I think it'll be fine, it'll keep recording. Thanks though. Umm, okay, that makes sense. Um, are there any other moments in your, in lab one that stood ^out to you for any reason or that were exciting or when you just had fun, in lab? And you can take a moment to think if, you know, feel free to like, pause and think if...
47	20:30	Caleigh	Um, well. I am not sure if this is exactly what you are looking for, but like-
48	20:32	Interviewer	I am not looking for anything. I genuinely I want to understand your experience that's what's most helpful for me.
49	20:37	Caleigh	Alright, so like on the very first lab, meeting, we had like- our instructor had like a powerpoint presentation. He was kind of explaining, to us like what, bacteria- how they mutate and reproduce and that kind of stuff. So it was almost like a *lec*ture form. And that went on for I would say like half an hour to like forty-five minutes. So like, just appl- being able to jump into the, lab and then like apply kind of what we learned, like that was- that was really interesting because for the first half hour I was sitting there thinking like, "oh like how am I supposed to be able to see this in real life" or something and then, and we got to doing the lab and I was like "oh wow next week we'll actually have results", so. I feel like. I guess that's the whole point of lab, so that you can see things and do things hands on. But, yeah that was really interesting and like valuable to me.
50	21:27	Interviewer	What do you- Why was it valuable?

51	21:30	Caleigh	Um, well, I guess like the first, like the first half hour was kind of just like any old lecture like- like- the lectures we have in bio fourteen usually. Umm so like, I was kind of like, I wasn't sure where that lab was going to go, so like I was really hoping we would do more hands on stuff. So I think it was just valuable that we got to, we got like the background knowledge from our instructor and then we got to somehow apply it to, the, lab we were doing.
52	21:58	Interviewer	How were you applying it to the lab you were doing?
53	22:01	Caleigh	Um well, ^mainly he gave us some background about the two separate strains so we knew, like, what we were putting on each plate. Like we- we *kind of* knew what to expect, even though our group didn't think about, how having antibiotics would change, the results. But, so- we just had some background so I think that was important. It was- otherwise we would have gone into lab not knowing because like, *those* bacteria, we wouldn't really know what they were expected to do at all. So yeah, just having a little background definitely helped.
54	22:31	Interviewer	Okay. Cool. Umm, can you tell me?- So all of the moments you just talked about right, the place where, and I think you talked about it a little bit earlier- in the earlier interview too where, you know there was the pipetting accident [yeah] umm, with the- with your group and you know the- where you analyzed, umm, the data in FALCOR. And all of the moments that you've talked ^about. Umm, did any of them, figure, in your lab report? And like how- what was- what was writing your lab report like for you?
55	23:03	Caleigh	Yea so like we definitely mentioned that we had a little bit of trouble with our experiment and we also mentioned that we used like FALCOR data to like compensate a little for it. But I think- I think the, majority of my report, we actually just got it back, so I- I basically just wrote, like I analyzed data that would have been more, correct and (laughs) like I don't want to say/ that data is correct>
56	23:24	Interviewer	/What do you mean?
57	23:25	Caleigh	>just like um, what the lab instructor expected us to see. So like data from FALCOR and data from like another lab section, I think it was like the Monday section and we borrowed their, like petri dishes and counted. {Mm} Yeah so we used, data that the lab instructor told us we were *supposed* to see, just like based off of what we know in like real life situations. So yeah it was kind of frustrating now being able to use our data but, we knew for sure that what we got- the results

we got were definitely *not* correct. Or I don't know I am hesitant to say the word "correct"/ in experiments

58	24:00	Interviewer	Why?
59	24:01	Caleigh	Just 'cause I feel like there's- there shouldn't *be* like incorrect- a correct like, result. It's just like every group is going to get like slightly different results and just like cause our were so far off doesn't necessarily mean they were wrong it just like, maybe something in the process we did was different from someone else. Yeah so I feel like just because we did something different doesn't necessarily mean they're wrong even though like, for the purpose of *learning* from the experiment, and learning about bacteria and how they mutate, um that data would not have helped us like come to the conclusions that we came to.
60	24:34	Interviewer	Mm can you say more about that?
61	24:37	Caleigh	Yeah, well, I guess from like a bio,lo,gist's point of view our lab instructor told us like we were supposed to see that the wild type had the advantage in a non-hostile environment and then that the mutant strain would have the advantage in a bacteria environment. So I guess that's just like a, accepted fact in like the scientific field, um but like when our data didn't sh- didn't like show that, or support those facts, um he told us like there's something probably, happened which like, we agree with just cause I feel like enough people have done experiments and like know about bacteria that like our tiny little experiment probably didn't like *disprove* this whole thing that's been accepted. Um, so, like we were- we were, willing, to take other groups data and like analyze that instead. But I just- I don't know I think it was a little frustrating to not be able to use our own
62	25:32	Interviewer	So do you think- do you think everyone in your lab. Umm, like if you imagine all of the students in your lab, (cough) do you think all of them, learn or take away the same things as you did from the lab? Or like what- what was, yeah what do you think about that?

63	25:54	Caleigh	Yeah, well I feel like- I know I was talking to one girl who's a senior right now. And like a second semester senior she was saying she'd taken a lot of other bio classes and done labs and she was saying like, it's really frustrating like, she wanted to end her sen- like her college experience with like, a nice and like interesting bio class. So it was really frustrating for her to have- to have like not done the experiment properly. {Mm} Um yeah but I feel like for me and I think other freshman since we're just starting out like, it was a very valuable learning process and we will *definitely* look forward to like better experiments in the future but, um like it wasn't as big of a deal to us. Yeah, so I feel like, yeah.
64	26:31	Interviewer	So I'm going to ask you a question that might sound really strange but like I'm trying to- because you talk a lot about things in the lab that are valuable for you in learning, umm, and my ^guess is not everything is likely to be valuable, right? [Yeah] Like some things are maybe ^not valuable. So I want to see like what are some of the things for you that- that you did in lab that you thought maybe were *not* valuable, in your learning process? Because that- I mean, I'm using your words here. Umm, do you- what- yeah...
65	27:02	Caleigh	Umm, so to start with we- our instructor has us read a bunch of like journal articles. Some of them are for homework and some of them are for class and we discuss them in class. And like, to be honest I don't really think those are like, important for our learning especially since a lot of the articles aren't even related to what we are doing. He kind of just- like I guess it's important to get experience reading journal articles. 'Cause like a lot of us are going to be doing that later on in our, like ^careers. {Mm} But, I- I feel like especially because the articles weren't really related to what we were doing I just- I,- A lot of us found that it was difficult to like understand what the articles were trying to get at. Um, and also we got to write up like summaries for some of them and I just thought that was like time consuming and kind of unnecessary.
66	27:47	Interviewer	Did you also have trouble making sense of- I know you said a lot of us did. [Yeah] Did you also?
67	27:54	Caleigh	Well, I feel like, the articles were just, umm. Like they were pretty dense so like I would have to read through parts like several time. So like I, when we had to write up a summary I didn't really have trouble, doing that it's just- it took like a lot of time and I feel like it wasn't as

like it didn't contribute as much to our learning as like a lot of the other lab activities do.

68	28:13	Interviewer	Are there other things that you thought were not so valuable, umm, in learning?
69	28:18	Caleigh	Ummm. I would say just like, during our three hour lab section, umm, anything that involves- like doesn't really involve like hands on doing stuff like I did not enjoy as much. Like there was a lot of reading and some, ^some discussion which was important, um, but I feel like we could have used the time better. Yeah just like if we're showing up for three hours in a lab setting with like our lab partners I would have liked to be doing like more hands on stuff instead of like reading articles which, maybe could have been done on our own time if we needed to do it at all.
70	28:55	Interviewer	So what do you mean be hands on stuff?
71	28:58	Caleigh	Um just like carrying out an experiment. Like um- So like, plating dishes in the first lab or like in the second lab we measured plants. So, I feel like, those are better things to be doing with our time when we are like meeting in our lab group.
72	29:14	Interviewer	Ok cool. Umm, thank you for sharing that with me. [Yeah, of course.] What about, um, I know you said simulations before I know you guys used FALCOR right (unclear). And then you guys also used another kind of simulation where it was kind of like a- it was kind of like a simulation and you were ^changing some things. [Yeah] And then- and- and then you were you know just doing some stuff with it. What, like what- I'm- I'm curious about, like how that- like was the useful? How did that play into the lab experience?
73	29:51	Caleigh	Yeah, um, I don't- I think this was with the second lab, I don't remember what like what, what changing stuff there was for the first lab,-
74	30:00	Interviewer	Did you guys have like in- in lab one there was like these bacteria,/ right and you could change their...

75	30:07	Caleigh	/Oh yeah yeah. Yeah actually I do remember that. Um I- I don't think it was very, useful in terms of actually writing the lab report. But it was like it was interesting for us to see what parameters or factors affected like whether the mutant or the normal- the wildtype strain would win. Um, so yeah it was interesting playing around with that kind of stuff, and just like getting a sense for like what factors affected which type of bacteria more. Um but I feel like- it didn't really help with, like writing the lab report. Or at least like I didn't incorporate any of that data into my report.
76	30:43	Interviewer	So ok so I'm going to ask you to - wait sorry, I am just going to back up a little bit. Why did you feel like it wasn't useful?
77	30:52	Caleigh	I feel like with, um- with- like a lot of those factors was beyond the scope of what we were actually trying to analyze or like determine was, was like a strong factor. I think we mainly focused on like whether it was an antibiotic environment or a normal environment.
78	31:08	Interviewer	So when you say *we* do you mean you and your group? Or do you mean...?
79	31:13	Caleigh	No I think it was our whole lab section. {Okay.} Yeah, I might be wrong. But I- I think/-
80	31:17	Interviewer	/You know better because I wasn't in your lab
81	31:20	Caleigh	Yeah I think like the point of the lab was just to see like which strain would do better in which ^environment. And there weren't like a lot of other, like the simulation took into account a bunch of other things, I don't remember all the other factors but, um, I just, I feel like it- it definitely modeled a more real life situations just ‘cause there are a lot of things that happen in our environment. {Mm.} Um but I feel like it was also beyond what we were expected to d- write up and analyze for our lab report. {Ok} Yeah it was a, interesting experience like seeing how- which strain would do better and like those comparisons but, we didn't really need to analyze that data for our report.
82	31:55	Interviewer	Ok ok and this was- this was something that you guys had explicitly like the lab instructor maybe kind of explicitly talked about.
83	32:02	Caleigh	Yeah. I think we had a worksheet we were supposed to fill out like, we were supposed to find like a f- a few conditions in which one strain would do better and like find a few conditions in which the other strain would do better. Um, so like we had to be able to, like understand the results in that sense but it wasn't incorporated into our report at all.

84	32:20	Interviewer	Ok. Ok. And um sorry and this was something you- how did you know it wasn't- like was that something your- the *TA* said or was it something that yo- that wasn't useful for *you* to incorporate? I am trying to understand how, you know you were making the decision about... [Yeah] Yeah.
85	32:39	Caleigh	Umm. Well I think that, we were given, I am pretty sure that we were given the question we were supposed to answer and like our whole report it was basically like, which strain would do better in which environment. So I feel like that question was specific enough that we weren't- we weren't expected to like incorporate all the other stuff.
86	33:00	Interviewer	Oh so you mean the question was spec- you- the question [yeah]- you interpreted as specific to the experiment. [Yeah.] Because that's what you were,- ok, ok. cool. So what feedback did you get on your lab report? And what, did you think of it?
87	33:14	Caleigh	Yeah so, um my, instructor told me that like a lot- a lot of it was kind of like the *way* I explained things. It was like, almost like organiz^ational. It was less so much like the bio and the data so that was- that was nice because, like we had analyzed another group's data and, like it was nice to be able to know that, like that- that data was expected and we analyzed it correctly and it was just more, like stylistic stuff that I know I will need to like focus on for my next report. {Mmm} So I feel like overall I'm like- I am pleased. (Unclear) And like there aren't any major changes I have to make, so. {Nice.} Yeah.
88	33:54	Interviewer	Do you have a ^sense for what- what the TAs are looking for in the lab report?
89	33:58	Caleigh	Yeah so I feel like, umm, well definitely like analyzing the data correctly which like I thought would be the biggest challenge or the thing I needed to focus on the most and, which like I did focus on it and it was correct, but like I didn't expect them to, want so much, like they really focused on like our, almost like our grammar, like down to that. {Mm} So yeah so just like the style of our writing too. So like that kind of surprised me and I didn't know that before I turned in that lab report. But I guess now for the future lab reports I'll know that they are looking at our writing too, not just like, the biology behind it, in our report.
90	34:36	Interviewer	So all of the comments were- all of you comments, or most of them, were about the stylistic elements of it.

91	34:42	Caleigh	Yeah or kind of just like, so we had four sections, like the intro methods results and then discussion. So, some of us- I feel like results and like discussion can kind of be like- it's, there's some grey areas like some, some of what I wrote could have been in either section, and he ki- our, instructor told me like, umm this part might have been better in another section. So it was kind of just like organizational stuff. {Mm. Mm.} Yeah.
92	35:09	Interviewer	Okay. Cool. Were you able to use any of that? I'm going to ask about lab two now. Were you able to use any of that feedback/ in writing up. //Oh okay. That's due next week, okay.
93	35:16	Caleigh	/Um well. I haven't written up my lab two report yet. //It's not due until next week. Yeah. So I will definitely incorportate that now, like now that I know more of what he's looking for. Um, so like definitely still, like focus on the *data* but, um I know- now I know to pay attention to like where- where each part, or like what goes in each section the best.
94	35:42	Interviewer	And when you say you know one thing to do is focus on the data like what are some of the things, you're- what are some of the things you're thinking to focus- like ho- Give me pointers for kinds of things you are looking for.
95	35:54	Caleigh	Um well definitely like so we- we learned a little bit about plants and how they're expected to grow and how they're growth changes in different environments so like, our, experiment we put- we put plants in like high CO2 environments and high like temperatures or like low humidity, so like we *have* a vague idea of how those factors will affect plant growth. So I guess one thing we are looking for is like whether or not our results match what we expect to happen. {Mm} So I guess like that's the first thing most people look for. And then um, we also look for places we made mistakes like if something doesn't line up with what we think, like we try to think back through the procedure like the methods of the experiment and see like if there are any other factors that we didn't account for that could affect like, or that could, um give us the result that we saw.
96	36:48	Interviewer	Wait, say that again? Sorry.
97	36:50	Caleigh	Um so like, if we- if we didn't get, results that we were expecting we would go back and like, go through the methods and the procedure to see if there were any other factors that might have like- or like, slipped into our experiment or like, stuff that we couldn't control.

98	37:05	Interviewer	So how do you- okay, so let me ask you a question specifically about lab 2 - I know you talked a little bit about what it's, like. Based on what you just said I'm curious about, how do you- so you said if your expecting to find a certain kind of results and if you don't find that, in lab two then, you kind of go through your procedure to make sure, {yeah} everything's in place. Like can you give me, can you give me a specific- did that happen with you guys in lab two?
99	37:30	Caleigh	Um, well the data we got were kinda like- our y- our instructor even told us this was a little messy. Um so but I feel like we had enough, data like we each, measured, six plants with, two like growths like leaves on them. So I feel like with our whole group, or our whole lab section we had enough information that like it wasn't that big of a deal, but like some of the data were definitely like a little bit off.
100	37:59	Interviewer	What do you mean off?
101	38:01	Caleigh	I don't remember the exact like plants but, some of the plants like based on the environments they were put in like they shouldn't have grown that way. So yeah so I mean that could- it could have happened for a variety of reasons like maybe we didn't turn up the CO2 all the way or maybe it got a lot of water right before we put it in the low humidity, environment. So like, I felt like there were a lot of reasons that we might not, necessarily be able to like determine which one caused those results. {Mm} But like we- we were told some of stuff we saw isn't- isn't what was expected.
102	38:38	Interviewer	Do you think that happens in real labs? Like finding stuff that's messy...?
103	38:44	Caleigh	Yeah I mean I feel like it definitely happens in real labs but, when you get to *deeper* and more advanced experiments you don't always have, like if you are a top scientist, you don't always have a mentor telling you, that didn't, that's not what's expected. So I think in- in these situations it's really helpful because like we- we know we, learn something in lecture and we expect that to happen in our labs but like when we don't- like we're not sure if our understanding is incorrect or if like the lab just didn't go as expected. So it's definitely helpful to have like, our lab instructor there telling us, or like keeping us on track.
104	39:24	Interviewer	Ok so in lab two, were there moments that, you found particularly or or, difficult?

105	39:34	Caleigh	Um I would say the second lab was definitely more simple and straightforward than the first one. So yeah I wouldn't really say challenging it's just like- The process of doing the lab wasn't really that challenging but getting some of the data that, wasn't what we expected like now as I am starting my lab report, like analyzing *that* is kind of challenging.
106	39:53	Interviewer	Can you tell me a little more about, you know, *why* it is challenging. And like and you can give specifics of the thing you are analyzing. Like in as much specific detail as you can, why is it challenging and how are you trying to ummm, you know sort of, deal with it. Deal with the report.
107	40:12	Caleigh	I actually haven't started, that- I haven't gotten that far into my report but, {okay} just like, so- we know- we know what's supposed to happen in those environments just from like our knowledge of biology and-
108	40:24	Interviewer	Which is what sorry? Just so, I know.
109	40:27	Caleigh	Um well like so we had c3 and c4 plants an in c4 plants the process of photosynthesis is slightly different, they're like separat- the two parts of photosynthesis are separated in space, so they will do better in hot environments because they can conserve water, um so like, they- they lose less water to like transpiration and evaporation. {Ok} So we know that C4 plants are supposed to do better when it's hot or when temperatures are high, but that wasn't always what we saw with our data so yeah it- that just got- it gets kind of confusing because I am not sure exactly how to proceed with my lab report its like I don't want to say like we did something wrong when like we followed the procedure pretty closely. So like I, am not sure like, if we did something wrong or if this plant is just somehow like slightly different. Yeah so like, we know- we are supposed to write about sources of error and that kind of stuff, but we are just not sure exactly what contributes to the results we see, so that is kind of challenging.
110	41:31	Interviewer	So w- what do you- so I know you've not finished it yet, or done a lot with it, but how- what- even if you've not like how do you think you are going to go about, you know, figuring out what to write and like dealing with the messiness of the data.

111	41:45	Caleigh	Yeah, I think the best way to approach it or at least what I think is the best way is just to like- to take into account everything that could have gone wrong and just like lay it all out there. So that- so I think that's important when writing the lab report because it is important to convey like what you know and like what I know is that all these things could have happened but we don't know which one it is so just laying it out,- all out there for the reader to see is I think that's how I am going to approach it.
112	42:12	Interviewer	Ok. Were there any other specific moments in the lab that were, and it could have just been a challenge that lasted for 2 minutes, you know? And not something that was really like, bigger scale. But were there any other moments you found challenging in the lab one that you found challening?
113	42:29	Caleigh	Um, in the first one?
114	42:30	Interviewer	In the second- in lab two, sorry.
115	42:34	Caleigh	Okay. Well, one of our plants, so like we measured it the first week and we were supposed to put it in our specialized environments and measured it the second week and one of our leaves actually fell off so we weren't able to measure how much that one grew. So it just like having a few holes in our data that's a little challenging. But like that's normal, other groups had that too. I don't know I guess it all like balances out in the end. But, yeah it was a little challenging just because we were supposed to like track the growth over three weeks and we weren't' able to do that with some of the plants.
116	43:08	Interviewer	So, what was that experience like for *you*? Like was it- And maybe (cough) maybe it didn't make a difference. And you were like "okay, you know." I- I- I want to know- like think back to the moment where you walked into lab and- (cough) you know you found that the leaf was broken or whatever what was that experience like for you? And then what did you, do?
117	43:31	Caleigh	Well, it was kind of, itwas frustrating because like we weren't able to analyze our individual group's data but I guess the whole point of having, many groups and like, a whole lab section, is that like we can combine everyone's data and work with it that way so like it was completely fine when we used the whole lab sections data, but it was just kind of annoying when we wouldn't contribute our full part to the data set. {Ah-huh. Ah-huh. Okay.}

118	43:58	Interviewer	Were there any parts in lab two, or any moments in lab two, when you found yourself being surprised by, what you were doing or what you found or, what you noticed?
119	44:11	Caleigh	Um. I was, I was surprised by like how much all the plants grew like regardless of their environment. So we know that some plants will grow slower in certain environments and other plants will grow faster, and like, we *did* see that but, I was just surprised by how much all plants, could grow even if there was a lot of co2 or high temperatures. Um, so, I guess like from a textbook or lecture we just know that one type will grow faster than the others but, like being able to see how much they actually grow and what the difference actually is like visually like I think that was surprising just because it was not what I expected at all.
120	44:49	Interviewer	In what way?
121	44:51	Caleigh	Um, I just expected like their like- if you put, the plant in a non-ideal situation, or environment I thought it would not grow very much at all but it still grew quite a bit like it might have just been like that particular type of plant like we worked with corn, rice wheat barley sorghum and like millet I think. Yeah so it might have just been those types of plants that grew a lot but I would think that if you put it in really high temperatures like don't give it any water give it a lot of c- um not enough carbon dioxide I feel like it would not grow very much at all but that all still grew. So like yeah that was surprising to be able to measure like we actually needed two rulers to measure the plant!
122	45:32	Interviewer	Ok. Okay. Were there any moments two, that you felt excited or, you know you felt like you were *really* engaged in what was going on?
123	45:44	Caleigh	Um yeah so the first week we were supposed to measure- we measured all the leaves, in both weeks and, on the first week we marked which plant or, which leaf had, the taller, or which leaf was the longest on each plant and the second week we actually noticed that the longest leaf was no- the longest leaf from the first week was no longer the longest leaf in a lot of the pants. Um, so like we- we don't really know. I guess part of our lab report is to try to figure out like what made that happen, but, um yeah it was just interesting to see how like thing can change so quickly just over the course of one week.
124	46:21	Interviewer	Mhm. Okay, cool. Any other moments that you can think of, when you were doing lab that, you f- were like felt like they were fun?

125	46:31	Caleigh	Umm. I think just like- so like each group was assigned a couple parameters like our group was high CO2 and low water. Um so like each group put their plants in different like containers that had those parameters and, it was just interesting to see the differences between the plants the following week. Yeah, and so like, because we knew exactly what was going on in each container like we- we could tell like which *factors* affected the growth more.
126	47:02	Interviewer	And that was like you found that personally interesting.
127	47:05	Caleigh	Yeah definitely. Because like we were just told- in lecture we were just told like that's what happened. Like we see the plants outside but like, when we have a controlled environment in the lab I think it's really interesting to be able to see, that and I think especially like we, we made those we kind of like made the experiment ourselves almost.
128	47:21	Interviewer	Mmm ok. Umm, can you tell me about um, things in this, um in lab two that you found were *not* so valuable for you? Um, you know in terms of what you were *learning* from lab two.
129	47:37	Caleigh	Yeah um, well, okay again we had a different articles, this time it was more related it was about plants and how like, climate change was just the rising temperatures and everything is, affecting how plants will be growing in like, twenty years from now. Um so I guess it was related, and the article was kind of interesting but having to write up a summary and like discuss it I just, I felt like was just like really time consuming and I would have learned more from a different activity I think.
130	48:07	Interviewer	What kind of- so generally what kinds of activities do you tend to prefer based on your, experiences with these two labs like what do *you* personally tend to prefer, or enjoy more?
131	48:18	Caleigh	I think what I learn from more is like actually doing the lab and getting the results and even writing up the lab report honestly. Um but like, I mean I guess that our lab instructors try to ^vary the activities that we do so they throw in a bunch of journal articles and a bunch of reading we have to do, and those like, *while* they do give some background and it's interesting to learn more I feel like with so much other work going on it's not the best use of time.
132	48:44	Interviewer	Okay. What, if I- if I were to call a biologist here. And, you know give them, what you did in lab one and two, and ask her- him or her, you know how do you- what do you think is the, least valuable part of

			what these students are ^doing, in their labs? What do you think they would say?
133	49:06	Caleigh	I honestly think, also think it would be like the journal articles or just reading. 'Cause I feel like, it's very valuable to, get practice like plating petri dishes or like measuring plants because a lot of us are going to continue on in like scientific careers and need to do all that stuff, but like, reading articles while like it's important to be exposed to that I also feel like we are doing a lot of reading in other classes, at least I know a lot of my classes we are reading journal articles too and I feel like they are more applicable in those, settings or just those, subjects ^in general. Um, so I feel like we are getting experience like reading- like reading *comprehension* and like, writing summaries of things. So, I feel like a bio lab especially like *lab* setting is not the greatest place to be doing more of that.
134	49:57	Interviewer	Mm ok cool. So I am going to ask you- you've talked about labs one and two, and just based on your experiences now in these two labs, umm, I am going to ask you a kind of broad question. And I want you to take a moment and think before you, you know, like you- just think about what you think- you want to say. If like, based on your experiences in labs one and two, what do you think- what do you think research that a biologist does look like? Like what does research in biology, for you look like? And I know it's really broad which is why I want you to think about what you, think about it. But like, yeah what do you think it is and what do you think they do day to day?

135	50:44	Caleigh	Um, well definitely making a lot of mistakes and having to like go, back and either redo the experiment or like figure out where you made a mistake and like change that part. {Mm} Um, which I feel like, 'cause we are working with bacteria that we have a lot of or plants that we can just go get more of it wasn't that big of a deal if we needed to redo the experiment. So I just feel like if you are working in maybe a medical setting, maybe like a drug trial or something where you have people and when there's a lot more at stake, I feel like, that will get very challenging sometimes. But so like, in our lab if you are just working with plants and something happens you go- you like, you tell your instructor they give you another plant. So like it's not that big of a deal when we make these mistakes. So I am glad we are doing these labs now because I feel like some of us are going to, like end up working with people or like animals maybe when the stakes are higher almost. {Uh huh} Yeah, so. I feel like I definitely see, um like experiments needing to be redone even in like a biologists career. Um also just like writing reports that, involve, like understanding different perspectives, just like if you don't see something if you don't see results that you expected being able to, try to think about like where those results came from. I think that's- that's something that will stay as you, progress through your career. Just 'cause there is no way for you to know exactly like where something messed up or where you changed something.
136	52:25	Interviewer	Ok anything else?
137	52:28	Caleigh	Sorry, Let me think about it. {Uh-ha}
138	52:34	Caleigh	So like where- like you're saying *what's* going to stick with you like throughout your career, right?
139	52:40	Interviewer	Yeah or like what do they *do*? Like what does a biologist do? Or what is biology about but that's, even broader?

