Biodesign Education in Early Childhood:

A Design-Research Study of the Tangible CRISPEE Technology and Learning Intervention

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Amanda Lenae Strawhacker

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Advisor

Dr. Marina Umaschi Bers (Chair)
Eliot-Pearson Department of Child Study & Human Development

Committee Members

Dr. Christine McWayne
Eliot-Pearson Department of Child Study & Human Development

Dr. Brian Gravel
Department of Education

Dr. Yasmin Kafai
Graduate School of Education
University of Pennsylvania

Abstract

Biodesign - the science of applying engineering strategies to the design of living materials to solve human problems - is growing as an emerging STEM field, penetrating industries of agriculture, medicine, energy, and civics. Today's young children are growing up in a world where questions of bioethics and biotechnology will be globally pervasive. It is important to prepare them to engage with the complex ethical questions of bioengineering, and to understand the immense power of this novel domain to solve problems that have long plagued humanity. This research explores ways that children engage in foundational STEM strategies while using CRISPEE, a novel tangible technology to playfully introduce foundational concepts of bioengineering. CRISPEE was designed to introduce concepts in a way that is developmentally appropriate for young children, in order to reach children before they develop negative stereotypes toward STEM professions. This paper presents the design-based research study of the 6-phase development cycle of the CRISPEE prototype and accompanying learning intervention. Data from two of the research phases were explored using qualitative interaction analysis techniques to arrive at a narrative understanding of how children engaged with the CRISPEE prototype, and what they can learn from a bioengineering learning intervention that uses CRISPEE. Seventy-one children aged 4-9 years comprised the total sample, with $n = 62$ children participating in a brief CRISPEE play-session held at a pop-up exhibit at the Boston Children's Museum, and $n = 9$ children participating in a 15-hour camp-style learning experience held during vacation week at the Eliot-Pearson Children's School. Results from the museum play-test study revealed that children engage in practices of sequencing, sensemaking, and creative design when using CRISPEE for the first time. Over half of the sample was able to master CRISPEE interactions within 10 minutes of playing with the tool. Results from the camp intervention study reveal that the CRISPEE tool and curriculum supported children's engagement with foundational concepts from bioengineering, such as "genes" and "bioluminescence". Further, children engaged with engineering and computer science concepts of hardware, software, and debugging, and bioengineering concepts of ethical consequences of biodesign. Findings reveal new areas of investigation for developing an evidence-based pedagogy of developmentally appropriate bioengineering education for early childhood.

Keywords: Bioengineering, STEM, design based research, early childhood education, bioethics, programming, tangible technology

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Chapter 1. Introduction

The founder of the World Economic Forum recently named bioengineering as the frontier of the "4th industrial revolution" (Schwab, 2017). New approaches and technologies in bioengineering, which applies principles of engineering design to the cultivation of biological materials, are having profound effects in almost every major industry, including agriculture, medicine, security, ecological conservation, and space travel. Bill Gates has called gene editing the single most important topic that Americans are not discussing at a national level (Gates, 2018). The most prominent new biotechnology, the CRISPR/Cas-9 gene editing system (also called CRISPR), has launched a new wave in awe-inspiring and anxiety-provoking genetic discoveries, and a new field called "biodesign" – the innovation branch of bioengineering. In the past decade, scientists have engineered strains of rice to prevent vitamin deficiencies, developed ways for same-sex parents to give birth to biological children, and begun research trials to cure HIV and genetic blindness. Already, the first genetically-modified human infants have been born in China in 2018. One geneticist at Harvard has even started a list of candidate genes for human enhancement, aimed at engineering improvements in memory, musculature, and even body odor for people of the future. This sounds like science fiction, but today it is easy to sequence anyone's DNA using do-it-yourself gene sequencing kits available at most pharmacies and grocery stores in the US.

Despite these advances, research continues to confirm that the general American public knows very little about genetics and many people harbor reductionist and even harmful misconceptions about how genes contribute to our personal identities. As this trend continues, it is likely that children entering Kindergarten today will be confronted with issues of biodesign and bioethics in their daily lives as early as middle and high school. In order to remain competitive on the world stage, we must prepare students today to become empowered citizens in a biodesign-enriched economy. More than training little bioengineers, however, we must prepare students not only with a basic understanding of the mechanics of biotechnology, but also a readiness to engage with the socio-ethical dimensions of creating and living among bioengineered designs. This dissertation work broadly focuses on investigating how to prepare the next generation to become STEM-literate citizens, so that they can responsibly guide society through the coming bioengineering revolution.

Chapter 2. A Brief History of Bioengineering Education

What is Bioengineering?

Bioengineering is an emerging interdisciplinary STEM field that unites practices of engineering and theories of computer science with materials and methods from biology to solve real-world challenges, all situated within the real-world context of ethics and civic responsibility that guide design and research (Weiss, 2001) (see Figure 1).

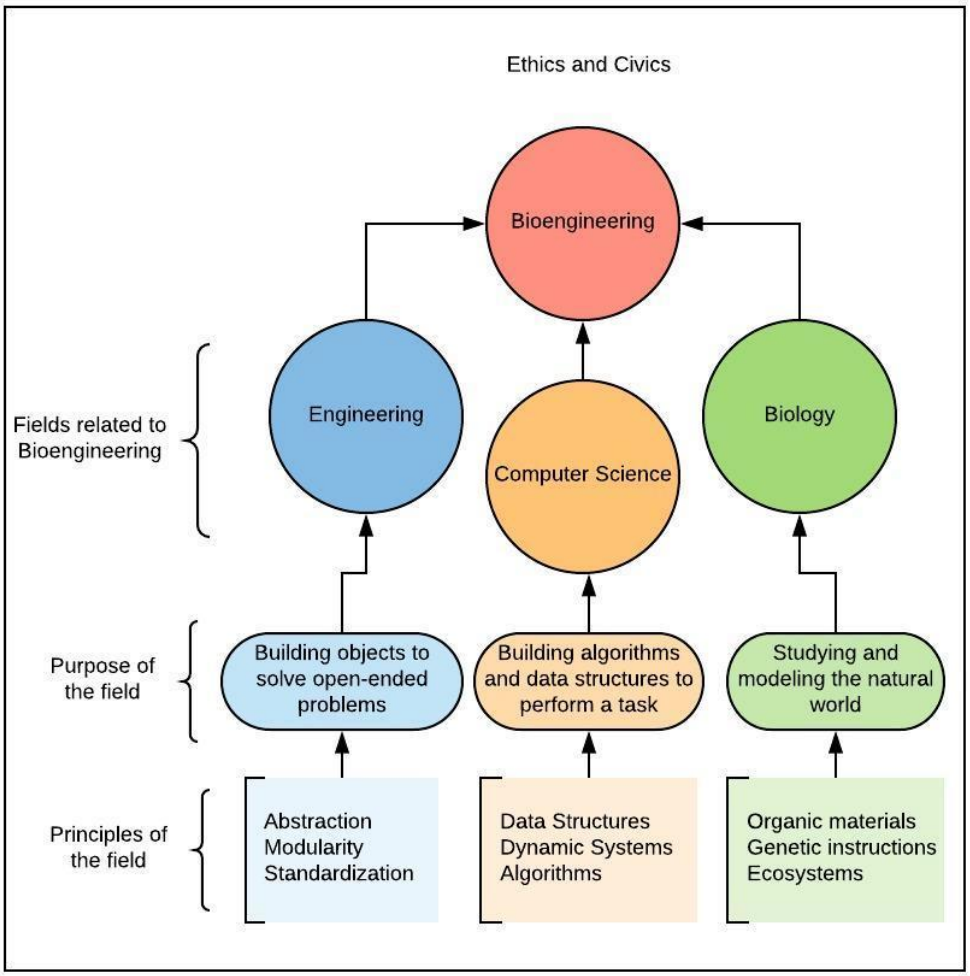


Figure 1. Diagram representing the related principles of engineering, computer science, and biology that comprise bioengineering.

Specifically, bioengineering draws upon core principles, or powerful ideas, from three disciplines: engineering, computer science, and biology (more on powerful ideas in later sections). Each field's contribution is unique yet interrelated.

From the field of engineering, bioengineers use ideas of modularity, standardization, and abstraction to guide their work (Endy, 2005; Kuldell, Bernstein, Ingram, & Hart, 2015). Modularity, sometimes called "decoupling", is the idea that parts of a process or system can be meaningfully divided from the whole into discrete components (Endy, 2005, p. 51). In computer construction, for example, this means that engineers designing the main board do not need to worry about designing other parts like the LCD screen, which is managed by a different team of engineers (Baldwin & Clark, 2006). Standardization is the process of conforming parts, materials, and processes to consistent, measurable, and agreed-upon standards. This principle is key for groups of engineers working in remote locations to be able to collaborate and share work. Automotive engineers in Germany can order parts from Japan using standard measurement systems to ensure that they do not need to adapt the part to fit their car. Finally, abstraction is the idea that components of a system or process can be organized into a structural hierarchy. This is useful because engineers can focus on a design challenge in one level of the hierarchy while holding constant details in the levels below or above it. For example, in software engineering, programmers can alter code at the level of an overarching system (e.g. a word processor) without worrying that they will somehow alter sub-functions (e.g. a spell-check tool).

Bioengineering also borrows principles from another foundational field, computer science (Endy, 2005; Kuldell, Bernstein, Ingram, & Hart, 2015). According to the Association for Computer Machinery (ACM), computer science is the study of computers and their algorithmic processes (Tucker, 2003). Computer scientists design experimental algorithms, theorize about why they work, and use those theories to inform new designs and data structures (Dodig-Crnkovic, 2002). Several core ideas relate to bioengineering, but perhaps the most relevant are algorithms, or sequences of commands in which the order matters, and control structures, or instructional commands that deal with the behavior of algorithms (e.g. a repeat loop and a conditional "if-else" statement are both control structures) (Bers, 2018). These concepts are specific to computer science, however, they function roughly the same whether applied to computer programs or genetic instructions (Bers, 2018; Endy, 2005). In fact, computer scientists and programmers have often looked to the natural world for inspiration, for example, to model genetic evolution (Yang, Wang, & Jiao, 2004), to make computer networks as interconnected as cell membranes (Păun, 2000), and even to dynamically model patterns and processes in the human brain (Goldberg, & Holland, 1988; Kraynyukova, & Tchumatchenko 2018). Now, bioengineers borrow ideas from computer science in order to interpret and design gene "programs", or genetic codes, to execute desired behaviors and traits in bioengineered cells and organisms. Computational logic and theories are used to build programs, but the programming language is genetic code (Kuldell, Bernstein, Ingram, & Hart, 2015).

In bioengineering, computer science and engineering principles are applied to the design of systems, but the systems are comprised of living cells and organisms with engineered characteristics (Endy, 2005). This means that biological concepts are necessarily involved in the construction of bioengineered organisms. The natural world adheres to a different set of constraints than the human-made one, and bioengineers need to be aware of biological concepts like gene mutation, inheritance, and chemical properties of organic materials (Kuldell, Bernstein, Ingram, & Hart, 2015). However, bioengineers can also take advantage of highly complex biological systems that have evolved over thousands of millennia (Endy, 2005; Kuldell, Bernstein, Ingram, & Hart, 2015; Pilnick, 2002). For example, bioengineers rely on the "central dogma" of biology, that genetic DNA codes will be perfectly copied and transcribed into functional proteins, in order to grow their engineered and programmed cells (Endy, 2005; Kuldell, Bernstein, Ingram, & Hart, 2015). In this way, bioengineers genetically alter new organisms like bacteria, often by infusing them at conception with genes taken from other organisms. These new organisms and their genetically-encoded traits are carefully designed to address problems in areas such as medicine, energy, and agriculture (Keasling, 2006).

As it is a young field, scientists are still debating the proper terminology to capture the diverse subfields that already comprise bioengineering (Kuldell, Bernstein, Ingram, & Hart, 2015). For example, researchers distinguish between genetic engineering, an older branch which focuses mainly on sequencing and modifying genetic material with the purpose of introducing new characteristics to organisms (e.g. Grimm, Kohli, Murray, & Maundrell, 1988), and synthetic biology, which aims to solve engineering problems by top-down designing and constructing engineered organisms with novel functions (Andrianantoandro, Basu, Karig, & Weiss 2006). This second branch is more philosophical, as scientists are very far from that level of biotechnological complexity. Proponents of synthetic biology have proposed science-fiction-sounding hypotheticals, such as bioengineering an acorn to grow into a treehouse shelter for humans, with glowing bioluminescent bark in place of electrically wired lights (Joachim, 2008; Kuldell, Bernstein, Ingram, & Hart, 2015). Researchers are now attempting to document and create biological materials in order to standardize a system of biological parts and devices that bioengineers can use to create living solutions to engineering challenges (Andrianantoandro, Basu, Karig, & Weiss 2006; Shetty, Endy, & Knight, 2008; Smolke, 2009). Since 2003, the International Genetically Engineered Machine (iGEM) Foundation (www.igem.org) has accumulated a library of standardized biological parts with the aim of someday using them to engineer solutions to human issues. iGEM's Registry of Standard Biological Parts contains over 20,000 "BioBricks", discrete genetic parts with documented properties and functions that can be used to genetically code novel engineered organisms (Shetty, Endy, & Knight, 2008; Smolke, 2009). Already, synthetic biologists have used this registry when engineering organisms to address pressing issues of marine pollution, agricultural crop hardiness, and terminal congenital illness in infants (Planta, Xiang, Leustek, & Messing, 2017; Reardon, 2015; Zewe, 2016). For the purpose of the research issues presented here, I propose the following definition of bioengineering: the deliberate modification of an organism's genetic instructions in order to design a living solution to address a human problem.

It is useful now to turn to the history of bioengineering, in order to more deeply understand the full context in which this field is emerging. In the next sections, I will summarize how humans throughout history have attempted to engage in rudimentary genetic engineering, and will describe key technological achievements that allowed bioengineering to evolve into the domain it is today. Next, I will focus on the ways in which novel bioengineering practices are already being taught and implemented in learning settings. Following this will be a discussion of the current field of bioengineering education.

A Brief History of Bioengineering

Early Ideas about Selective Heredity in Human History

For almost as long as humans have known about heredity and the bio-similarity of offspring to parents, we have tried to apply this knowledge to alter living things to suit our needs. Animal husbandry, the agricultural practice of selectively breeding livestock to achieve specific characteristics, has existed since the Neolithic Revolution (a stone-age era), around 10,000 years ago (Çakırlar, 2012). The biblical story of Laban and Jacob contains references to hereditary chance in sheep breeding, when a flock of pure white sheep begat lambs with black patterning in their wool (Genesis 30:25-43, Jewish Publication Society of America Version Tanakh [Old Testament]). Although the specific patterns of dark colors in the wool is seen as divine intervention, the main character, Jacob, clearly exhibits an understanding of rudimentary selective breeding practices. In ancient Greece, approximately 400 BCE, the philosopher Plato even theorized about applying these selective breeding practices to humans, suggesting that human reproduction could be secretly controlled and monitored by the state (Lee, 2003). This kind of unscientific reasoning, which erroneously attributes advantages to certain human groups based on heredity, can be directly or indirectly linked to political practices and structural inequalities in countless cultural histories ranging from the caste system in India (Banerjee, 2014), to the North American slave trade (Fields, 1990), to incestuous bloodlines among royal European families (Güvercin & Arda, 2008), and infamously, to the national selective breeding agenda of Nazi-era Germany in WWII that resulted in the genocide of millions of "undesirable" German and European citizens (Bergmann & Jucovy, 1982).

Bioengineering is Born

Since about the 1920s, the only engineers who worked with living organisms were grouped into a few specialized areas and worked with the smallest unit of life that was then known: the cell. Agricultural engineers worked directly with living crop strains, chemical engineers studied fermentation as a property of cell cultures, and HVAC (heating, ventilation, and air conditioning) engineers studied the impact of temperature and humidity on humans (The Editors of Encyclopaedia Britannica, 2016). In 1953, Watson, Crick, Franklin, and others discovered the structure of the DNA double-helix, allowing scientists to learn much more about the nature and function of genetic coding than ever before (Pray, 2008). This breakthrough shifted scientific attention away from selective heredity toward genetic re-engineering at the molecular level, where it remains today. The discovery of the structure of DNA led to medical advances, as well as the advent of biological weapons. Engineering meetings in the U.S. turned mainly to questions of medical technology, and the need for a deeper understanding of the biochemistry of the human body (Nebeker, 2002). Surgeons wanted to perform risky new procedures that required knowledge of topics like biological heat transfer, fluid dynamics of blood flow, and biomechanical models for prosthetic limbs, while defense specialists were interested in protecting humans from radiation bombs and sending manned missions into space to intercept long-range atomic missiles (The Editors of Encyclopaedia Britannica, 2016; Nebeker, 2002). Often, engineers who were interested in these questions needed to develop their own theories and methods, relying on insufficient biology training or becoming self-taught in specialized areas. It quickly became apparent that this new field required engineers who were trained and competent in the life sciences (Naik, 2012).

In 1954 the term “bioengineering” was coined, perhaps ironically, by a scientist named Heinz Wolff who began his life as a Jewish refugee escaping Nazi Germany (Goyal, 2018; Wolff, 2006). The same year he first used the term, Wolff founded the world’s first university program for bioengineering, the Division of Bioengineering Research at the U.K.’s National Institute for Medical Research (today, the Francis Crick Institute) (Wolff, 2006). The early days of bioengineering were dominated by addressing specific needs and challenges in medicine and defense, such as how to bypass the human heart during surgery and how to keep humans alive in extreme climates. Among other achievements, Wolff’s work in bioengineering contributed significantly to Project Juno, the private British-Soviet joint venture that sent a British researcher into space (Radford, 2017).

Soon researchers began to apply themselves broadly to the challenge of engineering solutions to human problems, and an agenda for the field of bioengineering began to take shape. By the end of the 1960s, around 180 U.S. universities had launched graduate and undergraduate programs with names like Medical Electronics and Biomedical Engineering, all designed to teach students to engineer with living materials (Nebeker, 2002). Professional societies, conferences, publications, and educational programs on the subject expanded, and in 1968 the International Electrotechnical Commission (IEC) held a meeting to standardize all aspects of biomedical equipment. At the same time, computers were introduced into biomedical research. For example, in 1965 researchers at Stanford developed a computer to predict the structures of molecules based on chemical compounds with expert-level accuracy (Nebeker, 2002). As more rule-based reasoning programs were developed, bioengineering adopted more concepts and practices from computer science to aid researchers in understanding complex living systems and chemical reactions. This mutual discovery in computation and bioengineering would continue into the 1970s and ‘80s, resulting in biotechnology advances such as computerized tomography (CT) scanners to enhance X-ray quality, laser and endoscopic procedures for non-invasive surgeries, and magnetic resonance imaging (MRI) to observe the inner workings of the brain (Nebeker, 2002).

Decoding Heredity: The Human Genome Project

In the 1990s, bioengineers in the U.S. took on a new research agenda: to learn the entire sequence of human DNA. This mammoth task, dubbed the Human Genome Project, was funded by the U.S. National Institutes of Health, the U.S. Department of Energy, and the Welcome

Trust, and enlisted over 2,000 internationally collaborating investigators during its research phase from 1991 to 2003 (National Human Genome Research Institute [NHGRI], 2010a). After this 12-year project was completed, scientists had successfully sequenced around 94% of all human DNA (International Human Genome Sequencing Consortium, 2001). At the time the project completed, this achievement was hailed as the first step toward new breakthroughs in eradicating all disease, because scientists now knew more about human evolution and genetic predispositions than ever before (Lander, 2011). The far-reaching impacts of this large-scale project are still being realized in areas of virology, medicine, disease, and more (Hood & Rowen, 2013).

Perhaps in light of a post-WWII-era mandate for ethical considerations in genetic research, about 5% of the Human Genome Project's $3 billion budget was allocated specifically to examine Ethical, Legal and Social Implications (ELSI) related to human genome research, with the goal of offering guidelines and recommendations for policymakers, researchers, and public communities (NHGRI, 2010a). The National Human Genome Research Institute (NHGRI) maintains that the ELSI program is "unprecedented in biomedical science in terms of scope and level of priority [and] provides an effective basis from which to assess the implications of genome research, [which] now serves as a model for large, publicly funded science efforts" (NHGRI, 2010a). In addition to impacting the project methodology itself (e.g. requiring the sequenced DNA to come from anonymized and consenting individuals), the ESLI project has generated widely-used genetic privacy guidelines (e.g. informed consent procedures for participants in genomics research) as well as draft legislation for legal handling of genomic data (e.g. health insurance nondiscrimination statutes) (NHGRI, 2010b; NHGRI, 2010c; NHGRI, 2018).

CRISPR/Cas-9: A cut-and-paste tool for genes

Other technological advances in bioengineering continued throughout the 1990s and early 2000s. In particular, this generation saw the rise of robotic technology as an aid in human genetics research. Robotic tools such as "automatic genome sequencers, robotic liquid-handling devices, and software for databasing and sequence assembly" shifted the level of biotechnological work from organ systems to cells and molecules (Nebeker, 2002, p. 23). One tool in particular that has rapidly altered the pace of genetic research is the CRISPR/Cas-9 gene editing system. CRISPR/Cas-9, also known as CRISPR (pronounced "CRISP-er"), is a technology at the intersection of genetics, robotic technology, and computer science. CRISPR harnesses the power of certain viruses that can "snip-and-paste" specific genetic instructions to remove unwanted DNA, insert new sequences, and even transfer DNA sequences across organisms from different species (Cong, Ran, Cox, Lin, Barretto, Habib, Hsu, Wu, Jiang, Marraffini, & Zhang, 2013). With the advent of this technology, scientists have officially entered a new era in genetic research. Geneticists no longer have to rely on the slow and randomized process of natural evolution to alter the DNA instructions of living things (Cong et al., 2013). Now, it is possible to address decades-old questions of agriculture, medicine, and exploration at the genetic level within a single researcher's lifetime. Scientists can identify and remove deleterious genes that are the root cause of terminal illnesses such as leukemia (e.g. Georgiadis & Qasim, 2017), create strains of pesticide-resistant crops that may alleviate the burden of food scarcity (Keasling, 2006; Planta, Xiang, Leustek, & Messing, 2017), create sustainable non-pollutant forms of plastic (Crawford, 2017), or use genetically-altered bacteria to create sustainable resources (e.g. food stores, oxygen generators) for human space travel (Menezes, Cumbers, Hogan & Arkin, 2014).

Science, Technology, and Society: Bioengineering Entering the Public Consciousness

Almost from its initial conception as a field, bioengineering has been fraught with ethical and legal questions. Now, with the advent of CRISPR and other high-precision gene editing technologies gaining public attention, ethical considerations are more pressing than ever before. Policymakers and industry leaders are beginning to take an interest in bioengineering, even putting the question of its use to a vote among their constituents (Kaebnick & Murray, 2013; Helme, 2013; Klein, Grossenbacher-Mansuy, Häberli, Bill, Scholz, & Welti, 2001). In some extreme cases, self-described "DIY bio-hackers" have begun to inject themselves on video streaming websites like YouTube with experimental vaccines and bacterial strains, disregarding warning statements from the U.S. Food and Drug Administration (FDA) about the illegality and dangers of do-it-yourself gene therapy (Mullen, 2017). A few have even launched companies marketing human genome-editing kits at lay-people suffering from illnesses like HIV/AIDS, promising to "make cutting-edge biomedical technologies available to everyone" (Ascendance Biomedical, 2018; The ODIN, 2018).

As gene editing becomes more common in newspaper headlines, researchers have attempted to measure the impact of these messages on public perception. In a study by PEW, 4,685 U.S. adults responded to questions about their level of enthusiasm or concern over potential gene therapy applications for human healing and enhancement now possible with CRISPR technology, including "gene editing giving babies a much-reduced health risk," "brain chip implants for much improved cognitive abilities", and "synthetic blood for much improved physical abilities" (Funk, Kennedy, & Sciupac, 2016). In general, participants were more concerned about *enhancement* than health *treatment*, and mixed about whether there will be more societal benefit or harm from gene re-engineering. Popular movies such as GATTACA have explored the ethical implications for a post-bioengineering society, in which social structure is dictated by genetic fitness and access to genetic information (Kirby, 2000). Shock-and-awe terms like "designer babies" impact public perception of genetic engineering, and regulatory groups have had to develop entirely new measures and approaches when evaluating the safety of experimental foods and medicines that have never existed before (Ensemble, 1998; Wohlers, 2013). Despite public uncertainty, innovation continues. Scientists involved in the "golden rice project", launched in 2002, aim to genetically enrich rice with vitamin A to combat vitamin A deficiency in malnourished populations (Beyer, Al-Babili, Ye, Lucca, Schaub, Welsch, & Potrykus, 2002). Another international team of researchers has borrowed this idea to create a strain of GMO rice to neutralize symptoms for sufferers of HIV/AIDS (Lotter-Stark, Rybicki, & Chikwamba, 2012). These advances are shifting the realm of scientific and medical possibility, but popular opinion and the slow pace of genetic research have fostered uncertainty about the effectiveness of GMO foods. Golden rice fields in the Phillipines have been destroyed by local members of anti-GMO activist groups (Kupferschmidt, 2013; Lynas, 2013). At the same time that this public outcry occurred in Asia, citizens in Europe touted genetic re-engineering as a life-saving "miracle" technique when scientists administered an experimental gene editing treatment and cured an infant in the UK of terminal leukemia (Georgiadis, & Qasim, 2017; Kirby, 2015).

Despite these controversies, the field of genetic engineering appears to be growing faster than ever before. Most adults advocate for more inclusive public discussions about using and implementing biotechnologies, regardless of ideological differences. Although there is empirical support that U.S. citizens would be open to a national dialogue, most adults in the U.S. are also uneducated about the mechanisms and consequences of bioengineering. Perhaps this is why

American philanthropist and tech magnate Bill Gates has said that "gene editing might be the most important public debate we're not having right now" (Gates, 2018).

The Question of Bioethics: Bioengineering in a Post-ESLI world

The past century has seen great strides for the field of genetics research, but the ethical questions involved in conducting bioengineering are far from resolved. How, then, is the bioengineering community addressing this challenge in professional training? In order to investigate how bioethics is being taught at the pre-professional level, a team of ethnographic researchers collaborated with members of a college-level bio-design team participating in an international competition to design engineered bacteria to solve human problems (Balmer & Bulpin, 2013). Researchers found that because of the competition structure, students considered ethical questions separate and secondary to the work of creating a functional biological part. For example, bronze and silver medal requirements related only to strong biological solutions, while gold medals were reserved for teams that also considered the ethical implications of their work. Further, students often reported that their designs had no bioethical implications whatsoever, indicating a lack of understanding of the responsibility involved in their work. The unsettling conclusion from this study is that among pre-professional bioengineering students and training institutions, "ethics are understood as being separate from the empirical collaborative work of creating biological machines" (Balmer & Bulpin, 2013, p. 319). Bioethicists argue that this decontextualizing of human practices from empirical work is caused by an industrial and product-driven focus that permeates bioengineering research, resulting in ethical considerations that are "rather superficial addenda to the work of engineering novel bacteria, which focuses mainly on the objects being made rather than the process of making them" (Balmer & Bulpin, 2013, p. 318; Frow & Calvert, 2013). As Balmer and Bulpin's study demonstrates, bioengineering educational institutions place value on ethical considerations in their field, but more work is needed to make the application of bioethics more directly tied to the design process for students.

The professional field of bio-design is similarly working toward a more meaningful integration of social and bioengineering sciences. In June 2018, Boston hosted the BIO International Convention, a global meeting of more than 18,000 attendees representing 67 countries and 7,000 companies (Biotechnology Innovation Association, 2018). Of the 19 session tracks that classified events and presentations, four tracks were directly or indirectly related to ethical questions, including talks on regulatory frameworks and intellectual property for gene editing, ethical value of and patient access to gene therapies, and results from outreach efforts to educate the lay-public about the motivations of bioengineering initiatives. Clearly the need for ethics in bioengineering is apparent to industry professionals, although researchers and educators are still actively investigating best practices for meaningfully integrating bioethics into instruction.

The state of bioethics in the field of bioengineering can perhaps be summarized by the words of Dr. Jennifer Doudna, co-inventor of the CRISPR/Cas-9 genome editing system. In a TED Talk in 2015, Doudna appealed to the global community to consider the ethical impacts and the future of gene editing. After noting CRISPR's many potential applications in the field of medicine and health, she reminded the audience that CRISPR might also be used in the near future for genetic enhancement – "designer humans, if you will" (Doudna, 2015). To emphasize the gravity of that reality, she explained, "this is why I and my colleagues have called for a global pause in any clinical application of the CRISPR technology in human embryos, to give us time to consider the ethical implications of doing so" (Doudna, 2015). Even as the creators of this new technology share a concern for its misapplication, researchers have already begun the work of experimentally applying CRISPR to the human genome (e.g. Georgiadis, & Qasim, 2017). Already the first genetically-engineered babies have been born in China, and they will pass on their edits throughout the duration of their family's history (Cyranoski, 2016). This and other experiments have caused a bioethics crisis in the field, and the international research community is calling a halt on all heritable human gene editing until they can determine safe and uniform protocols (Cyranoski & Ledford, 2018; Davies, 2019). It appears that humankind is much closer to realizing the capabilities of gene editing technology than we are to understanding the magnitude of that power. It therefore becomes critical to educate the next generation of scientists, citizens, and leaders about the responsibility involved in gene editing, in order to ensure that history does not repeat itself and again result in unnecessary human harm and social stratification.

In the next chapter, I take a broad look at the developmental capabilities of young children and argue for their theoretical readiness to engage with the foundational concepts and questions of bioengineering. I also review lessons learned from related educational fields of science, engineering, and computer science about how to effectively introduce and research novel STEM domains in early childhood education. Following this discussion, I propose initial suggestions and directions for creating a developmentally-appropriate curriculum for engaging young children in the foundational ideas and ethical questions pertinent to this emerging domain.

Chapter 3. Bioengineering as a Learning Domain in Early Childhood

Most bioengineering education programs are targeted at older students in high school, college, or pre-professional training (e.g. Kafai, Telhan, Hogan, Lui, Anderson, Walker, & Hanna, 2017; Kuldell, 2007). However, as prior research demonstrates, this type of program is already too late to change students' ingrained STEM attitudes, so they likely attract students who would already have been interested in STEM careers in college (Steinke, 2017; Sullivan, 2019 There are convincing practical and theoretical reasons to begin much earlier. In this chapter, I present socio-economic justifications for the benefit of introducing bioengineering in early childhood, as well as developmental theory perspectives relevant to this undertaking. I conclude by identifying the most promising powerful ideas and learning goals that might characterize a developmentally appropriate bioengineering curriculum for young children.

Bioengineering Education: Current Trends and New Directions

Currently, most explorations in educational bioengineering have been conducted as part of integrated STEM (Science, Technology, Engineering, and Mathematics) learning experiences in informal settings such as museums, or classroom settings for students in middle school through college (Harris, Bransford, & Brophy, 2002; Linsenmeier, 2003; Sheppard, Macatangay, Colby, & Sullivan, 2008). However, there are practical and theoretical arguments for introducing foundational concepts of this field much earlier, with children age 5-7 years. Bioengineering may seem too abstract and academic for young children to understand in a meaningful way. This preconceived cultural notion about the abilities and limits of young children's capabilities does not take into account the critical periods of exploration and curiosity that children naturally exhibit from birth through age 8, when we see children applying some of the same methods that scientists use to understand phenomena (Gopnik, Meltzoff, & Kuhl, 1999; Harlen, 2001; Phillips

& Shonkoff, 2000). Neither does it acknowledge the fact that new tangible interfaces make abstract concepts more accessible to young audiences. Previously, computer science and engineering were also thought to be too complex for very young children, but research shows that children as young as age 4 can learn foundational skills of engineering design and computational thinking, when the tools are designed to be developmentally appropriate (Bers, 2018; Clements & Sarama, 2003). Today many countries mandate computer science and engineering education in schools starting in Kindergarten, and life science has been taught to this age range for decades already (Cejka, Rogers, & Portsmore, 2006; Metz, 2007; Pretz, 2014). Bioengineering is a cross-cutting discipline that integrates science, technology, and engineering in developing solutions to problems that humans face every day, and this real-world interdisciplinary experience is critical for children's meaningful engagement with STEM fields (Clements & Sarama, 2003; National Research Council, 2007; Papert 1980).

The Lasting Impact of Early Intervention

Although bioengineering is an unexplored learning domain for young children, theories about children's readiness as well as the economic and social costs of investing in STEM education too late in children's development suggest that bioengineering is worth exploring as a way to prepare the next generation of STEM-engaged learners and citizens (National Research Council, 2007; Reynolds, Temple, Robertson, & Mann, 2001; Schweinhart, 1993; Sylva, & Wiltshire, 1993; Tao, Oliver, & Venville, 2012). Investing in young children has proven to be an excellent way to maximize educational effort and spending, by ensuring lasting impacts in children's learning and positive social outcomes (Cunha & Heckman, 2007; Reynolds, Temple, Robertson, & Mann, 2001; Schweinhart, 1993). The lasting positive social and academic impacts of early educational intervention in general, and early exposure to science education in particular, have been demonstrated by numerous studies (National Research Council, 2007; Reynolds, Temple, Robertson, & Mann, 2001; Schweinhart, 1993; Sylva, & Wiltshire, 1993; Tao, Oliver, & Venville, 2012). Further, Cunha and Heckman (2007) have demonstrated the extreme difference in monetary return-on-investment of early childhood programs compared to adolescent or middle-childhood programs, with early-age programs costing 35% less than late-age ones. These findings have been summarized in a model of development that reveals skill and ability acquisition to be developmentally cumulative, meaning that children who attain high achievement in one grade tend to remain high achievers in the next grade (Cunha & Heckman, 2007). These positive effects are thought to be even more pronounced in schools servicing lower- and middle-income families, where high-quality educational resources and early access to materials are often not available, resulting in these students starting off at a disadvantage relative to their peers who benefitted from early interventions (Judge, Puckett, & Cabuk, 2004; National Research Council, 2007; Tao, Oliver, & Venville, 2012).

Additionally, research into young children's developing identity awareness has revealed that children as young as age 4 are developing potentially harmful stereotypes about their own ability to participate in STEM fields (Sullivan & Bers, 2018). Girls and minorities in particular are thought to be excluded by traditional practices and attitudes in STEM classes, leading to lower involvement later in life, and low representation of women and minority professionals in STEM fields (Hill, Corbett, & St. Rose, 2010; Lummis & Stevenson, 1990; Metz, 2007). Fortunately, early intervention has been shown to combat these stereotypes. After a 6-week robotics intervention led by female teachers in a classroom setting, Kindergarten girls (ages 5-6 years) demonstrated decreased levels of coded stereotypic thinking and higher positive attitudes towards STEM fields (Sullivan & Bers, 2018). Although this is a positive finding, it highlights the ineffectiveness of current educational standards and policies for bioengineering education. Natural sciences curricula in the U.S. do not touch on microbiology until high school, and synthetic biology is reserved for higher education (NRC, 2007; NGSS, 2013). By this time, prohibitive and harmful stereotypes have already become firmly ingrained in people's self-identities (American Association of University Women, 2000; Steinke, 2017). Additionally, research on socio-economic status (SES) and parental attitudes shows that these stereotypes may be reinforced and learning may be supported in the home differentially depending on how well-resourced the families are (Bradley & Corwyn, 2002; Hart & Risley, 1995). One study of 1,456 Turkish families with pre-Kindergarten children found that high-SES families were more likely to prioritize science as a learning goal for their children compared with lower-SES families, and families from any SES level are more likely to prioritize other academic domains such as literacy and math to the exclusion of science (Saçkes, 2014). If our educational policies are going to serve traditionally excluded groups in this emerging STEM field, then exposure to foundational experiences with bioengineering must begin much earlier in a child's development.

Developmental and Epistemological Perspectives on Bioengineering Education in Early Childhood

Piaget: Cognitive Development and the 5-to-7 year shift

Developmentalists agree that children aged 5-7 years are in a critical transitional year for cognitive development (Sameroff & Haith, 1996). As early as 1928, Jean Piaget's famous clinical interviews with children demonstrated the quantitative shift in logical reasoning in this age range, with children spontaneously developing the ability to operate on quantities, conserve mass, and imagine spatial perspectives (Piaget, 1928). Piaget argued for stage-wise development, a progression of growth in children that consists of a self-organized sequence of growth in which milestones and plateaus develop within the child's mind (Piaget, 2013). He also proposed that developmental change stems from a child's interactions with the world around her, a concept he termed Constructivism (Ackermann, 2001; Piaget, 1928; Piaget, 2013; Piaget & Inhelder, 1967. Piaget's work on genetic epistemology, or the origin of knowledge in children, laid the groundwork for decades of research based on the premise that children's early reasoning does not represent a deficit or a gap in knowledge, but rather a qualitatively different system of thinking from that of adults (Sameroff & Haith, 1996). Research has since consistently yielded evidence to support Piaget's notion, that children's logic is not simply immature and incorrect, but rather adheres to its own internal consistency (e.g. Corman & Escalona 1969; Elkind, 1961a; Elkind 1961b).

Since Piaget's seminal work, cognitive researchers have continued to investigate the unique mental models and cognitive strategies of children aged 5-to-7 years. Karmiloff-Smith and Inhelder (1974) conducted several experiments in which children aged 4 to 9 years old balanced wood pieces with hidden weights on a balance bar. Children in the youngest range of the experiment (4 to 5.5 years) successfully used trial-and-error methods to find the balance point, while children in the middle range (5.5 to 7.5) were more likely to attempt pre-meditated methods (e.g. always starting with balance in the middle) and to demonstrate more failure at balancing as they progressively worked with the beams and attended to multiple factors (e.g. weight and length). The study concluded that children were exhibiting changes in their theories-in-action, the "implicit ideas or changing modes of representation underlying [their actions]" when they shifted from simple trial and error to deeper exploration of the beams and why they balanced (Karmiloff-Smith & Inhelder, 1974, pp. 196).

In other words, 5-7-year-olds are just as capable as younger children at successfully completing a cognitive task, but they are more likely to continue to explore using alternative and more complex approaches. Similar studies in areas of map-drawing and language (Karmiloff-Smith, 1984), mathematics (Blanton, Brizuela, Gardiner, Sawrey, & Newman-Owens, 2015; Siegler & Jenkins, 1989), science inquiry (Kuhn, Amsel, & O'Loughlin, 1988; Schauble, 1990), and computer science (Lawler, 1985) have confirmed this pattern of early success followed by later discovery (and failure) in the same task in this 5 to 7 year age group. Developmentalists are far from articulating the exact mechanisms of children's cognitive development during this time, but the evidence is overwhelming that ages 5 to 7 years are a critical period for children's learning and growth. Based on this body of research, I hypothesize that a child's ability to understand foundational concepts of bioengineering such as living and non-living materials, genes, and programmed instructions might alter dramatically between ages 5 and 7 years.

Bruner: Structure of the Discipline

Several decades after Piaget published his initial theories of cognitive development, psychologist Jerome Bruner advanced a controversial argument called the curricular hypothesis, in which he argued that "any subject can be taught in some intellectual honest form to any child at any stage of development" (Bruner, 1960/1996, p. 33). The underlying principle of this hypothesis is that any "academic discipline can be transformed via various modes of representation," (Deng, 2004, p. 152). By this logic, curriculum developers can adapt learning content to the developmental readiness of the learner rather than waiting for children to develop to a level where they can understand the formal or professional structures of the domain (Deng, 2004; Takaya, 2008).

Bruner’s hypothesis suggests that curriculum content should be organized according to the “structures of the disciplines,” which he loosely defines as “the most fundamental understanding of that field,” as identified by the “ablest scholars and scientists” (Bruner, 1960/1996, p. 32). Critics argue that this approach ignores the historical context within which a discipline emerged, in addition to leaving the core learning goals of any domain open to interpretation (Deng, 2004). Bruner’s response to these critiques is rooted in his assertion that “intellectual activity is the same, whether at the frontier of knowledge or in a third grade classroom” (Bruner, 1960/1996, p. 14), and thus educational content should reflect the real and authentic needs of the discipline’s professional, scholarly, and community societies. Another critique of the curricular hypothesis is that it does not address the challenge of how to make necessarily abstract or distant information more accessible to children’s everyday lived experience, in keeping with Piaget’s theory of Constructivism (Dengk 2004; Takaya, 2008). Deng (2004) theorized that early in his career, Bruner would have taken this critique as a matter of course, considering his argument in other work that the development of abstract ideas requires “a weaning away from the obviousness of superficial experience” (Bruner 1962/1979, p. 121).

Bruner’s structure of the discipline hypothesis is useful in shaping the initial curricular goals of any novel learning domain being introduced to a formal or informal learning setting. However, Bruner’s instructional methods for how to implement such a curriculum rely too heavily on memorization and abstraction to be meaningfully applied in the early childhood settings. In order for a learning intervention to be successful in the way Bruner describes, it must offer developmentally-appropriate activities and representations that build on children’s everyday lived experiences, in order to leverage their natural inclination toward concrete, experiential learning.

Dewey and Vygotsky: Learning in Context

The primary challenge with bioengineering education is that most of the processes happen at the microscopic level. Children must rely on powerful imaginations to conceive of even the most fundamental concepts, leading to the curricular challenge of how to present meaningful and accurate representations of bioengineering processes. John Dewey noted this exact challenge when he posed his continuity of experience principle in 1916, in which he pointed out that a learner's prior experience serves as "an intellectual starting point for moving out into the unknown" (Dewey, 1916/1996, p. 212). He argued that education is a continuous process of constructing and reconstructing meaning that forms the basis of knowledge, which necessarily begins with the learner's personal and lived experiences (Deng, 2004). Dewey acknowledged that for novel domains, this presents "the problem of discovering ways and means of bringing [ideas and concepts] within [children's] experience" (Deng, 2004; Dewey, 1938/1997, p. 73). However, other researchers have pointed out that this problem has always existed, and that children have creative ways of getting around this issue.

Developmentalist Lev Vygotsky rejected strictly individual-psychological explanations of learning and knowledge (including Piaget's Constructivism), arguing that these approaches only account for one aspect of learning, but ignore the role of culture and society in shaping children's development (Vygotsky, 1930/1981). According to his sociocultural theory, children necessarily approach new domains through socialization and cultural experience, first encountering ideas through interactions with others, and later, internalizing a form of the idea for themselves (Vygotsky 1930-1934/1978). Other researchers have explored this perspective as well (e.g. Gopnik & Wellman, 2012; Harris, 2012). For example, in his book *Trusting What You're Told,* Paul Harris outlined the ways that children learn about ideas that are invisible (e.g.

germs, oxygen), ambiguous (e.g. God, Santa Claus), and magical (e.g. mermaids, giants) (Harris, 2012). Because this information is gathered primarily through the testimony of adults, children must develop strategies to decide what is accepted as "real" information, and what is make-believe or pretend. The research summarized suggests that children at age 5-6 years attend to a range of factors centered around the person who communicated the new information, including their prior history of socializing with the person, the amount of credibility apparently shown to them by others, and the ease with which they can respond to probing, explanation-seeking questions. Eventually, children come to generally trust adult caregivers as reliable informants about hidden reality (Harris, 2012).

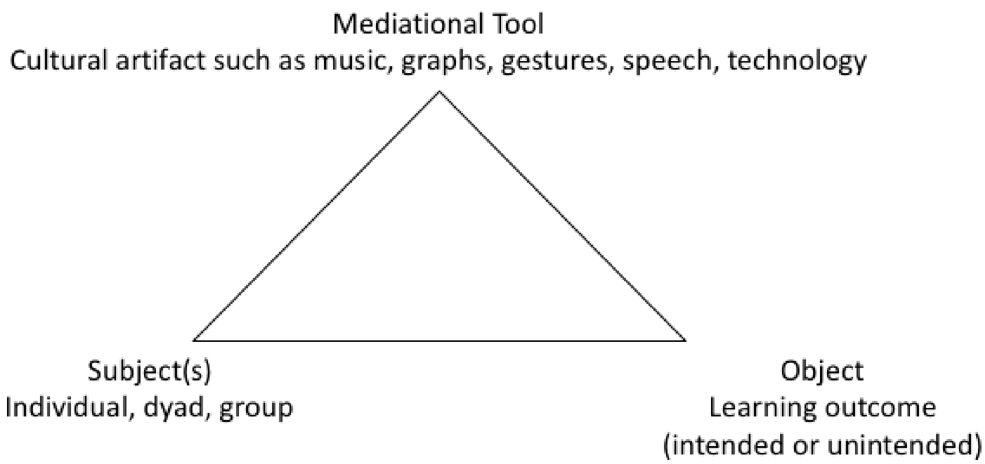


Figure 2. Vygotsky's Mediational Triangle. (Adapted from Edwards, 2005)

In his Activity Theory Model, Vygotsky further argued that the artifacts of culture act as mediators for transmitting information, saying "alongside the acts and processes of natural behaviour, it is necessary to distinguish the functions and forms of artificial or instrumental behavior, […because instruments] replace and render useless a considerable number of natural processes, the work of which is developed by the instrument" (Vygotsky, 1930/1981, p. 40-42). In other words, Vygotsky believed that cultural instruments - including language, symbols, artifacts, and technologies – all mediate relationships between the learner and the environment that are qualitatively different from non-mediated ones (see Figure 2) (Vérillon, 2000). Taken together, this literature suggests that a bioengineering intervention for young children should rely on concrete, lived experiences as an entry point to more abstract ideas. Further, cultural practices such as storytelling, imaginative play, and tools to support mental representations can all aid children's developing conceptualization of ideas that are impossible to experience first-hand, such as genetic engineering.

Papert: Powerful Ideas and Technological Tools for Learning

Vygotsky wrote broadly about psychological tools because he recognized that all human tools are heavily influenced by cultural context and are constantly evolving. Today, children's psychological toolkits include computers, robotics, and programming languages in addition to rhymes, crayons, and picture books. Seymour Papert, a prominent computer scientist who studied genetic epistemology with Piaget, took up Vygotsky's approach of focusing on children's tool-supported learning. He argued that when children use technological tools such as computers to produce and create content, the interaction transforms from a passive learning environment to a meaningful and personally-directed one (Papert, 1980). In his theory of Constructionism (an extension of Constructivism that emphasizes virtual and digital play), Papert argued that children can engage in qualitatively new learning experiences through the use of computer technology as they create and alter novel constructions and test theories through the act of programming their own rules in a digital world (Papert, 1980; Bers, 2018).

