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When Biology Learning Paradigms Shift: What Middle School Students Know, Think, And Learn About Synthetic Biology

Abstract

Science, Technology, Engineering, and Mathematics fields have incredible impacts on society and the planet. One example of such a field is synthetic biology—a modern biotechnology that involves the, often genetic, manipulation of cells or cellular outputs for practical purposes. This field influences agriculture, medicine, and manufacturing—to name a few. Concomitant with these advancements is the rise of professional communities and university level academic areas of study around synthetic biology. These activities—until recently—have been limited to commercial groups and experts due to the material and intellectual resources needed for field engagement. The emergence of lower cost portable lab tools, local community lab spaces, and interactive public exhibits has made synthetic biology accessible to field novices of all ages. Despite, there is little research that examines the affordances synthetic biology may provide K-12 learners. In fact, much of existing research related to K-12 learners often includes applications that have advanced considerably or that do not include synthetic biology. Moreover, much of existing research reports on high school students, while far less examines middle school students who have previously been shown to have well-formed perspectives about biotechnologies. The research presented in this thesis attends to this gap in the literature by addressing three overarching research questions, including: (1) what do middle school students know and think about synthetic biology and its various applications, (2) how do middle school students carry out synthetic biology as an active learning activity, and (3) how do synthetic biology-related contexts clues support student justifications about their perspectives? Mixed-methods are used to examine surveys, semi-structured interviews, video observation data, and student productions. Results suggest that while middle school students know very little about synthetic biology and its various applications, their well-formed opinions about the field include considerations of application utility, risks, benefits and safety. Findings also suggest that synthetic biology provides opportunities for learners to engage in personally relevant production and—when situated in detailed contexts—supports advanced justification practices. Priorities for future research and innovations in synthetic biology and science education are discussed.

Degree Type

Dissertation

Degree Name

Doctor of Philosophy (PhD)

Graduate Group

Education

First Advisor

Yasmin B. Kafai

Keywords

Argumentation, Biotechnology, Design Biology, Science Inquiry, Student Attitudes, Synthetic Biology

Subject Categories

Art and Design | Graphic Design | Science and Mathematics Education

WHEN BIOLOGY LEARNING PARADIGMS SHIFT: WHAT MIDDLE SCHOOL
STUDENTS KNOW, THINK, AND LEARN ABOUT SYNTHETIC BIOLOGY

Justice Toshiba Walker

A DISSERTATION

in

Education

Presented to the Faculties of the University of Pennsylvania

in

Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy

2019

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Dedication

This dissertation is dedicated to my generous late grandparents—Gladys Ruth and Theodore Roosevelt Walker—who taught me to be kind. It is also dedicated to those youth who stride onward and upward toward light—striving to make the world better for future generations.

Acknowledgements

The research presented in this dissertation is the result of extraordinary mentors, thought partners, and friends who not only took my research seriously, but who also made an authentic commitment to the long and sometimes uneasy process of growing my scholarship. I especially thank Yasmin B. Kafai, whose generosity and high expectations kept me motivated through this journey and whose kindness, consistency, and commitment was instrumental at every turn. My experiences learning from Yasmin have shaped the way I view the professorship and have fundamentally affected my appreciation for mentorship and its role in building character, self-confidence, and—importantly—persistence.

I also thank Sigal Ben-Porath who has always supported my endeavors and without question or hesitation. Sigal also taught me how to better understand the relationship between discourse and citizenship—and the strength that emerges when diverse perspectives are cultivated and expressed freely. This undergirds my position about the necessity of intellectual diversity in scholarship. I also thank Iris Tabak, whose insights directly shaped the work represented in this thesis. Despite very difficult time zones, Iris's willingness to meet and discuss my work fostered in me a deep sense of legitimacy in the Learning Sciences and in science education research.

While my doctoral advisor and dissertation committee members were pivotal in shaping this thesis, others played important roles in introducing me to communities that have provided critical insights about the field. In this regard, Karen M. Hogan—a kind, authentic, and brilliant biologist and entrepreneurial pioneer—has been a steadfast supporter as she not only introduced me to synthetic biology, but navigated me through a

complex network of professional relationships that have sustained me as a doctoral student and scholar. Karen's efforts played an important role in bridging my passion for life sciences with my current research. Similarly, Orkan Telhan has been among the most rigorous mentors I have had during my endeavors at Penn. His criticality, directness, and friendship always challenged me to think deeper and to strive unrelentingly. I am fortunate to know Karen and Orkan—without whom I may not have found synthetic biology or embraced it in my research.

I also owe thanks to Amanda Cottone, who has been an important friend and colleague. Amanda—always being a step ahead with her dissertation research—was always willing to give me insights about immediate milestones and always found a way to be encouraging. From helping me set benchmarks, to providing me lab or biological materials for my research—Amanda has always been in my corner and for that I am especially thankful. Deborah Fields has been an important figure in our research group. Deborah is always willing to engage closely with my writing, a process that can be unpredictable and cognitively demanding. Qualitative research is not an easy task, but Deborah has always been willing to support me and my ability to ask important and thoughtful questions. Her humor, seriousness, and intellect have always made my development as a qualitative researcher tenable and productive.

Friendships and informal mentorships have also been important in propelling my journey and scholarship. Aurora MacRae-Crerar's friendship has been a beacon of light when the challenges of doctoral research have been high. Her advice and optimism is contagious and sustaining. Michael T. Giang and his statistics savvy has helped grow my quantitative research skills beyond those I could develop alone or through formal learning.

I thank both Aurora and Michael for their contributions in my personal and professional development.

I want to also thank Vivian L. Gadsden who has been a special gift to me across many of the milestones I achieved at Penn. Vivian has given me advice, welcomed me into her home, and was present when I had a questions about my pursuits or needed perspectives when making decisions. Without having any stakes in my success, I always had a sense that Vivian believes in me and my future—and that has had a powerful impact on my awareness and sense of belonging in the academy. I am deeply thankful for the space and time she has given me during my time at Penn.

There are so many others I wish to thank for their contributions to me as a person and scholar. They include my mother, Alma Delia Rodriguez, and my siblings—Carman Delores, Charlie, and Andrea Fonseca. I also thank my partner, Patrick Cahill as well as my friends and colleagues with whom I have collaborated or written as a doctoral student: Mahiri T. Cleary, Gayithri Jayathirtha, Mia S. Shaw, Christopher Proctor, Peter Melley, Maya Heiland, Melissa Kurman, Sharon Ravitch, Stefan Slater, and so many others.

This research was also supported and made possible—in part—by the National Science Foundation grant #1623018.

ABSTRACT

WHEN BIOLOGY LEARNING PARADIGMS SHIFT: WHAT MIDDLE SCHOOL STUDENTS KNOW, THINK, AND LEARN ABOUT SYNTHETIC BIOLOGY

Justice Toshiba Walker

Yasmin B. Kafai

Science, Technology, Engineering, and Mathematics fields have incredible impacts on society and the planet. One example of such a field is synthetic biology—a modern biotechnology that involves the, often genetic, manipulation of cells or cellular outputs for practical purposes. This field influences agriculture, medicine, and manufacturing—to name a few. Concomitant with these advancements is the rise of professional communities and university level academic areas of study around synthetic biology. These activities—until recently—have been limited to commercial groups and experts due to the material and intellectual resources needed for field engagement. The emergence of lower cost portable lab tools, local community lab spaces, and interactive public exhibits has made synthetic biology accessible to field novices of all ages. Despite, there is little research that examines the affordances synthetic biology may provide K-12 learners. In fact, much of existing research related to K-12 learners often includes applications that have advanced considerably or that do not include synthetic biology. Moreover, much of existing research reports on high school students, while far less examines middle school students who have previously been shown to have well-formed perspectives about biotechnologies. The research presented in this thesis attends to this gap in the literature by addressing three overarching research questions, including: (1) what do middle school students know and think about synthetic biology and its various applications, (2) how do middle school

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1. Introduction to Research on Synthetic Biology and Middle School Education

1.1 Chapter Overview

Science, Technology, Engineering and Mathematics (STEM) fields have had an undeniable impact on society. They have shaped the ways in which we: understand the natural world, leverage such understandings to solve problems, and contend with the challenges and opportunities they create for society. Biotechnology is one example of a life science STEM field that has had such an impact. In fact, it represents a paradigmatic shift in life sciences for which epistemological traditions typically center around research questions—driven by induction (Anderson, 2002; Flick and Lederman, 2004; Torp & Sage, 2002; Welch et al., 1981)—toward an era guided by divergent thought (Cross, 2001; Cross, 1981; Waks, 2001) and intentional designs in which even living systems can be manipulated and repurposed. These shifts are reflected in contemporary industries, including medicine (Porter et al., 2011), agriculture (Beyer et al., 2002), and manufacturing (Ecovative Design, 2019), as fields are able to generate outputs that do not ordinarily exist in nature or that span beyond what was possible even a decade ago.

Within the broad landscape of biotechnology is a burgeoning area known as synthetic biology. Although there is currently no single definition that wholly encompasses this perspective, it can be conceptualized as a biotechnology that—often genetically—alters single cells, cellular outputs, or whole cellular systems with the intention of generating an outcome that is typically put to practical use (Khalil & Collins, 2011; Purnick & Weiss, 2009). A few examples of this are: the use of bacterial proteins that can be repurposed to change water melting points (BioDesign Challenge, 2019), use of photosynthetic bacteria to generate electricity (Sawa et al., 2017), and genetically

modifying yeast cells to produce a broad palette of color pigments or medicines (Yeast Art Project, 2019). These efforts are all developed to address 21st century societal challenges involving energy, sustainability, and health—to name just a few.

Initiatives in science education evolve as technological landscapes change; however, so far there have been few efforts that have taken into account these shifts in life science fields. In synthetic biology, such efforts have been limited, in part, by the fact that these technologies have typically only been accessible in commercial and academic settings, as the expertise and sophisticated lab tools needed to engage with the field have been limited to businesses and universities. This is reflected in the development of commercial industries whose efforts focus solely on synthetic biology or universities synthetic biology degree specializations. As a result of these access issues, there is little research that examines how synthetic biology fits in the existing K-12 science education landscape. There is also a lack of research in life science education that examines how these paradigmatic shifts can be leveraged for learning. This underscores a significant need not only for research that reconciles emerging biotechnology fields and science education, but advances in learning research discourse to include fields in which design and innovation undergird field practice. This need is especially paramount due to issues related to workforce pipelines and citizenship. In other words, there is a need to support occupational participation (AAAS, 2015) in biotechnology and its various fields and, more broadly, to develop citizens (NRC, 2012; NSTA, 2000) who are thoughtfully critical and literate decision-makers concerning the ways these innovations impact the planet. Some have characterized this latter goal as an aim to produce ethical stewards (Gutmann, 2011).

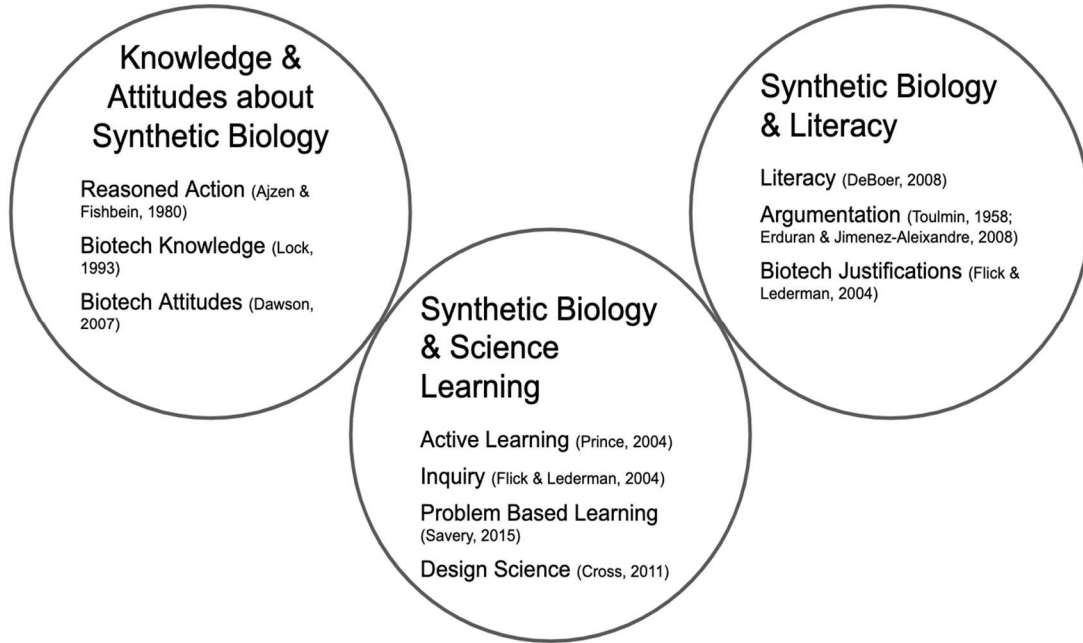
Recent developments to make the field accessible to a broader, non-expert, audience have created opportunities to address this need. These efforts have occurred through the development of public exhibits (The Tech Museum, 2018), community lab spaces (Genspace, 2018), and portable wet lab devices (Amino Labs, 2019) that have collectively made synthetic biology not only accessible, but simple to understand and carry out—two outcomes that have propelled the field beyond the confines of expert control and sophisticated laboratory spaces. Given these developments, there have been initiatives to introduce this biotechnology to K-12 learners. Examples of this include opportunities for elementary (Verish et al., 2018), middle and high school-aged (Kafai et al., 2017) students to engage with analog and digital synthetic biology simulations as well as living cells. These provide an opportunity to extend science education perspectives to include synthetic biology technologies, as a gap currently exists in the literature around these topics. More specifically, there is a dearth in the literature concerning: (1) information about what students know and think about this emerging field, which is necessary to guide science education policy initiatives or assessment, (2) how design in life science fits within or expands traditional science learning paradigms in order to inform education experiences, and (3) how academic participation may support learning, and such outcomes as increased literacy in order to promote civic engagement. The research represented in this thesis attends to these gaps by drawing on learning theory to examine science learning in a societal milieu that engages with life sciences in ways that are far different from what was possible not long ago. In doing so, this research provides insights into the state of K-12 learner conceptions about the field, considers design in science education landscapes that

emphasizes inquiry and solution driven learning, and points to ways to understand synthetic biology learning using traditional assessment frames typical of science literacy research.

1.2 Theoretical Foundations

In order to address science education and synthetic biology, the research presented in this thesis is fundamentally situated within constructivist perspectives on: (1) reasoned action, (2) active learning, and (3) literacy (see figure 1). Reasoned action is taken here to mean the ways in which knowledge and attitudes coalesce to inform thinking and—ultimately—behaviors (Ajzen & Fishbein, 1980). Active learning in this thesis refers to the iterative process of collecting information, reflecting, and sense making (Prince, 2004). Finally, literacy is meant to refer to the ability to reflect and engage critically with information (DeBoer, 2006; DeBoer, 2000; Hurd, 1958a; Hurd, 1958b). These perspectives guide research presented here in order to address educational objectives around teaching and learning. They are also meant to identify future directions in research on K-12 student groups in this era of synthetic biology.

Figure 1. Theoretical perspectives underpinning research in this thesis.



1.3 Perspectives on Student Knowledge and Attitudes

An example of reasoned action might involve a student deciding whether or not to select or persist in a focal area of study in science. Research in this area has long been used to help inform science education policy priorities aimed toward, for example, sustaining educational and occupational pipelines, encouraging intellectual and cultural field diversity, and developing measures to encourage broad public understanding about a set of ideas or technologies (AAAS, 2015; NRC, 2012). Efforts to understand what students know and think about a particular field has become a quintessential part of science education research across a number of STEM subject areas.

Research in this area with regard to biotechnologies has been taken up thoroughly across a variety of age groups and country contexts (Dawson & Venville, 2009; Ozel et al., 2009; Sadler & Dawson, 2012). These lines of inquiry have aimed to investigate what learners know and think about biotechnology and its various applications. This has been investigated in K-12 student groups using a variety of methods that typically involve assessing a student's ability to define or give examples of biotechnology-based applications (Dawson & Schibeci, 2003; Lock & Miles, 1993; Van Lieshout & Dawson, 2016). Much of the research in this area suggests that such factors as age (Klop & Severiens, 2007; Usak et al., 2009), focal area of study (Chen et al., 2016; Fonseca et al., 2013), and country context (Cavanaugh et al., 2005; Chen & Raffan, 1999; Dawson, 2007; Ozel et al., 2009) are related to student understandings of and perspectives toward the field. However much of this involves biotechnologies that have advanced considerably since the research was conducted and that do not include synthetic biology-based applications. The use of cells and cell systems to produce outputs like energy vitamins and textiles adds another

dimension to the field, to which very little research has been devoted. The first article in this manuscript addresses this gap by providing an update using synthetic biology applications to examine what a group of 66 middle school students know and think about the field and its contemporary applications.

1.4 Perspectives on Active Learning and Synthetic Biology

As science fields have evolved from a practice that spans beyond describing the natural world and toward one that is able to leverage those understandings for practical use, so has science education, as illustrated by active learning paradigms that emphasize inquiry (Deboer, 2006; Flick & Lederman, 2004) and problem solving (Savery, 2015; Torp & Sage, 2002) as frames for learning. Active learning is a process of practicing science (Brown et al., 1989; Harel & Papert, 2001; Lave & Wenger, 2001), as opposed to learning through didactic instruction that is often guided by instructors who are, in this view, situated as knowledge dispensers. In active learning, instructors are facilitators who lead learners through the development of questions to guide inquiry or the iteration of solutions that address real world problems (Freeman et al., 2014; Prince, 2004). While these perspectives have significantly shaped science education traditions, the emergence of synthetic biology fields has created a need for updates to existing paradigms. Engineering fields have taken up these updates using design science, an active learning approach that, unlike inquiry and problem-based learning, centralizes the social and cultural values and needs of those for whom designs are meant (Cook & Bush, 2018; Wrigley & Straker, 2017). The research in this manuscript builds on these perspectives by using BioDesign as a frame to examine synthetic biology learning.

Honey and Kanter (2013) characterize the use of design in science education as an embedded practice—a hallmark of active learning—in which learners create artifacts and iterate through their designs to create solutions to an array of societal problems. Such a perspective has been considered in a variety of engineering education subject areas (Dym, 1999; Gomez Puente et al., 2011; Strobel et al., 2013). To this end, efforts to understand the various affordances this perspective contributes to the science education research canon—in one trajectory—have been taken up in engineering and maker education wherein there is an emphasis on product development. While research in this area has provided important insights in understanding how to conceptualize learning in design science in STEM fields, far less research has taken up life science, in which objects often behave in unpredictable ways and operate along time scales that are not immediate—two factors that complicate engagement. Efforts to understand the educational affordances and constraints that exist when using design in life science has been taken up in research on BioDesign—the use of synthetic biology to develop products that make use of microorganisms and/or their cellular products that do not typically occur in nature (Kafai et al., 2017). Using perspectives on scientific inquiry, this thesis extends existing research by examining a small group of eight middle school students and their explanations of BioDesign projects and the obstacles they encountered in implementing designs. This not only gives insights into what it means to engage with BioDesign, but also provides important early steps in understanding how inquiry is taken up and supported in these emerging fields. These insights also highlight ways in which to broaden what is meant by inquiry in a science education landscape that uses knowledge and problem-solving not as ends, but as vehicles toward innovation and personally meaningful production.

1.5 Perspectives on Argumentation and Science Education

Another theoretical perspective taken up in this thesis is that of student argumentation. In addition to influencing K-12 education priorities, research along this trajectory aims to support students in their ability to reason critically through information (e.g., knowledge) and perspectives (e.g., attitudes)—hallmarks of research on scientific literacy, the complex set of cognitive processes that support critical engagement with social issues in STEM fields (DeBoer, 2008; Hurd, 1998; Hurd, 1958). This perspective has been characterized in science education as a fundamental contributor to occupational attainment (AAAS, 2015) and citizenship, as it includes the ability for all individuals to be able to make informed decisions around the nature of science and the consequences that emerge from its practice (Laugksch 2000; Ramaley & Haggett 2005; Turner 2008). Because reasoning is a cognitive process that is not readily observable, considerable research has examined student argumentation—the ability to convincingly advance a view by evaluating and asserting evidence and counter-perspectives (Erduran & Jimenez-Aleixandre, 2007). This has been assessed using a variety of analytical frames including student explanations. Examination of student explanations have been used to understand not only the relationship between knowledge and the ability to form a cogent argument, but also to ascertain the extent to which learners are able to navigate and justify claims (Erduran and Jimenez-Aleixandre, 2007).

With regard to biotechnology, research on argumentation has been conducted across a range of grade levels (Cavagnetto, 2010) and has sought to elucidate the relationship between argumentation and such factors as content knowledge (Sadler & Donnelly, 2006; Zohar & Nemet, 2002) and attitudes (Dawson & Venville, 2009).

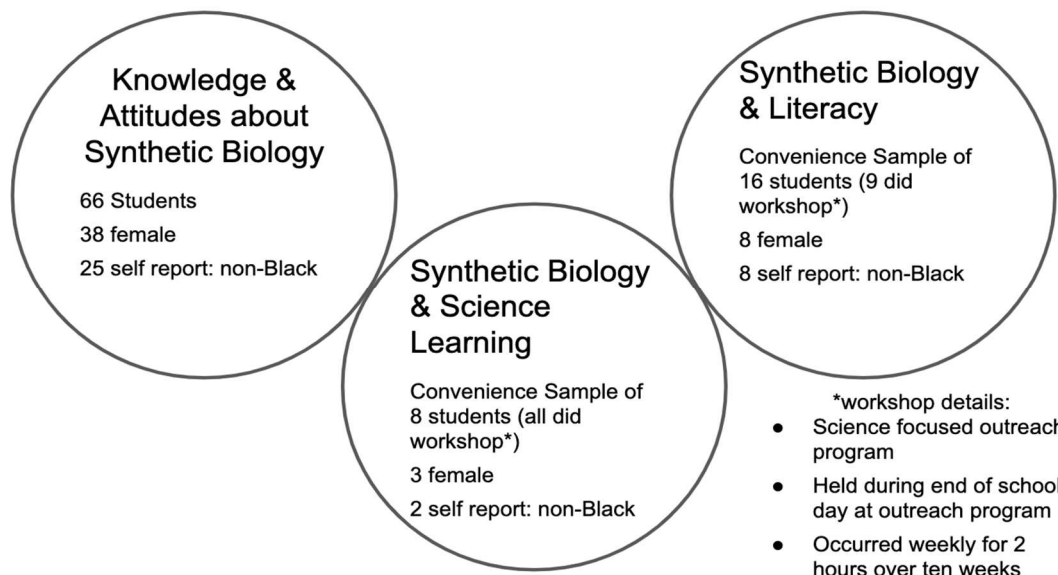
Research along this trajectory posits a Threshold Model for argumentation among K-12 learners (Sadler & Zeidler, 2005). This model suggests that learners use science knowledge to understand a particular biotechnology. It also suggests that once a threshold of information is attained, the extent to which biotechnology experts and non-experts can form an argument is virtually indistinguishable. This phenomenon has been attributed to other forms of information that learners may leverage to reason through and then argue their perspectives (Berland & Reiser, 2005; Sadler & Zeidler, 2005). As synthetic biology represents a burgeoning field about which K-12 learners are not knowledgeable or are largely unaware, it creates a viable frame through which to examine social and cultural forms of knowledge that learners may leverage to engage in advanced argumentation practices. Therefore, the third paper in this manuscript explores how a group of 16 middle school students leverage a type of informal knowledge (i.e., context clues) to form arguments. This research thereby extends discourse around this area by highlighting the ways in which informal knowledge serves as a cognitive tool for participants. In addressing this, this thesis illuminates insights into ways in which to support learners in argumentation practices when formal knowledge is unavailable—particularly among younger students who may not engage with advanced fields of study.