140	52:49	Caleigh	Yeah I mean I feel like, *definitely* doing a lot of experiments just 'cause, you don't- like even if you just believe what your textbook or your professor says like you definitely understand it better and you remember it better when you're actually doing it. This is totally off topic but in my high school we had a talk once. So he was a, I think he was a psychologist at Stanford, and he was say- he gave us a bunch of tests, and one of them was about remembering words, and he would like give us a word, and for example like ocean, and we were told, we were shown like five words- like five short words like ocean, and then we were shown five other words with one letter missing. Um, but like they were- the word was obvious enough that like you could figure out what letter was missing and, what he, sh- I forget exactly what he did, but what he showed us was that we remembered things so much better when you struggle a little bit and you have to figure out what that missing letter is. So we actually like, most people remembered the words better when they had a letter missing. So, I think what he was trying to tell us was that you understand things better when you have to think through it and almost struggle through it a little bit. So, I think that's partly why I remember things so much better in lab. 'Cause like we did it- we spent a lot of time and effort on it and we had to think through it. So, I think definitely, biology means having to, um I guess like make mistakes in the process and, but like figure things out, figuring things out for yourself too.
141	54:27	Interviewer	And you- like you- Do you see labs as kind of a way to help you remember what you do in lectures? Is that what you are trying to say?
142	54:38	Caleigh	Yea yea. Cause I feel like lab 2, out of the entire unit two on plants what I remember the most is how like carbon dioxide and temperature and water like affect plant growth um so I feel like that was a very important part of unit two that's why we did the lab on it but at the same time, doing the lab helped me remember it better.
143	54:57	Interviewer	So are you thinking, are you thinking of, is it that doing the labs, you know it's just and accident like, it's coincidental that doing the labs help you remember what you did in lectures, or do you think the labs are designed so that you remember what you did in lecture better? Which- Or maybe you are saying both or just one of them, I am not sure.

144	55:18	Caleigh	I- Well I think the labs are designed so that, we, can, do the lab on the most important parts of lecture. But like they definitely do help me remember what we covered in lecture. But like- So I guess I feel like the lab instructors or the people who design this lab know that doing the lab will reinforce, so I guess they- I- in my opinion they are choosing the most important parts of lecture to do a lab on.
145	55:42	Interviewer	And what what is their goal for you?
146	55:44	Caleigh	I think it's to help us remember lecture better, yeah. I don't know I might be wrong, but I- Yeah, I just I think they understand, like people who design the lab understand that doing it is going to reinforce what we learned, so that's why they are trying to- they're trying to pick out the most important parts for us to do the lab on.
147	56:12	Interviewer	Sorry I forgot to ask you one question. I know in lab two also there was some kind of simulation that you did, you changed some settings somewhere. Um, can you tell me a little more about what your experience with *that* was like, whether you thought it was useful for what you were doing in the experiment or, maybe not. I don't know.
148	56:33	Caleigh	Yeah, um so the factors that we changed were, basically the ones that we used in our lab like co2, temperature and like how much water there was. {Mm} Um, so it basically,- the simulation just kind of just made the plants grow faster. It kind of like compressed time almost. {Mm hmm} Which, um, which was important because we didn't have very much, like we just had two or three weeks to watch the plants grow. So it was nice to be able to, um use a computer simulation to, figure out like how those changes would be, how we would see those changes over a long period of time. {Mm} Um so like, it was interesting to use in that sense because like we can't- we can't really do that. Um like we can't watch our plants grow for a year, like we just don't have that kind of time. But what we saw with the simulations was, that it matched like the data we saw over 3 weeks. So like, I guess that was one difference between that lab and first lab where our data was more reliable so we knew that our data was probably like, what's going to happen in,- like if were to let the plants grow for a few more months.
149	57:42	Interviewer	Mm. So you were using, so you would assess what you were seeing in the simulation as, maybe more accurate if it reflected what you were seeing the in the experiments.

150	57:53	Caleigh	Yeah I think so, just because it's like a longer period of time, we're doing the simulation more times. So like, I feel like there is less chance that, I feel like the computer simulation wouldn't mess that up. {Mmm}
151	58:06	Interviewer	Oh wait, wo you are saying the other thing. Tell me what you are saying again? So I asked,/ that's okay. I asked, I thought you were saying, you trust what you see in the simulation, [yeah] if it reflects,- if it shows the same things as what you see in the experiment.
152	58:11	Caleigh	/Sorry, what did you?
153	58:24	Caleigh	Oh. No I think we, or at least my group we, we trusted, that we did the experiment right if that reflected what we saw in the computer simulation.
154	58:34	Interviewer	Mm mm. Ok. And was it the same for lab one too?
155	58:38	Caleigh	Yeah. Just because I feel like when we are doing something there's a lot more room for error than if a computer is doing something.
156	58:45	Interviewer	Mm ok. And what did you find for lab two did you find the simulation useful in any way in writing the report? /Well in, you've not written it yet.
157	58:53	Caleigh	Yeah definitely,/ just like, knowing that, we don't have to account- like if the simulation was completely different from the results we got we would need to know like- we need to expand the section on like the errors that we could have made or the possible errors we could have made. Um, but since they, the sim- it's kinda- the simulation is almost like, reinforcing like telling us that our results were expected.
158	59:20	Interviewer	Mm hmm. Ok cool. Ummm. I think that's it. Thank you so much.
159	59:29	Caleigh	Yeah of course.

Appendix 5.3—Transcript of Interview 3 with Caleigh

A note on notation:

, indicates a noticeable pause
/ns/ indicates an n second pause
- indicates interrupted speech
^ indicates a rising inflection
* indicates emphasis
[indicates student overlapping interviewer]
{indicates interviewer overlapping student}
(indicates a note, typically a paraverbal or gestural cue)

Line	Time	Speaker	Turn
1	00:02	Interviewer	Okay so um. We'll start by talking about the third lab. Which is your final lab. Um /2s/ were there any parts in your third lab that you found to be, um, particularly, challenging.
2	00:17	Caleigh	Yeah, so our- as you probably know our third lab we had like a student designed, component to it. So there was, umm, there wasn't any instructions or anything that we had to follow. We were just given all of the materials we could possibly imagine {okay} using, and we were asked to design, um, like an experiment to test a hypothesis of our choice. {mhm} Umm, and then, we met up with another group. S- and the two groups like talked about which, um, which experiment they liked better. And then the two groups decided on one and both of them did the same experiment so that we would have like some- some sort of, like, kind of like, a different set of results just in case like something didn't go right. Um, so my group decided to test whether or not beetles would prefer laying eggs on black beans, or brown beans {okay}. Um, so we had two groups, both did that experiment, and-
3	01:12	Interviewer	So you were kind of thinking the color would make a difference, [yeah] is that what you-
4	01:16	Caleigh	Yeah, because we had some pre-lab experiments that showed, that certain types of beans, like the black beans - and then the brown beans were cowpeas - so, like the black beans got a few more eggs than the cowpeas ^did, so we were just wondering if it was the color or if it was like the nutrient content of the beans. We just- like we were trying to figure out what *factor*, was making certain beans more appealing.
5	01:36	Interviewer	So how did you figure out which fac- like how did you distinguish color, from, nutrition-
6	01:42	Caleigh	Well we di- we, we kinda- our hypothesis was that it was, *color* that made, like, black beans more desireable and that it wasn't the nutrient content. {okay} So like we weren't sure, but that's what the hypothesis ^was. {u-hah} And, so one group got, results, that showed like one- like we did statistical tests, and we showed- one group showed that the difference was statistically *significant*, but our group, the results weren't very different. {Okay} So, it was just kind of hard to explain because, um, like, we had designed this experiment, there were two

groups doing it and, the two groups got very different results, so that was a little difficult...

7	02:19	Interviewer	So can you tell me a little more about how you were trying to- because like, how you were trying to separate, color from nutrition in the design of your experiment and like how you went about then analyzing ^your results.
8	02:29	Caleigh	Yeah so, well, it was a little difficult to figure out like nutrient content i- ^sspecifically. So we ha- we mainly just focused on color. Cause the color of the beans, it was a very clear difference like the black beans versus the cowpeas were like a beige color. So, we kind of just said that, the nutrient content didn't matter as much as the color, and we tested our hypothesis through ^that, perspective. And we also made sure that all the beans we used like weighed approximately the same ^amount. So that like controlled for the size or the mass. (unclear)
9	03:03	Interviewer	Oh, so all the beans like *including* the cowpeas and the, the ^mung beetle- beans. [The black beans, yeah] The black beans [yea]. Both of those you were making sure were all the same [yeah], ohh.
10	03:13	Caleigh	So- the only difference that was like very drastic was the color, so {okay}, that's what we tested.
11	03:18	Interviewer	Okay, and so then tell me what you ^found, and why that was ^challenging.
12	03:23	Caleigh	So, so, like I said two groups did the same experiment, and one group found that black beans got significantly more eggs, than the ^cowpeas. And our group found that the number of eggs laid on the two types were pretty similar. So, we don't know if their results were due to chance, or our results were due to chance. So it's just kind of hard because we only had two groups doing the experiment so like it was hard to tell which group had more like, reliable results.
13	03:49	Interviewer	*Yeah*. So what did you end up doing?

14	03:51	Caleigh	Um, so in our lab report we talked about, like, um- we analyed like both sets of data as if they were our own. And we talked about the possibilities that could have led to each, occurrence. But we weren't able to draw conclusions about which one, um, was like actually gonna be seen more com- more often in real life.
15	04:11	Interviewer	Mm. So wha- how did you explain your results?
16	04:14	Caleigh	We just- well, like like our hypothesis was that, there would be a difference in the number of eggs between the different colors ^. Um, so we just said that the beans- I mean the beetles don't really care what color the beans are, when they lay their eggs. They just want to lay their eggs on any bean, that's, there. {mhm} So that's how we explained, like, not finding a difference in ^ours. And for the group that did find a difference we said that they preferred, like the black beans because maybe they were darker, they were easier to see. (Laughs) Yeah, but like, with only two groups doing the experiment it was hard to come up with like concrete, {Yeah} results.
17	04:47	Interviewer	Yeah, I can imagine that. So, umm. Wha- how did you say- it's very interesting because when you talk about your lab reports, you know you ar- you're saying *we* did this and I'm curious about whether- did you- did you collaborate with your group in writing the lab reports? Did you guys work ^together? Or?
18	05:04	Caleigh	For the results section we were supposed to like come up with a- like a single results section for the whole group. {Okay} So we worked together on that, but that was mainly just, like saying we found this many eggs on this bean. So it was very straightforward. But the actual ^analysis of it- like we talked a little amongst our groups but writing it in the lab report was our own work.
19	05:23	Interviewer	So the- the talking you guys did in the ^lab, or were you also talking about and discussing it outside of lab?
20	05:28	Caleigh	Mostly in the lab. So the lab itself didn't take very long so we had some time to, just figure out- try to figure out why we saw those results.
21	05:36	Interviewer	Mm. So, did you feel like you were able to resolve them- this- these difficulties you faced? Or were you left feeling like...
22	05:43	Caleigh	I mean, I feel like talking about it in lab definitely helped but like, it was still hard like all of us, still found it difficult to explain like why the two groups got such different results. So I think just, providing,

possible explanations for it in our lab report, was like the best we could do.

23	06:00	Interviewer	So wait. I know how you explained your own results. I don't think I know how you explained why the two groups got ^different results. What- [yeah] what did you say?
24	06:07	Caleigh	(Smiles) We just- well, we thought that- 'cause we had put different beetles in, we just thought that certain beetles might, not have a preference while other beetles might prefer darker beans... Yeah, so we couldn't- we didn't have a way of putting the same beetles in each o- in each of the groups. So that was a factor that could have affected /2s/ the different results.
25	06:29	Interviewer	So that's- that's the explanation you, [yeah] went with? [unclear] Was- are there in any of the things you discussed in there?
26	06:36	Caleigh	Umm... we also talked about, so the time of day we put the beetles in we- the groups had to go in separately and my group went in about 11am. And then, we let the beetles sit there for twenty-four hours and then, at 11am the next day we counted how many eggs there were. And then the other group, had, gone in around like 5pm, and then like waited twenty-four hours 5 pm the next day they counted the eggs. So, we said that like we don't know what time of day has to do with how many eggs they lay, but we said that that could have been a factor because that was not controlled for in our experiment.
27	07:08	Interviewer	Okay, cool. Umm, were there any parts in the *third* lab that- or any moments in the third lab that you found, *surprising*. Or you were like, *"oh"*, you know? Uh, yeah.
28	07:21	Caleigh	I think it was just like, how, two groups that did, like almost the same thing, got such different results. That was really surprising, because we know the things that couldn't be controlled for but the things we *could* control for we- we thought we did pretty well. So we weren't expecting to see like so different results.
29	07:38	Interviewer	Were- were your results in the same direction? Even if they were insignificant, were they [yeah] in the same direction?
30	07:43	Caleigh	They were, but, just like, one was significant and one was not significant at all.
31	07:50	Interviewer	Were- were they significant combined? The results?
32	07:52	Caleigh	No, not even (laughs). [Ah, okay, okay] Yeah.

33	07:57	Interviewer	Okay, umm. Alright. Um, can you tell me about, some moments, uh if there *were* any, in lab three, when you felt like you were excited about, what you were doing?
34	08:09	Caleigh	Yeah, well I, really appreciated like the opportunity to be able to design our own experiment, because, um that's not something we usually get to do in the lab, and like a lot of different groups um, came up with really cool experiments. Like I don't know all the results of them but, like one group tested to see if the beetles prefer like laying eggs under shelter, they took like an egg car-ton put on. So just like coming, um, up with this ideas, and like seeing what other groups come up with, like I thought that was really interesting. {Mhm} Yeah and, that was definitely something that I hadn't *expected* going into like (this class). Like I thought our labs would be like, our instructor would tell us what to do. But having this opportunity, to, do what, we thought was interesting and then write up a lab report, that was, I thought a very valuable experience.
35	08:55	Interviewer	In what way?
36	08:55	Caleigh	Well just like- I know experimental design is going to be really important later on like whether, or not, you're going to go into hardcore bio research I think being able to think outside of the box and figure out *what* you're really interested ^in, and then, finding a way to get those ^answers. Um, I think that's, like a really good learning process, that, like we were really lucky to have.
37	09:16	Interviewer	Mm. Okay, cool. Umm, so I, like, you've talked about this a little bit already but I'm curious about how then, this experience of- like how lab three panned out for you, translated into how you work on the third lab- the lab report for the third lab. And, you know just *generally* how did you- because it wasn't ^even clear really what the big question might have [yeah, exactly] been. So like how did you end up you know figuring that ^out and then how- w- like how did you, work on it?

38	09:48	Caleigh	Yeah so we weren't exactly sure like what, our, what we were testing. Because we had a like pretty general hypothesis but we didn't have much, like research, or like knowledge behind why we chose that hypothesis. Because like I said we didn't really know much about the nutrient content or, what else was different beside- in the- between the two beans. So like it was a little confusing, um, approaching it that way. And also, just, because the two groups got such different results like I was really nervous about writing our lab report, because like, I wasn't sure if we had done something wrong... or if our TA would perceive, like our different results as like we had, designed a poor experiment. So yeah like, it was a little nerve-wracking having to, like, deal with the results and then put it into a lab report. But like we got our grades back. (Laughing) It wasn't that bad. It was... {It wasn't bad} Yeah, so I think, the like overall process of doing the lab definitely like, outweighs, like the cons of having, like, not so great data (unclear).
39	10:46	Interviewer	So how do you go about putting the argument- like how did you go about writing up the report?
40	10:52	Caleigh	Yeah. So, we talked about like the two different /1s/ two different results we saw. And, we, kinda- we almost wrote like two, mini lab reports within one like, analyzing the two different situations. And, so we have to talk about like why, we thought, both of the situations happened and, like what we could to do change- or to do differently to the experiment, to ^adjust for both of those. So, it was almost like double the work because we had to like, take into consideration {yeah} what other groups got.
41	11:24	Interviewer	Yeah. So, you said before that this was like the first time you designed an experiment yourself. [yeah] You didn't do that in labs one or two. So, was the process of writing the lab report this time- was it different from your ^earlier two lab reports or was it kind of similar? I'm just curious.

42	11:41	Caleigh	Yeah it was definitely different like it was, a l- it was harder because we weren't sure like, what direction we were supposed to be taking. But at the same time I feel like, it made me feel, like more comfortable taking more risks. Because I feel like with the first two lab reports like we did a lab like, our TA's know exactly what we did and I feel like he was looking for very, specific, like results inside our lab ^ report. But like with the third lab because everyone took like different approaches, I feel like we had more freedom with like how to, like structure a lab report and like present, our results. So like even though our results were really confusing I feel like we had more flexibility with how we like *conveyed* that information.
43	12:21	Interviewer	Mm. Mm. Okay. Um, cool. Ummm. There was something you just said that I wanted to follow up on. Let me think back, to what you said. /2s/ Yeah, so you said that like there- because there was no,- because it was kind of really open ended and you were kind of, right, framing your own question [yeah], it was kin- you didn't have to worry about what the TA, was thinking of what, you wanted. Like, that could have also been really nerve-wracking. [Yeah] Right? [Yeah] And, yeah. Can you talk about why that *wasn't* nerve wracking?
44	12:58	Caleigh	Yeah. Well like we weren't sure if our, like, if our experiment would be too simple or too complicated. It was kind of just do, whatever you're interested in learning about, and we weren't sur- we were interested in, the difference between bean colors but were weren't sure exactly, how feasible that was going to be through an experiment we had to do, like within a ^week. So we did get feedback from our lab instructor, like we had to write up a little like, proposal for what we were doing, and, like he approved it. So I think that was- that was really helpful like knowing that we were heading in the right ^direction, before we did the whole experiment and wrote up the lab report. So, I think like having that little bit of, of, like reassurance definitely helped.

45	13:37	Interviewer	Yeah, yeah, yeah. So wait- so okay- so I'm going to ask you now more generally about like all of the three labs together. [okay] So, you know you- you're saying that in the third lab like being, sort of- having like an open ended thing, umm, where it wasn't exactly clear what you needed to do and so that allowed you to say what you thought you wanted to say, was um like, was um, was exciting, right? And tell me if I'm putting words in your mouth. But was it like a good experience, it sounds like. [yeah] Generally, you are saying. Um, can you think about other moments- so it was like there was an uncertain situation, and, the way you responded to it, or, like, how you felt about it, you felt goodish about it. Umm, could you tell me about other, like, similar uncertain moments in the rest of the labs. And you can think about back to labs one, or two. And like, I'm- tell me a little more about how you- what those were like, and how you ended up responding to them.
46	14:40	Caleigh	Yeah, I feel like in labs one and two when we had our uncertain moments it was- we kind of felt like we were doing something wrong because, there was something, like, there were specific, guidelines for what we were supposed, to be doing. And if we did something wrong, um like that- it's very clear that we, did something that was not on the procedure. But with lab three, whenever- like when we had our uncertain moments, it was, it was kind of like, we kind opened another path for us to go down because like the whole thing was student designed. So like if we were intereste- more interested in one thing *after* realizing like we did something ^, then we would go down that path. Like there was just so much more, like flexibility within the third lab so, we didn't feel like we were doing anything wrong, even if like i- it deviated from our original plan.
47	15:27	Interviewer	That's interesting. So like I'm going to ask you to ^give me, you know a- two specific examples. One of when, it was an uncertain situation in which you felt like, you know it was harder and one where it was easier for you to to deal with.

48	15:41	Caleigh	I think- I remember in lab one we were like diluting some samples of bacteria. It was like e-coli and we wanted to make it more dilute so we were putting I think it was saline in it. Um, and we weren't sure how many times we were supposed to ^dilute it. And, like that was a little nervewracking because we weren't- we weren't sure if it was going to be too dilute or, like too concentrated. Um, so, I think *that* was hard because we knew there was a specific like concentration that we needed to get the bacteria to. But if, that had been in lab three where we had designed, our own experiment like we could have just- we could have stopped whenever like it didn't have to be a certain concentration. {Mm} So, just, just like knowing that our mistakes can be corrected, to, like fit what we were testing that made us feel a lot better in lab three.
49	16:29	Interviewer	And you felt like in lab three the mistakes could be corrected because, umm, because there wasn't someone telling you (unclear, interrupted)
50	16:37	Caleigh	Yeah, I think it was our lab instructor wasn't looking for like specific results. It was just kind of whatever, results we got we were supposed to analyze that to the best of our ability. So it was more of like the process and the analysis, in lab three. Versus like, I feel like in labs one and two, part of doing the lab was making sure that we could follow like a procedure or protocol.
51	16:57	Interviewer	So okay, I'm going to ask you a question that might seem really strange. [mhmm] But like I want you to tell me, or just talk me through, what were the things, that you saw in labs one or two- one and two, that made you think that you know the instructor might be looking for a specific thing, like a specific (g - hand motion). And what were the things in lab ^three, that made you think that, "I don't think taht they're looking for a specific thing here."?
52	17:20	Caleigh	Yeah well I feel like, from like a very, basic, point of view just like for labs one and two we were given, like, a procedure like, we were supposed to following it step by step an everyone- {like you knew you were given a worksheet or something?} Yeah, and everyone's given that same piece of paper, so our results should more or less be the same as those of our ^classmates. So it was really obvious if one group did something wrong. Umm, but with lab three like every- or every *two* groups did a different experiment and it was more of like- figuring out, what each group found from the results, like from th- *doing* the experiment, and not like whether or not each group did it correctly.

53	18:00	Interviewer	W- are there other things that- so so having like a worksheet the same worksheet being given to everyone made- like made you think of, like, this needs to be done correctly. [Yeah] I guess that makes sense. [Yeah] Were there other things? Umm, and like take a moment to think if you'd like but like other things for you triggered 'labs one and two are, (g) like protocol needs to be followed [yeah(laughing)] and three is more, open ended.
54	18:23	Caleigh	Umm /2s/ Well, I mean, our lab instructor did tell us that for like one and two we were learning, how to like write, a lab report like structure it, properly. So it just seemed like, there was- there was, a set of- set of instructions that he wanted us to follow, and that like, as we got *better* through, after lab two we were allowed to have more freedom in lab ^three. Kinda like, how, the difference between grammar and usage like once you learn proper grammar you could like kinda bend the rules a little bit to make your writing better so, it was kinda like he wanted to give us a very good foundation with labs one and two. And then, after- after that we were given like more flexibility. I feel like even with writing the lab report- um because all the groups got different results, an- he was very open to it. Like our grades showed that he, he didn't like grade too harshly because we got different results.
55	19:15	Interviewer	Oh so in labs one and two the grading was kind of-
56	19:18	Caleigh	I think it was more, it was very, strict. And it was almost like, he had a checklist and, he wanted to make sure like certain things were in our lab report.
57	19:27	Interviewer	Mm. Can you give me some examples of some of the things that were important to the TA for you to have?
58	19:33	Caleigh	Um, so like, he- we talked a lot about like the introduction section, and how it needs to tie into like the bigger picture. Um, for example, for bacteria we were looking at like mutation rates so, he wanted us to tie in mutation rates to how like, um, different organisms, more than just bacteria, like how *people*, do better in certain environments if they have a fast mutation rate. And so, just like, having to apply, what we're learning in lab to wha- why it matters, um, that was really important in the first two labs. And then like in the third lab, that- I feel like that mattered less because we, we couldn't really tie in like beetles laying eggs to like, other, organisms. Or like we hadn't learned, very much about like why beetles chose to lay eggs in those places so, we just had less background information, and I feel like he

			thought that was okay with the lab instructor because we've shown in the first two lab reports that we could do that.
59	20:31	Interviewer	Mm. Mm. Uh, other things that come to mind? In terms of like, why labs one and two, in the lab reports seemed like- or in general, seemed like more like, protocol-ish and the third one seemed more open.
60	20:46	Caleigh	Also just like how we analyze our results in the first two labs I feel like it was a very, rigid, way, that we had to go about analyzing our results in the first two like plants, um, he knew exactly like how much which kind of plant would grow, and in under what conditions they would do better, and I feel like that's just- it's so like scientifically accepted that, we couldn't analyze the results in a different way.
61	21:08	Interviewer	Wait, say more. Can you tell me more what you mean by that?
62	21:10	Caleigh	*Yeah*, I feel like, like we were comparing C3 and C4 plants and like every bio textbook out there will tell you that like C4 plants, do better in hot, environments. And if we got, results that showed our C3 plants did better, um like, we can't really write a lab report saying C3 plants do better. Because like everyon- like every scientist will tell you that C4 would do better. So I feel like, because they were very specific results that, they were looking for in the first two labs, like we had to write our report and analyze our data like around those. Around what was expected.
63	21:42	Interviewer	So did you feel like, in the first two labs, umm. You know of course scientists- you're right, there are some facts that might be thought of as 'this is accepted truth' whatever that means [yeah] with- in the biological world. Umm, but did you feel like if your results didn't suggest that, then, did you feel like you had the agency to make an argument saying 'this is what I found'. Or did you feel like you had to, bend your results to, somehow fit...-

64	22:12	Caleigh	Well we had to say like, this is what found. Like our- in the results section we presented our data and we said like this is what we- these are our results. And then- but then, if it wasn't- if it when against like one of those scientific truths then we had to like say, our like, potential sources of error, like where we made mistakes. Like, it was on us, and not like, the experi- or like, we had to figure out what we did wrong to get results that went against those scientific truths. Um, yeah- so that was just a- most of my lab report for the second lab was, like trying to explain like why we got, results that like (laughs) no other scientist would get. Yeah so, I feel like, just knowing that, knowing that, our results aren't expected, like that was a little difficult. Especially because like we knew that what the TA was expecting, for us to see.
65	23:04	Interviewer	Okay, cool. Umm, so okay. So, um, I'm going to ask you like now that you've experienced this whole semester, right of three labs, what's your sense for, um, why the labs are structured this way um, from the perspective of the instructor who is, like designing these. And I don't mean the TA, who's you know kind of leading the, thing but like you know the faculty members who are designing these labs. What do you think they have in mind? In designing them?
66	23:39	Caleigh	Well, I think the first lab like definitely, it went, along well with like unit one, like professor Chu's lectures. That's like the first, um, one-third, of, the, class.
67	23:50	Interviewer	What do you mean by went really well, with, it?
68	23:53	Caleigh	So like we talked about mutation rates and bacteria, um in the lab. And we talked like- talked about, like advantages of different mutations rates in lecture, and like how that relates to populations as a whole. So I feel like what we learned in lab really complements what we learned in lecture. For that unit. And then the th- the s-
69	24:10	Interviewer	And you're saying that is the, the- what are you saying about that with respect to the question?
70	24:16	Caleigh	Like i- it, complements what we learn in lecture really well.
71	24:20	Interviewer	So you're saying that the instructor did that deliberately. [I think so] So that the two go together.