Papert coined the phrase "powerful idea" to refer to concepts that are cross-cutting and impactful even beyond their immediate disciplines (Papert, 1980, p. 132). It is useful here to distinguish between powerful ideas and another term, wonderful ideas, coined by Piagetian scholar, Eleanor Duckworth (Duckworth, 1972). In her recommendations for applying Constructivist theory to curricular settings, Duckworth explains that wonderful ideas are personally-meaningful and transformative ideas that are developmentally constrained, and reflect a growing complexity in a child's ability to use new information to synthesize old knowledge or inspire a quest for new knowledge. Wonderful ideas reflect an individual child's personal development, but they are distinct from powerful ideas, which are grounded in a specific culture, history, and epistemological tradition (Bers, 2017). Powerful ideas, therefore, are not only impactful for child's personal development, but for the child's developing identity and role as a member of their society and culture. For example, democracy is a powerful idea from the field of civics, and algorithmic logic is a powerful idea from computer science, not only because it offers children a new way to resolve a schoolyard dispute, but also because it offers them a lens to understand a governmental structure, perhaps even the one that governs their own society. Through creative, open-ended programming, children can engage with powerful ideas from fields of literature, communications, logic, mathematics, fine arts, civics, and more (Bers, 2018; Resnick, 2006). In his seminal book, *Mindstorms*, Papert argued that there are three core principles that allow children to engage with the powerful ideas of a novel or intimidating domain: 1) the *continuity principle*, that domain must be "continuous with well-established personal knowledge from which ideas can gain a warmth and value as a 'cognitive' competence"; 2) the *power principle*, that the topic must empower the learner to develop meaningful projects that would not be possible without the domain; and 3) the *principle of cultural resonance*, meaning the domain must make sense and connect to the child's larger social context (Papert, 1980, p. 54). Papert also emphasized the importance of physical and tangible technological tools, as they leverage children's physical and intuitive knowledge that they collect from their bodies, which he called "body-syntonic" learning (Papert, 1980, p. 205). All of these principles offer pedagogical structure for the development of technological tools to aid children's engagement with powerful ideas from bioengineering.

In the next sections, I return to Bruner's idea of the structure of the discipline to outline the proposed structure for the domain of bioengineering which guided the intervention used in this study. I explore the constituent disciplines of bioengineering to arrive at a set of powerful ideas to guide the development of a bioengineering curriculum. Following Vygotsky's recommendation to offer tools that support children's mental representations, I also describe research on existing educational technologies to support children's engagement with powerful ideas from abstract domains.

Towards the Powerful Ideas of Early Childhood Bioengineering Education

Many questions still remain about how to implement bioengineering education in a developmentally appropriate way. Since bioengineering is by definition an interdisciplinary field, I chose to begin by drawing concepts and practices from the fields of engineering, life science, and computer science (Endy, 2005; Kuldell, Bernstein, Ingram, & Hart, 2015). Developmental researchers have investigated 5-7 year old children's cognitive growth as they explore these evolving educational domains. In the next sections, I will unpack each domain before presenting a proposed list of powerful ideas from the novel domain of bioengineering.

Science Education

Of the three subdisciplines that directly contribute to bioengineering, science education and knowledge has received the most rigorous investigation from developmentalists (e.g. DeBoer, 1991; Demetriou, Shayer, & Efklides, 2016; Driver & Erickson, 1983; Duit, 2016; Kelly & Licona, 2018). Dewey wrote that "the development of scientific attitudes of thought, observation, and inquiry [should be] the chief business of study and learning" (Dewey, 1931, p. 60), and suggested that knowledge in itself has no meaning when divorced from its process of inquiry (Deng, 2004; Kuhn, 1997). Despite the fact that many developmentalists agree (to varying degrees) on a stage-like progression of children's cognitive developmental achievements, the literature on the growth of science knowledge "appears to be moving away from a view of epistemic reasoning as stage-like [and] toward a view of students' reasoning as variable and context-dependent" (Metz, 2011, pp 54). Driver, Newton, and Osborne (2000) argue for a Vygotskian approach, saying that we cannot divorce the practice of science from its historical and social context, and therefore education should support argumentation-oriented science experiences.

How can we reconcile what we know about cognitive development in children ages 5-7 years, which is generally held to progress in a stage-like way, with science inquiry and design thinking, which have been shown to be variable and context-dependent across a range of ages? To address this question, researchers typically distinguish between "science inquiry", the process of asking and answering science questions, and "science content", the models, theories, and ideas that shape a cohesive understanding of scientific phenomena (Elby & Hammer, 2001, p. 554). In the next sections, I describe findings from research into children's developing science content knowledge, and then science inquiry. Science education theorists understand that both children and adults approach science activities with preexisting intuitions about the world around them to develop science content knowledge (Collins & Gentner, 1987; Driver & Easley, 1978; McCloskey & Kargon, 1988; Penner, 2000; White & Frederiksen, 1986). However, children typically show less cohesion and organization in their held beliefs (Hatano & Inagaki, 1994, McCloskey & Kargon, 1988). Hatano and Inagaki's (1994) research into children's naïve understandings of biology suggests that children predominantly form scientific theories by applying notions from their experiences with environmental activities (e.g. outdoor chores, raising animals) and health settings (e.g. dentist, doctor's office) to a global, vitalistic understanding of the natural world (Hatano & Inagaki, 1994). Generally, the science education research community agrees that these intuitive theories do not represent misconceptions or learning failures, but rather appropriate transitional ideas as children progress towards adult-level science theories (Gopnik & Wellman, 2012; Hatano & Inagaki, 1994; Kuhn, 1997; Vosniadou & Brewer, 1992).

Metz (2011) has investigated the potential for young children to apply their intuitive science knowledge and developing theory of mind toward science inquiry. Based on her findings, Metz recommends "a curricular design that foster[s] the students' personal investment in taking their ideas, claims, and methods as critical objects of thought" (Metz, 2011, pp. 106). In particular, she recommends allowing opportunities for children to practice self-directed inquiry to more deeply engage with science content. She also calls for educators and researchers to focus on "big ideas that transcend domain" so that children can immerse themselves in the experience of science as a discipline, and connect scientific approaches (e.g. inquiry, experimentation, critical evaluation) to domains outside of science (Metz, 2011, pg. 60).

Based on findings described above, the current study explores the transitional ideas that children exhibit as they progress toward an adult-level understanding of bioengineering. Since this field is novel and poorly understood even among adults, the research will also shed light on what distinguishes "appropriate" transitional ideas about bioengineering from misleading ones. Additionally, I applied Metz' (2011) recommendations for supporting children's self-directed inquiry to the design of the current study intervention, in order to engage them in the “big ideas” of bioengineering.

Engineering Education

In the past few decades, engineering education and learning settings (e.g. makerspaces) have become more popular as an educational domain in early childhood (Daley & Child, 2015; Martinez & Stager, 2013; Peppler, Halverson, & Kafai, 2016). Recent learning standards have introduced engineering as an application of science practices and concepts (e.g. Massachusetts Department of Elementary and Secondary Education [DOE], 2016; NGSS, 2013). Science and engineering share key features, such as design thinking and exploration, but they differ in important ways. Most specifically, the primary goal of science is to generate information through observation and experimentation, while the purpose of engineering is to build artifacts to solve problems (Cunningham & Kelly, 2017). The Engineering Design Process has become the analogue of science inquiry and the Scientific Method in engineering education, and it involves steps of identifying a problem or question, conducting research, developing a plan, building a model or prototype, testing the prototype, redesigning, and sharing solutions with other engineers and with the client who will use the finished prototype (Bers, 2014). Using this design process to structure engineering activities can support children as they learn to move from scoping a problem to solving it (Wagh, Gravel, & Tucker-Raymond, 2017).

Engineering education also represents a unique way for young children to hone cognitive and social skills that emerge between ages 5-7 years. Practitioners and researchers have connected engineering education to constructivism, because of the theory’s emphasis on engaging with the physical world to construct ideas and understand problems (Briede, 2013; Genalo, Schmidt, & Schlitz, 2004; Hadjerrouit, 2005; Martinez & Stager, 2013; Piaget, 1928;

Van Meeteren, & Zan, 2010). In line with Vygotsky's sociocultural theory, children can also benefit from engineering practices of collaborating in a group setting, considering the social context in which the engineered work is created (Tucker-Raymond & Gravel, 2019). For this reason, engineering programs for K-12 students often focus on community-building and social justice as the broad context in which engineering takes place, engaging children in problem solving to help their own classroom, school, or neighborhood (Riley, 2008; Thiel, 2015; Wohlwend, Peppler, Keune, & Thompson, 2017).

Based on engineering practices that are common among children and adults, Cunningham and Kelly (2017) propose 16 epistemological practices of engineering that children can and should explore, including working in a collaborative team to solve human problems, designing material artifacts, and comparing designs as a method of evaluating them. They concede that these practices are not unique to engineering, but instead represent cross-cutting disciplinary skills that can support engineering practices in a variety of content areas which will depend on the design challenge. This approach recalls Metz' recommendation to focus on "big ideas" of science inquiry rather than specific details of content.

Computer Science Education

Papert proposed that a programming language is a unique psychological tool (or as he called it, "transitional object" or "object-to-think-with"), because children can use it as a medium of exploration and creativity to explore powerful ideas through their design process (Papert, 1980, p. viii). He argued that a technocentric focus on a specific computer programming language as a learning outcome is too narrow, but a broad emphasis on programming as a medium of expression and communication supports children's understanding of powerful ideas from computer science and beyond. Papert's concept of powerful ideas subsumes Metz' (2011) big ideas of science inquiry and Cunningham and Kelly's (2017) epistemological practices of engineering, offering a framework to focus on the content and practices of any field that are applicable to many settings in professional and everyday life.

Bers writes that children can "use technology to make positive contributions to the development of self and of society" (Bers, Lynch, & Chau, 2009, pg. 22). She goes on to list six positive behaviors that children exhibit when engaging in developmentally appropriate digital explorations (Bers, 2012). These include three interpersonal skills of communication, collaboration, and community building, and three intrapersonal skills of content creation, creativity, and choices of conduct (Bers, Lynch, & Chau, 2009). This last behavior, choices of conduct, is especially relevant to bioengineering education. Prior research has demonstrated that although bioengineering educational initiatives emphasize the importance of ethical responsibility, bioethics is viewed by students and sometimes even by educators as an afterthought to the biodesign process (Balmer & Bulpin, 2013). They call for more research into how we can support bioengineering students to develop critical skills for identifying ethical dilemmas, evaluating consequences of different actions, and proposing solutions in their bioengineered designs.

Computational thinking has emerged as a core learning objective for computer science education in classroom settings (Barr and Stephenson 2011; ISTE, 2007; CSTA, 2011; Grover & Pea, 2013). Computational thinking is a term coined by Jeannette Wing, and refers to "the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" (Cuny, Snyder, & Wing, 2010; Wing, 2006). This type of thinking is reflected in many everyday tasks, such as planning the events in a day, learning the rules to a new game, following a recipe, or editing and revising an essay (Bers, 2018; Wing, 2006). Bers has operationalized this definition for a learning setting by identifying seven powerful ideas of computational thinking that children can engage with (see Figure 3).

Powerful Idea	**Related Early Childhood Concepts and Skills**
Algorithms	• Sequencing/order (foundational math and literacy skill) • Logical organization
Modularity	• Breaking up a large job into smaller steps • Writing instructions • Following a list of instructions to complete a larger project
Control structures	• Recognizing patterns and repetition • Cause and effect
Representation	• Symbolic representation (i.e., letters represent sounds) • Models
Hardware/Software	• Understanding that objects they interact with don't work by magic (i.e., cars, computers, tablets, etc.) • Recognizing objects that are human-engineered
Design process	• Problem solving • Perseverance • Editing/Revision (i.e., in writing)
Debugging	• Identifying problems (checking your work) • Problem solving • Perseverance

Figure 3. Powerful Ideas of Computational Thinking (Reprinted with author's permission from Bers, 2018).

Powerful ideas cut across disciplinary boundaries, meaning that bioengineering education will also rely on some of the computer science concepts presented above. For example, when learners engage with concepts of sequencing and editing genetic codes, they are also exploring computer science principles of algorithms and modularity. Bers' (2019) emphasis on positive technological development, and using technology to support communal values and goals, is a useful framework to respond to Balmer and Bulpin (2013)'s call for stronger emphasis on ethical decision making and systems-level focus in bioengineering education. Finally, programming technologies empower learners to construct and refine abstract mental models, which can support their understanding of abstract, microscopic, and time-spanning concepts that are foundational to bioengineering.

A Proposed List of Bioengineering Powerful Ideas

Papert defined a powerful idea as any concept that is “powerful in its use”, “powerful in its connections”, and “powerful in its fit with personal identity” (Papert, 2000, p. 727). He meant that in addition to being immediately functional and applicable in a range of settings, powerful ideas should also resonate with a child’s intuitive knowledge and experiences of the world. In seeking to define the foundational learning goals, or powerful ideas, of bioengineering, we can reflect on commonalities across bioengineering subfields. Papert’s focus on “powerful ideas” in computer science education echoes Metz’ call to engage children in domain-transcendent ideas of science, and Cunningham and Kelly’s emphasis on epistemological practices of engineering for young children (Cunningham & Kelly, 2017; Metz, 2011; Papert, 1980). Thus, a foundational approach to bioengineering should share a focus on cross-cutting concepts and transferrable practices, rather than detailed technical facts.

In choosing specific content to focus on, we may base the foundational ideas of bioengineering on other concepts that are already explored in early childhood learning settings. For example, according to the Next Generation Science Standards (a K–12 science content standards framework developed collaboratively by the National Research Council, the National Science Teachers Association [NSTA], the American Association for the Advancement of Science [AAAS] in the US) (NGSS, 2013), by third grade, children should understand that living organisms like plants and animals inherit traits from their parents (Standard 3-LS3 Heredity: Inheritance and Variation of Traits); that these organisms have unique life cycles (Standard 3-LS1 From molecules to Organisms: Structures and Processes); and that engineers solve human problems by weighing the consequences of various solutions and choosing the best course of action (Standard 3-5-ETS1 Engineering Design). All of these concepts are foundational to the field of bioengineering (Kuldell, Bernstein, Ingram, & Hart, 2015).

Based on a synthesis of research presented here, and informed by powerful ideas from contributing fields of engineering, computer science, and biology, I've arrived at the following preliminary table of suggested powerful ideas from the field of bioengineering (see Table 1) (Bers 2018; Kuldell, Bernstein, Ingram, & Hart, 2015; Metz, 2011; NGSS 2013; Penner, 2000; Wagh, Gravel, & Tucker-Raymond, 2017).

Table 1

Powerful Ideas for young children from fields related to Bioengineering

Computer Science PIs	**Engineering PIs**	**Life Science PIs**
• Algorithms[a] • Modularity[a] • Control Structures[a] • Representation[a] • Hardware/Software[a] • Design Process[a] • Debugging[a]	• Decoupling/Abstraction[b] • Standardization[b] • Modeling[c] • Design Process[d] • Ethical Design[e]	• Abstraction[f] • Gene sequences[f] • Probability/Mutation[g] • Heritability[h] • Inquiry[i]

[a]Bers (2018, p. 78). [b]Endy (2005, p. 451). [c]Brizuela & Gravel (2013). [d]Brophy, Klein, Portsmore, & Rogers (2008, p. 377). [e]National Human Genome Research Institute. (2018). [f]Kuldell, Bernstein, Ingram, & Hart (2015, p. 12). [g]Papert (2000, p. 725). [h]Pilnick (2002, p. 13). [i]Metz (2011, p. 51).

Taking inspiration from Bruner's concept of the "structure of the discipline", I propose the following initial concept map to highlight the most relevant and foundational powerful ideas needed to understand the discipline of bioengineering. Specifically, the three core ideas I have identified are: biodiversity through genetics (from biology), coding languages to organize instructions (from computer science), and design to solve human problems (from engineering). These three ideas are all foundational to the core learning goal of bioengineering that my research team used to design the CRISPEE intervention, and that I used to guide this study design: “Design living solutions to human problems using genes as a coding language”. In Figure 4 below, I visually represent how each subfield concept is bidirectionally related to the bioengineering concept, to indicate how advances in one domain iteratively impact the scope of understanding and possibility in other.

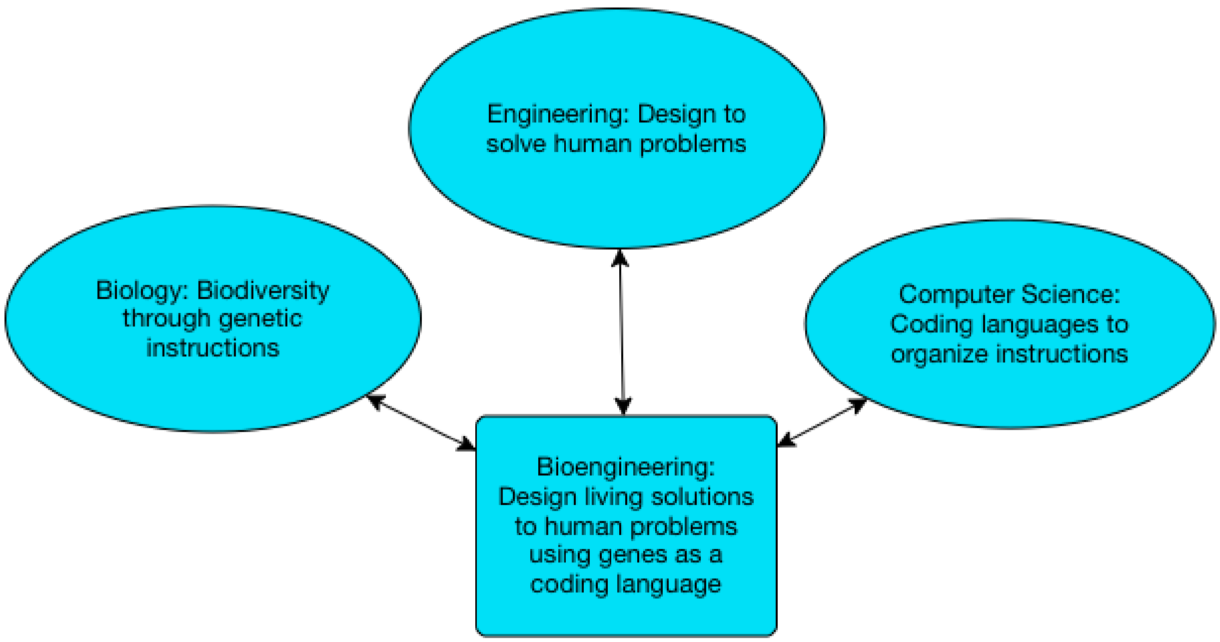


Figure 4. Proposed relationship of powerful ideas foundational to bioengineering.

These three powerful ideas can be broadly captured in the following domains: algorithms/sequencing, science inquiry/sensemaking, and the design process. Developmental research has shown that all three of these domains are critical for early learners to explore (e.g. Bers, 2018; Cunningham & Kelly, 2017; Metz, 2011; Sullivan, 2019). The following sections present a brief summary of research into these core areas and present an argument for these three concepts as the learning outcomes of interest in the dissertation research.

Learning Outcomes for a Bioengineering Education Intervention

Prior literature has demonstrated that sequencing, inquiry, and the design process are three domains that are critical for young children's early development and engagement with STEM domains. In the following section, I summarize research in these three domains and describe how they are relevant to foundational bioengineering content.

Algorithms and Sequencing

Algorithmic logic encompasses a wide range of skills and activities, but most definitions agree that an algorithm is a sequence of steps ordered in a specific way to solve a problem or achieve some end goal (Bers, 2018; Brennan & Resnick, 2012; Horn, AlSulaiman, & Koh, 2013; Wing, 2008). Sequencing objects, actions, or ideas is a foundational skill for young children, with cross-cutting connections to math (Purpura & Lonigan, 2013; Sarama & Clements, 2003), language and literacy (Brown, 2014; Snow & Matthews, 2016), and computational thinking (Bers, 2018; Brennan & Resnick, 2012; Kazakoff, Sullivan, & Bers, 2013). As a bioengineering concept, sequencing is critical to understanding the nature of genes as a series of instructional commands for the growth and functioning of living organisms (Ananthanarayanan & Thies, 2010; Kuldell, 2007).

Studies of young children and sequencing have demonstrated that early intervention with tangible technologies can support the development of this foundational understanding (Kazakoff, Sullivan, & Bers, 2013; Horn & Bers, 2019; AlSulaiman, & Koh, 2013). In one pilot study, researchers compared children's performance on a story-based picture-sequencing task before and after an intervention with a robotics kit designed for early childhood (Kazakoff, Sullivan, & Bers, 2013). Results showed that after a brief 5-day school-based intervention, children showed a statistically significant increase in their ability to order pictures in a logical way that followed a story-based plot. Bers writes that although algorithmic logic relies on computational thinking skills of representation and abstraction, the most foundational way to engage with algorithms is through sequencing (Bers, 2018). Children encounter sequencing in everyday experiences such playing rule-based games, getting dressed in the morning, and singing songs or telling stories from beginning to end. As children grow, they encounter more complicated algorithms, such as repeating loops (i.e., algorithms that repeat in whole or in part, such as the repeating chorus in a favorite song) and parallel sequences (i.e., multiple algorithms that happen simultaneously, such running while dribbling a basketball). As a bioengineering idea, algorithms can also extend beyond simple selection of genes. For example, certain genes actively switch on and off depending on environmental triggers, which conceptually ties into algorithmic principles of conditional and branching sequencing. For the purposes of the current study, I align with Bers' suggestion to focus pedagogical intervention on linear sequencing as the most foundational aspect of algorithms (Bers, 2018, p. 71), and I will refer to algorithmic logic and sequencing interchangeably.

Science Inquiry and Sensemaking

Inquiry in science education is the broad set of practices and activities that students use to develop knowledge and understanding of their own scientific ideas, as well as to learn the methods of professional scientists (National Research Council, 1996, p. 23). Elsewhere in this chapter, I've addressed research on young children's developmental capacities for engaging in general science inquiry practices (e.g. Lazonder & Harmsen, 2016; Metz, 2011). Sensemaking is an inquiry practice that relates specifically to identifying a gap in one's knowledge and using creative strategies to generate understanding, such as making connections to the real world or one's lived experience (Chen, Irving, & Sayre, 2013; Lindfors, 1999). Bioengineering is a novel field that children have very little first-hand experience with, thus learners must engage in some level of sensemaking to explore the concepts and topics in this field. For the purpose of this dissertation, I will focus on sensemaking as the primary evidence of inquiry in children's thinking.

In their summary of the sensemaking literature, Odden and Russ (2019) define sensemaking as "a dynamic process of building or revising an explanation in order to 'figure something out'", and note that these explanations are built with a combination of everyday and formal knowledge (Odden & Russ, 2019, p. 191-192). This definition positions sensemaking in three strands: 1) sensemaking as an epistemological stance, or the intention and motivation to clarify some gap in knowledge; 2) sensemaking as a cognitive process, or the actual work of blending prior experience and formal knowledge to cultivate various explanations; and 3) sensemaking as a discursive practice, or the ongoing dialogue that learners use (either in their minds or with others) to weigh evidence and refine their explanation (Odden & Russ, 2019). While all these strands are important and interconnected in practice, I will focus in the current study on the second strand, sensemaking as a cognitive process.

Other researchers who have examined this strand include developmentalists Karmiloff-Smith and Inhelder, who investigated "a child's action sequences and his implicit theories which the observer infers" (Karmiloff-Smith & Inhelder 1974, p. 195). In their research on children's exploration of physical blocks in a balancing task, they found that the "construction and overgeneralization of 'theories-in-action' appear to be dynamic and general processes which are not stage-linked" (Karmiloff-Smith & Inhelder, 1974, p. 195). I predict that these kinds of ideas will emerge as a pivotal unit of study as children engage with the novel CRISPEE prototype, another tool that requires children's physical exploration to understand. Similarly, diSessa (1993) and others have argued that children's sensemaking can be explained by the Knowledge in

Pieces (KiP) framework, in which children bring many intuitive pieces of knowledge (also called knowledge resources) to their learning experiences and add new ones through their lived experiences. They continually connect and revise connections between these knowledge pieces in order to shape a cohesive understanding of some phenomenon (Hammer, Elby, Scherr, & Redish, 2005; Sherin, 2006). From this perspective, sensemaking is the idiosyncratic process of iteratively exploring various connections or seeking new pieces of information to connect to existing pieces to resolve gaps in knowledge (Clark, 2006). By exploring children's changing explanations of bioengineering concepts throughout the intervention, I aim to develop an understanding of children's attempts to make sense of these concepts and reconcile them with their existing and intuitive knowledge resources.

The Design Process

The design process is a learning structure that has far-reaching cross-disciplinary connections to domains such as science, math, fine art, writing composition, and computational thinking, but is often linked with STEM education (Brophy, Klein, Portsmore, & Rogers, 2008; Bybee, 2011). In most fields, the design process consists of a series of steps, including asking a question or recognizing a problem, investigating and planning possible solutions, creating and iterating on a design, and finally sharing or enacting the designed solution to address the identified problem (Bers, 2018; Brophy, Klein, Portsmore, & Rogers, 2008; Ertas & Jones, 1996). The engineering design process has been used in education to engage children in creative problem solving and perseverance through failure (Andrews, 2014; Bybee, 2011). Design is also critical in computer science education, where the steps of the design process are used to organize thinking and help learners engage in planning and debugging their coded creations (Bers, 2018; Knochel & Patton, 2015).

The design process is an essential part of bioengineering, as scientists must engage in an iterative cycle of investigation, exploration, and refinement to create living solutions that address design challenges without disrupting natural processes and environments (Balmer & Bulpin, 2013; Kuldell, 2007; National Human Genome Research Institute, 2018). Because the consequences of novel biological designs are relatively unknown (e.g. Popp & Yock, 2008), a bioengineering curriculum must emphasize the ethical dimension of bioengineering work (Balmer & Bulpin, 2013). Fortunately, pilot research into children's ability to engage meaningfully with biological design has yielded promising results. In an investigation of BacPack, a tangible museum exhibit for exploring bio-design, researchers found that learners of all ages were able to engage in problem-solving and collaboration to create their biological designs (Loparev et al., 2017). They also found that children sustained their design activity through at least one design cycle, including planning, testing, and observing a simulation of their design (Loparev et al., 2017). In another study, 3rd-5th grade children in a 1-week educational bioengineering workshop engaged in engineering and biological design to explore the challenges of exploring outer space (Strawhacker, Bers, Verish, Sullivan, & Shaer, 2018). Children engaged in a simulation-style videogame to cultivate biological materials and use them to build mechanical parts needed to survive on Mars, and results showed that the design process helped children learn biological design concepts such as different uses for natural materials and bacteria. The current study explores ways to engage children at an even younger age in meaningful biological design, with an emphasis on the ethical constraints of working with living materials. This work is imperative given prior research (e.g., Balmer & Bulpin, 2013) that suggests high school and college students who are able to successfully construct viable biodesigns show difficulty explaining even basic ethical implications or consequences of their ideas.

Tangible technology to support engagement with Sequencing, Inquiry, and Design

As technological advances have allowed computers to become more physically interactive and intuitive, research has increasingly demonstrated the value of tangible tools as educational supports (Bers, 2008; Horn & Jacob, 2007; Ishii & Ullmer, 1997; O'Malley & Fraser, 2004; Shaer & Hornecker, 2010). Part of the appeal for learning is that tangible, physical computing allows learners to leverage spatial knowledge and kinesthetic forms (e.g. gestures, muscle memory) to engage in physical explorations of the information that the tangible objects represent (Blikstein, 2013; diSessa & Abelson, 1986; Papert, 1980). Particularly for early childhood, tangible tools represent a way to playfully engage with abstract ideas from a variety of disciplines by engaging with developmentally appropriate and familiar materials such as blocks and stickers (Horn & Bers, 2019; Resnick, Ocko, & Papert, 1988; Schweikardt & Gross, 2006).

Many tangible technologies for children today are actually programming languages for creative expression and problem-solving, which leads naturally to learning opportunities about sequencing (Bers, 2008; Flannery et al., 2013; Horn & Bers, 2019; McNerney, 2004). Brick-based systems, such as AlgoBlocks (McNerney, 2004), Slot Machines (McNerney, 2004), and the KIBO Robot (Bers, 2008) allow children to explore even complex algorithmic concepts like repeat loops and conditional statements, without detailed syntax rules that can overwhelm novice programmers (Horn & Bers, 2019; McNerney, 2004). In a study on the comparative effect of tangible and graphical (screen-based) interfaces on children’s ability to learn sequencing with LEGO WeDo robots, Strawhacker and Bers found that after a 6-week robotics intervention children who learned first with the tangible interface had a stronger understanding of foundational sequencing rules and programming instructions (Strawhacker & Bers, 2015).

Research is still ongoing regarding the success of using tangible technologies to support science inquiry, but research with screen-based tools has yielded promising results (Casey, Kersh, & Young, 2004; Hill, & Hannafin, 2001; Pange, 2003; Pelletier, Reeve, & Halewood, 2006). In one review of technology-supported inquiry learning, the authors note that twelve different technological tools that supported early and elementary-aged children's inquiry learning were also able to support children's learning of experimentation and simulation, resource gathering and verifying, and problem scoping, and critical dialoguing with other investigators (Wang, Kinzie, McGuire, & Pan, 2010). The authors further contend that "technology may encourage children to reflect on, and recognize discrepancies in, their own thinking by allowing them to review their own theories and compare those theories to others" (Wang, Kinzie, McGuire, & Pan, 2010, p. 385)

Tangibles have also been shown to engage children in biological design thinking (e.g. Loparev et al., 2017; Okerlund et al., 2016). Tangible and simulation-based technologies are useful in this area, because they allow children to engage with core metaphors of biological design without learning prohibitively challenging details of growing biological organisms (Kuldell, 2007; Loparev et al., 2017), not unlike the way that simple programming languages eliminate the need for children to master complex syntactic forms (Bers, 2018; Flannery et al., 2015). Children can use programming languages to plan, build, and revise their imagined digital creations. As children engage in this playful exploration, they are also engaging in important steps of the engineering design process, such as asking questions, designing solutions, testing and iterating on their ideas, and communicating their design with others (Brophy, Klein, Portsmore, & Rogers, 2008). Once children have learned the mechanics of a coding language, they can then begin to use it as a platform to realize their own creative ideas. Educational initiatives for older children have likened gene editing to “programming”, and use this programming platform to edit living organism to pre-determined specifications (Balmer & Bulpin, 2013). Given that tangibles have been shown to support young children’s engagement with engineering design (e.g. Bers 2014; Pinto & Osório, 2019), and design of biological systems (e.g. Loparev et al., 2017; Okerlund et al., 2016), the current study aims to develop a tangible tool to engage children in ethical biological design.

The CRISPEE technology presented in this study was built according to design principles widely acknowledged by the child-computer interaction community to support early learning, including using visual symbols instead of text-heavy displays (Druin et al., 2001), offering highly responsive digital feedback to support gestures (Said, 2004), affording opportunities for children to design their own digital creations (Bers 2019; Resnick, 2006), and constructing technologies out of familiar household or naturally-occurring materials such as wood, felt, and Velcro (Bers, 2008; Johnson, Wilson, Blumberg, Kline, & Bobick, 1999).

Informal Learning Settings

In addition to technological tools, developmental scientists understand the importance of the educational environment to supporting children’s learning (Harms, Clifford, & Cryer, 2014; Kuh, Ponte, & Chau, 2013; Pianta, La Paro, Payne, Cox, & Bradley, 2002; Strong-Wilson & Ellis, 2007). Informal learning spaces such as makerspaces, libraries, camps, and after-school settings, have been shown to support rich engagement with educational domains, particularly STEM subjects (e.g. Bernstein & Puttick, 2014; Gonsalves, Rahm, & Carvalho, 2013; Schnittka, Evans, Won, & Drape, 2016). This is a promising finding, given the documented challenges in the implementation of inquiry and design learning in formal settings (Chinn & Malhotra, 2002; Edelson, Gordin, & Pea, 1999; Lazonder & Harmsen, 2016; Vartiainen, Liljeström, &

Enkenberg, 2012). Informal learning spaces can support free play and creative engagement with novel or complex topics that are more challenging to explore within the constraints of the classroom psychosocial setting (Brooks, 2011; National Research Council, 2009; Wood, 2014). In order to support children's playful engagement with novel and abstract concepts of bioengineering, all research sites presented in this dissertation were chosen because they were designed specifically as informal learning environments for young children (Bers, Strawhacker, & Vizner 2018; Cohen & McMurtry, 1985; Feber, 1987).

Summary

The current study takes up the challenge of exploring a pedagogy of the novel field of bioengineering for young children. Prior research and developmental theory suggest that young children are uniquely positioned to benefit from early experiences with creative, open-ended STEM experiences, thus the target participants for this study were children aged 5-8 years. Prior research also suggests that children's bioengineering learning may be supported by interventions involving tangible interactive technologies and informal learning settings, which are designed to support exploration of the following core learning concepts: algorithmic/sequencing logic, sensemaking/inquiry, and the design process. In the following chapters, I describe how I worked with an interdisciplinary research team to develop, implement, and evaluate a bioengineering technology and intervention.

Chapter 4. Statement of Problem

The Problem

Prior research from related STEM fields suggests that young children may yield long-term gains from exploring developmentally-appropriate concepts from novel STEM fields such as bioengineering (Bers 2018; Clements & Sarama, 2004; Cunha & Heckman, 2007; Kuldell, 2007; Okerlund et al, 2016; Reynolds, Temple, Ou, Arteaga, & White, 2011), but there is little research on educational technologies or resources to support children's curiosity and learning in this novel domain (Okerlund et al, 2016; Kafai, Fields, & Searle, 2014; Kuldell, 2007). Tangible technologies, which provide children qualitatively new, developmentally appropriate ways to engage with ideas and techniques, have been shown to support children's engagement with foundational ideas relevant to bioengineering, including sequencing, inquiry, and the design process (Bers, 2018; Loparev et al., 2018; Papert 1980; Wang, Kinzie, McGuire, & Pan, 2010). By applying developmentally appropriate constraints to the design of technologies, (e.g. through frameworks such as the Positive Technological Development; Bers 2012), designers can create technologies and curricular interventions to promote the positive learning that all children must engage in to become self-confident, thoughtful, contributing members of their community and society.

The purpose of this study was to investigate the iterative six-phase process of designing and developing the CRISPEE educational technology and curriculum to introduce foundational concepts of bioengineering to young children, ages 5-8 years old. One of the six phases was designed to explore how children use CRISPEE in a 10-minute museum-style play experience, and another focused on how children engage with bioengineering topics during a 15-hour informal CRISPEE curriculum intervention. This study explores children's interactions and activity during these experiences, in order to identify ways that the CRISPEE tool and curricular supports contributed to children's engagement with powerful bioengineering ideas of sequencing, inquiry, and ethical design. In the following sections, I describe the research questions under investigation, and the design-based methodological approach guiding the implementation of this study.

Research Questions

This study aims to explore that ways that the design intervention, including the CRISPEE technology and bioengineering curriculum, contribute to children's engagement with foundational bioengineering ideas by addressing the following research questions:

1. How do children interact with the CRISPEE technological prototype?
2. What can children learn from an educational bioengineering intervention?
3. How does a bioengineering educational intervention support children's learning in developmentally appropriate areas of bioengineering thinking? Specifically, areas of algorithms/sequencing, science inquiry/sensemaking, and the ethical design process.

Chapter 5. Methodology

This study was conducted as an educational design experiment (Brown, 1992; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003). Design-based research has two primary research aims. One is to develop novel learning innovations such as learning interventions, technologies, and environments that improve upon traditional educational approaches. The second is to contribute, through the iterative evaluation of these innovations, to the current theoretical understanding of *how* and *why* these interventions support participants' learning outcomes (Brown 1992; Edelson, 2001; Rosebery, Ogonowski, DiSchino, & Warren, 2010).

In the following sections, I describe the research setting and learning goals of the intervention. Following this, I characterize design research methodology and explain how I applied this approach to the development and evaluation of the CRISPEE intervention. The research team was actively involved in the educational implementation of the intervention, and documented our work in order to study first-hand the activity in the intervention setting that contributed to children's learning. Finally, I conclude with a section on the data collected in the final phases of this study and the procedure for analyzing these data to address my research questions.

Design Team

This investigation was part of a larger program of research conducted jointly by Tufts University's DevTech Research Group and Wellesley College's Human Computer Interaction Lab, with funding generously provided by the National Science Foundation (IIS-1563932). The broad goal of the project, called "Making the Invisible Tangible", was to investigate how to design developmentally-appropriate, tangible, reality-based interfaces that allow young children to engage in scientific investigations of abstract concepts in bioengineering (Loparev et al., 2017; Okerlund et al., 2016; Strawhacker, Bers, Verish, Sullivan, & Shaer, 2018).

Researchers from Wellesley mainly implemented technical design specifications, while researchers at Tufts generally developed learning materials and educational intervention protocols. In keeping with design research methodology (e.g. Brown, 1993; Rosebery, Ogonowski, DiSchino, & Warren, 2010), all researchers from both institutions were present during data collection. Over the course of the 1.5-year data collection cycle, the research staff fluctuated seasonally due to normal turnover in the academic setting (i.e. research assistants left the project to study abroad, travel for vacations, or switch jobs year-to-year). A total of 15 undergraduate, high school, and post-baccalaureate researchers collaborated on the project, with two professors (Marina Bers at Tufts and Orit Shaer at Wellesley) and two researcher coordinators (Amanda Strawhacker at Tufts and Clarissa Verish at Wellesley) remaining constant throughout the study. Except for occasional absences due to illness, both research coordinators and all active members of the design team were present for all design and instruction sessions. Amanda acted as instructor and Clarissa as documentarian for all curriculum intervention sessions. Research assistants acted as teaching assistants during curriculum interventions, and were trained to work one-on-one with children (following IRB-approved data collection protocols) during user-tests and assessments with participants.

In the 6th and final phase of research, teachers from the school research site assisted with the implementation of the camp, and the lead teaching assistant, who goes by Katie according to her preference and the school’s custom of address, contributed as a research collaborator through post-intervention meetings with the lead researcher about the design of the curricular intervention. Katie is an experienced teaching assistant, with four years of experience at two different private schools. See chapters 7 and 9 for a discussion of Katie's contribution to the interpretation of the curricular intervention.

Research Setting and Recruitment

Research was conducted at a variety of settings over the course of this six-phase study, including user-testing sessions at Wellesley College (phase 1), informal multi-day workshops at Tufts University's Early Childhood Makerspace (phases 2-4), a temporary exhibit at the Boston Children's Museum (phase 5), and an informal holiday camp at the Eliot-Pearson Children's School (phase 6). With the exception of phase 1, which used Wellesley College as a convenient site for rapid user testing, the research settings for all phases were chosen because they were designed specifically as informal learning environments for young children (Cohen & McMurtry, 1985; Feber, 1987; Bers, Strawhacker, & Vizner 2018; Kuh, 2014).

During all design phases, researchers were present to lead educational activities, guide children in hands-on play sessions with CRISPEE, and interview or assess participants. Study participation was always on a volunteer-basis and free to participants. Recruitment information and announcements were widely circulated to ~4,500 subscribers to email lists and social media channels hosted by both participating research labs, as well as those of the Eliot-Pearson Department of Child Study and Human Development at Tufts and the Eliot-Pearson Children's School. Weekly announcements were sent starting approximately 1-2 months in advance of each phase. New enrollments were accepted until either the participant spaces were filled to a pre-arranged capacity (approximately 15 children for most sessions), or until the first day of testing. Researchers collected consent from parents and children on the first day of the sessions, or beforehand via electronic form submission according to the family's preference.

The exception to this recruitment style was the phase 5 study, which took place in the Boston Children's Museum, and was open to all interested families (no capacity limit) with a child between the ages of 4-9 years old. Researchers sent out announcements through the previously described channels in the week prior to testing days that a temporary interactive research exhibit featuring CRISPEE would be available to visit at the museum. Museum staff also promoted these events through their own social media outlets (subscriber numbers unknown), and verbally informed families about the CRISPEE research exhibit at highly-trafficked locations around the building on testing days.

Our total sample comprised *N* = 135 participants run, representing *N* = 125 children age 4-9 years after accounting for children who participated in more than one research phase. Table 2 below summarizes the age and gender demographic information of the sample, organized by study phase.

Table 2

Summary statistics for all child participants across the six-phase design study

Phase	Sample size	% of Total Sample	Age			Gender	
			Min	Max	M(SD)	M	F
Phase 1	*n* = 4	2.9%	4;0	8;0	5;9(1;9)	*n* = 2	*n* = 2
Phase 2	*n* = 14	10.4%	5;5	7;10	6;6(1;2)	*n* = 10	*n* = 4
Phase 3	*n* = 11	8.1%	4;11	7;10	6;4(1;1)	*n* = 9	*n* = 2
Phase 4	*n* = 15	11.1%	5;11	8;10	7;4(1;2)	*n* = 8	*n* = 7
Phase 5	*n* = 82	60.7%	4;9	12;0	7;1(1;6)	*n* = 42	*n* = 30
Phase 6	*n* = 9	6.7%	5;0	7;2	6;4(0;8)	*n* = 4	*n* = 5

Total Participants Run	N = 135	100%	4;0	12;0	6;11(1;4)	N = 73	N = 48

Design Based Research

The current study describes the development and evaluation of a new technology and intervention designed to support specific learning outcomes. Design-based research methodology (also called DBR or design research) places an inherent emphases on the integration of research and practice to contribute to the development of novel learning interventions (Barab & Squire, 2004; Brown, 1992; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Edelson, 2002). For this reason, I chose DBR as the most appropriate method for the current study. In order to clarify the method of the dissertation, it is helpful to describe the theoretical and epistemological orientations that characterize design research. Following this, I will describe how I used DBR approaches to address my research questions.

Learning scientists Barab and Squire (2004) outline several major features of design research that distinguish it from traditional psychological methods, including a focus on characterizing the context and process of the learning intervention, an investigatory model involving large numbers of complex and interconnected variables, a comfort with iteratively changing the research design to adapt to feedback and success of the design in the field, and research sites that are frequently located in the “buzzing, blooming confusion of real-life settings where most learning actually occurs” (Barab & Squire, 2004, p. 4). A methodology from the education and learning sciences, DBR represents a departure from more traditional research methods not as a rejection of those approaches, but rather in service of a different research aim, which is to develop innovations that are as useful for their practical applications as for their theoretical contributions (Barab & Squire, 2004; Brown 1992). Instead of focusing on controlling for “noise” and looking at a handful of specific variables, as in experimental lab studies, design experiments focus on the noise as a rich data set in order to make robust claims that are generalizable, reliable, and repeatable about how new designs support learning (Brown, 1992; Collins, Joseph, & Bielaczyc, 2004). Put another way, design studies can be situated as an exploratory stage of the large-scale iterative research cycle that feeds into later confirmatory effect studies (Nieveen, McKenney, & van den Akker 2006).

Perhaps because design research addresses formative questions that require investigation of the setting in which learning occurs, there are a fair amount of critiques facing this emerging methodology. Collins, Joseph, and Bielaczyc (2004) note that among other open issues, design researchers must deal with the complexity of real-world situations in their designs, large (and sometimes overwhelming) amounts of data arising from the common use of mixed ethnographic and quantitative data collection, and the challenge of comparing implementations and outcomes across iteratively changing designs. However, they also argue that the limitations of DBR can often be reinterpreted as its strengths (Collins, Joseph, & Bielaczyc, 2004). For example, the complexity of the real-world setting is also what affords design researchers the opportunity to arrive at a rich understanding of how an intervention resulted in learning (Plomp & Nieveen, 2007). On the other hand, comparing implementations and seeking relationships across diverse variables is an understandably complex challenge (Anderson & Shattuck, 2012). Fortunately, methodologists in this area are now identifying steps to make DBR findings more rigorous and meaningful.

Kelly (2004) identified an extensive list of theoretical recommendations to address common issues, including limitations of researcher bias (e.g. in selecting cases to present and data to analyze), focusing on identifying the necessary components of an intervention to achieve the desired outcome (rather than simply chronologically cataloguing the intervention experience), and ensuring that results are feasible and applicable (e.g. financially, pedagogically) for the practice settings in which they were designed. On a more practical level, learning scientists like Sandoval have also shared techniques and strategies to help researchers avoid the pitfalls of DBR. In the next sections, I describe two specific DBR methodological approaches that I used in this study to understand the relationship between the designed CRISPEE innovation and the resulting learning outcomes in children. These are conjecture mapping, a way to understand the justifications that contributed to changes across designs, and interaction analysis, an analytic approach specifically designed to take into account the complex setting of the learning intervention. Throughout this discussion, I will also explain steps I took to address issues raised in the DBR literature (e.g. Kelly, 2004), including limiting researcher bias and focusing on necessary components of the intervention.

Conjecture Mapping

One of the criticisms of design research is the moving target of the intended learning outcomes that designs are meant to support (Brown, Taylor, & Ponambalum, 2016; Kelly, 2004). Sandoval's (2013) conjecture mapping technique can help education researchers identify specific learning outcomes of interest and articulate their conjectures about how to achieve those outcomes through design choices. In the conjecture map, researchers describe the relationships between the practical and theoretical aspects of the learning tool design (Sandoval, 2013). Sandoval used the term "embodiment" to refer to the material artifacts or processes through which the design supports learning, or the way that learning is "embodied" in the intervention experience. Embodiments can include novel technology, curricular approaches, and social or discourse structures including discussion prompts and classroom conventions (2013). Sandoval also included “mediating processes” in his framework. If embodiments are the material aspects that contribute to learning, mediating processes are the activity of learners that demonstrates that learning is occurring (2013). Completing a test, engaging in a discourse structure, or participating in a collaborative project could all be mediating processes of a learning intervention. Typically, mediating processes are easy to observe, such as noting that a student is participating in a class discussion. Learning outcomes are also captured in the conjecture map, in order to clarify the intended conceptual or experiential knowledge that the design was intended to support in learners. The most important aspects of the conjecture map are the conjectures themselves. Design conjectures represent the arguments that researchers use to ascribe the learning evident in mediating processes to one or more embodiments of the design. Theoretical conjectures signify assumptions about how engaging in the intervention (and specifically in mediating processes) will result in learning outcomes. In Chapter 5, I outline the conjecture maps that guided the design of the CRISPEE intervention, concluding with the latest map outlining the study’s design and learning outcomes (see Figure 5). I employ Wilkerson’s (2017) “extended mapping” approach by outlining the iterative evolution of our conjecture maps across the six-phase design cycle, in order to emphasize the inter-related nature of the intervention design and the findings from each successive implementation.