1.6 Research Questions

In order to address perspectives raised in the theoretical milieu within which the research in this manuscript is situated, research questions convene around three trajectories involving middle school students': (1) knowledge and attitudes, (2) inquiry practices, and (3) argumentation. Using a mix of quantitative and qualitative methods (Ravitch & Carl, 2015), this research provides insights into the current state of student familiarity with and

perspectives toward synthetic biology and its various applications, thereby informing educational priorities in the field. These questions also advance new perspectives that existing science education paradigms could leverage from design science learning—a perspective that is reflective of contemporary science fields. Lastly, these questions illuminate the ways in which context acts as a “tool to think with” when learners have little background in a given field, therefore informing ways to support literacy and, more specifically, argumentation, as described in the literature. Research questions that guide these trajectories are described along with the methodologies used in order to provide an overview of how research design (see figure 2) is aligned with theoretical perspectives.

Figure 2. Research group and theoretical framework alignment.



The first strand in broad terms, asks: what do 66 middle school students know about synthetic biology and its various applications? This question is addressed using open ended survey questions and semi-structured interviews. Another guiding research question along this trajectory is: what do middle school students think about synthetic biology and its

various applications? This question is addressed using a closed ended Likert-based and open-ended questionnaire in order to understand how student attitudes vary—if at all—across application contexts (i.e., the type of organism on which the biotechnology is applied, or the output generated). Finally, research along this first strand asks: what explanations do middle school students provide for their attitudes toward synthetic biology? This question is addressed using semi-structured interviews and provides early insights into factors that younger student populations consider to guide their perspectives about synthetic biology. Collectively, these questions build on efforts to understand and advance life science education research on middle school students and modern biotechnologies.

The next strand attends to questions concerning in which ways synthetic biology can be taught and the affordances BioDesign offers as an active learning approach to inquiry. This is fundamentally guided by research questions: how do middle school students use BioDesign and with which forms of inquiry do they engage? Using video recordings, observation notes and student interviews from a case study group of 8 middle school students, this research provides insights into how BioDesign can be taken up with middle school students who don't typically engage with advanced life science topics or who are often considered to lack requisite knowledge necessary to participate. It also considers how inquiry perspectives can be expanded to include design perspectives and their various affordances. Framed this way, design science offers insights into the ways inquiry can be leveraged and expanded to support meaningful learning.

The final strand builds on the previous ones by asking: how do 16 middle school student attitude justifications change when students are provided context clues about

synthetic biology and its various applications? This question provides insights into how students justify their well-formed perspectives with little to no knowledge of the field. Together, these questions help bring to the surface various considerations students use and make when advancing and justifying their positions, providing important insights into student reasoning. They are addressed using open ended questionnaires and semi-structured interviews. This inquiry builds on existing research in argumentation by highlighting the ways in which learners use informal knowledge when domain expertise is limited, which ultimately points to ways to support novices (i.e., non-experts) in advanced argumentation practices.

The following chapters are therefore meant to be a starting point in science education research in order to advance discourse around synthetic biology and K-12 learners. Given the paradigmatic shifts that continue to drive life science innovation, this thesis aims to illuminate insights into the possibilities these shifts have for young learners who not only represent future generations of innovators, but also future citizen stewards of society and the planet.

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2. Middle School Student Knowledge Of and Attitudes Toward Synthetic Biology

2.1 Chapter Summary

Synthetic biology is a field that leverages design, biology, engineering, and computation to genetically engineer organisms to make usable products such as sustainably manufactured textiles, environmentally responsible chemicals, and personalized medical treatments. So far, only university students have had access to synthetic biology learning and we know little about what younger learners know and think of these new applications, which is problematic for reasons related to scientific literacy and field participation. This chapter addresses this gap by examining a group (n=66) of middle school youth (ages 11 to 14) in the United States to understand what they know and think about synthetic biology and its various applications. Analysis of survey and interview data suggests that middle schoolers know very little about synthetic biology, and their attitudes involve considerations that are typically observed in older student groups. Future opportunities and challenges to support student knowledge building and ethical reasoning in this emerging field are discussed.

2.2 Introduction

Modern biotechnology is marked by widely impacting advances in myriad enterprises, including manufacturing, agriculture and medicine—to name a few. In practice, these advances have yielded such important outcomes as the ability to: produce environmentally sustainable manufacturing materials (Zeller & Zocher, 2012), use viruses to target and eliminate cancer with perfect accuracy (Porter et al., 2011), and grow crops that provide essential biomolecules like beta carotene, (Beyer et al., 2002). Recently, the emergence of do-it-yourself lab tools (Amino Labs, 2019), community lab spaces (Genspace, 2018),

competitions (BioDesign Challenge, 2018), and museum exhibits (The Tech Museum, 2018) have created unparalleled opportunities for learners and citizen scientists of all ages to access and engage with modern biotechnologies that were previously costly, sophisticated, and, ultimately, inaccessible.

Because biotechnologies impact society in many ways and are increasingly more available, there is an urgent need to examine what kindergarten through twelfth-grade (K-12) students know and think about these tools and their various applications. This need has been described as broadly paramount because of issues related to occupational participation (AAAS, 2015) and civic engagement (Barton & Roth, 2004; Lindahl & Lundin, 2016). To this end, previous efforts have expressly argued that research involving K-12 students and biotechnology is an important step in educating future generations of practicing professionals (Mohapatra et al., 2010), civically engaged decision-makers (Van Lieshout & Dawson, 2016), and stewards of the planet (Gutmann, 2011)

One area of research where there is a persistent gap is that of middle school student knowledge and attitudes toward biotechnologies. While previous research has examined high school student knowledge of and attitudes toward biotechnologies (Dawson & Schibeci, 2003; Lock & Miles, 1994; Mohapatra et al., 2010; Van Lieshout & Dawson, 2016), far less has been carried out examining middle school students, beyond small (n=18) case studies (Anagun, 2012) or studies whose sample included a mix of high school and middle school-aged students. Furthermore, while these efforts have provided important first steps toward understanding middle school student perspectives, they have often reflected traditional biotechnologies, which have advanced considerably. One example of this type of biotechnology is an emerging field known as synthetic biology— in which cells

are genetically modified and essentially repurposed for useful applications. While it has recently gained attention in K-12 research on learning (Stark et al., 2018; Verish et al., 2018; Walker et al., 2018), very little research has examined what students know and think about this burgeoning biotechnology. In the United States (U.S.), this research gap is, in part, the result of a lack of attention in contemporary K-12 life science education learning frameworks that reflect traditional biotechnologies that are often treated as optional or minor fields of study (Reece et al., 2014) or are absent from the curriculum altogether (Pellegrino et al., 2014).

To attend to gaps in the literature around middle school students, modern biotechnologies and learners in the U.S., this study engages a sample (n=66) of students from two urban public middle schools located in the northeastern U.S. in order to address two research questions: (1) What do middle school students know about synthetic biology and its various applications? (2) What do middle school students think about synthetic biology and its various applications? (3) What explanations do middle school students provide for their attitudes toward synthetic biology? Collectively, these questions build on efforts to understand and advance life science education research on middle school students and modern biotechnologies. This is accomplished by discussing how middle school student knowledge and attitudes in this study compare to existing research. The study also includes a discussion of what middle school students know and think about modern biotechnologies and opportunities that exist to update contemporary K-12 science education learning priorities.

2.3 Background

2.3.1 Research on K-12 Student Knowledge

Research intended to explore what and how much students know about biotechnology was undertaken as early as three decades ago, when studies sought empirically to elucidate students' understandings using surveys in the United Kingdom (Lock, 1993; Lock & Miles, 1994). This research examined early forms of biotechnology that included the ability to genetically modify a bacterium to fluoresce in the presence of ultraviolet light, and the ability to genetically modify bacteria to be resistant to antibiotic strains that could then be used, for example, in traditional molecular biology research. In general—though with several exceptions—research on applications like these shows that student knowledge tends to be limited before formal instruction, as reflected in students' inability to describe biotechnology or give an example of a biotechnology-based process (Dawson et al., 2003; Lock, 1993; Van Lieshout & Dawson, 2016). Initial efforts concerning what students actually know about biotechnology and its diverse applications emerged in the 90s and has resulted in findings that suggest that student knowledge varies and likely depends on a range of factors, including: (1) age, (2) what students are studying, and (3) where students are studying.

Existing research on student knowledge and age primarily consists of high school aged students (Ozel et al., 2009) or high school students with an unspecified subset of middle school students (Dawson, 2007). This research suggests that older high school students tend to be more able to describe biotechnology and provide examples—sometimes categorically—of the field's applications or processes. For instance, using a semi-structured interview, Dawson (2007) demonstrated that students in Australia were increasingly able to provide “generally accepted [definitions] or provide correct examples

of biotechnology” as they progressed from grades 8, 10 and 12. Ozel et al. (2009) found that as “students’ age increased, their knowledge of biotechnology applications increased.” While these findings may be unsurprising to educators—recognizing that high school and middle school science education is often distinct in content and experience—they point to a gap in the literature on middle school students as a group. Examining middle school students would provide a more homogenous group of studies which would, as a result, provide insights into the ways in which education experiences may influence what students know about modern biotechnologies and their various applications.

Research also suggests that high school student knowledge of biotechnology may depend significantly on education experiences; that is, whether students are in concentrated biology, science or non-science academic tracks or trajectories. Fonseca and colleagues (2013) showed that students who had experienced more biology instruction had significantly greater knowledge of biotechnology than those who had not. This finding suggests that high schoolers who had engaged with science topics could describe or define biotechnology or provide examples of its various applications. Chen and colleagues (2016) reported a contradictory finding in Taiwan, where there were no statistical differences in knowledge of biotechnology between high school students taking advanced biology subjects and those not. As with research on student biotechnology knowledge and age, research here primarily consists of studies of high school students and, even within this group, there is apparent heterogeneity (i.e., education experience differs among students) as reflected in these contradictory findings. Furthermore, biotechnologies have advanced considerably, to include fields such as synthetic biology; therefore, research that does not

taken into account these developments may not only be limited in generalizability, but to some extent does not provide an accurate depiction of student knowledge.

With regard to country context, Chen and Raffan (1999) extended Lock's research by comparing high school students in the United Kingdom to those in Taiwan in order to understand country-based knowledge differences in what students knew about biotechnology. Using closed and open-ended surveys, they found that students in both countries had limited knowledge of biotechnology in absolute terms (i.e., when students in the same country are compared with each other), but when compared in relative terms (i.e., when students in different countries are compared to each other) using t-tests, there were significant differences between the two groups. In other words, students in the United Kingdom had a greater understanding of biotechnology than students in Taiwan. Furthermore, students in the United Kingdom were able to provide a greater diversity of examples of biotechnology-based processes than students in Taiwan.

Ultimately, Chen and Raffan (1999) attribute these differences to the “greater availability of general [biotechnology] studies and media resources” in the United Kingdom than in Taiwan. A similar view concerning resource availability was reported in Australia (Cavanaugh et al., 2005). Studies in Australia (Dawson, 2007; Dawson & Schibeci, 2003a) and Turkey (Ozel et al., 2009; Usak et al., 2009) revealed that students in those countries—at least in absolute terms—also had limited understandings of biotechnology. That is, students were, on average, only able to provide a few examples of biotechnologies and those examples tended to include basic uses such as using yeast in the production of beer and wine (i.e., food applications) and genetically modifying plants (i.e., agricultural applications), as opposed to medical applications such as genetically

modifying cells to produce a clone (Cavanaugh et al., 2005; Chen et al. 2016; Dawson & Schibeci, 2003a). This research also underscores a gap in the literature involving students in the United States, where comparatively less research on student attitudes toward modern biotechnologies has taken place.

In all, research suggests that age, science learning experiences, and country context are significant factors that correlate with student knowledge of biotechnology. While some studies have found different outcomes, these themes provide a frame within which to extend research by examining U.S. middle school students using modern biotechnologies, which often include applications that go beyond what was possible decades ago.

2.3.2 Research on K-12 Student Attitudes

As with research on students' knowledge, there is a dearth of research that examines student attitudes toward biotechnology. Collectively, research suggests that these attitudes tend to be cautious but highly variable and, perhaps, are dependent on or correlate with a host of factors including: age, gender, context, and moral considerations.

While research on the influence age may have on student attitudes toward biotechnology is limited, findings consistently suggest that older students tend to have more accepting attitudes. For instance, Dawson (2007) showed that younger students tended to be unaccepting regardless of application, but older students tended to be more accepting toward biotechnologies applied to microbes or plants. Similarly, Ozel et al. (2009) found relationships between age and student attitudes toward particular biotechnology applications. They reported that as student ages increased, so did positive attitudes toward biotechnologies involving DNA manipulation, animals and plants.

But, factors other than age also play critical roles. For instance, researchers have explored the relationship between student attitudes and gender (Chen et al., 2016; Dawson & Soames, 2006; Lock, 1993). Findings reveal that female students tend to have more cautious (Hill et al., 1998) and rigorous (C̆rne-Hladnik et al., 2009) attitudes than males across a range of biotechnology applications (Ozel et al., 2009). For example, Hill and colleagues (1998) reported that female high school students were more skeptical of biotechnologies used on plants or animals and expressed more safety concerns toward human consumption of such products than did males. Similarly, Usak and colleagues (2008) reported that, concerning animal applications of biotechnology (i.e., genetically modifying an animal), females were less “positive” than males. These results have been replicated in other studies and have shown that middle and high school females overall (Fonseca et al., 2012), and high school females in specific applications (Ozel et al., 2009), have less positive attitudes than males toward biotechnologies and their various applications. Furthermore, C̆rne-Hladnik and colleagues (2009) showed gender differences in student attitudes in terms of usefulness and moral acceptability, suggesting that females tend to favor these dimensions less than males. While there may be relationships between student attitudes and gender, far less research has examined this in younger children in whom sex and gender roles could still be forming. Therefore, this represents a gap in the literature that obscures the extent to which we fully understand student attitudes toward biotechnologies that carry complex and often intersecting ethical and sociocultural implications.

Furthermore, studies illustrate that students have what Lock and Miles (1994) have described as context-dependent attitudes toward biotechnology applications: student

attitudes depend on the type of biotechnology used and the target cell or organism to which the technology is being applied (e.g., microbes, plants, animals or humans). Numerous studies have shown consistently that students tend to be more accepting toward biotechnologies applied to microbes (i.e., yeast or bacteria) and plants, and less accepting toward animal or human applications. This trend has been reported in students in the United Kingdom (Lock & Miles, 1994), Taiwan (Chen & Raffan, 1999), Australia (Dawson & Schibeci, 2003b), the Netherlands (Klop & Severiens, 2007), India (Mohapatra et al., 2010), and Portugal (Fonseca et al., 2012).

In addition, research suggests that students' ethical orientations influence their attitudes. Črne-Hladnik and colleagues (2009) reported significant differences between dimensions of Slovenian student attitudes such as: (1) usefulness, (2) moral acceptability and (3) risk perception toward various biotech applications (e.g., agriculture, animal applications, disease applications and human germline applications). Specifically, they suggest that students found disease and agricultural applications of biotech more useful and morally acceptable than animal and germline applications. On the other hand, students found such applications in contexts like modifying animals, curing disease and manipulating human germlines more risky than agricultural applications such as increasing crop productivity (Črne-Hladnik et al., 2009). This finding suggests that attitudes toward biotechnologies are multifaceted and therefore exist at the intersection of multiple considerations.

Finally, student attitudes toward biotechnology depend on risk-benefit assessments and, even then, on the application being considered. For example, when weighing the risks and benefits of a biotech application in humans, overall, students took more utilitarian

stances, whereas, when considering risks and benefits to an individual person they had more egalitarian perspectives (Cavanaugh et al., 2005; Gunter et al., 1998). Klop and Severiens (2007) clustered attitude dimensions to create attitude types within which 574 middle and high school student closed-ended survey responses were categorized, including: (1) confident supporter (23% of students), (2) not sure (42%), (3) concerned skeptic (18%), and (4) not for me (17%). Their findings suggest that student attitudes depend largely on both how students evaluate biotechnology acceptability and the context in which the application is being used.

Modern biotechnologies like synthetic biology continue to have a significant impact on a range of industries. While efforts to expand education and non-expert access to the field have taken place over the last decade, there exists a gap in the literature examining what middle school aged students know about and think of these contemporary fields and their various applications. This gap is especially evident in the United States, where far less research has examined these contemporary biotechnologies. This study attends to these gaps by extending research in these areas—which will ultimately provide more encompassing perspectives about student attitudes, how they are mediated, and ways to support learning.

2.4 Methods

2.4.1 Schools and Participants

The sample in this study was composed of 66 middle school students ranging from eleven to fourteen years in age. Students were selected conveniently from schools partnered with a local science center outreach program. Student age distribution included 10 eleven year

olds, 17 twelve year olds, 27 thirteen year olds, and 12 fourteen year olds. Student grade distribution included 15 sixth graders, 19 seventh graders, and 32 eighth graders. Self-reported gender distributions included 38 female and 28 male students. Student racial distribution included 41 students who self-reported as black and 25 who self-reported as non-black. Of the sample, 17 students were interviewed. Student names were anonymized and presented as pseudonyms.

GW Middle School is a K-8 school that enrolls 257 students per year, of whom 79 are in grades 6-8. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 63% black, 19% white, 11% other/biracial, 4% Asian, and 4% Latino. According to school district definitions, approximately 98% of students at GWM are considered economically disadvantaged, 22% are characterized as special education, and 2% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 academic reporting period, achievement scores on statewide standardized assessments found that 41% of students at GWM were rated as proficient in reading, 34% in science and biology, 16% in math and algebra. This was based on achievement scores on statewide standardized assessments.

TR Middle School is a 5-8 school that enrolls 361 students per year. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 96% black, 2% Latino, <1% white, and <1% other/biracial. According to school district definitions, approximately 86% of students at

TRM are considered economically disadvantaged, 14% are characterized as special education, and <1% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 academic reporting period, 33% of students at TRM were rated as proficient in reading, 22% in science and biology, 11% in math and algebra. This was based on achievement scores on statewide standardized assessments.

2.4.2 Data Collection Instruments: Survey

The survey instruments used in this study were based, in part, on existing and widely published survey questions (Dawson and Schibeci, 2003b) that have largely been initially developed and used with Australian high school students and, primarily, with students outside of the U.S (Klop & Severiens, 2007; Ozel et al., 2009; Prokop et al, 2007; Usak et al., 2009). The questions used by Dawson and Schibeci (2003b) covered a variety of traditional biotechnology applications (see table 1) and asked students to draw a dividing line to indicate at which point respondents found a biotechnology application no longer acceptable. The survey instrument used in this study (see table 2) was drawn on Dawson and Schibeci's (2003b) examples and included applications used on microbes, plants, animals, and humans. But, it differed in the following aspects: (1) format, and (2) topics. First, the revised survey was organized categorically by organism and on a four point Likert-type scale (ranging from very acceptable to very unacceptable) which provides analytical opportunities to evaluate instrument reliability using such metrics as a Cronbach alpha score. Second, applications used in the piloted survey in this study include synthetic biology-based applications that involve atypical outputs like textiles and chemicals. The survey instrument and interview protocol were first piloted with a subset (n=8) of middle

school students in two semi-structured interview focus groups. Students were asked if survey items and interview questions were clear, understandable and relatable. Modifications were made when there was agreement between two or more students about item or question clarity, intelligibility, and context.

Table 1. Dawson and Schibeci, 2003a Survey on Student Attitudes Toward Biotechnology Applications.

Instructions: Read each of the statements below. Draw a line across to separate where you personally find the uses of biotechnology and genetic engineering acceptable. If you wish to change the order of any of the statements please do so.	
Statement	Application category
Using yeast in the production of wine and beer	microbial
Growing yeast for animal food	microbial
Using genetically engineered microorganisms to enable more efficient breaking down of human sewage	microbial
Altering the genes of plants to that they will grow better in salty soils	plant
Adding genes to yeast that is then used to make better tasting bread	microbial
Adding genes to plants to increase their nutritional value	plant
Altering genes in fruit to improve taste	plant
Altering genes in tomatoes to make them ripen more slowly and have a longer shelf life	plant
Inserting genes from microorganisms into crops to provide pesticide resistance	plant
Inserting genes from plants into animals	human
Changing the genetic makeup of farm animals to improve the quality of meat and milk	animal
Using genetically engineered cows to produce medicines for human use	animal

Altering the genes in an embryo to treat a genetic disease	human
Inserting genes from humans into the fertilized eggs of mammals	animal

Table 2. Synthetic Biology Attitudes Questionnaire.

#	Statement	Application Type
M1	Using yeast to make fabrics like leather	microbial
M2	Growing yeast to make food for animals	microbial
M3	Adding genes to yeast that is then used to add vitamins to bread	microbial
M4	Using genetically modified microorganisms (GMOs) to make natural color pigments or dyes	microbial
P5	Changing the genes (DNA) of a plant so that they can detect pollutants in water or soil	plant
P6	Changing the genes (DNA) in fruit to make them look better when aging	plant
P7	Changing the genes (DNA) in tomatoes to make them age more slowly and last longer when stored	plant
P8	Inserting the genes (DNA) from a microorganism into crops to protect the crops from pests or harmful chemicals	plant
P9	Adding genes (DNA) to plants so that they can have vitamins and be more nutritious	plant
A10	Inserting genes (DNA) from plants into animals to improve animal growth	animal
A11	Inserting genes (DNA) from plants into animals to make animals live longer	animal
A12	Inserting genes (DNA) from plants into animals to help animals produce more offspring	animal
A13	Using human-made viruses to insert genes (DNA) into farm animals to add vitamins and nutrients to animal meat, eggs or milk.	animal
A14	Using human-made viruses to insert genes (DNA) into farm animals to cause them to make medicines for human use (for example making a vaccine for the flu in an egg that is later eaten)	animal

A15	Inserting genes from humans into an unborn animal to increase the animals use (for example causing an unborn animal to produce a human organ like a heart that can later be given to a human with a heart disease)	animal
H16	Using a virus to genetically modify human cells to treat a disease like cancer	human
H17	Changing the genes (DNA) in an unborn child to treat a genetic disease	human
H18	Changing the genes (DNA) in an adult to treat a genetic disease	human
H19	Changing the genes in an unborn child to make them stronger or smarter	human
H20	Changing the genes in an adult to make them stronger or smarter	human

2.4.3 Data Collection Instruments: Questionnaire

A written questionnaire was used to assess student knowledge of synthetic biology. Students were asked: (1) What is synthetic biology? and (2) Provide an example of synthetic biology. You may provide more than one example.

2.4.4 Data Collection Instruments: Interviews

Interviews provided opportunities to further explore student reactions to synthetic biology-based surveys. Students were asked: (1) Describe the process of carrying out synthetic biology. Provide an example of synthetic biology. You may provide more than one example. Students were also asked: (2) Which on the survey you just took did you find to be the most acceptable? Why did you find that to be the most acceptable? and (3) Which on the survey you just took did you find to be the least acceptable? Why did you find that to be the least acceptable?

2.4.5 Data Collection: Survey

The survey was administered using Qualtrics—an electronic survey tool. Students completed the survey over the course of one hour during an academic class period in a computer laboratory. The researcher administered the survey by providing instructions and answering clarification questions when students were unclear about survey language or encountered technical challenges (e.g., advancing to a proceeding survey question before completing all required questions on a page). Surveys were completed in approximately 30 minutes.

2.4.6 Data Collection: Questionnaire

The questionnaire was also administered using Qualtrics. Students completed the questionnaire after completing the survey, during the same class period. The researcher administered the survey by providing instructions and answering clarification questions when students were unclear about questionnaire language or encountered technical challenges. Questionnaires were completed in approximately 10 minutes.

2.4.7 Data Collection: Interviews

Audio recorded interviews were administered by the researcher. Students completed individual interviews after completing the survey and questionnaire. The researcher answered clarifying questions when students were unclear about interview language. Interviews were completed in approximately 10 minutes.