72	24:25	Caleigh	I think- I- I don't know how they, design the labs. But I think that each- like the first unit was supposed to be population kinda, big picture ideas. And, umm, the second unit was plants and that's what we did in lecture. And our lab two was about plants. And the third one was about beetles and we talked a lot about physiology in the third unit. So, I think they were supposed to line up or at least they lined up very nicely, in my opinion. {Uhhuh} Yeah, and so, in the second lab, it was about plants, and we had learned, all about plants, in lecture. And we have learned, like- we have learned basically the exact opposite of what our results showed us. So it was definitely helpful to learn like the cor- learn the (g-air quotes)correct thing in lecture so we weren't- we weren't just taking our results and like learning from that. So it was helpful to know what we should have seen and then we did the lab and we saw something different and we wrote about like why we saw different things in the lab report.
73	25:21	Interviewer	Did you find that like- did you feel like that was a productive thing to do? Or did it just feel like, you know?
74	25:28	Caleigh	I mean it was definitely really frustrating, because like we, we don't even know what we did wrong. We can just, suspect. Um, so yeah it was really frustrating to have to write an entire lab report, about like, about why we might have messed up. So it almost like- if felt, like, the TA or like the whole process was kind of condescending.
75	25:51	Interviewer	Mm. In what way?
76	25:53	Caleigh	It's just like, a- we- we tried really hard to follow procedure, we thought were doing everything right and we knew what we were expecting because we had learned that in lecture, and then we got like completely different results. Yeah, so it was kinda, just like, all the blame was on us because w- we- we were the ones doing the experiment and it didn't turn out the way it was supposed to.
77	26:15	Interviewer	Mm. Okay. Um and then- so wait. So we were talking about like, how do *you* see, your perspective of how the instructor des- what the instructor has in mind in designing the labs.

78	26:28	Caleigh	Yeah um. I think, well, having more structure in the first two labs, was definitely something they had wanted. And then, I guess in the third lab, um, the self- like the student designed experiment, that just gave us more, like, more, freedom to do- to do what we wanted to do because, um we had already learned all these rul- (g)not rules, just guidelines and like, recommendations in the previous ^labs. So like, if the third lab had been done in the beginning of the semester I think everyone would have gotten like really, like unreliable data. So like, definitely, starting off and like building a solid foundation in the first two labs was really important.
79	27:09	Interviewer	Mm. Why do you think everyone would have got got unreliable data, if the first lab was open ended?
80	27:15	Caleigh	I think- we just- most people had not any experience with like experimental design. So having done two labs with like a set procedure, and then- and like part of the lab reports was, analyzing what could have been done differently in the procedure to make things a little better. So it was almost like we were critiquing things in the labs and then applied that experience and made our- design our own lab,, at the end.
81	27:41	Interviewer	Okay. Um, so you talked a little bit about the alignment of the content. And you talked a little bit about the beginning being more ^structured, um, as you were seeing and then later being more open-ended. Right? Are there other things- other goals that you think the instructor has in mind for um, students when their designing these labs or just, that's why they design them this way.
82	28:06	Caleigh	(Nervous laugh) Uhhh, I'm not sure exactly. I think, well I think the alignment was definitely really important because like we learned about it and then it was reinforced. And then we were given like the opportunity to think about like why some of those, like a little like off data could have ^happened. And I feel like thinking through that, almost like reinforces it even more because we're thinking of like other possibilities also. Umm, yeah, so like, if, if we had done lab two, if we had done the plant lab before we had learned about plants in lecture that would not have worked very well because we would have thought that our results like our- our incorrect results are what's really happening in real life. So, I feel like having, having had some background information from lecture definitely helped.

83	28:53	Interviewer	Okay cool. So like- so in, you know people that design curriculum for students and stuff, they they typically have this format of when they're designing they'll say 'by the end of the unit, students should be able to' and then they list [yeah] some things that should be important goals for them. [Yup] So if I were to ask you to like list *three* goals like that. That you think the person who design- or the people who design these labs might have had in ^mind, what do you think those three goals would be? (g-interviewee looks at ceiling)/2/ And, feel free to take a moment to think if you- if you'd like.
84	29:28	Caleigh	I think, just thinking about the first two labs definitely like being able to follow, like a procedure or protocol when you're handed like a sheet of paper with, the instructions. So just like knowing, where to get the materials and like how to put all the materials together to like follow instructions. I think that was really important in the first two labs. And then, you said three things? {Mhmm. Like three *goals* you think they had in mind. Three things they wanted you to get better at.} I think the second thing would definitely be, just when you get data that's not expected like how to properly explain why you think you got those results. And then, um being able to like *suggest* ways to like perhaps change the experiment. Like that was a big part of our lab report. Um, just like alter- like where you could change the experiment just a little to get the results that you had expected to see. So just like analyzing results that might, not have been expected. Umm, and then third, I think b- designing your own experiment was important because that's going to be helpful for a lot- I'm sure a lot of students are going to have to go on and like design experiments in other classes too. So just having, um, like an open ended assignment like that, where you could, really, figure out what you were interested in. Figure out how to go about, getting those answers.
85	30:49	Interviewer	So could tell me a little more about what that meant? [what-] In terms of how to do it. Like designing your own experiment.

86	30:57	Caleigh	Yeah so I think talking with like our group and then like another group, just like spitballing ideas back and forth was really helpful because they could tell us what they think was wrong with our idea and we can tell them like how they can change their idea a little bit. {Idea about?} About like how to design the experiment. So just getting like, feedback from your peers I thought that was really helpful. I was like, they're in- they're in the same class as us, they like in theory don't know much more than we do but, but just like, I guess different minds will think of different things, sometimes. So, yeah, it was really helpful to work with our peers in lab to, like come up with an experiment that everyone was interested in and everyone agreed on how to proceed.
87	31:37	Interviewer	Okay. Cool. Umm, so now, I'm going to ask you like, you know, given how you've described what the goals of the designer of these labs might be, how well does that fit, with what *you* wanted to ge- wanted to take away from these labs having signed up for (this class)? [Yeah] Like, do those two ^fit together, do they not fit together? Are there some parts that fit and others that don't? Um, yeah.
88	32:05	Caleigh	Yeah I mean, being able to like follow a procedure like that was definitely important to me, and I had some experience with labs in high school. But, just being able to follow more rigorous protocol and like do more labs was like, it was a great part of (this course). And then, analyzing the results. So like, I feel like in high school labs - those were my only other experience with Bio labs - like we got results that were pretty much expected so writing up a lab report was like summarizing results explaining why that is. Um, so having like the opportunity in (this course) to like write about why we got unexpected results, so I thought that was really interesting but it was also like really frustrating as we were doing it. Just 'cause like we- we weren't sure like what we did wrong. Um, so, I feel like I definitely got more experience, working towards meeting that goal, um, even though it was pretty frustrating along the way.
89	33:04	Interviewer	Um, were there things that you wanted to take away from lab that didn't quite align with, um, how the inst- how the designers had set up the lab?

90	33:14	Caleigh	Umm, I think, if we had, had like more and then shorter labs then that might have been more interesting. Just because I feel like the entire plant unit like all we did was this one lab, and our results weren't even like, 'correct', for lack of a better word. Um so, I feel like having more labs would give us more opportunites to kinda just like get, a better sense of how, labs should be done. And, just, maybe give us more chances to get like correct results. Yeah, it just seemed like having like one lab per unit, meant that all our results were like- everything, rested on that one experiment.
91	33:53	Interviewer	Mm. Mm. Um, what do you mean by correct results? Like, how are you thinking of that?
92	33:58	Caleigh	Um like well going into the lab we had a pretty good sense of what we were expecting. Especially for like labs one and two because we had learned about, a lot of that stuff in lecture. Um, so it was just, hard when the one lab we did for that unit, was- gave you completely different results from what, we had learned in lecture.
93	34:16	Interviewer	Do you think the instructor - like the designer of the lab -- wanted you to, you know get the same results? Or do you think they wanted you to have it either ^way and then like, f- how do you see what they were doing there?
94	34:30	Caleigh	Um, I ^think, either way they wanted us to have the experience of writing a lab report. Like, even, even if it means analyzing why you got results that weren't ^expected. Um but, I feel like even they were confused about why we got such, different results. Cause our lab instructors couldn't explain to us, and like noone knew where the mistake came from. Yeah, so I feel like they definitely- like they weren't trying to- trying to give us, like a faulty experiment. It just so happened to turn out that way, and they,- I still think think like we learned a lot from being able to write a lab report and like analyze why we got results that we didn't expect.
95	35:15	Interviewer	So wait, so- so think- so. Let me make sure I know what you are saying. So you're saying, in lab two though it turned out that you got results that, contradicted what you might have expected. Yet you're saying the designers of the lab might have been- were they- were they okay with that, or were they kind of bummed out that "oh shoot that didn't happen now". Like how do you think they responded to it?

96	35:37	Caleigh	Um, I think they were probably just like, 'we don't know what happened'. Like they were a little confused about what happened but, they knew that, even with, our like- even with the results that we saw we would still have a very valuable experience writing the lab report and trying to figure out where the specific error came from. So like I don't think they were too upset that we got, those results. It was just, I think they were more confused as to where they came from.
97	36:02	Interviewer	So like going in they were hoping you would get, is that what you're saying? [Yeah] Going in they would- they'd, *get* the results and then, it's ^confusing but it was like well there can be value in this [yeah]. Is that what you're saying? [Yeah, I think so.] Okay. Okay, cool. Umm, so I'm going to ask you a really general question now, and like think for a moment if you'd like, before you answer. Um, think back to all of the labs that you've done so far. And like, I want- I'd like for you to, talk about what you think will stick with you, from the labs (you've done?). What do you think you'll take away?
98	36:35	Caleigh	Umm, well definitely like being able to, analyze, results that, we thought were wrong- it was the first time I did that. And, just thinking through the whole process of writing up the lab report, was, definitely something I'll remember because like, well first of all it's the first time I've done it so, umm. {What about it?} Umm, just like I guess understanding that even if, your results aren't, what someones looking for like doesn't mean that there's no like value in the process. I guess like, in labs later on people are probably going to be messing up to and you're gonna have to like write, experiments- I mean write lab reports and, figure out, like where those mistakes came from. So being able to almost like troubleshoot and like think back in the process I thought that was really valuable and that's going to me like in my future classes.
99	37:28	Interviewer	Mm. Um, are there anything else? Other things?
100	37:38	Caleigh	Sorry, let me think.
101	37:39	Interviewer	Yeah, yeah, that's totally fine. I'm going to stop staring at you. (Both laugh)

102	37:48	Caleigh	I think um, being able to test some many different conditions because we had a, big, cla- or a like a big lab section. That was- like that's going to stick to me because, like usually- in the previous labs I've done everyone like does the same thing and, we have, like pretty much everyone gets the same results. Versus like in such a big class like some groups get, really good results other groups get really bad ones and, some, like, it's just, having, such a diverse, group or set of results, is something that's going to stick, to me because, it just shows how if you follow the same procedure or like th- you do, in theory the exact same steps you can still get different results.
103	38:31	Interviewer	Okay. Um, cool. So, um, do you remember how you felt at the beginning of the course? Um, in general about biology, about the experiments in biology. Uh, and like think back for a moment about you fffelt, in the beginning. And then I'll ask you the rest of the question. [Okay] /3s/ [Okay, yuh] Umm, and so like think back, in general to how you feel now about biology and to the experiments in biology. Um, and like I'll give you a minute to think about that. (g - nods head) /4s/ (g - nods again) I know it's a little vague. (both laugh) [No it's okay] So, between these two do you feel like, have they changed how you thought about what biology ^is? Um, and what experiments in biology were at the beginning of the course, to now like, do you see a shift, or not? I'm just curious.
104	39:33	Caleigh	Yeah, I think they, definitely changed. Because, going into (this course) like in January I had like- some of my friends had taken (a different biology course) and they had said like lab was like their worst nightmare like it was so complicated, like it was graded very harshly. So, I was expecting like, a very like rigorous and strict lab in (this course). And then, after the first lab when we got completely random *results*, I was like 'oh no, this lab report is going to be so bad, like our TA is going to give me such a bad grade'. And so like that was, really nervewracking at first. Um, but then we got our grades back and, because we had carefully explained like why we got such, like different results, our TA didn't take off that many points for the results that we got. Um so like that made me feel a little better. And then in lab two, when we also got different results um, but we explained- like again we explained, very carefully why we probably got those results. Um so like the grades weren't too bad. So I feel like, now, I- I- my whole like, perspective on it is like it- you're gonna mess up in, science labs, it's just a matter of when. (Both laugh) And like that's okay as long as you can explain why, why you think you got

			those results and you can come up with, like, small changes to the experiment to help you, like help, change the path you're taking. {Mm} Yeah, so I think- I feel like, um if I had felt this way at the beginning, of (this course) I would have been much more comfortable, with the lab.
105	41:06	Interviewer	So th- the shift was in terms of like how you were thinking about messing up.
106	41:10	Caleigh	Yeah, cause I was just scared that like if we messed up I get a terrible grade (in it?) but like, our TAs are, much more, I guess accommodating because they know that like, there are going to be mistakes made in a science lab.
107	41:22	Interviewer	And do you think this mis- like how do you see these mistakes in- what do- what do-, What do you think is the role of these mistakes in science lab?
108	41:30	Caleigh	I think, um like, it is really frustrating when you like, you first see your results. But like, I think it makes it a much more valuable process when you actually write in the lab report because you have to think harder of- for reasons, for like *why* those mistakes happened. Um so like- it definitely like involves a deeper analysis, when you're writing a lab report. Which is more work but at the same time I feel like you learn more that way.
109	42:00	Interviewer	Are there other things that you think have shifted in how you see biology generally?

110	42:10	Caleigh	Well, this was also the first time I did like a self, designed experiment. So I guess, it really allowed me to see how like opened ended um, labs can be. Because I had never had a previous lab where the teacher was just like, just do- you can figure out whatever, you're interested in. Um, so I guess that's going to happen more when you get to upper level classes, um. But yeah it really showed me how like open ended, and like, flexible labs can be even though were usually given a set of, protocol and procedures to follow.
111	42:42	Interviewer	So in the betting are you saying, like you were expecting labs to be more sta- like
112	42:47	Caleigh	Like more, I feel like more structures.
113	42:49	Interviewer	And were you seeing biology is, like how experiments in biology generally were done like that, or were you only seeing labs like that?
114	42:58	Caleigh	I think, just like a college lab class. Yeah. Like I wa- especially because there's so many people in (this course) I wasn't expecting them to give us so much, freedom, especially with their lab.
115	43:12	Interviewer	Okay, cool? Umm, I think that's all the questions I had. Umm, do you- does anything else, come to mind in terms of, how what you feel about biology has, or if anything has changed from pre to, now?
116	43:31	Caleigh	Um, let me think, one second. /5s/ Um, before I answer that can I just say like, for the third lab, um, I feel like it didn't tie in, as well with what we were learning in lecture. Just because we had mainly been learning about human physiology, which like I know it's hard to do in a lab. Like you can't work with humans in a lab. But, um working with beetles and counting how many eggs they laid that seemed like, a lit- it was pretty far off from humans breathing. So like, I don't know if, that was just because they couldn't really des- give us a better lab to do but like- I enjoyed the beetle lab and designing our own experiment I just feel like it didn't tie in very well with what we learned in lecture.
117	44:16	Interviewer	Why do you think the designers did that?
118	44:20	Caleigh	Umm. Honestly like, I feel like, they could not have designed an experiment that tied in very well just because we were doing like how the heart, pumps and like, humans breathing. But like, why they actually chose beetles and eggs laying I'm not quite sure. Like it's- it was- beetles are animals, I guess like, kind like, physiology but, like laying eggs is nnot anywhere near what we were doing in class.

119	44:47	Interviewer	That makes sense. That was kind of misaligned. [Yeah, a little bit] As compared to one and two. Mm.
120	44:55	Caleigh	Umm, so how it, changed, my thinking.
121	45:01	Interviewer	Or how do you feel? And maybe it didn't. And that's okay too. I just want to like, I'm curious, which way.
122	45:11	Caleigh	I think also like, going with like the open ended-ness like, it really changed how I think of a lab report? Like I used to think there was a certain way we had to, like write a report. Like these things have to be in there. And that was, that was more or less true for the first two, lab reports. But I think with the third lab report um, it was more like write whatever you think, was interesting and use whatever pieces you need in order to tell your story. So, I feel like, umm, that- at the beginning of (this course) I thought there are very specific pieces that we need to use in order for our TA to give us a good grade. But, towards the third lab I felt more like, um, they were letting us use our best judgement for what pieces we needed to include.
123	45:56	Interviewer	What made you feel that?
124	45:59	Caleigh	Um just because like we- every group did so different, in their like experiment design. So like- well first of all it would be impossible to have, a checklist for like what each group needs to include. But just how, open ended the whole, experiment process was I- it made me feel like, um, I could, be like more open minded about what I include in my lab report. And I feel like, for upper level classes like later on there's going to be more of, students using their own judgement on what's best to include.
125	46:35	Interviewer	Okay. That makes sense. That's cool, thank you so much.

Appendix 6.1—Transcript of Gp A's Episode

A note on notation:

( ) Indicates a note

{ } Indicates a person speaking out of turn

Bold or *text* indicates emphasis

Italics or ^text indicates high/rising inflection

Comments

, indicates a pause

,(ns) indicates an n second pause

- indicates an interruption

/ indicates overlapping text

Line	Speaker	Turn
1	TA	(Walking over) /How are we doing?
2	Nick	(Answering a previous question Damien posed) /Yeah, we would.
3	Damian	Um. (All turn to talk to TA) We're thinking about doing—growing them in the LB with lactose and then plating them on MacConkey/ plates.
4	TA	/Ok. Ok.
5	Damian	Uhh, so our question is, does like, access to a secondary, source of energy like lactose, benefit, survival, of the high mutator?
6	TA	Ok. Interesting, ok…what do you expect to see, I'm just curious?
7	Damian	Umm... I don't know. Honestly I'm not sure if it ^will impact it that much {TA: Yeah} because, there's no like negative, force acting to reduce,/ the population so (just the decrease?)-
8	TA	/Ok. Like Rifampicin was, ok. //Interesting
9	Nick	//There should be enough glucose on the plate, for them to grow as much as they would normally, but… (g- Turning back to look at paper on table while talking?)
10	TA	Interesting, so…hmm.
11	Damian	Maybe it would be/, competition for the same resources.
12	Nick	/W- Once we- Yeah. Yeah I guess once they start competing (unclear)-
13	TA	So- and then keep in mind right, the type of data that you're going to get. So on those MacConkey plates, which some of your plates will be, you'll be able to see how many of each strain grew, period. Right? *And* how many of each strain grew and was able to develop a lactose, metabolism mutation. {Nick: Mhm (with nod)} So I think, po*ten*tially, you could, get some data that tells you, some information. Right? So those are like some complex plates, to analyze at the end cause your- ra- the plates that we just grew it's kind of, you know just count how many grew on each plate but maybe think about alittlebit how as you start to think think about concentrations and stuff think about, what- like what categories of data you can get from a MacConkey plate that's got two strains potentially (on them?). What sort of things might you to be able to tell? Even if it's what you're saying- maybe your- your- the *an*swer to your question would be there is no difference.

But how would you be able to tell that? Like what would you have to see to suggest to you there would be no difference.

14	Damian	Wouldn't- (Laughs) Wouldn't it just be the same amount of growth in each strain? Like the same number of (bacteria?).
15	TA	So, maybe. Right maybe that tells you, something. But, potentially right you could see *that* but you could still see a differential, development of the lac mutation {Damien: Yeah}. Right where more of that happens (unclear). And maybe even, like think in terms of, "okay *if* you develop the lac mutation- are we *certain* that that's beneficial?" Like maybe in a certain environment it is, maybe in a certain environment its not? There are other potential effects it could have. ,(2s) But yeah, I would keep like—the thing that sticks out to me as you tell me about this design is I would think about it a little bit in terms of your expected results. Right as you kind of move forward and start to think about what kind of concentrations to use, what kind of plates you wanna set up—like if you're going into this somewhat anticipating - eh, it might not matter much like, what would the results have to look like to convince you that that's the case, and that might inform (a bit of?) how you design this. (3s) K, I'll be back.
16	Nick	[suck in air]
17	Damien	Oh god. [laughs] Okay.
18	Abram	All right. Here we go.
19	Nick	Alright. [slams paper on desk] Um.
20	Nick	So when…
21	Abram	Yeah.
22	Nick	Fuckin' A. uhhhh…

23	Damien	Okay, so lets say, on the final plate, we get equal growth. Like 100-100. (drawing on paper in front of him)
24	Abram	Mhm.
25	Damien	and this one's 39 and this one's 38.
26	Abram	Ok.
27	Damien	And so lets say like, 70 are glucose and 30 are lactose.
28	Abram	Mhm.
29	Damien	Let's say like, 95 are glucose and 5 are lactose.
30	Abram	Soo/...
31	Damien	/So what does that mean?
32	Abram	That means, um, the ones that are—the ones that umm, break down glucose would be dotted red right?
33	Nick	Does that mean that there's no, benefit to using more, or...uhhh.
34	Abram	Wait, would /that be like?
35	Nick	/Because we can't really like, isolate the, the one- (2s) because if we could have one that like only processes lactose (g - on each of the prior words forcefully taps paper with pen) {Damien: Yeah} that would be nice but, we definitely aren't gonna be able to do that. (1s) 'Cause we are not going to be able to grow. Umm... (2s) We're not gonna be able to grow the 39 on something that only has lactose probably. And we don't have a plate that only has lactose.
36	Damien	I think um, right right no you're right… (6s) The more I think about this, I don't think it's going to be an even number, between the two. I feel like, you can have a higher number of this, the higher number of the lactose ones, because they won't be competing with like all of these, for the glucose 'cause they can just use the lactose that {Nick: Yeah} nobody else is using. So you might have like a higher number of these guys. That's what I'm thinking.
37	Nick	Uh-huh. That that would make sense, once- 'cause once you get to that, point, yeah. I still find it like—I don't- I don't know how much they're going to compete for glucose or whatever. {Damien: Yeah} 'Cause like it seems like there should be enough glucose to go around.
38	Damien	Probably yeah.
39	Nick	Umm...
40	Damien	This seems like a very *vague* idea for an experiment. Like, /we don't know what we're going to see. We can't come up with a good theory. (laughs)

41 Nick /This is so frustrating

42 Damien It was a lot easier when, (laughs) it was just like they're going to die. (laughs)

43 Damien What do you guys think?

44 Abram Hmm?

45 Damien Do you think we should go with the lactose or with the RIF?

46 Nick We're locked in on lactose. We're doing this. We're going to figure out a way to do this.

47 Damien We are doing lactose? Ok. {Nick: Yeah}

48 Abram So what's the, what's the...what's the real-

49 Nick The- the whole—this thing's confusing me too with—when we grow it in lactose,

50 Damien Uh-huh.

51 Abram It also has ^glucose.

52 Nick there's not going to be like, that much of an advantage to use, lactose if there's /also glucose…

53 Damien /Right, right right. But the point—I don't know, I said we should grow it in lactose because, if the random mutations that happen in the high mutating strain, the 38, if they somehow develop lactose processing abilities, {Walt: Right.} then they'll survive. And-

54 Walt They'll have like a better advantage.

55 Abram There will be more of them.

56 Damien What?

57 Walt They'll have a better advantage.

58 Damien They won't have an advantage; they'll just be able to survive, {Walt: Okay} better.

59 Walt /With the lactose?

60 Damien Yeah.

61 Abram /Well won't more of them grow? If //that was the case?

62 Damien //Yeah, more of them- more of them will grow. Right. Whereas if they didn't have lactose- then...

63 Abram They would be the same.

64 Damien They wouldn't have any—yeah, you're right, I guess they would have an advantage, /so they'd survive onto the plate.