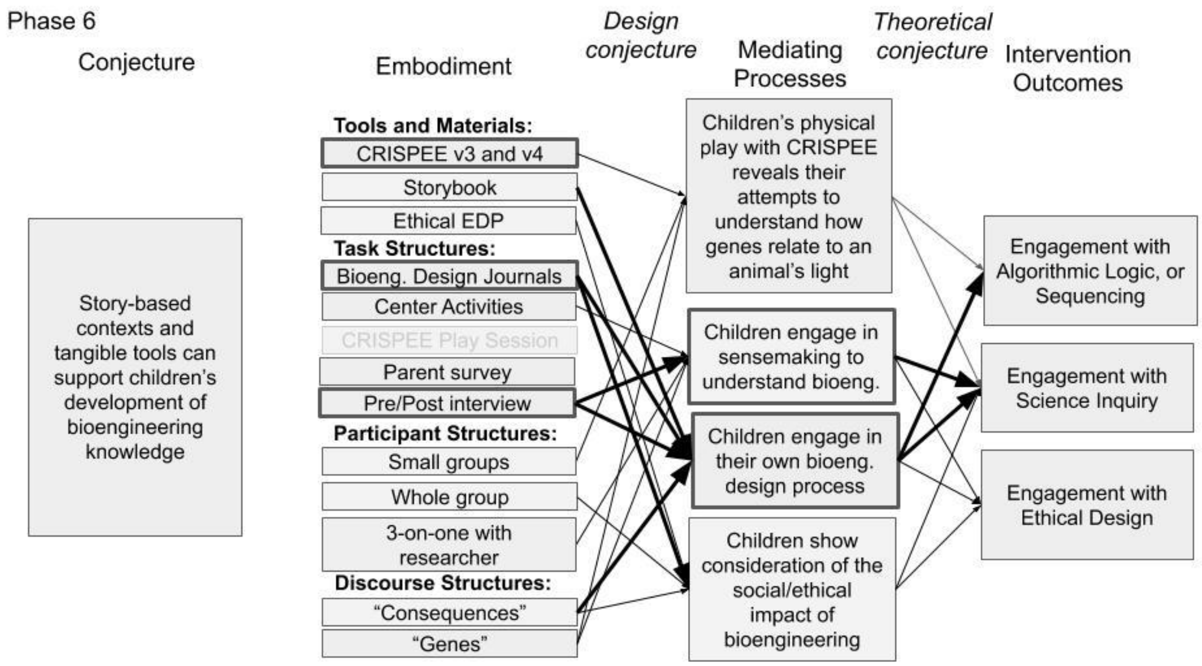


Figure 5. The latest conjecture map guiding the current study. See Chapter 6 for a discussion of the evolution of this map through the six-phase CRISPEE design project.

Interaction Analysis

A second major issue in DBR is how to systematically and meaningfully interpret data collected in complex naturalistic learning settings (Barab & Square, 2004; Kelly 2004). I used interaction analysis (IA) methods to select and interpret during CRISPEE design interventions. Interaction analysis is a qualitative methodological approach with roots in conversation analysis, ethnography, and social constructivist theories (Derry et al., 2010; Erickson, 2006; Goodwin, 2000; Jordan & Henderson, 1995; Yamagata-Lynch, 2010). The theoretical foundations underlying this method assume that knowledge and action are fundamentally social in origin; that by observing and investigating participants during naturally-occurring social and cultural interactions (e.g. with other people, with artifacts, with environments) that researchers can better understand their mechanisms of meaning-making and knowledge generation; and that the evidence for developing theories of knowledge construction should be deeply rooted in these empirically observable interactions (Derry et al, 2006; Erickson, 2006; Jordan & Henderson, 1995). This focus on unearthing how knowledge is socially created, shared, and used makes IA very useful for exploring questions about learning in informal education settings (e.g. Ajjawi & Boud, 2017; Lampert & Ball, 1998; Phillips, Watkins, & Hammer, 2018; Ramey, 2017; Yackel, Cobb, & Wood, 1999).

Interaction analysis begins by collecting high-fidelity records (primarily video and audio tape) of interaction sites of interest (Jordan & Henderson, 1995). Our design team selected informal learning settings (a makerspace, a museum, and a school-based camp) to ensure data was collected in "naturally occurring, everyday activities" where learning occurs (Jordan & Henderson, 1995, p.41; Lave & Wenger, 1991). We engaged as participant teacher-researchers, conducted *in situ* interviews, and documented child-made work to ensure that our data reflected the "blooming, buzzing confusion" of the designed learning intervention (Barab & Squire, 2004, p. 4; Jordan & Henderson, 1995). Following the recommendation of Jordan and Henderson (1995), we collected video footage of all data collection activity.

The dissertation research presented here comprises two main studies, which required one deductive and one inductive interaction analytic approach, respectively (Derry et al., 2010; Erickson, 2006). The first study, conducted at a museum setting in the Greater Boston area, investigates the interactions and patterns exhibited by a diverse sample of children. This study was more deductive in nature, attempting to arrive at a detailed description of how children play with the intervention technology, and so deductive interaction analysis techniques were used (Derry et al., 2010; Erickson, 2006). Deductive analysis involves investigating a narrow set of particular data cases or points in order to draw conclusions that are generalizable to a broader setting or population (Erickson, 2006). Specifically, Erickson's video analysis method was most useful for capturing and characterizing the novel interactions that the learning design was meant to elicit (Collins, Joseph, & Bielaczyc, 2004; Erickson, 2006). The second study, conducted at a school-based camp, investigates open-ended questions of what and how children can learn about bioengineering during a curricular intervention. This study requires exploration, and we used inductive methods to interpret knowledge-construction strategies of children in our sample. Inductive analysis involves investigating the breadth of available data in order to synthesize understandings about the learning that occurred in the particular study setting of interest (Erickson, 2006). For an in-depth description of the methods used, see chapter 7.

Learning Outcomes

Based on the developmentally-appropriate powerful ideas from bioengineering identified in chapter 3, I selected three ideas to focus on as the intended learning outcomes of the CRISPEE intervention. These are sequencing, sensemaking, and ethical design. I will seek evidence of children engaging in these outcomes as a result of specific elements of the learning design, including the CRISPEE technology, the Adventures in Bioengineering storybook, the Ethical Design Process poster and song, and the bioengineering design journal activity.

Initially, the learning outcomes of interest to this study were only sequencing and sensemaking. Through the course of the design experiment, a third powerful idea, ethical design, emerged as a learning outcome. These outcomes are distinct from the learning *processes* that we observed children using, such as playing with CRISPEE and sensemaking about bioengineering topics. These represent tools and strategies that children deployed to understand the disciplinary content of bioengineering. See chapter 7 for a discussion of how the learning outcomes were measured and attributed to the study intervention.

Data Sources

The principal sources of data varied across phases, and included the following: videotape and audiotape records, transcripts taken from those video and audio records field notes, children's written or drawn work during curricular sessions, and pre- and post-interviews conducted with groups of one-to-three children, to capture changes in their ideas during the interventions. Although this investigation comprised six phases of study documents, the dissertation focused on the two latest design phases in order to address the research questions. See chapter 7 for a detailed description of the analytic procedure for data collected during phases 5 and 6.

In chapter 6, I explain the overall structure of the six phases of iterative design and research that contributed to the development of the CRISPEE technological prototype and curricular intervention. After this discussion, I will focus on the phases of interest to this dissertation, phases 5 and 6. Finally, I dedicate chapter 7 to a discussion of the data collected during these two phases, and the analytic procedures I will use to analyze them.

Chapter 6. Designing CRISPEE, an Educational Bioengineering Tool-to-Think-With

In this chapter, I describe the experimental pilot interventions and findings that contributed to the development of the CRISPEE technology and accompanying curriculum. This project consisted of a six-phase design research cycle focused on piloting the CRISPEE technology and developing the associated curriculum. For the purposes of the dissertation study, I will focus on phases 5 and 6 as the main research intervention. Phases 5 and 6 both used the same CRISPEE version 3 (v3) prototype. This chapter outlines the conjectures, implementation, and findings of all six design phases that contributed to the development of three CRISPEE prototype versions and pilot curriculum materials. In later chapters, I will describe the phase 5 and 6 studies in more detail.

Here, I present a retrospective case analysis of the exploratory design phases of the CRISPEE technology using Sandoval's conjecture mapping technique. I borrow the extended mapping style of Wilkerson (2017), focusing on a chronological outline of how our research team designed CRISPEE in multiple phases, with successive designs informed by findings from previous phases to more effectively realize our intended learning outcomes of sequencing and inquiry. Table 3 presents the high-level context and design prototypes used in all phases. In the following sections, I describe each of these phases (both what was tested and what was learned) in more detail.

Table 3

Overview of the 6 testing phases of the CRISPEE project

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Study Context	30 minute user test sessions at Wellesley College	9 hour workshops at Tufts University	9 hour workshops at Tufts University	15 hour workshop at Tufts University	30 minute sessions at Boston Children's Museum	15 hour school break camp at Eliot-Pearson Children's School
Sample	*n* = 4 children ages 4-8 years *n* = 5 adults	*N* = 14 children ages 4-8 years	*N* = 10 children ages 4-8 years	*N* = 15 children ages 4-8 years	*N* = 82 children ages 4-9 years	*N* = 9 children ages 5-8 years
Data Sources	Video of Sessions, Pre/Post STEM assessments	Video of Sessions, Pre/Post attitude assessments	Video of Sessions, Pre/Post learning assessments	Video of Sessions, Original Pre/Post learning assessments	Video of Sessions, STEM Background Survey, Knowledge Pre-survey	Video of Sessions, STEM Background Survey, Original Pre/Post interviews
Curriculum Designs	Storybook and videos, Centers	Storybook, Plushies, Centers	Storybook, Plushies, Centers	Storybook, Plushies, Centers	N/A	Storybook, Curriculum
Technology Designs	CRISPEE v1	CRISPEE v2	CRISPEE v2	CRISPEE v3	CRISPEE v3	CRISPEE v3 and v4

Tracing the Design Phases of CRISPEE

CRISPEE was originally conceived as a way to engage children in playful exploration of gene editing, using the model of the CRISPR/Cas-9 gene editing system used by professional bioengineers. Pedagogically, CRISPEE is intended as a tool-to-think-with (Papert, 1980), a physical manifestation that children can touch and build with to learn about relationships between genes and living organisms (e.g. Wilensky & Resnick, 1999). The learning design encompasses the technological prototype, as well as curricular scaffolds to engage children in thinking with CRISPEE about bioengineering. The intended educational goals for the CRISPEE intervention are listed in Table 4, with connections to STEM learning standards for kindergarten and elementary school. See Appendix A for a full outline of the final curriculum and learning activity descriptions.

Table 4

CRISPEE connections to learning standards

Educational Goal	Learning Domains	Connection to Standards
(L1) Introduce basic concept of genetic codes as the underlying instructional language for the building blocks of all living things	Life Science	*NGSS K-LS1-1*. Use observations to describe patterns of what plants and animals (including humans) need to survive *NGSS K-ESS3-1*. Use a model to represent the needs of different plants and animals (including humans) and the places they live.
(L2) Introduce computer programming/coding as a metaphor for altering genetic instructions in living things	Computer Science	*CSTA K-2 1A-CS-02*. Use appropriate terminology in identifying and describing the function of common physical components of computing systems (hardware) *CSTA K-2 1A-AP-11*. Decompose (break down) the steps needed to solve a problem into a precise sequence of instructions. *ITEEA K-2 3.3.A*. The study of technology uses many of the same ideas and skills as other subjects.
(L3) Introduce the foundations of biological engineering as a field that applies engineering design to living biological materials	Engineering Life Science	*NGSS K-2-ETS1-1*. Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool. *NGSS MS-ETS1-1*. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions *ITEEA K-2 3.A*. The study of technology uses many of the same ideas and skills as other subjects.
(L4) Facilitate the design of genetic programs that create a desired output	Engineering Computer	*CSTA K-2 1A-AP-12*. Develop plans that describe a program's sequence of events, goals, and expected outcomes. *ITEEA 6-8 3.F*. New technologies and systems can be developed to solve

	Science	problems or to help do things that could not be done without the help of technology. *ITEEA K-2 9.B.* Expressing to others verbally and through sketches and models is an important part of the design process
(L5) Engage children in creative problem-solving to aid animals in relatable story-based challenges (e.g. finding home when lost).	Language Arts Social Studies	*NGSS K-ESS3-3.* Communicate solutions that will reduce the impact of humans on the land, water, air, and/or other living things in the local environment *ITEEA 3-5 5.C.* The design of technologies can impact the environment in good and bad ways. *ITEEA K-2 9.B.* All products and systems are subject to failure. Many products and systems, however, can be fixed.

Note. Reprinted with author permission (Strawhacker, Verish, Shaer, & Bers, 2019)

Figure 6 is a conjecture map I created from the initial intended design and conjectures pertaining specifically to the design of the technology. The conjectures mainly assumed that by engaging with a tangible technology that models elements of gene reprogramming, children would be able to explore the metaphor of genes as a coding language and would also demonstrate engagement with algorithmic logic and science inquiry while forming their ideas. As I describe in the following sections, the initial conjecture and assumed pathways to intervention outcomes were reexamined and revised during each subsequent phase of the project.

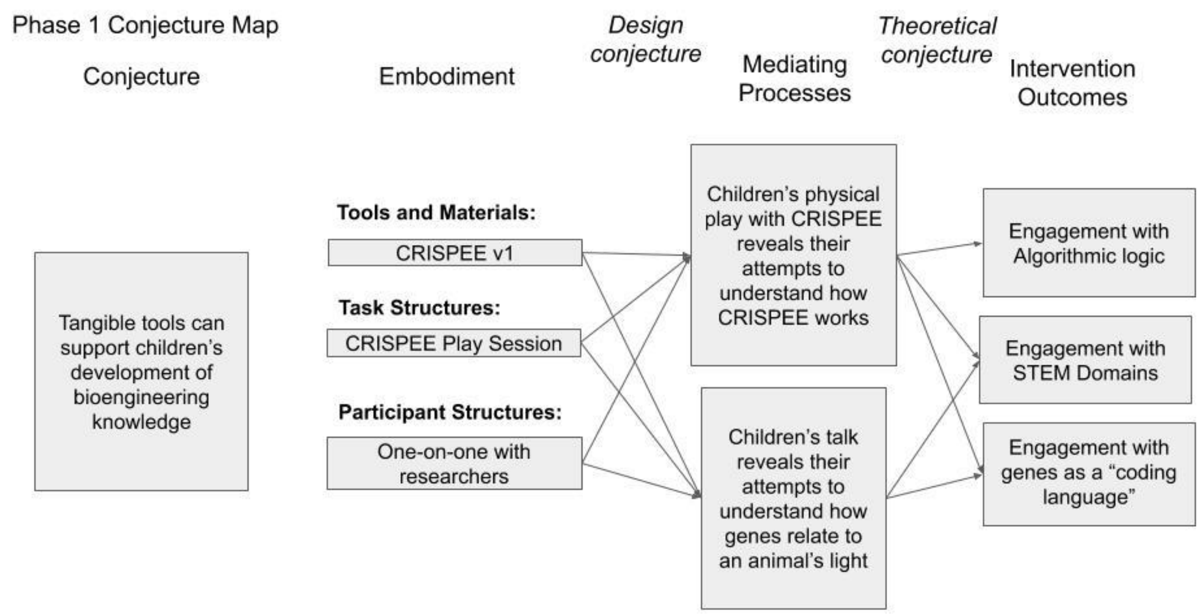


Figure 6. Conjecture map describing initial intended project designs and outcomes. This map reflects the conjectures explored in Phase 1 testing.

Phase 1: Adult and Child User Testing.

In our first phase, we invited a small group of children in grades K-3 and adults who work directly with young children (parents, educators, and early childhood researchers) to offer preliminary insights while using CRISPEE. For all participants, we framed their experience with a story-based task that introduced a living organism (a firefly whose body cannot light up) and presented CRISPEE as a tool to help by reprogramming the firefly's genes to produce light in various colors. Following this brief framing, participants were asked to play in an open-ended way with CRISPEE and attempt to change the light color using the blocks. After their first successful light-programming interaction, researchers prompted them to reflect on the possible meaning behind the blocks and their symbols, and their enjoyment and experience of the CRISPEE interaction.

Learning Design

Phase I tested CRISPEE version 1, the initial prototype of the technology.

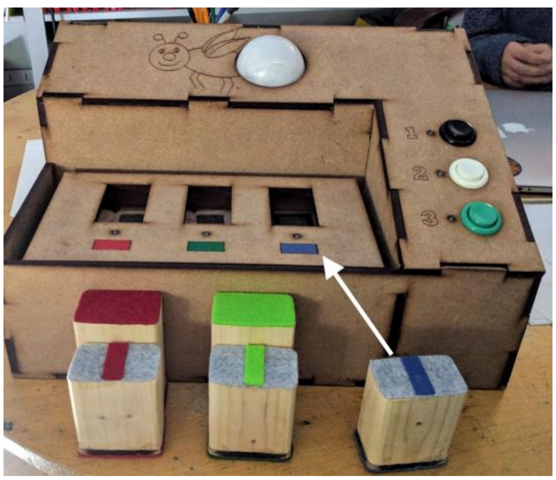


Figure 7. CRISPEE v1 with color labels under block slots.

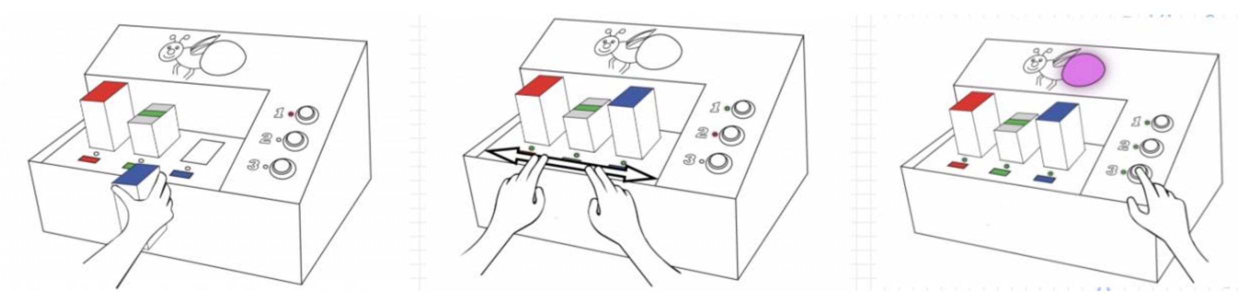


Figure 8. Interaction steps of CRISPEE v1. The interaction steps are: 1) Insert blocks; 2) Mix platform; 3) test for light color

Recent research in human-computer interaction has shown that tangible technologies can foster a developmentally-appropriate and playful introduction to science and engineering for young children (Bers 2012; Bers, 2018; Brown, 1992; Okerlund et al., 2016; Papert, 1980; Strawhacker & Bers, 2015; Sullivan, Strawhacker, & Bers, 2017). The design of CRISPEE was inspired by existing tools in biology laboratories (specifically, the CRISPR/Cas-9 gene editing system) and designed to align with the Positive Technological Development (PTD) framework for developmentally appropriate technologies in early childhood. The PTD framework is meant to aid educational tool and space developers by offering design guidelines rooted in developmental science and theory. When learning tools afford opportunities for self-directed, creative, open-ended play, children can "use technology to make positive contributions to the development of self and of society" (Bers et al., 2009, pg. 22). In the case of CRISPEE, we made the interactions (e.g. inserting blocks, shaking a platform, and pushing large buttons) very simple and used familiar construction materials (e.g. wood, Velcro) to ensure that children would take ownership over the design interaction and not feel overwhelmed by the building process. The goal of the tool is to model how bioengineers select the color of a bioluminescent organism by mixing genes that code for proteins that glow in the primary colors of light (red, green, and blue). All versions of CRISPEE use six blocks that can turn each of the three primary light colors "On" (tall, solid-colored blocks) or "Off" (shorter blocks with grey or black markings), simulating the six genes of bioluminescent animals that express or suppress those light colors. As these genes code for the primary colors of light, the resulting phenotype light is the mixture of the expressed genes, much the same as when you layer translucent colored plastic over a light source (Branchini et al., 2017; Viviani et al., 2016). Figures 7 and 8 show the version of CRISPEE used in Phase 1 of the study, as well as the three-step user interaction.

All five adult participants were able to build programs by placing blocks correctly in platform slots and use the buttons to test their program. Children had some trouble matching the correct block colors to the slots labeled in those colors. All participants also had challenges with the mixing stage, interpreting this to mean changing the order of blocks, but learned the interaction quickly once demonstrated by a researcher. Children also expressed excitement and delight when they created their first successful glowing light, and typically this inspired them to want to play with CRISPEE even beyond the user trial. The youngest participant, a Kindergarten-aged girl, methodically built a cyan light program while narrating her design choices, exclaiming, "I made my favorite color!" when it was complete. A second-grade girl quickly understood the symbolism of the On and Off blocks, and during her build session remarked that "the blocks she combined were to help the firefly", indicating that she also understood the metaphor of gene coding. A third-grade boy also engaged with bioengineering concepts when he asked, "Can we use the same genes [from a firefly] for lighting a zebra fish?". Finally, another third-grade boy commented that he thought he and his peers would be too old for CRISPEE, confirming our target age range of K-2nd grade children.

Several changes were implemented in the design of the interface after initial pilot testing (Verish et al., 2018). The most significant change was removing the labels below slots in the platform, which constrained where users could place red, green, and blue blocks. We saw much less involvement with algorithmic thinking than we anticipated. Children's play indicated that this was because the tool was offering too much scaffolding in the way of program design. CRISPEE v1 was designed so that only a certain color block could go into each slot (see Figure 7). This discouraged children who were curious about other sequences they said they would have liked to try. Since we identified algorithmic logic as a learning outcome of using the tool, we found it too limiting for children to have labels for each color. In order to offer children the freedom to make the discovery of CRISPEE syntax rules on their own, we removed color labels in v2, replacing them with a simple red/green LED (with red indicating when there is some error like a missing or double block in that slot). We also changed the "color off" block style from a stripe to an X based on children's feedback. This shifted focus from simply matching colors to ascertaining a coding rule.

Conjectures

In the initial phase, our design conjectures were fairly speculative and centered on the tangible, concrete nature of the tool to offer learners opportunities to engage with abstract ideas of bioengineering. For example, we expected that by physically manipulating blocks that represent specific color genes, learners would engage in a design process to program a specific light color. We theoretically conjectured that by engaging in a programming task in which the simulated outcome was the light of a cartoon animal, learners would: (a) engage with the algorithmic logic inherent in building and testing a code, (b) leverage existing STEM domain knowledge (e.g. they might use science inquiry to observe and deduce how CRISPEE functions), and (c) view gene editing through the metaphor of programming in a computer science context.

Findings

During pilot testing, no tester correctly guessed how to mix the gene program by moving the platform back and forth. To address this, we added arrows with indicator lights to clarify the "mixing" or shaking interaction. Two laser-etched arrows with white LEDs were added to the platform and were programmed to flash back and forth at the beginning of the mixing cycle and turn off when mixing began. Based on children's curiosity about mixing genes from different animals (a common practice in professional-level bioengineering), we also added interchangeable animal faceplates to adorn the output bulb. Children can still choose to program the firefly, but they are also given the opportunity to program an angler fish, a zebrafish, or a jellyfish. Only naturally occurring bioluminescent animals are depicted in these faceplates. We modified the user test interaction method by developing a protocol for inviting children to play with CRISPEE. This uniformity was added so that future user tests from different children could be compared with the knowledge that children received similar framing and prompting throughout the sessions. This protocol was formalized as the CRISPEE Play Session.

After this initial user testing phase, we realized that we did not observe much of a relationship between the CRISPEE v1 technology and children’s talk about genes. We concluded that a curricular intervention would address this gap, so we shifted our focus to designing the early childhood curricular intervention within which we envisioned CRISPEE being deployed. This included designing a picture book to be read to large groups of children to provide a story-based context for using CRISPEE; an array of small-group free-play center activities to support children’s play in key STEM domains related to bioengineering; and pre/post assessments to quantify changes in children’s STEM attitudes and ideas during CRISPEE interventions.

Figure 9 shows a conjecture map that describes the above-described changes to the technology and intervention. Items (boxes) or relationships (arrows) that were added or revised are outlined in bold, to indicate that they are the result of feedback or findings from prior phases. In addition to many embodiments added as we looked ahead to a curricular intervention plan, we also updated our learning outcomes to reflect a new focus on sequencing (called “algorithmic logic” in the conjecture map) as a learning outcome for children in the study.

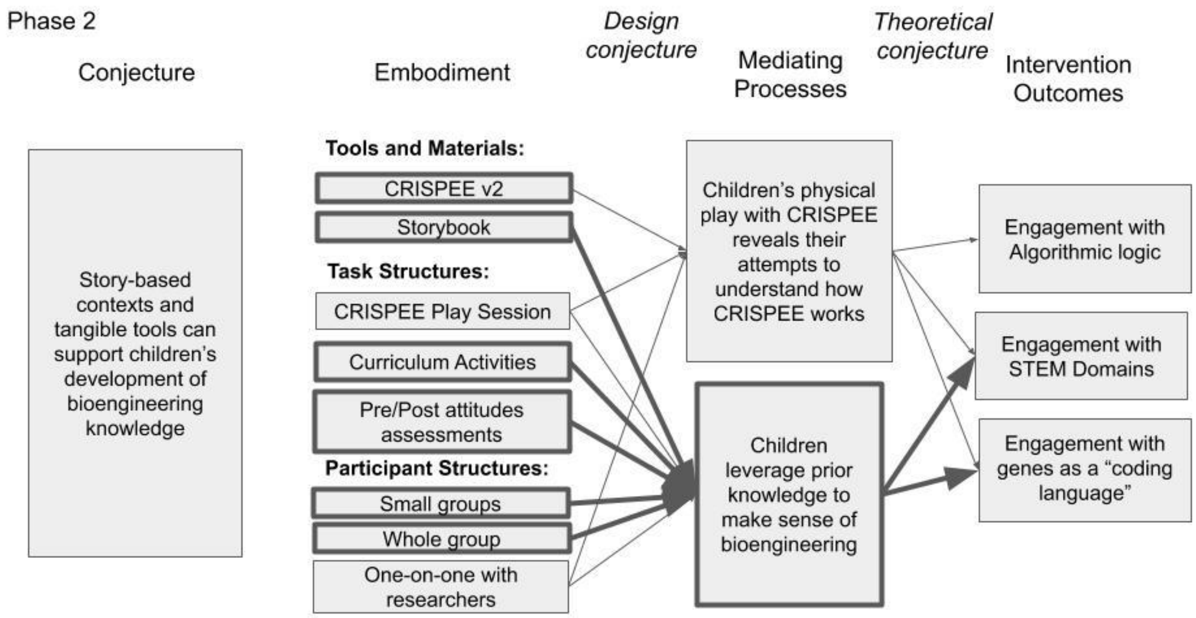


Figure 9. Conjecture map revisions after Phase 1 user testing.

Phase 2: Pilot CRISPEE Workshop using Attitude Assessments

Learning Design

As we launched phase 2, we predicted that exploring bioengineering content through a story-based curricular context would shape children's understanding of related STEM fields of biology or life science and engineering. To explore these conjectures, *N* = 14 children aged 5-7 years agreed to participate in a 3-day workshop held during the Boston Public Schools February Vacation Week. The workshop was offered for free at the Early Childhood Makerspace at Tufts University. Children participated in brief small-group researcher-scaffolded user tests ("play sessions") with CRISPEE and spent the rest of the time in hands-on play with STEM-themed activity centers (see Figures 10-14). Children were also able to play with child-size functional STEM clothing and equipment to help them more deeply identify with science professions and activities.

Figure 10. Children explore the CRISPEE free-play center.

Figure 11. A boy plays with a project, prisms, and colorful glass beads at the light physics center.

Figure 12. Children put protective lab clothing to prepare for an activity at the chemistry center.

Figure 13. A girl builds a structure in the engineering center

Figure 14. Children use clipboards, pencils, and crayons to observe living creatures in the biology center.

In the workshop, children were invited to play with CRISPEE v2, a version of CRISPEE designed without the colored labels below the block slots (see Figure 15). In response to phase 1 findings that children would have preferred to create their own block sequences, the labels were replaced in v2 with a simple LED feedback light that flashed red or green. Green lights indicated that a block was functional, like a single color block in a program. Red lights indicated that the block was non-functional and needed to be replaced. This usually occurred when children added two blocks of the same color (e.g. Red On and Red Off), or left the block space empty.

In addition to the updated technology, we also introduced an original storybook called, Adventures in Bioengineering: The Story of Bob the Firefly (see Figure 16). The story is about an anthropomorphic firefly whose genes do not allow him to glow. When he gets separated from his firefly friends, he enlists the help of a bioengineer to help him program his genes to glow and resolve his problem. This whimsical story offered a context for children to understand one example of why bioengineering might be a useful technological choice.

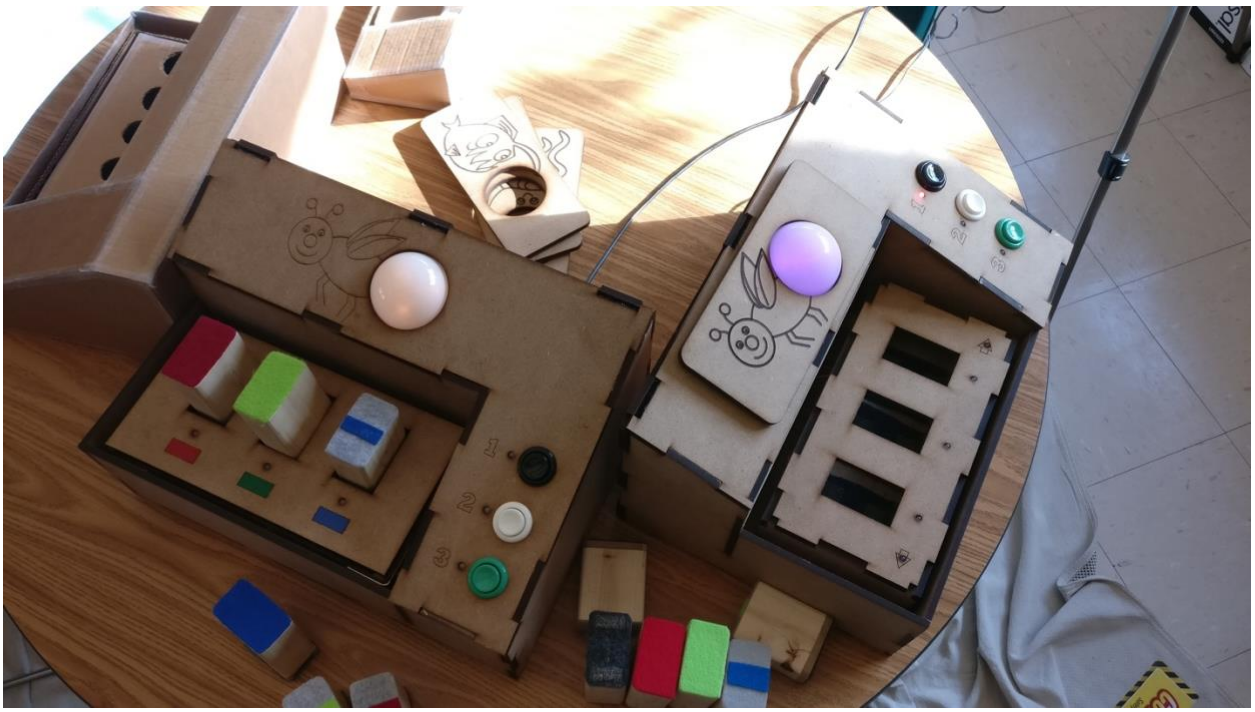


Figure 15. CRISPEE v1 (left) with block color labels, was replaced by CRISPEE v2 (right), which used the same technology and blocks but with LED feedback lights below each slot and side-arrows to prompt platform shaking.

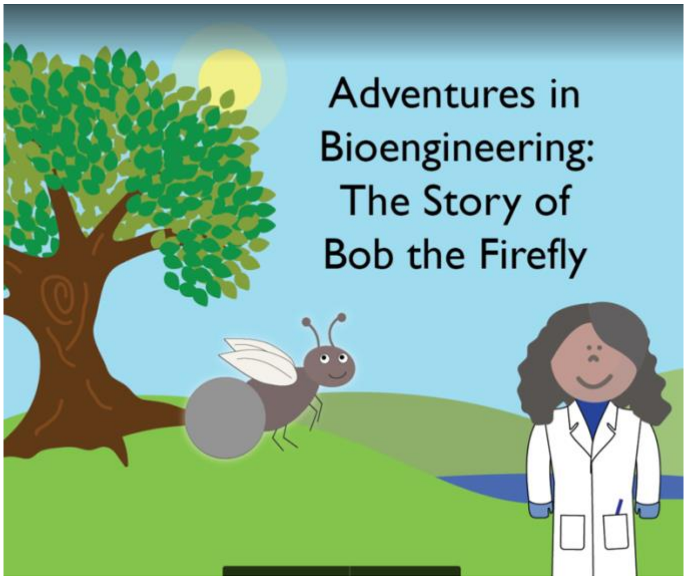


Figure 16. The Adventures in Bioengineering storybook offered children a story-based context to situate bioengineering as a helping field.

Children’s attitudes about engineering, life science, and bioengineering were assessed using pre and post surveys. We selected relevant items from the widely-used Engineering is Elementary (EiE) assessment of engineering attitudes and knowledge (Cunningham & Lachapelle, 2010). We also used the EiE as a model to develop original attitude surveys about life science and bioengineering, using content and vocabulary that had been presented in the workshop and Adventures in Bioengineering storybook (Strawhacker, Verish, Shaer, & Bers, 2019).

Conjectures

Entering phase 2, we conjectured that exploring bioengineering content through a story-based curricular context would shape children’s understanding of related STEM fields of life science and engineering. We also expected that hands-on curricular activities involving science equipment like pipettes, magnifying glasses, and protective lab clothing, would improve children’s positive attitudes and engagement with science domains. Finally, we conjectured that by altering the CRISPEE technology to allow children to create their own color sequences, that we would see more engagement with the learning domain of sequencing as children built their block programs.

Findings

Findings from phase 1 assessments showed that children demonstrated marginal improvement in some areas of engineering, life science, and bioengineering learning. In other areas, children showed no change and, in some cases, showed evidence of conflating or confusing elements of the three subfields after the intervention (Strawhacker, Verish, Shaer, & Bers, 2019). In semi-structured CRISPEE play sessions, we observed children using various strategies to understand the function of CRISPEE, including dramatic play with stuffed animals, social collaboration and turn-taking with peers (e.g. “I’ll be the button-pusher and you pick the program), and mirroring/mimicking behaviors while other children played with CRISPEE.

A surprising finding was that high-scoring children who showed little change on pre-to-post assessments demonstrated a trend not captured by our tests. After the intervention, these children were curious about why bioengineers chose to make the design changes they did (Strawhacker, Verish, Shaer, & Bers, 2019). This led us to re-evaluate our assessment methods in phase 2, shifting to a more open-ended and exploratory activity style. We also added an original “ethical decision-making” activity and assessment.

Figure 17 shows a conjecture map that describes the above-described changes to the technology and intervention. Items (boxes) or relationships (arrows) that were added or revised are outlined in bold, to indicate that they are the result of feedback or findings from prior phases.

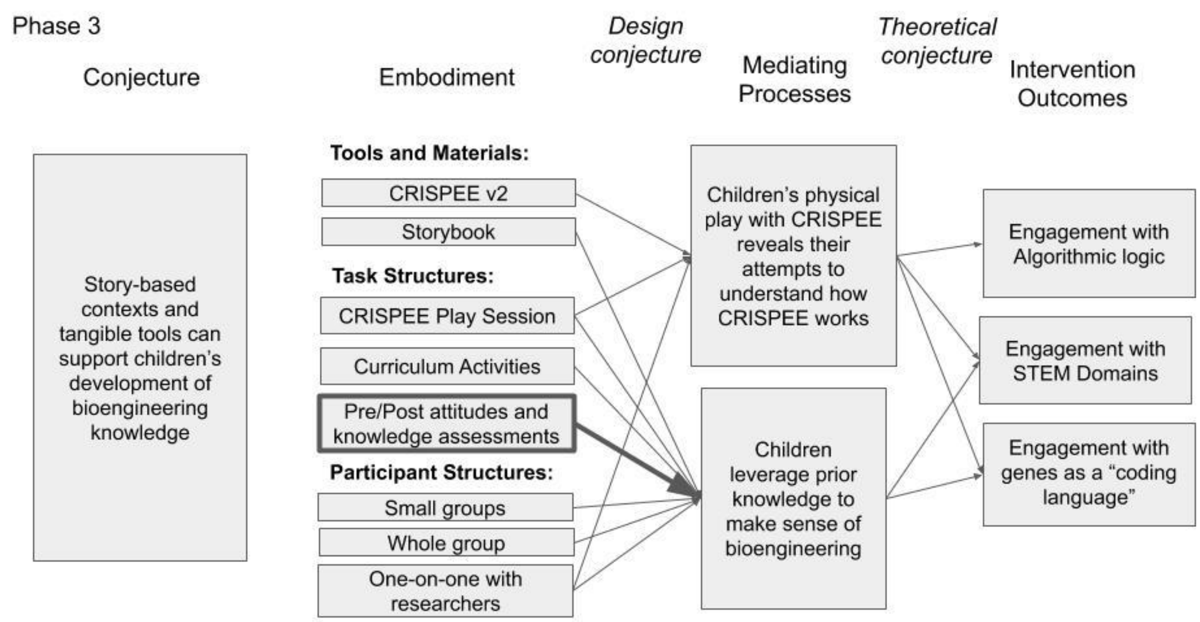


Figure 17. Conjecture map revisions heading into Phase 3 testing.

Phase 3: CRISPEE Workshop using Learning Assessments

Learning Design

After phase 3, the design team felt that the curriculum intervention had shown promise for supporting children's STEM learning, but that our assessments were not capturing the richness of their knowledge. To address this, we held a second 3-day workshop and altered the assessment methods. The design and implementation of phase 3 was very similar to phase 2. N = 10 children aged 4-7 years participated in a 3-day workshop offered for free to children ages 5-8 years during the Boston Public Schools April Vacation Week. The workshop was offered for free at the Early Childhood Makerspace at Tufts University. Children in this workshop engaged in the same activity structures and play sessions as in phase 2, including engineering, life science, light physics, and chemistry centers; access to child-appropriate lab and safety equipment; and small-group CRISPEE play sessions with a researcher present.

In addition to attitude assessments, children completed three pre and post assessments of their life science, engineering, and bioengineering knowledge. We again administered the EiE assessment of engineering attitudes and knowledge (Cunningham & Lachapelle, 2010), and added the SLA, a validated life science inquiry and knowledge assessment (Samarapungavan, Mantzicopoulos, Patrick, & French, 2009). We also added a third original assessment modeled on the SLA but designed to capture bioengineering content (Strawhacker, Verish, Shaer, & Bers, 2019). This bioengineering content reflected only topics that had been introduced in the storybook, such as vocabulary words like “genes” and “bioluminescence,” and equipment (e.g. lab coats) and materials (e.g. living things) used by bioengineers

Conjectures

In phase 3, we maintained the conjecture that exploring bioengineering content through a story-based curricular context would support children’s understanding of bioengineering. We also modified our outcomes to include STEM learning rather than general STEM attitudes, specifically about foundational life science, engineering, and bioengineering concepts.

Findings

Children’s pre-test responses showed that they already harbored preconceptions about science and engineering, as well as topics not taught in early elementary school such as what genes are and how biological traits (e.g. hair color, height) are inherited from family members. In post-tests, children showed little or no change in life science and engineering knowledge, but significant increases in bioengineering knowledge. Half the sample (n = 5) was able to correctly define “genes” and explain how genes function as instructions for living beings in post-tests, compared with n = 2 correct answers in pre-tests. This was unexpected, considering children’s play did not center much around genes. Indeed, children did not reference genes or animals when working with CRISPEE, focusing instead on light colors.

In addition to pre-to-post changes in children's understanding of the key concept of "genes", two findings also suggested that children were engaging in science inquiry when completing post-tests. First, children began to explicitly identify the goal of bioengineering work as "helping", "fixing", or "solving problems" for people, animals, or the environment. This identification of bioengineering as a helping field indicates that children may have viewed bioengineering as a goal-directed, problem-solving enterprise. Second, at least three children asked in post-tests (but not pre-tests) about the purpose and justification (the "why") of bioengineering work when they heard an example of a real-world bioengineering experiment. This suggests that these children were thinking about the broader impact of bioengineering and trying to identify a helpful purpose behind decontextualized bioengineering examples. By asking about the bioengineers' motivation for gene editing, the children were effectively asking, "what problems can we solve with bioengineering?" We assume that these two findings can probably be attributed to the curricular focus on the Adventures in Bioengineering storybook-context. Prior research in science education (e.g. Metz, 2011) supports our interpretation of these findings as early indicators of developing science-inquiry skills.

Several technological findings resulted in a version update to the CRISPEE prototype. One issue was that children would sometimes remove or swap blocks in their program before they had completed a test cycle, but CRISPEE was not built to interrupt a test. Therefore, some children associated certain programs with incorrect color outputs, or assumed it was somehow random. Additionally, the LED light at the top of CRISPEE used a mix of red, green, and blue LEDs to create white when viewed from distance. However, children often peered closely at the light and noticed the distinct colors, resulting in confusion and sometimes an assertion that some animals can glow “rainbow” colored. Finally, children were confused by the aesthetic design of the “Off” blocks in CRISPEE v2, which showed a grey felt background with a red, green, or blue stripe on top to indicate which color was being turned off. All of these design issues were addressed in the updated CRISPEE v3 prototyped, described in the next section.

Figure 18 shows a conjecture map that describes the above-described changes to the technology and intervention. Items (boxes) or relationships (arrows) that were added or revised are outlined in bold, to indicate that they are the result of feedback or findings from prior phases. Additionally, greyed-out boxes and arrows indicate embodiments and/or mediating processes that were not relevant for the next phase of testing. Based on the findings from phase 3, we modified the conjecture map to reflect a new focus on science inquiry as learning outcomes in the CRISPEE intervention design. We also removed “engagement with genes as a coding language” and added “engagement with Ethical Design” as a learning outcome, to align with our finding that children were more curious about ethical justifications for bioengineering work after learning about real-world bioengineering examples. We also set this learning outcome as a goal for the upcoming phase, to seek ways to support children’s creative design with CRISPEE, an outcome that was not obvious in children’s play with CRISPEE in previous phases.

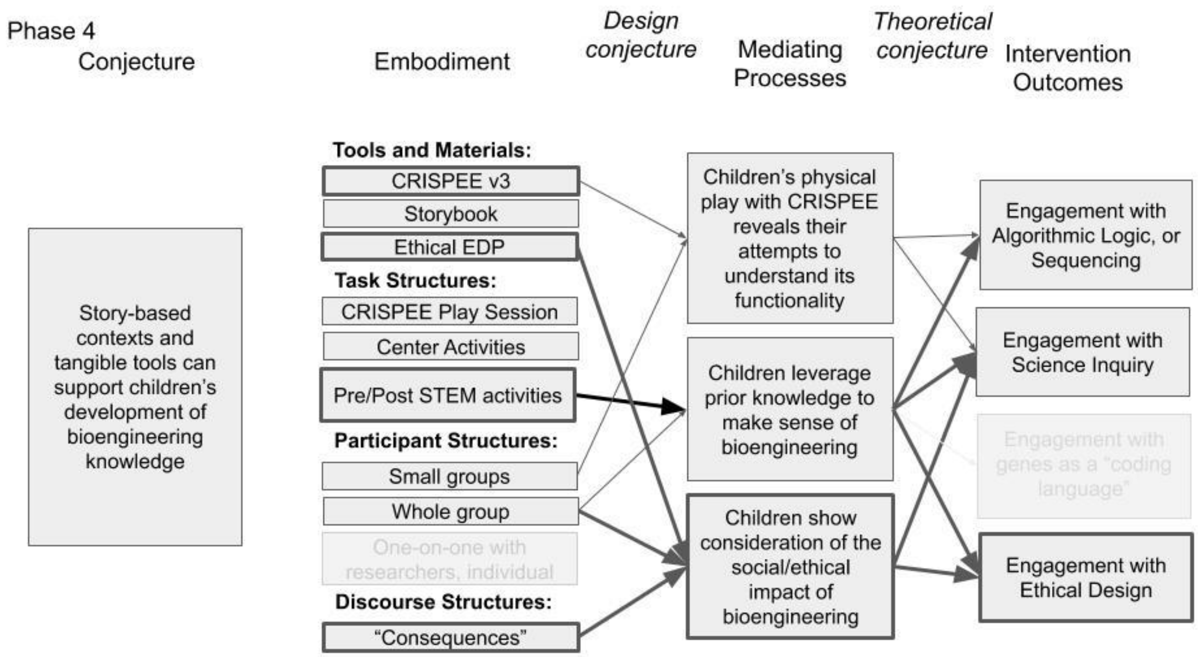


Figure 18. Conjecture map outlining next steps in Phase 4 testing.

Phase 4: Pilot Bioengineering Curriculum with Children.

Learning Design

Phase 4 was similar to the previous 2 phases, but with some important changes. First, the session was extended from three days to five days to allow children more time to engage with learning content. The pre/post assessment measures were also changed from one-on-one verbal assessments about STEM to hands-on small group activities that required children to engage with STEM practices. For example, whereas in phase 3 children individually answered questions regarding their feelings about engineering, in phase 4 they were asked to work with a small team of children to build a structure with certain design constraints. Finally, a learning goal was added to the curriculum related to bioethics and "consequences". In order to explore these new concepts, we introduced the vocabulary words, "consequences", "values", and "ethics". Children completed a brief activity in which they identified and compared their most strongly felt personal values (e.g. caring about family, the environment, or friendships). After acknowledging that values differ across people, we talked about how scientists and engineers use their values to decide which problems to try to solve, and which solutions are best. We drew children's attention to the fact that because scientists are also people, they have their own values and sometimes make decisions differently even from other scientists. Finally, we introduced the original teaching material, the Ethical Design Process (see poster in Figure 19), an adaptation of the Engineering Design Process taught in early childhood settings (e.g. Brophy, Klein, Portsmore & Rogers, 2008; Sullivan, Strawhacker, & Bers, 2017) as a way to show how bioengineers use ethical considerations to help make their biological designs. We hoped that by explicitly teaching steps of a bioengineering design process, that we would see children begin to engage in their own creative designs.