2.4.8 Data Analysis: Survey

Closed-ended Likert-based survey questions were analyzed using an SPSS statistical package to generate descriptive statistics. Before analyzing quantitative survey data, the

researcher validated constructs related to synthetic biology-based applications by calculating a Cronbach alpha reliability score for survey items composing each. Reliability analysis yielded significant ($p < 0.05$) results for four constructs, as shown in table 3 below. In order to examine factors that relate to student attitudes toward synthetic biology-based applications, an analysis of variance (ANOVA) with age, grade, and gender (factors) and survey construct scores (dependent variable) was carried out.

Table 3. Reliability Statistics for Survey Constructs.

Construct	Number of Items	Cronbach Score
Microbial based application	4	$\alpha = 0.449^*$
Plant based application	5	$\alpha = 0.620^*$
Animal based application	6	$\alpha = 0.784^*$
Human based application	5	$\alpha = 0.827^*$
* $p < 0.05$. Scores with $\alpha > 0.800$ reflect good consistency among items in a given construct. Scores with $\alpha > 0.700$ reflect fair consistency. Scores with $\alpha < 0.700$ reflect poor consistency.		

2.4.9 Data Analysis: Questionnaire

Open-ended questionnaire responses were aggregated into a spreadsheet and descriptively coded by two coders according to the code book provided in table 4 below. Coders applied codes independently and disagreements were resolved in order to reach 100% consensus. Responses in which the student indicated they could not respond or responded “I don’t know” were given a score of zero. Instances in which students provided an incorrect

response were given a score of one. If a response was correct, a score of two was assigned. Then, descriptive statistics were calculated in order to summarize student responses overall. Illustrative examples were drawn from the actual survey to provide illustrative context for survey responses.

Table 4. Open-ended Survey Question Response Code book.

Code	Definition	Example
0	Instances in which a student remarks that they are unable to answer or cannot provide an answer to a survey question.	“I don’t know”
1	Instances in which a student provides an incorrect definition or makes no reference to synthetic biology-related objects (e.g., organisms or DNA) or processes (e.g., making an organism or materials).	“Synthetic biology is something that is electronic”
2	Instances in which a student provides a correct definition or makes reference to synthetic biology-related objects (e.g., organisms or DNA) or processes (e.g., making an artificial or fake organism or material).	“Synthetic biology is where you make a fake organisms”

2.4.10 Data Analysis: Interview

Interview question responses were audio recorded and subsequently transcribed using the Rev.com transcription service. Next, transcripts were imported into Dedoose, a qualitative data analysis software. Qualitative data was analyzed using a descriptive approach (Ravitch & Carl, 2015). Specifically, interview text was excerpted by question. Codes were developed to describe student responses as reflected in the code book provided in table 5 below. Codes were applied independently by two coders and disagreements were resolved in order to reach 100% consensus. Responses in which the student indicated they could not respond or responded “I don’t know” were given a score of zero. Instances in which

students provided incorrect or erroneous responses were given a score of one. If a response was correct, a score of two was assigned. Then, illustrative examples were drawn from transcripts to provide more granular and triangulated perspectives on student survey responses.

Table 5. Interview Question Response Code book .

Code	Definition	Example
0	Instances in which a student remarks that they are unable to answer or cannot provide an answer to a survey question.	“I don’t know”
1	Instances in which a student provides an incorrect—or overly broad—process description or makes no reference to synthetic biology-related objects (e.g., organisms or DNA) or processes (e.g., making an organism or materials).	“I think it's like DNA, and changing things.”
2	Instances in which a student provides a correct process description or makes reference to synthetic biology-related objects (e.g., organisms or DNA) and processes (e.g., making an artificial or fake organism or material).	“If you change the cells of a certain animal, like a mutation for a good or a bad reason” or “like you use GMOs to enhance the products so that it looks nicer over time or lasts longer”

2.5 Findings

The first section addresses the first research question: what do middle school students know about synthetic biology and its various applications, while the second section addresses the second and third research questions: what do middle school students think about synthetic biology and its various applications and what explanations do middle school students provide for their attitudes toward synthetic biology?

2.5.1 Student Knowledge of Synthetic Biology

When surveyed, the large majority of students (86.4%) indicated that they could not describe synthetic biology (e.g., “I don’t know”). Of the remaining students, 4.5% provided incorrect responses (e.g., “Synthetic biology is something that is electronic”) and 9.1% provided correct responses (e.g., “Synthetic biology is where you make a fake organism,” “I don't know but my guess is the study of false or fake DNA,” or “I guess it's biology having to do with synthetic material”).

These findings were corroborated during interviews in which students were asked to describe how synthetic biology is carried out. Students most commonly responded that they could not or “I don’t know.” Only one student answered correctly. There were two instances in which students provided correct answers but asserted later that context clues from the survey they had taken for this study just before informed their insights. This is illustrated in Donald’s response, “well, [it] was on the survey. There's like switching DNA and using animal's DNA for synthetic biology and stuff like that, but I don't know. What I'm trying to say is, is it legal issues of synthetic biology? If you use different animals’ DNA, or you take DNA from a plant or something like that, like that I saw on the survey.” Here, Donald provided a correct answer concerning how synthetic biology is carried out, involving DNA being changed in animals, but admits to having used context clues from the survey to inform his answer. This result suggests that students interviewed who provided a correct response to this particular question may have been leveraging context clues from the survey and questionnaire that they completed earlier.

2.5.2 Student Attitudes Toward Synthetic Biology

Overall, 57.4% of student responses were accepting of synthetic biology applications using microbes, plants, animals, and humans in different degrees

Figure 3 shows that 56.8% of student responses were accepting overall toward microbial-based synthetic biology applications but there were large differences between contexts. With regard to specific microbial-based application survey items, 66.7% of student responses were accepting of applications that involve using microbes to produce animal food (M2) or more nutritious food products (M3). This is compared to 43.9% of student responses favoring applications that involve making textiles and pigments such as leather (M1), and 42.4% of responses favoring applications that involve the production of dyes (M4). Many student responses favored applications involving food. For instance, Daniel noted that his favorable attitude toward animal food production is, “because it's giving animals food to eat. It's giving them food to eat so they won't starve.” Similarly, Kendra stated, “because yeast helps make bread so it would be more helpful if we had more [vitamins.]”

Figure 3. Student Attitudes Toward Microbial-Based Applications of Synthetic Biology. “ALL” represents average acceptance rate (57.4%) across all application categories. Microbe (M) 1-4 represents average acceptance rate (56.8%) across all microbial-based applications.

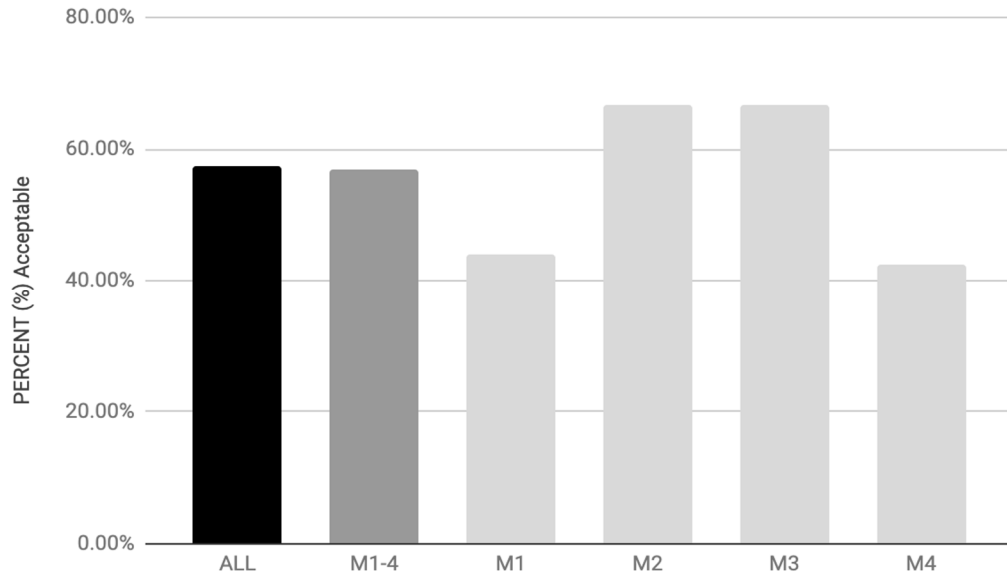


Figure 4 below shows that 65.2% of student responses were accepting overall toward plant-based synthetic biology applications. This is higher than the proportion of student responses that were accepting of synthetic biology applications overall (i.e., 57.4%).

With regard to specific plant-based application survey items, 83.3% of student responses were accepting of synthetic biology applications that made plants more nutritious (P9). In addition, 68.2% of student responses were accepting of applications that involved using plants to detect environmental pollution (P5) and delay rot (P7). Similarly, 63.6% of student responses were accepting of synthetic biology applications that involved making a plant resistant to crop pests. Tasha’s response provides a good illustration: “because it showed that it's another way that plants can get nutrients and vitamins instead of using the sun as usual.” Jake presented a similar rationale for his attitude when he answered, “I think

[plant applications are] the most acceptable because it's better to use it on plant life, because plants don't really have a life, so it's better to test it on plants, instead of humans.” By contrast, 42.4% of students were accepting of plant applications used for aesthetics (P6). During an interview, only one student, Alan, remarked about this application when he noted, “changing genes in tomatoes. If it looks ripe, you're probably going to buy them, but if you eat it it won't be ripe so that's false advertisement. I don't think that's acceptable.”

Figure 4. Student Attitudes Toward Plant-Based Applications of Synthetic Biology.

“ALL” represents average acceptance rate across all application categories. Plant (P) 5-9 represents average acceptance across all plant-based applications.

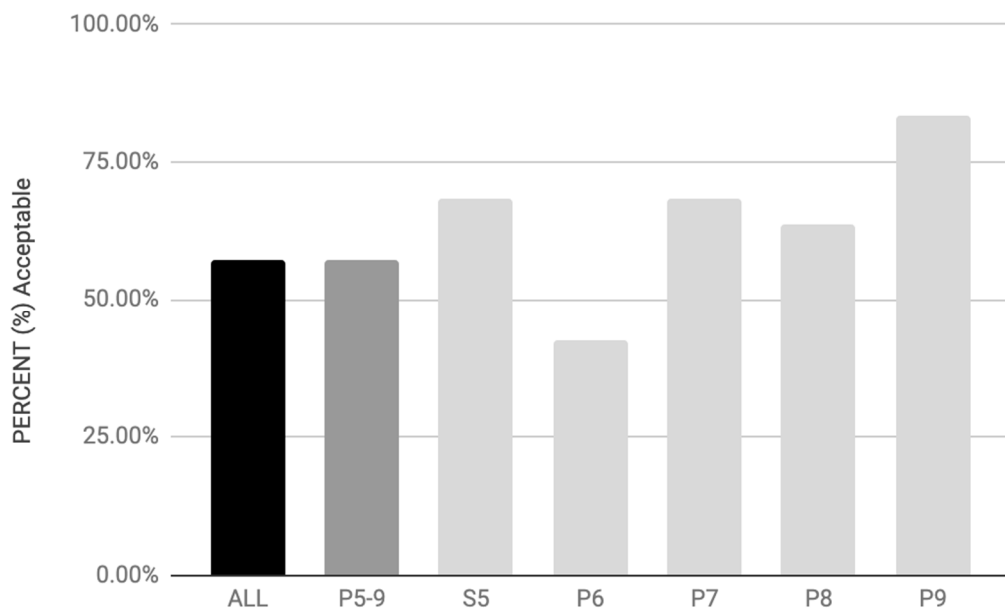


Figure 5 below shows that 52.0% of student responses were accepting overall toward animal-based synthetic biology applications. By contrast, 57.4% of student responses were accepting of synthetic biology applications overall.

With regard to specific animal-based application survey items, 71.2% of student responses were accepting of applications that increased animal lifespan (A11). 60.6% were

accepting of applications that benefitted animals in terms of growth (A10). Similarly, 54.6% were accepting of applications that increased animal offspring production (A12). Students responded differently to applications that led to animal exploitation, such as use in human medical applications such as delivering nutrients (A13 at 40.9%), medicine (A14 at 40.9%), or for organ production (A15 at 43.9%). For instance, Maya explained her attitude about animal-based applications for the production of organs as “because [it’s] testing on animals, which I don't think is right.” Other students asserted similar sentiments indicating that such an application may pose risks or even “agitate the animals, or make them unhealthy, or [make them] feel upset.”

Figure 5. Student Attitudes Toward Animal-Based Applications of Synthetic Biology. ALL represents average acceptance rate across all application categories. Animal (A) 10-15 represents average acceptance across all animal-based applications.

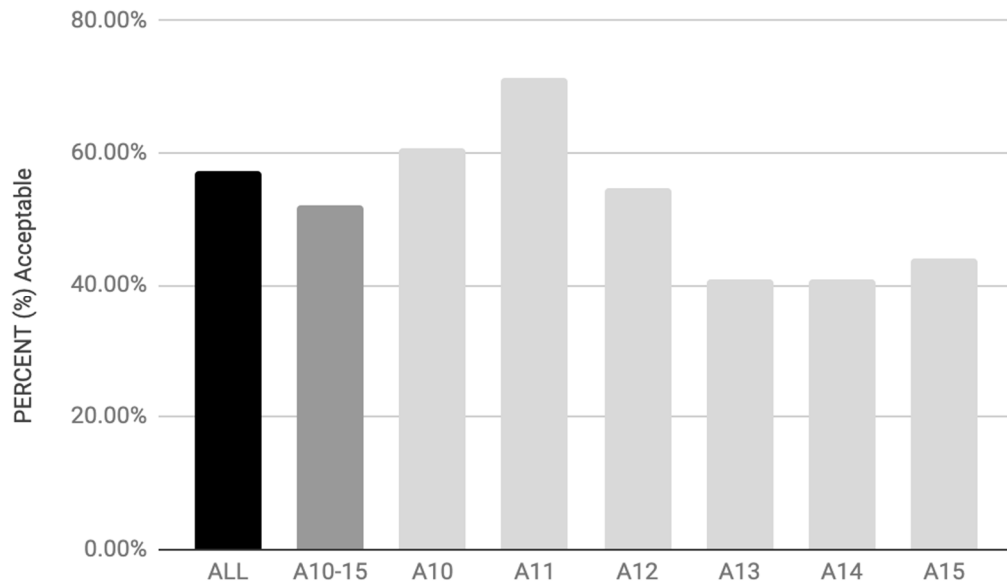
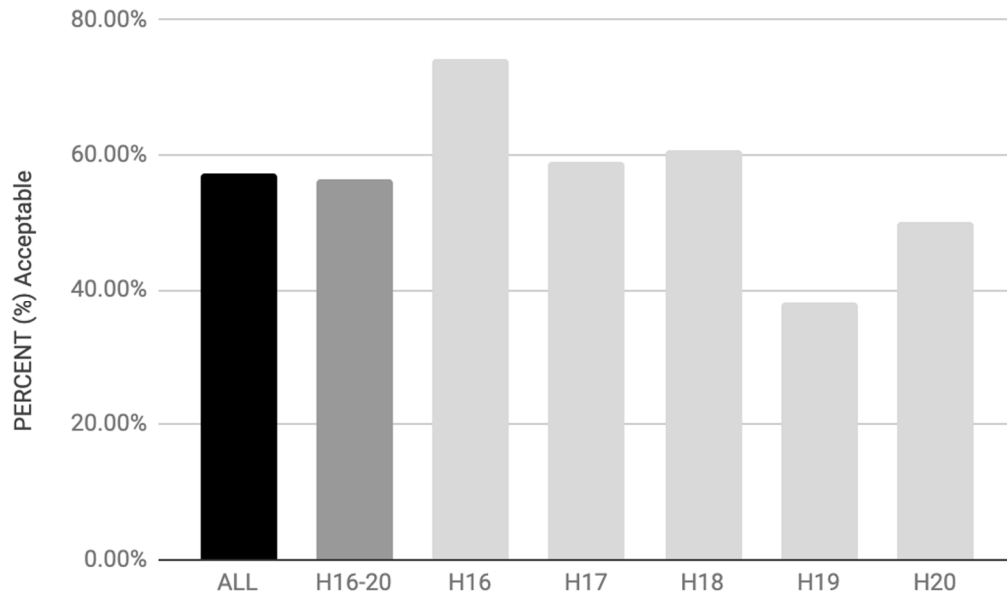


Figure 6 shows that 56.4% of student responses were accepting overall toward human-based synthetic biology applications. By contrast, 57.4% of student responses were accepting of synthetic biology applications overall.

With regard to specific human-based application survey items, 74.2% of student responses were accepting of medically essential applications such as treating a disease—such as cancer (H16). Also, 60.6% of students' responses were accepting of applications that prevented human disease postnatally (H18). Similarly, 59.1% were accepting of applications that prevented human disease prenatally (H17). During interviews, students often described their acceptance of the application in relation to their own personal experience. For instance, Dan explained his attitude toward the use of human-based synthetic biology applications to treat human disease: “[I find this application acceptable] because cancer is such a deadly disease and it's so common, that anything that can help out, or cure it in a way, to me, is really acceptable because my Aunt has it, [and died] with it, and something that'll cure it will really help.”

By contrast, 50.0% of student responses were accepting of human-based applications that generated elective increases in strength or intellect postnatally (H19). Similarly, 37.9% of student responses were accepting of human-based applications that generated elective increases in strength or intellect prenatally (H20). This is corroborated in an illustrative example from Sam who explained, “changing the gene to make adults stronger or smarter [is unacceptable] because it makes people think different and it might have a bad effect on them.”

Figure 6. Student Attitudes Toward Human-Based Applications of Synthetic Biology. ALL represents average acceptance rate across all application categories. Human (H) 16-20 represents average acceptance across all human-based applications.



ANOVA results showed that student attitudes toward microbial, plant and human-based synthetic biology applications did not vary with respect to age or grade. By contrast, the results showed that student attitudes toward animal-based synthetic biology applications varied significantly with respect to age (ANOVA, $F=3.767$, $p<.05$, $df=3$). Detailed analysis showed that twelve year old students had less frequently accepting attitudes toward these applications than eleven year old students (Scheffe post-hoc test, $p<.05$).

ANOVA results also showed that student attitudes toward microbial and plant-based synthetic biology applications did not vary with respect to grade. By contrast, the results showed that student attitudes toward animal and human-based synthetic biology applications varied significantly with respect to grade (ANOVA, $F=5.052$, $df=2$, $p<.05$,

and ANOVA, $F=4.064$, $df=2$, $p<.05$, respectively). Detailed analysis showed that seventh grade students had less frequently accepting attitudes toward both these applications than 6th grade students (Scheffe post-hoc test, $p<.05$).

ANOVA results showed that student attitudes toward all synthetic biology applications did not vary with respect to gender ($p>0.05$).

2.6 Discussion

This research showcased middle school student knowledge and attitudes toward synthetic biology. To accomplish this, a group of middle school students were surveyed and interviewed on 20 synthetic biology-based applications involving microbes, plants, animals, and humans. Overall, findings suggested that while students undoubtedly had limited knowledge of this burgeoning field, their attitudes and explanations reflected—in part—those previously reported in high school-aged students. The following sections discuss the implications of synthetic biology for contemporary science education. Reasons that middle school students provide important considerations are discussed, as well as the implications of these findings for science literacy. Finally, findings on demographic based differences reported here are discussed in order to examine how age and grade may influence student knowledge about the field. Future research directions in line with these four discussion points are also addressed.

2.6.1 Student Knowledge

Findings in this research show that the vast majority of middle school students surveyed in this study had a very limited knowledge base about synthetic biology and its various applications. This is not surprising given that this topic is seldomly taught formally in

middle schools and typically is optional. Survey and interview results reflect this point consistently as students—when asked—were infrequently able to define synthetic biology, describe how it is carried out, or provide an example of a synthetic biology-based application. These results are consistent with research over the last three decades in the United Kingdom and Australia that suggests that, despite societal influences, middle and high school-aged students are fundamentally unfamiliar and unknowledgeable about biotechnologies (Dawson et al., 2003; Lock, 1993; Van Lieshout & Dawson, 2016).

In the few instances that students were able to provide an answer, it was often based on context clues drawn from the survey itself, as several students admitted candidly. When correct responses were not drawn from survey context clues, students were, at best, able to describe synthetic biology in relation to DNA. This reflects a more limited understanding than previous research has shown with middle and high school students who could only provide food or agriculturally related examples (Cavanaugh et al., 2005; Dawson, 2007; Dawson & Schibeci, 2003a). Concomitant with studies that suggest that greater access to education experiences and related public discourse (Cavanaugh et al., 2005; Chen & Raffan, 1999) supports student awareness about these fields, government agencies internationally have taken strides toward including them in high school learning. Despite these efforts, they are typically treated as optional topics of study and often not included in middle school life science learning. Therefore, these findings reaffirm the need to introduce these topics to younger learners—in order to meet international academic priorities as well as support civic engagement among future generation decision-making.

2.6.2 Student Attitudes

This study illustrates that middle school students surveyed demonstrated what Lock and Miles (1994) described as context-dependent attitudes—a finding that has also been reported among high schoolers in Taiwan (Chen & Raffan, 1999), Australia (Dawson & Schibeci, 2003b), the Netherlands (Klop & Severiens, 2007), India (Mohapatra et al., 2010), and Portugal (Fonseca et al., 2012). When looking more closely into synthetic biology applications, it is important to note that these modern biotechnologies often involve the production of non-living outputs (e.g., textiles) or are applied at the intersection of two organisms (e.g., plant genes in animal cells). Furthermore, these outputs very often involve processes (when applied to animals) that can be exploitative. These new contexts are an important place to continue research as they nuance what is known about student attitudes toward biotechnologies. They also provide opportunities to understand the complex ways in which learners negotiate and form their attitudes toward a particular application. Taken with the earlier finding that students know very little about synthetic biology and its various applications, it is clear that students not only have well-formed perspectives, but that those attitudes are based on other experiences they bring to formal learning environments—experiences that would provide important insights into the science learning and educational experiences that best leverage them for learning.

2.6.3 Student Attitude Considerations

The findings also offered important insights about the middle school students studied: that students in this age group make very similar considerations when evaluating synthetic biology applications and deciding whether or not an application is acceptable. These considerations have previously been reported as often embedded in ethical or moral

judgements in high school groups (Črne-Hladnik et al., 2009; Gunter et al., 1998). Similar results emerged in human-based synthetic biology applications as students were more frequently accepting of applications that they considered medically necessary than those that were perceived as optional. These results suggest that while the majority of research in this area focuses on high school students, middle school populations are also able to offer ethical evaluations of modern biotechnologies and their various applications—findings previously reported about high school students. This further underscores the importance of examining middle school attitudes toward modern biotechnologies; such research would provide insights into ways to support student scientific literacy and reasoning—competencies that are considered central to civic and occupational engagement.

2.6.4 Demographic-based Differences

Findings reported here suggests that demographic categories such as gender and race have little to nothing to do with what middle school students know or think about synthetic biology and its various applications. This provides an important insight about teaching and learning in regard to such goals as knowledge building, literacy, and occupational participation in that it dispels narratives that suggest learner perspectives may be the result of biological categories or social constructions. This discrepancy also highlights the fact that middle school students are distinct populations that cannot necessarily be understood using the corpus of existing literature on high school students. Importantly, grade and age differences reported here, which are inconsistent with findings reported with regard to middle and high school student groups (Dawson, 2007), point to important opportunities for science education teaching and learning. Specifically, this outcome suggests that while

younger science students know very little about emerging biotechnologies like synthetic biology, they have well-formed perceptions and make measured considerations about the field and its applications. In teaching and learning, this provides an important place to build literacy—that is, by designing learning experiences that provide learners opportunities to practice reasoning through their considerations. These contradictory findings with regard to age and grade also suggest that students may be flexible in regard to their attitudes as they continue to form perspectives and judgements. This underscores the need for education research and science learning experiences that support cognitive development around reasoning about modern biotechnologies—particularly because middle school students assessed here have already demonstrated an ability to engage with these cognitive activities.