65	Nick	/We have to- We have to like assume that resource— for anything to ^happen we have to assume that like glucose becomes sparse. At some point. For there to be like a difference between the two, {Damien: mhm} overall glucose has to become sparse, because if there's- if glucose isn't sparse they're both going to be fine, {Damien: Right.} because there's nothing that, like, kills them. But-
66	Damien	Do you want to use the thing? Um the computer program?
67	Nick	Wait, could we /do this on the computer? Maybe we could.
68	Abram	/Is this the plan?
69	Damien	And just like increase the metabolism mutations, and like decrease the other two and see what happens?
70	Nick	(laughing) Why not?
71	Damien	Actually just try it.
72	Damien	It'd be fun. /See what happens.
73	Nick	/Yeah, screw it, no let's bring it up, let's do it.
74	Abram	Pull it up?
75	Damien	Oh did you log out?
76	Abram	No I did not.
77	Damien	You did. It's right there. Solid.
78	Abram	Um. What am I doing?
79	Nick	Ok so, turn down lethal,/ and-
80	Abram	/(unclear)
81	Damien	Yeah. Like-
82	Nick	Turn off the antibiotic because we don't need that.
83	Damien	Turn it to like 3%.
84	Abram	3% ahhh.
85	Damien	That's fine that's fine.
86	Abram	Oh, four.
87	Damien	And turn down resistance because we don't need that.
88	Abram	All the way down?
89	Damien	Yeah. There's no antibiotic so. And then, change the mutation rate to like ten and one.

90	Nick	Yeah. Or do like *point* one. Something like really small. And then...
91	Abram	(Unclear)
92	Damien	What is that?
93	Abram	(One three nine. This is sixty three?)
94	Damien	Oh Maybe we should make it the same.
95	Nick	Yeah yeah start with it the same.
96	Walt	For the different strains?
97	Damien	Yeah. Like a hundred-hundred, or something.
98	Abram	Yeah. Oh c'mon.
99	Damien	Oh yeah you have to move the text box. Or just move that. Or maybe you can move that one. You just moved it a second ago.
100	Nick	Nothing's easy.
101	Damien	There you go.
102	Abram	Does that work?
103	Nick	Sure.
104	Damien	No you're above the other text box now. Okay.
105	Abram	Ahh.
106	Damien	Okay yeah.
107	Abram	What is this? Boom.
108	Nick	This program's trash.
109	Damien	(To researcher, who approaches the group) We're just trying to move the slider but it's like over the textbox.
110	Nick	Wait just click on it.
111	Abram	Got it.
112	Nick	Just get it close- yeah. Drop it on like 98 and then, just click on the other side of it- like click or the green on the other side of it. Or, right there. Just click on the green on the other side of it.
113	Abram	The other side? On the other side? Oh good. And then?
114	Nick	Yeah.
115	Abram	Ok we are good to go?
116	Damien	Yeah.

117	Nick	Just do it real- do it kind of fast.
118	Abram	Want me to- oh whoops.
119	Damien	Okay, so, hit setup. Halt, then setup. {Abram: Okay.} And then go.
120	Damien	Oh it's going (unclear).
121	Nick	Alright so blue is… /oh no, now they are coming back.
122	Damien	/So metabolism-
123	Damien	Metabolic benefits don't really have an impact. That much.
124	Damien	Or wait, which one/ had the high mutation rate?
125	Nick	/Or does it?
126	Abram	Oh, that? /The red had the higher-
127	Damien	/The red one? So red should have a higher metabolic benefit.
128	Nick	Why did blue start out winning? That doesn't make any sense.
129	Damien	Okay, now red's going up.
130	Abram	Okay.
131	Nick	Yeah. But the metabolic benefit like...
132	Abram	(Unclear)
133	Nick	But is being able to digest lactose, a metabolic, benefit?
134	Damien	That is a question. I ^think it is.
135	Nick	That- That is our question! Oh my god!
136	Walt	That is our question. Wow.
137	Abram	[Laughs]
138	Nick	But then...
139	Abram	I mean the red is winning.
140	Nick	Okay, so.
141	Abram	A lot.
142	Damien	So. I guess metabolic benefits are beneficial?
143	Abram	Theoretically, yeah.
144	Nick	(Laughs)
145	Walt	Red does have a much higher mutation rate though.
146	Damien	Yeah.

147	Nick	Wait so it could be like is...
148	Abram	Should we like, lower it?
149	Damien	No that's like modeling what we need, because 38 has a much higher mutation rate than/ 39, so.
150	Abram	/Oh ok
151	Researcher	What were you guys just trying to do?
152	Abram	Oh we were just modeling um, how, oh I guess, how the two different strains would, grow if um put in a- what was it?
153	Damien	The lactose environment
154	Abram	Lactose environment and I guess it also has glucose at the same time.
155	Damien	Yeah.
156	Abram	Yeah the red with the higher mutation rate just won out. Just because I guess it's because it can digest the lactose and the glucose at the same time while the blue {Damien: Yeah} /can only digest glucose.
157	Nick	/But this doesn’t- Yeah.
158	Researcher	How are you guys comparing lactose because here you had agar and um rif right? How are you comparing lactose? I am curious about how you were mapping lactose onto this.
159	Damien	We were just thinking lactose would act as a metabolic benefit so we kind of just turned off the antibiotic and looked at the effect of the metabolic benefit mutations.
160	Damien	But I don't think we are sure anymore if being able to digest lactose on this plate would be a metabolic benefit ‘cause they would still be in the presence of glucose.
161	Nick	But that might be our question that we end up asking.
162	Researcher	Huh.
163	Damien	Yeah so, I guess if we observe that the one that has a higher mutation rate does much better than the other one then it would be a metabolic benefit.
164	Researcher	Say more.
165	Damien	Hm.
166	Researcher	Why?
167	Damien	Why?
168	Researcher	Yeah why would you expect that? Or why would you (unclear) that?

169	Nick	Cuz, I think, maybe at some point like glucose would end up becoming sparse if they are both plated together and they're competing for the glucose, but if one of the strains uh after we grew them in the presence of lactose ended up being able to metabolize lactose, if they could use lactose as a resource that might help them, survive better than the other one.
170	Researcher	Okay cool.
171	Nick	So that, is where we are.
172	Researcher	Okay.
173	Nick	I think it makes sense.
174	Damien	I think it makes sense too so, maybe we should go with it.
175	Nick	I think we have to run it by him, but
176	Abram	What? Does it not? Like-
177	Damien	...able to
178	Nick	I mean there is no way to like really ensure that.
179	Walt	Can we word it a little bit differently?
180	Damien	Yeah.
181	Nick	Yeah I just wrote that down. I don't think this is-
182	Walt	Like, does an *ability* to digest glu- lactose. A secondary energy source. Benefit a population of E coli?
183	Damien	(Writing) Beneficial- beneficial.
184	Nick	Do we know- Okay, and we'll know that they're able to- see that's the thing though, we are not going to know that they're all able to digest lactose until...
185	Damien	Until we get to the end.
186	Nick	Yeah.
187	Damien	But by growing it in this media we expect that some of them might have that mutation.
188	Nick	Yeah.
189	Damien	Also like, I don't understand…
190	Nick	You know what I'm saying? I feel like there's a hole. I feel like there's definitely a hole.
191	Damien	No but like-

192	Nick	(sighs) Or yea Because if we grow- This is where we are growing them, we got a lot of guys. {Damien: ^Yeah} and like say like these ones can uh (2s) can digest lactose, can metabolize lactose, {Damien: yeah} so once we, (1s) once we plate them, we still have like all these guys are still plated - not just those.
193	Damien	Yeah?
194	Nick	And do we know if these will do both glucose and lactose or will they just do glucose?
195	Abram	Isn't that just like what we are hoping for with the mutation?
196	Nick	What's that?
197	Abram	Isn't that what we are expecting for with the mutation? It will like mutate to like be able to break down lactose.
198	Nick	Yea. But will it be doing glucose and lactose? I don't know if that matters.
199	Abram	I feel like, uh?
200	Damien	If it mutates to digest lactose then I assume it would be able to use both glucose and lactose to survive.
201	Nick	Yeah.
202	Damien	If they don't get the mutation it is just glucose.
203	Abram	Isn't that just our question though? Because like what if it doesn't?
204	Damien	Wait.
205	Abram	Right?
206	Damien	(D calls LA over) Wait I have a question. I just had to think of it. So what um- I don't know. So we're thinking about asking the question would, being able to metabolize lactose as a secondary resource be beneficial to *E. coli* survival? Would that make sense in the context of this-?

Appendix 6.2—Transcript of Gp B's Episode

A note on notation:

( ) Indicates a note

{ } Indicates a person speaking out of turn

Bold or *text* indicates emphasis

Italics or ^text indicates high/rising inflection

Comments

, indicates a pause

,(ns) indicates an n second pause

- indicates an interruption

/ indicates overlapping text

Line	Speaker	Turn
1	TA	So play with this for a while. See if you can make some sense of *your* experiment using the simulation. Um, yeah. And as questions as you have them. As me and (LA) walk around.
2	Mary	(whispers) Is it going to work this time?
3	Sujan	Oh yeah.
4	Mary	I literally didn't mention it in my like, whichever, I guess second one they're like "mention any like inspirations in the simulation" I like just didn't talk about it at all.
5	Sujan	(Laughs)
6	Karl	(Laughs)
7	Mary	I was like "well, nope. Not inspired."
8	Sujan	You were *not* inspired.
9	Mary	I could have been like "I was not inspired by this."
10	Sujan	(Laughs) I wonder if we can actually do like our, um,/ thing?
11	Mary	/Yeah I think we can change the concentrations and all that, stuff.
12	Sujan	Can we grow them in LB+RIF?
13	Mary	Well that'd be fun.
14	Karl	Yeah 'cause the (unclear).
15	Sujan	Okay. I'll just come around then. (referring to moving to gather around the computer)
16	Karl	Um, we can't change, growing conditions, right?
17	Mary	We can't what?
18	Karl	We can't change like intubation conditions.
19	Sujan	We can or can*not*?
20	Karl	Can't.
21	Mary	Okay. So. Antibiotic - okay, should we just work through each one? Or should we just compare the last two (unclear). /Oh no, the first one?

22 Karl /Okay so- what questions did we- like we were talking about? Um...

23 Mary The first one like, if we'd done it again, and like lowered the rate of, lethal mutations could we have more growth of the- would we have had any growth of the E938. (2s) Or was that not a question? Like, based on our data. Unless you guys would rather focus on the next two. Which is fine too-

24 Sujan Sorry, I was-

25 Mary the next two plates. Or should we like do any simulation of the first LB. And like change whether like what types of mutations happen in the-

26 Sujan Oh cause it ^is kind of weird that like-

27 Mary Mhm. So antibiotic off-

28 Sujan none of the E938 survived.

29 Mary I did this, (Unclear). Is this a screenshot? Took a picture.

30 Karl Oh, I'm so sorry.

31 Mary It's okay.

32 Sujan Oh!

33 Mary What's it called?

34 Sujan Umm, biosim, maybe?

35 Mary Or, mmm.

36 Karl Try going to Start menu we can find it. Program list.

37 Sujan Oh that's a picture. Okay. Sorry I was gonna go back in it, yeah.

38 Mary (To researcher) What's the name of the program do you know?

39 R NetLogo. I have updated the model for you so you should have the new model.

40 Sujan Oh okay.

41 Mary Thanks. Net. Net net net net net.

42 R You see that red arrow? That should be it.

43 Mary Oh that's it. Cool.

44 Sujan Oh!

45 Mary Great. Okay. Turn this off. /Show resistance. Sure but we don't have anything.

46 Sujan /Yeah. Why not?

47 Mary Initial- wait. We want red and blue. Which is which.

48 Karl Why don't we let blue be blue and red be green?

49 Mary Okay.

50 Sujan Okay.

51 Karl So blue is, 939.

52 Sujan /938.

53 Mary /(more to self) Start with six ^hundred.

54 Sujan Blue is 938.

55 Karl Yeah 938.

56 Sujan Ummm...

57 Mary Okay, yeah. So this needs a more. Like we don't have much more. Like rep-

58 Karl We don't know (unclear) though.

59 Mary Should we change-

60 Karl This is lifespan.

61 Mary Oops.

62 Sujan That's where we change the speed. So we can just make it like s- as fast.

63 Mary Yeah wait but don't we want a mutation- that's gonna change. So this will be like one, something, and this will be, how much more, like five or ten? I don't know.

64 Karl Would it be by orders of magnitude? So (unclear)

65 Sujan Do you want to just do ten? For now. And then we can see. And then we can figure out- okay so- at least some of it has to be resistance.

66 Mary Well we don't have a- we should do no resistance because we have antibiotics off. We're doing the LB one.

67 Sujan No but like it's still gonna mutate. That's like their- a- a percent of ^mutations. So it can still have like the resistance mutation. Cause it's the same strain. And we'll just keep that consisent for all of them.

68 Mary And then- should we make the lethal? We should make an *equal* chance of lethal and metabolic. And resistance. Like make it equal for all three of these.

69 Sujan Okay.

70 Mary Though I feel like it real life- it's like, you're less likely to get a...

71 Karl So if we had metabolic and lethal equal then, that would be like, no effect.

72 Mary It won't/ let me change the-

73	Sujan	/Oh because they would cancel each other out.
74	Karl	(No?) (unclear)
75	Mary	It won't let me change the lethal. Oh wait, there was a reason. I remember you like... that's why. Ahh.
76	Karl	Does the (gestures off camera)
77	Mary	Yeah. So we want to do like-
78	Sujan	Well actually yeah he's right if we make them all equal, then like/ (unclear) lethal-
79	Karl	/We could try like to see if that's-
80	Mary	Is that the same thing as like zero you mean?
81	Sujan	Yeah. It might be that like there's like/ a really small percent for resistance?
82	Karl	/I think- yeah I think our data suggests that there might be more lethal mutations because, they die.
83	Sujan	And just because it's like in the rif environment like the ones that had- even if there's not a lot of them, the ones that had resistance just survived.
84	Mary	Is that what we're doing, first?
85	Sujan	Yeah.
86	Mary	Is this all good?
87	Sujan	Yup. And he said we could make it at like fastest.
88	Mary	How many generations do we want?
89	Sujan	What are like? So those are both the same thing, right? What is the white?
90	Mary	Showing. It's showing resistance.
91	Sujan	Okay.
92	Mary	But we don't have any antibiotic.
93	Sujan	Okay.
94	Sujan	Wait so in this one is kinda like, oh it makes sense that there's an even split because of mutation rate.
95	Mary	Even split of what?
96	Sujan	Um. Numbers? Well, no- I was going to say blue and red. Looks like they all are just resistant now. Like-
97	Mary	To *what*, though? That's what-
98	Sujan	They could be resistant.

99	Mary	Like what are they resistant to.
100	Sujan	Just like whatever they mutate. And it just has no effect on like where they're growing.
101	Mary	Oh like, if you put in, antibiotics it would be resistant. Okay.
102	Sujan	Yeah.
103	Mary	How long do we wanna go?
104	Sujan	Maybe we could stop this then like /increase-
105	Mary	/Look it's coming back together though. That's actually kinda interesting.
106	Sujan	Do you want to make like a high percentage of lethal? Because that's be possibly what-
107	Mary	I want to see what happens here, it looks like it's coming back together which is a weird.
108	Karl	It's real weird.
109	Mary	And like this is decreasing now. Whoa. (3s) I want to see what happens after they touch again.
110	Sujan	Does this mean that it's a hundred percent beneficial? /They all have-
111	Karl	/So all of them have a beneficial mutation-
112	Sujan	Oh 'cause I guess the ones that have lethal, just die.
113	Mary	Mm... So they're both beneficial but they're gonna like what, be equal? Are they going to cross again. What? (2s) Oh because, this one mutates more. But they're still the same replication rate.
114	Sujan	WHAT!? What is it doing there?
115	Karl	Is it just (unclear-fluctuate?)?
116	Sujan	Oh it might.
117	Karl	(quiet) Because if you like here there's also-
118	Mary	But like why would they do a trade-off? Like why would it? (2s) Oh maybe it's just like hitting their like carrying capacity. Then they start to die then the other one starts to go up.
119	Sujan	Oh maybe.
120	Karl	Already?
121	Mary	But then why would they go to like, almost zero.
122	Sujan	Wait is this gonna come back? Cause if it is, then-

123	Karl	/Yeah let's see if it-
124	Mary	/(unclear) let's see what it does.
125	Karl	Yeah.
126	Sujan	Blue was doing so well, and then they died.
127	Karl	And red is/, going on (unclear)
128	Sujan	/And now red is like, a hundred percent. Wait so-
129	Mary	They like can't stay there forever though.
130	Sujan	I know yeah. Yeah-
131	Mary	Maybe it's gonna go back down.
132	Sujan	Oh but see now *red* has all beneficial.
133	Mary	Wait what? Don't they both have all beneficial?
134	Sujan	Yeah but before red didn't-
135	Karl	So the increase in percentage of red matches up with,
136	Mary	The blues the mutator strain?
137	Sujan	Mhm.
138	Karl	Cause the increase in blue matched up with the increase in blue here. And the increase in red here matched up with the increase in red here (points).
139	Mary	Wait say that again?
140	Sujan	But I'm confused why it switched.
141	Karl	Like, for beneficial mutations the increase in blue here as a percent, matched up with the increase in blue percent over here. And then, as benefical mutations increased for red the red /(unclear).
142	Mary	/Now it's just like tapering off. Wait this kinda is like what we said. Wait which did we say was the mutator? Yeah like there's no blue in our LB plate.
143	TA	So wait. So tell me what you've kind of set up here.
144	Mary	So we were trying to first mimic the, no rif in either the growth or the plate. {Okay}. And we made all of the chances each kind of mutation- which probably isn't real but like, equal. But we still are having like the high mutating strain dying off it looks like.
145	TA	Hm... so your, so your- which one is your high mutator?
146	Mary	The blue.

147	TA	So your low mutator is like- so on the right side you see how these graphs are red now? That means that only one strain's still alive. {Mary: Oh!} So blue is totally gone.
148	Mary	Should I pause it? (Unclear)
149	TA	Oh you can let it keep running. I mean it's up to you. {Mary: Okay.} And it looks like you're on the way to that happening on this side maybe. It's just not quite there yet there's a few blue, still stuck in there.
150	Mary	Mm. Hanging on.
151	Sujan	Oh. (Laughs)
152	Mary	So is it even though like- well I guess it's like once you have- That's confusing wait. I would say like between, if you have an equal rate of having lethal, and then, beneficial mutations...
153	Sujan	Like wouldn't the ones with the lethal mutations just *die* and not be able to pass /on that?
154	Mary	/Oh so but then- and then you have a smaller population-
155	Sujan	Wouldn't you only have- the only ones that survive and have offspring are the ones that have beneficial mutations.
156	Mary	But then with it, you have a smaller population and then like twenty-five percent of those are gonna get mu- bad mutations. / Or harmful mutations
157	Karl	/Could it be that um... //So since-
158	Mary	//So we keep like, quarter, whatever that is. Quarter-
159	Karl	/Since blue maintains higher than red, so blue has ///(types of?) positive mutations have a higher effect, at the start. {TA: Okay} But then, as population increases, um, it also mutates harmfully more, but then, by that time red is picking up mutations (unclear).
160	Sujan	/So even if you have a good mutation you could maybe end up/// having a bad mutation-
161	Mary	///So isn't it if this is the population, and like-
162	Mary	Okay, I'm just gonna do like half and half. Like half of them get, the bad, mutation, {Sujan: Yeah} they die off here's your new, population. Okay, now half of these are going to get the bad and die off. And only the good ones can- Now in this population/ half of those are going to get- eventually it just goes to extinction.
163	Sujan	/I see what you're saying

164	TA	(to Karl) /Interesting. That feels like it kind of jives with that second graph, right? {Karl: Yeah} Like that rate- how frequent those beneftical mutations are, yeah? That feels reasonable to me.
165	Mary	That's confusing though. Okay wait, so I just made and argument and now I don't know if I believe myself. {Laughter}
166	TA	Okay. So I was listening to him, so go.
167	Mary	Okay, ignoring the other, things that are going on like if you're just looking at the beneficial and lethal. If it's like fifty-fifty for the chance because we have them equal here. You like start with like 10, and then like 5 of them die off because they got the lethal mutation. And then a new generation and half of those 5 will die off because-
168	TA	So remember, that your mutation rate also plays a role. So not every cell mutates.
169	Mary	Oh that's true. So it wouldn't be like half of the whole. Okay that's true.
170	TA	Right. So that kind of throws in a,nother, layer of complexity in that. If you have 10 cells, some number of them- however many mutate, half of those maybe get the lethal, half of those maybe get the beneficial but it's not half of the overall population.
171	Mary	Like eventually even if you- if you have that like beneficial, and lethal, like fifty-fifty, they're eventually gonna, die off.
172	TA	Try it and see!
173	Mary	Well that's what we. Oh. I don't know. Okay, what do we wanna do next?
174	Mary	Now what do we wanna do? Do we want to mess with this again, or should we start playing with the other two?
175	Sujan	Maybe, do you want to add antibiotic? /'Cause then that would kind of-
176	Karl	/Should we run it again?
177	Mary	And we'd do it without resistance-
178	Karl	Just like run everything the same way, just to see what happens. 'Cause if it...
179	Mary	I feel like with the same thing but I wanna know what happens, if we get rid of resistance, 'cause we're not looking at that at all, and then do. Fifty of this. Fifty of this.
180	Sujan	Uh-huh.
181	Mary	I don't know if this is a good i-
182	Mary	No!

183	Sujan	(Laughs)
184	Sujan	Yes.
185	Mary	Do we want to try that? Or is there anything else we want to mess with?
186	Karl	Nah let's try this.
187	Sujan	Okay. So.../ do we want-
188	Sujan	/So, blue is high mutator? Alright so ^again, blue, what? So why do they have more beneficial? So this must be like-
189	Mary	//No it's just because they're mutating faster
190	Karl	//But they're also dying off- and they're also dying off more. So blue is also dying, a lot. Cause for every mutation,/ like there's a half chance of dying.
191	Mary	/Cause we don't have something that says, lethal. If we had some that said lethal it would also be more lethal for the blue-
192	Sujan	Wait this is percent. So now it's just basically a hundred percent, have beneficial?
193	Mary	No but it's like/, percent beneficial is like, of beneficial mutations.
194	Karl	/Yeah because everyone is, dead
195	Karl	Of mutations, like one hundred percent are beneficial.
196	Sujan	Oh is that what it's saying?
197	Karl	/Of the ones that are alive and (unclear)
198	Mary	/No I think it's like of beneficial mutations what percent of all beneficial mutations are accounted for by blue and what are accounted for by the red.
199	TA	(walks over) Wait wait wait. So what are you trying to interpret?
200	Sujan	But that doesn't add up.
201	Mary	What this graph is telling us.
202	TA	So that second level graph. {Yeah}. So that is- yeah let's think about this for a minute. So generations, and perc^ent beneficial mutations.
203	Mary	Oh. Wait /what happens when they turn red?
204	Sujan	/They're all. //So that means it's just red.
205	TA	//That means the other strain is gone. So blue is gone.
206	Mary	So we can like stop it now.
207	TA	So what I *believe* this is is, the percent of cells that have the beneficial mutation.

208	Sujan	So when it gets to a hundred it means basically, all the cells have it. So even though blue has a hundred percent beneficial,/ it just dies.
209	Mary	/It also means-
210	TA	Why?
211	Mary	Becuase it's also having lethal.
212	TA	Right.
213	Mary	'Cause it's fifty-fifty.
214	TA	So even if you *have* the beneficial mutation you pass it on, you still have a chance of also passing on a lethal mutation, and then wiping that out.
215	Sujan	Okay. Yes. So it's a hundred percent but maybe there's only like five, left. /Okay got it.
216	Mary	/Does that mean this is done, moving?
217	TA	Right, exactly. It's not telling you anything about- so the thing telling you about population size is that top graph.
218	Mary	/So it's like done we can st- pause it.
219	Sujan	/Alright, yeah.
220	TA	So that one there's not much left to see. Interesting.
221	Karl	Oh and every lethal mutation decreases rate by 100% while beneficial only increases by like/, 50.
222	TA	/Sure. Sure.
223	Sujan	Yeah. Okay so, I guess// this makes sense then with our control. Where like, you know, having mutations, is-.
224	Mary	//Okay so what's happening here?
225	Mary	What did you do?
226	Sujan	Print screen. Yeah.
227	Karl	Yeah.
228	Sujan	Whew. So what. I guess this is kinda similar to like our neutral environment again. Yeah.
229	Karl	Wouldn't it be pretty cool if we took like samples from- like we viewed the plate every however many hours or so,/ just to see the distribution of each.
230	Sujan	/Just to see! Yeah. Because maybe like the high mutator was doing well in the beginning,// and they just died.
231	Karl	//Yeah. Sure. And we might see that if we-

232	Sujan	Yeah.
233	Mary	So this one is, LB, Agar, two?
234	Sujan	So now do we want to add, resistance? /Or can we add, antibiotic.
235	Mary	/Okay so. Antibiotic.
236	Sujan	And maybe we'll have some be able to be resistant now.
237	Mary	Is there any way? Oh there is a way. Okay. Well let's do the thing. I'm trying to figure out how we can simulate first being grown without antibiotic, and then being put in antibiotic. So can we like do it, pause it, and then keep going.
238	Sujan	Yeah.
239	Mary	Go pause. So /like do it without antibiotic first.
240	Sujan	/Uh huh. But we probably want some to //be resistant.
241	Mary	//What percent- so like.
242	Sujan	Do we want to make it equal? I guess that it kind of has the same effect. In that...
243	Mary	I think we should do it all equal just because we don't know.
244	Sujan	Okay.
245	Mary	Even though in reality I feel like there aren't as many...
246	Sujan	Resistant...
247	Mary	Well I was gonn say there aren't as- well yeah, but there probably also aren't as many like-
248	Karl	There probably- I feel like there /definitely would(n't?) be two of them.
249	Mary	/-Lethal.
250	Sujan	Yeah.
251	Mary	So I guess because we don't know. So we'll, do this. This is all good.
252	Sujan	Yep. /And then we'll pause it.
253	Mary	/And then so resistance, antibiotic off, then we'll, okay. (Mary singing quiety while they all look at the computer screen.)
254	Sujan	So we should make sure we switch it before like, something, completely dies out.
255	Mary	Oh, yeah. Wait how many generations do we have in 24 hours?
256	Sujan	They- don't they replicate like every twenty minutes? /So probably a lot.