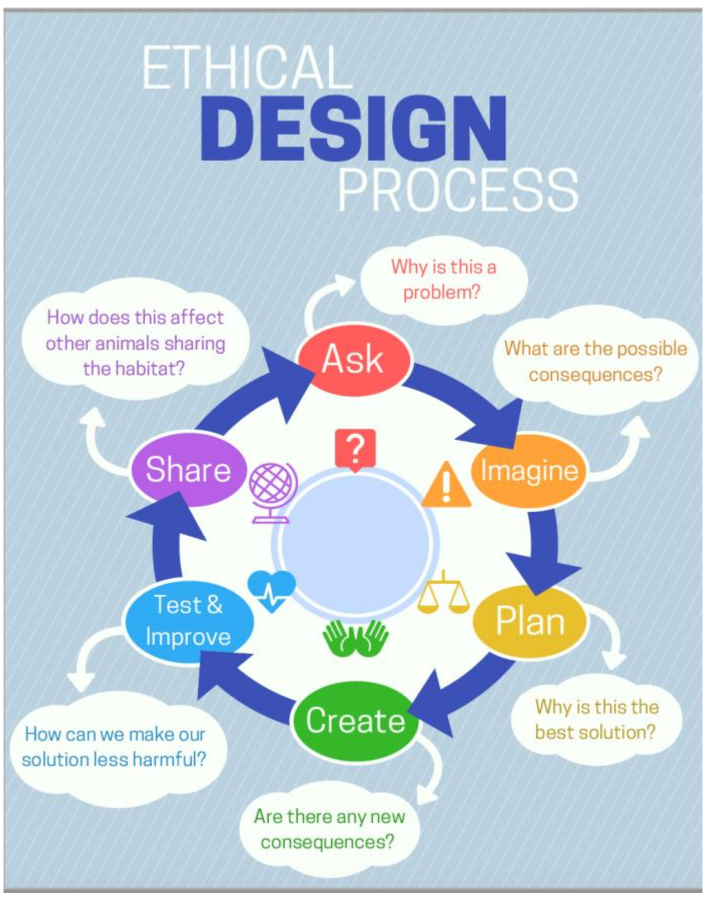


Figure 19. The Ethical Design Process teaching material introduced in phase 4.

Children in the phase 4 camp used CRISPEE v3, an updated prototype inspired by user findings from v2 studies. CRISPEE v3 has all of the same visual and interactive functions as the previous version, but with an update to the firmware that essentially interrupted a testing session if children removed any of the blocks from the platform. This was created in response to the common problem of children changing their program designs halfway through a test without realizing that CRISPEE must complete a full testing cycle. This meant that children would often see a mismatch between their program and the light displayed, because CRISPEE was displaying the light from an old program they had begun earlier. With this new update, children would be able to leave their initial work incomplete to attend to a new idea, much as they do when working with traditional materials like crayons and wooden blocks. Additionally, the original LED lights in the CRISPEE were replaced with an LED strip with more color options, to avoid the confusion of children viewing the white light as a mix of red, green, and blue LEDs. Finally, the Off blocks were redesigned so that instead of a colorful strip against a grey background, the markings show a red, blue, or green background identical to the On blocks, but with a black X through the center. Two other block designs were user-tested with a group of 4 children, and all unanimously agreed that the black-X design was the clearest "Off" signal (see Figures 20-22).

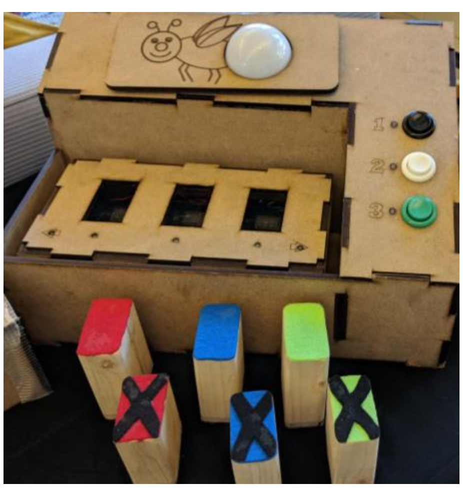


Figure 20. The CRISPEE v3 platform used the same design as v2, except the grey striped off blocks were replaced with colored blocks with black X's to indicate turning the color off.

Figure 21. LED-equipped plush animals showed off children's CRISPEE programs.

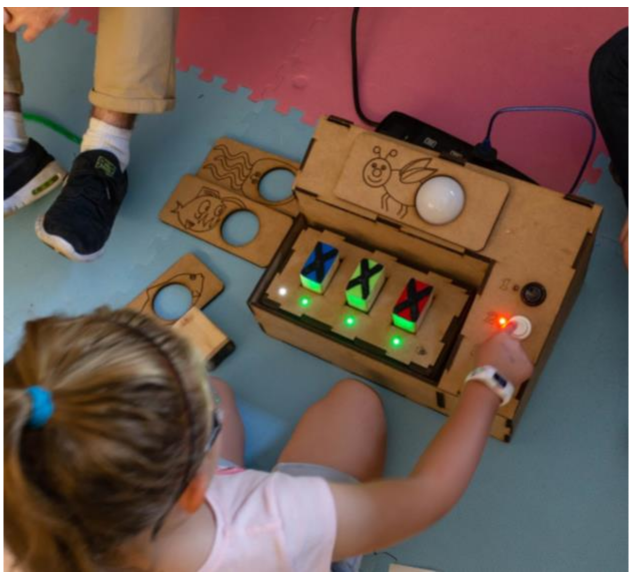


Figure 22. A girl plays with CRISPEE v3, with added interchangeable faceplates showing different bioluminescent animals on them.

We assessed bioengineering subdomains, but instead of using quantitative measures, we engaged children in open-ended play experiences related to the domain of interest. Researchers observed their play to assess engagement with developmentally appropriate engineering design concepts of planning, sturdy building, and iterative revision (Cunningham & Lachapelle, 2010; Sullivan, 2016). A similar task was designed to engage children in science observation to assess science inquiry/knowledge, and children completed a play session with CRISPEE to assess their bioengineering awareness. We also developed (in collaboration with a philosophy professor from Wellesley College) and piloted an original fourth assessment to gauge children's ethical reasoning. In this task, children answered a few open-ended questions to earn a reward (stickers) and then engaged in a conversation about whether and how to share stickers with other peers who didn't complete the task.

Conjectures

In phase 4, we conjectured that exploring bioengineering content through a story-based curricular context would support children's STEM understanding. Specifically, we assumed that story-contexts would situate bioengineering as a helping field, and that with this framing, an ethical design framework (i.e. the Ethical Design Process) would support children in thinking about their own bioengineering designs.

Findings

In brief, the results suggested that children in our sample were able to engage in engineering practices like planning, sturdy building, and iterative design; could match unfamiliar animals to their natural habitats based on observations about their characteristics; were able to complete simple programming tasks at a level consistent with prior research on children in this age range (e.g. see Flannery & Bers, 2013); and demonstrated a variety/range of strategies for dealing with the "ethical sticker task", including keeping all the stickers, sharing stickers equally, and giving their own stickers away.

While the open-ended assessment activities revealed a rich set of data about children's design skills and ethical reasoning, the results about children's "sharing" values ultimately felt removed from the kind of ethical reasoning that bioengineers use when evaluating costs of a particular bio-solution to a society or ecosystem. For example, because the activity focused on sharing or keeping personal items of value (i.e., a sticker), children used rationalizations from personal and emotional experiences, such as, “I don’t even like this sticker so the new friend can have it”, or, “Everyone should share because it’s a rule in my classroom.” We found that children were less personally invested in questions of biodesign, and thus offered different types of explanations, such as prior knowledge and hypothetical situations (e.g., “Maybe the animal’s friends will treat it differently if it looks different from them”). While either approach is perfectly acceptable to use when justifying ethical choices, we found that the personal motivation justifications were unique to sticker task and did not show up in bioethics conversations, making it less useful as a comparative measure to explore children’s ethical reasoning.

Additionally, we found the resulting data was so rich and broad that it was difficult to draw connections and conclusions specifically regarding our learning outcome of engagement with genes as a programming language. We concluded that, while bioengineering may be comprised of related subfields, we needed to focus on identifying what children know or can learn about bioengineering concepts before drawing parallels to related fields. Further, our CRISPEE assessments demonstrated that children could master the basic functions and of CRISPEE relatively quickly, but that, consistent with our phase 2 and 3 samples, many children came into the camps with a surprisingly high awareness of genetics and engineering to begin with. We wondered if this might be caused by our homogenous sample of volunteers from families affiliated with or supportive of the DevTech Research Group. This led to a directional shift for our phase 5 study toward a larger, broader sample of children. Also consistent with previous phases was a lack of much imaginative play or discussion about genes or animals when children worked with CRISPEE. This was a finding we would return to in phase 6.

Figure 23 describes the conjectures guiding phase 5, in which researchers collaborated with the Boston Children's Museum to host a walk-in exhibition for children to engage in CRISPEE play sessions. Children participated in the same researcher-guided play session activity from the Phase 2 and 3 studies, but this time with significantly less background introduction to bioengineering (e.g. they did not read the bioengineering storybook).

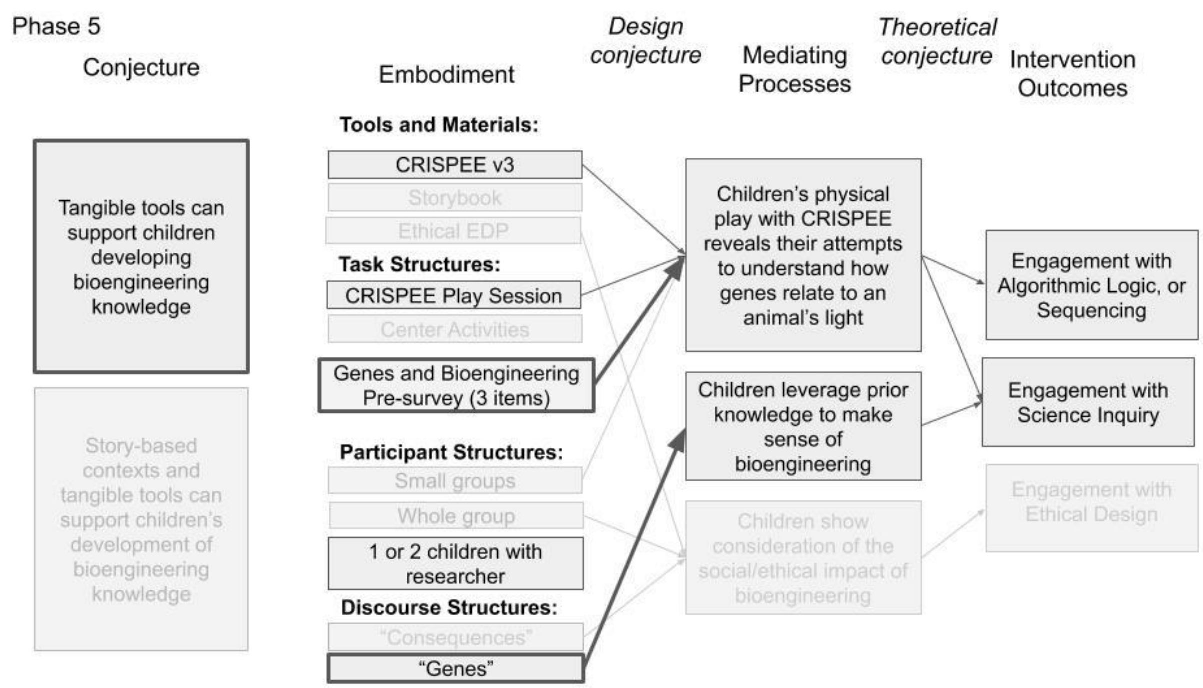


Figure 23. Conjecture map exploring the specific question of whether CRISPEE can support children a larger and more diverse sample of children, based on research findings from Phase 4.

Phase 5: Scaling CRISPEE to a Broader Population of Children and Families.

Learning Design

Children in this study used CRISPEE v3, the same version of the prototype used in the Phase 4 camp. Children in this sample were among the regular museum visitors on testing days, which included weekends, holidays, and some evenings. Although the museum still represented a non-random sample of families that are able to bring their children to museums in their free time, we also attended during times when entry fees and museum hours were relaxed (e.g. “$1 night” evening events) to remain accessible to low-income and low-access families (see chapters 7 and 8 for more details of the sample). We reached N = 82 children, resulting in a larger group than any of our previous phases.

To assess children’s learning, we collected video of children’s play sessions and developed a coding scheme based on prior observational measures (Relkin, 2018) to capture children’s engagement with foundational bioengineering concepts. After an in-depth literature review to identify what those concepts are, and five rounds of inter-rater reliability testing to determine whether we agreed on how to identify evidence of these concepts in children’s play, we arrived at an observational measure (called the CRISPEE Play Scale) to reliably capture children’s engagement with two concepts: algorithmic thinking and science inquiry. From the literature review, we identified areas of sequencing, inquiry, and design process and constructs of interest. Since design process can only be observed in the course of children’s authentic design experiences, including iterative revisions and brainstorming phases which were not present during play sessions, this concept was removed from analysis. Items in the Play Scale were adapted from research on algorithmic thinking in young children (e.g., Bers, 2018) and on children’s science inquiry (e.g., Metz, 2011). First, the team inductively explored the data corpus from the museum sample and developed an initial video coding scheme to describe and compare children’s CRISPEE interactions. Next, we divided the footage into sessions where children were working individually (22 sessions) and sessions with pairs of children (20 sessions). We randomly selected a sub-sample of 3 play sessions from each group, representing 14% of the total sessions to transcribe (Lombard, Snyder-Duch, & Bracken, 2010; McAlister, Lee, Ehlert, Kajfez, Faber, & Kennedy, 2017). Using these cases, we deductively examined transcriptions and videos to identify a codebook to capture children's actions while using CRISPEE. The lead researcher and undergraduate assistants coded the test cases with this draft codebook through two rounds of coding, meeting after each round to agree on discrepant codes. Finally, the codebook was refined through unanimous agreement about coding definitions, examples, and inclusion/exclusion (see Appendix D for a full description of the codebook used to code all CRISPEE play sessions collected in the museum study).The Play Scale measure was pilot-tested on play session tapes from phase 1 and allowed researchers to get familiar with a comparison group.

Children also completed a very brief pre-interview to determine their level of exposure to terms like "genes" and "bioengineering". While children participated in this activity, their parents/guardians were invited to complete a brief 20-item survey about their children's level of exposure to STEM and bioengineering activities at home and school. This was included to address the finding from Phase 4, that children may have some knowledge about bioengineering topics prior to an educational intervention, and to identify where children might be obtaining that experience.

Conjectures

Based on findings described above, we decided that for phase 5 we needed to scale the study activity and measures down significantly to home in on children's experience and understanding of CRISPEE and bioengineering specifically, while simultaneously broadening our participant population to include children from a more diverse range of backgrounds. We reasoned that by diversifying the participant population, we would arrive at a more realistic view of what prior knowledge the average child might bring to a bioengineering activity, and what they would take away from an experience with CRISPEE.

Findings

Chapter 7 presents the analytic procedure that we used to explore the phase 5 data for evidence of the CRISPEE tool a tangible support for children's engagement with sequencing. Figure 24 describes the conjectures guiding phase 6, in which children completed a four-day bioengineering workshop led by the research team as part of the camp offerings of the Tufts-affiliated Eliot-Pearson Children's School.

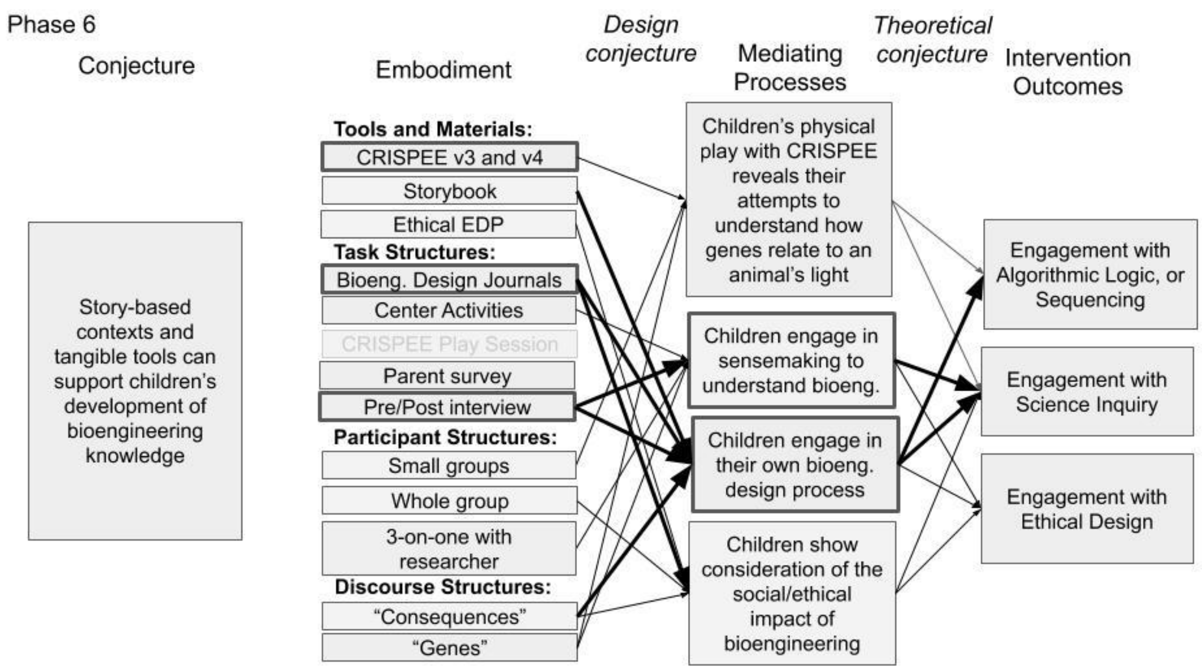


Figure 24. Conjecture map for Phase 6, the most recent curricular intervention phase.

Phase 6: Testing the CRISPEE Tool and Curriculum in a School Context.

The main change in this phase was an emphasis on storytelling as a sensemaking strategy for children in our camp. The storytelling focus emerged from the unresolved question in phase 4, of what occurs when children can engage directly in a bioengineering design process. We learned from our phase 4 study that although children were able to understand the interactions of CRISPEE to produce a light, there was less engagement with the metaphor of programming genes or using genes as a coding language to change living things, one of our long-standing learning outcomes. Findings from phases 2 and 3 showed that the Adventures in Bioengineering storybook was a useful learning support for children to understand the basic concept of what a gene is. We decided to extend this learning support by adding a curricular activity involving a “bioengineering design journal” to help children envision and plan their own bioengineered design. We hoped that by scaffolding children’s design thinking, we would see them begin to engage with bioengineering as designers and content creators, and to manipulate the CRISPEE “genes” as a coding language to realize their creative visions. In order to more deeply explore the relationship between sensemaking and ethical design with CRISPEE, we encouraged children to use the storybook and ethical design process as references for scoping problems and evaluating their designs in the design journals. The journals became a useful assessment data source, as they offered a view into children’s reasoning about the utility and consequences of biological designs.

In line with findings from Phase 4, we also shifted the assessment format to more narrowly focus on inquiry and ethical design. Instead of a series of different tests about related existing fields, we administered one pre/post interview task in which a researcher showed children (in groups of 3) a video about a commonly available bioengineered animal (GloFish™, a lab-created bioluminescent zebrafish) and a naturally-occurring non-glowing zebrafish. Researchers asked children to describe what they observed and offer ideas about why the two fish looked different. Then the researcher explained that a human scientist had created the change somehow, and asked children to guess or explain what could have happened. This narrow conversation prompt allowed for children to converse with each other and explore a variety of ideas about the phenomenon of bioluminescence and bioengineering design, which was much closer to the actual CRISPEE curriculum focus.

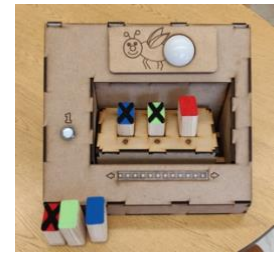
In chapter 7, I describe the analytic procedure that we used to probe the phase 6 data for evidence that children used CRISPEE play, sensemaking, and creative design activities as structures to support their engagement with sequencing, sensemaking, and ethical design in bioengineering.

Reflection

Analyzing the four conjecture maps presented here was a useful way to trace the history of this project and CRISPEE development (see Table 5), but it was even more useful as a technique for identifying gaps in our predictive model. For example, although we had been observing one of our intended learning outcomes, “engaging with genes as a coding language”, as early as phase 1, it wasn’t until phase 3 that we realized that this outcome was not as well-supported by the CRISPEE tool without the storybook, which provided a context for children to understand the function of genes. Recognizing the importance of storytelling in children’s understanding of the tool prompted us to offer curricular supports for children to take ownership of that storytelling, the bioengineering design journals. In turn, these journals offered us an assessment measure for the learning outcome, “engagement with positive and negative consequences of bioengineering”, that we had suspected existed but that we hadn’t yet been able to capture. After engaging in this process, I agree with Wilkerson’s finding, that engaging in conjecture map analysis “made more evident the implicit commitments we were enacting in our design choices” (Wilkerson, 2017, p. 11), allowing us to more clearly see the relationship between our design and the intended (and unintended) outcomes that they yielded.

Table 5

CRISPEE Prototype Version History

	CRISPEE v1 	**CRISPEE v2** 	**CRISPEE v3** 	**CRISPEE v4** 
Platform Feedback				
Check Blocks	Color labels under block slots and red/green LEDs	red/green LEDs	red/green LEDs	red/green LEDs
Shake Platform	Block slot LEDs turn green	Arrow LEDs blink white and Block slot LEDs turn green	Arrow LEDs blink white and Block slot LEDs turn green	Arrow LEDs blink white and LED Strip fills with white
Off Block Design	Grey Background, RGB Colored Line Foreground	Grey Background, RGB Colored Line Foreground	RGB Colored Background, Black X Foreground	RGB Colored Background, Black X Foreground
Reset to Test New Program	Complete program or Restart CRISPEE	Complete program or Restart CRISPEE	Auto-reset when block is removed	Auto-reset when block is removed
LED-interactive plush animals	Not compatible	Not compatible	Compatible	Compatible
Button Interaction	1. Check Program, 2. Mix Program, 3. Test Program	1. Check Program, 2. Mix Program, 3. Test Program	1. Check Program, 2. Mix Program, 3. Test Program	1. Check Program

Chapter 7. Analytic Procedure

Although this investigation comprised six phases of study documents, the dissertation will focus on the two latest design phases in order to address the research questions. For both phases 5 and 6, I will explore the data collected and present my plan for analysis of these data to address the three research questions identified in the Research Statement of Problem:

1. How do children interact with the CRISPEE technological prototype?
2. What can children learn from an educational bioengineering intervention?
3. How does a bioengineering educational intervention support children's learning in developmentally-appropriate areas of bioengineering thinking?

Although all questions were explored in both phases, phase 5 more directly addressed question 1, and phase 6 focused on questions 2 and 3.

Phase 5: The Museum Study

The main research question driving design phase 5 was: 1) How do children interact with the CRISPEE technological prototype? This phase was primarily conducted as a pilot study to explore how a larger sample of children interact with CRISPEE, in order to contextualize results from curriculum interventions. During phase 5, data were collected from N = 82 children over the course of 6 visits to the Boston Children's museum that all occurred between November 2018 and February 2019 during holidays and/or weekday evenings, sometimes also overlapping with the museum's $1 entry nights.

Data Collection and Sample

Data from phase 5 primarily consisted of video footage and field notes of children's physical interaction with CRISPEE. Children were recorded while they engaged in a brief 3-item survey to assess their prior level of experience with foundational bioengineering topics, and throughout their first hands-on experience playing with CRISPEE.

These hands-on experiences followed a protocol developed during Phase 2, called the CRISPEE play session. Play sessions typically lasted between 10-15 minutes. During these play sessions, children were first asked three open-ended questions to determine their level of experience with three foundational bioengineering concepts. The three questions were:

1) Can you point to something in this room that is alive? How do you know it is alive?

2) Have you ever heard the word “bioengineer?” Can you tell me what you think that means?

3) Have you ever heard the word “genes”? Can you tell me what you think that means?

During questions about vocabulary words, researchers would spell the word out on paper for them to see.

After answering the questions, children were invited to build and test a functional program with CRISPEE. Children had the option to work alone or in teams of two during these play sessions. Two researchers were present during all sessions, with one interacting directly with children and the other collecting video records and field notes. During this time, parents and guardians were asked to complete an optional 20-item survey describing their child(ren)’s demographic background and relevant STEM experiences (see Appendix B to review the full survey). The three pre-interview items, as well as the parent responses to the “STEM experience and background survey” will mainly be used to explore the demographic background of the sample and will not contribute to the analyzed data.

Fifty-eight play sessions representing *N* = 82 children were collected during museum sessions. Inclusion criteria for play sessions required that children’s birthdates were listed on consent forms to verify that they were in the target age range of 4 to 9 years old. Additionally, children must have completed all three pre-interview questions and engaged with the CRISPEE tool for at least 10 minutes in the same group structure. For example, sessions were excluded if they started with one child and a second child joined halfway through, but not if both children were present for the initial 10 minutes. This is because it was difficult to draw conclusions about the overall effect of working individually or with a partner to explore CRISPEE for the first time. After removing cases where these criteria were not met, the remaining data comprised 42 sessions representing a final sample *N* = 62 children (see Table 6).

Table 6

Demographic Information for Museum Sample (Phase 5)

	Single Child Play Session	Pair Children Play Session	Total
Age			
4 years	*n* = 1	*n* = 0	*n* = 1
5 years	*n* = 3	*n* = 14	*n* = 17
6 years	*n* = 7	*n* = 9	*n* = 16
7 years	*n* = 4	*n* = 8	*n* = 12
8 years	*n* = 5	*n* = 3	*n* = 8
9 years	*n* = 2	*n* = 4	*n* = 7
Gender			
Male	*n* = 14	*n* = 20	*n* = 34
Female	*n* = 9	*n* = 19	*n* = 28
Group Arrangement			
Single	*n* = 22	-	*n* = 22 (22 sessions)
Dyad	-	*n* = 38	*n* = 38 (19 sessions)
Total			*N* = 62

Analytic Procedure

A research team of six graduate researchers, a post-doctoral researcher, and a research professor from the DevTech Lab met three times to explore the footage from phase 5 for evidence of children's engagement with sequencing, sensemaking, and ethical design while using CRISPEE. Following Erickson (2006) and Jordan and Henderson (1995), we engaged in a deductive analysis of children's interactions, focused on characterizing children's CRISPEE interactions. Table 7 describes the completed and planned activity of the research team and aligns this with Erickson's (2006) four-step inductive interaction analysis method.

Table 7
Planned Research Activities for Museum Study Data Analysis

Step	Deductive Data Analysis Method (from Erickson, 2006)	Study Procedure
1	Select one event and use it to determine the "Communicative/pedagogical functions of research interest" (p. 186)	Six researchers viewed two sample videos and transcripts and used it to identify children's physical play interactions with CRISPEE that were of research interest. These play behaviors became codes.
2	Identify the instances of interest exhaustively within an event (p. 186)	Six researchers re-viewed the sample videos and agreed on a coding scheme. Two researchers reached inter-rater agreement and used the scheme to exhaustively code all instances of codes in all video footage.
3	Tabulate the frequencies of the interactions of interest. Visually display (e.g. through a flow chart or frequency table) the distribution of those instances across different parts of the event (p. 186)	All codes have been tabulated. Currently, two researchers are investigating ways to visually represent the distribution of codes across each CRISPEE interaction.
4	Use transcripts or quotes to provide a detailed description of what various types of interactions look like in practice (p. 186)	Researchers identified a useful way to visually represent codes across CRISPEE interactions, then compared them to create narrative descriptions of several of the most common interaction types.

First, the team inductively explored the data corpus from the museum sample and developed an initial video coding scheme to describe and compare children's CRISPEE interactions. The lead researcher and two research assistants viewed all play session footage and read all field notes. Following this data survey, we divided the footage into sessions where children were working individually (22 sessions) and sessions with pairs of children (20 sessions) and focused only on the 22 individual sessions during the first round of analysis. We randomly selected a sub-sample of 3 individual play sessions representing 14% of the individual sessions to transcribe (Lombard, Snyder-Duch, & Bracken, 2010; McAlister, Lee, Ehlert, Kajfez, Faber, & Kennedy, 2017).

Using these three cases, we deductively examined transcriptions and videos to identify a codebook to capture "communicative/pedagogical functions of research interest", specifically, children's actions while using CRISPEE (Erickson, 2006, p. 580). The lead researcher and undergraduate assistants coded the three test cases with this draft codebook through two rounds of coding, meeting after each round to agree on discrepant codes. Finally, the codebook was refined through unanimous agreement about coding definitions, examples, and inclusion/exclusion criteria. This process was repeated for the sub-set of 20 sessions representing pair-work children, adding codes to capture socially-mediated CRISPEE interactions. See Appendix D for a full description of the codebook used to code all CRISPEE play sessions collected in the museum study.

Although Erickson (2006) warns against using time-sampling techniques to avoid bias in the data, we opted to use a method of time-sampling to inclusively code for all instances within 15-second segments of time in the first 10-minutes of each session. We concluded that because the codes represented activity that occurred inclusively within the 15-second segments (and not at every 15-second pause), our coded data was sufficiently exhaustive and persuasive to capture the richness of the interactions. The coding team re-coded the test cases and tested for inter-rater agreement using Krippendorf's alpha, a statistic that calculates rater disagreement (rather than correcting percent-agreements), making it robust to common inter-rater limitations and useful for handling missing data, variations in numbers of categories coded, scores from multiple coders, and comparing agreements across nominal, ordinal, interval, and ratio data (Hayes & Krippendorff, 2007). Rater agreement using Krippendorf's alpha was achieved at $\alpha = 0.940$, well above the recommended agreement of $\alpha \geq .800$ (Hayes & Krippendorff, 2007, p. 87). Following this, two trained researchers coded the all 21 individual play session video sessions.

We followed Erickson's (2006) recommendations for deductive analysis, including tabulating and visually representing the frequencies of occurrence of different CRISPEE interactions, and then developing detailed descriptions (through either case selection or composite case representation) to evoke a narrative of typical interactions observed during play sessions. Finally, these tabulations and narrative descriptions were used to explore the research question of this study.

To address the question, "How do children play with the CRISPEE technological prototype?" I followed Erickson's (2006) recommendation to use video and transcript data to create detailed descriptions of what various CRISPEE play interactions look like in practice. My outcome of interest was the proportion of time that each child spent on specific interactions (codes) in their session, and particularly the ways that interactions signified children's engagement with algorithms and sequencing while testing CRISPEE programs (see table 8).

Table 8

Overview of Museum Study Data Analysis Plan

Research Question	Data	Analysis
1. How do children interact with the CRISPEE technological prototype?	Parent-completed STEM Background Survey Coded video footage from CRISPEE Play Sessions	Description of trends in play session codes Visual charts (frequency tables or flow charts) to show activity codes in children's CRISPEE play. Narrative descriptions of CRISPEE interaction patterns observed during study

Phase 6: The Camp Study

The main research questions driving phase 6 were: What can children learn from an educational bioengineering intervention?, and How do stories support children's learning with CRISPEE? Data were collected from N = 9 children over the course of a four-day informal camp held at the Eliot-Pearson Children's School during the 2019 Boston Public School February Break Week.

Data Collection and Sample

Children participated in a curriculum-style intervention that took place in the 1st/2nd grade classroom at the Eliot-Pearson Children's School (EPCS). EPCS is a private, tuition-based school in Medford, MA that offers needs-based aid to eligible families according to Massachusetts state guidelines. It is also a laboratory-demonstration school affiliated with the Eliot-Pearson Department of Child Study and Human Development at Tufts University. The Children's School enrolls approximately 80 children. It has preschool through second grade classes that vary in length and frequency. The school curriculum focuses on inclusion, and the administration has a stated mission of recruiting a diverse student body that is representative of the local neighborhood and context. EPCS tuition rates range from $12,272 to $20,504, dependent upon classroom schedules and class groups. Financial aid is provided to an undisclosed proportion of their student body.

Daily activities involved large group activities such as thematic discussions, games, and storybook readings, and small-group/individual work at rotating STEM-themed centers, including a regular center dedicated to unstructured free-play with CRISPEE. All curricular activities had been piloted during design phases 2-4, with the exception of a design activity involving “bioengineering design journals” with worksheets for children to imagine their own creative application for gene editing. Assessment measures took the form of pre- and post-intervention interviews. During interviews, the lead researcher took groups of children in groups of three to a quiet area of the camp classroom and showed them videos of naturally-occurring non-glowing zebrafish and genetically-engineered bioluminescent zebrafish. Children were asked after each video to describe their observations. Then the researcher informed children that both videos depicted zebrafish, and asked why they looked different. After some discussion, the researcher further prompted that scientists called bioengineers had done something to make them different, and asked children what the bioengineers could have done to change the fishes’ appearance (see Appendix D for full interview protocol). These group interviews and all large- and small-group activities were video and audio recorded for later analysis.

Time	**Tuesday 2/19** Meet CRISPEE	**Wednesday 2/20** Coding with Genes	**Thursday 2/21** Ethical Bioengineering	**Friday 2/23** Final Animal Projects
8:30-9:15	**Indoor Play**			
9:15-10:00	*Welcome Circle* 1. Pre-Interviews 2. Light Table 3. CRISPEE free play	CRISPEE I: Intro Science Activity- Observing and Documenting	Ethics activity- Values & the Engineering Design Process Design a helpful animal	*Closing Circle* 1. Post-Interviews 2. Light Table w/ large fish
10:00-10:30	**Snack**			
10:30-11:15	Start Storybook 1. CRISPEE Free play 2. Light table	Design a glowing animal (worksheet) Build your animal with CRISPEE	Design a helpful animal CRISPEE free play	Technology Circle: Design Share out
11:15-12:00	Centers- 1. CRISPEE Free play 2. Light table 3. Glow book + glow squishies Finish Storybook	Centers: 1. CRISPEE Free Play 2. Glow books scavenger hunt	Centers: 1. Microscopes + cells 2. Glow art	Hands-on Fun Centers: - Chemistry table - Light Table w/ large fish - CRISPEE free play End circle: Group Bioengineering a giant Bob
12:00	**Lunch**			

Figure 25. The daily schedule of activities for camp. See appendix A for a full CRISPEE curriculum.

Figure 25 outlines children's daily research and play activities (see appendix A for a full curriculum summary). Children were invited to pause their regular open-ended play centers to participate in brief (20 minutes or less) research activities, such as a pre-assessment or a play session with CRISPEE. Pre- and post-surveys were administered one-on-one by researchers in a quiet section of the makerspace. During the CRISPEE play sessions, researchers led groups of two-to-four children through guided play with the CRISPEE tool in a separate room. Both the lead education researcher and lead technology designer were participant-observers in these CRISPEE play sessions.

Nine children participated in the 4-day camp (see Table 9). Seven children were enrolled as students at EPCS, in the same classroom where the camp was being held. Of the remaining two campers, one had a sibling enrolled in EPCS and both attended other schools in the Somerville area, one at a public school and one at a private school. Five children had prior experience with CRISPEE technology. Four children had participated in the phase 5 museum study in November 2018 (four months prior), and a fifth child had attended the phase 3 curriculum workshop in April 2018 (10 months prior).

Table 9
Summary statistics for Camp Sample (Phase 6)

	Sample	Percent
Age		
5 years	*n* = 2	22.2%
6 years	*n* = 5	55.6%
7 years	*n* = 2	22.2%
Gender		
Male	*n* = 4	44.4%
Female	*n* = 5	55.6%
Children with prior experience from camps/museum	*n* =5	55.6%
Total	*N* = 9	100%

Analytic Procedure

The principal sources of data from phase 6 were videotape and audiotape records, transcripts taken from those video and audio records, field notes, children's written or drawn work during curricular sessions, and pre- and post-interviews conducted with groups of three children, to capture changes in their ideas during the interventions. The research questions guiding this design phase were:

- What can children learn from an educational bioengineering intervention?
- How do stories support children's learning with CRISPEE?

The Tufts-side research coordinator (Amanda) met with a group of six graduate students, post-doctoral researchers, and a research professor from the DevTech Research Group to iteratively examine the data. We used an interaction analysis approach to analyze videotapes and transcripts from phase 6 (Erickson, 2006; Jordan & Henderson, 1995). We followed Erickson's (2006) six-step suggestions for inductive interaction analysis, described in detail below. I chose this method since the research questions were focused on understanding the interaction process of children's hands-on play with CRISPEE, and their use of storytelling as a mechanism to engage with bioengineering concepts of sequencing, sensemaking, and ethical design. I attempted through this method to attend to both "subject matter and learning with close attention to the behavioral organization of the social interaction, verbal and nonverbal" (p. 581). In Table 10 below, I outline Erickson's (2006) six-step inductive interaction analysis method and align with the completed and planned activity of my research team.

Table 10

Planned Research Activities for Camp Study Data Analysis

Step	Inductive Data Analysis Method (from Erickson, 2006)	Study Procedure
1	Review the entire interaction event as a whole, adding field notes and time-codes to organize the data corpus (p. 183-184)	Three researchers viewed all footage and created a Video Content Log with annotated field notes and time stamps of all activity.

2	Review the entire event again, creating a timeline of major transitions in activity boundaries and social interactions (p. 184)	Three researchers re-viewed all footage and created a Video Corpus Timeline with notation of major participants, activities, and transitions,
3	Choose a single segment of tape with a socially dynamic interaction. Create a transcript and focus primarily on non-verbal or speech interactions. Focus first on one participant and then on the second (p. 184)	Three researchers created a transcription of a sample tape of two children engaging with CRISPEE. Six researchers viewed the tape and transcription and created a preliminary codebook to capture interactions.
4	Repeat Step 3 until there is enough descriptive information to answer research questions. Transcribe all sections or only those that contain phenomena of interest (p. 184)	Six researchers have met twice times to explore the data for themes and phenomena of interest. We are still in the process of selecting specific interactions.
5	Review all or part of the event with some participants in it to determine their interpretation of events and interactions. Usually this is conducted after steps 1 and 2 (p. 185)	The lead researcher met with Katie, a participating teaching assistant who was present during the camp, to discuss field notes and child-made work.
6	Determine the typicality or atypicality of transcribed instances, with a focus toward internal generalization and situating the instance in the context of the whole interaction (p. 185-186)	Once we agreed on transcripts of interest, six researchers met again to review data corpus and determine typical and atypical interactions.

First, a content log was generated from the video footage to summarize all activity documented during the curricular intervention. Following this, two levels of analysis were conducted on the data, and a third one is planned. The transcripts of all CRISPEE and storytelling sessions were examined for episodes of rich interactivity. Six episodes representing 88 minutes of footage were identified and transcribed. Sessions were iteratively examined for evidence to demonstrate children’s engagement with sequencing, sensemaking, or ethical design. During these sessions, all members of the research team shared opinions and worked toward consensus about each clip that was discussed, in order to avoid researcher-bias in the interpretation of children's mental states and motivations during interactions (Jordan & Henderson, 1995). Around this time, the lead researcher also met with one of the participating teachers, Katie, who was present throughout the camp. Katie also worked with seven of the nine children in the camp throughout the rest of the school year, as their regular classroom teaching assistant. Together, Amanda and Katie reviewed most elements of the camp intervention to glean Katie's interpretation of the events, and she also shared insights about all of the children she knew from working with them extensively as a classroom aid.

In the third round of analysis, the multi-viewer team continued to explore these excerpts in order to reach agreement on major "events, transitions, and themes" in the interactions that most speak to the three learning outcomes of interest (Derry et al., 2010, p. 9). These outcomes were treated as themes for further investigation (Charmaz & Belgrave, 2007). We chose specific excerpts from the identified sessions for analysis, with an emphasis on tracing connections between elements of the learning design and evidence of children's engagement with sequencing, sensemaking, and ethical design. We used analytic memos to refine our list of major themes and codes relevant for further investigation, such as children's justifications for their bioengineering designs, and disciplinary bioengineering concepts (e.g. genes) that inspired conversation and curiosity among children (Charmaz & Belgrave, 2007). This process helped us to home in on connections between the learning outcomes and the elements of the design intervention that contributed to those outcomes. See Appendix G for a full description of the codebook of themes and codes used to analyze all transcript data collected during in the camp study.

To address the question, "What can children learn from an educational bioengineering intervention?" I used children's pre- and post-interview transcripts to arrive at an understanding of children's understanding of bioengineering concepts at baseline and after the intervention, and any changes in children's bioengineering knowledge (see table 11).

To address the question, "How does a bioengineering educational intervention support children's learning in developmentally-appropriate areas of bioengineering thinking?" I used video and transcript data to characterize children's engagement with CRISPEE and the curricular materials (see Table 11). After this, I followed Erickson's (2006) recommendation to use video and transcript data to characterize children's learning experiences with CRISPEE and the curricular materials as typical or atypical of other learning during the camp. This allowed me to create a narrative understanding of what specific elements of the learning design contributed to children's engagement with the intended learning outcomes of sequencing, sensemaking, and ethical design. Finally, I examined these narrative descriptions in light of any pre-to-post changes in children's interviews to characterize the role that the learning intervention played in changing children's ideas.

Table 11
Overview of Camp Study Data Analysis Plan

Research Question	Data	Analysis
2. What can children learn from an educational bioengineering intervention?	Pre- and Post-interview task Transcripts from camp sessions	Narrative description of children's understanding of bioengineering concepts at pre and post. Comparison of children with and without prior exposure.
3. How does a bioengineering educational intervention support children's learning in developmentally-appropriate	Pre- and Post-interview task Selected transcripts from camp sessions (episodes	Narrative interpretation of children's engagement with sequencing, sensemaking,

areas of bioengineering thinking?	when children engage with sequencing, sensemaking, or ethical design)	and ethical design during selected transcripts. Interaction analysis of children's engagement with sequencing, sensemaking, and ethical design during camp sessions.

Chapter 8. Results from the Museum Study (Phase 5)

The research question guiding the museum study was: How do children interact with the CRISPEE technological prototype?

In the following sections, I summarize the results from the latest analytic stage, which involved exploring demographic indicators on the STEM background survey completed by parents during children's CRISPEE play and tabulating the behavioral codes of children who worked individually during CRISPEE sessions.

STEM Background of the Sample

Of the sample of 62 children, *n* = 44 families completed a survey about their children's experience and interest related to STEM domains. Results of this survey are summarized below.

The average age of children whose families completed the survey was 6;11 years (SD = 1;6), with the youngest participant aged 4;9 and the oldest aged 9;11. Per parent report, 56.8% (*n* = 25) children were male, 38.6% (*n* = 17) were female, and 4.5% (*n* = 2) of families chose not to answer. Regarding highest level of parent education, 4.5% (*n* = 2) reported holding a trade school degree, 22.7% (*n* = 10) held a bachelor's degree, 70.5% (*n* = 31) held a degree beyond a bachelor's, and 2.3% (*n* = 1) chose not to answer. The majority of children (79.5%, *n* = 35) did not have a family member in a bioengineering or biotechnology field. Of the *n* = 9 (20.5%) who did, four children had a father in a biotech field, two had a mother, two had both parents, and one preferred not to say.

Parents also responded to questions about their children's recent engagement with STEM topics at home or school, and the amount of STEM-themed activities and materials at home. Table 12 summarizes the findings from this survey. Finally, 42 parents responded to 3-point Likert-style the question, "Have concepts of genes, DNA or related biology topics been introduced at home?" Responses were roughly evenly split, with 18 families (40.9%) selecting 0 ("Not at all") and 21 families (47.7%) selecting 1 ("Somewhat"). Three families (6.8%) selected 2 ("Yes, thoroughly").

Table 12
Parent Responses to the STEM Background and Interest Survey

	N	Min	Max	M(SD)
In the last 6 months, how often has your child explored the following STEM domains (at home, at school, or at other informal learning spaces)?*				
Engineering, Building	43	1	5	3.4 (1.2)
Robotics, Coding	42	1	5	2.3 (1.3)
Biology, Life Science	41	1	5	3.2 (0.9)
Ethical Problem-Solving	41	1	5	3.0 (1.4)
In the past 6 months, how many activities about bioengineering, microbiology, or DNA has your child participated in?	37	0	4	1.0 (1.2)
How many materials related to bioengineering, microbiology, or DNA are present in the child's home?	35	0	4	1.3 (1.2)
How many materials related to robotics or programming are present in the child's home?	38	0	4	1.6 (1.0)
On a scale of 1-5, how much do you think your child is interested in science, technology, and engineering?**	44	3	5	4.5 (0.67)

Note. *These items used 1-5 Likert-style responses, with 1 = Never and 5 = Very Often (daily or almost daily)
Note. **This item used 1-5 Likert-style responses, with 1 = Not at all Interested and 5 = Very Interested

Overall, the results of this survey show that the sample of families who responded to the STEM background survey are highly educated (over 93% of the sample earned a bachelor's degree or higher), and around one-fifth of the sample had some kind of family connection to a bioengineering field. In the six months prior to the study, children's engagement in STEM activities averaged a score of 2 (Rarely, less than once per month) for robotics and coding activities, and 3 (Sometimes, around once per month) for engineering, biology, and ethical problem-solving activities. Families reported that children had engaged with bioengineering or genetics activities an average of once in the past 6 months, that they had between 1 and 2 bioengineering-related toys at materials at home. Finally, the average family reported that their child expressed an extremely high level of interest in science, technology, and engineering(M = 4.5; SD = 0.67). In sum, the sample of 44 families who participated in both the survey and the CRISPEE play session reported moderate engagement with STEM activities at home and in other learning settings.

CRISPEE Play Sessions

N = 62 children participated in the CRISPEE play session. The research team coded all 42 play sessions, including 22 in which children worked individually with CRISPEE and a participant-researcher, and 20 partner sessions in which children worked in pairs with a participant-researcher. Figure 26 shows a summarized version of the codebook, with definitions and examples for all codes (see Appendix D for the full codebook with exclusion and inclusion criteria).

Category	Code	Definition	Examples
Indirect CRISPEE Interactions	Planning Sheet	Child interacts with CRISPEE planning sheet or paper blocks	Touching/pointing to any of the following: - worksheet-style planning mat - velcro paper blocks - velcro paper light circles
	Exploration	Child interacts with CRISPEE in a way other than building or testing a block program	Touching/pointing to any of the following: - blocks outside of CRISPEE (e.g. building tower, sorting blocks on table) - buttons - platform - other CRISPEE element (storybook, plushie, planning sheet)
Direct CRISPEE Interactions	Build Program	Child interacts with CRISPEE to build a block program	- Adding new blocks to CRISPEE - Emptying CRISPEE of all blocks - Changing/swapping same blocks in program (i.e. same program in new sequence) - Changing/swapping different blocks in program
	Witness Bug	A bug or malfunction in the technology occurs while child is using CRISPEE	Typically this is a false-negative red feedback light in the third slot, but could be any kind of bug in feedback lights or incorrect color light as a result of a tested program. CRISPEE should only light up red in two cases: 1) empty slot, and 2) double-block colors.
	Debugging	Troubleshooting resulting from bug in the technology	rearranging blocks in program (spinning, pushing in harder) to resolve a bug in the technology (false-negative feedback light)
Test Functional program	Test Functional Program	Child tests any functional program in CRISPEE	Child presses buttons 1-3 to test any functional R-G-B program for the first time
Test Non-Functional Program	Test Double-Block Program	Child tests non-functional program with two blocks of same color in CRISPEE	Child presses button 1 to test programs like the following: R-r-G; B-r-b; G-g-_
	Test Missing Block Program	Child tests non-functional program with 1 or 2 blocks missing from CRISPEE	Child presses button 1 to test programs like the following: G-g-_; _-B-_; R-_-b

	Test Empty CRISPEE	Child tests non-functional program with all 3 blocks missing from CRISPEE	Child presses button 1 to test the following program: _-_-_
Test Alternative Construction	Test Alternative Construction	Child tests alternative CRISPEE/program construction	Child presses button 1 to test any of the following "programs": - upside-down blocks - blocks in between slots - blocks stacked in a tower
Social codes	Turn-based talk or gesture	Children verbally or physically declare "turn" boundaries, specifically individual turns Applies to entire tests (Steps 1-3)	- pushing partner's hand away - saying "it's my turn", "your turn is over", or something similar - moving the CRISPEE to face themselves or partner - using body/arms to prevent partner from touching or working with CRISPEE - removing other child's program from CRISPEE - taking turns creating their own start-to-finish test
	Collaborative/role-based talk or gesture	Children verbally divide up "jobs" or specific tasks up by child for a single test Children use gestures to prompt, remind, or help each other in their role Applies to steps within a single test	- announcing roles ("I'll be the button-pusher", "you need to add the blocks," or something similar) - children respond to partner's prompts (e.g. child 1 says "push the button" and child 2 pushes it) - Take turns completing steps within one test - Arranging blocks on table for partner to insert into CRISPEE
	Researcher Prompting	Researcher volunteers information or prompts with questions or gestures (i.e. children did not ask for help or clarification)	Individual Codes: - prompting questions ("What do you think this blocks means?") - prompting to assist behavior/actions ("Did you want to try this block?") - offering information ("Can I share something with you about this CRISPEE?")