2.7 Conclusions and Implications

Overall findings suggest that middle school students assessed in this study have limited to no knowledge about synthetic biology and its various applications. This is evidenced by the vast majority of students who could not define, describe or provide an example of the field, its processes, or its various applications which span microbes, plants, animals and humans. This underscores the need to develop learning activities for younger students, given the field's presence in so many out of school spaces and commercial enterprises. This is especially important as this group represents future generations that will need the knowledge and literacy necessary to engage civically—as future decision-makers—with the field's future directions, risks, and impact on society.

In terms of middle school student attitudes toward synthetic biology-based applications, these findings suggest that these students have clear perspectives about the

potential risks, consequences and benefits of the field. In this study, students found microbial and plant applications more acceptable than those involving animals or humans. While these are important first steps in understanding middle school student perspectives about the field, they represent an important outcome: that middle schools students may not only have opinions, but such opinions are grounded in relation to their sociocultural experiences, ethical orientations, familiar relationships, and—importantly— their ability to consider the impact of these technologies on other non-human living things (e.g., microbes, plants and animals). This, in itself, highlights the need and impetus for future research examining the complex ways in which K-12 learners negotiate and justify their perspectives about modern biotechnologies. In other words, because students explain their perspectives in ways that span multiple considerations (e.g., cultural norms, ethics, social relationships, and non-human perspectives), more research is needed to examine how to create learning experiences that support learner participation and literacy in these increasingly ubiquitous fields.

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3. What Middle School Students Say about BioDesign Learning

3.1 Chapter Summary

Science education has undergone several paradigmatic shifts, from perspectives that emphasize inquiry, to those that draw on problem-based approaches to guide learning. With the emergence of fields such as synthetic biology, a modern biotechnology wherein the focus is on generating practical and often living products, science education also increasingly emphasizes design as a form of inquiry learning. While much of the literature describing how K-12 students use design to think and learn in various STEM fields, far less research has examined the affordances and challenges of such an approach in the life sciences. One particularly promising contexts for design in life sciences is synthetic biology—where cells are often modified genetically and then used for some practical application or use. This study reports on the design and implementation of a synthetic biology design activity—BioDesign—in a local science center with two classes of middle school students, ages 12-14, to address the following research questions: (1) How do middle school students carry out synthetic biology, and (2) With which forms of inquiry do students engage? Analysis of class-wide interviews, video recordings, observation notes, and lab journal entries show that students engage in inquiry when planning and implementing their BioDesigns. These findings suggest that synthetic biology taught using design is a viable approach to teaching students emergent life science topics while concurrently developing practices that have previously been shown to support science inquiry. Challenges associated with BioDesign as well as the extent to which this perspective is compatible with traditional science learning frameworks are discussed.

3.2 Introduction

Significant efforts in science education and education research have aimed to provide students with learning opportunities that prepare them for future occupational (AAAS, 2015; NRC, 2012) and civic (Gutman, 2011; NSTA, 2000; Trefil, 2008) participation in modern Science, Technology, Engineering, and Mathematics (STEM) fields. These efforts are reflected in well-studied active learning paradigms characterized as experiences that promote collaboration, cooperation, and self-directed problem solving (Freeman et al., 2014; Prince, 2004). Active learning approaches are central in science education models that emphasize Inquiry Based Learning (Anderson, 2002; Flick and Lederman, 2004; Torp & Sage, 2002; Welch et al., 1981) and Problem Based Learning (PBL) (Savery, 2006)—two approaches that are also meant to model practice in traditional STEM fields.

These efforts have been shown to support positive science learning outcomes in key learning research, namely: self-perception and field interest (Johnson & Johnson, 2008), knowledge building (Metz, 2005; Zohar & Nemet, 2002), argumentation (Duschl & Osborne, 2002; Faieze et al., 2017), and literacy (Cavagnetto, 2010; DeBoer, 2000; Hurd, 1958a; Hurd, 1958b; Roberts, 2007). The emergence of contemporary engineering fields that emphasize design has created a need for expanded perspectives about science education and learning. One such example in life science fields is synthetic biology—a modern biotechnology that leverages synthetic biology approaches to manipulate cell behaviors or outputs and, ultimately, produce a functional or useful product.

Major challenges in research on learning in synthetic biology, in particular, include those related to access, given that the expertise and material resources needed to participate were previously only available in sophisticated commercial or university laboratories. The

development of community labs (Genspace, 2019), museum exhibits (Building with Biology, 2019), and do-it-yourself portable lab tools (Amino Labs, 2019; Kafai et al., 2017), and workshop activities (Walker et al., 2018) has made this field increasingly accessible to field novices and, in particular, K-12-aged learners.

In addition to providing access, we also need to understand the various ways in which learners engage in design-specific activities, or about the affordances, or challenges, such an approach would provide middle school students, a group that does not typically engage in specialized science fields of study. This research addresses these gaps in the literature by examining student discussions when participating in class wide activities and when working in small groups to plan and implement BioDesign activities. To understand how middle school students engage in and respond to BioDesign, this study is guided by two research questions: (1) How do middle school students carry out synthetic biology and (2) With which forms of inquiry do students engage? These questions provide important early insights into how design based science activities fit in or extend existing K-12 active science learning paradigms. This is accomplished by examining and discussing student conversations in specific contexts. This research also includes a discussion of the various ways in which Design Biology can support middle school learning.

3.3 Background

3.3.1 Active Learning in Science

As a field, science has evolved from an activity whose goals are primarily descriptive to one that strives to provide solutions to specific world problems, to one that leverages what is understood about the world and its inner workings to develop an outcome that is not only

functional, but reflective of social and cultural priorities (Cross, 2011). Alongside this evolution have been educational efforts to develop active learning models that not only reflect the field at large but provide opportunities to participate professionally and civically. Examples of these models include: (1) inquiry-based science, (2) problem-based science, (3) and design-based science—which collectively represent paradigmatic shifts from a perspective that is guided by questions to one that aims to develop culturally significant solutions to complex problems (Bybee, 2006; Cross, 2001; Savery, 2015). In the next section, these science education models are reviewed both in terms of their theoretical underpinnings and in how they are typically formulated in science education. Then, a closer review of design-based science is conducted in order to understand how existing science education research has conceptualized and assessed learning from this perspective.

3.3.2 Inquiry Based Learning

An early form of active learning in science education, inquiry has often been characterized as involving “processes and ways of thinking that support the development of new knowledge” (Flick & Lederman, 2004). This approach has aimed to produce such outcomes as the ability for learners to: (1) engage with a set of practices and (2) reflect on knowledge that these practices unearth. This is an iterative back and forth process of actively doing and reflecting on what is done. In contemporary K-12 classrooms, this is reflected in learning activities that include research question development, experimentation, data collection, data analysis and, at times, the synthesis of new ideas. In practice, students are situated at the helm of learning facilitated by an instructor who guides them through experiments that are designed to address a question concerning some phenomena.

In life sciences, this process typically relies on rote protocols that lay out how to handle and manipulate biological materials. Student work is then catalogued in a structured lab journal or presentation that is meant to reflect the systematic or—so called—scientific method that can then be assessed. This type of life science inquiry is common in K-12 education and reflected in events like science fairs—which represent a popular way of showcasing it. Such an active approach has been widely examined in science education research as an alternative to passive and traditionally didactic instruction and, in principle, is thought to also provide learners with educational experiences that authentically reflect field practices (Bybee, 2006; Colburn, 2000).

Science education research suggests that inquiry contributes to a range of positive learning outcomes in K-12 learning (Cuevas et al., 2005; Lee et al., 2005), myriad STEM subject areas (Sesen & Tarhan, 2013), grade levels (Lee et al., 2006), and learning environments (Gibson & Chase, 2002; Slotta, 2004). Research has also considered inquiry implementation strategies and their impact on student learning (Hmelo-Silver et al., 2007; Howes et al., 2009; Liu et al., 2010). While these approaches have been investigated thoroughly and have shown significant promise, they have also been met with criticism for often being decontextualized or disconnected from real-world situations (Lee et al., 2005; Rodriguez, 1997) or culturally relevant (Carter, 2008; Emdin, 2016; Lee, 2002) contexts. Others have argued that, as a practice, this approach is only reflective of traditional STEM fields whose objectives typically focus on inductively understanding or describing phenomena—in contrast to emerging fields that are solution-focused and often attend to social and cultural priorities. Consistent with these outcomes have been efforts to develop

science learning paradigms that support practical and socio-culturally relevant learning experiences that are reflective of where science as a field is moving.

3.3.3 Problem Based Learning

A different approach to science inquiry has been emphasized in PBL (Albanese and Mitchell, 1993; Barrows & Tamblyn, 1980; Boud & Feletti, 1997; Vernon & Blake, 1993). This learner-centered approach is characterized by an emphasis on self-direction, in which learners use their existing knowledge—no matter how well developed—to solve a problem (Savery & Duffy, 1995). As in the case of inquiry based learning, teachers are situated as facilitators of learning as opposed to primary sources of knowledge. However, instead of using research or investigative questions to guide engagement, learners typically aim to identify a solution to some technical challenge or problem. PBL is also distinctly characterized as an open-ended process which does not typically involve scaffolds designed to guide learners toward a structured set of practices or skills (e.g., question formation, experimentation, and analysis). In practice, PBL often leverages problems so that learners have opportunities to collaborate and draw on their interests or expertise from a range of academic disciplines (Savery, 2015; Torp & Sage, 2002). Authentic problems are considered central to PBL not only because of opportunities to engage with complex and often intersecting challenges, but because they situate the learner in a real-world context that makes learning personally meaningful, interesting and relevant (Savery, 2015; Savery & Duffy, 1995; Wijnia et al., 2015). In many ways, this approach addresses criticism of scientific inquiry and the ways in which it is sometimes disconnected from the real world or cultural relevance.

PBL has been taken up in life science education topics that often involve health professions or technical education. In K-12 environments, this often involves the use of case studies or simulated clinical experiences wherein learners learn about a patient symptom or condition and are charged with collecting this information by consulting with peers, asking questions, and identifying plausible solutions. As in inquiry based learning, questions are used; however, in PBL, questions are meant to identify unknowns as a way toward developing a solution. Data is collected and used as a way to better conceptualize an often messy problem and as a means to iterate through solutions. One can imagine middle or high school students in a health related technical program collaborating and ordering diagnostic tests to diagnose (i.e., identify a problem) and treat (i.e., identify or develop a solution) a patient with some hypothetical disease.

This approach has been shown to support a variety of positive learning outcomes including concept mastery (Gijbels et al., 2005; Strobel & Barneveld, 2009; Yadav et al., 2011), skill development (Allen et al., 1996; Dochy et al., 2003; Gijbels et al., 2005; Gordon et al., 2001), and self-regulation (LeJeune, 2002; Schraw et al., 2006), as well as academic interests (Tandogan & Orhan, 2007). These findings suggest that PBL is indeed a viable approach to contextualizing science learning in ways that are personally meaningful to K-12 learners. However some have critiqued this approach—highlighting challenges associated with developing adequately complex problems that are situated in social and cultural norms. For instance, in K-12 education, PBL is often taken up as an activity that involves semi-structured active learning, often leaving out related socio-scientific and ethical issues, or only including them as an ancillary addendum. An example of this would be engineering students working through the problem of building a bridge

that can sustain a given set of stresses or physical challenges and adding on a conversation about sustainability or the impact of the solution has on the environment and society. Stated differently, PBL is—by definition and design—situated in a context that is often culturally relevant, but not always within social and cultural factors related to class, the environment, etc. As a result, there is less research on the affordances including such considerations would provide. This is especially important as science fields are constantly undergoing shifts from approaches that are predominantly descriptive investigations of the natural world and ones that leveraged those understandings to solve problems to a field that also involves forefronted consideration of the impacts those solutions have on many aspects of society. This is reflected in modern biotechnologies—a hallmark of contemporary sciences wherein design considerations are often intricately woven into societal constructions.

3.3.4 Research on Design in Science Education

Design approaches to science education have been taken to not only address criticisms of inquiry and problem based approaches to learning, but also as a way to introduce contemporary advancements in science fields. Design has long been characterized as having at least three intersections with science, namely: the science of design, scientific design and design science (Cross, 1981; Cross, 2001). The former two have aimed to (1) understand and improve design as a discipline and (2) describe the explicit and non-explicit practices of design. These have been taken up in education to advance the design field as a professional practice. On the other hand, design science—an area concerned with taking knowledge about the natural sciences and putting them to practical or functional use—is the perspective used to situate science education in this study. While design science shares with inquiry and problem-based learning its theoretical foundations in constructivism—the

Dewian, Piagatian, or Vygotskian notion that learning is situated in experiences that involve cognitive and social interactions—it is distinct. This distinction is illustrated in a theoretical comparison Waks (2001) makes between inquiry and design when he explains:

[Dewey] posits that scientific inquiry is merely an intermediate stage in a process which begins when practice becomes unsettled or problematic. This leads to a ‘time-out’ from practice for reflection, during which inquiry guided by the methods and spirit of the sciences yields causal connections to apply in practice.... Schon, however, rejects the idea of reflection as a “time out” from practice for scientific inquiry [and instead argues practitioners] “reflect-in-action.”

This distinction, though subtle, suggests that traditional (i.e., inquiry and problem based) approaches to learning are theoretically underpinned by the idea that while learning occurs by doing, it involves reflective and practical actions that are independent and iterative. Design based learning, on the other hand, can be understood as processes in which reflection and practice are interwoven and situated within acts. This perspective—that learning is embedded in practice—is not unique to design and has been well theorized in K-12 education research (Brown et al., 1989; Harel & Papert, 2001; Lave & Wenger, 2001). This distinction is illustrated in a comparison of learning that exclusively engages science topics in isolation from specific contexts and learning that takes place in a place such as a design studio where the activity is embedded in specific contexts (Waks, 2001) and where designers actively consider “the needs and values of those for whom they are designing” (Cook & Bush, 2018; Wrigley & Straker, 2017).

This perspective has been examined in a number of K-12 STEM academic subject areas (Bell et al., 2018; Bequette & Bequette, 2012) and especially in engineering (Dym, 1999; Puente et al., 2011; Strobel et al., 2013), wherein production is prioritized. This approach to design science has also been characterized by Honey and Kanter (2013) as

“making,” wherein learners have opportunities to design and produce material artifacts to express themselves or use in some practical application (e.g., making an electronic device that uses a computer program to behave or respond to some interaction in a specific way). In doing so, students learn as a means of accomplishing their personal goals—a process that, like inquiry and PBL, often involves an iterative use of data and reflection to address challenges encountered. In practice, these products are very often meant to reflect social and cultural values, as well as to address societal problems.

While this approach to K-12 science learning has provided important insights into ways to advance science education paradigms, little research has been done to illuminate the possibilities of this perspective for contemporary life science fields. Therefore, the emergence of synthetic biology access has created an opportunity to conceptualize life science education differently—and in a way that is not only beneficial and relevant to learners, but reflective of societal values. BioDesign, a synthetic biology activity that focuses on producing artifacts that are culturally relevant and that reflect societal values, is a promising approach to gaining these insights. This research aims to examine how BioDesign supports inquiry and provides learning experiences that are relevant to middle school students.

3.4 Methods

This study examines a convenience sample of eight middle school students across four science groups in an urban city in the northeastern region of the United States. These students participated in a hands-on synthetic biology workshop held at a local science outreach center—also the site of this research study. Schools, described in the next sections, were identified by the science outreach center located in the same city. At

different points in the workshop (e.g., planning and implementation), student conversations and material artifacts were documented and examined. Students were also asked about their projects and the challenges they encountered during implementation. Recorded data was analyzed using qualitative methods.

3.4.1 Schools and Participants

The sample in this study is composed of eight middle school students, four from each of two schools (GW Middle School and TR Middle School described below), ranging from eleven to fourteen years in age. Students were selected conveniently from schools partnered with a local science center outreach program. These students were conveniently selected because they had participated in all BioDesign planning and implementation activities. This group had also been asked specific questions about their BioDesign projects and challenges they encountered during implementation. Student age distribution included one twelve year old, four thirteen year olds, and three fourteen year olds. Student grade distribution included one seventh grader, and seven eighth graders. Self-reported gender distributions included three female and five male students. Student racial distribution included six students who self-reported as black and two who self-reported as non-black. All students participated in ten two hour weekly synthetic biology-based workshops held at a local science based outreach program in the same city. Student names were anonymized and presented as pseudonyms in this study.

GW Middle School is a K-8 school that enrolls 257 students per year, of which 79 are in grades 6-8. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 63%

black, 19% white, 11% other/biracial, 4% Asian, and 4% Latino. According to school district definitions, approximately 98% of students at GWM are considered economically disadvantaged, 22% are characterized as special education, and 2% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 recent academic reporting period, achievement scores on statewide standardized assessments found that 41% of students at GWM were rated as proficient in reading, 34% in science and biology, 16% in math and algebra. This was based on achievement scores on statewide standardized assessments.

TR Middle School is a 5-8 school that enrolls 361 students per year. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 96% black, 2% Latino, <1% white, and <1% other/biracial. According to school district definitions, approximately 86% of students at TRM are considered economically disadvantaged, 14% are characterized as special education, and <1% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 recent academic reporting period, 33% of students at TRM were rated as proficient in reading, 22% in science and biology, 11% in math and algebra. This was based on achievement scores on statewide standardized assessments.

3.4.2 Workshop Design

The workshop implemented in this study took place over ten weeks and included sessions (or twenty contact hours) that focused on synthetic biology and the development of an actual GMO food product that is fortified with a hypothetical nutrient selected by students.

In addition, students were tasked with developing a package and marketing campaign that was related to their baked product. This campaign required the design of: (1) food item ingredients (i.e., recipe), (2) a uniquely shaped silicone mold, (3) relevant packaging, (4) relevant promotional and informational materials. These tasks were distributed across workshop meetings as shown in table 6. These tasks were collectively presented to students as a design challenge.

Table 6. Workshop Overview: Day, Lesson Topic, and Lesson Description

Day	Lesson Topic	Lesson Description
1	Introductions	Introduction to synthetic biology and BioDesign challenge.
2	Product Packaging and Design	Investigate existing products, packaging, and package design iterations.
3	Baking Mold Design	Investigate existing silicone bake mold and mold design iterations. Meet expert product designers.
4	Introduction to Genetic Transformations and Create Baseline Designs	Learn about DNA and genetic modifications. Use a standard cake recipe to bake a cake. Carry out a yeast genetic transformation.
5	Experiment with Design Variables	PLANNING: Consider design variables for package, cake ingredients, and silicon mold.
6	First Mold Iteration and Package Design	IMPLEMENTATION: First silicone mold and package construction with initial design variants.
7	First Bake Iteration	IMPLEMENTATION: Test bake with initial ingredient variants.
8	Second Mold Iteration	IMPLEMENTATION: First silicone mold construction with initial design variants.

9	Second Bake and Package Design	IMPLEMENTATION: Second bake and package construction with initial design variants.
10	Design Challenge Presentations	Present final package, cake, and silicone mold designs.

In completing the workshop design challenge, students were asked to genetically modify a yeast cell line (i.e., *saccharomyces cerevisiae*) such that the organism would produce beta carotene—a vitamin A intermediate. Students accomplished this by following a protocol that involved mixing specific reagents (shown in figure 7a). Next, students fabricated the newly transformed cells in a portable wet lab device known as the Biomakerlab (shown in figure 7b). Students then isolated transformed yeast cells and grew pure colonies in a petri dish to both confirm that the genetic transformation took place successfully and to enrich for cells that would later be used to bake a beta carotene enriched food product (shown in figure 7 c-d).

Figure 7 (a-d). Genetically Modifying Yeast Cells to Produce Beta Carotene

Figure 7a. Aliquoting Reagents for Transformation

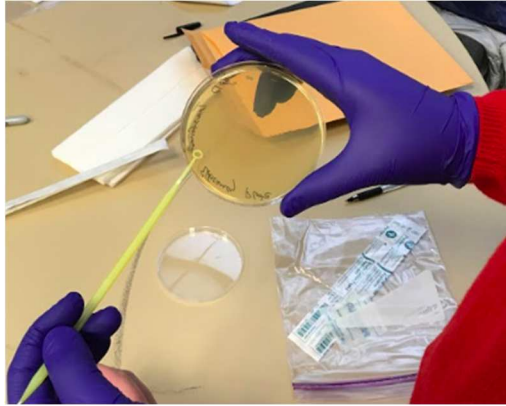


Figure 7c. Isolating Pure Cell Colonies

Figure 7b. Fabricating Transformed Yeast Cells



Figure 7d. Collecting Genetically Modified Cells



In addition to genetically transforming a strain of yeast cells to be used in a baked product prototype for their design challenge task, students were asked to develop a food grade silicone baking mold in a design consistent with the metaphorical product they would produce for the workshop design challenge. This process involved aliquoting and mixing silicone reagents according to a protocol set by the silicone manufacturer (see figure 8a). Then, students built a cast for their molds by either following approaches provided by workshop instructors or developing an approach of their own (see figure 8b). Cast shapes were designed by students and involved using a pre-formed object or an object that was 3D printed by students. Once both the silicone and mold cast were prepared, students assembled the materials (see figure 8c) and troubleshooted through any assembly challenges (e.g., buoyant objects or cast disassembly). Once the silicone cured in the cast, students disassembled it from the cast and were left with a usable silicone baking mold that would be used to bake their GMO cake prototypes (see figure 8d).

Figure 8 (a-d). Designing Unique Casts and Silicone Molds

Figure 8a. Mixing Silicone Mold Reagents

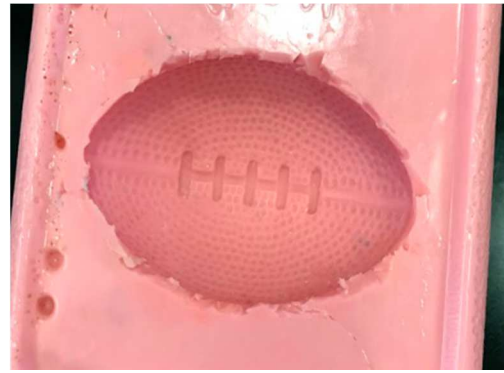
Figure 8b. Designing Mold Shape and Cast



Figure 8c. Assembling Silicone and Cast



Figure 8d. Producing Usable Silicone Baking Mold



In order to produce a GMO baked cake prototype consistent with their unique design challenge aims, students were given a sample recipe to guide their approaches. They were able to deviate from this guide in order to develop a food product that met their unique specifications. This process involved assembling food product ingredients (see figure 9a) and mixing in genetically transformed yeast cells that would fortify the food product with beta carotene (see figure 9b). Next, students added the mixture to their pre- designed silicone baking molds (see figure 9c). Baking times varied and students considered such variables as silicone mold depth, baking temperature, and ingredient composition. After baking, they removed cakes from silicone molds to reveal a final outcome that was then used in a presentation for their final design challenges (see figure 9d).

Figure 9 (a-d). Developing and Producing a Nutrient Fortified Food Product

Figure 9a. Designing Specific Baked Outcomes



Figure 9b. Incorporating GMO Yeast Cells



Figure 9c. Assembling Ingredients for Baking



Figure 9d. Producing Baked GMO Cake



While genetically modifying yeast cells, designing and building silicone baking molds, and developing unique ingredient recipes consistent with their unique design challenge goals, students concurrently developed a package and marketing plan that would be used during their design challenge presentations. This process involved identifying and researching specific nutrients that synthetic biology-based approaches could be used to fortify the hypothetical food product that would be represented by their GMO baked cakes (see figure 10a). Then, students designed food packaging and marketing materials that

would be consistent with the design challenge goals (see figure 10b). Using these designs, they modified and assembled their packing using a variety of materials available at the workshop site. Materials included plastics, bioplastics, and cardboard (see figure 10c). Package and marketing materials included such sections as: product names, product directions and use, unit costs, nutrition facts, warning labels, and any other items consistent with the student design goals. Once designs and products were assembled, students brought all of them together and presented them publicly to an audience convened by the science center outreach program (see figure 10d).