257 Mary /So wait wait. I'm just gonna keep going.

258 Mary The red looks like it's about to just.

259 Sujan Die?

260 Mary Well that did kinda happen actually, theoretically. Wait should we calculate how many generations?

261 Karl (Very quiet) Oh gosh, what happened here?

262 Sujan Oh it's saying how many there are. So maybe we should-

263 Mary Well that's how many cells, though. Not how many generations.

264 Karl There might be a recovery of red though, 'cause this is the same as our first one- so maybe red will (unclear) back.

265 Mary So do we want to calculate like the in- how many was it like 17 hours we had it incubating? 17 hours. What?

266 Sujan And it's 20 minutes?

267 Mary So, times three.

268 Sujan So 51.

269 Mary So 51, generations? {Sujan: Yeah} Oh so we went like way past. Should we start it over and do like 51 generations?

270 Sujan Okay. So where does it say how many generations though?

271 Karl /Is it ticks?

272 Mary /Generations. (points)

273 Sujan Oh! Okay. So yeah we'll go up to like 51.

274 Mary Turn it slower. I guess I can stop it. Okay. Tell me when. Do you want 51?

275 Sujan Yeah. Alright we can stop, yeah.

276 Mary Okay. That's about representative.

277 Sujan Yeah.

278 Mary So we have like a decrease still. Okay so *then* what do we want to do we want to do. /We want ten-

279 Sujan /And then add on. Yeah.

280 Mary And then keep going? For how much longer?

281 Sujan /Twenty four hours.

282 Mary /Twenty four, times three

283 Sujan So like 72.

284	Mary	Wait, but like 60 plus 72
285	Sujan	So we go up to /a hundred and, thirty//-
286	Karl	(Mumbled) /A hundred and... //two
287	Sujan	Whoop! Oh.
288	Mary	Cool.
289	Karl	(Laughs)
290	Sujan	(Laughs)
291	Mary	Hundred, and, thir- probably next one.
292	Sujan	Yeah probably next one. Yesss... Alright. So what is that one? That's one with antibiotic?
293	Mary	What did it- what? Is it-
294	Karl	Why is this one so grey?
295	Mary	Why? (Laughs)
296	Sujan	So does that? Sorry-
297	Mary	Wait so thats- oh that- that gray? Is- look, these are act- that's like an optical illusion. These still colors are- the backgrounds are the same, it looks like they're not, but- wait the reds are different colors though. Why do they like-
298	Sujan	/I think that one has the antibiotic.
299	Karl	/Because the red developed mutation, I mean resistance and (unclear)-
300	TA	Yeah, so you definitely have antibiotic on.
301	Sujan	/So that one-
302	Mary	/Oh they're all- so these are all resistant.
303	Sujan	So this one *doesn't* have antibiotic?
304	TA	Right. {Sujan: Oh, okay.} So region one will never have antibiotic. {Karl: Oh okay.}That's just to be able to compare.
305	Mary	Oh we tried to do, wait what did we do?
306	Karl	Oh that makes sense okay.
307	Mary	Oh/ well we did two things we did first growing it with this off //and then continued with it on. So the graphs I guess represent what we're trying to look at.
308	TA	/Say- //Yep, and then turned it on.
309	TA	Oh yeah, definitely.

310	Mary	So we should save this. So this would be like our second simulation.
311	Sujan	Right.
312	Mary	Should we change any of this though, well, let me see if /(unclear)-
313	Sujan	/That's the only one that we- this one is- //that's what we wanna look at.
314	Mary	//So it kinda like shows. Except for it's showing- like we didn't have any {Sujan: Yeah.} and maybe it's 'cause, concentrations...
315	Sujan	I mean they also start with more, that says six hundred, and I think with our calculations it was like, a ^hundred or something.
316	Mary	Should we change that?
317	Sujan	I think if we make it lower though then it might be harder to tell which (unclear) simulation like with this like /because we have more, it's probably like more representative
318	Mary	/Because we see them. So like what could we mess with- so I'll take a picture of this. Okay. Umm. What do we want to mess with in terms of- I 'x'ed out of, that.
319	Sujan	Should we maybe do it. I feel like we kinda *know* what'll happen if it's just like, in antibiotic, already, right?
320	Mary	(Whisper) (I've gotten used to Mac?)
321	Sujan	You can control print screen.
322	Mary	No wait I'm trying to- /take it.
323	Sujan	/Did you just? Okay
324	Mary	Welp, now I just c- hm.
325	Sujan	Oh! (Just to?) print screen that. Oh I see.
326	Mary	Wait let me go back.
327	Sujan	Just go back. Yeah.
328	Mary	No worries.
329	Karl	I feel like we should like, so what were the *holes* in our experiment? What did we not cover with the...
330	Mary	The concentrations was like... /is like something we wanna mess with.
331	Sujan	/Probably, yeah.
332	Karl	Yeah. So.

333	Mary	I think we should like mess with one more thing, in this second version. With like concentrations or like ^something, that will be relevant for us and then do like two versions of the the third plate. But I don't know what we- what we would change.
334	Sujan	Do we wanna change...
335	Mary	So this is LB-R, one.
336	Sujan	Yeah. Should we change the population size? Or should we change...
337	Mary	What would be? Okay, what's like a problem we could have. There could be competition-
338	Karl	Between, strains?
339	Mary	Oh there could be competition like- okay so the LB tube is like, should- oh! I have it. Okay. The LB tube, oh but we kinda, give it the chance to do that. Nevermind.
340	Sujan	(Laughing) No!
341	Mary	I was gonna say the LB tube is like the control in that like, we lost, all of the mutator strain. And so then what we could have been like not plating, any,
342	Karl	Right.
343	Sujan	Right.
344	Mary	(unclear) growth or something. But like it kinda shows up. But that means that, oh but *this* is representative of that. Nevermind. Because we stopped it and then continued and it was already like fewer.
345	Sujan	Yeah.
346	Mary	Right? Percent of each strain what's the difference between these two?
347	Sujan	So this has no antibiotic.
348	Mary	Right. So. Oh but at that point where it stops...
349	Karl	Hm?
350	Mary	Okay now I'm confused because...
351	Karl	So this plate just has no antibiotic.
352	Sujan	Yeah, right.
353	Karl	/And this like plate is (unclear)
354	Mary	/But when s- but when we turn it on-
355	Karl	Yeah, it was like here, because, //more blue- more blue had
356	Mary	//Oh, it was showing that.

357	Mary	Yeah so we *did* start with like less. So it was representative. Okay so that's not, something we need to test. Umm...
358	Sujan	Uh... What about a concentra- can we change concentration?
359	Mary	Like what if we changed this actually and tried to make it representative.
360	TA	(To whole class) Okay I don't want to interrupt anything because you guys are doing some really cool stuff /in the simulation but just keep in mind in about twenty-ish minutes have //something ready to present to another group. Use simulation figures,/// um, something on a whiteboard, some plates. //// Um something that you can show look at that handout to kinda get a sense of what you wanna have in your presentation. But. Keep- you don't have to stop in the simulation just keep an eye on the time.
361	Mary	/Lets' try putting to equals a hundred?
362	Sujan	//Okay. That's like we would have had, theoretically.
363	Mary	///(Unclear).
364	Sujan	////Oh no, it's actually fifty.
365	Mary	(Makes a noise -- appears to be finely adjusting a slider) /Ah, nice!
366	Sujan	/Yeah buddy!
367	Mary	Okay. And then this is off. And then just start over. Right?
368	Sujan	Yeah.
369	Mary	And wait, tell me when to stop. What are we doing?
370	Sujan	Oh /like fifty, around fifty yeah.
371	Mary	/Like fifty...
372	Sujan	Okay. //And then we turn it on.
373	Mary	//Okay exactly the same as last time.
374	Sujan	So maybe we'll see, a lot less red?
375	Mary	And then a hundred thirty something.
376	Sujan	Yeah.
377	Mary	(Humming a song)
378	Sujan	Oh yeah if you see that, it's like almost at zero percent now.
379	Karl	(Unclear)
380	Sujan	Okay.
381	Mary	Okay, what's going on?

382	Sujan	So like here because there's less there's just- it *seems* like there's le-/ a lower percent. Yeah.
383	Karl	/So we still have a little bit. We still have a little bit of red on this one.
384	Mary	So like basically there was even less though than before?
385	Sujan	Yeah. / So the other one it does go down.
386	Mary	/So it does kinda show- and what would be the reason for that? So like this is even more representative, of ours...
387	Sujan	So it could be just like- because it started out with less, umm, //there's just a small percent that will survive, yeah.
388	Mary	//Like, if it gets killed off right away-
389	Mary	Yeah, that makes sense. Okay. I buy that. Okay. Desktop, okay. This was LB, R2. More representative, okay. Now let's do. Should we do the same thing like six hundred, and then fifty? Oh wait was that fifty calculation based on what? Because we did double that.
390	Sujan	So the fif- so we doubled it. But we also doubled it-
391	Mary	Fifty of each.
392	Sujan	Yeah.
393	Mary	Right. So, should we do like? What would two things we'd want to do for the next,- should we keep it at fifty right now?
394	Sujan	Sure and just kinda like. Umm...
395	Mary	So what are we trying to show? We need Rif twice so it's already on.
396	Sujan	That would kinda just be growing it, on antibiotic.
397	Mary	How do we like take- yeah but the problems is it's like, what we need to represent is like taking some of the cells out, because- which we can't really do on here.
398	TA	(Laughs) Why do you want to do that?
399	Karl	Oh we /can just- we can just change the starting number, starting number of plates. Starting number of population.
400	Mary	/For representing our third type of plate?
401	TA	Right.
402	Mary	You mean like pause it and then change that? And then keep going?
403	Karl	Yeah so we can run it, for how many ever generations until we know how many of each there are, and then like restart.

404	Mary	Alright, so how many generations would we do? What do we say, same thing?
405	Sujan	It's like fifty?
406	Mary	Fifty.
407	Sujan	Yeah.
408	Mary	Okay. Wait, just tell me when.
409	TA	So you're trying to simulate your, la- like that rif-rif, thing?
410	Sujan	Yeah.
411	Mary	Okay, so that would be, mmm-
412	Sujan	Wait antibiotic's- oh it's on, okay.
413	Karl	So that's interesting/ like too much-
414	Sujan	/There's literally-
415	Mary	Oh but it already killed out. So that was like random. (Laughs) Okay.
416	Karl	So this (unclear). We would just have like all...
417	Sujan	Should we- /should we try to stop it before they all die?
418	Mary	/Okay but then change- but then how much do we take out though if your i- like if we just keep going with this idea?
419	Sujan	Ummm.
420	Mary	Was it one-
421	TA	So wait, explain to me *why* you want to take some out. What are you trying to model?
422	Sujan	So we're trying to pretend that/ (unclear) and then like taking s- umm, doing the dilutions. //To plate.
423	Mary	(To K) You know we should have more (unclear), right? Or no, am I lying. Fifty's how much we plate, we should have more in the intial tube though, right?
424	Karl	Yeah.
425	TA	//OH! I see. I see.
426	Sujan	Yeah.
427	Mary	Oh wait, so I should redo this. We have to reset it up because/ it's in the tube first.
428	Sujan	/Do you want to try it again, and maybe stop it before it dies?

429	Karl	(To M) Right yeah yeah yeah. We can just like have more-
430	Mary	(To S) Yeah no but we need to change this number like it's how much we have in the plate theoretically.
431	TA	Interesting, that's actually kinda neat.
432	Karl	So we get how much-
433	Mary	Not in the plate, in the tube. There's more in the tube and then we put fifty on the plate. /So we need the tube first.
434	Sujan	/Oh! So maybe make it like, whatever it was before //six hundred or something.
435	Karl	//Doesn't matter.
436	Mary	Wait how much did we put in?
437	Karl	'Cause we don't really know how much we put in before we intubate it.
438	Sujan	/Yeah.
439	Mary	/No we did, we do. //We put in-
440	Sujan	//Oh! But it's like one billion, or something.
441	Mary	It was a hundred/ micro-
442	Karl	/It's like (unclear)
443	Mary	Was it a hundred microliters? Of each.
444	Sujan	Yeah and it's one billion cells...
445	Mary	Well we can't really do that.
446	Sujan	We could just make it like really high.
447	Mary	Okay.
448	Sujan	Oh 'cause we didn't *initially* start with like one billion like it goes up to that amount, so.
449	Mary	Oh that's what we theoretically have. So-
450	Sujan	So maybe just put it up to like six hundred or something.
451	Mary	Now it's doing that thing where it won't let me edit it.
452	Sujan	Oh does it think it's like, clicking on text? Maybe right click and see if it's like, selecting on something?
453	Karl	Maybe just setup or pause or something?
454	Mary	Do what?
455	Karl	Click like, maybe this to reset it?

456	Mary	No it's like letting me click on the thing-
457	Karl	Oh, man.
458	Mary	Oh man.
459	Karl	(Laughs)
460	Sujan	Oh you /can't even hold down? Oh!
461	Mary	/Hold it down (unclear)
462	Karl	So like both at the same time.
463	Sujan	(Laughs)
464	Mary	Oh yes, that is efficient. Okay wait. There has to be something going on. This is gonna be a hell of a wait. We have to find a more efficient way to do this.
465	Karl	Okay what are we trying to get to?
466	Sujan	Just do select and deselect and see if that works. I think that worked last time. Yay!
467	Mary	Yeah, right. You genius. Okay. Let's me go up to a thousand.
468	Sujan	Let's just do a thousand, I guess. Because why not. And then we'll put it down to fifty?
469	Mary	So we'll do this, until it gets to fifty two and then put it down to...
470	Sujan	Yeah.
471	Mary	Right? Okay.
472	Sujan	Oh! It's dead.
473	Karl	(Laughs) It just died.
474	Mary	Wait though, isn't that representative- oh it's not representative.
475	Karl	It is, I would say this is pretty representative, right?
476	Mary	But we had like a *few* dots.
477	Karl	Yeah that might've just be like statistical, like anomaly.
478	Sujan	Yeah.
479	Mary	Yeah, I guess like in /comparison basically like zero.
480	Sujan	/Should we increase the //red's mutation rate?
481	Karl	'Cause we basically had lawns of,/// three- we had lots of 938
482	Mary	Oh that's true because we actutally don't know what the mutation rate difference is.

483	Sujan	Maybe if we increase.
484	Karl	But then we only had like one or two, /939 so it then is pretty much just like-
485	Mary	/Yeah it could have been that this mutation rate is, too big. Like the difference is not actually that much.
486	Sujan	Do you wanna put red to five?
487	Mary	Wait hold on let me finish with what we said we were gonna do.
488	Karl	Or do you wanna do like, ten to twenty. Because with that case we could have...
489	Sujan	Have more yeah.
490	Karl	Right. We could get some mutations for 939 as well.
491	Sujan	Yeah.
492	Mary	Hold on. Let me just finish with this. Simula- snap a pic!
493	TA	Any luck with that?
494	Mary	Umm, wait what was I doing? Hm. I mean no because it died out but-
495	Sujan	(Laughs)
496	TA	(Laughs)
497	Mary	Well, then this isn't really gonna be (off? awful?)
498	Karl	You can just compare like/ (unclear)-
499	Mary	/We were trying to like, show, hold on this is about to switch. Hmmm. Okay. We were trying to show how like- first mimic, it growing it in the tube with the Rif. So we put it up to like a thousand for the number of cells, {TA: Okay} instead of starting with fifty because we saw that changing that like affected it. But then it just died out.
500	Sujan	//Like immediately.
501	TA	//So wait. I'm not super clear on it. So you started *what* at a thousand?
502	Mary	Because in the tube we put like a hundred microliters of each.
503	TA	Right.
504	Mary	Which is like-
505	TA	I see.
506	Mary	So we were trying to like say that we have more cells so it wouldn't necessarily just get wiped out (unclear) but it, still did.
507	TA	It still didn't work. Okay.

508	Mary	So, but we're also wondering if like mutation rate is a problem like maybe it's not *actually* one to ten. So we're trying to figure out why we got any green at all. On the lawn one. Which is basically honestly zero like everything. Cause there's a lawn and like, ten.
509	Sujan	/And like ten. Yeah.
510	Mary	So it kind of is.
511	TA	So remind me in your experiment, not the- what you actually did they were fifty-fifty mix?
512	Sujan	Yes.
513	TA	So you had, what'd you say a hundred microliters of each strain. Okay. And so you were operating under the assumption, that when you stuck those in a Rif environment, and they all just (mimics pipetting).
514	Mary	(Unclear). Oh.
515	TA	You just pipetted them out of the culture tubes and into the rif mixture. So what's your anticipation of like in that moment, what did that makeup of cells look like of who survived?
516	Mary	Well we're saying there were fewer...
517	Karl	Definitely majority high mutator.
518	TA	Okay.
519	Sujan	Yeah.
520	TA	Why do you think anybody survived. I mean I know that you know that they did, because you saw them on your plate. But, what does that tell you?
521	Mary	Because we like- oh wait.
522	Sujan	So maybe just like in starting they had that mutation already.
523	TA	Okay. Okay. So like grab 'em out of that stock culture, /some number-
524	Mary	/But I guess it's still- like we still would probably have ten to the ninth.
525	TA	Not ini- not like right away. Right but after they (unclear) for a while.
526	Mary	No but I'm saying like- oh. No like in the rif incubuation tube it's like, say like- three percent I don't know something really small of the low mutator strain had this mutation for the resistance, to get to ten to the ninth we're starting with, 18, or whatever.
527	TA	Right, that's fair.
528	Mary	And getting- but like, would that still make it to ten to the ninth?

529 TA How many?

530 Mary Like seventeen hours.

531 TA When did you actually come in seventeen hours? Probably.

532 Mary So that shouldn't have been like a problem.

533 TA I mean it's a reasonable, question to ask.

534 Mary Yeah.

535 TA Yeah it's a challenging thing to model you're like, trying- 'cause I see what you're trying to do. You're trying to model what you had in your tube, and then you're trying to model what happened once you put it on the plate. /That's tricky.

536 Mary Yeah because we weren't putting fifty-fifty onto the plate.

537 Karl Hm.

538 Sujan Do you want to just, /play with the mutation rate?

539 Mary /But I don't know how to-

540 Sujan Let's maybe do what like um// we previously said, like ten and twenty.

541 Karl //Like ten and twenty.

542 LA So remember, you can hit pause, and change conditions.

543 Mary Yeah that's what we've been doing, /but we still- we're still trying to find the right way to change the conditions that would represent like, the Rif tube, like what it's gonna look like at the end of the Rif tube and then going, then like a select few of that going to the rif plate and that's- we're having trouble, mimicking. Or representing.

544 LA /Have you guys, are you still (unclear)-

545 LA Yeah. I mean you guys did have pretty,// strange resu- ah cool! Cool results.

546 Mary //Specific...

547 Mary Yeah. Umm

548 LA Also, I was thinking about your, your results. And, like the fact that you got a lawn. And. I'm assuming that you plated an undilute amount of cells. When you did that right?

549 Mary Mhm.

550 Sujan Yeah.

551 LA So maybe keep in mind, right, when you're talking about (unclear) have a lawn.

552 Mary Yeah.

553 Sujan So let's try this and see if any red survive.

554 Mary What am- what is this- /do you want to start at fifty two?

555 Sujan /We could maybe- we could maybe have it a little bit higher. Just so.

556 Karl But let's definitely start with one. Because //(unclear)

557 Mary //Should we go back to...

558 Sujan Yeah we- aw is it.

559 Mary Oh it's *this* thing that's selected. Oh! Okay wait can I just move this over?

560 Sujan This is a really, strange thing, that it lets you select (unclear)-

561 Mary I know. Do you want a thousand?

562 Sujan We'll just do a thousand, yeah. 'Cause let's see if red survives before it gets to fifty.

563 Mary Oh wait, we're supposed- we're supposed to have data to show people. We can show them these pictures. And we can show the (unclear) thing.

564 Karl (Unclear, quiet)

565 Sujan Okay stop. Yay! Some red survived! Okay.

566 Mary Okay. So now what?

567 Sujan So now /we-

568 Mary /We go to fifty? //But woudl it be fifty-fifty though?

569 Karl So //try to remember the- remember the, so this is like seventy eight three, point nine percent.

570 Mary Can you do that calculation Karl?

571 Sujan So wait what are we doing? We're doing seventy percent of like /the original?

572 Karl /So fifty

573 Mary /Like seventy-thirty. We could do. //Or seventy-five-twenty-five, whatever you want to do.

574 Karl So //just- well-

575 Sujan //Okay so like seven hundred. So like seven hundred. Wait what are we/ how many are we, putting in.

576 Mary /Of fifty.

577 Sujan //Oh so thirty-five.

578 Mary //Seventy percent of fifty, so like-

579	Karl	Yeah so like thirty-five.
580	Sujan	But we can't go that low. The lowest you can do is fifty, I think.
581	Karl	Oh really?
582	Sujan	Yeah.
583	Mary	No it's all good.
584	Sujan	Oh you can do zero, oh!
585	Karl	So you have like thirty-five and, uh
586	Sujan	And fifteen. Wait isn't fifty, isn't it of a hundred?
587	Mary	Mm mm, /because remember we were gonna do fifty-fifty so we need- it should be over-
588	Karl	/No we went with- Oh right.
589	Mary	No, oh you're right it should out of a hundred.
590	Karl	So just seventy three and um.
591	Mary	Oh yeah, that's what it is.
592	Sujan	Yeah.
593	Mary	So this is, twenty...
594	Karl	Seven. (Unclear) three?
595	Mary	No I know I'm trying to get. Argh. Ah! I'll do twenty-nine if I get there, okay.
596	Sujan	And then, seventy...
597	Mary	One.
598	Sujan	We'll try seventy one.
599	Karl	Oh why didn't you try clicking? Like you can click, right?
600	LA	Just a reminder guys. You're gonna be (unclear) other groups in just less than five minutes, so if you guys have stuff you wanna show them,/ drawings or pictures
601	Mary	/Does it count if we show just like what we downloaded onto the computer?
602	LA	Um if you can come up with a quick, more visual representation (unclear) that would be ideal.
603	Mary	Like I meant do this, but this might not be.
604	LA	If you just want to put that,/ on- on a thing- onto the whiteboards that's (unclear) yeah that'd be good.
605	Mary	/Onto here?

606 Mary (To LA) Cool. Great. (Back at computer) Wait, so should I go now?

607 Sujan Yeah. A hundred and thirty-ish, yeah.

608 Mary (Humming) I'm so tense right now. I just want (unclear).

609 Sujan But like red is going up now!

610 Mary (Makes a distressed noise)

611 Sujan No. That's not really what we saw either. Cool. I feel like they're /gonna cross-over.

612 Mary /Wait what happened?

613 Karl Should we just adjust mutation rates until we get what we want?

614 Sujan (Laughs) Get what we want!

615 Mary So what's the problem with this?

616 Sujan So, there's just a lot of red now. Like it was like down, and then /when we changed it-

617 Mary Which one? I'm like, so confused.

618 Sujan So red is the low mutator.

619 Mary Okay.

620 Sujan But like,/ it's kinda going up.

621 Mary Oh, wait what? This aint right. Okay so we need to make it. This difference, //more. Let me re-start. Should I like, take a picture of this or no? Sujan: //Yeah, so maybe, five and twenty.

622 Mary (To Karl, who is working on a white-board) Wait do you mind if I scooch in here. Thanks dude. Okay, should I, take a- should I take a picture of this to say I saw (unclear). Just in case. Preference.

623 Sujan Sure, just in case we don't get something else.

624 Mary Alright. Don't want them to make us stop I want to keep doing this.

625 Sujan I know.

626 Mary This is like important.

627 Mary /So what is this called? I guess LB-LB. I mean.

628 Sujan /So what are we gonna call this? R, R-R. What did we call the other ones?

629 Mary R-R. That's fine. And then //one.

630 Sujan //Then one, yeah.

631 Mary Okay. So now. What do we wanna do, like...

632 Sujan So maybe like five, twenty?

633 Mary And do the same thing /so we- a thousand

634 Sujan /Yeah, a thousand. Is it gonna.

635 Mary Ooh, oh, oh. Oh my god. Oh nevermind.

636 Sujan Oh there we go.

637 Mary Okay. Yeah?

638 Sujan And then we got to, one fifty.

639 Mary (Humming)

640 Sujan Alright, and so what's a percent? So we're just gonna do like 82 and 18?

641 Mary Mhm.

642 Sujan Or as close to those as we can get.

643 Mary I didn't realize I could click to.

644 Sujan How are you doing that?

645 Mary You can click on the thing which (nods towards Karl) he pointed out.

646 TA (To class) So, definitely start thinking about the kinda stuff that you're gonna wanna show to some other groups. Take another fiveish minutes. /Like I said I'd like you to have some representations of //your data. I'd like to have something from your simulation. And then make sure you're prepared a little bit to just talk, another group through what you did, what you found, and why you think you found it.