Figure 26. Codebook of CRISPEE play interactions

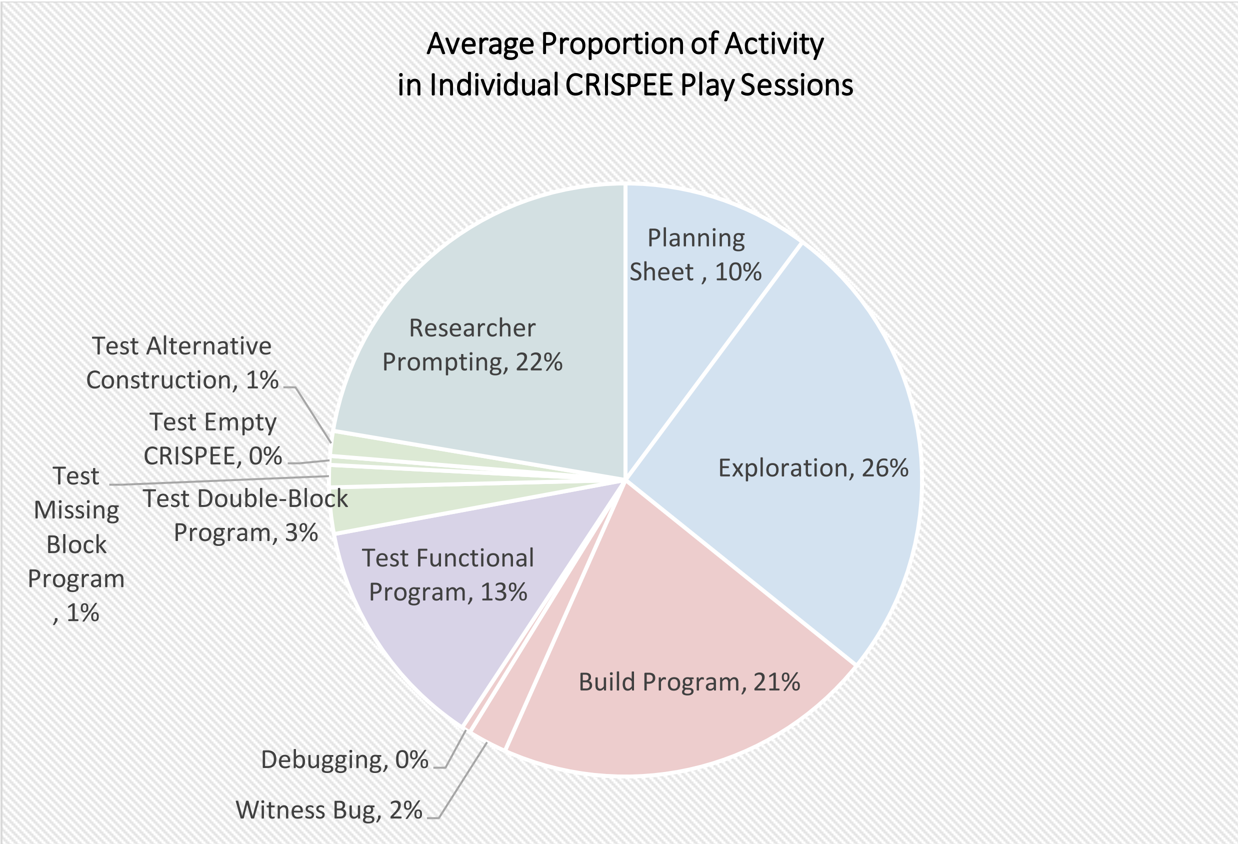


Figure 27. Average proportion of coded activity for children in individual CRISPEE play sessions. Colors of the pie slices coordinate with the colors of code categories in the codebook (see Figure 26)

On average, children working individually spent around one-third (36%) of their 10-minute play session exploring CRISPEE, including building with blocks in front of CRISPEE, touching the buttons and light elements, and examining the interior electronics of the kit (see Figure 17). This category also included all moments when children engaged with the program planning sheet, a supporting material that allowed children to either predict or record programs and their resulting lights. Because it was challenging to determine when children were using the planning sheet for planning or documenting purposes, or simply playing with the pieces, the coding team agreed to categorize this as non-programming exploration. Children spent approximately a quarter (23%) of their time building programs with CRISPEE. one-fifth (18%)

of their session testing functional and non-functional programs, and another quarter (22%) of their time conversing with the researcher.

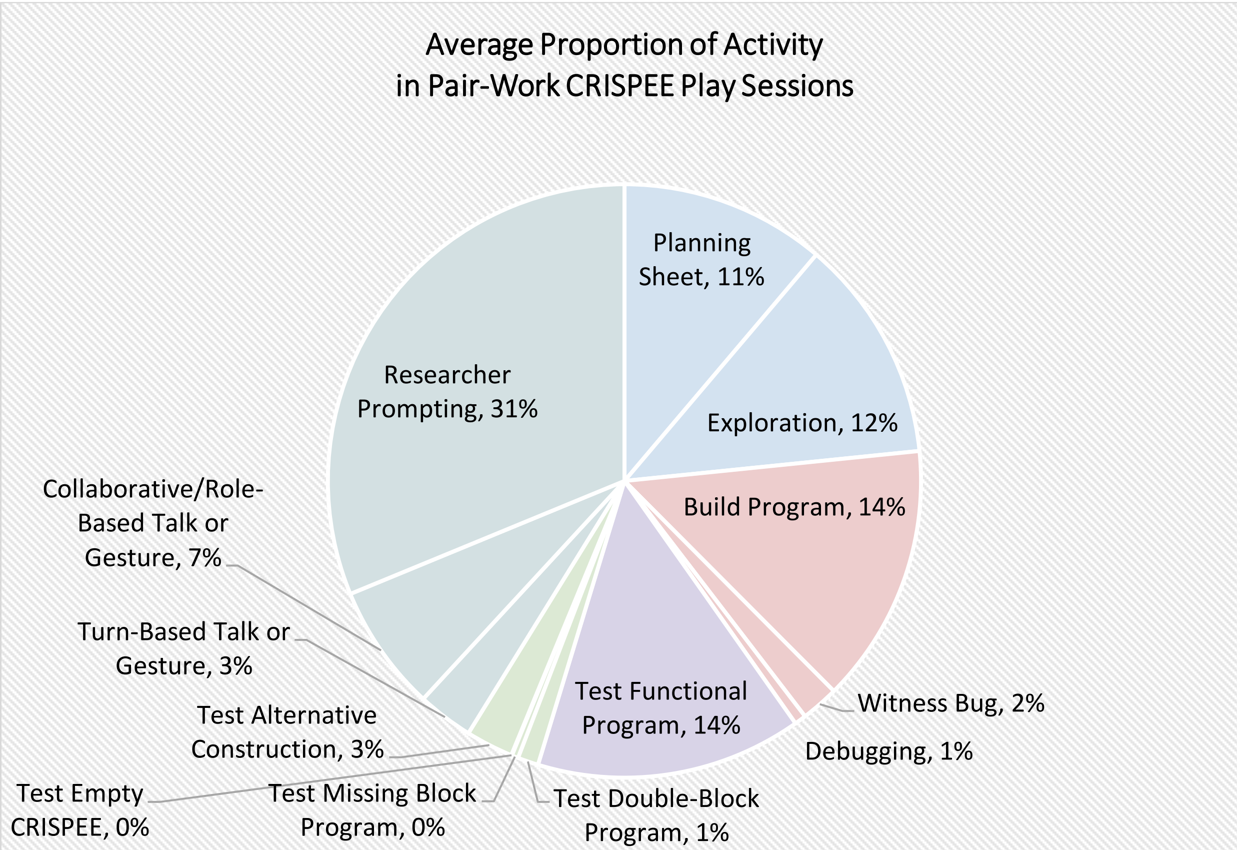


Figure 28. Average proportion of coded activity for children in individual CRISPEE play sessions. Colors of the pie slices coordinate with the colors of code categories in the codebook (see Figure 26)

On average, children working in pairs spent nearly half (44%) of their time their 10-minute play session negotiating or collaborating with their partner and responding to researcher prompts to elucidate their thinking (see Figure 28). In addition, engaging in peer interactions, which individual play participants did not do, children in groups engaged in much more researcher prompting. This is because in addition to regular prompting for clarification of children's ideas, researchers needed to prompt more often to clarify differences between each child's thinking, especially when (as often happened) one child predominantly interacting with the technology while the other child observed. Compared with individual participants, children working in pairs spent less time planning programs and exploring the prototype (23%), slightly less time building programs (17%), and roughly the same proportion of time testing functional and non-functional programs (18%). Additionally, the proportion of time spent testing functional program (individuals – 13%; pairs – 14%) to non-functional program (individuals – 5%; pairs – 6%) was roughly the same across group types. Figure 29 shows a sample case of one child's coded play behaviors over the chronological length of the play session.

Children's Ideas while playing with CRISPEE

Researchers coded all behaviors in a single play session for each child, arriving at a chronological timeline of codes (see Figure 29 for example). These tables and children's video transcripts were then explored for trends. From children's talk and interactions, four main categories emerged of children's ideas about how CRISPEE functioned (see Table 13). Most children exhibited different ideas at different times during a single play session, altering their working their based on evidence from their most recent tests.

Figure 29. Sample Timeline chart from a case child (BCM110, a boy aged 8[4])

Table 13

Ideas that children expressed about how to change CRISPEE's light color.

Idea	Explicit Evidence	Implicit Evidence
A) **Sequence** of blocks activates colors	- Predicts that order/sequence of the blocks will impact light - May also predict that On and Off blocks cannot be mixed (e.g. says they are "different languages")	- Tests programs with same blocks in different order multiple times - Attempts to debug a correct "off" program, expecting to see light
B) **X blocks adds** color	- Predicts that X blocks affect light by adding or increasing light - Predicts that mixing On and Off of same color will make "more" of that color - predicts that X blocks will affect hue (lightness/darkness) of light	- Leaves empty slot (rather than adding X) - Attempts to debug a correct "off" program, expecting to see light - Tests programs with both On and Off blocks of same color
C) **X blocks inhibit** color* *the correct idea for CRISPEE functionality	- Predicts that X blocks affect light by removing or decreasing light - Predicts that mixing On and Off of same color will not work (e.g." this will confuse CRISPEE")	- Debugs by removing On and Off blocks of same color - Tests programs with one of each of the three colors - Does not mix On and Off of same color in one program
D) **Something else** other than the blocks controls light color	- Predicts that feedback lights relate to block color (e.g. red light means add a red block) - Predicts that one location or slot activates light differently (e.g. "this slot is stronger") - May also predict that On and Off blocks cannot be mixed, or must be mixed in a certain proportion (e.g. "it only works when we use one X")	- Tests alternative (e.g. upside-down, stacked) block configurations - Tests other interactions besides blocks (e.g. buttons, animal faceplates)

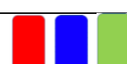
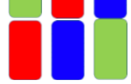
Children held an incorrect idea for an average of 2-4 tests before moving on to another one, although this number depended on the kind of tests they were attempting to run. Because it took the average child 5 minutes to complete 2-4 tests, children's codes were explored for their *most dominant* idea during the first half (minutes 0-5) of a play session, and the second half (minutes 6-10) of a 10-minute play session. I say “most dominant” idea since each child might hold more than one at a time, or switch between them rapidly, so we assigned children the idea that they showed the *most* evidence of during the 5-minute increment. This allowed me to see children’s main idea when first playing with CRISPEE, and their idea after collecting evidence after playing with CRISPEE for several testing rounds. In the following sections I describe examples of each idea in practice using a variety of participant transcripts as examples.

Idea A: Sequence Matters

Children with the sequencing idea hypothesized that they could change the color of CRISPEE’s light by re-ordering the same three blocks. The most common evidence of this idea was when children created the same light color multiple times in a row during their testing session. Of the total 62 children, 17 showed evidence of this idea during the first 5 minutes of their play with CRISPEE. This idea typically extinguished after repeated tests yielded the same color light, and only 5 children maintained this idea beyond the first 5 minutes of playing. Table 14 shows the tests that one boy (aged 6[1]) completed in his first 5 minutes of playing with CRISPEE. He rearranged the order of the same three blocks and made a white light for his first four tests, then removed those blocks entirely to explore the X-marked blocks. Eventually, he decided to mix solid and X blocks, and discovered a new color.

Table 14

Play Session Tests during first 5 minutes of CRISPEE play, from child with Idea A (Male, age 6[1])

Test	Time point during 10-minute test	Program Tested	Light Result
1	1:00		White
2	2:45		White
3	3:00		White
4	3:15		White

5	4:15		Off
6	5:15		Magenta

The most consistent sign that children held the sequencing idea was that their first few tests made either a White or Off light, because children with this idea sometimes also asserted that the solid and X blocks should not be mixed (see Table 15). For example, one boy (aged 9[11]) suggested that the two types of blocks "have different programs" inside of them. Another boy (6[5]) created an Off program early on, then emptying the program exclaimed "maybe [the light is off] because of all of the X blocks!". He then ignored the X blocks for nearly his entire session, because he explained "CRISPEE really does not like that." In the absence of more information about what caused the light to turn off, he assumed that any X blocks would silence all other blocks. It is possible that other children worked under this same assumption, which could explain the pattern of White being the most popular light color for children with Idea A.

Table 15

First four programs from a representative sample of children with Idea A.

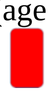
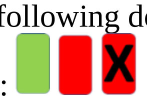
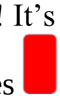
Child ID	Child Gender	Child Age	Test 1	Test 2	Test 3	Test 4
BCM05	M	4(9)	Off	Off	Off	White
BCM79	M	6(2)	White	White	White	Off
BCM97	F	7(2)	White	White	White	Cyan
BCM59	M	8(0)	White	White	White	Magenta

One possible explanation for children beginning play sessions with the sequencing idea was that they were focused on making a visual pattern out of the blocks. For example, one girl aged 5(9) asked at the beginning of her session, "Can I make a pattern?" and narrated her patterns out loud as she re-arranged the same three blocks for several tests in a row. Another explanation might be prior experience with a programming language or other technology that emphasized sequencing. For example, when I explained to one boy (6[5]) that we would be programming genes, said he knew about programming from the KIBO robotics kit, and spent his first three CRISPEE tests re-sequencing the same program.

Idea B: The X Blocks Add Color

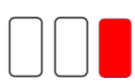
Idea B was characterized by children believing that the X blocks would somehow enhance a color rather than turn it off. Eight children held Idea B at some point in the first 5 minutes of their CRISPEE play session, and five children (four of whom were different from the original eight) explored this idea in the second half of their tests as well. Unlike the sequencing idea, most children only held this idea briefly before moving on to a different working model.

Children with idea B described X blocks as making "less [color] than the full color block" (girl, 6[4]), as the "little color" that helps the "big color" (boy, 8[4]), or as the "darker color" compared to the brighter solid block (girl, 8[11]). These were usually guesses made before children had tried to use X blocks in a program. Figure 30 shows a transcript segment of a conversation between a researcher and two boys (aged 6[5] and 5[11]) who held different ideas about the X blocks (all names are pseudonyms).

Transcript Segment: Idea B	Analytic Memo Interpretation
Yash (age 6[5]): [presses button 1, red lights under  and ]. Aww…	Yash tries the following double block program:  I point out that CRISPEE will not let us continue the test, because of red feedback lights below the two red blocks.
Amanda: Uh oh! It's confused about these two blocks [touches  and ].	
Yash: Yeah	Yash acknowledges the feedback.
Victor (age 5[11]): [Takes  out of CRISPEE]	Victor, Yash's partner, removes one of the doubled red blocks.
Amanda: [Holds up  and  side-by-side.] If this is a program that tells Bob's body to light up	

different colors, what do you think this program block tells it to do? [Holds up only  for them to see.] What's this gene for?	I ask the boys what they think is the difference between the two red blocks for our light programs.
Yash: Hmm, don't make a color.	
Amanda: And what about this one? [Holds up only  block]	Yash guesses that a solid block turns the light off, and an X block turns the light on.
Yash: Make a color.	
Amanda: So, [holding up ] You think that this one will turn all the colors off, right?	
Victor: [smiling] No, on! [points to white light from planning sheet]	
Amanda: Oh, it turns the light on? We have different guesses?	Victor indicates that he has the opposite hypothesis to Yash's.
Yash: See? [tests . White light comes on. Yash mutters quietly] Oh yeah…this *makes* the light. [slowly removes blocks from CRISPEE]	Yash tests the program we have been talking about. He realizes from the test evidence that his idea is incorrect, and the block roles are reversed.

Figure 30. Transcript Segment from child with Idea B (Male, age 6[5])

Idea B was more difficult to identify by children's program logs because it was not characterized by a specific testing pattern, and because children usually extinguished this idea more quickly than the sequencing idea. When children tested a "double block" program (containing a solid and X block of the same color), they were usually (but not always) testing idea B. Other common tests included programs with missing blocks. For example, one boy (aged 6[0]) attempted to make a red light by testing the program, , hypothesizing that the 

and  blocks would add a small amount of those colors to his light. However, because CRISPEE rejects double block combinations, these tests were always non-functional and children interpreted the red feedback lights in different ways. After a failed test, children usually understood the rule that CRISPEE needs a block of each color, but would sometimes interpret differently and develop other ideas about CRISPEE rules (these are described in the section on Idea D).

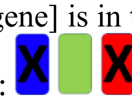
Idea C: The X Blocks Inhibit Color

Idea C – the correct idea - was the hypothesis that the X blocks inhibited whatever color they show on their background. For example, a program with all three colors in X blocks ( ) will turn CRISPEE's light off, and program with two colors in X blocks and one solid block () will shine in the color of the solid block. Multiple solid block colors mix according to light physics principles. So, a yellow light is created by combining the primary light colors of green and red, and silencing the color blue ().

Unlike the other ideas, which children would take up and later reject, none of the children who adapted this idea ended up rejecting it later on, presumably because it was ultimately supported by the CRISPEE interaction evidence. Across entire sample, 15 children expressed this idea at some point in the first 5 minutes of their play-test with CRISPEE, compared with 35 children by the end of each test. This was the most common idea that children held at the end of a play session regardless of age, gender, or group type (partner or individual), meaning that more than half of my sample was able to arrive a correct understanding of the CRISPEE mechanics within 10 minutes of playing with the tool.

The main physical evidence that children held idea C was that they would successfully test many different colors in a row. In some cases it was unclear if children actually held a mental model about what was occurring or simply combining different sets of blocks and memorizing their output, for example, when children tested functional and non-functional programs in succession. During play sessions, researchers prompted children to understand their thinking, usually by asking for predictions about what color a program would make, or asking them to explain (or guess) how they made a certain color. Table 16 shows several typical answers from children with the X-inhibits-color idea included.

Table 16
Sample responses from museum participants to the question, “What do the X blocks mean?”

Child Sex	Child Age, in Years(Months)	Verbal explanation of Idea C
M	5(11)	“The X’s mean no blue, no green, no red”
F	5(9)	“X might stop it from making light”
M	6(2)	“This one [block] has an X so it doesn’t have this color. No X means it [the color gene] is in the firefly”
F	7(8)	While testing the program:  “I think that it [the light] will be green because these two [X] blocks mean ‘off’”
M	8(3)	“Even though there’s an X which is blocking, it’s still making the other colors. Even though it’s sort of blocking, it’s still making purple. I think it’s to teach us that there’s more than one DNA inside us to make the entire body”
M	8(9)	While testing the program:  “Maybe [it will make] red. Actually, maybe blue because both of these [green and red] are crossed out.”

Idea D: Something Else Controls Color

Throughout testing, children also developed various unique ideas that were unrelated to the color of the blocks. 20 children, nearly one-third of the total sample, held some kind of D-type idea in the first half of their play session, and by the second half of the session that number dropped slightly to 16 children, around one-quarter of the sample.

Alternative ideas were rooted in an interesting mix of evidence from the CRISPEE kit and assumptions or prior knowledge about genes and color mixing. For example, one girl (9[3]) saw the X blocks and exclaimed, “Oh wait these are X chromosomes! Maybe it tells if Bob is a girl or a boy. And maybe these [solid blocks] are O chromosomes!” Another child (female, 8[4]) was confused about the color mixing of light. When asked why all solid blocks () made white, she replied “I have no idea. I [would] think it would be brown but I know it’ll be white.” This led her to misinterpret the block functions because she could not see the block colors as logical primary colors for the light that they mixed to create.

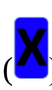
Other children did not understand the CRISPEE mechanics, and constructed programs with extra components, including extra blocks squeezed into the coding platform and pieces of the planning sheet balanced on the control panel (see Figures 31 and 32). These children offered little or no explanation for a causal mechanism for the light color when asked. Other children attributed causal explanations to non-color elements of the CRISPEE. For example, a boy (6[1]) discovered through trial and error that double block programs would not work, but his interpretation of this finding was that CRISPEE rejected all programs with more than one X block in the code. D-type ideas were difficult to identify because they could even emerge when children completed successful tests adhering to CRISPEE programming rules. A boy aged 6(0) who had just completed a successful test of a red light explained that “the green X () is making the red () even brighter, and blue X () is trying to defeat the green X.” In his imaginative explanation, the blocks are story characters with human-like motivations, and their changing allegiance was the cause of the light colors. These kinds of non-scientific ideas were persistent in children, because they were difficulty to disprove with an experimental set of CRISPEE tests.

Figure 31. Child (Male, 6[1]) engaged in alternative construction with blocks, indicating a D-type idea.

Figure 32. Child (Male, 6[1]) engaged in alternative construction with planning sheet pieces, indicating a D-type idea.

Summary of Findings related to CRISPEE Theories-in-Action

Throughout play session testing, the $N = 62$ children from a variety of backgrounds and STEM experience levels expressed one or more of the four ideas identified through behavioral coding. Nearly half (*n* = 29) of all children shifted between ideas, and *n* = 33 children held the same idea throughout the entire session colors (for a table with all children's coded ideas, see Appendix F: Table of all Museum Study Participant Child Ideas). Of children who changed ideas, *n* =15 of these maintained the same incorrect idea, and *n* = 18 began and ended their session holding idea C, the correct one. Children's ideas may be stage-linked, since children aged 5 years and younger held more D-type ideas in general, and specifically more ideas related to alternative construction (e.g. building towers out of CRISPEE blocks to change light color), and children aged 9 and older showed more D-type ideas rooted in prior biology knowledge (e.g. assuming CRISPEE X blocks were related to X-chromosomes). More research is needed to determine if these differences can be attributed to developmental stage differences or a byproduct of the convenience sample and idiosyncratic differences in children's personal experience.

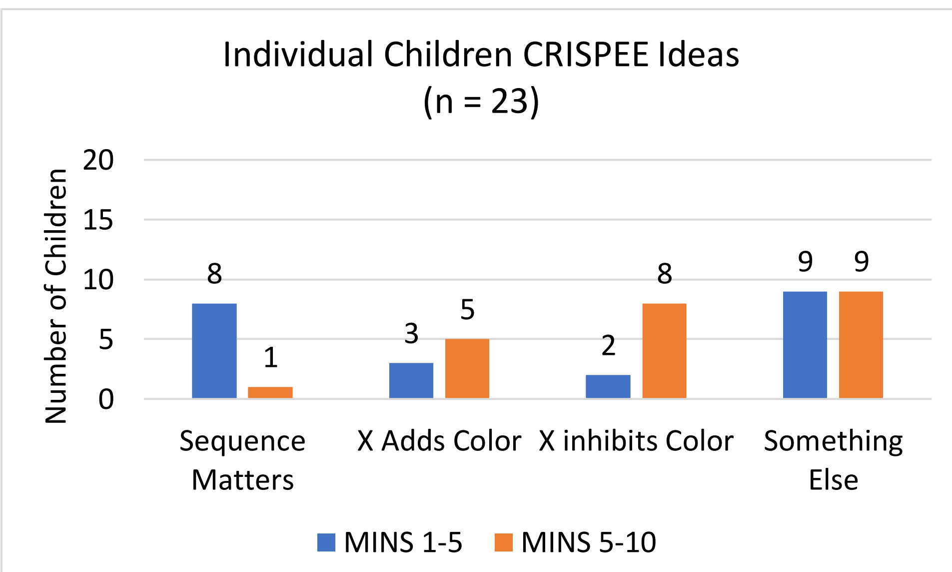


Figure 33. Individual Children's predominant CRISPEE ideas during the first half and second half of their 10-minute play sessions.

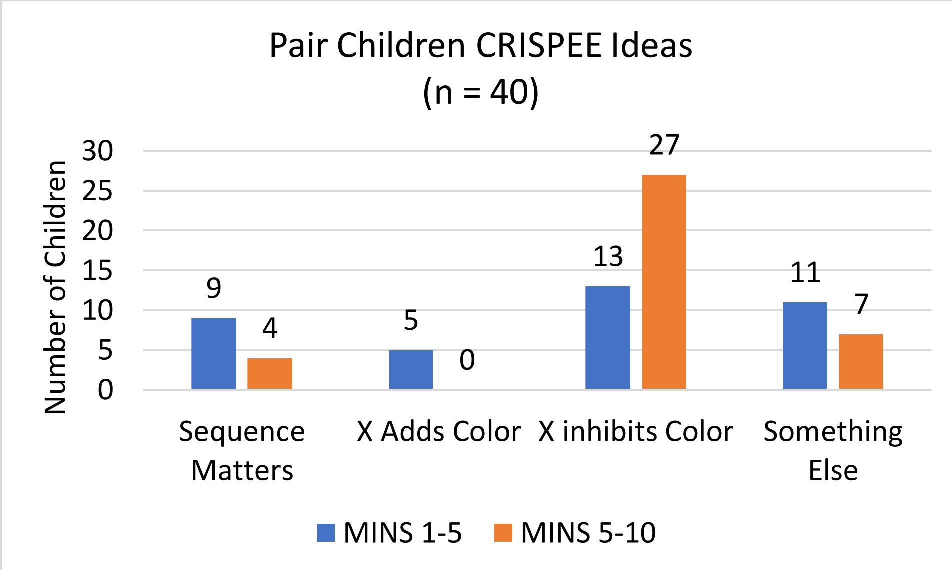


Figure 34. Pair-work Children's predominant CRISPEE ideas during the first half and second half of their 10-minute play session.

Figures 33 and 34 display the proportion of each type of idea that children held during the first and last halves of their play sessions. The major differences between children who participated in pair-work session and individual sessions was that pairs of children showed more exploration of alternative ideas (D-type) in the first half of their play sessions, perhaps spurred by a spirit of playful exploration that occurred with a child partner but not with a single adult research observer. In both individual and pair-work sessions, Idea C was the most popular idea by the second half of the session, meaning that the majority of children in the total sample eventually arrived at the correct idea of CRISPEE functionality. However, the proportion of children who ended the session holding the correct idea what higher in the individual sessions (70% of individual session participants) than it was for the pair-work sessions (48% of pair-work session participants), suggesting that children who spend more one-on-one time with the CRISPEE ended up developing more evidence-based ideas and exploring fewer alternative ideas.

Enjoyment and Engagement

Finally, regardless of the ideas that children held, every child who participated in a play session was motivated to keep playing for the duration of the required 10 minutes, often asking for more time. Figures 35, 36, and 37 display the common reactions of shock and joy that children often experienced during their first time programming CRISPEE's light to glow. This joy quickly translated to a personally meaningful goal, such as seeing CRISPEE glow in their favorite color. Children were highly engaged for the duration of play sessions.

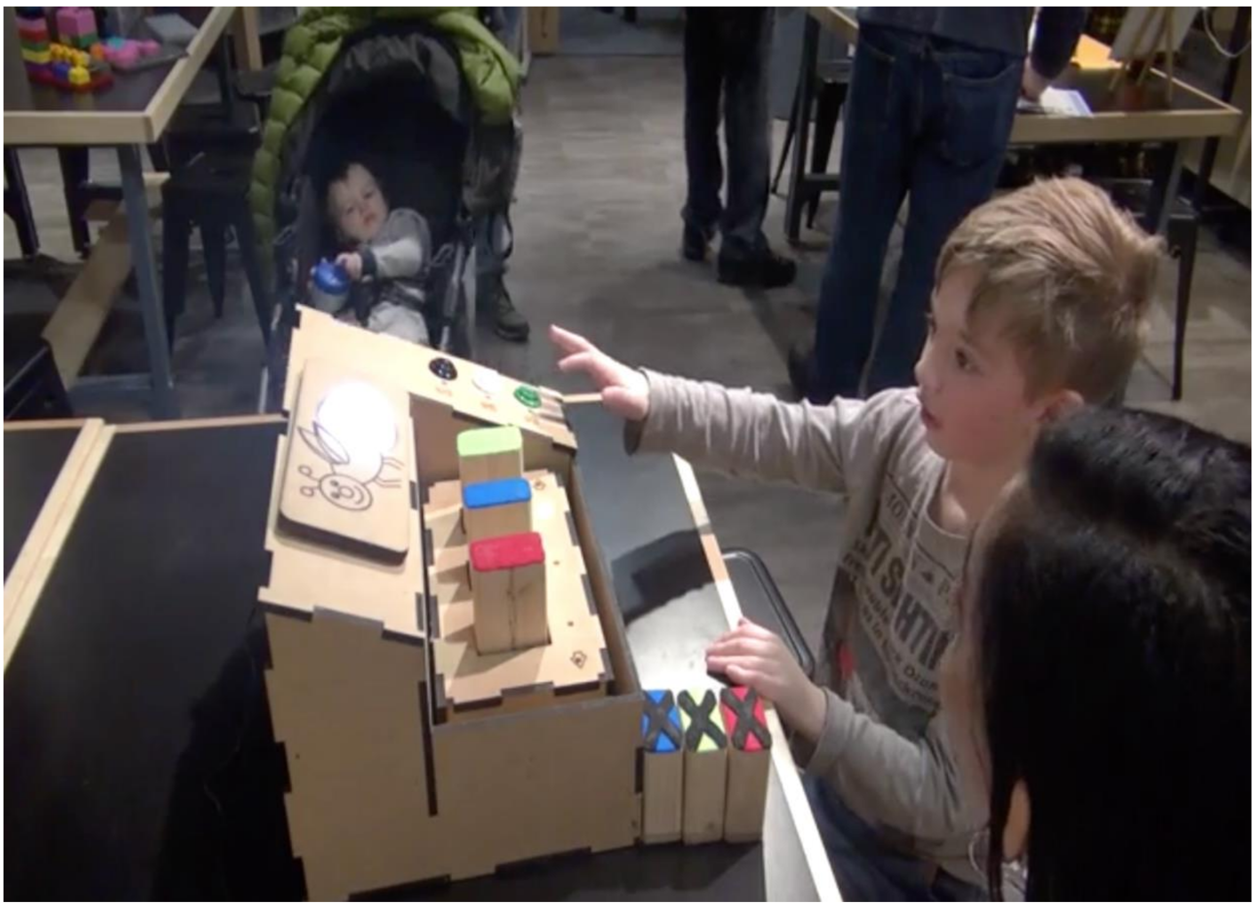


Figure 35. A museum study participant (boy, 6[1]) tests his first program. Initially, his reaction is shock and he literally freezes with wide eyes upon seeing his white light.

Figure 36. After a moment, the boy (6[1]) is overcome with excitement and joyfully exclaims “I did it! I did it!”

Figure 37. Two sisters (left, aged 5[5]; right, aged 9[3]) are delighted to see their first light creation.

Chapter 9. Results from the Camp Study (Phase 6)

The “Camp Study” (phase 6 of the overall design study) was designed to explore *n* = 9 children’s learning with CRISPEE during a naturalistic learning intervention using all the curricular supports described in Chapter 7, “Analytic Procedure”. The study was designed to address the following two questions:

4. What can children learn from an educational bioengineering intervention?
5. How does a bioengineering educational intervention support children’s learning in developmentally-appropriate areas of bioengineering thinking?

To address the first question, I used children’s pre- and post-interview transcripts to explore of their understanding of bioengineering concepts at baseline and after the intervention. To address the second question, I used video and transcript data to characterize children’s engagement with CRISPEE and the curricular materials as it related to sequencing, sensemaking, and ethical design. In collaboration with a senior member of the interaction analysis team, I explicitly defined what each of my learning outcomes of interest look like in the transcripts. We also used the transcript evidence to identify what elements of the learning design contributed to the learning outcome. We completed these tasks using analytic memos to explicate our understanding and interpretation of the learning themes (Charmaz & Belgrave, 2007). Finally, I examined these narrative descriptions in light of any pre-to-post changes in children’s interviews to characterize the role that the learning intervention played in changing children’s ideas. The following sections describe this work, beginning with a discussion of the themes that emerged from an inductive analysis of the data corpus.

Themes and Codes in the Data

I used the combined transcripts, collected children's works, and researcher meetings and memos from the camp study, and arrived at a codebook that I used to inductively categorize the bulk of the transcript data (see Appendix G for a full description of themes and sub-codes). Figure 38 shows the visual relationship of themes and codes with each other. Code categories were inclusive of their constituent sub-codes, but were also codes in their own capacity. For example, a transcript segment coded at the node Biodesign would also code for Design Process, but a transcript could also be coded separately at Design Process without double-coding its sub-codes. All coding was completed using the qualitative research software Nvivo 12 for Mac.

Figure 39 shows a code tree depicting the relative proportion of the 1114 total codes in the transcripts. The size of the boxes corresponds to the proportion of data that was categorized at that code, and nested boxes represent relationships between themes and codes. This visual representation highlights the major themes that emerged throughout coding rounds.

The most prominent theme of the camp was Life Science, comprising a third (33.3%) the total coded camp transcripts. Life Science was defined as moments when children were "exploring or investigating nature or properties of living things". This theme comprised codes of science practices (e.g. asking questions, making observations) as well as recurring content topics (e.g. genes, bioluminescence).

The theme of Mental Models was the second most common, representing 13.5% of the data, and was defined as children's attempts "to understand or explain differences between bioengineered and non-engineered animals, or to generally explain luminescence in living and non-living things". This theme emerged mainly (but not entirely) during pre/post interviews. During these interviews, children watched videos of non-glowing zebrafish, and a patented

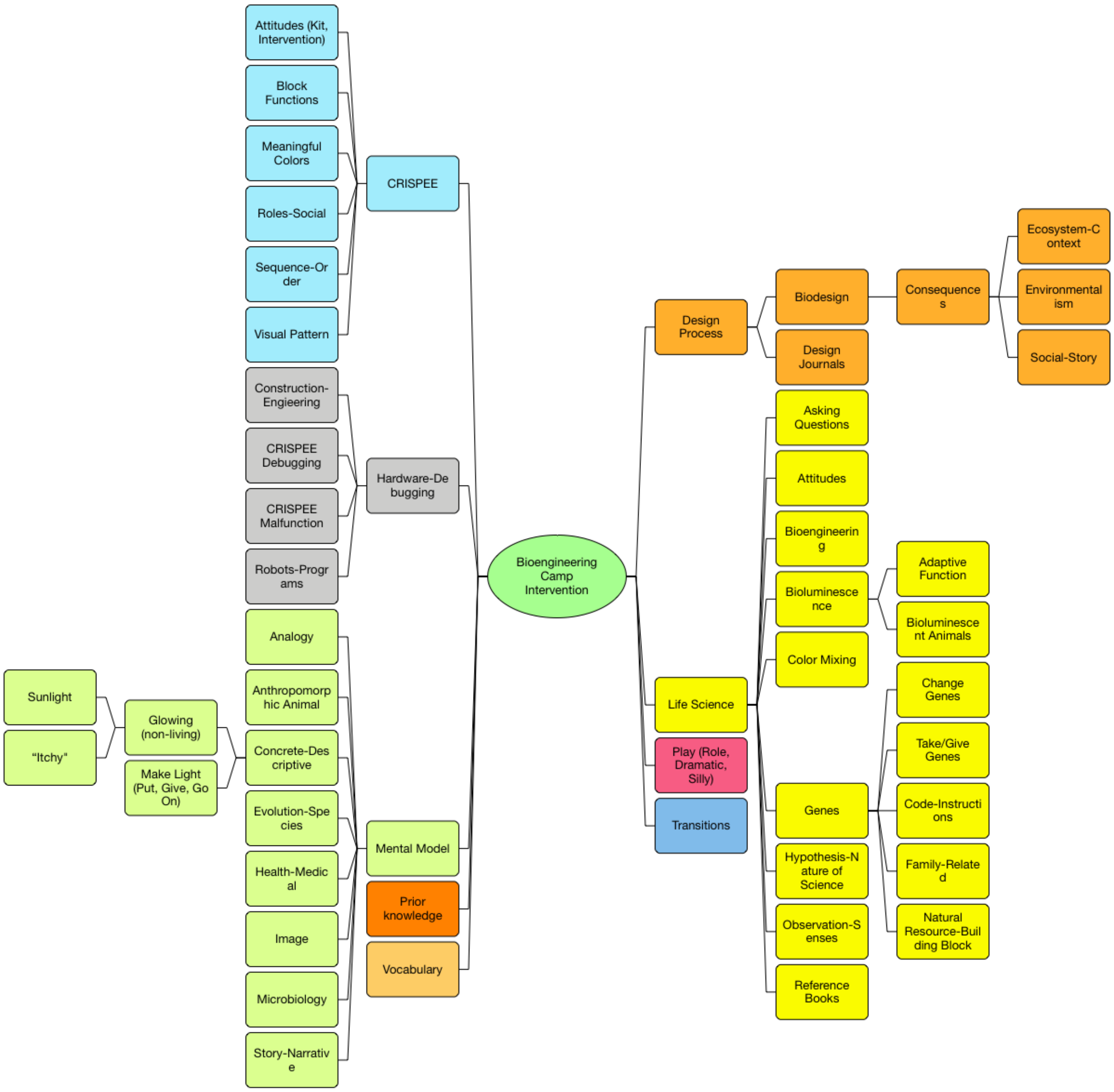


Figure 38. Hierarchy of themes and codes generated from inductive analysis of all camp transcripts, child-made work, and field data.

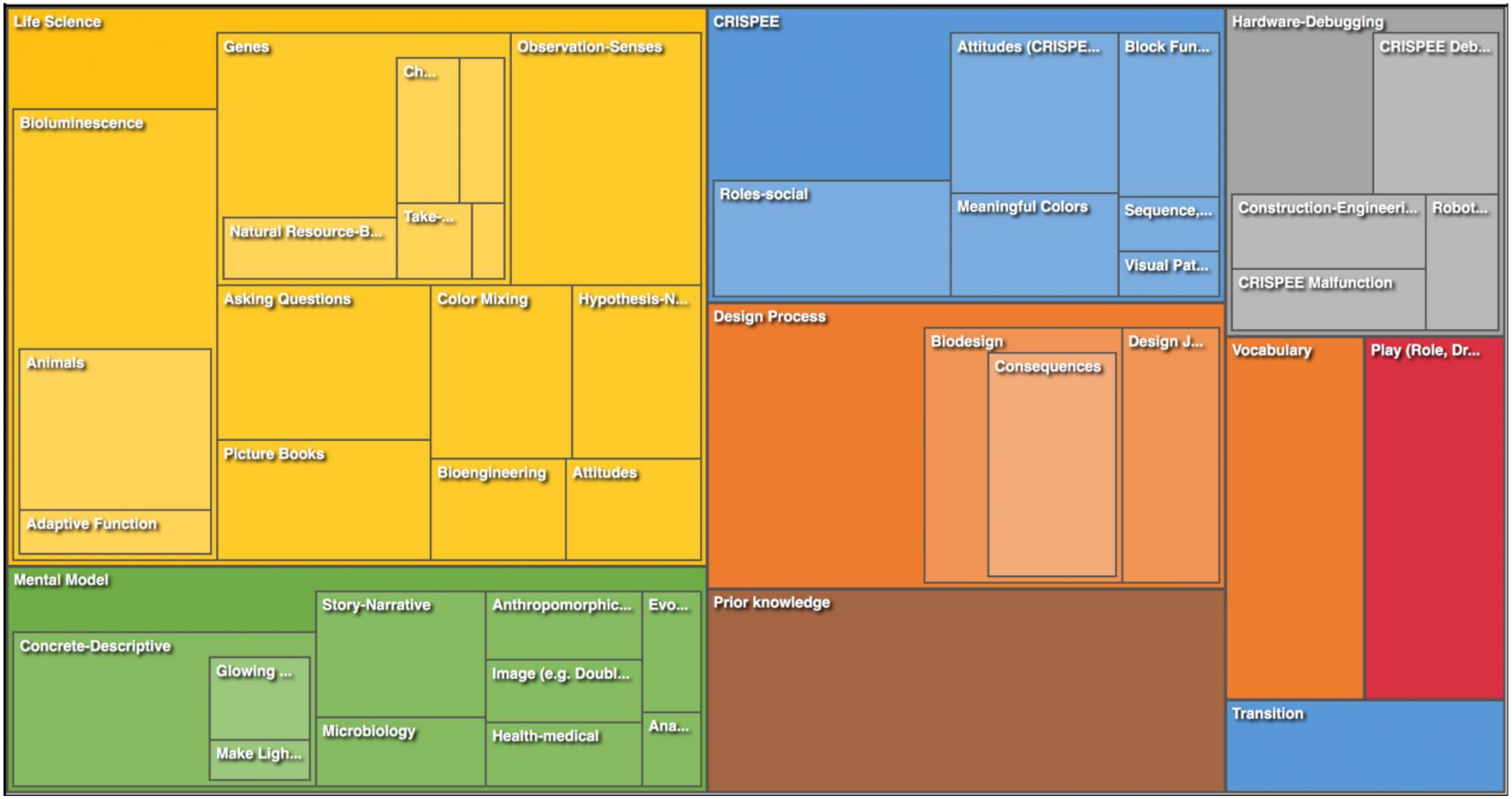


Figure 39. Treemap of themes and codes for camp data corpus. Boxes of themes (color-coded) and smaller boxes of codes within each theme. Boxes are sized corresponding to the relative proportion of data that fell into each code.

bioengineered zebrafish called a "Glo-fish" that glows in a variety of neon colors. After viewing the videos, I first asked children to explain their best guess about why the fish were different. Next, I explained that a human scientist had changed something about the fish, and asked if they had a guess about what the scientist could have done to result in bioluminescent fish. The phrase "Mental Model" refers to the explanatory models children most likely held based on their explanations of the phenomenon of bioluminescence. Code examples include Concrete-Descriptive explanations (using direct observations to inform ideas), Story-Narrative explanations (using a plot- or character-driven explanation), and Anthropomorphic Animal explanations (ascribing human-like motivations or behaviors to the animals being engineered).

The third major theme in the data corpus was CRISPEE (13.0% of coded data), defined as any "interaction with or about the CRISPEE prototype". This theme included codes like Roles-Social (children socially organizing their CRISPEE interactions) and Block Functions (children talking about or attempting to test the functions of the CRISPEE blocks in relation to the light produced).

Design Process, defined as "any creative expression of design planning, ideating, creating, and/or iterating; referencing the design process" was another common theme (12.7% of codes). Design Process comprised codes of Biodesign (any engagement with the design process specifically involving genes/animals/bioluminescence) and references to the Bioengineering Design Journal (an open-ended workbook-style learning support offered in the camp).

Prior Knowledge (9.0% of codes) was a diverse theme that actually comprised a single broad-sweeping code, and captured diverse references to "prior experience (e.g. through children's media, anecdotal experience, picture books) as a way to explain or ask questions related to the intervention".

Hardware-Debugging interactions, or “any reference to building or repairing human-made hardware, parts, or machines”, accounted for 7.8% the data. These codes involved any interactions or talk related to building, robotics, or machinery, as well as conversations about the CRISPEE prototype itself as an object of investigation. For example, many children observed malfunctions in CRISPEE, which sparked their curiosity about the construction and materials involved in building it.

The remainder of the data fell into codes of Play behaviors (4.3%), novel science-themed Vocabulary (4.3%), and Transitions between activities (2.2% of data).

Children’s Learning with CRISPEE: Pre-to-Post change

To address the research question, “What can children learn from an educational bioengineering intervention?”, I used children’s pre- and post-interview transcripts to characterize their understanding of bioengineering concepts at baseline and after the intervention. During pre-interviews, children demonstrated varying levels of prior experience with bioengineering in general, and with CRISPEE in particular. By post-interviews, many children incorporated references to the design process, engineering/hardware, and the CRISPEE kit into their responses. In the next sections, I describe trends from the pre-interviews and then the posts. I first describe how children were organized for each small-group interview, and then describe overall trends from the camp interviews. All names presented are pseudonyms.

Pre-interview findings.

The nine child participants were divided into three groups of three children for interviews. Since several participants had already participated in prior phases of the CRISPEE design work, children were organized into groups with similar levels of experience. Groups were numbered from 1 (least collective experience) to 3 (most collective experience). Samantha, Melody, and Carlos (Group 1) had the lowest combined experience with CRISPEE. They had never played with it before the camp or participated in other CRISPEE sessions. However, due to the naturalistic test setting and scheduling limitations on the school's end, they had read the CRISPEE storybook just before participating in the interview, allowing them to explore bioengineering concepts (but not the CRISPEE prototype) prior to their interview. Caroline, Krista, and Zora (Group 2) had mixed prior experiences with CRISPEE. Caroline and Krista had participated together in a 20-minute CRISPEE play session, but had never read the storybook. Zora had never seen any elements of the CRISPEE kid prior to the camp. Yash, Kevin, and Henry (Group 3) had the highest combined level of prior experience with CRISPEE in the camp. In the 12 months prior to the camp study, Kevin had participated in another 3-day CRISPEE camp, and both Henry and Yash had each participated in a 20-minute CRISPEE play session. All three had read the storybook prior to their pre-interview.