Figure 10 (a-d). Researching, Designing, and Producing a Package and Marketing Campaign

Figure 10a. Researching Package Marketing Strategy

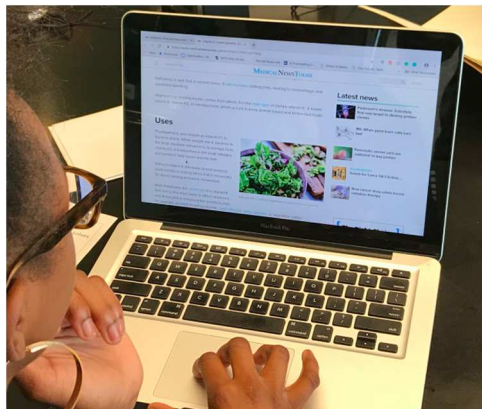


Figure 10b. Designing Package and Marketing Approach



Figure 10c. Assembling Package Materials

Figure 10d. Produced Package and Marketing Campaign



3.4.3 Data Instruments and Collection: Video Recordings of Classroom Discussions

Video recordings were collected on workshop days five through nine, when students were asked to plan and implement their BioDesigns (see table 6). Class wide discussions and, when possible, student pair conversations were recorded.

3.4.4 Data Instruments and Collection: Researcher Observation Notes

Observation notes were collected in-person during workshop activities and after each workshop, using video recordings and three guiding questions: (1) What do students say about their BioDesign projects? (2) What challenges do students encounter when implementing their BioDesign projects? (3) How do students overcome challenges encountered when implementing their BioDesign projects? Observation notes were also collected daily during workshop debriefs with instructors in order to corroborate observations.

3.4.5 Data Instruments and Collection: Student Lab Journal Entries

Students were asked, but not required, to use a lab journal to help plan and document their BioDesign projects. Guiding prompts were sometimes used and included: (1) What problem are you solving? (2) How are you solving the problem? (3) Draw a quick sketch

of your new mold. (4) Draw a quick sketch of your new package. These prompts provided in worksheets and instructors recommended students use the questions to guide their planning and reflections. Lab journal entries were photographed after workshop activities.

3.4.6 Data Instruments and Collection: Student Interviews

Audio recorded interviews were administered by the author. Students completed individual interviews after completing the BioDesign workshop and took place over a period of about 10 minutes per student. Interviews took place at the workshop site. Students were asked: (1) Tell me about your BioDesign project, (2) What challenges did you face when doing your project?

3.4.7 Data Analysis: Video Recordings

Video recordings were used to identify and detail moments identified in observation notes. When observations notes pointed to a moment when students were—for instance—overcoming a challenge, the research reviewed and transcribed video of the instance when available. Then, illustrative examples were drawn from those observations.

3.4.8 Observation Notes

Observation notes were assessed for moments when the author observed students describing, planning, or implementing their BioDesign projects. This took place on workshop day five through nine. The author also assessed moments when students were describing a challenge or having to overcome a challenge. These observations were then selected, if they could be triangulated with video recordings, workshop instructors, and/or lab journal entries.

3.4.9 Data Analysis: Lab Journal Entries

Student lab journal entries were photographed and notes were assessed for moments when the author observed students collecting or recording information related to their BioDesign projects. These data sources were used to corroborate observations made in video recordings and/or lab journal entries.

3.4.10 Data Analysis: Interviews

Interview question responses were transcribed using the Rev.com transcription service. Then, transcripts were imported into Dedoose, a qualitative data analysis software. Specifically, interview text was excerpted by question. Interview data was analyzed using a descriptive approach (Ravitch & Carl, 2015). Next, illustrative examples were drawn from transcripts to provide more granular and contextualized interview responses.

3.5 Findings

Findings are arranged in two sections, each addressing the research questions: (1) How do middle school students BioDesign, and (2) With which forms of inquiry do students engage? Qualitative data are provided to illustrate student responses and provide context. The first section focuses on the BioDesign planning and implementation. The second focuses on challenges encountered. These ideas are described in the following sections.

3.5.1 Planning and Implementing Relevant BioDesigns

While the BioDesign activity in this workshop required learners to develop a project within a set of constraints (e.g., they were asked to devise a food product and product packaging), students had latitude to select their own design variables (e.g., the type of nutrient delivered in their food product and the materials that would make up their package designs). Rihanna

and Jade along with Nicholas and Allen were two pairs of students who provided illustrative insights into the ways in which students created BioDesign products that were personally relevant.

Jade and Rihanna had an interest in developing a cosmetic-related product. In fact, the two mentioned being interested in this as a career option, either in healthcare or something related. In coming up with an idea that was along these lines, the pair searched out potential ingredients. This involved researching, collecting, and discerning between relevant information. Ultimately, the pair ended up settling on a project that would address issues related to dermatological skin conditions. At one point, Rihanna revealed that she suffered from eczema (i.e., ectopic dermatitis) and had experienced—especially during the winter seasons—intense itching that was very distracting. As a result, she and Jade had decided to research and identify biomolecules that could be used to treat symptoms caused by this condition (see figure 11a).

Figure 11a. Jade researching causes of eczema (e.g., ectopic dermatitis).

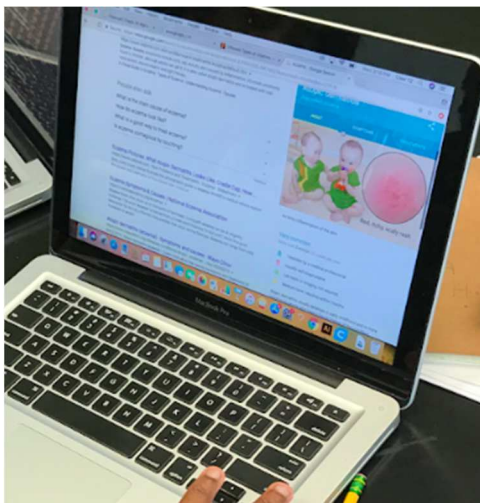


Figure 11b. Jade and Rihanna's 3D printed snowflake.



Figure 11c. Silicone mold used to bake a

Figure 11d. Snowflake-shaped cake

snowflake-shaped cake.



produced using mold designed by Jade and Rihanna.



In completing this research, the pair identified B12 as an important vitamin involved in relieving symptoms associated with eczema and so set out to design product packaging that was consistent with this theme; as Rihanna explained, “We chose this because I get eczema and it really itches. We [are] making a cake that helps stop the itching.” Here, Rihanna and her partner identified the rationale for their selection—which was primarily due to her personal experience with this condition. Later, as the two developed their packaging, Jade explained their selections for a cake mold shape: “We chose a snowflake because...because it represents the winter and you know snow...that’s when Rihanna gets the symptoms the most. We chose this type of blue because it looks like ice in the winter and it looks good too.” Here, Jade is explaining design decisions that are consistent with this idea about eczema and the effect it has on Rihanna.

The pair eventually 3D printed an object that was shaped like a snowflake and that would later be used to build a cast of their silicone baking mold and ultimately bake a snowflake-shaped cake (see figures 11b-c). Furthermore, the choices they made in terms of the shape and colors were all consistent with this idea (see figure 11d). This example

illustrates how much of the pairs' engagement coalesced around addressing an issue that was personally relevant—from firsthand experience, and in a way that was consistent with their expressed career aspirations.

In a different but similar instance, another student pair—Katana and Daniel—put together a BioDesign activity that addressed challenges associated with being vegetarian. While neither of the pair were vegetarian, themselves, they argued that being so creates a risk for malnourishment. And so, the pair set out to identify and catalogue related nutrients as reflected in Daniel's lab journal entries (see figure 12a).

Figure 12a. Daniel's lab journal entry.

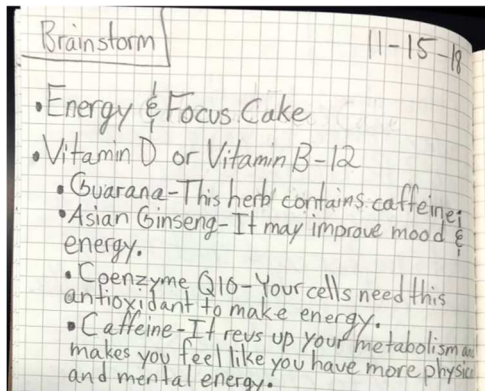


Figure 12b. Katana and Daniel's 3D printed soccer ball.



Figure 12c. Silicone mold used to bake a soccer ball-shaped cake.



Figure 12d. Soccer ball-shaped cake produced using mold designed by Katana and Daniel.



When asked about these final design decisions, Katana explained:

Okay, I'm doing a project with vegetarians because vegetarians don't get enough protein. As we know, they're vegetarians, so they don't like to eat meat. And people, everybody needs protein. And if you don't have protein, anything could happen. Your body could feel like you're weaker, you won't have as much energy as people who do eat protein. So we're making a cake with some iron and stuff in it, like the stuff that they need without them eating meat. So we're putting all the vitamins that they need to make them stronger. And not visibly stronger, but inside, healthier.

Here, Katana explained her team's design in the form of a justification in which she identified a need for vegetarians (i.e., protein consumption) and used that to justify her team's design of a synthetic biology based food product that contains the nutrient. To do so, Katana and Daniel planned to introduce these nutrients into their food product using a genetically modified yeast cell that produces specific nutrients (i.e., protein and iron). She then went on to explain that including these in a food product would further help mitigate the adverse effects of protein deficiencies. Katana and Daniel gathered these facts during research, but integrated them into their design choice explanations, which are related to the ingredients she selected and her pair's target group—vegetarians. Next, the pair selected and 3D printed a relevant object, a soccer ball, to signify the benefits this product would have for vegetarian athletes (see figure 12b). This object was then used to make a silicone mold that would ultimately be used to bake a soccer ball-shaped cake (see figures 12c-d) designed to provide nutrient supplements for vegetarians.

Both pairs presented here illustrate how learners were easily able to situate their BioDesign projects in topics that were personally relevant. Given the ubiquity of food and health, BioDesign afforded an opportunity for learners to engage with the field in a way

that was culturally relevant as reflected in their design decisions which, for other pairs, included considerations of mental health, vision health, and athletic health, to name a few.

3.5.2 Encountering and Problem Solving BioDesign Challenges

In addition to planning their BioDesign projects, students were asked to implement their designs using an array of materials used in baking and product packaging. This implementation included building silicone baking molds and product packaging. In carrying out these projects, students very often encountered challenges related to using some of these materials. To overcome these challenges, students very often (1) leveraged worksheets developed by workshop instructors to help with troubleshooting or (2) developed solutions of their own—problem solving techniques that were typical given the array of student designs. An illustrative example of a challenge wherein learners leveraged material resources made by workshop instructors included a pair—Simon and Dom—who set out to design a food product shaped like a football. Specifically, the group was observed struggling with assembling their cake mold and had previously used objects that created molds that were too shallow for baking, or that had not adhered to a cast appropriately.

When asked about this latter challenge, Simon responded:

- Researcher: Did you have any challenges along the way when you were trying to make your molds, or make your cake and stuff? Did you have to ask for help at all?
- Simon: Just because we had to ask a question why the hot glue gun was not working for this shoot. That's the only really that we did.
- Researcher: Okay. What was the hardest part about doing the activities?
- Simon: Really, it was just trying to find what solution would be better. Like, hot glue gunning it down, pushing it down-
- Researcher: You're talking about making your mold and anchoring the object inside the plastic?
- Simon: Yes.

- Researcher: Cool, alright. How did you go about deciding what you wanted to do?
- Simon: We first tried one option and saw if that works, because we wanted hot glue down it first. Then we [thought] that that was not working, so we went with option two that would probably turn out with a better one anyway.
- Researcher: Okay. So, you tried both of them and whichever one-okay.

Simon's team first chose to build and assemble a silicone cast using one of two suggested approaches provided by the science center outreach program. While Simon's team had the option of developing or using a different approach (i.e., one not provided by the science center outreach program), he and his partner chose to problem solve the issue using resources provided by the workshop instructors. The solution his team ended up selecting was a second option—also provided by the science center outreach program—which involved adding their cast object/shape to a pool of silicone that would cure around the object and create a shape. Simon and his partner problem solved this using a trial and error approach that depended—in part—on the object design they developed. When that approach did not work (i.e., the object would not adhere to the bottom of the container they were using) they solved this problem using an alternative option, instead of trouble shooting or designing another altogether. This resulted in a functional mold that would be used to successfully bake a cake designed as they had intended. This example illustrates challenges that were typical in this BioDesign activity, as students aimed for designs that were sometimes difficult to implement. In the case of Simon and Dom, the challenges they encountered with adhering an object in such a way as to produce a useful cast was solved using material resources available.

There were also moments when students encountered challenges that involved problem solving that required generating novel approaches not previously offered by

workshop instructors. This was the case for Nicholas and Mark, whose cake design (see figure 13a) required the construction of a silicone mold shaped like a lightbulb to reflect the product's support of brain health. The two attempted to achieve this by 3D printing the shape (see figure 13b), but Mark argued that the mold produced would be too small as he observed shapes produced by others. Mark also found it difficult to situate that shape in silicone such that it would produce a detailed mold. The two settled for using an actual lightbulb. They took this approach recognizing, as Mark noted, that "if this breaks, there will be glass everywhere." Here, Mark referenced the point when the two would need to remove the lightbulb from the silicone, which could have resulted in glass shards that could also inadvertently have gotten mixed into the cake during baking. When asked about how the team solved this problem, Nicholas replied:

- Nicholas: Combining the thing to make the silicone was fairly easy, but the hardest part was trying to get the light bulb to stay down since, like what we saw, it kept floating back up.
- Researcher: How'd you end up fixing that?
- Nicholas: So we used some of the putty that's used to mold. We put it on a part of the light bulb so that the knob part would stay down, and the rounded part of the light bulb would like a part of it would stay up but then it would be enough for it to mold.
- Researcher: Did that work out?
- Nicholas: Yeah, it worked really well.
- Researcher: How'd you prevent the glass from breaking inside the silicone?
- Nicholas: I don't really know. I just thought that it was just luck. When I cut it out I just went around the bulb and then I just stopped so that I couldn't cut into it, and then I tried to see if I could just like take it out. And I saw that it was loose. And then I remembered that, Oh wait. It's like a knob. It's like one of those things that you swivel clockwise, so I did that, and I took out the thing without breaking.

Initially, they decided to place their object into a pool of silicone (i.e., the approach Simon’s team ultimately used); however, they encountered problems associated with buoyancy. In other words, his object would not stay submerged. To troubleshoot this, Nicholas and Mark found some malleable putty and used it as a counterweight to keep their object submerged. They also wrapped their silicone cast with masking tape as an extra precaution to make sure the object would not float and ruin their design (see figure 13c). An added complexity was that the object they were using—a real glass lightbulb—was fragile and so they needed to figure out how to remove the fragile object from the cured silicone mold in a way that had not been provided by workshop instructors, who had not accounted for such an approach. To accomplish this, Nicholas and Mark observed that the object looked like a knob and so the team removed it by lifting and twisting it clockwise, like a doorknob. This plan worked and they were able to produce silicone molds that they later used in their test bakes (see figure 13d). Here, Nicholas and Mark encountered a challenge that had not been encountered before and, as a result, had to come up with a unique troubleshooting strategy. This strategy was ultimately based on the hypothesis that because the way the bulb was situated in the cured silicone was reminiscent of a knob, it could be engaged like a knob in order to be removed.

Figure 13a. Nicholas and Mark’s lightbulb cake design idea.

Figure 13b. Objects being considered for Nicholas and Mark’s silicone mold and cake design.

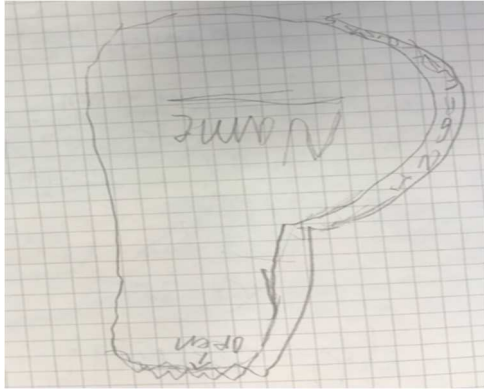
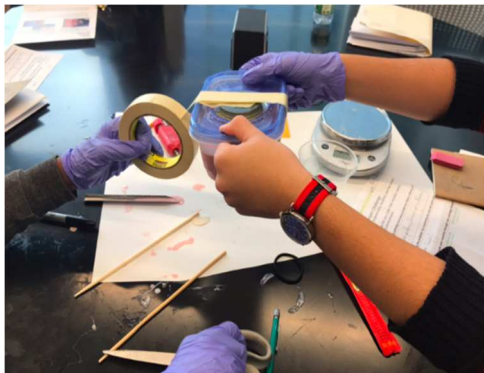


Figure 13c. Nicholas and Mark collaborating to solve a buoyancy issue with their object and silicone mold design.



Figure 13d. Silicone mold designs used for test bakes.



These examples illustrate how students in this BioDesign workshop problem solved through challenges that were both expected and resolvable using resources available and also unexpected, thereby requiring novel solutions.

3.6 Discussion

This research aimed to understand how middle school students participate in a BioDesign activity. It also sought to examine how BioDesign fits in active learning paradigms on science inquiry. This research addresses a gap in the literature concerning the ways in which life science subjects that use design based approaches fit in a science education landscape that emphasizes inquiry. Overall, findings suggest that BioDesign provides an

expansive entry into learning that is culturally relevant and personally meaningful. Findings also suggest that students were able to engage in such inquiry practices as (1) data collection and analysis and (2) problem solving when planning and implementing their BioDesign projects. These findings are discussed in order to provide insights about the inherent affordances and challenges of BioDesign with design science approaches in the life sciences. Future directions for research are also discussed.

3.6.1 Culturally Relevant BioDesigns

A major criticism of science education approaches that are guided by active learning strategies has been that these approaches often exacerbate the participation disparities that such an approach is meant to disrupt. This criticism has been met with calls for new approaches to science teaching that engage with the vast social and cultural perspectives learners bring to learning environments (Carter, 2008; Emdin, 2016). As a result, there have been efforts in science education research that examine ways in which to engage with the personal interests that diverse learners bring with them in their pursuit of science education (Lee, 2002). Life science education often involves the use of living organisms that must be handled using narrow and often rote procedures. This makes it difficult for learners to engage with the subject in ways that are personally meaningful.

This study provides insights into how design can bridge this disconnect between the somewhat prescriptive nature of the field with the expansive possibilities learners have to be creative. While genetically modifying yeast cells was an important part of the BioDesign workshop, it was, in many ways, eclipsed by activities that focused on producing objects that could hold these cells for their intended purposes (e.g., cake batter, silicone molds, etc.). Such a space, wherein organisms interact with inanimate objects for

the purpose of generating something new, is exactly what BioDesign creates in science learning. It was also the key to how learners in this study were able to be creative and vested in activities that reflected their personal interests. The fact that Jade and Rihanna could design and build a snowflake-shaped cake that contained a cell that they genetically modified is a reflection of the possibilities that BioDesign brings to science learning. Not only did this object mean something to the two students, in that it represented a real life experience for Rihanna, but it also represented an amalgamation of a complex set of science skills put to work. To be able to build something in a life science classroom that is personally meaningful and therefore culturally relevant is an important stride away from active life science learning that is mostly scripted and provides only limited freedom for personal expression.

This argument can be made for any one of the BioDesign projects represented in this study and is reflected in the array of very different products designed by students. From athletic equipment to lightbulbs, these representations in many ways reflect the various ways diverse learners come to know science and engage with it personally. In other words, students did not produce the same products, nor were they focused on arriving at some final or correct answer—outcomes that are typical of life science education. Instead, BioDesign created a moment for learners to occupy a learning space that involved the development of a product whose design features (e.g., cake ingredients, shape, and nutritional value) were centered around the cultural values of those for whom the designs were meant (Cross, 2001). This is akin to perspectives in making (Honey & Kanter, 2013) with one important distinction: these objects involved the use of living cells with constraints that are uniquely distinct from inanimate objects (e.g., circuits, electronics, etc.). Still, BioDesign provides

important contributions to science education in that it supports participation that is personally relevant and is embedded in practices that are interwoven with culture, science, and contexts that are reflections of practice (Brown et al, 1989; Harel & Papert, 2001).

3.6.2 BioDesign and Inquiry

In addition to examining the ways in which learners engage with a synthetic biology activity, this research aimed to understand how inquiry is taken up in BioDesign. Findings reported here suggest that practices that are typically characterized as involving inquiry (e.g., question formation, data collection, information synthesis, and problem solving) occurred throughout the workshop. This is significant given the importance of this type of active learning for science education and research (Bybee, 2006; NRC, 2012). In fact, the literature is replete with evidence that suggests this approach to learning supports positive outcomes in myriad STEM fields (Anderson, 2002; Slotta, 2004).

An insight that this research contributes to the canon of research on inquiry and life science is that for BioDesign inquiry is not disconnected from practice, but instead occurs simultaneously with activity. Dewey characterized this disconnection as “time-out” moments when learners pause to reflect about some piece of evidence before moving to re-engage with an activity (e.g., a science experiment) that is meant to promote learning (Waks, 2001). Instead, BioDesign involves inquiry that is connected with the activity. This also means that, in BioDesign, inquiry is not a vehicle used to arrive at some end but instead a tool in a whole set of tools that coalesce to help learners achieve a goal. For students in this workshop, this meant that researching and problem solving through challenges were practices afforded by inquiry, but leveraged to achieve their final BioDesigns. For Nicholas and Mark, a lightbulb made the most sense for their design as it served as a metaphor for

their food product. Seeking out information and problem solving through their challenges was just a means of actualizing that metaphor.

This suggests that, for BioDesign, inquiry can be characterized as one of many cognitive tools that learners use to explore, examine, explain and evaluate their ideas. In this way, BioDesign and inquiry overlap to create affordances that would be difficult to achieve with only one of the two. After all, inquiry alone does not necessarily account for or reflect recent advancements in biotechnology fields that leverage design. Similarly, it would be difficult for design to evolve without thoughtful investigations and reflections about the world, what already exists, and the cultural contexts within which design ideas are conceived.

3.6.3 Traditional Science Education and Design Science

Ultimately, this study situates design science in an existing milieu of active learning paradigms in science—namely, inquiry. Collectively, this research shows that inquiry—in terms of knowledge building and problem solving—is embedded in design science using synthetic biology. While there is significant science education research that reports on the affordances and challenges of inquiry, that literature does not include life science field advancements that rely significantly on design. Synthetic biology is one such field. This study presents a case in which middle school students used design science as a frame to learn synthetic biology. Previous research (Walker et al., 2018) has shown that this approach supports learning in traditional learning frameworks as measured by contemporary learning standards (NRC, 2012), but less research has examined the relationship between inquiry and design.

The BioDesign workshop reported here intentionally included moments for learners to experiment with materials and iterate through their problems—hallmarks of inquiry perspectives. Furthermore, the activity was intentionally situated in a culturally relevant context so as to provide opportunities to design solutions that reflect cultural and societal values—an important distinction in design science. In this way, this study illustrates how design science learning activities are congruent with traditional learning paradigms. Giving learners a chance to put their learning to use is, after all, the goal of all science education. In this regard, design science education is essentially just a reflection of the current era within which science as a field exists—a paradigmatic shift from inductively understanding the world and toward an approach that leverages these processes using design. Still, future research should examine ways to explicitly correlate the relationships between inquiry, problem based, and design science learning. Furthermore, future research should consider ways to leverage technology to capture student discourse (e.g., explanations) during the learning process in design science, which would provide insights into ways in which to scale assessment measures and better understand student learning.