647 Mary /(Whispers) Okay. Yeah.

648 Sujan Yeah.

649 Mary //Wait, gotta pause.

650 Sujan Yeah. Gotta pause. (Unclear) one thirty. No!

651 Mary (Laughs)

652 Mary (Quiet) I think we just keep our, old explanations.

653 Sujan Alright, I think that's about it.

654 Mary Also why is that at 126?

655 Sujan M-.

656 Mary Whatever we've been doing (unclear) so I'll just do it like that.

657 Sujan Yeah.

658	Mary	So. Even more change to the mutation rate?
659	Sujan	Yeah. So maybe do five, and, maybe just increase the blue to like...
660	Mary	But we want. Do we think it would be like a thirty percent, mutation rate?
661	LA	So a reminder. It might be helpful if you guys like put in what, (unclear) twenty was.
662	Karl	(Holds up marker). Yeah. That's it.
663	Mary	Umm... you know what I mean?
664	Sujan	Sorry, what did you say?
665	Mary	Like a thirty percent mutation rate, is that normal?
666	Karl	This isn't- is this percent?
667	Mary	Do you remember like what those slides said? For like bacteria like, {Sujan: Ohh} something something to the- you know what I mean is that crazy like thirty percent.
668	Sujan	I ^guess.
669	Mary	'Cause if we're making these-
670	Sujan	Let's just do it 'cause like, 'cause I mean. We'll see if that like makes a difference. 'Cause it's a *little* bit better.
671	Mary	Is this, no.
672	Sujan	(Unclear).
673	Sujan	See it's like getting. It's like better, but, yeah.
674	Mary	Oh (yeah it?)-
675	Sujan	Nah it's- it's fine. Okay there we go. And then, maybe like eighty five, and fifteen? I don't really.
676	Mary	Eighty seven,- oh oh, I see.
677	Sujan	I don't. It's probably a little bit lower than eighty five, but that's fine.
678	Sujan	So close.
679	Mary	Ohhh! Sorry. Is this good?
680	Sujan	Yeah.
681	Mary	(Humming)
682	Sujan	(Scoffs) No this makes me so mad!
683	Mary	Is it too much now?
684	Sujan	/It's like-

685 Mary /I'm like watching the numbers so, wait I'll, look in a second.

686 Sujan Yeah.

687 Mary Wait what happened now.

688 Sujan Red did better.

689 Mary Why? Why did it cross over?

690 Sujan I don't know!

691 Mary Oh because it was like used to the conditions? Maybe it became like (air quotes) stable conditions.

692 Sujan Hmmm...

693 Karl What happened?

694 Mary So wait what does that mean we need to do with the mutation rate?

695 Sujan So maybe we need to make red have a higher mutation rate too? Because like blue has a higher mutation rate, but it's also probably like getting more lethal. {Mary: Mhm.} I don't know I feel like, /I think it's really hard to simulate.

696 Mary /I want to get what we have. R. R. Oop, E R.

697 Mary Okay. Wait, so.

698 Sujan Maybe let's try this one more time. Okay.

699 Mary What are we trying to get- we don't want- it's the problem is is like staying at this point or whatever that's just like a high enough percent- we need like an even lower percentage, right? Of viable, red?

700 Sujan I almost feel like when we change the population it's not actually changing it. Because wouldn't we like see a lot less then on those plates? And it doesn't seem like it's actually doing that.

701 Mary Mmm. So should we do this again and then not change it and see if it came up with the same thing? Just remember it was at like eighty five and whatever.

702 Sujan Yeah.

703 Mary And then just.

704 Sujan Sure.

705 Mary Yeah.

706 Sujan We start at a thousand?

707 Mary And we keep it at a thousand.

708 Sujan Yeah.

709	Mary	(Unclear)
710	Sujan	And so just go to like a hundred and thirty.
711	Mary	Yeah. No I feel like it did change something though because like when we stopped here all of a sudden it was going out again. Remember? /Yeah it definitely is diff- so it definitely is working. Yeah.
712	Sujan	/That's true.
713	Mary	Okay so then we need to still fiddle with something, then. Okay. Yeah no, so that's not what's happening. But, so that's working.
714	Sujan	So maybe increase the red mutation rates? So that some of it is lethal? Ten? I don't know.
715	Mary	But then ten and thirty versus./ (Quietly) Let's try it.
716	TA	/(To class) Alright, so in the interest of time we're gonna go ahead and, stop everybody where they are. I know some of you are still, playing with some simulations// and that kinda stuff but I wanna make sure we kinda get a chance to hear from everyone. /// So just logistically I wanna give you a little bit of a sense of how this next thing is going to work. (Lengthy description of how the presentation activity will be organized. Following conversation happens while TA is talking.)
717	Sujan	//Just to see what happens. ///Now it's not changing.
718	Mary	Is that not good?
719	Sujan	I don't think it's changing enough.
720	Mary	Okay, should I do the (unclear) thing?
721	Sujan	I don't know what- maybe we're just not gonna get it.
722	Mary	Should I make it all even lower?
723	Sujan	(Unclear)
724	Mary	(Whisper) What is it? Sixty-five?
725	Sujan	(Whisper) Wait, maybe. No.
726	Mary	(Unclear).
727	Sujan	(Whisper) Oh wait, (unclear).
728	Mary	Did I do this one already?
729	Sujan	No no no wait, it's like working.
730	Mary	(Groans)
731	Sujan	Okay. So we can stop there. YES!

Appendix 6.3—Unit 1, Week 2 worksheet guiding experimental design, 2017

Competition Experiment Handout

Your next challenge is to set up a competition experiment that will tell you something about the relative fitness of the two strains. In order to investigate this, you will set up a culture or cultures and then use plating techniques to help you quantify the growth you observe.

Use this handout to guide your design and to take notes. You will be asked to write up a more detailed account of your design for homework.

Your first set of tasks is to make some decisions about how you will set up your experiment (the culture(s) and the plates). Keep in mind the lists below of materials available to you for culture and plate set up:

Materials available to set up competition cultures

- Stock culture of each strain that have been grown overnight (using same procedure we used in previously)
- Sterile LB to make dilutions
- Sterile saline to make dilutions
- LB with rif
- LB with lactose

Materials available for plating (all plates have amp)

- Agar
- Agar + Rif
- Agar + Lactose metabolism detecting agent (MacConkey media)

Discuss your experimental design with your group. To focus your thinking and discussion, write and/or draw out some answers to the following sets of questions (You will have to answer these questions individually for homework).

Before you begin a few practical considerations:

- Due to resource limitations, you may use no more than 6 plates in your design.
- Before you leave today, you need to formally 'sign out' and label the plates you will need.
- You will likely need to come in outside your lab time to finish plating.

Before you leave checklist

- ❑ Initial cultures are set up
- ❑ Initial cultures are labeled and placed in water bath
- ❑ Plates you will use are labeled with group name and plate ID
- ❑ You have written down who will come to do the plating and exactly what amount they need to add to each plate and at what dilution
- ❑ Exchanged contact information with your lab group
- ❑ Checked in with TA
- ❑ Cleaned up (wipe down bench, any glass dilution tubes in sink, discard waste)

Name_____ Group_____

Research Question(s)

- What is the research question or questions that you are investigating?

Experimental Design

1. How will you set up initial cultures?
    a. What volumes/concentrations will you use?

    b. What is your reasoning these choices?

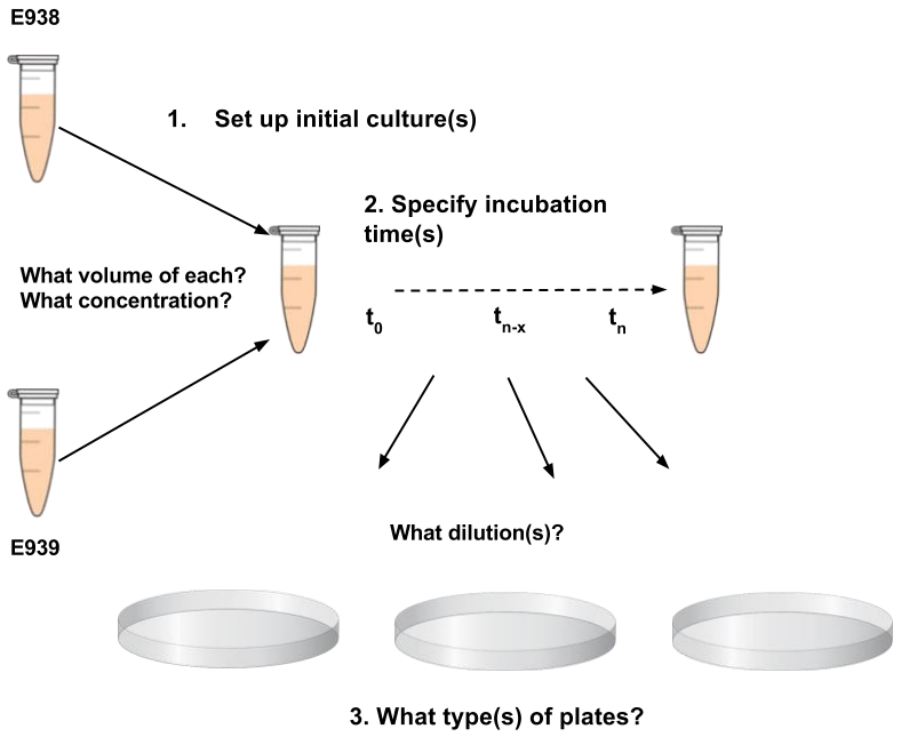
2. After what time(s) will you sample and plate from these cultures?
    a. What time(s)? Who will be able to do this sampling?

    b. What is your reasoning for these choices?

3. On what types of media will you plate your sample?
    a. What dilutions will you plate on each? (~how many cells?)

    b. What is your reasoning for these decisions?

You may find it helpful to diagram your plan.



Anticipated Results

- What do you expect to see on each of your plates? Why?

- What are the sources of uncertainty in your experimental design that make you uncertain about what you might see?

Future Considerations

- How might your experimental design be different if you were not limited by our constraints?
- What other research questions would you ask if you weren't limited by our constraints?

Appendix 7.1—Transcript of Week 2 of Gp 1's Investigation

Moment	Line	Speaker	Turn
1	1	K	Alright so. {Addressed to Jackie -- Alaad is only just returning with a whiteboard.}
1	2	J	So I'm just gonna read this thing.
1	3	K	So let's try to choose something that's not, very- that's not a pain to do.
1	4	J	Yeah. Especially- I can't come in tomorrow, that's for sure.
1	5	K	Yeah.
1	6	J	Looking at apartments.
1	7	A	You think we could do something where like we test uh, which strain's beneficial when resources are like plentiful and which strain's beneficial when resources are sparse?
1	8	K	Yeah so j- testing like, if we have a lot of food or a lot of resources or
1	9	A	Yeah.
1	10	K	Okay.
1	11	K	So we could grow...
1	12	A	We could do one with like a lot of lactose and one with not a lot of lactose.
1	13	K	Is lactose- does lactose help them grow?
1	14	A	I think so that/ they use like a-
1	15	J	It's a food.
1	16	K	Yeah that's what I thought. I'm just making sure. Okay, so just write down. Yeah that doesn't sound too intensive either, right?
1	17	A	(Very quiet) I don't think.
1	18	K	So would we have like two control plates? We could see like what happens when, 939 grows, with a lot of food. What happens if 938

			grows with a lot of food. And what happens when the two of them grow together. We'll see which one-
1	19	J	Yeah we can put them- we can probably use four plates. Two with agar and two with the addition of lactose. Especially /because one of the strains won't have- won't be able to digest lactose. Also. We should probably ask if the kind-
1	20	K	/So we're going-
1	21	K	If they can both di- like what they can both-
1	22	J	Do and can't/ do.
1	23	K	/Agar they can definitely both do right?
1	24	J	Yeah.
1	25	K	Then let's just do agar instead of lactose.
1	26	J	That's not going to do anything though. 'Cause we already did them on agar. That's why we wanna compare them on /agar and then on lactose.
1	27	K	/No but that's why we want- we want to do- see what happens together. For together.
1	28	A	We need four plates?
1	29	J	If they're, combined?
1	30	K	Yeah.
1	31	J	I don't know if that's, the best idea or if that would be allowed.
1	32	K	Why?
1	33	J	I'm not sure I'm just- hmm...
1	34	K	And what's your idea in mind?
1	35	J	Umm. I was thinking we would see how the two different strains grew on regular old agar versus how they both grew on the lactose.
1	36	K	And when you say both grew on the lactose you'd put in, nine-th-
1	37	J	In like different plates.
1	38	K	Okay.
1	39	J	Yeah
1	40	K	That's good that's better. Alright.

1	41	A	So, we need four plates then right?
1	42	K	Yeah.
1	43	J	Yeah.
1	44	K	And then, we would be testing whether one mutation is like-?
1	45	J	Yeah whether the higher mutating one can digest lactose versus the other one. Because I know usually they can't. We should- we should ask if the different types can- I'll go ask if the different types can digest lactose.
1	46	K	And we're just seeing which one digests lactose better?
2	47	TA	Yeah?
2	48	J	I have a quick question about the two different strains.
2	49	TA	Mhm?
2	50	J	Can they bo- can one digest lactose and the other one can't?
2	51	TA	Neither of them right now can.
2	52	J	Okay, so it would be a good test to see if you plated them both on agar, and lactose, (unclear) plates whether the higher mutator would evolve to digest lactose?
2	53	TA	Yeah and the reason I was just saying to (another student) um. So. You- the reason we have untransformed and transformed bacteria is because with those MacConkey plates, which are the red plates, the way actually like digests lactose is you get a colony, even if it can't digest lactose. If it can digest lactose it gets a red dot in the middle. And when you have color colonies like the green or the red
2	54	J	It doesn't work
2	55	TA	It doesn't work. So you have to use untransformed.
2	56	J	Okay.
2	57	TA	And that means that you can't plate them together. They have to be sort of what we did here like 938-
2	58	K	They have to be put on separate plates.
2	59	TA	Yeah.
2	60	A	But do you think we could actually test this? (Shows TA the whiteboard.)
2	61	TA	What would you be testing?

2	62	A	Which strain grows better in a resources scarce environment and which grows better in a resource plentiful environment.
2	63	TA	So when would you be growing them. Like, in the tube? Like if you look at the diagram I think on the back, so are you talking about growth in that tube? Or growth on the plate.
2	64	J	Growth on- we were going to put them on, two- each strain on a regular agar, plate. So, just normal environment. And then we were going to put each strain on lactose and see, if the higher mutating one did better on the lactose than the lower mutating one. Because it had a resource it could tap into and potentially get a mutation that allows it to use it.
2	65	TA	So keep in mind that we're focusing on the fact that mutations happen in the tube and then when you plate them it's just a kind of way to look at what colonies are already in the tube. So how could you ask the same question, knowing that? And if you look on there you've got different types of treatments that you can include in your tube. You don't just have to grow them in LB- which is the sort of the growth medium. You can grow them in supplemented LB. So take a look at that, and see if that makes sense.
2	66	K	You can grow them with uh, lactose. Yeah.
2	67	J	Yeah, you can grow them in LB plus lactose and, see, if, that, would, yeah.
2	68	A	So the agar would be uh present in the broth, right?
2	69	K	Yeah.
2	70	J	What?
2	71	K	Wait.
2	72	A	So, is it possible that we dilute the agar?
2	73	J	No.
2	74	A	/Like so there's less.
2	75	K	/No we're not gonna dilute the agar.
3	76	J	Okay. Um. So we grow the normal ones in sterile LB. Just in the regular ol' LB. {Begins writing on her worksheet. Kyle also begins writing on his.} "Grow the untransformed in LB." (saying what she's writing)
3	77	K	So we're- they'd be in two separate, containers.

3	78	J	Yeah. (Mumbling to self quietly) "Plate, on, agar. (unclear) {Alaad starts writing on whiteboard here} in LB+Lactose. Plated, on, MacConkey. (Unclear)"
3	79	K	So the normal ones will be plated on agar, right? And then the other ones will be placed on lactose?
3	80	J	Yeah. Let me think for a minute. (~10 seconds of silence) Would we want to just grow them all, in, LB+Lactose because it doesn't really matter if you put them on agar if they were grown in LB+Lactose or what. We could just grow them all in that because in the presence of lactose they're not going to be in the presence of lactose once you put them on the agar. So it's not going to really make a difference. Just to make it easier on us. And make it so there's only one variable changed.
3	81	TA	(in distance, to whole class) Keep in mind guys that we're operating under the assumption that the tube is where mutations are happening. And plating is a way for us to see what has grown in the tubes.
3	82	J	So that seems like a good experiment.
3	83	K	Repeat it.
3	84	J	It seems like a good experiment.
3	85	K	Repeat our experiment one more time.
3	86	J	So we're going to grow normal untransformed bacteria in the LB+Lac and then plate it on agar,/ to see-
3	87	K	/Does the transformed not even matter for this- do we need transformed?
3	88	J	We need untransformed.
3	89	K	No just like- I know that.
3	90	J	It does matter.
3	91	K	But no like. Can we just use untransformed for the experiment/ do we need transformed bacteria?
3	92	J	/Yes. No we don't need any transformed// bacteria.
3	93	K	//That's- okay.
3	94	J	Yeah. Cause we don't want the color.
3	95	K	Don't want the color yeah exactly.
3	96	J	So we do that. And then we grow the second set of bacteria, in-
3	97	K	So we would grown 93, 9 or whatever.

3	98	J	Yeah. 939 and 938. So we have two different kinds. So the first two plates will be, agar. And we put a little bit of each on those. And then the second set of plates will be, the, lactose ones. And we put a little bit of each on that. And we would expect to see probably equal growth/
3	99	K	/on the agar.
3	100	J	on the, agar- just plain old agar ones. And, then, we'd probably expect to see very little growth on the lactose plate for 9 3 9. Cause that's the low mutator. And we'd expect to see a lot for 938 beacuse that's the high mutator.
3	101	K	Alright that's good.
3	102	J	Okay.
3	103	K	But then like what did she say like thi- didn't she say the plates are not supposed to have a lot of uh- they're not the plates where mutation, is undergoing.
3	104	J	Yeah. That's why we're growing it in lacto-
3	105	K	Then why does it matter where-
3	106	J	lactose
3	107	K	Why does it matter if they're placed on the agar. Oh because, okay. / Nevermind.
3	108	J	/Because that's aft- they're mutating in the tube so that's why we want to put lactose in the tube because it would possibly initiate mutation,
3	109	K	For lactose.
3	110	J	for lactose yeah. It doesn't matter on the agar that's why we can put it all in lactose, L- L- fluid. Because once you put it on the agar it's going to eat agar. Because when it eats lactose it just gains the ability to eat lactose, but when you put it on the lactose then you get to see 'oh, which one did a better job of mutating.'
3	111	A	(Drawing a circle in air pointing to the whiteboard) This is what we expect right?
3	112	J	Yeah.
3	113	K	Alright. Wait. 939's the. We want more of the 938.
3	114	J	Yeah. Cool.
3	115	K	Let's call her over. Before we start writing.

3	116	J	(Reading off the worksheet) What is the question, or questions, that you are-
3	117	K	Wait before we start writing things down let's have her- let's go over...
3	118	J	Okay.
3	119	K	Yeah.
3	120	J	Could you take care of that while I just run to the bathroom? She's probably gonna be busy for a while anyway. (Jackie leaves)
3	121	K	Yeah. Sure.
4	122	K	(Looks over at whiteboard contemplatively for a few seconds.) (To Alaad) So is our question different then?
4	123	A	How? Would we- do we change it to, how they react to lactose instead of resources plentiful?
4	124	K	Just. Which strain grows better-
4	125	A	In lactose-based environment?
4	126	K	(chuckles) Yeah basically which strain grows better in a lactose-based environment. And we expect the uh high mutator, yeah.
4	127	K	Right because the agar is the control.
4	128	A	(Nods)
4	129	K	The one thing we have to like figure out though is like how to like plate each strain, you know?
4	130	A	We're going to need four tubes then, right? Four tubes as well? Or two?
4	131	K	Just two because, yeah.
4	132	K	And we'd be using sterile- sterile LB. For untransformed strains. (Pause. Stands.) I'll walk up to her. (Pause. Jackie returns. Kyle fills Jackie in) She's still talking to people.
4	133	J	(Laughs) Yeah.
4	134	K	Basically like. Our thing works. We're gonna change the question though. So instead of asking like which one goes better resource saving, the question is which strain grows better, in lactose.
4	135	J	Yeah. That's pretty much it.
5	136	K	The one thing we have to figure out though is how to like plate stuff then (unclear) stuff, you know?
5	137	J	Yeah. I can't come in tomorrow at all.

5	138	K	No yeah, like, Monday maybe. Next week.
5	139	J	I can't do Monday, I've got two tests on Tuesday.
5	140	K	Well I have two tests. How bout then Wednesday.
5	141	J	Okay maybe I can do that. Let me. We just need to talk to her about like- timeframe kinda thing. Cause, I'm busy, Friday Saturday Sunday Monday.
5	142	K	Yeah I have two tests on Tuesday too. I'd prefer to do after Tuesday.
5	143	J	Yeah same.
5	144	K	Like Wednesday morning would be best.
5	145	J	I can't do mornings. How early?
5	146	K	Like, twelve?
5	147	J	I've got class.
5	148	K	Eleven?
5	149	J	I guess I could but I don't want to come all the way down here at 11.
5	150	K	If you have to do it you gotta do it, you know?
5	151	J	I know. Like I have, after 4- after 3 or 4 free every day. So I'd much rather do it at night then-
5	152	K	Oh then do uh- just do-
5	153	J	Except not tomorrow because tomorrow I've got, things due but-
5	154	K	How about Tuesday afternoon, like at 4:30.
5	155	J	Can you do- that's kinda when we're- I'm going to be studying, what do you have Wednesday?
5	156	K	Wednesday I have lab for comp sci.
5	157	J	Wait. Tuesday that's after the test.
5	158	K	Yeah that test-
5	159	J	Okay yeah.
5	160	K	I have the bio test.
5	161	J	Bio test. And I have a history test.
5	162	K	(To Alaad) Does that work for you too? Like Tuesday afternoon.
5	163	J	/We don't all have to be here. That's the thing. I don't think.
5	164	A	/Tuesday what time?

5	165	K	But it's good to have at least two people here. To double check. (Pause) She's gonna check this off, should we figure out how much stuff we have to- like how do we dilute it, you know?
5	166	J	I don't really understanding dilutions completely I'm not really- I'm not really good at certain mathy things. So.
6	167	LA	(Unclear) where you are.
6	168	J	Yeah. We're wondering if our- if our, experiment is like
6	169	LA	(Unclear)
6	170	J	Yeah. Something.
6	171	K	We're asking which strain grows better in a lactose based environment. And the way we're going to do that is by using- we're growing untransformed E939, E938 in a sterile LB-
6	172	J	No in a lactose LB.
6	173	K	Yeah no they both have lactose so it doesn't matter, which one.
6	174	J	No these are two different versions of this. If you look over there there's three different versions of LB. There's sterile LB, LB+Rif, and LB+Lactose. Yeah, we want the lactose one.
6	175	K	Okay LB+Lactose.
6	176	LA	There's also LB + Amp.
6	177	J	Yeah we're not going to want- we don't want it because of the- we've got to use the untransformed, stuff. So that- so that (laughs).
6	178	K	So we'd be growing that in, the LB+lactose. And then after they've grown, we plate them. So we used agar as a control to plate 939, 938 on agar plates and then we grow- we place 939, 938 respectively on lactose plates. And we expect 938 to, have more growth because they have a higher mutation rate so, when exposed to lactose in the, in the container, it'd be more likely to generate a mutation.
6	179	LA	(Unclear) um.
6	180	K	We're just not sure about diluting stuff and like setting it all up.
6	181	LA	Right. Um.
6	182	K	Yeah. And how long it's going to take.
6	183	J	And what like the procedure is coming in to like do that and what not.
6	184	K	Yeah.

6	185	LA	Okay. (Unclear) dilutions for the most part, will be- I mean it also depends on if you guys wanted to plate a high concentration or a low concentration. But if you're not. Like 'cause I know some groups are trying to do like a high concentration *versus* a low concentration of certain things. (Unclear) dilute it the way that you (unclear).
6	186	J	So we would dilute a little *less*?
6	187	LA	Beacuse you guys didn't get anything?
6	188	J	Yeah we barely got anything.
6	189	LA	Yeah, that might be, (Unclear). Definitely an option. /And I think-
6	190	J	/Just go 10^5 instead.
6	191	LA	Yeah maybe. Definitely go to (the TA). That'll be something that you guys do when you're in here on your own. So you won't be even diluting tonight. Um.
6	192	K	Yeah so once we dilute and plate it how long- how much time should we give it to grow?
6	193	LA	Once you dilute and plate it. Um...
6	194	K	We can't really come in until like Tuesday afternoon.
6	195	LA	You guys can't come in until next Tuesday to plate?
6	196	K	To do the entire thing.
6	197	LA	Okay. So I think the way it's gonna happen, and I'm not sure you should talk to (the TA), is you guys are gonna come in and you'll plate, and you'll put it in the incubator, and then, TAs will take them out of the incubator after a two day period.
6	198	K	Okay.
6	199	J	So two days. That gives us time until Thursday.
6	200	K	I don't know if you're supposed to choose- did it say on here somewhere if you're supposed to decide how long it stays in the incubator?
6	201	J	I don't think.
6	202	LA	I think it's normally (48 hours?). (Unclear)
6	203	K	Okay fine.
6	204	LA	If you guys want to get (unclear).
6	205	J	Okay. Two days. Two days. Everything's incubated for two days it seems like.

6	206	LA	Yep.
6	207	J	Okay.
6	208	K	Yeah and dilution. We're just going down to 10^5.
6	209	J	Yeah. 10^5. Because 10^3 just didn't work well. Just in case.
6	210	K	Alright.
6	211	J	And if it's all a big flop then it's our first flop.
6	212	K	Should we still talk to the TA about this?
6	213	LA	Yeah check with the TA and then ask her if she wants you to come to me to get cells.
6	214	K	Okay, yep. Let's just like walk up to her. (Stands)
6	215	J	Cause that would be. Ours is *fairly* simple. But it's going to be kind of interesting. I was hoping we'd choose to use the lactose plates because I'm kind of interested.
6	216	K	We are using lactose plates.
6	217	J	I know that's what I said I'm glad we are because I was interested in using them as soon as she first mentioned them.
6	218	K	Yeah. Alright. Want to go explain it to her?
6	219	J	Okay, sure. Well, we should wait until she- we should just kind of wave our arms around.
6	220	K	We've been waiting for her for like twenty minutes though.
6	221	J	That's why you gotta go like this. (Raises hand)
6	222	K	This is actually a really good plan. Let me take a picture of this. This is a good drawing.
6	223	J	I will, take a picture as well. There we go.
6	224	K	(To A) Write like 10^5 cells.
6	225	J	Do you want me to try to explain the question, and what not?
6	226	K	I can do it again if you want me to.
6	227	J	No I can do it if you want.
7	228	J	Okay, we have our experiment planned out.
7	229	TA	Okay, talk me through it. What's your question.