Figure 40 depicts the codes that emerged in children's pre-interview transcripts. Children's talk primarily centered on Prior Knowledge and Sensory Observations related to Life Science topics. These codes accounted for approximately half of all coded pre-interview transcripts (47%), with the rest of the codes divided among discussion about life science concepts such as genes and bioluminescence. For a more detailed view of the codes, see table 17.

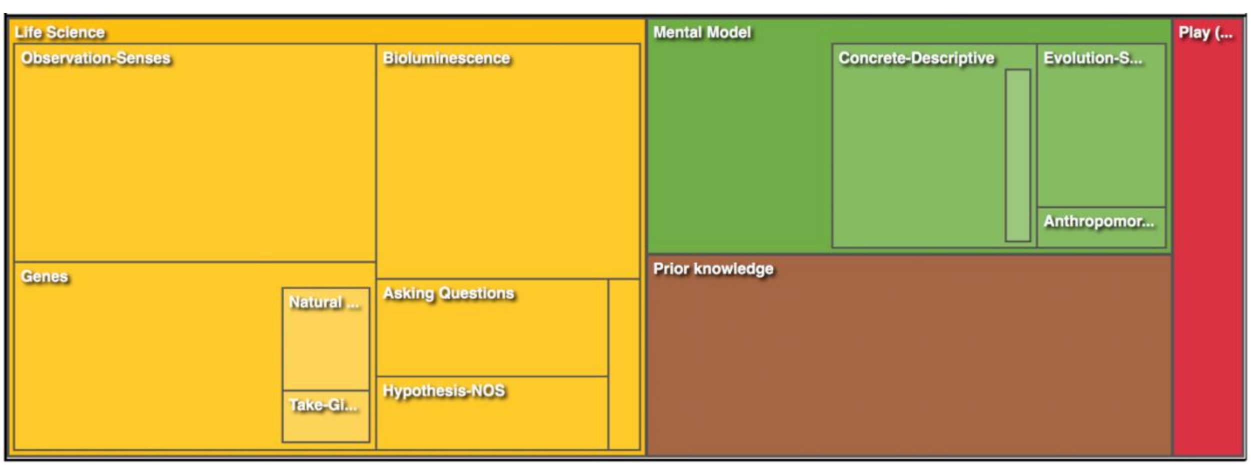


Figure 40. Treemap of all codes captured in children's pre-interviews.

Table 17

Total Codes from all Camp Pre-Interviews

Code	Count	Percent	Cumulative Count	Cumulative Percent
Life Science	25	21.0%	25	21.0%
Prior knowledge	17	14.3%	42	35.3%
Observation-Senses	14	11.8%	56	47.1%
Mental Model	14	11.8%	70	58.8%
Bioluminescence	11	9.2%	81	68.1%
Genes	9	7.6%	90	75.6%
Concrete-Descriptive	7	5.9%	97	81.5%
Play (Role, Dramatic, Silly)	5	4.2%	102	85.7%
Asking Questions	4	3.4%	106	89.1%
Evolution-Species	4	3.4%	110	92.4%
Hypothesis-NOS	3	2.5%	113	95.0%
Natural Resource-Building Blocks	2	1.7%	115	96.6%
Bioengineering	1	0.8%	116	97.5%
Take-Give Genes	1	0.8%	117	98.3%
Anthropomorphic Animals	1	0.8%	118	99.2%
Make Light (Put, Give, Go On)	1	0.8%	119	100.0%

At some point in every interview, I prompted each child to describe their "best guess" about the cause of the bioluminescence in some of the zebrafish, and after they gave their answers, I explained that a scientist had somehow been involved in the change and asked them the same question again. Children drew on a broad range of prior experiences to help them grapple with glowing and non-glowing versions of the same animal (zebrafish). They made connections to personal lived experiences such as fishing trips and pet fish, formal science concepts like predator/prey relationships and aquatic habitats, and their observations of the fishes' behavior and appearance to explore the interview topic of bioluminescent fish.

Children’s responses often (but not always) indicated a mental representation they were using to model the biological mechanisms they imagined. These quotes were coded broadly under the theme Mental Models, although children’s mental representations were perhaps not always coherent “models” as much as a constellation of facts and ideas that they surfaced to form a working idea (e.g. in the style of di Sessa’s [1993] Knowledge in Pieces framework). Children’s talk evidenced a mix of models in their thinking, with the same child often using multiple and sometimes contradictory explanations to describe the bioluminescence phenomenon. Several types of models emerged in pre-interviews, including Concrete-Descriptive understandings (e.g. tautological suggestions that animals glow because they “have light”), Evolution-Species relationships, Analogies to human differences, and models involving Genes.

Children’s Concrete-Descriptive models typically showed that they were seeking evidence through their first-hand observations to understand bioluminescence. These models typically did not offer a causal explanation of bioluminescence, but rather a description of what it is. These were usually children’s first responses in the interviews, and perhaps represented an attempt to understand what they were seeing (at least one child expressed that they had never seen or heard of glowing animals before the camp).

Some children tried to explain both the differences and similarities among the zebrafish and Glo-fish by categorizing them into different “families,” “kinds,” “types,” and “species” of the same fish. Other children offered ideas involving Human Analogy, such as comparing bioluminescence in fish to traits of ethnicity, sex, and skin/hair color in humans. Often children combined these ideas with a vague model of selected traits, similar to the accepted scientific explanation of species-level evolution (hence the Evolution-Species code). For example, Caroline explained "the fish got separated from each other because they have different genes", which brings to mind a model of evolutionary selection for different traits. Carlos hypothesized about differences in habitats and adaptive traits, suggesting that the glowing fish might be "nocturnal" or might have "see-in-the-dark" vision that the other zebrafish do not. Transcripts indicate that children with the Evolution-Species of mental model were aware of some kind of relationships among the fish, perhaps akin to an adult conception of a branching evolutionary tree, and were trying to fit zebrafish and Glo-fish into this model.

Six of the nine children in the camp made unprompted references to genes during the pre-interview, although when prompted they offered diverse definitions. Caroline explained that genes "are something that makes you you,"; Samantha said "there are genes for what color they [fish] are, what colors they glow, how big they are,"; Melody emphasized that "they aren't jeans!"; and Yash and Henry agreed with Kevin's definition, that when he said genes he meant "like the genes that make you glow or have a different light". Of these six, five mentioned characters or plot points from the original CRISPEE storybook (Adventures in Bioengineering). The sixth child (Caroline, who had no prior CRISPEE experience) referred to a picture book that she owned at home called The One and Only You, by the gene sequencing company 23andMe (this book was also available during camp as a free-choice offering, which Caroline recognized and pointed out to the researchers). When asked to explain what they meant by the word "genes", children's answers suggested some awareness that genes are a kind of physical bodily material that "makes" living things. One child said, "genes are something that makes you you", a definition that resurfaced a handful of times throughout the camp as well.

Some children attempted to work the concept of genes into their understandings of bioluminescence. When children mentioned genes in relation to bioluminescence, they usually referred to the CRISPEE storybook. Specifically, it seems that children were using the storybook plot as a model to explain how two similar or even identical animals (two fireflies or two zebrafish) could exhibit such a different trait (glowing or non-glowing), and recalled the vocabulary of "different genes" from the story. Only one child's talk (Samantha) suggested that she held a model of actually changing genes by "putting them in" the fish, but more information would be needed to understand how she is conceiving of the concept of "genes" . All children who brought up the word "genes" seemed to understand that they were somehow related to differences in living things.

Post-interview findings.

Post-interviews were also conducted with children in groups of three. However, because of the naturalistic setting and children's idiosyncratic schedule changes, the groups changed a bit in posts. Groups were still numbered from 1 to 3, with Group 1 having the least combined amount of pre-camp CRISPEE experience and Group 3 having the most. Group 1 was Samantha, Melody, and Zora, the three girls who had zero experience with CRISPEE before the camp. Group 2 was still a mixed experience group, with Caroline and Krista, who had participated together in a 20-minute CRISPEE play session, and Carlos, who had never worked with CRISPEE before the camp. Group 3 was unchanged, and still had Yash, Kevin, and Henry, the three boys with the highest combined prior experience with CRISPEE.

Figure 41 depicts the codes that emerged in children's post-interviews. Children's talk in posts still showed a focus on Life Science, Mental Models, and Prior knowledge. However, children covered more topics in post-interviews, with CRISPEE, the Design Process, and Hardware-Debugging emerging as three important themes that were not present in pre-interviews (see Table 18). For a more detailed view of the codes, see table 18.

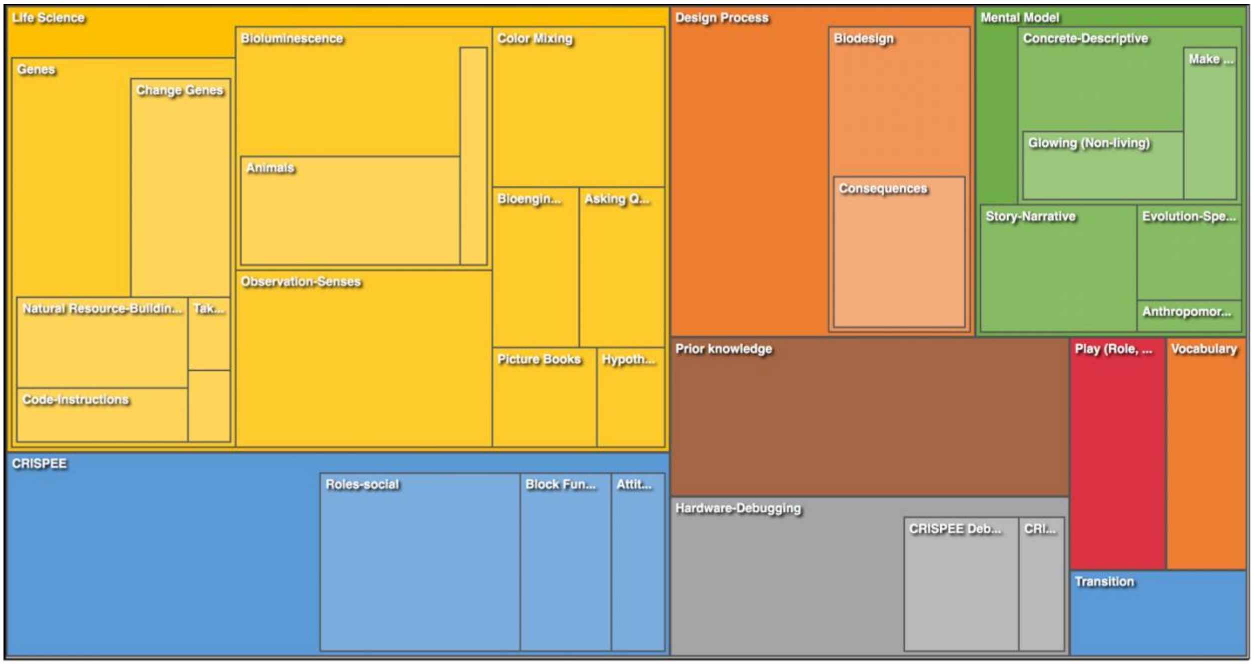


Figure 41. Treemap of all codes captured in children's post-interviews.

Table 18

Total Codes from all Camp Post-Interviews

Code	Count	Percent	Cumulative Count	Cumulative Percent
Life Science	42	13.0%	42	13.0%
CRISPEE	27	8.4%	69	21.4%
Design Process	22	6.8%	91	28.2%
Genes	21	6.5%	112	34.7%
Mental Model	21	6.5%	133	41.2%
Prior knowledge	17	5.3%	150	46.4%
Bioluminescence	15	4.6%	165	51.1%
Observation-Senses	13	4.0%	178	55.1%
Roles-social	11	3.4%	189	58.5%
Concrete-Descriptive	11	3.4%	200	61.9%
Hardware-Debugging	10	3.1%	210	65.0%
Biodesign	8	2.5%	218	67.5%
Animals	8	2.5%	226	70.0%
Color Mixing	8	2.5%	234	72.4%
Change Genes	7	2.2%	241	74.6%
Story-Narrative	6	1.9%	247	76.5%
Play (Role, Dramatic, Silly)	6	1.9%	253	78.3%
Block Functions	5	1.5%	258	79.9%

CRISPEE Debugging	5	1.5%	263	81.4%
Natural Resource-Building Blocks	5	1.5%	268	83.0%
Vocabulary	5	1.5%	273	84.5%
Asking Questions	4	1.2%	277	85.8%
Bioengineering	4	1.2%	281	87.0%
Glowing (Non-living)	4	1.2%	285	88.2%
Transition	4	1.2%	289	89.5%
Attitudes (CRISPEE, Camp)	3	0.9%	292	90.4%
Consequences	3	0.9%	295	91.3%
Ecosystem-Context	3	0.9%	298	92.3%
Code-Instructions	3	0.9%	301	93.2%
Picture Books	3	0.9%	304	94.1%
Make Light (Put, Give, Go On)	3	0.9%	307	95.0%
Evolution-Species	3	0.9%	310	96.0%
CRISPEE Malfunction	2	0.6%	312	96.6%
Adaptive Function	2	0.6%	314	97.2%
Hypothesis-NOS	2	0.6%	316	97.8%
Sunlight	2	0.6%	318	98.5%
Social-Story	1	0.3%	319	98.8%
Family-Related	1	0.3%	320	99.1%
Take-Give Genes	1	0.3%	321	99.4%
Anthropomorphic Animals	1	0.3%	322	99.7%
Itchy	1	0.3%	323	100.0%

Note. Shaded rows represent codes that were not present during post-interviews only, and absent from pre. All codes from pre-interviews were also present in posts.

Although pre- and post-interviews were all roughly the same length of time, conversation was rich enough in posts that transcripts comprised 323 total codes, almost triple the 119 codes from pre transcripts. All codes that were present in pre-interviews were also present in posts, suggesting that children were not shifting away from their prior-held ideas, but perhaps were expanding on them with novel ideas introduced throughout the camps. During pre-interviews children mainly described bioluminescence as a trait of certain "types" of zebrafish (e.g. tropical, nocturnal). This hypothesis was still present in posts, although children had more elaborate explanations about how Glo-fish came to be. Children incorporated concepts introduced in the camps, such as genes, CRISPEE, and biodesign into their answers.

Some explanations for bioluminescence still relied on concrete experiences and observations, physical descriptions, or a mix of both. For example, children used toys and books as a model for how living organisms glow. Yash argued that the fish in both videos were actually exactly the same, but that the Glo-fish had spent more time "closer to the sun". This recalls models of how glow-in-the-dark toys and stickers (which we used throughout the camps) will not glow unless they've been sufficiently "charged" by being left in sunlight. Carlos referred to Glo-fish as the "itchy fish." This initially confused coders, until we realized that he had engaged in a conversation earlier in the camp about how to determine if the pages of glow-in-the-dark picture books would glow or not. The children agreed that if you rub your hand over the page and it feels itchy, "that's how you know if it will glow". Carlos had applied this heuristic of itchy (glowing) vs smooth (non-glowing) picture book pages to glowing and non-glowing animals.

As in the pre-interviews, six of the nine children mentioned genes in their post-interview (although interestingly, it was not always the same children). Group 1, the group with the least prior experience before the camp, was especially interested in discussing genes as a mechanisms for causing bioluminescence, while simultaneously surfacing novel vocabulary from the camp (e.g. bioengineer, bioluminescence). Overall, children who mentioned genes seemed to agree that they were instructions for living things, that they were important for biodiversity, and that they were distinct from the homophonic word, jeans (denim pants).

Children mentioned genes in both pre- and post-interviews, but talk of changing, taking, or giving genes was much more common in post (8 references) than in pre (1 reference). This suggests that children were shifting towards an idea of genes as a malleable or editable element of living things, rather than something unchanging. Further, their references to “changing” genes was typically in response to the question about how some zebrafish came to glow, indicating that they had an idea of genes relating to an animal’s physical appearance. In some cases it seems this was a broad understanding of genes bring related to many aspects of an organism, such as Samantha’s description that a fish’s genes could code for what color they are, what colors they glow, how big they are.” Other children seemed to associate genes specifically with bioluminescence, such as when Kevin defined genes as things “that make you glow or have a different light.” Finally, references to changing genes were more often aligned with an understanding of Glo-fish as altered zebrafish, rather than a separate ‘type” or “kind” of zebrafish. This subtle difference represents a departure from the Evolution/Species hypothesis (in which Glo-fish were understood as a natural variant of zebrafish) that was prevalent during pre-interviews, towards an understanding of Glo-fish as zebrafish that have been superficially altered. Occasionally, they also referenced CRISPEE while discussing genes. For example, in his post-interview, Kevin suggested that Pam (the bioengineer from the CRISPEE storybook) changed the fish by putting them into CRISPEE. Carlos also suggested “maybe they used CRISPEE?” in response to the question, what did scientists do to make these zebrafish glow. The transcripts also suggest that children viewed genes as a material in living organisms that could be extracted and modified, similar to an organ or a natural resource that can be harvested from an organism. For example, in pre-interviews Melody, Samantha, and Carlos all made references to “switching genes,” “taking genes from one animal and giving it to another”, etc. However, in posts, Samantha also suggested that a consequence of using genes from a plant would be that “you can take them from all the aloe plants in the world and there would be no aloe plants left with those genes." She is arguing that resource scarcity and depletion could be a negative consequence of creating biodesigns with existing genes.

Part of the post-interview protocol involved inviting children to play with CRISPEE to determine how they understood the prototype mechanisms, and whether they surfaced the metaphor of gene editing. All of the nine children in the camp were able to successfully build and test a program to produce a light on CRISPEE by the post-interview. Children expressed positive affect and playful attitudes when working with CRISPEE. Only one child (Samantha) verbally stated the idea of "programming" genes as a mechanism for creating bioluminescence, when she said during her post-interview, "Zoe [the Zebrafish] has no-glow genes […] but we can program her genes to make her glow". Since the CRISPEE prototype involves the metaphor of programming blocks as genes that can be re-programmed, it is interesting that so few children used this language. However, many children mentioned CRISPEE in connection with designing or changing an animal's light, or mentioned genes in connection with bioluminescence. This suggests that CRISPEE was a useful tool to support their mental representations about the design process of altering the appearance of living things, whether or not they extended that model to incorporate the concept of an invisible genetic instructional language.

Finally, one group of children (Group 1) spent a significant amount of their post-interview discussing design consequences, and ethical repercussions of biodesign. This was the same group with the only child in the camp (Samantha) who demonstrated a clear and consistent understanding of genes as a programming language for living things. Their conversation represented largely child-directed, spontaneous discussion about an original design idea that Zora proposed, and the possible consequences for her bioengineered organism. The girls demonstrated naive conceptions of biology, including plants having a "healing force". Additionally, in weighing ethical consequences of making an animal bioluminescent, one girl used both fictional story-based ideas ("[her friends] might laugh at her") and non-fictional ecosystem-based ideas ("predators might see her") to justify decisions. They also talked about genes as a depletable resource of a plant that can be harvested, similar to how other children were conceiving of genes as a natural resource within living organisms. Finally, the girls also engaged in a respectful dialogue evaluating the pros and cons of their friend's design idea.

Pre-to-Post Comparisons.

In conclusion, children's talk in pre- and post-interviews demonstrated two main types of mental model to address the question, "what is the difference between zebrafish and Glo-fish". No new models emerged from pre to post, but the proportion of children whose talk aligned with each model shifted dramatically.

I call the first one the Evolution-Species Model. A child with the Evolution-Species model might answer that Zebrafish and Glo-fish are related but distinct types of animals. Possible causes for their physical differences included mechanisms similar to natural selection, such as splitting off of genetic ancestors (e.g. "they got separated from each other"), normal within-species diversity (e.g. "there are different types of humans, like Indians and Americans"), and adaptation to unique habitats (e.g. "maybe they're nocturnal"; "they are closer to the sun"). Sometimes children with this model would reference genes that animals had, but in the same way the animal might have any other adaptive trait. For example, Henry answered in posts that the main difference between zebrafish and Glo-fish was that Glo-fish had "more genes" (presumably more "glow" genes) because they were located deeper in the ocean. Although more genes might be a reference to biodesign, his use of habitats to justify his answer suggests he is thinking of selective pressures rather than human intervention.

I call the second model, Biodesign or Changing Genes Mental Model. Children with this idea might suggest that Glo-fish and zebrafish are the same, but Glo-fish are Zebrafish that have had their bodies or genes altered by a scientist. Explanations included references to the CRISPEE kit or storybook (e.g. “Maybe Pam used CRISPEE to change them”), to scientists who *added* parts or genes to animals (e.g. “they put new stripes in them”), or to scientists who *changed* parts of genes in the animals (e.g. “some scientists […] took out some of the genes from in the fish and then made them into like another type of gene”; “the Glo-fish are zebrafish but their genes are changed so that they don't seem like it”). This model is a shift away from a cognitive model with two categories of fish that are distinct but related, toward a model of a single category of fish that has been artificially altered to appear distinct.

Based on children’s responses during pre- and post-interviews, I tallied the codes that fell into each type of mental model to arrive at the strongest or most prominent model evidence from each child’s talk in the transcripts. While it may not be possible to understand children’s exact mental models, Table 19 below shows the mental model with the most code evidence for each child before and after the camp intervention. In pre-interviews, eight children held a mental model that relied on metaphors similar to adult-conceptions of evolutionary change and species-level differences. One child indicated a mental model that involved humans intervening to alter an animal’s genetic instructions. This ratio was nearly reversed in post-interviews, with seven children exhibiting a mental model related to biodesign through gene editing, and only two children maintaining an evolutionary-species model.

Table 19

Children’s predominant mental model during pre- and post-interviews.

Child	Pre-Interview Mental Model	Post-Interview Mental Model
Carlos	Evolution-Species	Change Genes

Caroline	Evolution-Species	Change Genes
Henry	Evolution-Species	Evolution-Species
Kevin	Evolution-Species	Change Genes
Krista	Evolution-Species	Change Genes
Melody	Evolution-Species	Change Genes
Samantha	Change Genes	Change Genes
Yash	Evolution-Species	Evolution-Species
Zora	Evolution-Species	Change Genes

The results from the pre- and post-interviews suggest a few key findings. First, confirming prior research into children's knowledge construction (e.g. di Sessa, 1993; Hammer, Elby, Scherr, & Redish, 2005; Sherin, 2006), children leveraged existing knowledge from a diverse range of experiences as part of the sensemaking process to cultivate their mental models. Second, when confronted with a question about how scientists could alter an animal's appearance, most children in my sample began the study with a mental model that was similar to adult-level conceptions of evolution and species relationships, and concluded with a mental model similar to adult-level conceptions of gene editing. This means that children may be developmentally capable to explore the concept of genetic instructions earlier than previously believed. Third, children in my sample used elements from the CRISPEE intervention, such as the CRISPEE prototype, storybook, and design process activities, to inform their emerging mental models about changing genes. This suggests that the intervention was successful in engaging children in concepts of gene instructions, the engineering design process, and ethical dimensions of creative bidoesign. In the following section, I explore the question of what elements of the intervention specifically supported children's engagement with these concepts.

Children's Engagement with Powerful Ideas of Bioengineering: During-Camp Findings

To address the second question, "How does a bioengineering educational intervention support children's learning in developmentally-appropriate areas of bioengineering thinking?", I used video and transcript data to characterize children's engagement with CRISPEE and the curricular materials as it related to sequencing, sensemaking, and ethical design (although as I will show, more themes emerged in the data). We used the transcript evidence to identify what elements of the learning design contributed to the learning outcome. Table 20 outlines our memo notes about how we recognized evidence of the theme in the data, how we believe that the learning design contributed specifically to those themes, and specific transcript selections that exemplify the theme in practice.

Transcript Examples of Themes

In Appendix H, I've selected transcript clips that capture each theme, and annotated with analytic memos (generated from the meeting with myself and the post-doctoral researcher) to describe how each moment relates to the enactment of the learning outcome. The memos presented in transcript tables reflect these two researcher interpretations. At times, these interpretations also include insight from Katie, the teaching assistant who was present for all camp activities and who worked with the majority of the campers (seven of the nine) during their regular classroom activities at EPCS.

Initial and Emergent Learning Themes.

Based on my review of the literature, I had identified three core themes going into this data analysis. These were: 1) Sequencing and Algorithms from the field of computer science; 2) Inquiry and Sensemaking from the field of life science; and 3) The Design Process from the field of engineering (see Table 21). In the sections below, I describe how I did indeed find evidence of

Table 20
Initial Learning Themes in Camp Data

Theme of Interest	Defining the theme	Design elements that prompted engagement with Theme	Transcript Examples
Sequencing	- Children follow algorithmic testing pattern while playing with CRISPEE kit - References to programs	- Classroom games with turn-taking and cause-and-effect - Connections to computer programming in discussions/books - CRISPEE interaction rules for creating a light	- Yash's CRISPEE program plan - Zora's CRISPEE debugging
Inquiry/ Sensemaking	- Connections to prior knowledge or experience - Questioning whether information is "real" or "factual"; questioning the source of information - References to genes or microbiology	- Reading and allowing children to respond to Adventures in Bioengineering Storybook - Topical reference texts available to children - Open-ended discussions and prompts - Bioengineering Design Journal prompts - Constructivist learning approach, allowed children to discover and explore with CRISPEE and center activities.	- Kevin's Storybook Questions - Whole group conversation about Genes during CRISPEE story - Yash's Virus Story
The Design Process	- Any creative expression of design planning, ideating, creating, and/or iterating - References to the design process	- Bioengineering Design Journals - Plot from Adventures in Bioengineering storybook that modeled a design cycle - Design a Biosensor Game	- Samantha's Cyan Light - Design a Biosensor Game

Table 21
Emergent Learning Themes in Camp Data

Theme of Interest	Defining the theme	Design elements that prompted engagement with Theme	Transcript Examples
Hardware/Software	- Children referencing machinery/parts or programs/instructions - References to Robots - Discussion about engineers and builders	- Connections to computer programming in discussions/books - Discussion about CRISPEE's construction, builders, etc.	- Henry's hardware questions - Caroline, Yash, and Henry's CRISPEE center exploration
Debugging	- Debugging a CRISPEE hardware malfunction (not a coding or block order challenge)	- CRISPEE technology (malfunctions) - Engagement with engineers and researchers who built CRISPEE	- Carlos and Caroline's conversation with a CRISPEE engineer - Zora's Debugging Notes
Ethical Design	- References to solving problems - References to consequences of design (positive or negative) - Moments when children are discussing or working on their Bioengineering Design Journals	- Ethical Design Process anchor chart and song - Imagination-based activities - Real-world examples of bioengineering projects - Prompts to consider unexpected consequences of designs	- Henry's Cheetah Design - Zora's Aloe Lotion Design - Bioengineering Design Journals

all three themes in children's play. However, sequencing turned out not to be the most prominent powerful idea from computer science that surfaced in the data, and the design process was more nuanced with ethical underpinnings than I previously predicted.

After analyzing data from the CRISPEE museum study (see chapter 8), I felt confident that children engaged with the computational idea of sequencing and algorithms when physically interacting with CRISPEE. However, it appeared that children in the camp engaged with sequencing mostly during their first experiences with CRISPEE, and over time their play shifted to focus more on exploring the other powerful computational thinking ideas. Specifically, children grappled with the relationship between Hardware and Software, and engaged in technological Debugging. Similarly, when engaged with the engineering Design Process, there was enough emphasis on the ethical impacts of design that Ethical Design became a theme in its own right. These themes emerged both at a meta-level about the CRISPEE prototype itself (e.g. expressing curiosity about how it was built, who made it, etc.) and at the level of planning and implementing their light designs. In the following sections I first describe findings from themes related to computational thinking (Sequencing, Hardware/Software, and Debugging), then findings from Inquiry/Sensemaking, and finally conclude with trends from the Design Process and Ethical Design themes. For each theme, I will describe trends across the camp, and then describe 1-2 representative case examples.

Computational Thinking Themes

Sequencing

Children's behavior was coded as Sequencing when it involved directly or indirectly using logical order when building programs, and building programs to match a visual pattern. These codes together account for just 7% of all behaviors during CRISPEE play interactions, and

0.9% of all coded behaviors during the camp. Further, all sequencing codes emerged during the earliest transcripts from the camp data, during the first few minutes when children engaged with CRISPEE.

Some children mentioned the KIBO robotics kit as a reference for prior familiarity with programming when they first began working with CRISPEE. KIBO is a tangible programming environment also developed by the DevTech Research Group, and is used to teach engineering and programming at the host school (EPCS) during the regular academic year. Thus, the seven campers who attended the school outside of the camp were also familiar with KIBO. KIBO instructions are performed in a specific order, meaning that sequence matters when coding. However, CRISPEE is not sequence-dependent, and different combinations of the same blocks will always result in the same color light. This may explain why many children explored sequencing early in the camp, but extinguished the relatively quickly (e.g. no sequencing behaviors were coded at all during the second half of the camp). During his first experience with CRISPEE, Yash stated a plan to test a program in CRISPEE with the same blocks in a different order, explaining that he knew about programming from working with KIBO. As with several of the museum participants, Yash spent a portion of his CRISPEE play session building the same program in a different order to determine whether sequence matters. However, he showed a relatively high commitment to his “sequence matters” idea, using 19 of his total 28 programs to test repeat programs (compared to the average 2-4 tests that it took children in the museum study to reject a sequencing idea). His reference to KIBO indicates that his firm commitment to his idea about sequencing may have been transferred from his experience with the other technology, rather than something that organically arose from his interactions with CRISPEE.

Zora did not attend EPCS, and had never played with CRISPEE or KIBO before the camp. Interestingly, she also explored the "sequence matters" idea while working alone at the CRISPEE center during choice time, but only after the prototype malfunctioned (unbeknownst to her) and she had to troubleshoot what had previously been a functional program. Her initial reaction was to change the order of her program several times and test again. Incidentally, the malfunction resolved itself while she removed and re-built the program, and so it seemed that changing the sequence did actually resolve her issue. This example shows how working with a malfunctioning prototype could lead children to form incorrect ideas about how to build correct CRISPEE programs. However, by the post-interviews none of the children changed the sequence of blocks as a troubleshooting strategy, perhaps because it did not consistently resolve programming issues.

Hardware/Software & Debugging

Although Hardware/Software and Debugging are distinct topics, they blended together in the transcripts because of the prototyped nature of the CRISPEE kit. Often, children's curiosity about the CRISPEE hardware was initiated by a malfunction, resulting in a debugging process with Clarissa, a co-researcher and the engineer who built the CRISPEE prototype. Clarissa attended the camp as a research aid specifically because of the fragile state of the prototype. Her presence at the camp, and her willingness to open CRISPEE and show children how it worked "under the hood", directly influenced children's curiosity about how the kit was made.

The kits at the CRISPEE center regularly malfunctioned. Rather than closing the center and counting this as a tech failure, I kept the center open and allowed up to three children at once to observe and assist while Clarissa repaired the kits. Perhaps inspired by other center activities that involved using their five senses to make observations about living organisms, the children began to make observations about the CRISPEE kits while Clarissa worked. For example, Henry noticed that the wood material smelled “like a bonfire”, and closely examined the moving platform to see if it “uses wheels, like the KIBO robot”. He was especially curious about how CRISPEE could produce light when seemed be made of non-electronic materials. When examining the conductive Velcro on the programming blocks he asked, “is that stuff Velcro? How can it do stuff if it’s just cardboard or wood?” The children’s curiosity inspired us to leave a laptop at the CRISPEE center with videos running to show how different parts of CRISPEE were made, which in turn let to further exploration about hardware and software. For example, when we left a video running about laser-cutting to show why the CRISPEE wood smelled like it was burned (because it actually was burned by a laser), Caroline asked, “What else can that laser thing cut? Can it cut glitter? Can it cut paper?” Watching Clarissa fix CRISPEE became a favorite camp past-time, and Carlos, Caroline, and Krista even stayed for extra time during their post-interview to watch Clarissa repair a CRISPEE.

Figure 42. Child-made drawing of CRISPEE hardware malfunction.

Even after Clarissa repaired the malfunctions, finding the next malfunction became a source of collaborative troubleshooting at the CRISPEE center. Zora began collecting field notes when she found a CRISPEE error. Figure 42 shows a picture she drew of CRISPEE to show Clarissa exactly what program she had tried, with the words "does not work" written below the drawing. During one episode, children were surprised to find that the program for a blue light, which everyone knew how to make, was returning a magenta light. Melody reacted with extreme surprise, crying out, "What!? I think CRISPEE's confused, Blue and X's don't make purple!" Yash, Zora, Samantha, Henry, and two research aids all worked together to solve the problem, and eventually discovered that CRISPEE blocks were not compatible across different prototypes, a discovery that surprised even Clarissa. Without the children's willingness to explore and test different solutions, it's unlikely that this issue would have been resolved, since most of the researchers gave up before the children did!

Sensemaking & Inquiry

Children's Sensemaking and Inquiry behaviors were captured by a broad range of codes, including all codes contained within the themes of Life Science, Mental Models, Prior Knowledge. Life Science generally applied to any talk or interaction when children were exploring nature of properties of natural life. Codes from this theme related to practices of Sensemaking and Inquiry, included Asking Questions (specifically, questions about whether information was "real" or factual), posing Hypotheses (about a specific phenomenon, or more generally about the nature of science and behaviors of scientists), and using Senses to make Observations (e.g. about living creatures or the CRISPEE prototype). Coders paid particular attention to children's sensemaking about topics relevant to the intervention, including bioengineering, genes, and color mixing with light. The Mental Model codes also comprised sensemaking strategies, as they represented children's changing explanatory models of concepts like bioluminescence and genes that were presented in camp. Finally, Prior Knowledge contributed directly to children's Sensemaking since all children attempted to understand new ideas by comparing to some other, more familiar concept. The codes that contributed to the theme of Sensemaking & Inquiry comprised 55.7% of all coded transcript content. This means that more than half of all children's conversations and interactions at the camp were dedicated to making sense of the new topics being presented, which makes sense given the novelty and abstract nature of the learning content.

Children often engaged in sensemaking during read-aloud storytimes as a way to interpret and evaluate novel information about bioengineering that was presented in the camp. This was a productive time for this work, since 1) the storybooks were usually presenting new information for the first time, and 2) the entire camp community was focused on the new ideas at the same time, allowing children to share and compare reactions and thoughts in real-time. Confirming prior research (e.g. Harris, 2012), children often asked probing questions to determine the legitimacy of new ideas when they were presented for the first time. For example, during the first large-group circle when children heard the Adventures in Bioengineering storybook read aloud, Kevin was very curious about who wrote the story, and whether the characters were "real". During this storybook, I introduced the vocabulary word, "genes", which sparked a range of sensemaking responses from the children. Henry recognized the visual representation of a double-helix presented in the book and confidently identified it as a picture of a gene. Yash related the idea of gene instructions to his prior experience with the robotic KIBO kit and programming instructions. Carlos thought that genes must be found inside our bodies, specifically in the head and the heart. Kevin attempted to make sense of genes by connecting with prior knowledge regarding health and medicine: “You know at the doctor’s […] when they give you open heart surgery? They open your body and see your genes.” Kevin may or may not have ever undergone open-heart surgery, but the fact that he knew the term is evidence that he had some knowledge about the medical field. By bringing it up, he indicated that he thought it might be relevant to connect knowledge of health and bio-medicine to the idea of genes. This transcript shows that children brought a wealth of prior background to bear when interpreting a novel concept (in this case, “genes”), and also that the source and truthfulness of information was important to them in deciding whether to trust concepts presented in the intervention.

In another circle meeting, the children heard the book Meet Bacteria by Rebecca Bielawski. Yash was very excited to share his detailed knowledge about the process of how viruses spread at the cell level. He seemed to connect this to a visual cartoon in the storybook that showed bacteria packed tightly, and to the word “multiply”. When I asked Katie about this episode afterward, she explained that Yash’s father works as a lab scientists in a pharmaceutical company, and she guessed that is how he came across his knowledge of viruses. During that same transcript, Zora took up Yash’s description of cells that multiply to tell a story about pink eye, explaining that you have to finish all of your medicine even if you think the illness cured, because “all of the sudden there’s just one tiny one [unit of pink eye?] left and it multiplies and it multiplies.” In the same transcript, both Yash and Zora used personal experiences about invisible biological processes (in Yash’s case, viruses, and in Zora’s, pink eye antibiotics) to make sense of the information about bacteria presented in the book. Once we concluded, Samantha urgently raised her hand at the end of the book to ask, “Amanda! Amanda! Can you name two types of bacteria?” When I admitted that I would need to do some research first, she has the idea to bring the book with her to the microscope center where she can compare images in the book to the slides of bacteria under microscope. She wanted to conduct her own research to see if she could find the same types of bacteria that she learned about from the story. In this example, Samantha was probing to find out if I was a reliable information source. Additionally, all three children found a way to compare the novel ideas being presented in the camp to other experiences or ideas that they could relate to, indicating that they were attempting to integrate the new ideas with their already-established mental models.

Children also engaged in sensemaking about CRISPEE. For example, when playing with CRISPEE for the first time, Henry tried to make sense of the materials that CRISPEE was made of (“How can things do things if it's just cardboard or wood?”), the electornic chip inside of it, (“I wish the Storybots [children’s TV characters] were in [CRISPEE], because they go inside of computers”), and even how the coding bricks were supposed to represent genes (“There’s genes inside your body…so your hardware's genes?”). His sensemaking activities mainly focused on how CRISPEE was made, how it could function, and how the hardware of the prototype connected to the hardware living bodies.

Other children spent more time on the programming rules of how to code lights with CRISPEE. During her first visit to the CRISPEE center, Samantha spent several minutes trying to test a non-functional program while Melody kept insisting that “CRISPEE will be confused”. Finally, Samantha asked “How do I make it not confused? Oh, it’s confused! No wonder it’s confused” and immediately removed an incorrect block. When a teacher asked what she did, she and Melody answered in unison that CRISPEE can’t have two of the same color. Although no one explained the rule to Samantha, Melody’s framing of CRISPEE as a sentient being with “confusion” allowed Samantha to seek a logical rule that might somehow aid CRISPEE’s "comprehension", leading her to correctly identify the coding rule (i.e. CRISPEE does not accept two blocks of the same color). As Samantha kept building, three other children looked up to observe her coding process. Once she had made a correct program, Yash remarked in approval, "that won't make CRISPEE confused" and turned back to his own work. The other children immediately took up this concept of CRISPEE's confusion to wordlessly communicate with each other about when the correct coding rules were being applied, suggesting that they were all sharing the same mental model of CRISPEE's coding rules. This example demonstrates how nascent children's sensemaking process could be, and also how collaborative children were when making sense of new topics and procedures.

The Design Process

Children were coded as engaging in the design process when they expressed or acted to realize a specific design goal, iteration, or plan; or engaged with their bioengineering design journal worksheets. These codes together accounted for 12.7% of all coded camp behaviors. In contrast to Sequencing, Design Process codes emerged mainly after children's initial introduction to CRISPEE. The first recorded codes of Design Process behaviors occurred during the large-group conversation about the CRISPEE storybook, and were most common during moments when children were actively playing with CRISPEE, such as during CRISPEE center-time, and when they were having conversations related to design, such as during small-group Bioengineering Design Journal activities.

Children's original CRISPEE designs were usually inspired by their desire to see a certain color glowing in the animal faceplate. When children expressed a reason that the color was important to them, this was coded as a Meaningful Color design goal. Children selected Meaningful Colors for a variety of reasons. For example, Henry was very excited to code a yellow light because, “That's actually the real color of fireflies”. Samantha learned from the CRISPEE storybook about the color cyan. When she explained the plot of the story in a circle discussion she said, “[Pam] created a gene program and so it would make [Bob] this beautiful cyan light and cyan is a special blue that only appears in light.” Later on at the CRISPEE center, she announced that she wanted to see CRISPEE make the cyan color, and delightedly jumped for joy when she finally discovered the correct code. Melody worked alone at the CRISPEE center for several minutes before motioning for a teaching aid to come look at her design., saying “I gotta show you something! I made a color that’s unbelievable!” While showing off her magenta light, she explained that it’s her favorite color. Afterward, she went on to explain that she designed it by combining red and blue blocks, and stated “it’s the only color CRISPEE makes with these two colors.” Her exploration of how to create a color that was meaningful to her ended up inspiring a design exploration of CRISPEE’s coding rules. Other children may also have learned about CRISPEE’s coding rules by first exploring meaningful colors and learning how to re-create them. One piece of evidence supporting this idea is that when children explained how CRISPEE worked, either by showing a peer or explaining to researchers during the post-interviews, they invariably started the conversation by stating a specific color that they knew how to make. Perhaps learning how to consistently code for a meaningful color helped children master the unintuitive color-mixing rules of light physics that CRISPEE uses.

Children were prompted to engage with design when using their bioengineering design journals, which offered worksheets for each step of the design process, and in hypothetical designs developed in large-group circle conversations. For example, on the final day of camp, children played a game in which I presented a design challenge for them to solve by designing an animal that could glow in different colors depending on what it sensed in the environment (for example, a fish might glow blue in cold water and red in hot water). This game was inspired by the children's favorite picture books available throughout the camp, which showed examples of real animals that used bioluminescence as a visual sensor (e.g. to indicate the proximity of a predator). During the game, I presented the challenge of an airborne toxin that's invisible to humans, but we know of an animal that can sense it. Throughout the conversation, my role was primarily to offer structure to the conversation, and to offer some prompting to remind them of natural biosensor animals they have already learned about. Together, the children collaboratively decided how to address the problem. After they scoped the problem and focused on how to locate the toxin, they identified the best animal to use to solve the challenge. For example, Melody suggested using Angie the Anglerfish (one of CRISPEE's four animal choices) in case the toxin was coming from "a stream of water [from] under the ground?", but Caroline thought that Bob the Firefly was a better choice because "he's flyable, and if there's a river, when he's flying, he just has to keep on flying [over it]". Finally, they selected and programmed light colors for their bioengineered animal, often choosing personally meaningful colors that they knew how to make and wanted to incorporate into the large-group design.

Ethical Design

Children's behavior was coded as Ethical Design when they engaged in conversations or activities hypothesizing about potential consequences of designs. Just under one-quarter (23.9) of all children's design process behaviors were coded as relating to ethical design, and ethical design codes accounted for 3.4% of all coded behaviors during the camp. This low proportion can perhaps be partially explained by the fact that ethics was introduced late in the camp schedule, as it was one of the most advanced concepts. Children were required to first understand the general concept of gene design before they could meaningfully engage in a conversation about design consequences. For this reason, all of children's ethical design activities occurred during the second half of the camp.

Children were prompted to engage in steps of an ethical design process through large-group activities and an Ethical Design Process anchor chart and song. One main activity, called Design a Helpful Animal, invited children to imagine a problem they could solve by bioengineering an animal, and then to consider positive and negative consequences of that design. Children identified diverse and interesting problems to solve, and offered creative solutions.

Several children wrote in their design journal about environmental problems they cared about. For example, during the circle conversation when children explored this activity, Melody shared a memory of a trip she had taken to Florida, where she learned that the sea turtle population there was becoming threatened because the turtles were eating plastic bags polluting their habitat, instead of their normal diet of jellyfish. For her design, Melody wanted to "give fox smell genes to turtles", so that they could tell the difference between plastic bags and jellyfish. In addition to the positive consequence of saving turtle populations, she identified a negative consequence of turtles suddenly starting to hunt food that foxes eat, as a result of sharing their "smell gene".

In a similar vein, Henry worked on a design idea to help cheetahs (his self-described favorite animal) by giving them "more genes" to be "smarter and faster". Although it's not clearly represented in Henry's design journal page (see Figure 43), his talk with Yash and Katie (teacher) focused on the dangers of poachers threatening the cheetah population. Yash and Katie validated and extended his idea by offering vocabulary ("endangered") to capture his concern for the cheetah's welfare ("why cheetahs are getting killed"). This example indicates Henry's conviction that an ethical purpose for bioengineering should involve serving or helping animals to escape harm, an ethical purpose that both his friend and his teacher readily understood and accepted.

Figure 43. Henry’s design journal page describing his idea to enhance cheetahs with genes to help them escape poachers.

Inspired by Melody's turtle design, Caroline drew pictures of plastic bags floating in an ocean of sea creatures, and wrote a line from the perspective of the animals: "Don't litter because I can die." Although her design doesn't suggest a bioengineered solution, it indicates that she was connecting biodesign to environmental maintenance and ecological stewardship. Zora's design involved giving the genes from a lobster's thick shell to sharks, and wrote an emotional plea below her drawing to stop hunting sharks: "Why do people hunt sharks anyway, what did they do to you?"

Three children identified story-based problems and offered solutions that were rooted in fiction and make-believe. Samantha wrote a story about a cat that wanted to be beautiful, so it changed its own genes to glow a "pretty" blue light, but a consequence of her design was that the cat "could get too much attention and get scared and run away". In her example, the ethical consequences of design were rooted in a moralistic narrative about an individual animal rather than an ecosystem-level issue. Carlos and Krista both made designs directly inspired by the Adventures in Bioengineering storybook. Carlos wrote a story about a firefly being afraid of the dark, and his solution involved coding it to glow brighter so it could see in the dark, and "giving it food and water". Krista's story design involved a human girl getting lost in a forest, and using glowing paint and firefly friends to find her way home. All three of these examples indicate that the children were using storybook structures to guide their understanding of a problem and solution.

Finally, two children did not engage at all with the design aspect of the activity, suggesting that it was perhaps too complex for some children. Kevin drew a photo-realistic picture of a lobster, perhaps finding a way to engage in an activity that was overwhelming for him. Yash wrote the word "Nothing" for every section of his page. Since all of these activities were optional and child-directed, it's possible that this activity felt too school-oriented for Yash, or perhaps he was conscientiously objecting to the idea of editing genes, or simply rejecting the idea of genes. This idea would align well with his post-interview transcript, in which he explained the difference between zebrafish and Glo-fish as proximity to the sun, and nothing to do with genes. When I asked Katie about their responses, she confirmed that these patterns of behavior are typical of both children when they confront an activity or topic that they feel is advanced and intimidating for them. This finding offers valuable insight for future design phases of the CRISPEE intervention. For example, perhaps the Design a Helpful Animal activity should be introduced more slowly, and with more examples to inspire children's design process.

Findings from this theme suggest that most children in the camp were able to engage in a meaningful way with ethical dilemmas related to biodesign work. Interestingly, none of their ideas were designed to aid *humans*, but instead focused on ways to aid *animals*, either at the ecosystem level or at the level of individual anthropomorphic creatures. In reality, bioengineered animals are primarily created to solve human problems. Perhaps children are too altruistic in their thinking at this age to think about animals as a resource to serve human needs, or perhaps their attitudes are a product of the fact that anthropomorphic and empathic animals are commonly cast as protagonists in children's media. In any case, future iterations of this intervention should consider ways to explain the purpose of bioengineering work, both as it's currently being used by scientists, and ways that the field could be improved by a more sustainable and environmental approach.