3.7 Conclusions and Implications

This study presents a case in which middle school student explanations are examined to understand the nature of students' thinking when engaged in a biology based design science activity. Collectively, findings suggest that student explanations provide a viable method for assessing student design thinking—a measure of learning. Insights offered also suggest that student explanations prompted by specific questions about process and challenges provide insights into distinct types of design thinking students engage with in implementing design science projects. Importantly, this research also offers insights into

the ways in which design science is congruent with existing approaches to science education. A key affordance of this approach is that design science also supports learning in fields that reflect contemporary advancements in life sciences. While this case study only examines a small sample of students and their BioDesign projects, it illuminates insights about the distinct ways in which learners engage in life science inquiry and design activities. Future directions for research around process journaling, prompting, and design technology may provide important next steps for research on BioDesign and K-12 learning.

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4. A Case of Middle Schoolers' Use of Context to Explain and Justify their Attitudes About Synthetic Biology

4.1 Chapter Summary

Science education continues to be an international priority for reasons related to occupational and civic engagement. Yet, little attention has been placed on burgeoning biotechnologies such as synthetic biology—wherein cells or cellular materials are designed and then used for practical applications. This neglect is largely due to these emerging biotechnologies being previously deemed inaccessible to younger students. This research uses a mixed-methods approach to examine a group (n=16) of middle school students' arguments concerning their attitudes toward various synthetic biology-based applications. Nine of the students assessed participated in a synthetic biology based design workshop at a local science center; the others did not. Analysis of student explanations show that students leverage context clues to justify their perspectives. These findings suggest that learners use these clues—along with informal sources of knowledge—to make sense of and reason through their perspectives. Opportunities to support argumentation—a measure of reasoning and literacy—in emerging science fields like synthetic biology are discussed.

4.2 Introduction

Given the role and impact of science technologies on society and the environment, significant research has attended to the ways in which learning can support scientific literacy—the ability to engage critically with social issues surrounding science and technology (DeBoer, 2008; Hurd, 1958; Hurd, 1998; Roberts, 2007).-Scientific literacy is also important in informing the ways in which students evaluate new advances in science. One particular example of such is biotechnology—and its myriad benefits in such genetics-

based areas as medicine (Goeddel et al., 1979), agriculture (Barton et al., 1987), and the environment (Rojo et al., 1987), which have had significant impacts on society and the planet overall. Existing research has made considerable inroads into understanding what high school and middle school students know (Dawson, 2007; Lock, 1993) and think (Ozel et al., 2009; Usak et al., 2009) about biotechnologies and their various applications, as well as the various ways in which high school students use this knowledge to form cogent and well-reasoned arguments (Sadler & Dawson, 2012; Dawson & Venville; Sadler & Donnelly, 2006). While these perspectives provide important insights about student argumentation and reasoning, far less research has examined middle school students and their argumentation practices regarding biotechnology.

Furthermore, existing research has involved traditional biotechnologies that have—in the past decade—advanced considerably. An example of one such advancement includes a modern biotechnology known as synthetic biology—wherein cells are genetically modified to generate practical and useful behaviors or products, such as in the production of textiles (Adidas, 2019), construction materials (Ecovative, 2019), and chemicals such as vitamins or pigments (Kuldell et al., 2015). As a result, there is a gap in the literature concerning middle school students that owes in part to the fact that synthetic biology has previously only been accessible to sophisticated commercial and university lab environments.

To attend to these gaps in the literature, this study engages (n=16) of students in an urban public middle school located in the northeastern U.S. in order to address two research questions: (1) How do students' justifications change when provided context-specific details about synthetic biology and its various applications? (2) What considerations do

students make when justifying their attitudes toward synthetic biology and its various applications? Collectively, these questions provide important insights into science teaching and learning about modern biotechnologies using measures of literacy with and without formal knowledge.

4.3 Background

4.3.1 Argumentation in Life Science Education Research

As a result of efforts to support occupational participation and civic engagement to address these impacts, the literature is replete with studies that examine K-12 learning in biotechnology. One such line of research involves argumentation—an expressed form of cognitive reasoning (Erduran & Jimenez-Aleixandre, 2008). This research is of particular significance because argumentation is conceptualized as an important component and indicator of student reasoning (Sadler, 2004), literacy (Sadler and Zeidler, 2005), and decision-making (Sadler and Zeidler, 2003) in matters that often exist at the intersection of complex social and cultural dilemmas. As a result, much needed research has focused on the ways in which learners use information such as content knowledge (Sadler and Donnelly, 2006), evidence (McNeill et al., 2006), and affective perspectives (Sadler and Zeidler, 2005) to explain (Berland and Reiser, 2009; Sandoval, 2003), justify (Jiménez-Aleixandre et al., 2000), and/or reason (Zohar and Nemet, 2002) through their scientific positions.

Along this theoretical trajectory has been research that examines the various ways in which information, such as content knowledge, data, and opinions, mediates learning. Specifically, research has attended to the question of how learners reason through

information and the ways in which this information promotes communication practices, critical thinking and, ultimately, scientific literacy (Erduran and Jimenez-Aleixandre, 2007). In this framing, reasoning is often defined as the cognitive process by which learners evaluate claims, weigh evidence, and/or rationalize their perspectives about a particular idea. Because reasoning is a cognitive process that cannot readily be observed, research has focused on student argumentation—the various ways in which learners think through, explain and justify their perspectives (Berland & McNeill, 2011; Van Eemeren et al., 2004; Zohar & Nemet, 2002). The theoretical underpinnings of argumentation research originate from Toulmin models that examine discourse around the ways in which individuals use information such as data or knowledge to make claims, evaluate or rebut counterclaims, and draw or advance a conclusion (Toulmin, 1958). In science education, significant research argumentation has been examined in myriad fields and this has often included examination of content knowledge (Sadler & Donnelly, 2006; Zohar & Nemet, 2002), problem solving (Duschl & Osborne, 2002), inquiry (Sampson et al., 2011), literacy (Berland & Reiser, 2009; Bricker & Bell, 2008; Faize et al., 2018), and/or instructional design or pedagogy (Berland & McNeill, 2010; Garcia-Mila et al., 2013; McNeil et al., 2006; McNeill & Pimentel, 2010).

As biotechnologies have emerged in professional and educational settings, so has science education research (Dawson & Venville, 2009). In K-12 education, this line of research has sought to understand the complex ways in which learners reason through their attitudes toward biotechnologies and their various applications. Research from this perspective suggests a Threshold Model for argumentation among K-12 learners. Specifically, this model suggests that learners use science knowledge to understand a

particular biotechnology—a necessary step in forming an argument about a particular application. It further suggests that once a threshold of information is achieved or mastered (i.e., a learner understands what a question is asking on a survey or assessment), then the extent to which domain expert (i.e., science majors) and non-expert (i.e., non-science majors) students engage in argumentation is virtually indistinguishable. These findings have been replicated in a range of biotechnology contexts involving microbes, plants, animals and humans. Others have attributed these findings to the possibility that learners use alternative forms of knowledge that are not rationalistic (i.e., fact-based) to reason through their perspectives. These forms of knowledge have been characterized as intuitive and emotive—that is, based on informal intuitions or emotions, which are influenced significantly by sociocultural perspectives including religion, ethical-orientations, and personal experiences, to name a few (Sadler and Zeidler, 2005).

Despite these findings, far less research has examined informal knowledge or cognitive tools (e.g., intuitive and emotive) that learners may leverage to practice reasoning when formal knowledge is unavailable or not present. This perspective, though not widely studied, is consistent with Piagetian traditions that suggest that learners engage in a variety of cognitive dialecticals to support sensemaking that often involve the use of evidence and pre-existing theories to evaluate an idea (Erduran and Jimenez-Aleixandre, 2007). Therefore, research in this area is of particular importance for younger learners who, until recent decades, had little access to emerging fields such as biotechnology and—to an even lesser extent—formal biotechnology-based learning experiences, and yet have well-formed attitudes toward the field and have been shown to be developmentally able to reason critically through their perspectives (Kuhn, 1999). By examining how comparison group

students leverage intuition and emotion, it may be possible to design learning experiences that support advanced reasoning practices (i.e., argumentation practices), without needing to participate in advanced and rapidly changing biotechnology fields. This research attends to this gap in the literature by examining how middle school-aged students use context clues to justify their attitudes toward a modern biotechnology known as synthetic biology. In attending to this gap, it ultimately provides insights toward supporting scientific literacy among middle school-aged students.

4.4 Methods

This study examines a convenience sample of 16 middle school students in an urban city in the northeastern region of the United States. Of this sample, a group (n=9) participated in a hands-on synthetic biology workshop held at a local science outreach program. The remaining students (n=7) represented a comparison group who did not participate in the workshop. Students were conveniently drawn from two local public middle schools located in the same city. These schools, described in the next sections, were identified by a local science outreach center in the same city. Students were surveyed using an open and closed-ended survey and interview questions. Data were analyzed using descriptive statistics and qualitative descriptive coding.

4.4.1 Schools and Participants

The sample in this study is composed of 16 middle school students, 8 from each of two schools (GW Middle School and TR Middle School described below), ranging from 11 to 14 years in age. Students were selected conveniently from schools partnered with a local science center outreach program because they had participated in semi structured

interviews. Student age distribution included 1 eleven year old, 1 twelve year old, 8 thirteen year olds, and 6 fourteen year olds. Also, student grade distribution included 1 sixth grader, 2 seventh graders, and 13 eighth graders. Self-reported gender distributions included 8 female and 8 male students. Student racial distribution included 8 students who self-reported as black and 8 who self-reported as non-black. Of the sample, 7 students did not participate in a synthetic biology-based learning activity; this group is herein referred to as comparison group students. The remaining 9 students participated in 9 two hour weekly synthetic biology-based workshops held at a local science based outreach program in the same city. These students are referred to herein as experienced students. Student names were anonymized and presented as pseudonyms in this study.

GW Middle School is a K-8 school that enrolls 257 students per year, of whom 79 are in grades 6-8. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 63% black, 19% white, 11% other/biracial, 4% Asian, and 4% Latino. According to school district definitions, approximately 98% of students at GWM are considered economically disadvantaged, 22% are characterized as special education, and 2% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 recent academic reporting period, achievement scores on statewide standardized assessments found that 41% of students at GWM were rated as proficient in reading, 34% in science and biology, 16% in math and algebra. This was based on achievement scores on statewide standardized assessments.

TR Middle School is a 5-8 school that enrolls 361 students per year. As reported in publicly available demographic sources, the gender distribution for the school overall is 50:50 female:male and this varies marginally at each grade level. The ethnic distribution of students attending the school is as follows: 96% black, 2% Latino, <1% white, and <1% other/biracial. According to school district definitions, approximately 86% of students at TRM are considered economically disadvantaged, 14% are characterized as special education, and <1% are considered English language learners. These latter three categories are determined by definitions asserted by the local school district. In the 2017 recent academic reporting period, 33% of students at TRM were rated as proficient in reading, 22% in science and biology, 11% in math and algebra. This was based on achievement scores on statewide standardized assessments.

4.4.2 Workshop Design

The workshop implemented in this study took place over 12 weeks and included 4 sessions, each of which was held for 2 hours (or a total of eight contact hours) that focused on synthetic biology and attitudes toward the field, as shown in table 7. These activities took place in the middle and at the end of the workshop (i.e., during weeks 6-8 and 11). In week 6 of this study, experienced students were introduced to synthetic biology through viewing a short video and slide presentation. Then, experienced students engaged in a card game activity to learn about the various applications used in the field. Next, these students participated in a lab activity that involved genetically modifying and growing yeast cells that produce beta-carotene, a vitamin A intermediate.

During week 7, experienced students were introduced closely to an agricultural synthetic biology application and discussed as a class the risks and benefits to humans,

non-humans and the environment when carrying out synthetic biology applications. These students were then introduced to their performance task, which required they design and develop a baked product that used genetically modified yeast cells to fortify it with nutrients. This performance task was problematized with topics discussed earlier in the course.

During week 8, experienced students were introduced to four synthetic biology-based applications and asked to evaluate each in pairs and in terms of the application's risks and benefits. Then, these students discussed their considerations as a whole and continued developing their performance task product designs.

During week 11, experienced students presented their final BioDesign performance task product designs. They were asked to identify risks and benefits in the package labeling for consumer use. Together, these risk and benefit assessments and BioDesign activities, in which students used synthetic biology techniques to generate and use a genetically modified organism in a practical application, represented the context within which they engaged with synthetic biology.

During this time, the comparison group of students were participating in traditional elective courses available at their respective schools.

Table 7. Weekly workshop guiding objectives, questions and corresponding activities.

Week	Topics
6	Guiding Objective: Students will be introduced to synthetic biology in order to learn how it works and about its various applications.
	Guiding Questions: What is synthetic biology? How does it work? How is it applied?

	<p>Class Activity: Yeast cell transformation lab Present synthetic biology introduction video Introduce PowerPoint presentation about synthetic biology Play genetic transformation card game Review examples of synthetic biology-based applications in microbes, plants and humans</p>
7	<p>Guiding Objective: Students will be introduced to the potential benefits and risks of synthetic biology in order to learn how it impacts humans, non-humans and the environment.</p> <p>Guiding Questions: What are the human, non-human and environmental benefits of using synthetic biology in food-based products? What are the human, non-human and environmental risks of using synthetic biology in food-based products?</p> <p>Class Activity: Introduce BioDesign performance task Present synthetic biology risks and benefits video Introduce PowerPoint presentation about Golden Rice Guided Practice: Golden Rice risks and benefits think-pair-share</p>
8	<p>Guiding Objective: Students will collaboratively evaluate the potential benefits and risks of synthetic biology in order to learn how they uniquely impact humans, non-humans and the environment.</p> <p>Guiding Questions: What factors are important to consider when evaluating the risks and benefits of synthetic biology on humans, non-humans and the environment?</p> <p>Class Activity: Present four vignettes showing microbial, plant, animal and human synthetic biology applications Think-Pair-Share activity and reflections on each of four vignettes Begin final presentations to include implications section</p>
11	<p>Guiding Objective: Students will present final presentations that include a section on implications that assert risks and benefits of their synthetic biology application.</p> <p>Guiding Questions: What important benefits and risk information should be considered when using a synthetic biology-based application?</p> <p>Class Activity: Final Presentations of products and packaging</p>

4.4.3 Data Collection Instruments: Student Attitude Justification Survey

A decontextualized survey that was broad and asked students about their perspectives in limited detail (see table 8) was used to collect student justifications about synthetic biology based applications involving microbes, plants, animals, and humans. This question type I instrument was decontextualized and students were asked to justify their perspectives about a broad statement about synthetic biology applications.

Table 8. Student Attitude Justification Survey (Question Type I).

Justification Statement 1 (JS1)	Using the scale below, rate how much you agree with the following statement: I believe that it is okay to genetically modify microorganisms (like bacteria or yeast) for use in synthetic biology. Complete the sentence: I made my selection above about microorganisms and synthetic biology because_____.
Justification Statement 2 (JS2)	Using the scale below, rate how much you agree with the following statement: I believe that it is okay to genetically modify plants for use in synthetic biology. Complete the sentence: I made my selection above about plants and synthetic biology because_____.
Justification Statement 3 (JS3)	Using the scale below, rate how much you agree with the following statement: I believe that it is okay to genetically modify animals for use in synthetic biology. Complete the sentence: I made my selection above about animals and synthetic biology because_____.
Justification Statement 4 (JS4)	Using the scale below, rate how much you agree with the following statement: I believe that it is okay to genetically modify humans for use in synthetic biology. Complete the sentence: I made my selection above about humans and synthetic biology because_____.

4.4.4 Data Collection Instruments: Student Attitude Justification Interview

Students were also asked to explain their responses to the detailed synthetic biology attitudes survey (see table 2) they were given at the end of the workshop period. The

partially contextualized survey (i.e., question type II) asked them to review a survey list of synthetic biology-based applications that included a target organism and product and identified which on the list was least and most acceptable. Then, students were asked: (1) Tell me about your answers to the survey questions. Which on the list did you find the most acceptable? Why? and (2) Tell me about your answers to the survey questions. Which on the list did you find least acceptable? Why?

Then, students were asked to explain their perspectives about detailed examples of synthetic biology-based applications in contexts (i.e., question type III) related to the risks and benefits of each application (see table 9). Following each vignette, students were asked: (1) Would you support Modern Meadow? Why or why not? (2) Would you support Arctic Apples? Why or why not? (3) Would you support Quant Worm Industries? Why or why not? (4) Would you support CAR-T therapy? Why or why not?

Table 9. Student Attitudes Toward Synthetic Biology-based biotechnologies semi-structured interview questions (Question Type III)

[Microbial application] The Modern Meadow company has developed a type of leather that is not made from animals! They reconstruct DNA in bacteria to produce a protein (this is a transformation like you did in class). The protein is then processed into usable leather. A major advantage of this process that you can now have leather products without killing animals. However, the impact that this might have on the environment or living things is unclear. For instance, we don't know how these leather producing bacteria will affect normal bacteria in the environment.
[Plant application] The Arctic Apples company developed and sells apples that do not turn brown since they silence the enzyme in the cells of an apple that cause it to change color. If an Arctic Apple is bitten, sliced, or bruised, the skin still remains fresh-looking, which can decrease the number of apples thrown away for turning brown. This also means that the apple will last longer. However, the long-term effects of silencing this enzyme in apples is unknown.
[Non-human animal application] Quant Worm Industries developed a way to cheaply clean up pollutants in the environment. In order to do this, they must genetically-engineer a giant earthworm to hatch millions of babies in the soil of a coal mine for

example, which will all glow after consuming pollution (so you can see them after they have consumed a pollutant). This makes it easy to clean up these areas safely and in large quantities. That's the good news. The bad news is that afterward, miners have to dispose (and kill) of the millions of pollution-filled glowing earthworms.

[Human application] Recently, the U.S. Food and Drug Administration (FDA) approved a new form of cancer therapy that has shown promise in eliminating tumors where other treatments have failed. The therapy works by using parts of the HIV virus (which is good at entering white blood cells) to genetically-modify white blood cells to recognize and destroy cancer cells. This treatment has been shown to be beneficial in the treatment of blood, breast, and colon cancer in children and adults. Many experts in the field are calling this genetic engineering approach a new "pillar" of therapy because it does not involve rigorous chemotherapies or invasive surgeries. Others have criticized the approach because of its cost to consumers (which costs nearly 1 million dollars today) as well as the potential impact it may have on humans or other species if the HIV-derived cells mutate, which has not been known to occur in these contexts, but is understood to be a risk given the rise of mutant forms of flu and staphylococcus for example.

4.4.5 Data Collection Instruments: Survey

The survey was administered using Qualtrics—an electronic survey tool. All students completed the survey over the course of a one hour during an academic class period in a computer laboratory. The researcher administered the survey by providing instructions and answering clarification questions when students were unclear about survey language or when they encountered technical challenges (e.g., advancing to a proceeding survey question before completing all required questions on a page). Surveys were completed in approximately 30 minutes.

4.4.6 Data Collection Instruments: Interviews

Audio recorded interviews were administered by the researcher. Students completed individual interviews after completing the survey and questionnaire. The researcher answered clarifying questions when students were unclear about interview language. Interviews were completed in approximately 20 minutes. Interview question responses were subsequently transcribed using the Rev.com transcription service. Then, transcripts were imported into Dedoose, a qualitative data analysis software.

4.4.7 Data Analysis: Survey

Survey responses were aggregated into a spreadsheet and descriptively coded by two coders according to the code book provided in table 10. This code book was adapted from a widely used conclusion-based argumentation instrument (see table 11) developed by Hogan and Maglienti (2001) and used to examine high school student argumentation (Berland & Reiser, 2011; Osborne et al., 2004). Codes were applied independently and disagreements were resolved in order to reach 100% consensus.

Table 10. Attitude Justification Code book.

Level	Description	Example
0	Does not mention any relevant justification for attitudes.	“I don’t know” or “we’ve been starting to do that here at the science center and i think as far as I’ve done it’s been going pretty well!”
1	Mentions some relevant justification for attitudes. Also bases justification on agreement with personal inferences or views.	“I made my selection above about microorganisms and synthetic biology because transporting DNA can be for a good cause to help people with certain things In need.”
2	Mentions multiple justifications for attitudes. Primarily bases justification on agreement with personal inferences or views.	“[I find this acceptable] because we’ve done this before, and I don’t think it weren’t very acceptable that we would be allowed to do this as eighth graders and ...[also] because you’re adding healthy vitamins to something that may not have it.”
3	Mentions some relevant justification for attitudes. Does not base judgments on agreement with personal inferences or views.	“i disagree because if something was to go wrong and the plants die we have no more oxergyn.”
4	Mentions multiple justifications for attitudes. Does not base judgments on agreement with personal inferences or views.	N/A

Table 11. Conclusion Based Argumentation Code book (Hogan & Maglienti, 2001)

Level	Description
0	Does not mention any relevant strengths and weaknesses of the conclusion
1	Mentions some relevant strengths and weaknesses of the conclusion, but not the major ones. Also uses agreement with personal inferences or views as a basis for judging the conclusion.

2	Mentions some strengths and weaknesses of the conclusion, but not the major ones. Does not base judgments on agreement with personal inferences or views.
3	Mentions the major strengths and weaknesses of the conclusion, but also uses agreement with personal inferences or views as a basis for judging the conclusion.
4	Mentions the major strengths and weaknesses of the conclusion. Does not base judgments on agreement with personal inferences or views.

Responses in which the student indicated that they could not respond or responded “I don’t know” were given a score of zero. The same score was given to responses that were erroneous. Instances in which students provided one justification that was based on a personal view was given a score of one. If responses included more than one justification, each of which was based on a personal view, a score of two was applied. Instances in which students provided one justification that was not based on a personal view was given a score of three. If responses included more than one justification, each of which was not based on a personal view was given a score of four.

4.4.8 Data Analysis: Interview

Interview data was analyzed using a descriptive approach (Ravitch & Carl, 2015). Specifically, interview text was excerpted by question. Codes were developed to describe student responses as reflected in the code book provided in tables 10 and 12. The code book in table 12 was generated from categories identified by Črne-Hladnik and colleagues (2009). The author and another coder applied codes independently and resolved disagreements in order to reach 100% consensus. Next, illustrative examples were drawn from transcripts to provide more granular and contextualized interview responses.

Table 12. Attitude Considerations Code book.

Code	Definition	Example
Safety Concern	Instance in which student describes an immediate (or short term) concern for a single adverse application-related outcome.	“[No, because] I wouldn't want somebody to eat an apple that's already brown and then for them to get sick and then it falls on the company as the liability.”
Usefulness/ Utility	Instance in which student describes consideration of the immediate (or short term) benefits or utility of an application.	“STUDENT: I mean, I think it's a pretty great idea, because pollution is a really big problem in the world that we have now, and I never really usually see worms anywhere, but I do think I would support them. “
Risk/Benefit	Instance in which student describes both an adverse and beneficial outcome in an immediate (or short term) future involving an application.	“I suppose actually, I'm kind of in the middle for it, because since the good thing is that you won't have to kill animals for the leather because I love animals. There are people that love animals and killing animals just doesn't seem right, but the fact if there's a bacteria that could possibly affect other bacterias and probably bacteria, and probably cause a new disease or sickness to erupt.”
Long Term Impacts	Instance in which student describe a concern for an adverse or beneficial long term outcome.	“ No, 'cause like I said earlier, you can't really tell if it's aging, and, like you said, we can't really tell what the long term effects are on the apple.”
Other	Instance in which student describes a concern not related to adverse or beneficial outcomes.	“No, because it should be free 'cause why would you want to”

4.5 Findings

Findings are arranged in two parts. The first section addresses study research questions: (1) how do students' justifications change when provided context-specific details about synthetic biology and its various applications? and (2) how do middle school students justify their attitudes toward synthetic biology and its various applications? Quantitative and qualitative data are provided to summarize student responses and provide qualitative context.