7	230	J	So, our question is. Which strain will grow better, in a lactose environment. And our plan, is, to, take the, 939 and 398, and grow all of it in the- not all together but in the-
7	231	K	Separate- /LB + lactose tubes
7	232	J	Two separate /tubes, in the LB+ lactose. And. Then we're going to, dilute it down to 10^5. Because 10^3 was a little bit of a flop last time. So just maybe just a little bit more- a few more cells to- /ensure-
7	233	K	They'll be down to 10^5 and then, we'll use agar as control for 939/938. We expect lawns or significant growth on both plates, and then, we grow two separately on lactose plates to see which would grow better. We expect 938 to grow better because, it's a higher mutator. It's more likely when growing lactose that it will develop a mutation against that.
7	234	TA	Okay. A couple things. Um. What kind of colonies are you- or sorry, what kind of strain are you guys using?
7	235	J	Untransformed.
7	236	K	Untransformed.
7	237	TA	Okay untransformed. Also another thing. With the MacConkey-lactose plates, everything will grow on it, but they have an indicator, that will change color/, as the colonies can digest lactose. So even those that um are just regular non-lactose digesting, they should still grow on there, but what happens is- there's a word for it I should know it but it basically forms a red dot in the middle of the colony. And that's how you know it's digesting lactose.
7	238	J	/Ohhhhh yeah. Okay so they turn red.
7	239	K	So the ones with more red dots, will be.
7	240	TA	So that's just for (unclear), while.
7	241	J	Yeah, for (unclear).
7	242	TA	Yeah. So I would, I think I would still dilute down to 10^3 for the agar plates. I think that was most likely a stock issue, not a you guys issue.
7	243	J	So 10^3 for the whole thing? 'Cause I mean they're all gonna be growing.
7	244	TA	Yeah. MacConkey, I don't know if we tried that yet.
7	245	K	What do you mean tried what?

7	246	TA	Like- sorry if *we* tried that yet if we, if I know, what dilution you should put.
7	247	J	I think if you said that they grow on all plates, then we should probably go 10^3 for those as well, (unclear).
7	248	TA	That is true, yeah.
7	249	J	So I think just 10^3 across the board?
7	250	TA	Yeah I think that's a good. You also have six plates. So if you want to try two dilutions, you could do that.
7	251	K	Yeah.
7	252	J	And, um, would Tuesday, afternoon be a good time for all of us to come in and do the dilutions on that?
7	253	TA	So you can, um, set, I think everyone is supposed to set their culture tubes up to day. Meaning someone or two of you or three of you will come in tomorrow.
7	254	J	Okay. Because I know I can't come in tomorrow. I'm seeing an apartment. And that's, not...
7	255	K	I'm not sure if I can come in tomorrow, either.
7	256	TA	Okay. Um.
7	257	K	Wait so we'd be plating tomorrow?
7	258	TA	That would be the idea, yeah.
7	259	K	Okay.
7	260	J	How late does this stay open?
7	261	TA	I think it's on there. (Walks to front of room) There's no labs tomorrow, so, probably- this room is open until ten.
7	262	J	Til ten at night? Okay then I could come in later because the apartment thing is at five forty five, (unclear) it's not even over and I-
7	263	TA	/This would be free all day honestly from 10 to 10.
7	264	J	/Honestly. Yeah so would, would it already be diluted? Or would I just do the dilutions?
7	265	TA	You would have to do the dilutions because you would assume that when you're growing them it grows to 10^9th.
7	266	J	Okay. Honestly if- I could just do the whole thing myself, if none of you can come in tomorrow.
7	267	K	Tomorrow what time?

7	268	J	Like, I don't honestly know that's the thing. Because I have no idea how long an apartment tour is going to take. Like talk about leases and all that I've never done this before? So like, probably fairly late.
7	269	K	I mean if you don't mind doing that.
7	270	J	Yeah I don't mind. I mean, sometimes it's like quicker doing things by yourself, 'cause then it's just like "okay I know what I'm doing" / bam bam bam done.
7	271	K	/(Unclear). (To TA) We'll do that.
7	272	TA	Okay. So, before you leave today, you'll have to set up your actual culture tube.
7	273	J	Okay. That's really quick. We can just put some of that in the tube and put some of that in the other tube.
7	274	TA	Yeah. So there I have those plastic tubes on the left. You'll want to aim for five milliliters of the broth.
7	275	J	Five milliliters of the broth?
7	276	TA	And (LA) did you check, how, what the volume for the-
7	277	J	Is that 500 microliters?
7	278	LA	You're gonna put five milliliters of the LB-/
7	279	J	So that's 500 microliters?
7	280	LA	You can use the /(pointing) green.
7	281	TA	You can use these guys.
7	282	J	Oh, okay, cool.
7	283	LA	And then you're gonna use one hundred (unclear).
7	284	J	Okay, cool. How bout we just-
7	285	K	How about we just do that right now.
7	286	J	Yeah.
7	287	K	Wait so how many hours do they incubate at?
7	288	J	Two. Somebody else takes them away.
7	289	K	Alright.
7	290	J	(To TA) So where do we put the plates when we're done with them? Do we have some kind of a label? How long?
7	291	TA	Yeah. Go- go ahead and put your name on them. But our coordinator's gonna care of taking them out. It's just easier.

7	292	J	So it doesn't matter if it's roughly two days or more than two days?
7	293	TA	No it's okay. He's gonna take them out at the right day. Before you guys leave, if you guys go to the Google Drive again. On that same spreadsheet there's another tab. It doesn't need to be completely filled out, it's mostly for you to come back and check in as a record. It's also for me to know, keep track of-
7	294	J	Before we get the cells can we just fill this out and then do that?
7	295	TA	Yeah. That's a good idea.

Appendix 7.2—Transcript of Week 3 of Gp 1's Investigation

Moment	Line	Speaker	Turn
1	1	K	So can't we just draw that picture again for the uh, presentation? Like with the cir- plates. The red dots or whatever.
1	2	A	(Nods)
1	3	K	Did it work?
1	4	J	Yeah we got plenty of them that grew.
1	5	K	Wait so these are the lactose plates?
1	6	J	Yes.
1	7	K	Okay.
1	8	J	They used- they were all four of them taped together before. I have no idea how they ended up like this but they did.
1	9	J	Yeah there we go there's our control plates. Look pretty much the same.
1	10	K	Yeah that's-
1	11	K	Can you flip it over the other way? Oh. Just take it off.
1	12	J	These do look redder than those.
1	13	K	Okay which is the uh, the 938?
1	14	J	(Points) This is the 938.
1	15	K	Oh let's go!
1	16	J	And this is the 939.
1	17	K	It worked.

1	18	J	It did work. Yeah, 'cause look, these are definitely doing their thing.
1	19	K	(to J, who is holding a plate up to the ceiling lights) Here take it off again so we can see more clearly. Just put it down and then.
1	20	J	Yeah we can ask, we can ask questions about what they're supposed to look like if they're digesting lactose.
1	21	K	Thats- yeah, this-
1	22	J	'Cause these two look like they're digesting lactose. I'm not sure about any of the other ones.
1	23	K	Yeah I /can ask.
1	24	A	(Pointing) None of these are, right?
1	25	K	None of those are.
1	26	J	Definitely none of these are.
1	27	A	And I think, all of these are. Look at them. They're all red.
1	28	K	Like, the ones that are big and red.
1	29	J	Give me one second (grabs handout). (To self) "c'mon".
1	30	K	We don't have data for this, we can just- like it's more like, qualitative.
1	31	J	Put 'em on the, put 'em against the white (on top of a white paper for contrast)
1	32	A	//They look (unclear)
1	33	K	//Okay this is/ definitely the lactose-
1	34	J	/These have bubbles in them, though. Versus that's- if you hold it up to the light (lifts plate up and turns for them to see) you can see that they've got bubbles and it's not-
1	35	K	How 'bout we like Google like (unclear)-
1	36	J	-I think. I'm not really sure if those are like-
1	37	K	Or ask her if that's the right thing for MacConkey.
1	38	J	They're coming around to take a look at our /stuff, so we can just wait until they come.
1	39	K	/Oh they are? Alright so for the presentation we don't need any data. Like we don't have any charts or anything. We should just draw what we see.
1	40	J	Yeah.
1	41	J	We don't- it seems to have worked perfectly.

1	42	K	I think so yeah.
1	43	J	'Cause the 938-
1	44	K	/The 938 has stuff.
1	45	J	/ The 939, is just pink. Like um, growing on a pink medium.
1	46	K	Oh we have to do the simulation too.
1	47	J	Yeah. Just these are just on some agar.
1	48	K	Yeah just put that there for the time. Like, we still have to do the simulation on the computer.
1	49	J	I'm gonna- I'll take a picture, a photograph, of these.
1	50	K	Yeah.
1	51	J	Each.
2	52	A	Wait how do we replicate lactose on this?
2	53	K	We can- that's what she was saying we can't do that.
2	54	J	Um let me see. Can you turn the- tilt the computer this way? Um/
2	55	K	/No she was saying that you can't really do that.
2	56	J	Yeah.
2	57	K	Just wait 'til she comes around. Just talk to her about all this.
2	58	J	Yeah.
2	59	K	Let's just chill out a sec.
2	60	J	I think it would be just beneficial mutations go up.
2	61	K	And then like-
2	62	J	Yeah.
2	63	K	Lethal go down to zero.
2	64	J	Keep lethal and resistance at zero because- it's not- that's not- well you could put lethal up a little bit because of,/ realistically there's going to be some. Yeah.
2	65	A	/Like 5%. That's good.
2	66	K	Right there.
2	67	J	If you want to get it exactly to a point just click on either side of the little sliding bar and it'll move by a degree of one.
2	68	K	Oh, okay.

3	69	J	I'm just gonna take pictures of these.
3	70	K	Yeah, I'll do that too.
3	71	J	Here's the white background for this (pulls some blank paper).
3	72	K	It's so annoying how every- like after every lab we have to write a four page paper.
3	73	A	(Quietly) Yeah.
3	74	K	(Laughs)
3	75	J	I came from chem first.
3	76	K	You just had a chem lab?
3	77	J	Chem is a hell of a lot more annoying than this. You've got to write a full lab report after every lab.
3	78	K	This is like the equivalent though, really.
3	79	J	No no no! You've got to write one, you've got to generate graphs-
3	80	K	Wait. When you took the pictures you just do it this way?
3	81	J	Yeah when I took these just do it on an angle so you can see the little bumps. The reflection- the glare isn't that bad just get like-
3	82	K	Alright. (Pause) It's hard to see it, whatever. Alright. Where's the... alright. Okay.
3	83	J	Cool.
3	84	K	(to A) Do you want to take pictures of it? Or?
3	85	A	I'll take 'em later.
3	86	K	Alright, sounds good.
4	87	TA	How are you guys doing?
4	88	J	Um, looks pretty good, /yeah.
4	89	K	/Yeah. We're not sure how you can tell like if they actually have lactose or not.
4	90	J	Yeah, /like these are obvious,// but like-
4	91	TA	/Yeah. //Yeah, so-
4	92	J	With these little pin dots in them is that, is that- mean anything because these don't have the dots as much- or are those just bubbles?
4	93	K	Yeah we can't really.
4	94	TA	Hmmmm. Let me see this one?

4	95	J	Cause this one, doesn't, have those little splotches as much.
4	96	J	If you want you can have like a white background. I've been doing that just putting them on um, / this.
4	97	TA	/Yeah that's interesting.
4	98	J	It makes them easier to see.
4	99	TA	Um.
4	100	J	'Cause these almost look like they've got little bubbles in them but I only see a couple in here like that one.
4	101	TA	Yeah... I feel like my- at first I was like 'oh only those two colonies are digesting lactose, but/ now it's like, hard to know-
4	102	K	/Yeah but now it's like.
4	103	J	//I think there's at least this one more.
4	104	A	//I was gonna say there's a whole lot more.
4	105	TA	(to A) You think most of them are?
4	106	A	Yeah.
4	107	TA	Or all of them.
4	108	A	/Mostly all of them.
4	109	K	/The 938 plate or 939// plate?
4	110	J	// Yeah like this- there's a little bit of like bright red in that one.
4	111	TA	There's one in there. So what's the difference between these two plates?
4	112	J	This is the low, uh, the low mutator and this is the high mutator.
4	113	TA	Okay. Okay.
4	114	J	Which, makes sense.
4	115	TA	Ummm... Let me just look. Let me look at one other person. I'm just gonna bring a lactose plate over here.
4	116	J	Okay. I guess it worked a little too well.
4	117	K	I think it worked.
4	118	TA	So this is like another groups'. And all of those colonies in the background, the smaller ones. Those we're interpreting as not digesting lactose. (Everyone leans over to look at plates, including A.)
4	119	J	Okay.

4	120	TA	I'm trying to figure out if those look different in color from the ones-
4	121	K	I think those- I think those are different than the 939 plate.
4	122	TA	Yeah.
4	123	K	Those are like lighter.
4	124	TA	So, so you think all of them could be digesting?
4	125	J	I think they used a different concentration. That's all I think.
4	126	TA	Oh yeah, they did.
4	127	J	This seems more like almost like a lawn.
4	128	TA	It almost is. Yeah.
4	129	J	We used a very. We used like 10^2. A very low concentration.
4	130	TA	Oh okay. Um. And did you use? No no. Did you use transformed cells or no?
4	131	J	No.
4	132	K	We used untransformed cells.
4	133	TA	But there isn't- They're not- They weren't grown together, right?
4	134	J	(almost together) They were grown separately.
4	135	K	(almost together) They were grown separately.
4	136	TA	So that's the difference /between this at least-
4	137	J	/'Cause these were control plates.
4	138	TA	I think that's why the colonies look different, or these were- these were transformed cells.
4	139	J	Oh that's- that's-.
4	140	TA	Or sorry, yours were transformed cells and these weren't.
4	141	J	No they were.
4	142	A	No these are untransformed.
4	143	J	They're not colored. See these were our controls.
4	144	TA	Okay.
4	145	J	We had two control plates just so-
4	146	TA	Gotcha
4	147	J	-there's really not much of a difference.

4	148	TA	Well, I guess you can. I would just try analyzing it both ways (laughs). Assuming all of these are /lactose digesting.
4	149	K	So assuming both 939 and //938 are lactose digesting.
4	150	J	//Yeah 'cause these don't look like it. These just look like they've been grown on something that's pink. There's nothing really here-
4	151	TA	I mean you could convince me either way.
4	152	K	I think those are lactose digesting and those are not.
4	153	J	Yeah. I think there's a couple in here because / there's like a couple-
4	154	TA	/You think all of these are, //or these two.
4	155	K	//No I think that- those two.
4	156	TA	Okay.
4	157	J	It's kind of strange because-
4	158	TA	Wait. Alaad, what do you think?
4	159	A	I thought that almost all of these are digesting lactose. Like that's what I thought.
4	160	TA	So yeah, you guys-
4	161	A	/These are like *ob*viously like that, these are //like obviously have like no pigment to them.
4	162	J	/Because there's a dis-
4	163	K	//I can't see any discernable difference between that and that.
4	164	J	There's a di- a lot of these aren't digesting *much* lactose it doesn't look. But there's a distinct difference between the ones with little red spots in the middle. Almost like zits or something weird like that. /And there's just a couple in here.
4	165	A	/I mean if it was just- if it was just the background then we would see almost the same thing over here, wouldn't we?
4	166	J	And there's just a couple in here that are different //from the rest of them.
4	167	TA	//That's true a lot of these have dots in them.
4	168	J	And /like only //like one- two three four five, six
4	169	A	/So that's- that's-
4	170	TA	//Do you see that Kyle?
4	171	K	Is that 938?

4	172	TA	This is 938, yeah. So like, if you look like that (holds plate up to light).
4	173	K	Oh yeah you're right.
4	174	J	/I can count like six in here that have those teensy little dots in them.
4	175	TA	/Yeah this is the right way
4	176	K	What's that looking like for 939?
4	177	TA	Jackie, can you hold it up to the light?
4	178	J	Yeah like, right there, right there.
4	179	TA	Oh that's a good way to look at it.
4	180	J	And not like- like these over here don't have that while this one, like that one does. And I'd say that's probably digesting lactose and not the rest of them.
4	181	K	Overall this plate has more lactose digestion, than that plate.
4	182	TA	Yeah. Does that make sense?
4	183	J	Yeah. That's the results we were expecting to see.
4	184	K	Yeah.
4	185	TA	Cool. So maybe try and take pictures like that/ because I was able to see the lac- to see the little pinpoints.
4	186	J	/Yeah I can do that. How, what do you know, what their concentration was?
4	187	TA	I don't. I can check with them.
4	188	J	Okay, I'm just curious.
5	189	A	Should've asked about the simulation. Oh well.
5	190	K	Oh yeah the simulation.
5	191	A	Oh I think we got it though.
5	192	K	Oh actually.
5	193	A	I mean, the red strain should be more, right?
5	194	K	Wait is the red?-
5	195	A	The red should be like- since they're beneficial,
5	196	K	Yeah. I mean we can't. The thing is they can gro- like they can still grow in the lactose plate. (To Jackie. Oh can I do the same?) {That is, take a picture of the plate.}
5	197	J	Yeah yeah.

6	198	J	Is it actually taking a picture or is it-
6	199	K	Should we answer these questions now?
6	200	J	That was a pretty good picture.
6	201	TA	Jackie they used a 10^3 concentration.
6	202	J	Okay there was a difference.
6	203	TA	So 10 higher than you.
6	204	K	Okay.
6	205	J	Cool. Thank you!
6	206	TA	Yep.
6	207	K	So should we answer these, questions or-
6	208	J	Yeah we could probably jot some stuff down.
6	209	K	"So what was the question your group was trying to address in your experiment." Are high mutators more likely to develop lactose-
6	210	J	-digesting ability.
6	211	K	Yeah.
6	212	J	The blue one seems to be weird. {Remarking on neighboring group's transformed bacteria strain}
6	213	K	I'm surprised that many red grew on 939. I thought the low mutator would be more, pronounced but.
6	214	J	It did, um, that there were a couple-
6	215	K	No but-
6	216	J	Oh, total?
6	217	K	Yeah like-
6	218	J	Because look they're- it's agar it's the same as this stuff it just has lactose added. So there was nothing to inhibit them from growing.
6	219	K	I know but I'm just saying I'm surprised that many of them took up lactose.
6	220	J	Yeah, it was kind of-
6	221	K	That's what- that's what I'm saying.
6	222	J	I mean there's always a chance for something to mutate.
6	223	K	Alright whatever let's go with the assumption that it worked it just makes it much easier.

6	224	J	Yeah. It does. I mean not all of these are digesting lactose. There's, I can only could like, around 10. Out of all of these. That are.
6	225	K	Yeah.
6	226	J	Versus like a vast majority of these guys.
6	227	K	Yeah.
6	228	J	Do we have to count our colonies? Like to say which are digesting and which are?
6	229	TA	It's up to you. However you wanna.
6	230	K	Just say like overall.
6	231	J	Okay, just say like. Like less than half more than half. Like estimate.
6	232	TA	I mean you're gonna have pictures.
6	233	K	Alright so, for our data. We don't use data for this, let's just take pictures and like, say overall qualitatively there are more lactose digesting colonies on the {misspeaks, corrects} 938 macconkey plate than the 939.
6	234	J	I'm glad I remembered to label them. When I came in today- you know you get that like 'oh crap I left the oven on' kinda feeling? I was like, did I label them with the right numbers? Yeah I did.
6	235	K	Right.
6	236	J	Thank goodness.
6	237	J	Our control plates came out good.
6	238	K	Yeah.
7	239	A	This is the results we should be getting, right? (Turns computer to group members.)
7	240	K	Yeah that's- that's fine.
7	241	J	(Pointing to plate) Look I accidentally stabbed it with a pipette tip. And made like a little hole. (Alaad laughs. K says "Oh.")
7	242	K	Alright I'm ready to write my 1.3 assigment now. (J laughs)
7	243	K	For 1.2 did you take a picture, and use a diagram to show what the plates were? I like drew out, and like-
7	244	J	Yeah in the 1.2 I didn't do any- I didn't do any drawings I just wrote, stuff.
7	245	K	Yeah I was taking up space too.

7	246	J	Yeah.
7	247	K	'Cause I was running out of stuff to- like I feel like after the first paragraph-
7	248	J	God I was, I was running out of things to say by the time I hit five hundred words.
7	249	K	(to A) Yeah how'd you write like 800 words? Like how'd you write so much for the 1.2 assignment?
7	250	A	I literally, spent my first paragraph just like summarizing 1.1 cause I had not idea how had no idea how to get to the word requirement.
7	251	K	Yeah yeah.
7	252	A	So like, my first 300 words were basically, 1.1 condensed.
7	253	K	Yeah.
7	254	A	And then another like 400 words for this.
7	255	K	I feel like, I feel like this is gonna be like five pages though because (unclear)
7	256	J	I fit like-
7	257	K	Why else would we have two weeks to do this?
7	258	J	Because, we don't have lab for two weeks. /It'll be like other weeks.
7	259	K	/No like, (instructor) last semester we didn't have lab, we'd still have to turn it in by e-mail.
7	260	J	Eh, it depends on the lab instructor because when I was in chem we still had two weeks to do it no matter- no matter if it was.
7	261	K	Okay. That's good to hear. Alright so.
7	262	J	I had (instructor) too she was just- that was just her way of doing it.
7	263	K	Okay so for this what change would we make to our experimental design to get data that would help to answer the question? Would we make any changes or just like, would we keep the same overall parameters?
7	264	J	I don't know. I would keep the same overall, thing.
8	265	K	Alright, do you want to like take a screenshot, of that or whatever?
8	266	A	I was recording.
8	267	K	Were you? Okay.
8	268	J	Oh so you got the simulation running?

8	269	K	Yeah.
8	270	A	Yeah. (Turns computer to face others.)
8	271	J	Did you get it on high beneficial, /metabolic benefit?
8	272	A	/This is uh. The red strain should be more than the blue strain.
8	273	K	Yeah.
8	274	A	Because the beneficial (unclear).
8	275	K	So for the question or how it has to- or what are the patterns over time, you say the patterns, the patterns are stable. And like. The patterns are stable because the red overall are more, prevalent than the blue.
8	276	J	The red's the high mutator, right?
8	277	K	Yeah.
8	278	K	"Are the patterns specific to the initial settings slash parameter values you chose? Or do they apply over a large, range of parameters?"
8	279	J	Why do you have the resistance on?
8	280	A	It's only 5%.
8	281	K	It's barely on, it's like 5.
8	282	J	Oh.
8	283	A	I mean that's- that would be natural, right?
8	284	K	Yeah.
8	285	J	Yeah. Probably doesn't really matter like if it's high or low in this one. Because resistance isn't what we were testing. So it makes sense.
8	286	A	Yeah lethal is at 5%, resistance is at 5%, and metabolic benefit is at 90%.
8	287	J	Gotcha, that makes sense.
8	288	A	And the red strain mutates ten times faster than the blue strain.
8	289	K	So what are you saying for the second question about the parameter- or the patterns specific to the initial settings slash parameter values?
9	290	J	Will it be, in our lab, /things
9	291	TA	/Yeah, I just have to put it on there.
9	292	J	Okay. I mean I'm not doing it tonight, so.
9	293	TA	Yeah.
9	294	J	I have other things I need to do, and sleep to be had. So.

9	295	K	A thousand words.
9	296	J	A thousand words is not that bad.
9	297	K	It's 200 words more than it should be.
9	298	J	Yeah. I guess that's true.
9	299	K	If you put in graphs and stuff -- like put in the picture and explain it.
9	300	J	Yeah. We can make a figure like we did last year. Explain what it shows and get a few from that.
9	301	K	Yeah I know that's what I did for the last, like I feel like I'm doing the same thing again, honestly.
9	302	J	Oh I didn't do that, so.
9	303	K	I shouldn't have put that down for this one.
9	304	J	Oh it's 800-1000.
9	305	K	But like I feel like if you go for the upper limit it's better.
9	306	J	I'm not going for the upper limit. You kidding me? I get like fifteen words over the lowest. 'Cause I tend to be very concise, with whatever I'm answering, so I always tend to be on the lower half, of-
9	307	K	Alright so "discuss what you're investigating" (reading what's on the screen)
9	308	K	So what are we presenting for the group?
9	309	J	I think they apply over a large range of parameters? There's a lot of situations where a high mutator would do better.
9	310	J	I'm pretty proud that ours came out pretty good.
9	311	K	Yeah.
9	312	J	It's nice. I like that we just picked a simple thing. And it just worked.
10	313	LA	Did you guys get the results that you expected?
10	314	K	Yeah, we did.
10	315	J	Yeah, we did.
10	316	LA	Yeah?
10	317	J	Yep.
10	318	LA	Have you thought about how you're going to present this information yet?

10	319	K	We'll probably draw the two plates on the whiteboard and explain, why we got we got.
10	320	LA	Okay. Yeah. If you guys are, not doing anything you can definitely grab a white-board.
10	321	K	Okay, sure.
10	322	J	We've got one.
10	323	LA	Yeah then you can go ahead and, try to, start, artistically representing your plates.
10	324	J	I can draw.
10	325	K	I'll get a red marker too.
10	326	J	Okay.
10	327	K	We'll need the whole table to draw.
10	328	K	Are the black plates the agar plates? And the red are?
10	329	J	No I'm just gonna.
10	330	K	You're just gonna draw at random. Okay.
10	331	J	We don't need to draw the agar ones. I can draw them like small-
10	332	K	Yeah.
10	333	J	Like in the corner or something. This is the outside of the plate to make it less distracting.
10	334	A	You guys want me to send you the mp4 file?
10	335	K	Oh yeah, sure. Let me just type in my e-mail.
10	336	J	What are you doing?
10	337	A	Oh I'm sending both of you the mp4 file.
10	338	J	Of the- of the thing?
10	339	A	Yeah the simulation thing.
10	340	J	We need that?
10	341	K	Just. Just to have it.
10	342	J	My, personal stuff e-mail. (Handing laptop back.)
10	343	J	(Drawing dots on the whiteboard) We're just going to represent other colonies by this with a little red dot in the middle?
10	344	K	Did you send it yet?
10	345	A	Not yet. It's uploading.