Enjoyment and Engagement

Children showed consistent enthusiasm and excitement while working with CRISPEE, even requesting extra time to play at the CRISPEE center up to the final day of the camp. As with the museum study, children often experienced joy and surprise during their first time programming CRISPEE's light to glow, and their first design goal was usually a personally motivated one, such as when Melody wanted to show her teachers how she made CRISPEE glow in her favorite color, or when Samantha wanted to create a color she had learned about from the CRISPEE storybook (see Figure 44). Children voiced that they enjoyed the physical interactions of CRISPEE, the felt and velcro materials on the blocks, and the fact that it created a glowing colorful light.

Figure 44. On the third day of camp, Samantha and Melody dance gleefully when Samantha successfully creates the cyan light she has been trying to program.

Summary of findings from Camp Intervention

In summary, children did engage with the three main themes of interest (sequencing, sensemaking, and the design process), and two more themes emerged as perhaps more relevant.

Table 22

Tallies of themes and codes for each camp study participant.

			Computational Thinking		Sensemaking			Design Process	
Child	**Sex**	**Age**	Sequencing	Hardware-Debugging	Life Science	Mental Model	Prior knowledge	Design Process	Ethical Design
Carlos	M	6(8)	0	9	41	13	8	8	3
Caroline	F	6(0)	1	11	77	22	26	18	8
Henry	M	6(6)	1	21	51	11	22	2	0
Kevin	M	5(11)	0	1	40	19	17	10	4
Krista	F	6(7)	1	3	22	10	5	6	0
Melody	F	5(0	0	8	35	21	10	11	7
Samantha	F	7(0)	0	10	58	27	10	17	8
Yash	M	6(8)	6	20	49	15	22	3	1
Zora	F	7(2)	0	4	27	15	8	5	4
Average			1	9.7	44.4	17	14.2	8.9	3.9

Table 22 shows the number of moments when each child expressed an idea or an interaction related to the code of interest (meaning, a child might have more than one of the same code in a conversation if they expressed more than one unique ideas in that code). Sequencing was much less relevant for children in my sample than previously believed. In contrast, hardware/software and debugging concepts were incredibly important for children in my sample, with children having an average of about 10 conversations or interactions related to these ideas. The CRISPEE kit itself seemed like the most important element of the design intervention, and hardware and debugging conversations frequently took place while children were working with CRISPEE.

Children also spend a huge proportion of their time making sense of the content, averaging 44 conversations about observation and exploration of natural and life science, but also through shifting mental models to explain biological phenomena such as bioluminescence, or recalling relevant prior knowledge. The picture books available in the camp, particularly the Adventures in Bioengineering storybook, spurred children's curiosity about life science and many of their mental models. Many of children's sensemaking interactions also occurred during center activities and pre/post interviews, when children directly observed animals or life science artifacts (e.g. microscopic plates, organic materials like seashells).

Children frequently engaged in design activities, and to a lesser extent, in ethical reasoning about the consequences of design. Children most often engaged in design when engaged with the CRISPEE free-play center and the design process posters. Group conversations and the bioengineering design journal sparked many of the conversations about ethical consequences of design ideas.

Finally, similar to children in the museum study, camp participants were motived to play with CRISPEE after first successful light program. They still found the tool exciting and engaging by the last day of camp, and even a month later at a return visit to the Tufts University Early Childhood Makerspace, where CRISPEE is currently exhibited.

Chapter 10. Discussion

What Can Children Learn from a Bioengineering Experience with CRISPEE

Summarized below are the major findings related to the research questions of this dissertation. All findings are explored in-depth in the following sections.

1. How do children interact with the CRISPEE technological prototype?

During the museum study, children exhibited a range of play behaviors that were motivated by roughly four categories of ideas about how the CRISPEE tool worked. Theories focused on the representational meaning of the coding blocks, as well as the interaction of the blocks within the CRISPEE platform. The conclusion from this work is that after just 10 minutes of playing with CRISPEE, the majority of children were able to arrive at a correct understanding of the meaning of the blocks and their interaction with CRISPEE. Children were more likely to master the correct interactions if they had worked with the tool individually, compared to children who worked in pairs. All children, regardless of whether they worked alone or with a partner, were motivated to keep playing with CRISPEE, and found it enjoyable and engaging to play with.

2. What can children learn from an educational bioengineering intervention?

Children in the camp intervention explored a range of powerful ideas, particularly the design process and ethical outcomes, practices of science observation and inquiry, and the computational relationship between hardware and software.

3. How does a bioengineering educational intervention support children's learning in developmentally appropriate areas of bioengineering thinking?

The CRISPEE prototype seemed most useful for engaging children in the concepts of hardware and software. Sensemaking and inquiry were supported by the picture books and story contexts introduced throughout the camps. The design process, and especially the exploration of bioethics, was directly supported by children's engagement with the bioengineering design journals and discourse structures of considering positive and negative consequences of designs.

The following sections explore the developmentally appropriate powerful ideas of bioengineering that emerged throughout the study and describe how the design intervention contributed to children's engagement with these powerful ideas.

Toward an Understanding of Developmentally Appropriate Powerful Ideas for Bioengineering Education in Early Childhood

Chapter 3 explored Bruner's recommendation to outline the structure of a discipline as an initial step toward developing its pedagogy. I proposed a structure of relationships among foundational powerful ideas bioengineering (see below Figure 4 from chapter 3). Specifically, sequencing in computer science was used for organizing instruction, which is relevant for genetic creation. Sensemaking and Inquiry practices of young children in biology may inform how they make sense of biodiversity and genetic instructions, which is a foundational concept for biodesign work. The engineering design process is an integral part of any process of designing solutions to human problems.

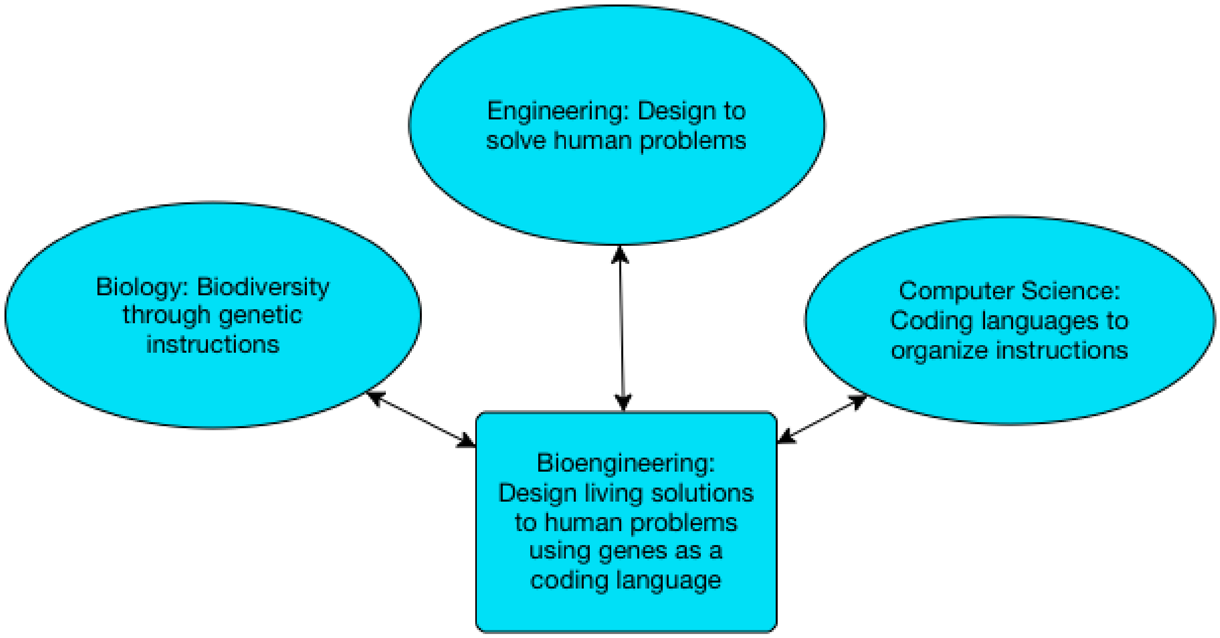


Figure 4, from chapter 3.

In this dissertation study, the three constructs of Sequencing, Sensemaking, and Design were explored as learning outcomes for the CRISPEE intervention. Research findings suggest that the ideas presented in Figure 4 are foundationally related to bioengineering. More importantly, new relationships emerged that offer insight into the nuanced ways that children approach these powerful ideas. In the following section, findings regarding each of these ideas are summarized, and an evidence-based model of the relationships between these foundational bioengineering ideas is proposed.

Hardware/Software; A Foundational idea for Bioengineering Learning

Prior research on computational thinking in young children (e.g. Bers, 2019; Horn & Bers, 2019; Sullivan, 2019), suggests that sequencing/algorithmic logic should be an important learning outcome of any bioengineering intervention. To some extent, that is what was found in the current study. Children in both the museum and the camp studies used sequencing to approach the CRISPEE tool for the first time. However, it would be more accurate to describe sequencing as one of the many sensemaking strategies that children employed to understand the CRISPEE tool the first time they engaged with it. Hardware and software emerged as a more relevant powerful idea from the field of computer science. Specifically, children who understood the concept of software as instructional information and hardware as some machine or object that enacts the software instructions had an easier time understanding the concept of CRISPEE's blocks as information that controlled the light-emitting part of the prototype.

The recommendation to expose children to the concept of hardware and software is not new or unique to this research. For example, the K-12 Computer Science Framework (a curricular resource developed jointly be members of the Association for Computing Machinery, Code.org, Computer Science Teachers Association, Cyber Innovation Center, and National Math and Science Initiative in partnership with states and districts) states that by second grade, children should understand that computing systems are composed of physical components called hardware which is controlled by instructions provided in a compatible software system (K-12 Computer Science Framework, 2016). Seymour Papert theorized that teaching children to code, allowed them to understand and control the hardware-software relationship, thus allowing children to metacognitively understand their own thinking processes in a richer way (Papert, 1980). In a meta-analysis of studies on children's cognitive gains from learning computer programming, one research team found that children who learned coding outperformed their non-coding peers in areas of creative thinking, metacognition, and reasoning, lending credence to Papert's claim (Scherer, Siddiq, & Sánchez Viveros, 2019), Although there is little research on the metaphor of hardware-software in early childhood as an avenue toward biology and engineering education, researchers working with older students (e.g,. high school) have found that by presenting a computational metaphor of biological systems, students with very little prior science and engineering experience were able to design novel and interdisciplinary biodesign projects (Kuldell, 2007; Subsoontorn et al., 2018). This recent finding echoes an established understanding from the professional sciences, that biological systems can serve as useful physical substrate for computing with natural hardware and genetic software (e.g., Denning, 2017; National Research Council, 2006).

Some children used the idea of hardware and software to explore the CRISPEE prototype itself. They wanted to understand who had built CRISPEE and how it had been built. Especially during moments when the prototype was "bugging", or malfunctioning, children were more likely to engage in debugging practices alongside adults. In the camp, this was an authentic engineering experience, since they were observing adults engaging in the debugging process as engineers rather than as teachers introducing them to the topic of "hardware." This contributed to children identifying and demonstrating the engineering practices that adults modeled, as evidenced by their enthusiasm to observe and assist when a CRISPEE malfunction occurred.

Hardware and software also became a useful lens for some children to understand their biological counterparts, organisms and genetics. For example, Henry, a camp study participant, asked during his first conversation about genes whether "our genes are hardware." He was attempting to understand the relationship between genes, which that are a *part* of our bodies, and gene instructions, which *program* our bodies. Other children used the word program to describe the ways that genes interact with the body, such as when Samantha from the camp study explained that a Zebrafish does not glow, but "we can program her genes to make her glow." This suggests she is interpreting genes as an instructional software language, and our bodies as the hardware that enacts the program. This indirectly taps into another computational thinking idea, Representation, that may be a useful concept to explore in future work with CRISPEE (Bers, 2018).

The relationship between hardware and software may have been more important for the current intervention than sequencing because of the level of abstraction that our design team chose to represent gene programming. Bioengineering education researchers (e.g. Endy, 2005; Kuldell, 2007) describe the many layers of representation that occur when teaching and learning about microbiological processes. Although sequencing is a key concept at the level of DNA base-pairs, genes are much larger "containers" of DNA that do not need to be sequenced in a particular way. Just the presence or absence of genes in an organism's genome makes them a "gene carrier," and yet more genes are required to express any genes that are carried. We could have chosen to work at an even higher level of abstraction, such as the protein, cell, or organ level of a body, which undoubtedly would have called up other representational forms and computational analogies. Because of the nature of the metaphor that CRISPEE was built to represent, the idea of software that encodes for hardware was ultimately more relevant for children to explore.

Another explanation is that hardware/software is actually a more powerful idea for exploring bioengineering than sequencing is. Support for this idea is that the primary method of biodesign as it is practiced today is borrowing useful genes from existing organisms and implanting them into other creatures' genomes (Kuldell, 2007). To extend the computational metaphor, this makes biodesign seem closer to uploading and running software onto some existing hardware. In contrast, the primary method of computer programming involves creative design of all elements of a novel system, from the rules of a code to its stepwise execution (Bers, 2019). It makes sense that in this context, the practice of sequencing is more relevant than the knowledge about the machinery through which a code is executed. My findings in this area suggest an understanding of the hardware/software relationship actually is, for theoretical and practical reasons, more foundational to a bioengineering learning intervention for young children, or at least one like CRISPEE that introduces bioengineering at the level of complete genes, than the level of DNA base-pairs (the building blocks of genes) or proteins and organs (the materials that gene instructions code for).

Children meaningfully engaged with Bioethics as part of their Design Process

In the camp (but not the museum sessions), children had the time and freedom to explore the idea of consequences to biodesign, and they used their sensemaking strategies of storytelling and imagination to develop a range of creative and thoughtful solutions to problems they had identified. Children in the museum study rarely broached the subject of ethical implications of biodesign, and when they did it was generally to suggest some positive reason, such as making medicine to help sick people. When camp participants made sense of biodesign, they also began by exploring themes of health and medicine. Children's conversations about genes surfaced references to open-heart surgery, "growth genes" (perhaps a reference to hormone therapy), viruses and bacterial illness, antibiotics, and homeopathic plant remedies. Presumably, these references were inspired by a combination of seeking to understand the mechanisms of gene editing, as well as to identify examples in their lived reality that might connect to the abstract idea of "genes." In the second half of the camp, as children developed more confidence and mastery of the bio-design process, children's conversations turned to questions of environmental protection and animal activism. Children referenced endangered species, toxicity in natural environments, animal habitats, ecosystem dynamics such as predator/prey relationships, and eco-harmful human practices such as pollution, poaching, and over-fishing. Some of these references can be clearly traced to elements of the design intervention. For example, the Adventures in Bioengineering picture book and the Bioengineering Design Journal activities introduced topics like toxic materials and medicines created from plant genes. However, the majority of these references, particularly those of endangered animals and environmental protection, arose from children sharing personal experiences and opinions during large-group circle discussions.

The challenge (or perhaps the benefit) of discussing bioethics with children of this age range was that they did not seem to have a mindset of the world and its organisms as a library of resources to engineer solutions to human problems. In fact, most of their design suggestions were focused on improving the lives and habitats of the animals they wanted to bioengineer, such as making cheetahs that could outrun poachers and sea turtles that could naturally avoid ingesting plastic. This mirrors an emerging movement within the biodesign field itself. The University of Pennsylvania has for three years hosted an annual meeting (funded by the National Science Foundation) called Learn.Design.Compute with Biology, a symposium for “scientists, designers and educators to discuss novel learning platforms and activities to advance biological design, synthetic biology and computation education at K12 and beyond.” (Telhan, 2020). At each meeting, participants discuss ethical implications for biodesign, forwarding efforts to sustain or enhance ecological systems rather than increase economic gain. As the fast-paced worlds of climate science, global economies, and genetic technology all shift and advance, it is more pressing than ever for tomorrow’s voters and decision makers to explore the ethical implication of biodesign from all perspectives, including but not limited to human benefit. As the imperative grows to introduce young children to these complex issues early, one heartening finding from this study is that children’s generally altruistic attitudes may offer a unique insight into the pedagogical mission of this emerging STEM domain.

From a developmental perspective, a major finding from this research is that young children are more prepared than perhaps previously believed to engage in complex and meaningful conversations about bioethics and human impact on the natural world. The Next Generation Science Standards states that children in K-2nd grade should learn about how human activity can minimize our impact on environmental systems [K-ESS3-3], a recommendation which aligns well with the abilities and interests of children in my sample (NGSS Lead States, 2013). However, the standards suggest grade 5 as the earliest time to invite students to use science observations and evidence to imagine ways to protect environmental resources [5-ESS3-1], and high school as the first time students should imagine technological solutions to reduce the impact of human activity on natural systems [HS-ESS3-4] (NGSS Lead States, 2013). While creating technologically valid and evidence-based designs is certainly complex enough that it can wait until high school, prior research has already confirmed that children as young as grade 2 can benefit from self-motivated inquiry and design activities (e.g. Brophy, Klein, Portsmore, & Rogers, 2008; Metz, 2011). My research findings confirm that young children are curious about bioethics, and when given appropriate activity framing such as the bioengineering design process anchor chart and journaling activities from my intervention, they can design creative and compassionate solutions to problems that are personally meaningful to them.

Children used Science Inquiry & Sensemaking to approach Bioengineering

Rather than being a powerful idea in its own right, sensemaking was the lens/strategy that children used to connect to the nascent powerful ideas of bioethical design and the metaphor of hardware/software. Confirming prior research (e.g. Deng, 2004; Dewey, 1916/1996), concrete experiences were still a reliable source of information gathering for children. For example, during the museum study when I asked how to tell if a plant is alive, a characteristic response was, “you just feel it” (boy, age 6[5]). In the camp study, children mixed explanations of bioluminescence that involved genetic causes as well as proximity to the sun, indicating a mental connection between naturally glowing animals and inorganic glow-in-the-dark toys.

Children in the camp also used picture books and storytelling to guide their science explorations, apparently viewing both plot-driven fiction books and reference texts as valid and reliable sources of information. This is logical when one considers that I was asking children to make a large imaginative leap by introducing the concept of a tiny and invisible programming language for our bodies, and explaining it as a scientific fact. When children felt more confident about the concepts they were exploring, they began to invent their own stories, sometimes inspired by the ones we read together and sometimes original. In many of the stories, they introduced an animal that began to glow, and considered consequences for their character’s newfound ability. Finally, the CRISPEE tool itself was a useful experiential learning tool that supported children’s sensemaking around gene editing. At end of the four-day camp, seven of the nine participants could describe how an animal’s appearance could change as a result of gene-editing and bioengineering, compared with only one child at the beginning of the camp. Many of these descriptions involved direct references to the CRISPEE prototype of storybook. For example, while observing a recorded video of real Glo-fish, Kevin suggested that maybe they were glowing because Pam (a bioengineer character from the CRISPEE storybook) changed their genes. Watching the same video, Carlos suggested that a scientist had “put them on CRISPEE” to change their appearance. References to CRISPEE were more common than references to genes, meaning that the designed learning tools were still serving a supportive role in helping children to conceptualize science concepts like genes and bioluminescence.

Although tangential to the act of sensemaking, children also volunteered opinions about science that I was not necessarily investigating, but which offered a unique insight into children's impressions of science inquiry. During my first meeting with children, I typically asked them if they knew about science and wanted to play some science-themed games with me. During the museum study, one responded enthusiastically that "I just always wanted to do science, but I never got the chance" (boy, 6[5]). A girl in the same study explained "My dad teaches science, but I don't know about much of it. I actually do want to learn science, but I don't know when's a chance that I can." Her responses suggest that exposure to science at home may not be enough to instill a sense of science identity and belonging in children. In the camp study, Caroline and Krista told me that they both wanted to be scientists when they grew up. In Caroline's case, she explained that "I saw a commercial about, I saw something on the news about it [being a scientist] and so that's why I want to be one." Children's enthusiastic curiosity about science as a learning domain was a promising indication that they felt personally motivated to explore the bioengineering ideas presented in the CRISPEE intervention.

Evaluating Conjectures of the CRISPEE Design Intervention

We designed CRISPEE to support children's exploration of the domain of bioengineering, more specifically gene-programming with bioluminescent animals. In the conjecture map guiding the latest phase of research, I hypothesized that the task structures of camp would lead to engagement with sensemaking and the design process, that discourse structures of considering consequences and genes would lead to children considering ethical consequences of their design, and that interacting with CRISPEE would support children to explore bioengineering through the lens of sequencing and programming (see Figure 24 from chapter 6). In general, the results of this study support my predictions about these embodiments, mediating practices, and outcomes. However, I was surprised by what I found when I looked specifically for evidence of children using the CRISPEE prototype as a tool-to-think-with. Recall the image of the Vygotsky's Mediational Triangle (Figure 2 from chapter 3). In Figure 45 below, I've adapted that triangle for the current study, with CRISPEE as the mediating tool and Bioengineering as the learning outcome of interest. In the coming sections, I explore my findings to understand the relationships along the edges of the triangle that connect the learner, the tool, and the learning outcome.

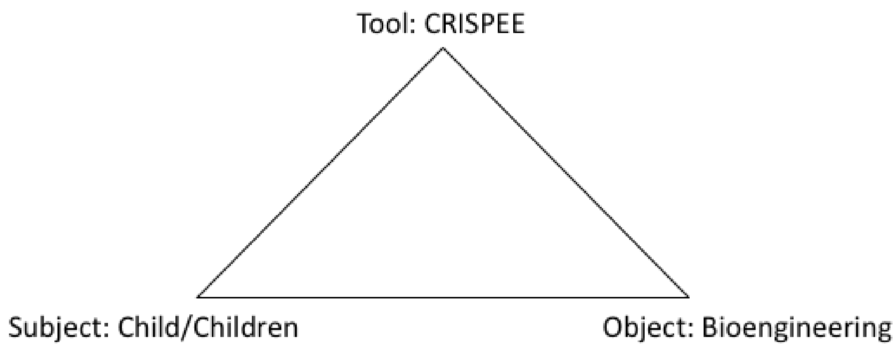


Figure 45. An application of Vygotsky's Mediational Triangle to the current study.

My results suggest that it is possible for children to understand how to use CRISPEE, but not understand the metaphor of gene editing. Of the nine children who fully mastered the CRISPEE interaction in the camp, only seven of them could describe how an animal's appearance could change using the concept of gene editing, and one of those children (Yash, age 6[8]) flatly rejected the idea that genes existed at all. In the museum study, 33 children left after 10 minutes with a fairly comprehensive understanding of the mechanics of CRISPEE's programming blocks. With the current data, it would be difficult or impossible to say how much these children related their CRISPEE interactions to the metaphor of gene-editing, but based on the low proportion of gene-related ideas in the pre-interviews from children in the camp study, it seems unlikely that it was majority of the children. Thus, understanding CRISPEE does not necessarily lead to an intuitive understanding of gene editing. Perhaps these children are engaged in a mediating triangle similar to what is observed in Figure 46, in which there is a strong connection between the child and tool but the connection between the tool and the object of learning is nascent, and thus the learner shows no relationship with the learning outcome.

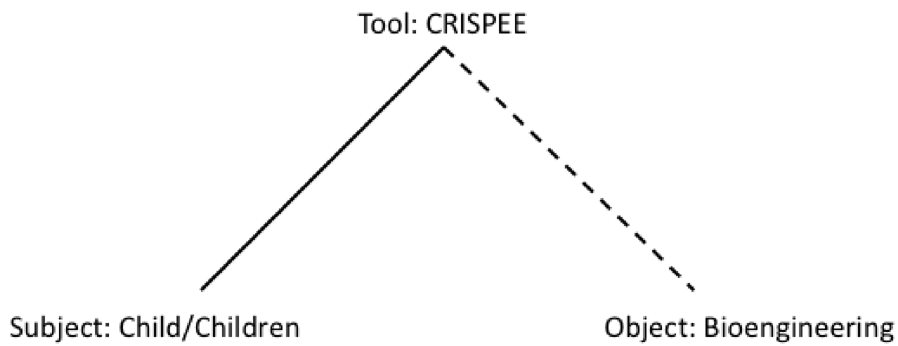


Figure 46. For some children who mastered the CRISPEE interactions, the connection between CRISPEE and the metaphor of gene editing was nascent, and they did not engage directly with the learning domain of bioengineering.

In contrast, the few children who did have prior experience with the concept of genes tested fewer non-functional programs and took less time in general to arrive at the correct understanding of how to use the CRISPEE prototype. Further, all of the children in the camp and museum studies who clearly articulated an understanding of genes as a series of instructions for living bodies, also demonstrated that they understood the basic syntax of building programs with CRISPEE. For example, camp participant Caroline (6[0]) already knew about genes and seemed to understand the CRISPEE interactions after just three tests the first time she approached the tool. Thus, although the tool itself was not her first exposure to the idea of genes, it was a tool that she quickly understood and took up to further explore the learning object of gene editing (see Figure 47).

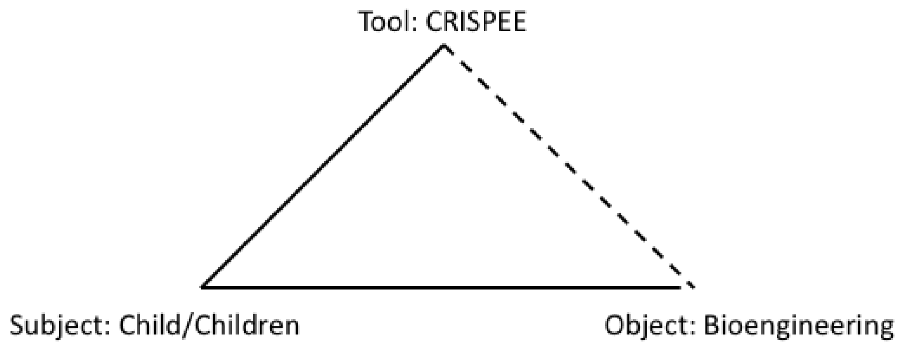


Figure 47. Children who already had some prior experience with bioengineering seemed to find CRISPEE interactions intuitive. These children were more likely to engage in biodesign activities.

Children have a richer understanding of CRISPEE if they also understand genes. Some children only understood the tool, but did not connect to the outcome, meaning they are still working through the tool as an object, and need more time to approach the true object of study.

Synthesizing the Powerful Ideas of Bioengineering

In his book, *Mindstorms*, Papert invites us to envision a domain of knowledge as a community of powerful ideas. In so doing, he argues, we are one stop closer to an epistemology of powerful ideas (Papert, 1980, p. 137). Figure 48 shows the “community of powerful ideas” that emerged in the design study of the CRISPEE intervention. The trapezoids represent intersectional powerful ideas that emerged through thematic analysis of children’s interactions during the camp. The clouds represent the ideas that children brought to bear in their sensemaking endeavors about bioengineering, and in particular, about the novel powerful ideas of bioethical design and living organisms as hardware/software systems.

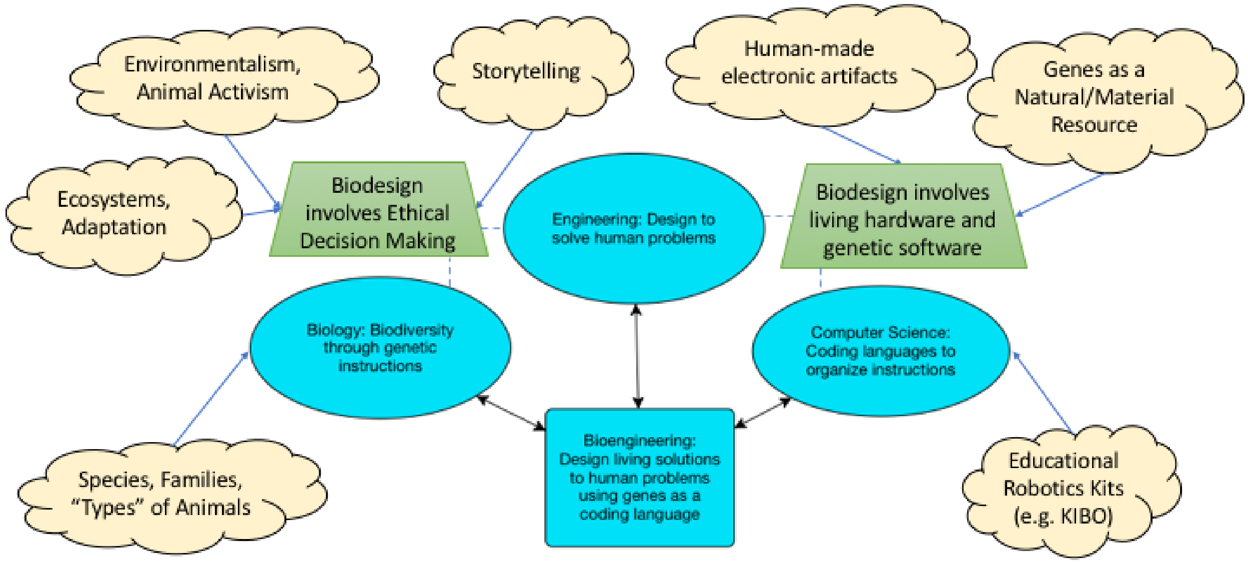


Figure 48. Expanded proposed relationship of bioengineering powerful ideas, including children's unique entry-points to each concept.

Children's sensemaking around bioengineering comprised personal experiences, such as educational technologies and books they had encountered; formal science concepts such as species, ecosystems, human-made artifacts; and even moral/political ideologies such as environmentalism and animal rights activism. These various "entry-points" to the larger bioengineering conversation might be generalizable to other children or specific to my sample, but the intersectional powerful ideas that emerged from their explorations are broad-reaching learning goals that are foundational to children's engagement with biodesign. Thus, I present an amended model of the relationships among foundational bioengineering concepts, which includes two new powerful ideas: 1) Biodesign involves ethical decision making, and 2) Biodesign involves living hardware/software systems.

Chapter 11. Limitations and Future Work

Limitations

Implementation and Sample

This study was held in two informal learning settings (a busy children's museum and a school-hosted vacation camp) and was subject to the challenges of conducting research in naturalistic settings. It was impossible to control for unexpected schedule changes due to children's absences, etc. In some cases this impacted data collection methods, such as requiring several camp children to take their "pre-interview" assessment after the intervention activities had already begun, and changing the arrangement of children's groups from pre- to post-interviews. However, since one of the stated goals of design research is to embrace the "buzzing, blooming confusion" of real-life learning settings, (Barab & Squire, 2004, p. 4), these challenges can be re-interpreted as part of the rich tapestry of social interactions that comprised the study context. In the current study, it would be nearly impossible to characterize children's learning without the context of their daily explorations, curiosities, moods, and friendships. For example, by recording CRISPEE play as a free-form center activity, chidlren showed what they understood about CRISPEE by teaching each other how to use it. Researchers could easily have learned that children intentionally chose specific colors for their biodesign explorations, but children's connection to their chosen color would be lost without footage of them discovering and exploring the same colors through picture books, imaginative play, and light table activities. Without a clear picture of the social, educational, and personal dynamics of the learning setting, children's bioengineering design journals, and their creative and thoughtful biodesigns, would have been sadly misinterpreted, losing the richness of children's process by retaining only a decontextualize artifact of their thinking.

Because this was a design study, researchers conducted and led all the learning activities explored in the camp. The fact that, for example, the engineer who built CRISPEE was present during the intervention almost certainly impacted children's reaction to the tools, to the research team, and to the learning topics being presented. While the intervention is still in development, it would be beneficial to explore the constraints and opportunities of having regular classroom teachers or informal space facilitators deploy the intervention on their own. In addition to learning which elements of the intervention need to be refined before being used by non-researchers, a major next step is to investigate what kind of educator preparation would be required to help a facilitator feel confident and comfortable to explore the sensitive and complex topics presented in the CRISPEE intervention.

Finally, this study was conducted with a small sample of children who had unusually high access to STEM concepts and experiences. Several children in my sample had parents who were themselves professional scientists or engineers A surprising amount of children had prior experience with vocabulary words like "chromosome" (girl, 9[3]) and "heritable trait" (boy, 8[3]), and many also had experience with computer science concepts like programs, robotics, and the engineering design process. Additionally, the bioethical consequences identified by children in the camp study often centered on themes of environmentalism, animal rights, and reducing human impact on natural systems. The ideas that children surfaced certainly reflect the cultural milieu in which these specific children, in this cultural moment in time and geographic location, understood and interpreted bioengineering. It would be fascinating to explore the sensemaking strategies of children with different experiences, for example, children from rural/agricultural backgrounds that might take a different approach toward animals and ecosystems, or children whose communities hold cultural or religious beliefs about gene editing. In future iterations of this work, implementing the camp study with a larger and more diverse sample of children, perhaps from one or more entire classrooms, schools, or districts, would offer clarity to the findings presented here. Future research questions should focus on how generalizable the results of the museum and the camp study are, and what differences arise in how children construct and ethically justify their biodesigns. Further, a larger-scale study begs the question of implementation and facilitation. A logical next step for the design of CRISPEE would involve preparing practitioners to lead their own implementation of the curriculum, and then exploring what role the educator plays in shaping children's experience with the CRISPEE kit, storybook, and learning intervention.

Technological Limitations

The CRISPEE prototype was hand-built by students at Wellesley College and Tufts University, and thus, was more susceptible to technical issues than a commercially-available product. The prototype very sensitive to rough play and frequently malfunctioned. Future work should investigate the question of CRISPEE as a tool-to-think-with using a more robust version of the technology. That said, malfunctions were useful for furthering understanding of authentic ways to draw children into engineering practices, and to highlight the importance of the hardware/software concept for young learners.

Future Work

Next Phase of CRISPEE Design Cycle

A large pool of data was collected as part of this dissertation research, some of which was beyond the scope of this project to present in great detail. For example, a lengthy interview with a classroom teacher from the camp's host school, who knew several of the camp children personally, revealed insight into teacher attitudes and challenges that could help inform the next iteration of the CRISPEE intervention, but was at times unrelated to the qualitative themes explored in the camp data. Additionally, the museum study data was analyzed using a coding rubric focused on interactions and physical engagement with CRISPEE, but could also be re-examined for qualitative themes, such as children's representational awareness or questions relating to hardware and software.

Future iterations of the CRISPEE prototype and intervention will expand the scope of the findings already explored. The design team had already developed a concept for a future iteration of CRISPEE that involves biosensors, which could engage children in the computational thinking concept of conditional sequences. There were already some promising early results about this idea from camp data, when children engaged in conversations and design journal activities related to biosensors. A tangible technology would support children's conceptualization of the concept and allow further insight into children's developing ideas about genes and bioengineering.

Exploring Bioethics in Early Childhood

A core finding from this work is that children are not only developmentally ready, but personally motivated to explore the ethical dimensions of biodesign work. Children in my sample offered creative and diverse strategies for engaging in ethical decision making, using imaginative storytelling and formal science concepts to construct their arguments. Future work should seek to explore how children weigh the bioethical consequences of design work, and what knowledge they bring to bear when making these kinds of decisions. This is a precursor to the important work of preparing children to have conversations about complex ethical issues with no clear "right answer," a skill that future generations will need to embrace as they progress towards a bioengineering-enriched world.

Chapter 12. Conclusion

Advances in bioengineering are pervasive in modern society, impacting the food that we eat, the medicine we take, and the fuel that we use to power our electronics. As children enter this swiftly evolving world, biotech innovation is rapidly outpacing our ability to meaningfully educate children in novel STEM domains and prepare them for the world in which they are growing. Results from my research with the CRISPEE tool and intervention reveal that not only are children as young as five able to engage with foundational concepts of biodesign such as ethical design and gene "programming," but further, many children hold preconceptions about genes and DNA even before they participate in a bioengineering intervention.

This research represents one of the first attempts to investigate biodesign as an educational domain in early childhood, and it barely scratches the surface of young children's attitudes and ideas about this emerging field. Ultimately, the purpose of this research is not to prepare our world with a future workforce of bioengineers, although this might be a byproduct. This work is important for educating children about the gray areas of STEM innovation, particularly when the materials of engineered designs are living organisms. Voters and decision makers of tomorrow will be asked to address serious challenges in areas of climate, economies, and human rights. Bioengineering may potentially hold solutions for these grave and sweeping issues, but with grave and sweeping consequences that future leaders will need to balance, and future citizens will need to understand. As bioengineering continues to grow as a global and national issue, it is critical for researchers, educators, and policy makers to address the pressing need for evidence-based pedagogy and developmental practice recommendations to prepare young generations for a biotechnology-enhanced future.

Appendices

Appendix A. CRISPEE Intervention Full Curriculum

Bioengineering with CRISPEE

A Curriculum Guide for introducing Bioengineering in Early Childhood

DevTech Research Group
Eliot-Pearson Dept. of Child Study and Human Development
Tufts University

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CRISPEE Learning Objectives & Standards

Learning Objectives Overview

The CRISPEE tangible bioengineering tool was designed to inspire the next generation of innovators by exposing young children (ages 5-8 years) to these emerging areas at the intersection of science and technology. In addition to introducing early elementary aged children to concepts of science and technology, the Bac2Mars game was also designed to foster development of basic reading comprehension, mathematics skills, creative problem-solving, collaboration, and more. In order to do this, the Bac2Mars game and all educational support materials were designed to align with state and national standards for education including: Next Generation Science Standards, Common Core Standards, P21's Framework for 21st Century Learning, and more. This document walks you through an overview of each of these standards and how the design of CRISPEE aligns with them. Finally, this document also provides you with a breakdown of each educational CRISPEE video and game, as well as the tool itself, and how specific CRISPEE content ties into the learning objectives.

In some cases, our educational content ties in with standards for older children in places where no early childhood standards exist for a given topic. We do this because we believe there is a need to re-envision what children can and should be learning in Kindergarten, particularly in the area of STEM education. For decades early childhood curriculum has focused on literacy and numeracy, with some attention paid to the natural sciences. However, in today's world, science and technology are combined in new and creative ways and thus the range of concepts traditionally explored in school needs to be extended. While understanding the natural world is important, developing children's knowledge of the surrounding human-made world of technology and engineering is also valuable. Biological engineering is an example of an emerging field that integrates life sciences and engineering, the natural world and the human-made world that children can and should begin to learn about from an early age.

Why Bioengineering in Early Elementary School?
While a significant amount of research focuses on STEM education for the later elementary, middle and high school, and college years, little research is focused on learning abstract scientific concepts in the foundational years. We know, however, both from an economic and a developmental standpoint, that educational interventions that begin in early childhood are associated with lower costs and stronger, more durable effects than interventions that begin later in childhood. Additionally, we know that women and minorities are still underrepresented in many STEM fields. Prior work demonstrates the importance of piquing the interest of girls and minorities during their formative early childhood years before stereotypes regarding these traditionally masculine fields are ingrained in later years. Therefore, it is critical to continue developing engaging STEM-focused tools, games, and materials, such as BactoMars, to begin engaging children from their earliest schooling years.

The CRISPEE tangible and curricular content are designed to align with the following standards:

Next Generation Science Standards (NGSS)
The Next Generation Science Standards (NGSS) are K–12 science content standards. Standards set the expectations for what students should know and be able to do. The NGSS were developed by states to improve science education for all students. CRISPEE specifically connects to NGSS standards related to Life Science and Ecosystems, as well as Engineering, Technology, and Applications of Science. While the BactoMars game is

targeted to early elementary school students, it addresses some science themes that are typically not introduced until middle or high school. BactoMars attempts to introduce these concepts in a playful and easy-to-follow way that is developmentally appropriate for elementary school children, even though many of the standards we link to are for older children. Find out more about NGSS standards here: https://www.nextgenscience.org/

International Technology and Engineering Educators Association (ITEEA)
The Standards for Technological Literacy: Content for the Study of Technology, also called STS, identify engineering and technology content necessary for K-12 students, including knowledge, abilities, and the capacity to apply both to the real world (https://www.iteea.org/Publications/StandardsOverview.aspx). STL were designed by the International Technology and Engineering Educators Association (ITEEA), and articulates what needs to be taught in K-12 laboratory-classrooms to enable all students to develop technological literacy. As a technological prototype to model current trends in biotechnology, CRISPEE is itself a novel technology to support children's learning about technological advances in new and emerging STEM fields.

Computer Science Teachers Association (CSTA) Standards
The Computer Science Teachers Association (CSTA) is a professional association that supports and encourages education in the field of computer science and related areas. Started in 2004, CSTA supports computer science education in elementary schools, middle schools, high schools, higher education, and industry. CSTA standards for computer science education (https://www.csteachers.org/page/standards) were updated as recently as 2017 and include introductory lessons that begin as early as kindergarten and span through high school. These lessons are divided into concepts, sub-concepts and practices. CRISPEE's hardware and software components support children's developing computational thinking skills, as well as computer science practices of writing and iterating on programs.
Putting it into Practice
Below is a breakdown of each lesson of the CRISPEE curriculum and educational support materials, as well as supplemental activities that are linked to specific learning standards.

Table 1
Lesson Summary

	Theme	*Content*
Day 1	What is Bioengineering?	Children are introduced to the CRISPEE tool by reading the Adventures in Bioengineering storybook. They explore light mixing and the engineering design process, and learn that genes are like a coding language for living bodies.
Day 2	What is Science Observation?	This lesson focuses on science inquiry and observation. Children engage in life science

		center activities, and research bioluminescent animals found in nature.
Day 3	What is Ethical Engineering Design?	Children are introduced to concepts of “values” and “ethics”, and learn about how we can use these to guide decisions that we make. They also explore “consequences”, and consider positive and negative consequences of our engineering designs.
Day 4	Bioengineering a Helpful Animal	In this lesson, children are introduced to the concept of biosensors, which are genes that give special instructions based on the animal’s environment. Children combine all that they have learned about bioengineering to collaboratively design a way to help humans find toxic gas that only animals can sense.

Table 2
Sample Timeline

Time	**Tuesday** **What is Bioengineering?**	**Wednesday** **What is Science Observation?**	**Thursday** **What is Ethical Engineering Design?**	**Friday** **Bioengineering a Helpful Animal**
8:30-9:15	Outdoor Play			
9:15-10:00	*Welcome Circle* Read Adventures in Bioengineering Storybook	Guided group play with CRISPEE Science Activity: Observing and Documenting	Group Activity: Values & the Engineering Design Process	Group Activity: Design a Helpful Animal
10:00-10:30	**Snack**			
10:30-11:15	Centers: 1. CRISPEE Free play 2. Light table	Design a glowing animal (worksheet) Build your animal with CRISPEE	Ethical Design Activity CRISPEE + Plushie free play	Hands-on Fun Centers: - Chemistry table - Light Table with large animals - CRISPEE free play
11:15-12:00	Centers: 1. CRISPEE Free play 2. Light table 3. Glow books Finish Storybook	Centers: 1. CRISPEE Free Play 2. Glow books scavenger hunt 3. Additive vs. Subtractive Color Mixing	Centers: 1. Microscopes + cells 2. Glow art	*Closing Circle* *Distribute Design Journals to take home*
12:00	**Lunch**			

Curriculum & Learning Objectives

The following table walks through how each lesson of the CRISPEE curriculum, educational support materials, and supplemental activities are linked to specific learning standards.

Table 3
CRISPEE curricular content and connections to learning standards

Bioengineering Curricular Content Goals	Learning Domains	Connection to Learning Standards
1. Introduce basic concept of genetic codes as the underlying instructional language for the building blocks of all living things	Life Science	*NGSS K-LS1-1*. Use observations to describe patterns of what plants and animals (including humans) need to survive *NGSS K-ESS3-1*. Use observations to describe patterns of what plants and animals (including humans) need to survive
2. Introduce computer programming/coding as a metaphor for altering genetic instructions in living things	Computer Science	*CSTA K-2 1A-CS-02*. Use appropriate terminology in identifying and describing the function of common physical components of computing systems (hardware) *CSTA K-2 1A-AP-11*. Decompose (break down) the steps needed to solve a problem into a precise sequence of instructions. *ITEEA K-2 3.3.A*. The study of technology uses many of the same ideas and skills as other subjects
3. Introduce the foundations of biological engineering as a field that applies engineering design to living biological materials	Engineering Life Science	*NGSS K-2-ETS1-1*. Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool *NGSS MS-ETS1-1*. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions *ITEEA K-2 3.A*. The study of technology uses many of the same ideas and skills as other subjects
4. Facilitate the design of genetic programs that create a desired output	Engineering Computer Science	*CSTA K-2 1A-AP-12*. Develop plans that describe a program's sequence of events, goals, and expected outcomes *ITEEA 6-8 3.F*. New technologies and systems can be developed to solve problems or to help do things that could not be done without the help of technology

		ITEEA K-2 9.B. Expressing to others verbally and through sketches and models is an important part of the design process
5. Engage children in creative problem-solving to aid animals in relatable story-based challenges (e.g. finding home when lost)	Language Arts Social Studies	*NGSS K-ESS3-3.* Communicate solutions that will reduce the impact of humans on the land, water, air, and/or other living things in the local environment *ITEEA 3-5 5.C.* The design of technologies can impact the environment in good and bad ways *ITEEA K-2 9.B.* All products and systems are subject to failure. Many products and systems, however, can be fixed

Day 1: What is Bioengineering?

Overview: On Day 1, children will be introduced to bioengineering and learn, through an original storybook, one example of how bioengineering can help solve problems. Children will also explore light physics and practice building light programs with the CRISPEE tool for the first time.

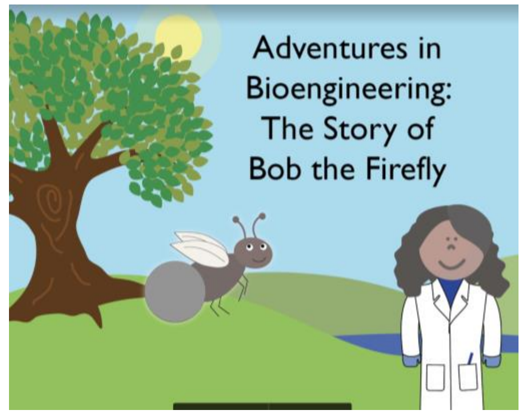
Prior Knowledge	**Objectives**		
Familiarity with the colors produced by mixing solids (e.g. paints and crayons)	Students will understand…	Students will be able to…	Bioengineering Powerful Ideas:
	• Bioengineers are special engineers who build things out of living parts • Bioengineers use science as well as engineering • Light colors are produced from a mixture of red, green, and blue light	• Define and utilize the key vocabulary introduced • Identify the fact that light and paint mixes differently	• Representation • Inquiry • Algorithms • Control Structures

Materials	Vocabulary

• CRISPEE Storybook: Adventures in Bioengineering: The Story of Bob the Firefly
• Light Table
• CRISPEE Kit
• Storybooks:
  ○ Rosie Revere, Engineer by Andrea Beaty
  ○ Ada Twist, Scientist by Andrea Beaty
  ○ Glow by W. H. Beck
	• Engineering: Building things to solve problems
	• Biology: The study of living things
	• Bioengineering: Modifying the genes of a living organism
	• Bioluminescence: The quality of glowing animals
	• Bright vs. dim
	• Color names: red, blue, green, white, magenta, yellow, cyan

Warm Up (10-15 minutes): Gather into a circle to welcome children and do introductions. Begin by asking children what they already know about science, engineering, and ask if they have heard of bioengineering. After a physical ice-breaker, such as "The Wind Blows", explain that we are going to to read a book together to learn more about bioengineering.