4.5.1 Student Justifications When Context Details Increase

In this study, students responded to survey and interview questions related to synthetic biology applied to microbes, plants, animals, and humans. There were three categories of question type (i.e., I, II, and III) that varied by the degree of context provided in the question and ranging from the most decontextualized (i.e., question type I), to somewhat contextualized (i.e., question type II), to the most contextualized (i.e., question type III). Findings reported in the next section are organized by question type, grouped by student, and detailed below.

4.5.2 Justification Quality with Minimal Context Clues

With regard to question type I, in which students were asked to explain their ratings toward microbial, plant, animal, and human applications, responses included various justifications for their attitudes. For microbial-based applications, this most commonly included one or more justifications related to personal inferences or views. King pointed to a personal inference about synthetic biology benefits when he wrote, "I made my selection above about microorganisms and synthetic biology because transporting DNA can be for a good

cause to help people with certain things in need.” Here, King provided one justification—human benefits—that is not explicitly based on any formal data, knowledge, or facts. Nicholas provided a similar insight when he noted, “I am fond of the way we can improve our lives and our world by modifying microorganisms and other forms of life. However, I’m still concerned about the unknown risks we face when dealing with this topic.” Nicholas explained: (1) his fondness for the benefits synthetic biology applications have for humans and the world, as well as (2) his concern for the risks that may emerge with its use. Both King and Nicholas’s responses provide illustrative examples of workshop student attitude justifications that did not include any formal data, knowledge, or facts.

A similar outcome emerged in response to plant applications, and was reflected in Sims’s response, “we don't want to treat a plant like it's not like humans too.” Here Sims’s one justification using a comparison between plants and humans does not—again—reference any explicit formal data or knowledge. Similarly, Nicholas provides a detailed justification for his position when he wrote, “Plants have certain qualities and traits that can be incredibly useful for tasks or other things. However, the problem of a genetically modified plant spreading and taking down other plants in its way (which may sound far-fetched) is a possibility.” Nicholas’s justification involves a consideration of the benefits and potential risks or “problems” plant-based applications of synthetic biology may pose. For plant-based applications, one workshop student provided a justification that was not based on personal inferences or views. This came from Keturah when she wrote, “i disagree because if something was to go wrong and the plants die we have no more oxergyn” The reference to oxygen here refers to a biological human need that would be eliminated if plants were adversely harmed using synthetic biology.

For animal-based applications, experienced students included justifications that were—like microbial applications—based entirely on personal inferences or views. This is evidenced in Sims’s explanation as he noted, “[i]t can help animals for the better not to wipe them out.” Sim provided one justification that was based on his personal views concerning the benefits this technology would pose for animals. Similarly, Nicholas’s answer provided multiple justifications based on his personal views or inferences as he wrote, “Animal lives can greatly improve and in return, genetically modified animals have the possibility of helping humans as well. But the cost is that these animals can possibly get slaughtered.” These justifications included: (1) mutual human-animal benefits and (2) the costs (i.e., risks) to animals if animal-based synthetic biology applications are used too often.

Regarding human applications, experienced students included justifications that were based entirely on personal inferences or views. This is reflected in Nicholas’s response when he noted a risk: “genetic modification of a living human sounds and is risky since there are a lot of unknown factors that may be faced during the process.” King provided a similar justification for the benefits when he wrote, “I chose this because helping humans that something could possibly help us live longer is always good.” Like Nicholas and King, all experienced students who could respond regarding human-based synthetic biology applications included only one justification.

There were also instances in which experienced students could provide no justification, including: 33% (n=3) for microbes, 22% (n=2) for plants and animals, and 11% for humans. These were instances in which experienced students answered “I don’t know” or provided an incomplete or erroneous response like, “i just agree” or “we've been

starting to do that here at the science center and i think as far as I've done it's been going pretty well!”

For question type I, comparison group students’ responses included explanations for their attitudes toward microbial, plant, and animal applications that only included one justification and were based on personal inferences or views. For instance, when asked about microbial applications, students wrote, “its okay if they do this because it can be used to help people with natural things,” “I agree because bacteria and yeast might be disgusting but it has to be used in synthetic biology,” or “i dont think its right that u modify mirco organisms for synthetic biology.” These examples reflect instances in which student justifications were based on their personal views about microbial-based synthetic biology benefits to humans, what is disgusting, or morally acceptable, respectively.

When asked about plant applications, comparison group students wrote, “[I’d] say no because plants have a big effect on the world and if something happened to them the world could,” “i made my selection above bout plants and syntheic biology because i don tthink science and plants dont work good togther,” or “I agree because plants need to be tested.” These justifications were wholly based on personal views or inferences related to opinions about broad risks of using synthetic biology on plants, the relationship between science and plants, and the need for plant testing.

When asked about animal applications, comparison group students submitted, “no because animals have a big effect on the world,” “i dont think animals and science mix together,” or “its not okay because it can cause harm to the animals.” Similar to explanations for plant-based synthetic biology applications, student justifications were wholly based on personal views or inferences related to opinions about broad risks of using

synthetic biology on plants, the relationship between science and plants, and—uniquely— a concern for animal welfare.

Finally, when asked about human applications, comparison group students asserted similar justifications relating to risks to humans; as one student wrote, “its not okay because you don't know the long term risks of these things on humans.” Others replied with consideration of the relationship between science and humans and human welfare. All remaining responses included instances in which comparison group students provided no justification including: 57% (n=4) for microbes, 43% (n=3) for plants, 29% (n=2) for animals and humans. These were instances in which comparison group students answered “I don't know” or provided an incomplete or erroneous response like, “humans shouldnt have anything to do with this” or “i think it would be ok for plants.”

4.5.3 Justification Quality with Limited Context Clues

With regard to question type II, which asked students to explain their most and least favorable rating overall, all workshop student explanations about either microbial, plant, or animal applications included justifications that were based on one or more personal inferences or views. Experienced students gave responses that included one justification such as, “because I feel...if we all have a goal in life...we don't need exactly, like down to the DNA, to be able to...be better than someone.” This was in response to the question of whether or not it is acceptable to genetically modify a child or adult for aesthetic or elective purposes (i.e., to be stronger or smarter). No workshop student replied “I don't know” or provided an erroneous response for this question type. King also offered a detailed justification when asked about using synthetic biology to treat a child or adult for a genetic disease as he explained, “I think it's acceptable because everybody is not born the same,

and if it would be better, if everybody was born like the same so other people wouldn't have different challenges to face or something so their life wouldn't be harder, and it'd just be all equal." Here, King is using moral evaluations to justify his position, arguing that such an application would eliminate differences and—ultimately—the challenges individuals face as a result of those differences. With regard to question type II, experienced students also provided explanations that included more than one justification, as illustrated in Dylan's response about genetically modifying yeast to produce vitamins to be used in food as he explains, "[I find this acceptable] because we've done this before, and I don't think it weren't very acceptable that we would be allowed to do this as eighth graders and ...[also] because you're adding healthy vitamins to something that may not have it." Here, Dylan explained that this application is acceptable because (1) the risks are low—as reflected in the fact that middle school students in his workshop carried out this exact process—and (2) because adding a nutrient or "healthy vitamin" is ultimately a benefit.

With regard to students who did not participate in the workshop designed for this study, 39% (n=2) of explanations about microbial, plant, or animal applications included justifications that were not primarily based on personal inferences or views. This is illustrated in Tianna's reply when she commented about the use of synthetic biology in yeast in the production of animal food: "I find it acceptable because animals need, yeast, and fruits, and vegetables to live off of and also to survive." Here, Tianna explained that this use of synthetic biology supports a biological need for animals to survive and is not based on any personal view or inference. All other explanations included a justification based on a personal inference or view. This is illustrated in Saafir's explanation concerning

the use of synthetic biology to genetically modify plants to detect soil pollutants when he said, “that was the most acceptable because it wouldn’t have a bad effect on a person.” Here, Saafir is considering the impact such an application would have on humans as the justification for his attitude. There was one instance in which a non-workshop student replied “I don’t know” or provided an erroneous response.

4.5.4 Justification Quality with Detailed Context Clues

Regarding question type III, which provided students with detailed context about synthetic biology applications, all workshop student responses provided justifications for attitudes toward microbial, plant, and animal applications that were based on one or more personal views or inferences. For microbial applications, 44% (n=4) of experienced students provided a justification that was based on a personal inference or view. All remaining responses (n=5) included justifications that were based on more than one personal inference or view. This is illustrated in Sims’ detailed explanation:

No, because there’s good bacteria and bad bacteria. If it only affected bad bacteria, I would be fine with that because basically, it’s just over dominated the bad bacteria, so we really don’t have to worry about that, but if it affects both, there’s going to be something wrong. Because, you know, amoebas, they absorb abilities from other cells, so if those bacteria are able to absorb bad bacteria abilities, then people could be getting sick.

Sims explained that he disapproved of microbial based applications because of his concern for what he termed “good bacteria” and the potential impact such an application would have on those types. He also explained that it is possible for bacteria to transfer traits after having gone through the synthetic biology application (i.e., being genetically modified) and that this could also have adverse outcomes.

For plant and animal applications, 56% (n=5) of experienced students provided justifications that were based on personal inferences or views. This is illustrated in Dylan's reply in which he explained about plant applications of synthetic biology, "I don't think I would because just because it looks fresh doesn't mean it is, right? It could be completely rotten, but it looks fine. It's like if I had a cut in my stomach where it wasn't on the flesh, it was an inner wound, then you wouldn't see that. You'd think I was fine. But I think I'd be dying, right?" Here, Dylan uses a metaphor to explain his justification of his disapproval of synthetic biology being applied to a plant—in this case an apple that would later be consumed. All remaining responses (n=4) included justifications that included more than one personal inference or view. Keturah's reply is illustrative of this as she explained her indecision, "Yes and no, maybe. Yes because it does help the environment, it make sure that our lungs are not infected by then again no, because worms help the soil and without soil being good we cannot grow plans and be able to eat vegetables and stuff." Keturah justified her uncertainty as she weighed the benefits to humans against the effects animal applications of synthetic biology would have on food chains. For human applications, 75% (n=6) experienced students provided justifications that were based on a personal inferences or views. For instance, as Hodges explained, "No, because it should be free cause why would you want to...you should want to give it to them, like give back to the people." Hodges justified his disapproval of the human-based application of synthetic biology in terms of the economic costs such an application would have for consumers. All remaining responses (n=2) included justifications that included more than one personal inference or view. There were no instances in which a workshop student answered "I don't know" or provided an erroneous response. However, one student declined to provide a response for

the human-based application. Similarly, all comparison group student responses provided justifications for their attitudes toward microbial, plant, and animal applications that were based on one or more personal views or inferences.

For microbial applications, 86% (n=6) of comparison group students provided justifications based on personal inferences or views. This was evidenced by comments like: “I would because they ain’t killing animals no more,” “Yes, because I eat animals...if we could figure out a way to use that to our benefit, then why not”, or “I would say no...[because you could get sick].” These responses reflect student justifications in consideration of: (1) animal impacts, (2) human benefits, and (3) human risks. The remaining response (n=1) included a justification that was based on more than one personal inference or view.

For plant applications, 71% (n=5) of comparison group students provided justifications based on personal inferences or views. An example is Tianna’s reply in which she commented on synthetic biology being applied to an apple food product, “I wouldn’t want somebody to eat an apple that’s already [aged] and then for them to get sick and then it falls on the company as the liability.” Here, she considered risks and liabilities in her justification. All remaining responses (n=2) included justifications that were based on more than one personal inference or view. This is reflected in Michaela’s response when she explained, “No. Because you don’t know the long term effects, and it could be unhealthy or harmful to humans to eat.” Michaela was considering the impact in terms of both human health and harm.

For animal applications, 43% (n=3) of comparison group students provided justification that were based on personal inferences or views, as evidenced in Donovan’s

point, “I would support it cuz it clean the pollution.” Angel expressed a similar justification as she explained, “Yes. Because there’s other worms out there, so it wouldn’t be bad just to throw a few worms away...at the same time, you still can clean out the dirty stuff in the sewer.” Both of these examples show students supporting an animal application because of the environmental benefit its use affords. All remaining responses (n=4) included justifications that were based on more than one personal inference or view. An example is Michaela’s explanation for her disapproval of animal applications of synthetic biology when she noted, “No. Because you’re killing the worms and worms are also used for other things and you’re killing them here.” Michaela justified her disapproval based on the impact the application would have on worms, which also serve as food web decomposers. Libby made similar points as she explained, “it would be a waste, because a worm could be [used for] gardens and everything. They help some plants grow, and everything.”

For human applications, 43% (n=3) of comparison group students provided justifications based on personal inferences or views, as illustrated in Saafir’s point about human-based synthetic biology applications, “no, because there’s not enough details about what the after-effects would be.” 57% (n=4) of comparison group students provided justifications that were based on more than one personal inference or view. There were no instances in which a workshop student answered “I don’t know” or provided an erroneous response.

4.5.5 Student Justifications for Attitudes Toward Synthetic Biology Applications

In order to ascertain the various ways in which students in this study justified their attitudes toward synthetic biology and its various applications, students were read a vignette describing a particular application of synthetic biology (as shown in table 9) and asked to

describe their attitudes toward that application and explain why they held that perspective. In general, students were evaluated in terms of whether or not their responses included consideration of: (1) safety concerns, (2) usefulness or utility, (3) risk/benefits simultaneously, and (4) long term impacts. These a priori categories were considered mutually exclusive and assessed accordingly. The following findings are organized categorically by application type.

4.5.6 Student Considerations Regarding Microbial Applications

When asked to explain the reasons for their attitudes toward microbial-based synthetic biology applications, students responded using consideration of (1) safety concerns, (2) usefulness or utility, and (3) risks/benefits, simultaneously. An example of a safety concern emerged as Natasha explained, “no, because they don't What if it spread and kill people? If you wearing a jacket, right, and it's made out of that, it could break out that person's skin and cause ... yeah.” Here, Natasha explained that the leather generated by synthetically developed bacteria could pose human harm. Other students had similarly specific concerns about the potential harm to humans, including such outcomes as: sickness or disease, allergic reactions, mutations that create harmful bacterial strains, the spread of harmful bacterial strains, and potential adverse environmental effects. In contrast, a student asserted a point about the potential benefits this technology could pose; Dylan explained, “I think I would [support this application] because I eat animals, but I also want to save more animals so that I could eat them, so I would support it because there's bacteria everywhere, and you know, if we could figure out a way to use that to our benefit, then why not.” Here Dylan points to several human benefits of using microbes to produce leather, which is ultimately based on the potential to reduce animal harvesting for the sole

purpose of producing textiles (i.e., leather)—so that humans have more livestock (i.e., meat) to consume. Other students expressed simultaneous considerations of risks and benefits of using a microbial-based application of synthetic biology. This is illustrated in Natasha’s response:

I suppose actually, I'm kind of in the middle for it, because since the good thing is that you won't have to kill animals for the leather because I love animals. There are people that love animals and killing animals just doesn't seem right, but the fact if there's a bacteria that could possibly affect other bacterias and probably bacteria, and probably cause a new disease or sickness to erupt. That's where I'm really in the middle with this.

Natasha presented a perspective that considered both the benefit of using a specific application of synthetic biology on microorganisms and a counter perspective involving the risk of this for humans.

4.5.7 Considerations Regarding Plant Applications

With regard to plant-based synthetic biology applications, students justified their perspectives using considerations that involved (1) safety concerns, and (2) risk/benefits simultaneously, and (3) long term impacts. For instance, Katana—who was opposed to an application involving apples—explained, “No, because there are better ways to not make an apple turn brown. I usually put lemon juice on my apple when I'm done, if I'm not finishing it all. Put lemon juice, stick it in the refrigerator, it doesn't turn brown. That's the healthy way of doing things. People don't think the natural ways.” Katana expressed concern for the potential side effects of using synthetic biology to genetically modify a plant for consumption. She went on to provide alternative approaches consistent with her claim/concern. Other students expressed similar sentiments that were primarily concerned with human health and the potential for such an application to cause sickness. Keturah

responded with an explanation that involved consideration of both the risks and benefits of the same specific plant-based application of synthetic biology as she explained, “I mean yes and no, because then it would be less food waste, which would make more food for more people so that would kinda end the world hunger problem. But then again no, because you don't know what side effects can happen after eating it, you don't know if you could become sick or you don't know how long the apple was sitting there.” Keturah was considering both the food security benefits such an application would provide and the adverse outcomes it could have on humans. In addition, students commonly asserted explicit considerations for the potential long term impacts synthetic biology applications on plants could have in terms of impact on human safety, as illustrated when Donovan explained, “it might hurt your body and next week, a couple weeks later you get sick.” Other students expressed similar concerns about long term effects.

4.5.8 Considerations Regarding Animal Applications

Regarding animal-based synthetic biology applications, students justified their perspectives using considerations of (1) safety concerns, (2) usefulness or utility, (3) risk/benefits simultaneously, and (4) long term impacts. Marcus’s explanation provides an illustrative example of a consideration that weighed safety concerns—in this case for animal well-being as he noted concerning the use of synthetic biology applications in animals to remediate the environment, “no. because it's killing...it's killing them for no reason. Well, [inaudible] you're sending them to the sewer to eat pollution but you're going to kill it eventually, so no.” Here Marcus’s explanation is directly related to his concern for animals in this application—a response that is consistent with egalitarian perspectives. On the other hand, Nicholas’s explanation in support of an application using animals to

remediate the environment illustrates how students justified their perspective about its benefits as he noted:

I would support it. Especially because worms at this point they're not really close to extinction. Or endangered. Being endangered. And the fact that you could use these worms to remove pollution especially in sewers or in the environment. It's really helpful, so just killing off things like worms I really feel like that wouldn't really be that bad. So I definitely feel like I would support it.

While Nicholas expressed a consideration for the animals being used in this application, his acceptance of this application is a result of the benefit he perceived would result overall—a response that is consistent with utilitarian perspectives. Other students expressed similar explanations. Students also considered the risks and benefits of such an application simultaneously. This is evidenced when Sims explained, “For me, it's kind of in the middle...I would kind of support it, kind of not because it's easy to clean up the environment very fast, so they'll eat any type of pollution, plastic, and waste. That's one reason why I would support it, but the half of me saying I would not support it is because, basically, you have to destroy the worms.” Sims was acknowledging the benefits of this animal-based application in remediating the environment, but expressed concern for adverse impacts such an application would have for the animals being used. As a result, he indicated being “in the middle” with his perspective. Other students had the same balanced concerns for the environment and animals in the specific application presented.

4.5.9 Considerations Regarding Human Applications

Students were also asked about a specific human-based application of synthetic biology. With regard to this application, students justified their perspectives using considerations that involved (1) safety concerns, (2) risk/benefits simultaneously, and (3) long term

impacts. When advancing explanations that involved safety concerns, students considered such adverse outcomes as therapeutic side effects, mutations, and disease in humans. An example of this is Natasha's explanation:

No, because there's not enough details about what the after-effects would be...because a couple of thoughts ran in my mind. So you're using the HIV to reprogram the white cells to fight cancer, so what if they just fight cancer and not fight any other sickness that a person may get? And they won't be able to fight those things off but you can fight the cancer off and that won't be good because you're ... Like us, that's suppose to fight any, every type of sickness off. And another thing is, that's in my mind, the biggest thing having two really bad sickness in one, Both can, or have the ability to kill you, so why put both of them in you at the same time? It just doesn't sound right. It doesn't feel right.

In this instance, Natasha pointed to multiple safety concerns in the use of a specific application of synthetic biology in humans. All of her considerations were around the potential harm such an application could have on human life. Other students expressed consistent concerns. Contrastingly, Sims' explanation included consideration of both the risks and benefits of such an application as he noted:

Yes, and no, because the mutation part, if that's a good mutation, then it can probably make it even stronger if the cancer is stronger, and if that does not happen, then that would be a clear no. No, because honestly, why do you want to charge people a bunch of money when they're already starting to die? Honestly, it should honestly, be for free for people who have this stuff, if you have insurance, for free. Honestly, it should just be for everybody. If they do get cancer, it's wiped out immediately.

Here, Sims addressed a concern about potential mutations that could emerge in carrying out such an application, but framed it as a potential benefit. He went on to point to financial consequences as an adverse concern affecting this "yes, and no" perspective. Others had similar explanations that included cost-based justifications as either risks or benefits, as illustrated in Natasha and Sims' explanations

4.6 Discussion

This research aims to examine what a group of middle school students think about synthetic biology and its various applications. It also seeks to understand the various ways in which these younger students justify their perspectives, as well as the role context clues may play in supporting their ability to articulate such explanations. Overall, findings suggest that: (1) these younger students were able to assert justification patterns typically observed in older student groups who tend to be more knowledgeable on the subject, and (2) when students were provided increased context clues in the form of vignettes, justification pattern differences between knowledgeable and comparison group students looked similar. These findings are discussed in detail below.

4.6.1 Context Clues and Argumentation

A central aim of this paper is to examine how middle school student justifications change when context clues are provided about an application. This goal is to address the need in science education to develop occupationally and civically literate stewards of the field. Because attitude justifications have previously been conceptualized as being an important component of argumentation, an approximation of student reasoning (Erduran and Jimenez-Aleixandre, 2007), it has been a focal area of study of student learning and literacy (Cavagnetto, 2010). Accordingly, findings in this study suggest that middle school students, who had little to no formal instruction about synthetic biology and its various applications, but had well-formed attitudes toward the field, used context clues to explain and justify their perspectives. This is evidenced when making qualitative within-group comparisons of student explanations across three question types, each of which provided progressively more context. Specifically, students in both the workshop and comparison

groups were often unable to provide any justification for their attitudes when asked to explain, in broad terms, whether or not they found a particular application acceptable (e.g., microbes, plants, animals, or humans). This occurred less when students were given a more contextualized question (e.g., the use of bacteria to produce a pigment or textile such as leather), and not at all when students in both groups were provided a detailed description of an application in the form of a vignette (see table 9). This finding suggests that learners may use context clues to explain their attitudes toward the field when no formal knowledge or instruction is available.

Also, when qualitatively comparing workshop and comparison groups (i.e., a between-group comparison), this study found that when students were asked to explain their attitudes using a broad and decontextualized (e.g., type I) question, comparison group students more frequently indicated they did not know how to respond, did not understand the question or provided an erroneous explanation. This finding is consistent with the “Threshold Model of Content Knowledge Transfer” described by Sadler and Donnelly (2006). This model suggests that individuals require a limited threshold of knowledge in order to understand and respond to a particular question. Once that threshold is met, the difference between individuals with a basic understanding and an advanced non-professional understanding of a question becomes indistinguishable. Sadler and Donnelly found that high school students in these groups (basic and advanced) were able to attain similar levels of argumentation quality. Furthermore, qualitative group comparisons revealed that students in the workshop group had a more varied range of justification quality when asked in broad terms (i.e., type I questions) about their perspectives. Taken with the previous finding that workshop group students were more often able to describe

and provide examples of synthetic biology, this suggests that content knowledge (or past learning experiences) may have been leveraged differently as compared to those students with less content knowledge and who could otherwise not have provided viable justifications for their opinions. Sadler and Zeidler (2005) have also suggested that learners may use personal experiences and—importantly—context to situate their perspectives. Findings in this study also suggest that once those perspectives are situated in a context, workshop and comparison group students primarily use intuitive and emotive forms of knowledge to explain their justifications. This is evidenced by the fact that few to no students used any formal fact or data to justify their positions, but they had a variety of justifications grounded in a myriad of moral or ethical considerations.

Taken together, these findings not only suggest that providing comparison group students context clues provides a viable way to make learning advanced topics like synthetic biology more accessible, but it also provides opportunities for younger learners to engage in argumentation practices that involve intuitive and emotive forms of informal reasoning and that have previously been shown to be instrumental in supporting scientific literacy for occupational and civic participation.