10	346	K	Yeah.
10	347	K	Were the red ones the ones that have, lactose?
10	348	J	I'm going to put red dots in them. But those are the big ones.
10	349	K	Oh those are the big ones, okay.
10	350	J	I'm just drawing circles first.
10	351	A	Okay you guys should have it.
10	352	K	Yeah I got it. Alright.
10	353	J	They look like creepy little eyeballs.
10	354	J	Alright there's a couple that aren't, mutated.
10	355	J	There we go.
11	356	A	Oh my, what happened here. The blue dominated now.
11	357	K	Oh really?
11	358	A	Yeah.
11	359	J	What?
11	360	A	That's alright, /we got the important part.
11	361	J	/What happened?
11	362	K	Nothing.
11	363	A	That's amazing.
11	364	K	They kept on fighting, never gave up. It's still running, the simulation? Can you like stop it and cut off the last half?
11	365	A	No I uh, I only took like 10 seconds of the part where we were like right.
11	366	K	Oh good. (Laughs) That's what I like to see.
11	367	J	So I'm gonna write in big letters here, the name of our question.
11	368	J	There.
11	369	K	Great.
11	370	J	Cool.
11	371	J	(Too quiet to hear)
11	372	TA	(to A) I'm going to come back, A, real quick. Because there's a couple people that came over. (Walks away.)
11	373	K	How did this happen?

11	374	A	That's what I want to ask her. Like /why would they-
11	375	J	/Let me see.
11	376	A	Why would this even happen?
11	377	J	Did you mess with something?
11	378	A	I didn't mess with anything. It’s all the same.
11	379	K	It's an incredible turn of events. Whatever.
12	380	J	How'd you guys do on the exam?
12	381	K	I did well.
12	382	A	Me too.
12	383	J	Did pretty well, got an eighty. Which is pretty good.
12	384	K	I made a couple silly mistakes, but-
12	385	J	I need to go over it. They're easier than the (prior biology course) exames.
12	386	K	Ah. I guess, in some respects. I thought it was about the same but-
12	387	A	Are the (other bio course) exams all multiple choice too?
12	388	K	Yeah.
12	389	J	Yeah they're the same format they're just /(unclear)
12	390	K	/Why is it that chem, they can have like, not multiple choice for more students but for bio they can only have multiple choice...
12	391	J	I don't know. Because chem is more based on math. I guess bio isn't based on math.
13	392	TA	Alaad, you guys had something?
13	393	A	Oh, we don't understand this.
13	394	TA	(Laughs.) So what are you trying to do?
13	395	A	So the red strain- we put the lethal and the resistance at very low because we didn't really care for that.
13	396	TA	Okay.
13	397	A	And we put the benefit- metabolic benefit at 90%. So the blue- red strain should be based off of the high mutating one. Initially they were higher.
13	398	K	Yeah.
13	399	J	It was like that for a very long time.

13	400	A	It was for a very long time but now the blue are like, the red just basically aren't there.
13	401	TA	Yeah. I mean the red. There's no red in here/ I don't think.
13	402	J	/Did someone step on our bacteria and cause genetic drift while we weren't looking?
13	403	A	There's like, I don't even know if they're- how can I see. It's either like-
13	404	TA	I think when this goes red. That means that the red went extinct over here.
13	405	A	Okay.
13	406	TA	When the text turns to red.
13	407	A	But why would it go extinct?
13	408	TA	Umm... so, what do you guys think do you have any hypotheses?
13	409	J	Someone stepped in it when we weren't looking and caused genetic drift.
13	410	TA	(Chuckles) Someone stepped in it? Okay, I'll pose another thing. Did you try a second time?
13	411	A	Oh we should try that again.
13	412	TA	But, beyond that. Trying to grasp at a/ possibility.
13	413	J	/Did it hit carrying capacity and //just plummet?
13	414	K	//Maybe red picked up lethal.
13	415	A	I mean but the-
13	416	TA	What Kyle?
13	417	K	Maybe red picked up a lethal mutation, and then, that-
13	418	A	Okay but, it's only 5% and it's not like every single /one of the red ones-
13	419	K	/I know but like,// maybe what we're seeing right now is an anomaly
13	420	J	//Is there a carrying capacity in this thing?
13	421	TA	Ummm.
13	422	J	Like (unclear) overpopulated?
13	423	TA	There is in the sense that the total population really hovers right around twelve thousand. So, yeah.
13	424	K	Yeah.

13	425	A	/Wait is red extinct in this one too now?
13	426	J	/ So it can't get more but when it hits that it's not like it's gonna die.
13	427	TA	No, but it's gonna die once it hits its lifespan.
13	428	J	Okay.
13	429	A	Does this mean that red is extinct in this one too now?
13	430	K	So red's extinct in both.
13	431	TA	Uh. No 'cause there's still some here.
13	432	A	So why is this red?
13	433	TA	Hmmm. Does that mean that there's no... I thought- I think- I don't know. I don't wanna mislead you. Red might not be extinct. I mean you can still see that red is in here.
13	434	A	They're dying out (unclear)
13	435	TA	I mean it's very unlikely that they could come back from that. I don't think I've seen it.
13	436	J	Did the antibiotics accidentally turn on? But there's no antibiotic on that side.
13	437	A	Antibiotic's off. If it had turned on then the blue should have died.
13	438	TA	But I don't want to discount Kyle's idea.
13	439	K	I feel like it picked up a lethal mutation.
13	440	A	But like-
13	441	K	Like, the odds are so-
13	442	A	(unclear) pick up a lethal mutation.
13	443	K	It could have spread, I don't know. The odds are so low that what we're seeing right now could be a very, high statistical anomaly.
13	444	TA	It's only 5%, but red is mutating at a ten times faster, speed, or/ more frequently.
13	445	J	/Yeah. So that's pretty wild.
13	446	TA	So run it again. See what happens.
13	447	J	That has nothing-
13	448	A	Is it possible to keep this one running and have a second one at the same time?

13	449	TA	I don't think so. Umm. But you could (turns to face researcher -- we don't have an extra computer, right?) They wanted to keep this one running but run another one. Is that possible?
13	450	Researcher	There's like. Yeah there's computers in here.
13	451	TA	Oh there's (unclear). Can you get one? Thanks. (Researcher)'s gonna get you one. Um and, yeah that's a good idea actually. And see if they actually die off. Okay yeah, what was I gonna say? Right. Umm... What was I gonna say, after you said can we keep? Urrrr... I can't remember. I'll come back if I remember.
14	452	A	Okay so these are-
14	453	K	The red's mutating at a ten times bigger rate, so. Although it's much lower the lethal mutation-
14	454	A	Yeah but, what I'm saying is that is it possible- there were five hundred initial ones. If all of them had picked up a lethal mutation they should have died off a lot sooner.
14	455	K	I don't know, this is so minutae(?). I'm sure the second time it's going to be normal.
14	456	J	We actually get to work with non-microscopic things the next time we come to lab!
14	457	K	What are we doing next time?
14	458	J	Plants. Mimosa plants. They're really cool.
14	459	K	Plants are fun.
14	460	J	I'm really glad because we get to keep 'em! It's like so exciting I love these type of plants.
14	461	A	Alright. Red is extinct in both of them now.
14	462	K	They're extinct now?
14	463	A	Uh-huh. All reds.
14	464	K	That's life. Some die. Some don't.
14	465	K	So what are we waiting for now?
14	466	J	I thought we're going to get another computer?
14	467	K	Okay.
14	468	J	I guess we can stop this one now because the red is gone.
14	469	K	Yeah the red's g- just pause it.

14	470	A	It's lovely.
14	471	K	I'm not going to do this for like two weeks.
14	472	J	Same. I'm going to wait 'til like the last minute.
14	473	A	I wonder what would happen if I turn on the antibiotics right now.
14	474	J	Noth- well.
14	475	A	They should all die.
14	476	K	They should all die.
14	477	J	Yeah.
14	478	K	Yeah.
14	479	A	Oh wow they didn't all die.
14	480	J	Yeah, because you had resistant ones.
14	481	A	Yeah but it's like-
14	482	J	But okay. Let's try again, with our parameters. Without the antibiotic.
14	483	K	They should still have 100% though. Cause all the red are already dead. You can never have 90% of one thing.
14	484	A	I don't think these are any resistant cells. Oh no there is like, a couple.
14	485	J	There's no red. It's extinct.
14	486	A	That's amazing.
14	487	TA	Okay I rem- okay I remembered what I was going to tell you. Um. So. It might be interesting to play with the threshold at which the lethal matters. So right now you're at 5% lethal. And maybe that's making the difference for the high mutator to lose. But what if it's 1%. Is the high mutator then going to win? So you can sort of play with that threshold.
14	488	K	K: Yeah let's just pause it this and-
14	489	TA	So here's a second one. I know they died already.
14	490	K	Yeah, okay.
14	491	A	Okay, let's do this. Let's turn this to, 1%. Let's turn this to 1%. Let's turn this to, 99-/ 98%
14	492	J	/98%. Do you have the antibiotic?- Yeah, it's off.
14	493	A	Oh yeah, antibiotic's off. Setup. Alright.
14	494	K	Oh wow.

14	495	A	(Speaking quietly to self as working on setting up sim on other computer)
14	496	K	Try doing the same one as before, for, this one.
14	497	A	Same parameters?
14	498	J	Yeah the same parameters as we did the first time.
14	499	A	Got it.
14	500	K	That was adjusted to ten.
14	501	J	It was a five. Lethal and resistance were at 5.
14	502	A	Yeah I remember.
14	503	J	And benefit was at 90.
14	504	J	Oh that's strange, that one's all black.
14	505	A	What?
14	506	J	That, screen is all black and this one you've got one black one one sort of reddish one.
14	507	K	Yeah.
14	508	A	(Unclear) with this computer?
14	509	J	It's a different kind of computer so I guess that- kinda makes sense.
14	510	K	Alright.
14	511	K	Let's go.
14	512	K	What the hell?
14	513	A	What happened?
14	514	K	Why are the red not dominating, from the start?
14	515	J	Can I see?
14	516	A	Well /I mean-
14	517	K	/Oh here they are. Oh yeah.
14	518	A	I mean there's nothing killing the blue yet, so.
14	519	K	There's no, lethal?
14	520	A	I mean, lethal is at 1%.
14	521	A	It took them like, five thousand generations to, uh, get to where it was though.

14	522	K	Well now we're at like 495. When we stopped, how many generations did we have?
14	523	A	When we stopped, I think around seven thousand?
14	524	K	Damn.
14	525	K	It seems like that 5% lethal is making a big difference.
14	526	A	Mhmm.
14	527	K	Cause everything else is the same. Reistance too. The fact that lethal and resistance are both at one, /is resulting-
14	528	A	/But this hap- this happened last time too where the blue, nearly died off and then just came back.
14	529	K	Well let's see what happens this time.
14	530	A	Oh that friggin' smells.
14	531	K	Yeah.
14	532	K	What are we waiting for?
14	533	A	I think we're supposed to present our work.
14	534	K	Can we start the presentations then? We present to them, they present to us. (Unclear).
14	535	A	(Laughs)
14	536	K	(To J) Did she give you ten out of ten first one?
14	537	J	What?
14	*[21]	K	Did she give you ten out of ten, on the first?
14	538	A	(Shakes head) No.
14	539	K	Yeah it's def-/ yeah.
14	540	J	/I got eight out of ten.
14	541	A	Same.
14	542	K	It's so subjective, I feel like.
14	543	A	(Unclear)
14	544	K	Whatever.
14	545	A	Did she comment on yours?

[21] In the process of extracting the transcript from InqScribe to Excel (for coding) this line was somehow folded into the text on line 537. I have updated the word and line count totals in the Chapter 7 analysis to amend this error (neither line was coded as being a bid for their investigation, nor engagement with a bid). The original line numbering has been preserved to maintain any references to the transcript after this turn.

14	546	K	Like the same thing that she said in class. Like, you have to answer the first half of the question, or whatever.
14	547	TA	How's it going?
14	548	K	Now it's back to what we expect.
14	549	A	This is the 1%. And it's following the exact same pattern as the 5%.
14	550	TA	Okay.
14	551	A	And this is the 5% that we were running last time.
14	552	K	And now it's- yeah.
14	553	A	And now I'm pretty sure that they're both going extinct.
14	554	TA	(Laughs) Okay, interesting.
14	555	A	Yeah. So like, now the 1% is acting like our 5% from last time and the 5% is what we were expecting (the 1%?)
14	556	TA	Okay. That's great. And everything was set the same way.
14	557	K	Yeah.
14	558	A	Yeah. This is set the exact same way as last time.
14	559	K	This is the same as the first one it's just, /bringing the resistance down.
14	560	A	/So this is what we expected last time to happen. But it didn't. And this, is what we expected this time, like- we expected these two- you get what I mean right?
14	561	TA	Okay. Yeah. You expected both of these outcomes?
14	562	A	Well, /we expect-
14	563	TA	/What's the difference between these two right now?
14	564	A	This is 1%.
14	565	TA	Oh okay. And that's 5%.
14	566	A	And this is 5%. But this is what we saw last time with the 5%. And this is what we were expecting last time for 5%.
14	567	TA	Right. Okay. And is this your first time running both of these or?
14	568	K	Yeah.
14	569	TA	Okay.
14	570	A	Well this one we're running the second time now, right? (pointing to 5% run)
14	571	TA	Yeah.

14	572	A	And this is the first time we're running this one.
14	573	TA	Okay. Alright. Interesting.
14	574	A	Yeah.
14	575	TA	Alright, well I-
14	576	A	'Cause this is exactly the same thing that happened last time with the red were dominating for a while,/ and then they died.
14	577	TA	/Right, and then they, fell-
14	578	J	This one is still doing and- being fairly normal.
14	579	A	Yeah.
14	580	TA	Well I/ like that you're running it for a really long time.
14	581	K	/Now- now-
14	582	J	Hm. I could probably put a simulation, right here or.
14	583	K	It's fine. We'll just (unclear).
14	584	J	We could just hold up a computer.
14	585	A	Oh, blue is extinct.
14	586	K	There we go. (Knocks on table.)
14	587	K	Are you guys ready to present?
14	588	J	Yeah.
14	589	S1	I think I'm going to be BSing my, /(unclear) results for ours.
14	590	K	/That's fine. Just so we can go and-
14	591	S1	It's a lot of hypothetical. Actually yeah let's just- let's get it moving. Yeah that's true.
14	592	K	Alright do you guys wanna start?
14	593	S2	Let's.
14	594	K	We can start.
14	595	S2	No. No thank you.
14	596	J	We should ask her, so we don't do all this for nothing.
14	597	K	Alright.
14	598	J	What time is it?
14	599	K	It's like seven.
14	600	A	It's like seven something.

14	601	K	Yeah.
14	602	K	Alright, let's present so we can-
14	603	J	Damn look at that.
14	604	A	Yeah.
14	605	K	Wow did the blue take the lead? Okay.
14	606	A	The blue's gonna take the lead in that one too.
14	607	K	Let's just ignore this and pretend that that's the right thing.
14	608	A	Yeah but in this one. One of them is getting what we expected and in the other one the blue's gonna dominate.
14	609	K	Oh the blue's making a comeback?
14	610	A	Yeah.
14	611	K	Okay l- /Are you guys ready to go?
14	612	A	/So why don't we *just* concentrate on this one.
14	613	K	Okay we can go.
15	614	S1	Wait are people starting already?
15	615	K	They're starting over there.
15	616	S1	Oh that's what's going on. Okay.
15	617	K	Yeah, so.
15	618	S1	I wasn't really paying attention.
15	619	K	That's fine. Alright.
15	620	K	So what was our question, exactly?
15	621	J	(Unclear - purest?) question.
15	622	K	Okay so our-
15	623	J	Is the higher mutator more likely to develop the ability to digest lactose?
15	624	S2	So yes.
15	625	K	/Yeah s-
15	626	J	/Yeah that's pretty much what- that's pretty much what we found. (J&K laugh)
15	627	J	So. This was our low mutating plate versus our high mutating one. Over there.

15	628	S2	Oh and so most of them had like a small red but then the E938 had big reds, essentially?
15	629	J	Yeah. And this. And over here we had a few that mutated to digest it. /Just like it was about like around ten, I think.
15	630	K	/But overall there- But overall there was a lot more on E938.
15	631	J	Yeah overall there was a whole lot that didn't- weren't digesting it but on this one the majority of them were, and there was only a couple that weren't digesting it. So. Yeah. That's pretty much what we found this, our simulations were really weird. (Looks towards Alaad.) We put the right parameters but eventually like- and blue almost went extinct which is the low mutator. But then red- but then it came back and kinda kicked red in the ass and we don't really know why it did that. Because we only have our lethal mutation on 1%. On one of them and 5% on the other. But it keeps doing that. And then in another one the blue finally did go extinct on one side, and on the other side it's coming back again. And we don't really know why it's doing that. We did not see that in real life.
15	632	S1	So it's really just chance, I guess.
15	633	K	Yeah it's more random then-
15	634	A	Except like-
15	635	J	I feel like the red just picks up more lethal mutations. As it goes through generations and eventually it just keeps dying off.
15	636	A	So we like ran a total of like six simulations. Out of the six, four times the high mutating strain died off.
15	637	J	Yeah. Probably because we had a chance for lethal mutations all- we didn't have that many generations in this one (points to plates), so.
15	638	K	/Yeah.
15	639	A	/Yeah.
15	640	J	It wasn't as-
15	641	K	It wasn't as long.

15	642	J	-long lived. So if there's like a chance for lethal mutations and the environment. Because we don't- we didn't have anti-antibacterial properties on our simulations either. If the environment is like stable. Kind of like what we were looking for like- Like kind of like what we were looking at up, with just a regular, agar plate. Like if an environment is stable, usually a low mutation is a benefit. But if there's a- if there is a- there was a stable environment the low mutator eventually came back and won most of the time. But this, was- this was different we couldn't replicate the lactose there. This was a slightly different environment and, we saw results with what we thought we were going to see versus the simulation so. That, that was good.

Appendix 7.3—Unit 1, Week 2 worksheet guiding experimental design, 2018

Experimental Design Handout

Your challenge is to design and set up an experiment that will help you address a question you have about the conditions under which low/high mutating strains of *E. coli* have an advantage.

Use this handout to guide your design and to take notes. You will be asked to write up a more detailed account of your design for homework.

Before you begin a few practical considerations:

- Due to resource limitations, you may use no more **6 plates** in your design.
- Before you leave today, you need to formally 'sign out' with your TA and label the plates you will need.
- You will need to come in outside your lab time to do your plating. Labs will be open every morning this week from 9am to 1pm and every afternoon from 4:30pm to 5:30pm.

Questions to Guide Experimental Design

1. Before you decide on all the details of your design, discuss some possible questions you might investigate with your group and write them below. Keep in mind that your question is likely to shift as you go through the design process.
2. As you discuss your ideas, use a **whiteboard** to sketch out your experimental design ideas.
3. Your final design will need to specify the materials you need and how you will use them. Use the list below to map out the details of your experiment. Make sure to fill out the form on the back of this handout that describes and explains your design choices (this will help you complete assignment 1.2).

Materials

The following materials will be available to each group (but if there is something else you want, please ask, it may be possible).

Bacterial Cultures (4 types)

- E939 (low mutator, untransformed)

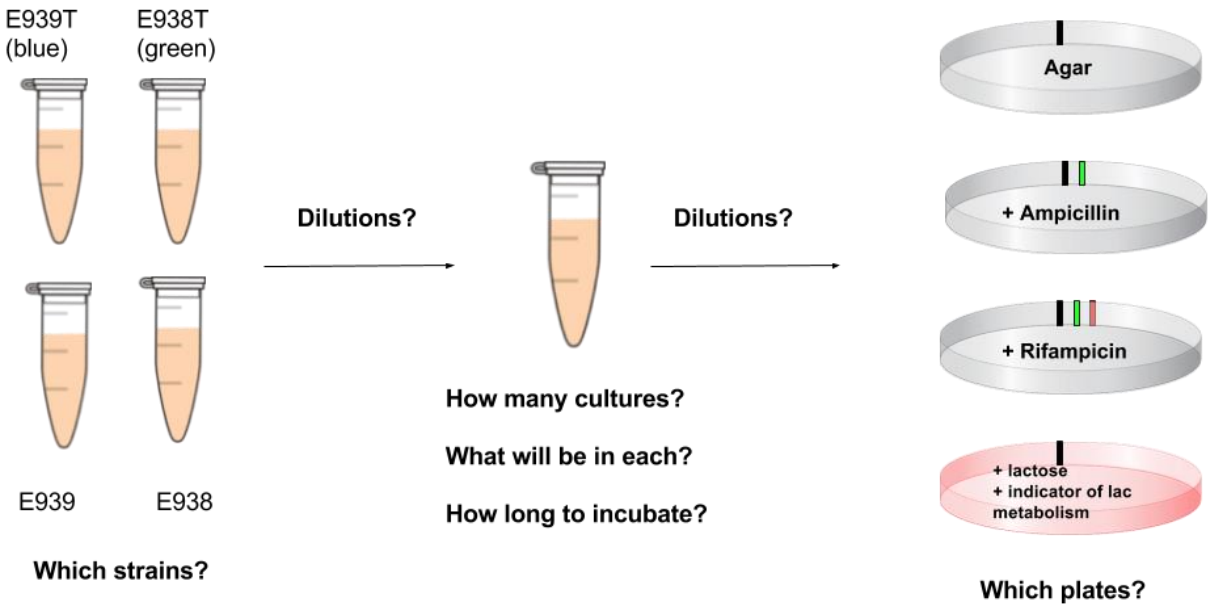
- E938 (high mutator, untransformed)
- E939T (low mutator, transformed blue)
- E938T (high mutator, transformed fluorescent green)

Materials to setup experimental cultures

- Glass dilution tubes
- 15mL plastic culture tube (do not snap lid all the way closed)
- Sterile LB (for untransformed strains)
    - plus rif
    - plus lactose
- Sterile LB + amp (for transformed strains)
    - plus rif
    - plus lactose

Plate Types (5 types)

- Agar plates (with or without Amp)
- Agar + Rif plates (with or without Amp)
- Agar + Lactose + Lactose metabolism detecting agent (MacConkey media)



Name_____ Group_____ Lab Section_____

Research Question(s)

- What is the question or questions that you are investigating?

Experimental Design

1. How will you set up experimental cultures?

a. What number of initial cells will you add? Of which strain(s)? In what kind of culture environment?

b. What is your reasoning these choices?

2. How many hours will you leave your cultures to incubate?

    a. At what time will you plate them? Who will be able to do this?

    b. What is your reasoning for these choices?

3. How will you plate your cultures?

    a. On what types of media will you plate your sample? What dilutions will you plate on each? (~how many cells?)

    b. What is your reasoning for these decisions?

Anticipated Results

- What do you expect to see on each of your plates? Why?

- What are the sources of uncertainty in your experimental design that make you uncertain about what you might see?

Plating Protocol

Plating Materials (available during open lab time)

- 1 spray bottle of 70% alcohol
- 1 wand for sterilizing bench
- Sterile saline (for diluting experimental cultures)
- One sterile 10ml pipet
- Green pipet pump [for 10ml pipet]
- 200ul capacity micro-pipettor
- Sterile yellow pipet tips
- 1 alcohol burner
- 1 dish of 70% alcohol
- Glass spreader
- **Your experimental cultures (describe them):**
- **Sterile glass tubes for dilutions (how many):**
- **Your plates (describe them):**

before you begin – put on gloves and goggles and lab coats

Fill in your dilution procedure (if applicable)

1. Describe which experimental cultures you will dilute and by how much:

2. Clean the top of your lab bench with 70% ethanol solution to remove dust and contaminants

3. Obtain sterile capped glass tubes and label to reflect dilutions you need

4. Use sterile **10 ml** pipette to fill each tube with _____ml of sterile 0.85% saline

5. Using a 200 ul pipettor and a new sterile pipet tip to add _____ to dilution tube. Be sure to gently mix each of your cell cultures by pipetting up and down several times.

6. Vortex to mix

7. As appropriate create new glass tubes with saline and diluted culture to obtain final desired dilution as described below:

Fill in your plating procedure

For each of your plates specify:

- Plate type
- Strains to be plated
- Dilution amount
- Volume plated

1. One at a time, for each of your plates, plate the appropriate volume of the appropriate culture, with the 200 ul pipettor, using a new sterile pipette tip for each culture. Again, make sure your cell culture is well mixed by gently pipetting up and down several times before pipetting.

2. Dip the glass hockey-stick shaped spreader in alcohol, flame it, and then let it air dry until cool (about 5-10 seconds is enough time). Touch the spreader to the surface of the agar, away from the culture drop, just to be sure it has cooled down. Then spread the drop of bacterial culture evenly over the agar surface by holding the spreader and gently rotating the petri plate.

3. Let the petri plates sit **upright for 15 minutes** before moving them. (This allows the bacterial cells to adhere to the agar surface.)

4. Flip plates **upside down** (to prevent condensation), wrap together 5 plates in cellophane, label with your lab group name and lab section, and place in incubator.

5. Your TA will take your plates out of the incubator after ~2 days and place in the fridge.

Clean Up

- Put all **plastic** (contaminated pipette tips and tubes) in biohazard containers at your lab station and at the end of lab dump them into the biohazard waste bin in the front of the room, near the incubator.
- Dump out the solutions in the **glass tubes** into the flask full of bleach then place **glass tubes** go in the soapy water in sink.

- Wipe down lab table with ethanol.
- Wash hands!