4.6.2 Student Justifications

This study also sought to examine the various considerations middle school students included when justifying their attitudes toward synthetic biology and its various applications. This is in order to address the gap in the literature on factors that may influence younger-aged student perspectives. The findings in this study suggest that students make distinct considerations when explaining their attitudes toward synthetic biology applications which are aligned with studies of high school students (Dawson, 2007;

Dawson & Schibeci, 2003; Lock & Miles, 1994). These considerations appear to depend on context and are similar to those observed in high school-aged student groups. Specifically, Črne-Hladnik and colleagues (2009) reported that high school-aged students consider such factors as safety, utility, risks, benefits and overall impacts when evaluating a given biotechnology application. Using findings reported by Črne-Hladnik and colleagues (2009) as an a priori coding scheme, findings suggest that students in this study make similar considerations about microbial and animal-based applications to those about plant and human-based applications. Specifically, students in this study primarily considered (1) safety, (2) utility, or (3) risk and benefits simultaneously when explaining their perspectives about plants and animals—wherein long term impacts were considered the most. When considering what may account for these considerations, a closer examination of instrument constructs may provide a clue. Specifically, synthetic biology-based applications in the current study include elective applications for humans and biosensing applications in plants. These applications are distinct from those used in prior research and thus harken back to the need to update instruments to include a wider and more expanded range of applications which have even broader impacts on society and in myriad ways. Interestingly, students seemed to situate their justifications in egalitarian, utilitarian or mixed orientations. This was reflected in student responses that primarily considered application safety concerns, utility, and risk/benefit.

4.7 Conclusions and Implications

An important conclusion of this research is that modern biotechnologies such as synthetic biology provide an important vantage point into student learning toward occupational and civic engagement. Because of this, much research is needed to understand how to support

literacy in this rapidly growing field, and particularly in younger students who are increasingly able to access the field in both formal and informal learning environments. This research shows that younger students not only have well-formed opinions about the field, but make thoughtful moral and ethical considerations that are typical in older students. Furthermore, this research suggests that a viable way to support argumentation practices that are essential to scientific literacy would be to situate learning in contexts that provide learners with a meaningful perspective from which to construct their ideas, explanations, and justifications. This requires opportunities for learners to leverage their various ways of knowing while at the same time supporting opportunities for them to make intersectional and critical considerations about modern biotechnologies and the ways in which they affect society and the planet. While this research only examines a small number of students, it provides insights into how even middle school students can engage with complex biotechnologies. Future research should examine more closely the relationship between application context, argumentation and learner ethical orientations in order to better understand how to support intellectually and socioculturally diverse learners and move toward occupational attainment and civic literacy.

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5. Future Directions: Middle School Student Science Education and Synthetic Biology

5.1 Chapter Overview

The findings presented in this manuscript collectively address three overarching research questions concerning a group of middle school aged students' knowledge, attitude, and synthetic biology inquiry. These questions include an assessment of what students know about synthetic biology as reflected in their ability to define, describe, or provide examples of the field and/or its various applications. Along this theme is also an inquiry into what this same group think about synthetic biology and its various applications. A second line of inquiry in this collection of papers is organized around the ways in which middle school students engage with BioDesign. Research along this idea examines how this approach to synthetic biology provides opportunities to engage in scientific inquiry that is driven by design. Thirdly, this research assesses a subset of middle school student justifications for their perspectives on various synthetic biology applications, as well as how context clues relate to the nature of those justifications. The following sections are organized along these three lines of inquiry, as overall findings are summarized and then discussed. Together, these ideas illuminate insights into the state of student knowledge and perspectives, the potential added value design offers in contemporary life and science learning, and the various ways in which context clues support argumentation practices (e.g., justifications).

5.2 Middle School Student Knowledge and Attitudes

Research presented here on middle school student knowledge suggests that students examined in this study knew very little about synthetic biology and its various applications. This was reflected in their limited ability to define, describe or provide examples of

synthetic biology. In fact, survey results presented herein suggests that at least nine out of ten students could not describe the field, or, to a lesser extent, provided incorrect or erroneous descriptions. These findings were consistent in semi-structured interviews. And, within the group of students who provided correct responses, there were at least two instances of interviewees admitting to having used clues from the survey instrument to deduce that synthetic biology was “like DNA, and changing things.” In short, middle school students examined in this research knew very little about the field despite its increasing societal presence. This finding is expected because middle school students do not typically learn about specialized life science topics related to biotechnology. Moreover, when those topics are discussed, they are typically treated as optional.

While research presented here shows that middle school students know very little about synthetic biology, when asked about various applications of the field, students had well-formed opinions that varied in terms of the organism to which the technology is being applied and the outputs being generated. Specifically, just over half of students surveyed indicated they were accepting of microbially based synthetic biology applications, overall. Marginally more students were accepting of applications involving the production of animal and human food products, whereas fewer thought it was acceptable to use synthetic biology on microbes to generate manufacturing materials such as textiles or dyes.

Similar findings emerged for animal and human based synthetic biology applications—in that a little more than half of students surveyed thought that these applications were acceptable. A closer analysis of responses regarding animal applications revealed that students were marginally more in favor of applications that would benefit animals directly (e.g., growth, longer lifespan, or more offspring) than applications that

would benefit others—such as humans (e.g., human medical applications). With regard to human based applications, marginally more students reported being accepting of synthetic biology being used to treat human disease (e.g., in adults, children, or prenatally) and fewer for elective genetic modifications (e.g., to alter physical appearance). In contrast to microbial, animal, and human based applications of synthetic biology, nearly seven out of ten students reported finding plant based applications acceptable. Consistently, students rated applications in plants that involved increasing their nutritional value, environmental sensing, and protection against pests more favorably than applications that involved improving plant aesthetics (e.g., appearance when bruised or rotten). Ultimately, these findings suggests that context matters when introducing learners to synthetic biology as learners use those details to make sense of and make personal connections with the field and its various applications.

Student semi structured interviews revealed that student perspectives involved considerations related to: safety, utility, risk/benefit, and long term impacts—findings that have previously been reported concerning older student groups. When assessing collective data, ANOVA results suggested that students’ perspectives only varied by age (i.e., twelve year old students were generally less accepting of animal based applications than 11 year olds) and grade level (i.e., seventh grade students were generally less accepting of animal and human based applications than sixth graders).

5.3 Synthetic Biology and Active Learning

A second line of inquiry addressed in this dissertation centers around BioDesign and the affordances of such an approach for contemporary science education. This line was guided by the overarching question: how do middle school students engage in BioDesign and how

does such an approach support inquiry? This is addressed using a subset of prompted conversations and video based observation notes. Findings suggest that when implementing BioDesign projects, students were able to produce culturally relevant artifacts. Examples include projects that reflected students' personal interests and products that were designed for specific audiences and their unique needs. Findings also suggest that students were able to engage in inquiry practices when implementing their projects and overcoming obstacles associated with their designs. Specifically, students engaged in data collection across a variety of topic areas as well as problem solving in ways that leveraged tools provided by workshop instructors or devising their own unique solutions. These findings provide important insights about how synthetic biology based science learning fits in the broader active learning landscape. Specifically, this approach provides opportunities for learners to engage with inquiry simultaneously with the process of production. In other words, data collection and knowledge construction occur at the same time as learners explore and test their ideas as they work with materials that are both living, unpredictable, and meant to have a useful function. This is distinct from approaches that separate inquiry into steps (e.g., question formation, data collection, analysis, and reflection). These findings underscore the ways synthetic biology learning offers a paradigmatic shift in how active learning takes place and the potential affordances it creates as a result.

5.4 Justifications Change with Context Clues

A final key finding presented in this manuscript is with regard to the ways in which a subset of students justified their perspectives when given varying degrees of context clues about the application. Two groups of students—who had and had not taken a synthetic biology based workshop—were asked to justify their perspectives about whether or not they found

a particular synthetic biology application acceptable. Questions presented to students varied and were characterized as type I, II and III—from least to most context.

When provided the least level of context (i.e., question type I), students who had taken a synthetic biology based workshop were able to provide justifications that included a variety of considerations (e.g., risk/benefit assessments, utility, safety concerns, or long term impact) that were largely based on one or more personal inferences or views. This occurred across all application types (e.g., microbial, plant, animal, or human). As few as 33% of students in this group were unable to give justifications for their perspective when asked in broad or abstract terms (e.g., what do you think about synthetic biology being applied to animals?).

By contrast, students who had not participated in a synthetic biology based workshop activity more frequently—as often as 57%—were unable to provide justifications when asked in broad terms. These qualitative group differences disappeared when more context was introduced in the question (e.g., type II and III), as student explanations in both groups included one or more justifications that were based on personal inferences or views—and no student was unable to provide a justification for their perspective. These qualitative between-group similarities were evidenced across all application types (e.g., microbe, plant, animal, or human) when students in both groups were given detailed contexts about the use of a given application.

5.5 Discussion

Collectively, findings presented in this manuscript offer much needed insights into the state of middle school student knowledge of, perspectives on, and learning in synthetic biology. This need is ultimately motivated by issues related to citizenship and—to some extent—

occupational participation. In other words, given the increasing impact synthetic biology has on many commercial and academic enterprises in medicine, agriculture, manufacturing and the environment—to name a few, research on learning with K-12 age groups is necessary if the goal of science education is to develop future generations of ethical stewards of the planet. Therefore, the research and findings present here represent important early steps in examining middle school students and synthetic biology. The following section discusses findings presented in this research in order to situate it within the broader science education research landscape, as well as to chart out important next steps and future directions for research and practice. This is done through a critical analysis of findings in relation to existing research, followed by a discussion of ways to extend research.

5.5.1 On Middle School Student Knowledge and Attitudes

Existing research on what K-12 aged students know and think about biotechnologies and their various applications suggests that learners in these age groups know very little about the field (Lock & Miles, 1993; Dawson et al., 2003; Van Lieshout & Dawson, 2016). Examination of what students know specifically shows that middle and high school students are typically only familiar with those applications related to human food or agriculture. Findings here are consistent with and, in fact, extend this research by also showing that students know even less about applications that involve the production of manufacturing materials or medicine—areas of synthetic biology that have gained prominence. Others have attributed this to the lack of access to academic experiences and media attention (Cavanaugh et al., 2005; Chen & Raffan, 1999).

These findings also emphasize issues related to societal engagement and academic settings that typically treat biotechnology topics—if they address them at all—as options. And, when those topics are addressed, they typically only include traditional biotechnologies which have advanced considerably from simple manipulations of bacterial cells to demonstrate genetic modification technologies. Furthermore, such activities are typically available only to high school students, despite middle school students having well-formed perspectives about the field and having previously been shown to have some formal knowledge and understanding of it (Lock & Miles, 1993). Therefore, findings here highlight a continued need to introduce K-12 learners to these fields—which is consistent with international efforts to modernize science education. Future research could build on these efforts by going beyond evaluating student knowledge of a field, and toward ways to assess understanding—the ability to negotiate and transfer domain-specific knowledge to new applications.

With regard to middle school student attitudes toward synthetic biology and its various applications, the research presented here suggests that, overall, they have well-formed perspectives that involve a range of considerations—all of which have been shown in high school students. In broad terms, evidence of these considerations is illustrated in the fact that students in this study showed what Lock and Miles (1993) characterized as context-dependent attitudes—that is, attitudes that depend on the organism to which the technology is being applied. The middle school students reviewed in this study also had attitudes that were illustrative of those found in previous studies that reported high school students being more accepting of plant based applications, overall, than those involving

microbes, animals, or humans (Chen & Raffan, 1999; Dawson & Schibeci, 2003; Fonseca et al., 2012; Klop & Severiens, 2007; Mohapatra et al., 2010).

While these results provided important evidence and justification for providing synthetic biology educational experiences to younger student groups, more granular consideration of student attitudes provided important insights into directions for future research. Because synthetic biology often involves the production of non-living manufacturing materials, results in this study suggest that middle school student attitudes toward each context often depend on the output being generated and the purpose of those outputs. For instance, students often found outputs that were generated for medical applications or that were non-exploitative more acceptable than those involving elective outcomes for aesthetics or using animal life for human exploitation (e.g., to grow an organ, etc.). Consistent with previous research, middle school student justifications in this research often involved ethical and moral reasoning (C̃rne-Hladnik et al., 2009; Gunter et al., 1998), an important area of research on student literacy and reasoning, as well as indicators that have been used to understand civic and occupational engagement.

While research presented here suggests that student attitudes are independent of gender, examination of age found that younger students were more accepting of animal based applications than older students. Although these findings are inconsistent with results reported by Dawson (2007), they underscore the role age, and, more likely, education, plays in shaping student perspectives. They also emphasize the need to update research to include synthetic biology—with its nuanced applications—to unpack the various ways in which learners make sense of the field. These results point to important future directions in research on ways to support younger students in complex reasoning about modern

biotechnologies such as synthetic biology, as well as on how learners use information (e.g., content knowledge) in the reasoning process.

5.5.2 On Middle School Synthetic Biology Learning

BioDesign represents a paradigmatic shift in science education from an active learning approach that emphasizes learning guided by questions to an approach that also includes considers societal values for which designs are meant. Because BioDesign activities can occur in a space in which learners have to think through how organisms will interact with objects that then interact with users, these activities provide them with a wide array of creative possibilities. This is not typical in life science education in which the focus often involves the study of living organisms that must be handled using a narrow set of approaches. These handling constraints—in part—contribute to the criticisms life science education has received with respect to intellectual and cultural diversity (Emdin, 2016; Carter, 2008). BioDesign shifts the focus to how users will interact with objects created from living organisms, which broadens the ways in which cells can be used to create. As a result, learners are more able to engage with activities that are personally relevant and culturally representative of who they are and how they understand science. These affordances have previously been described in science activities that involve computers and electronics, but not living organisms (Honey & Kanter, 2013; Harel & Paper, 1991). This research, therefore, provides early insights into the ways in which life science experiences can be personalized and leveraged creatively.

Findings in this research also show that BioDesign, with its incremental approach to science, not only leverages inquiry practices, but provides opportunities for learners to problem solve through challenges that result from the process of implementing designs.

Over the course of two phases, which included planning and implementation, students had opportunities to collect relevant data, iterate through their designs and leverage multiple modes of understanding to convey a logically cogent final product. Outcomes suggest that BioDesign leverages inquiry as a means of accomplishing a design outcome. The salient implication here is that not only can inquiry be a primary context through which to engage science topics, but it can also be a means of creating more complex activities that involve an amalgamation of practices that exist at the intersection of multiple academic domains. Using this logic, inquiry as a singular practice is still an important perspective, but expanding to include design would mean that inquiry is among many strategies that coalesce to promote complex cognitive practices. Stated differently, design provides a context in which inquiry—as reflected in such behaviors as research question formation and data analysis—is among many cognitive tools used to explore ideas and produce artifacts that reflect student interests and their mastery of complex practices.

5.5.3 On Middle School Student Justifications about Synthetic Biology

Findings presented here on middle school student attitude justifications suggest that information (e.g., knowledge and context) are instrumental in argumentation, even when formal knowledge about a specific field is available. In the case of this research, that information was delivered in the form of context clues embedded in a series of survey and interview questions posed to students. Specifically, this research found that, when asked, very abstractly, whether they found a particular synthetic biology application acceptable, students who had not taken a synthetic biology based workshop frequently could not provide a justification, or provided one based on a personal inference or view. Students who had taken a synthetic biology based workshop were more frequently able to provide a

justification—presumably because of their past experience engaging with synthetic biology related topics. However, when both provided more context embedded in the question prompt, both were very often or always able to provide a justification.

Previous research has examined learner justifications—a component of argumentation used to assess student reasoning—as a measure of literacy (Cavagnetto, 2010; Erduran and Jimenez-Aleixandre, 2007). Sadler and Donnelly (2006) have advanced a Threshold Model of content knowledge transfer that ultimately suggests that formal knowledge is leveraged as a tool to make sense of ideas (i.e., make a question about a particular biotechnology application intelligible)—a necessary step in being able to form an argument. This is typically reflected in findings in which domain experts and non-experts often have similar argumentation patterns. Along this line, research has pointed to informal sources and forms of knowledge to account for the fact that domain experts and non-experts often have similar forms of argumentation skills. This idea is consistent in research presented here, as students were progressively more able to provide justifications as context about a particular synthetic biology application was provided.

This finding has important implications for educational practice and research. First, it underscores the importance of context in learning. Students always bring myriad personal and cultural experiences to learning environments. Such experiences shape not only their perspectives, but how they understand a particular set of information. This perspective on experience has been taken up in science education frameworks that highlight the importance of situated learning (Brown et al., 1989). When middle school students were prompted with questions filled with contexts, they were able to make sense of the information within their existing systems of thought. This not only suggests that synthetic

biology should be contextualized, but shows that it is possible and quite viable to engage learners in advanced forms of argumentation without necessarily requiring formal or detailed knowledge of a subject. In consideration of the existing education landscape, wherein biotechnologies are not typically discussed with K-12 groups, this provides an important insight into how to support literacy toward both future occupational field participation and—importantly—civic engagement.

5.6 Limitations

While this research provides early insights into the various ways in which synthetic biology fits into existing science education and research, it has inherent limitations that provide opportunities for future research. One limitation is with regard to research presented here on middle school student knowledge and attitudes. Although, this research was carried out with a group of students who are demographically underrepresented in life sciences, it is nevertheless a relatively homogeneous group in terms of self-reported racial categories and therefore not representative of the broader population of the United States. Through examining representative samples, it is possible to identify potential disparities that exist between demographically distinct student populations, which could better inform research and policy initiatives. Using this same logic: though, in this research a group of 66 students was assessed, a scaled examination of student knowledge and research would give a more complete depiction of what students know and think about synthetic biology and its various applications. This would also shed light on the ways in which social and cultural factors influence middle school student perspectives.

Another important limitation of this research is that it primarily examines student knowledge of the field—as does much of the related literature. However, knowledge is

only one indication of awareness about a particular set of information or a field and—to an extent—altogether different from being able to understand it. Therefore, a logical next step in research would be an assessment of student understanding of the field and its various applications. Research along this line of inquiry will help fully inform education research and learning design. Similarly, an evaluation of student attitudes is in many ways a composite evaluation of something that is dynamic and exists at the intersection of many considerations. Research examining how attitudes change, as well as how myriad considerations shift and shape those attitudes would be an ambitious and important next step toward understanding middle school students as they develop in this era in which synthetic biology shapes many aspects of society.

The BioDesign workshop carried out here only represents one of many possible activities within which to study learning. Important next steps in research should consider how activities beyond medicine and food support learning outcomes that have been shown to be important parts of active learning. While food and medicine affect many aspects of society—making them familiar contexts within which to situate student learning, many others exist, including such topics as energy security, environmental protection, and sustainable manufacturing, to name a few. As a result, the research presented here is limited in that it only represents an early step in a long trajectory of possible research. This research is also limited in scale and so future research should consider ways in which to leverage technology to not only broaden access, but demographically expand students studied. One way to accomplish this is to leverage simulations, models or other visualization objects that can provide opportunities for students to engage in design driven inquiry.

With regard to research on student argumentation, an inherent limitation of this research is that it relies on student explanations to ascertain reasoning and—ultimately—student literacy. While there is a corpus of research that has leveraged this approach, future research should include other forms of production to assess reasoning and learning. Discourse analysis and journaling—although not exhaustive—provide viable alternatives for assessing learning and student reasoning. Also, while the research presented here suggests that learners leverage context to think through and justify their perspectives, many other forms of informal knowledge may be involved. It is therefore reasonable to direct future research toward uncovering those forms of knowledge in order to broaden possible points of entry for students to engage in advanced argumentation practices and reasoning. Collectively, these limitations are not meant to suggest any shortcomings, but instead to identify important and productive next steps in research on synthetic biology and K-12 science education.

5.7 Conclusions

As innovations in life science continue to develop and impact society, the need for updates to science education research and perspectives on how to support learning in these fields will continue to grow in urgency. Synthetic biology—and its influence on myriad industries—is one such field, for which the urgency is exacerbated by the fact that it is increasingly becoming available in informal environments and to novice learners. The research in this manuscript represents an early step toward examining and unpacking learning in a contemporary science education landscape in which inquiry and problem based learning are the primary active learning paradigms that have informed research for decades. Design perspectives offer new directions that leverage and extend what we know

about a science education that will provide future generations of learners with opportunities to participate in the field, but also navigate the complex and often messy outcomes that will inevitably emerge from synthetic biology. Furthermore, research here advances new directions in research toward supporting student knowledge building and literacy in an era in which movies such as *Chimera* and *Jurassic Park* are no longer far-fetched mythological science fiction, but in the realm of the possible.

Overall findings suggest that middle schools students assessed in this study have limited to no knowledge about synthetic biology and its various applications. This is evidenced by the vast majority of students who could not define, describe or provide an example of the field, its processes, or its various applications, which include microbes, plants, animals and humans. This underscores the need to develop learning activities to support K-12 learner participation given the field's presence in so many out of school spaces and commercial enterprises. This is especially important as K-12 learners represent future generations that will need the knowledge and literacy necessary to engage civically—as future decision-makers—with the field's future directions, risks, and impact on society.

In terms of middle school student attitudes toward synthetic biology-based applications, findings suggests that these students have clear perspectives about the potential risks, consequences and benefits of the field. In this study, students found microbial and plant applications more acceptable than those involving animals or humans. These first steps in understanding middle school student perspectives about the field. An important finding here is that middle schools students may not only have opinions, but their opinions are grounded in relation to their sociocultural experiences, ethical orientations,

familiar relationships, and—importantly— their ability to consider the impact of these technologies on non-human living things (e.g., microbes, plants and animals). This, in itself, highlights the need and impetus for future research examining the complex ways in which K-12 learners negotiate and justify their perspectives about modern biotechnologies. In other words, because students explain their perspectives in ways that span multiple considerations (e.g., cultural norms, ethics, social relationships, and non-human perspectives), more research is needed to examine how to create learning experiences that support learner participation and literacy in these increasingly ubiquitous fields.

This study presents a case in which middle school students participated in a synthetic biology activity. Insights offered suggest that BioDesign, with its open ended approaches that are reminiscent of problem based learning, offers an important entry culturally relevant learning. This is because the focus of design is the people for which products are meant. Importantly, this research also offers insights into the ways in which design science is congruent with existing approaches to science education and which have been shown to support learning. This includes the iterative processes of inquiry that involve gathering knowledge and reflecting on that information for use in new applications. A key affordance of this approach is that design science supports learning in fields that reflect contemporary advancements in life sciences. While this case study only examines a small sample of students and explanations, it provides insights into the distinct ways in which learners engage in inquiry in life science related design activities. Future directions for research around process journaling, prompting, and design technology provide will important next steps for research on BioDesign and K-12 learning.

An important conclusion of this research is that modern biotechnologies such as synthetic biology provide an important vantage point into student learning toward occupational and civic engagement. Because of this, much research is needed to understand how to support literacy in this rapidly growing field, and particularly in younger students who are increasingly able to access the field in both formal and informal learning environments. This research shows that younger students not only have well-formed opinions about the field, but thoughtful moral and ethical considerations that are typical in older students. Furthermore, this research suggests that context based learning may be a viable way to support argumentation practices that are quintessential to scientific literacy. In other words, learning should be situated in contexts that provide learners with a meaningful perspective on which to construct their ideas, explanations, and justifications. This requires opportunities for learners to leverage their various ways of knowing while at the same time supporting opportunities for learners to make intersectional and critical considerations about modern biotechnologies and the ways they affect life, society and the planet. While this research only examines a small sample of students, it provides important first steps toward updating and illuminating discourse in a science education field that is underrepresented in the literature and with a student group that will increasingly need to engage with it and its impact on society. Future research should examine more closely the relationship between application context, argumentation and learner ethical orientations in order to better understand how to support intellectually and socioculturally diverse learners and move toward occupational and civic literacy.

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