Framing Activity (20-30 minutes): Bioengineering Storybook
Make sure children are sitting in spots where they can see the book, Adventures in Bioengineering: The Story of Bob the Firefly. Before beginning the book, ask the children about the cover; see if they have any predictions about what the book is about or if they have any questions about the words of the title.



Adventures in Bioengineering was written in tandem with the creation of CRISPEE, and it introduces all of the key bioengineering concepts and vocabulary. This overview introduces the concept of DNA or genes as a coding language. Genes give our bodies the instructions it needs to know how to grow. Throughout the story, call children's attention to the vocabulary introduced in the book. Additionally, encourage dialogue about the choices presented in the story. Some guiding questions are:

- What is coming from the bodies of the fireflies in the story? Have we seen glowing animals like that in real life? Do we know of other animals that glow?
- Why do you think Bob is nervous about using CRISPEE to change his light color?
- What is bioengineering? What kind of things can we do with bioengineering?
- What kind of things do we think have genes? What kind of things can genes help our bodies do? Do genes change how we think or feel about things?

Since the book is long, it may be a good idea to divide the book into two readings.

Free Play in Centers (60-75 minutes): Allow children to break into small groups to explore the following center activities:

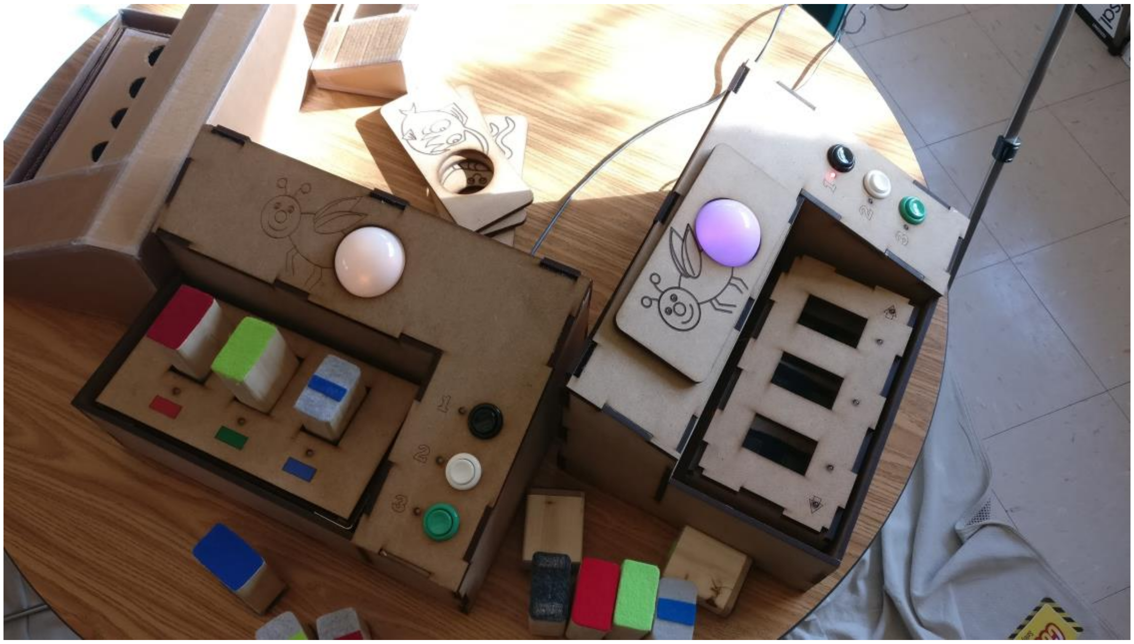
Light Table: The light table provides the opportunity for children to explore the concepts of light mixing. Because CRISPEE applies the concepts of light mixing to bioengineering, the children will need a firm understanding of light mixing in order to fully grasp the logistics of CRISPEE itself.

Activity: Discuss natural light and ask children about the words that they use to describe different types of light during the day. The students will likely be familiar with the primary and secondary colors: red/yellow/blue and orange/green/purple. However, the fundamental colors of light pigments are different: red/green/blue. This may be very confusing for children to understand, which is why the light table is an easy and fun way to explore these ideas and the surprises that this light mixing might bring.

Take it further: Introduce further concepts about light mixing and how it compares to paint mixing. The children could compare paint-mixing to light-mixing by providing small samples of paint and allowing them to compare the similarities and differences in the way that color mixes.

Scale it back: Eliminate the light-related vocabulary and simply leave the light table out as a free-play station.

<u>CRISPEE Free Play</u>: At this station, children will have the opportunity to explore free play with CRISPEE. They should be familiar with the general concepts through the CRISPEE Storybook, yet they might still be unsure of how the tool works. This is absolutely fine, that is the purpose of this exploration! The purpose of this station is for children to explore their own inquiry.



Activity: Leave CRISPEE out for free play. Allow students to explore the tool and develop an understanding of how the controls work. Prompting questions include:

- How did you make that color?
- What do you think the blocks do to the color?

Reflection and Wrap-up (15 minutes): End with a discussion of the day's events and address any questions children may have. Offer time to let them share what they made or worked on. Time permitting, you may read one of the day's storybooks or invite children to work on an activity sheet from their design journals.

In order to keep families involved, you can send home a note to update them about what children worked on through the day. Sample Day 1 note below:

Dear Families:

What we did today:	Today we had a very busy day! We learned about many of the things we will explore throughout the week, including the science of **biology** (or *the study of living things*), **engineering** (*building things to solve problems*) and a special kind of person called a **bioengineer** who uses engineering and biology to solve problems. We also read an original storybook about a firefly named Bob and his bioengineer friend named Pam. We also learned that some animals glow! This natural phenomenon is called **bioluminescence** and helps animals in many ways. We also met and played with CRISPEE for the first time. CRISPEE can help us learn how to use bioengineering to change the color of an animal's light.

How to continue the learning at home:	To bring **engineering** home, offer opportunities to notice the human-made world and how different objects were designed and built. Engineers are involved in building everything from furniture to electronics to clothing! You can also find examples of glowing animals in the world. Going to a pet store or aquarium and finding the animals in real life would be best, but you can also find videos or pictures of glowing animals online. Recommended Reading: Rosie Revere, Engineer and Ada Twist, Scientist by Andrea Beaty; Glow by W. H. Beck

Day 2: What is Science Observation?

Overview: It's time for the students to become scientists! In this lesson, students will make observations about artifacts from nature by using as many of their senses as possible.

Prior Knowledge	**Objectives**		
	Students will understand...	Students will be able to...	Bioengineering Powerful Ideas:
• Genes are like instructions inside of our bodies that tell us how to grow • Bioengineers can use special machines to change genes	• Scientists use their five senses to make observations about the world • Scientists document their observations • Living things all have genes but they are different instructions and/or in a different order • There are two different forms of color mixing	• Utilize more than one sense in order to make observations and make predictions or guesses about things that they cannot observe • Explain that animals have different genes than humans • Consider the result of different forms of color mixing in their environment	• Representation • Inquiry • Algorithms • Control Structures • Debugging • Design Process • Trade-offs • Systems Thinking

Materials	Vocabulary

• Living and non-living natural artifacts
• Magnifying glass
• Observation document
• Easel with paint/markers
• Storybooks:
  ○ Our Family Tree by Lisa Westburg Peters
  ○ *Optional:* The One and Only Me by 21andMe Inc.
	• Observe: to notice or perceive something
	• Document: record of something in written, photographic, or other form
	• Prediction: a guess or estimate about something that will happen in the future, often because of something else
	• Senses: The ways that the body learns about the environment. These include sight, smell, hearing, taste, and touch
	• Additive color mixing: in light mixing, different all colors are

	combined to create white ● Subtractive color mixing: With solids, all colors are combined to create black

Framing Activity (20-30 minutes): What is a Scientist?
Beginning in a circle, ask the children what they think scientists do. Discuss what they think a scientist can be. Next, ask the students which senses they can use to make observations. Briefly discuss what it means to *document* observations and why this is important for scientists to do.

Free Play in Centers (60-75 minutes): Allow children to break into small groups to explore the following center activities:

<u>Observation Station pt. 1, Five Senses:</u> Allow children to explore various living and non-living materials using their five senses. Encourage them to use multiple senses to observe a single object (avoiding taste or smell for toxic items). Help children remember to record their observations in their Engineering Design Journals (see Curricular Materials). Some ideas for materials to explore include:

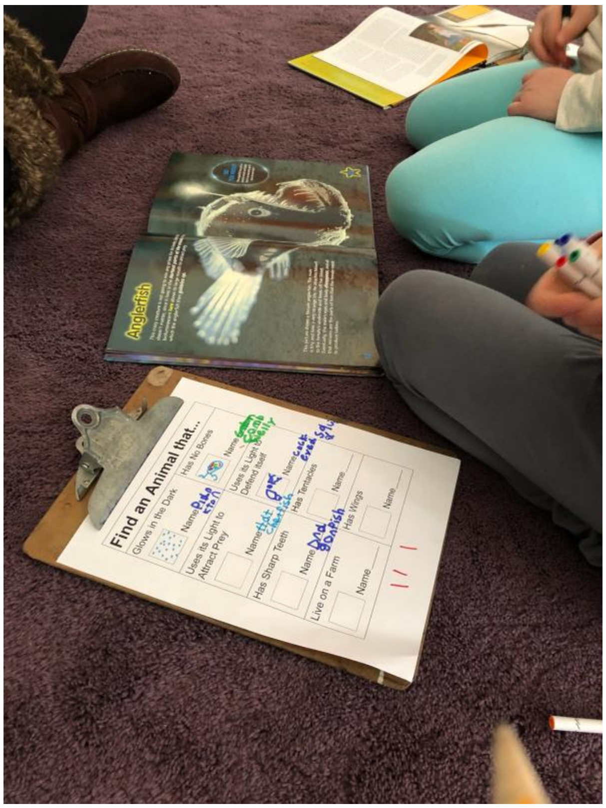
- Coffee beans
- Tea leaves
- Cinnamon sticks
- Sand
- Flour
- Leaves and branches
- Seashells and marine artifacts
- Living plants or animals (e.g. a class pet), if available

Encourage children to use gentle care when handling materials, especially if they are observing living things.

CRISPEE Free Play: In this activity, CRISPEE is again offered as a free-play station. Children should have a stronger concept of bioengineering and will be able to consider CRISPEE as a bioengineering tool, rather than a light mixer. Encourage the children by asking prompting questions such as:

- Do you think glowing animals have genes like these blocks inside their bodies?
- Why do you think CRISPEE is confused by a program with a Off and an On gene of the same color?

Encourage children to explore the animal faceplates. Notice with them that the genes function the same way no matter which animal they are using.



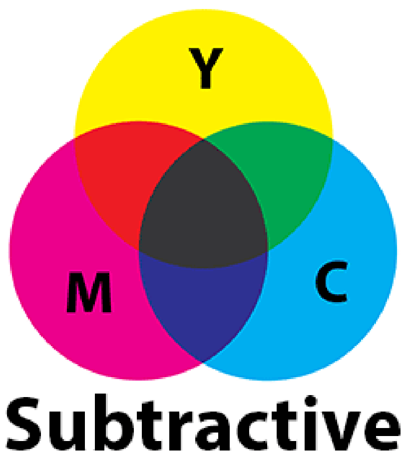
Glow Books Scavenger Hunt: Using their design journals, students will explore the unique biological qualities of animals by looking through the books about glowing animals and searching for animals with special qualities. This activity will give the students a foundation for understanding how bioengineers can build solutions with natural animal traits. This activity will encourage them to think of the differences between animals and reiterate the fact that most (if not all) of their characteristics come from their genes.

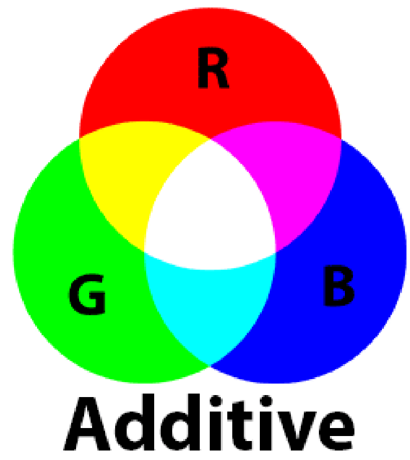
Allow children to explore books about genes, animals, and bioluminescence (see materials for book list). Adults can read through part or all of the worksheet with children beforehand to know what they're looking for.

Additive vs. Subtractive Color Mixing: This station allows children to explore the differences between light color mixing and solid color mixing. After their exposure to the light table on Day 1, students may be confused about mixing red, green, and blue rather than the primary colors that they may have been exposed to in art classes. Additive colors combine red, green and blue together to form white (as seen in the light table). Subtractive colors, on the other hand, combine cyan, magenta and yellow to create black (as children can prove with paint mixing).

Provide each child with two printed worksheets with three-ring venn diagrams; allow children to track the light color mixing patterns on one sheet and paint/solid color mixing in the other.

Example of additive vs. subtractive color mixing diagram





https://www.maketecheasier.com/why-printer-use-cmyk/

Reflection and Wrap-up (15 minutes): End with a discussion of the day's events and address any questions children may have. Offer time to let them share what they made or worked on. Time permitting, you may read one of the day's storybooks or invite children to work on an activity sheet from their design journals.

Sample Day 2 note to families below:

Dear Families:

What we did today:	Today we played with science tools like **magnifying glasses** to help us **observe** living things. We learned about **biology**, the study of living things, and how biologists and other scientists learn about animals by observing them. We also learned about how bioengineers solve problems by re-sequencing **genes**, or *instructions (like a program or a recipe) inside of the bodies of living things*. Bioengineers can make things like medicines and learn about animals by exploring their genes.
How to continue teaching at home:	To help your child continue to use their **biology** skills, you can help them notice the natural wildlife surrounding your home or in your yard. Ask your child questions about the important features of the animals and their corresponding habitats. To help your child remember these lessons you can ask them to explain what genes are and why living things look different. All living things have genes, including humans! Children can think about genes by noticing things about animal families that are similar from parents to their babies, and special traits that different animals have. What kinds of genes do you think they have?

	Recommended Reading: Our Family Tree by Lisa Westburg Peters; The One and Only Me by 21andMe Inc. (Note: 23andMe Inc. is a gene sequencing company)

Day 3: What is Ethical Engineering Design?

Overview: Children will begin this lesson by thinking about how engineers build things using the engineering design process. They will also learn about ethics and values, and consider how our values can help us make choices and think about consequences of our choices. Finally, students will put everything they've learned to use to ethically design their own helpful animal.

<table>
<tr><th rowspan="2">Prior Knowledge</th><th colspan="3">Objectives</th></tr>
<tr><td>Students will understand...</td><td>Students will be able to...</td><td>Bioengineering Powerful Ideas:</td></tr>
<tr><td>• Genes are like instructions inside of our bodies that tell us how to grow
• Bioengineers can use special machines to change genes
• Bioengineers use science as well as engineering</td><td>• Ethics are very important for bioengineers at every stage of their work
• Bioengineering is a tool for problem-solving
• Some animals have different senses than humans</td><td>• Justify a decision based on a specific value
• Consider bioengineering as a problem-solving tool to give animals senses from others</td><td>• Inquiry
• Algorithms
• Debugging
• Design Process
• Representation
• Trade-offs
• Systems Thinking</td></tr>
</table>

Materials	Vocabulary

• Ethical Design Process poster
• Microscopes and slides
• Storybooks:
  ○ Meet Bacteria by Rebecca Bielawski
  ○ The Invisible ABCs by Rodney P. Anderson
	• Value: Something you care about and might be the most important thing to you in life
	• Ethics: Values that we use to help us make decisions.
	• Microscope: A tool used for viewing very small objects, such as animal or plant cells
	• Cell: Tiny building blocks of any living thing, typically only viewable through a microscope

Framing Activity (20-30 minutes, may be broken up across the day): First gather in a circle where everyone can see the teacher. Begin by asking the students if any of them have heard of the word "value" and asking if someone can share what it means. Next, ask the students to each share one thing that they value - one thing that they care about. Offer examples such as family, friends, nature and the environment, animals, school, etc.

Introduce Engineering Design: Introduce students to the engineering design process. Start by moving through the major steps (ask, imagine, plan, create, test and improve, and share). You can read books (e.g. If I Built a Car by Chris Van Dussen) to reinforce the concepts. For students who have previously been introduced to the engineering design process, you may want to move on immediately. For students who are new to the concept, you may decide that waiting until later in the day to revisit the engineering design process is necessary.

Introduce Ethics: Begin by discussing the concept of values, or things that we care about and even love. You can leverage body-syntonic learning by describing a value as a feeling of caring that comes from our hearts. You can use the values worksheet from their bioengineering design journals to help children identify their own values.

Introduce the Ethical Design Process: If the students are already familiar with the engineering design process, then the transition to the ethical design process should be a smooth one. For many students, this may be their first introduction into conversation about ethics, so it is easiest to connect the ideas to things that they value and care about, such as family/friends and love/kindness.

After you have introduced both engineering design and ethics, you can move on to the Ethical Engineering Design Process by showing them the Ethical Design poster. (Alternatively, you can simply add ethical questions to each of the steps on an engineering design process poster.) Explain to the students that bioengineers must make sure that they are making ethical decisions throughout every step of this process, which means that they have to choose a value that is important to them and their designs. They may "ask" how to build a solution that helps humans, or that does not hurt animals. Remind students that when we "imagine" solutions, we can also imagine ways the solution can have *consequences*, or results that happen because of something else. At the "planning" stage, a bioengineer would decide which animal has a gene that could help this problem and whether it is safe to use that gene. Ask ethical questions at every stage of the engineering design process.

Free Play in Centers (60-75 minutes): Allow children to break into small groups to explore the following center activities:

CRISPEE Free Play: In this activity, CRISPEE is again offered as a free-play station.

Activity: By now, children should be very comfortable building and testing programs on CRISPEE and explaining how CRISPEE simulates gene editing. You may choose to further support their free play in these areas, or to foster their curiosity about how CRISPEE was built. Encourage them to remember their five senses from the previous lesson on science observation, and prompt them with some questions:

- How do you think CRISPEE was built? Who built it?
- What do you feel/smell/see? What clues do your observations give you about the materials that CRISPEE is made out of?

Children may notice the burned edges of wood on the CRISPEE casing, the wires on the interior that power the lights, or the bulb that glows in many colors. Offer a computer with videos that show how engineers use laser-cutters to cut wood, soldering irons to make circuits, and how LED lights can be programmed to change colors.

Take it further: You can explain that CRISPEE is a *prototype*, or an engineer's first try at making something. Invite them to look for "bugs" or errors to fix, or other ways to improve CRISPEE. Have them record their observations using pictures and words so that other engineers can benefit from their helpful observations.

Observation Station pt. 2, Microscopes: In this activity, students can explore life at a tiny scale using microscopes. This activity works very well as a station with one or two students per microscope. Prep the microscopes with a slide already positioned to view clearly through the lens.

Activity: Open by asking students if they have heard of a microscope before, or can guess what it does. What do they think a microscope can be used to see? Invite them to observe slides with just their eyes, and then show the same slides under a microscope. Reinforce that a microscope can show us things that are so small that we almost can't see them! Before the students have the opportunity to begin exploring with the microscope, give them a quick demonstration on adjusting the lens and being very careful with sharp or fragile glass materials. After they are ready, leave the microscopes open for supervised free exploration.

Take it further: Students may wish to draw their favorite slide and keep it as an observation for their Bioengineering Design Journals.

Scale it back: Some students may struggle with adjusting the microscope and can only view blurry shapes. It is helpful to have an adult involved with the technical implementation of the station.

Glow Art: Students will have the opportunity to work with glow-in-the-dark tape, stickers, crayons, or paints to freely create their own artwork. This will allow students to engage with and express themselves through glowing light.

Activity: Leave pieces of glow in the dark tape and colored sheets available for students to freely create artwork. Encourage students to compare glow in the dark materials with bioluminescence. You can draw children's attention to the fact that glowing tape was made by engineers, but they may have gotten inspiration for glowing things by learning about bioluminescence in plants and animals.

Take it Further: Allow children to look at picture books about bioluminescent animals to inspire their artistic exploration.

Group Activity: Ethical Design (30-40 minutes)

Group Activity: Remind them of the Adventures in Bioengineering storybook and the Ethical Design Process. Explain that today, we will use ethical design to solve a problem together as a group.

Begin by walking through the ethical design process steps together using the familiar example provided by the storybook. To expand on the storybook, ask the students if they can think of any consequences that could have arisen from bioengineering Bob's light. For example, is there any particular reason that one color would be better than another for Bob? What kinds of things could we test and improve to help Bob? As a group, walk through the design process and think carefully about the consequences of every design step. Reiterate the importance of testing and improving, because no one ever comes up with a perfect solution the first time.

Ask the students if they can think of a different problem that can be solved with bioengineering. This conversation will likely need support and scaffolding, so listen closely to their ideas and help point out ideas that they can grow into bioengineering solutions. After having a brief conversation about these problems as a group, divide into one-on-one pairs with children and adults. Some examples that children might come up with include:

- Pollution in natural habitats
- Medicines that humans need
- Animals that are endangered of going extinct

Individual Activity: Give students time to choose one problem they want to focus on, and try to develop their own solution. Encourage them to think of ways bioengineering can help. For example, can they think of another animal that has solved the same problem somehow? What genes might they have that can be borrowed?

Always consider whether or not your solution is harmful (to humans, animals, the environment, etc.), and if so, revise the design to become less intrusive and harmful.

Reflection and Wrap-up (20 minutes): End with a discussion of the day's events and address any questions children may have. Offer time to let them share what they made or worked on. Time permitting, you may read Meet Bacteria by Rebecca Bielawski and invite children to make connections from the storybook to their explorations with the microscopes.

Sample Day 3 note to families below:

Dear Families:

What we did today:	Today, we discussed **values**, or *a person's beliefs about what is important*. We thought about our own values, and noticed that many of us have some values that are the same and some that are different. We'll keep talking about values as we explore ethical questions of bioengineering throughout the week. We read the book Meet Bacteria by Rebecca Bielawski, and explored bacteria on our own using **microscopes** to see tiny cells and organisms. We also played with different iterations of CRISPEE and learned how **prototypes**, or test versions of products, can be made with techniques like **laser cutting**. Finally, we discussed the ethical design process, and how bioengineers think about **consequences,** or *things that happen because of something else*, and **tradeoffs,** or *corresponding positive and negative outcomes from a decision.* Finally, we began to think about the consequences of creating bioengineered animals and releasing them into natural habitats.
How to continue teaching at home:	To help your child explore animal senses, you can help your child observe animals in the real world and discuss how their genes are different from ours. To connect to our ongoing ethical discussions, we recommend that you invite children to consider both positive and negative **consequences**, or results, of choices (their own or someone else's).

	To support our discussion about **values**, you can talk about shared priorities that are important to you, your family, or your culture. Remind children that other people may have different or similar values, and that we can still be friends and get along by talking about our values. Recommended Reading: Meet Bacteria by Rebecca Bielawski; The Invisible ABCs by Rodney P. Anderson

Day 4: Bioengineering a Helpful Animal

Overview: The students will work together as a group to bioengineer Bob to change colors in various environments. This gives the students an opportunity to apply their knowledge of light color mixing, gene editing and the ethical design process in the simulation of a real world bioengineering application. This will be a good activity to wrap up the curriculum and all the topics covered.

Prior Knowledge	**Objectives**		
	Students will understand…	Students will be able to…	Bioengineering Powerful Ideas:
• Familiarity with Bioluminescence • Familiarity with CRISPEE	• How bioengineers can use ethics and values to help them to solve problems	• Consider the consequences of bioengineering designs	• Inquiry • Algorithms • Control Structures • Design Process • Representation • Trade-offs

Materials	Vocabulary

• Ethical Design Process poster
• Microscopes and slides
• Oversized CRISPEE Animal Poster
• Light Table
• CRISPEE
• Food dye (various colors)
• Graduated cylinders
• Test tubes
• Waterproof bin
• Storybooks:
    ○ Stronger Than Steel: Spider Silk DNA by Bridget Heos
    ○ Gregor Mendel: The Friar Who Grew Peas by Cheryl Bardoe
	• Biosensor: Special genes that give our bodies new instructions depending on what information is coming to our senses. Biosensors work like an “If statement” in computer science.
	• Toxic/Toxin: Toxic means poisonous or harmful to living things. Toxins are materials (like food, water, or gases) that are toxic to humans or animals.

Group Activity: Design a Helpful Animal (30-40 minutes)

Activity: Recall prior conversations with students about their senses, and explain that some animals have different senses. For example, pigeons can use sight to identify certain kinds of diseases (e.g. breast cancer) in humans even when medical machines cannot. Sometimes these senses cause their bodies to change physically in different environments. Usually this happens without the animal trying or realizing. Discuss why animals might have these special abilities. Explain that this is caused by a special gene, called a *biosensor*, that can change how an animal's body looks depending on what it can sense about its environment.

Distinguishing between extraordinary senses and biosensors

Extraordinary senses	Biosensors
● A dog's strong sense of smell ● An hawk's ability to see ● A bat's exceptional hearing	● A chameleon changing color ● Coal miners used canaries for years because canaries were better at detecting toxins than humans. (You may want to discuss the consequences of this solution.)

After this discussion, provide the following example: in an imaginary forest, there is a toxic (or poisonous) gas that is harming the animals and plants that live there. Humans are trying to clean it, but they cannot see or smell the toxin. How can we bioengineer Bob to help humans find the toxins?

Work with students towards a solution that involves changing Bob's light to indicate to humans when he senses a toxin. Ask students to choose colors for each type of environment (toxic and non-toxic). Record these choices with a CRISPEE planning sheet.

You can use the oversized animal posters and light table for this activity, or a CRISPEE placed in the middle of the circle to give children a visual to follow along. To make this more interactive, you can assign students to different roles:

- Toxin-holder: One or more children can hold different objects, such as oversized test-tubes of colored water, to represent a toxic material in the environment. Invite them to stand in different spots around the carpet/room holding their "toxin".

- Bob the Firefly: Allow children to role-playing as Bob, and to walk near and far from the "toxins". As they approach the different environments, how should Bob's light change? Students can carry large posters or papers of different colors to show off their glowing firefly light, or other children can program his light with the Light Table or CRISPEE.
- Gene Programmers: Some children can decide on Bob's light programs. Help them consider that they need a program for each environmental circumstances (e.g. what color is his light in toxic environments? Non-toxic?). The gene programmers can change the light table accordingly as Bob moves near and far from the toxins.

At the end of the activity, discuss with students both the positive and negative ethical consequences of bioengineering Bob. What could have happened if we had chosen a different color?

Take it Further: Encourage children to think about predators or prey who may not be used to certain light colors, to consider camouflage, etc. Focus on intended as well as unintended consequences that we can predict. You can end with a discussion of what questions bioengineers need to ask when they build gene programs like this.

Free Play in Centers (60-75 minutes): Allow children to break into small groups to explore the following center activities, and any others from earlier in the curriculum that were favorites with children. (CRISPEE should always be available as a free-play station.)

Chemistry Table
Activity: The students will work with water and dye to explore a different form of color mixing. Set up tubes with water and drops of different colored food dye. Provide child-size safety equipment like lab coats, gloves, and goggles. Allow for free play with the water tubes. Encourage students to discuss the difference between the food dye mixing and color mixing.

Take it Further: As students work with the dye, they may have questions about why the colors are mixing differently. This is a good opportunity to discuss the difference between light and other types of color mixing, such as paint mixing.

<u>Oversized Animals Activity</u>

Activity: This can be a free-play extension before or after introducing the Collaborative Engineering Activity. Set up the oversized animal poster board with the light table and encourage free play. You can offer conversation prompts about how the colored knobs on the light table compare to CRISPEE blocks.

Take it further: Set up CRISPEE next to the light table and ask students to recreate the light. Discuss with students whether there any consequences to changing an animal's light.

Reflection and Wrap-up (15 minutes): End with a discussion of the week's events and reflect on how much everyone has learned. Offer time to let students share what they made or worked on. Time permitting, you may read one of the day's storybooks or invite children to work on an activity sheet from their design journals. Allow them to take their Bioengineering Design Journals home after the final circle. If appropriate, this can be a special time for glow-in-the-dark prizes and treats!

Sample day 4 note to families below:

Dear Families:

What we did today:	Today, we put all the steps of our ethical engineering design process to work! The *ethical* **engineering** design process consists of six steps: 1) **Ask**: *Why is this a problem?* 2) **Imagine**: *What are the possible consequences*? 3) **Plan**: *Why is this the best solution?* 4) **Create**: *Are there any consequences for the animal?* 5) **Test & Improve**: *How can we make our solution less harmful?* 6) **Share**: *What are the consequences for the habitat or to other animals?* Bioengineers can use special genes to engineer animals that change when their bodies sense things in the environment, such as toxins or other animals. We also learned about animals that change colors when they sense specific things.We can know just by looking at their light color if the air is safe to breathe or if the water they're swimming in is warm! We used everything we have learned throughout the week to create a final group project with CRISPEE. We applied the engineering and ethical design process to design animals that can sense things like toxins in the environment, find their friends, and glow different colors to alert humans to changes in the environment. We also revisited a variety of play activities from the first day of the curriculum to see how our understanding of engineering, science, and ethics has grown.

	Today we also did hands-on playful science activities using **pipettes, lab coats, beakers** and other chemistry tools to explore properties of water and oil. We also made **glow-in-the-dark art** using glowing tape! Finally, we were all very excited to share our work in a final share-out circle! We focused on the importance of explaining our decisions and talking about our ethical engineering choices.
How to continue teaching at home:	We really want to thank you for allowing us to go on this journey with your child. Your help and contributions have aided your child and our research immensely. To progress our teachings for your child we recommend that you continue discussing observational skills as well as how to ethically justify their problem solving decisions. Some of our favorite reading and viewing from the week, and other suggestions: The Invisible ABCs by Rodney P. Anderson Stronger Than Steel: Spider Silk DNA by Bridget Heos Meet Bacteria by Rebecca Bielawski Glow by W. H. Beck Gregor Mendel: The Friar Who Grew Peas by Cheryl Bardoe Octonauts cartoon: "Octonauts and the Long-armed Squid" (Season 2, Ep. 11)

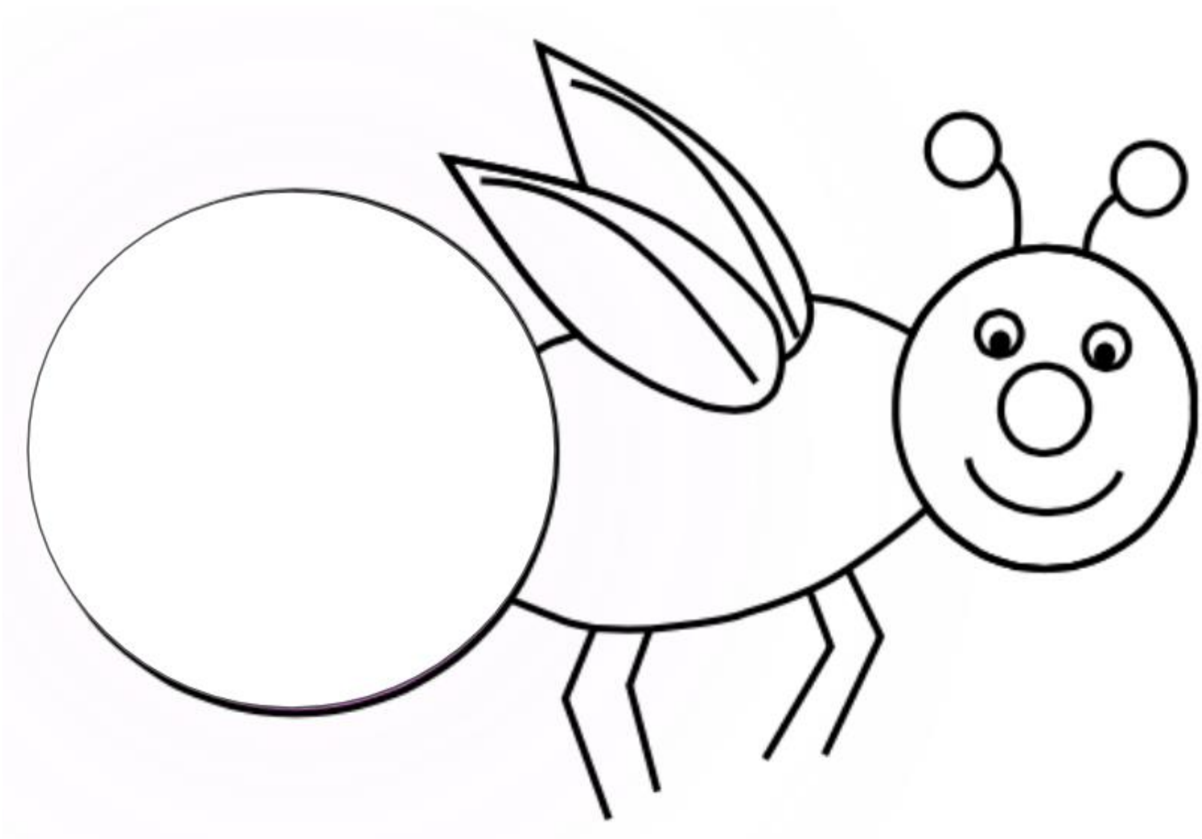
Curricular Materials

In the following sections, you'll find:

- Ethical Design Process Poster
- Bioengineering Design Journal Pages, including
    - Science Investigation worksheets
    - CRISPEE Program Planning Sheet
    - Picture Book Scavenger Hunt: Bioluminescent Animals
    - My Values Worksheet
    - Helpful Animal Worksheet
    - Bioengineering Word Search
    - Bioengineering Coloring Sheets


ETHICAL
DESIGN
PROCESS
Why is this a problem?
How does this affect other animals sharing the habitat?
Ask
What are the possible consequences?
Share
Imagine
Test & Improve
Plan
Create
Why is this the best solution?
How can we make our solution less harmful?
Are there any new consequences?

My Bioengineering Journal



Name: ______________________________________

name: ______________________________

Scientist use their senses to investigate.

looks like:	feels like:

smells like:	sounds like:

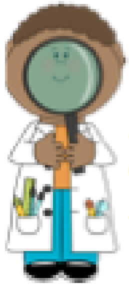
Write a sentence about your object.

____

____

____

Name____Date___________________

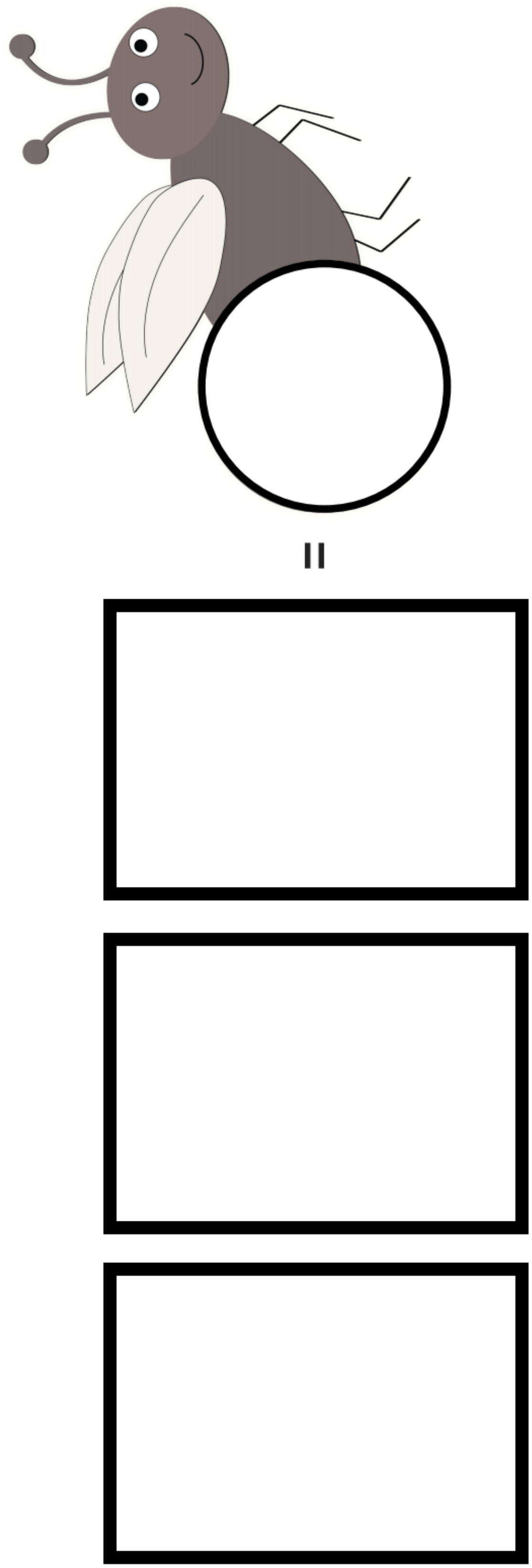


OBSERVATION STATION RECORDING SHEET

Scientist's use their eyes and hands to **observe** matter. Choose an object to observe like a scientist. Record your findings in the chart below.

I am observing a(n) ______________________________

color(s)	
pattern/design	
size	
shape	
texture	
sketch	



Find an Animal that...

Glows in the Dark Name:______	Has No Bones Name:______
Uses its Light to Attract Prey Name:______	Uses its Light to Defend itself Name:______
Has Sharp Teeth Name:______	Has Tentacles Name:______
Live on a Farm Name:______	Has Wings Name:______

Draw…
The Scariest Animal   Animal Name: _______________
The Silliest Animal   Animal Name: _______________
Your Favorite Animal

Animal Name: _______________

My Values

Values are a person's beliefs about what is important. Everyone has different values, and we may have some that are the same! What are some of your values?

 Family	 Friends
 School	 Animals
 Helping people	 Honesty

Name: ________________________

My Helpful Animal

My problem is: ______________

____

____

____

____

____

My animal:

____

Name: ______________________

Why this animal solves this problem: _______________

____

____

____

____

One reason my idea might be helpful is

____

____

One reason my idea might be harmful is

____

____

NAME:_______________________________ **DATE:**_____________

A to Z Teacher Stuff
www.AtoZTeacherStuff.com

Bioengineering Word Search

Y	J	I	C	H	F	I	R	E	F	L	Y	N	V	W
E	N	L	Y	V	T	H	S	C	I	E	N	C	E	E
L	L	H	L	T	Z	E	B	R	A	F	I	S	H	K
L	I	B	I	O	B	R	I	C	K	C	W	Q	I	M
O	G	B	I	J	E	L	L	Y	F	I	S	H	U	G
W	H	R	D	O	M	H	W	H	I	T	E	E	S	E
O	T	B	E	N	E	I	A	Z	A	G	P	T	E	N
Q	Z	L	C	E	Z	N	C	P	D	C	V	W	S	E
S	P	U	I	D	N	R	G	R	V	N	Y	V	U	I
M	R	E	D	X	R	X	X	I	O	P	A	A	I	B
T	O	Z	Q	B	K	O	Z	V	N	S	E	C	N	R
F	G	X	C	R	I	S	P	E	E	E	C	R	C	F
N	R	Y	B	R	Z	A	Y	P	J	A	E	O	E	V
M	A	G	E	N	T	A	T	S	E	R	W	R	P	D
J	M	I	A	Q	Y	N	U	X	G	R	I	E	J	E

BIOBRICK
BIOENGINEER
BLUE
CRISPEE
CYAN
DNA
DROPPER
FIREFLY
GENE
GREEN
JELLYFISH
LIGHT
MAGENTA
MICROSCOPE
PROGRAM
RED
SCIENCE
WHITE
YELLOW
ZEBRAFISH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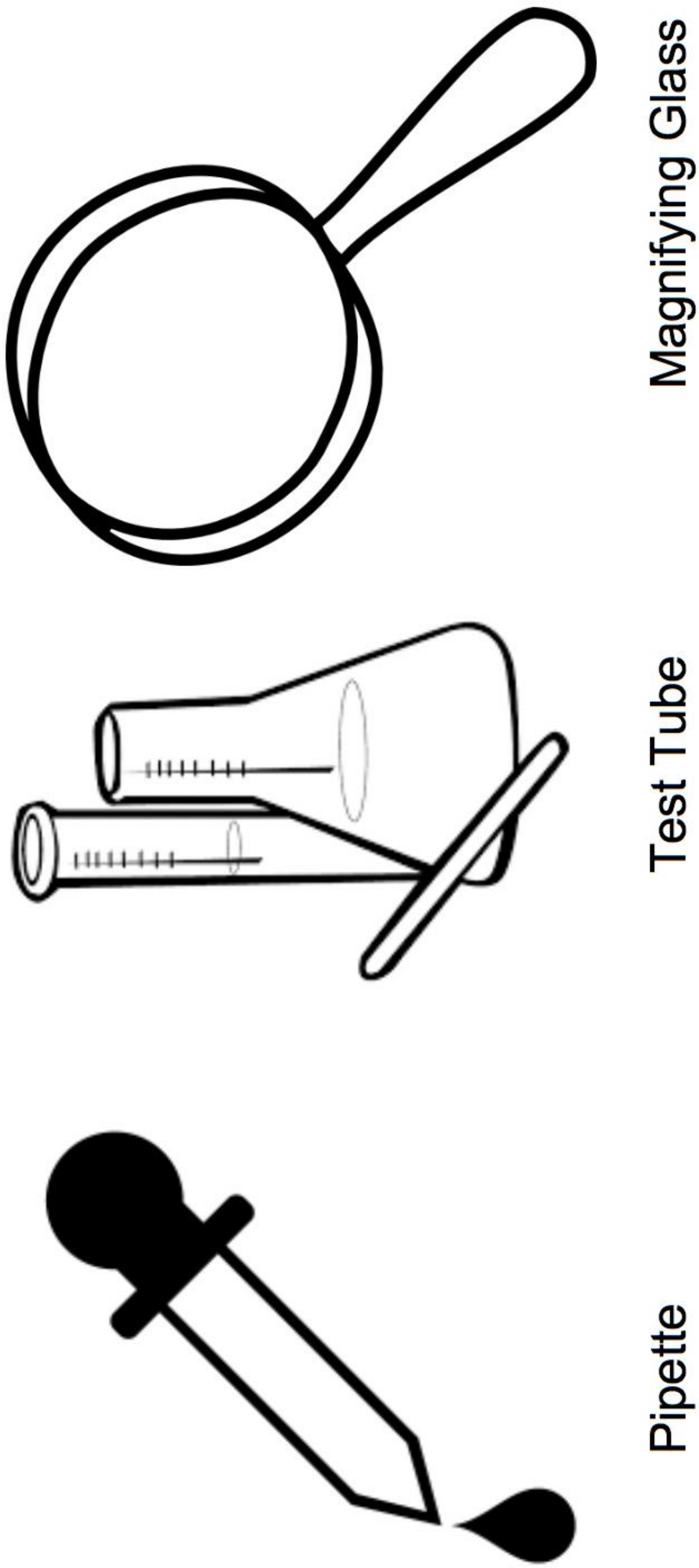
Pipette
Test Tube
Magnifying Glass

Appendix B. CRISPEE Museum Survey

Child's Name:

Bioengineering Interest and Background Parent Survey

This survey is part of a study conducted by the DevTech Research Group. We are investigating foundational ideas of bioengineering as a potential learning domain for early childhood. Please complete this survey to help us learn about your child's background and experience with bioengineering.

Please try to answer the following questions as honestly as possible to the best of your knowledge. If any questions make you uncomfortable, feel free to skip them. Certain questions may pertain to your personal home life. These are not meant to make you uncomfortable, but rather to gain a more holistic understanding of your child's educational experience inside and outside of the classroom, and are rooted in prior research about what impacts children's science knowledge. Please feel free to reach out to the study coordinators if you have any questions.
Thank you for your participation!

1. Child's Birthdate: __________________ 2. Child's Gender: ______________

3. Child's School/District: ____

4. Child's Ethnicity _________________________

5. List the individuals who live in the child's household(s):

Relationship to Child (e.g. father, mother)	Gender	Highest level of education attained

Use extra page if needed.

6. Do you or anyone in the child's family work in biotechnology or a related field? Circle one:

Y / N
If yes:
Relationship of family member(s) to child: ____
Occupation of family member(s) (select all that apply):

- ❏ Bioengineer/Geneticist
- ❏ Laboratory Scientist
- ❏ Medical Professional
- ❏ Other:____

7. How present is religion/spirituality in your child's life? Circle one:

1	2	3	4	5
Totally absent	Somewhat absent	Neutral (neither present nor absent)	Somewhat present	Very present

Please select all that apply to your child:

- ❏ Attend regular religious services
- ❏ Practice religious ceremonies and/or holidays at home
- ❏ Attend religious schooling
- ❏ Other:____

8. What religion(s) or spiritual perspective(s) does your family practice? (optional):

____

9. In the last 6 months, how often has your child explored the following STEM domains (at home, at school, or at other informal learning spaces)?

	1 - Never (0 times in the last 6 months)	2 - Rarely (Less than once per month)	3 - Sometimes (around 1x per month)	4 - Often (around 1x per week)	5 - Very often (daily or almost daily)
Engineering, Building					

Robotics, Coding					
Biology, Life Science					
Ethical Problem-Solving					

10. In the past 6 months, which of the following activities about **bioengineering**, **microbiology**, or **DNA** has your child participated in?

- ❑ Visited a museum exhibit on bioengineering/microbiology/DNA
- ❑ Met an adult who works in bioengineering/microbiology/DNA (household members not included)
- ❑ Used bioengineering/microbiology/DNA science kit
- ❑ Visited a website about bioengineering/microbiology/DNA
- ❑ Played a video game about bioengineering/microbiology/DNA
- ❑ Watched a movie or tv show about bioengineering/microbiology/DNA
- ❑ Played a game about bioengineering/microbiology/DNA

11. Which of the following materials related to **bioengineering**, **microbiology**, or **DNA** are present in the child's home?

- ❑ Chemistry/science kits or tools (e.g. microscopes, crystal growing, etc.)
    - ❑ *if yes, how many kits or tools:* ___
- ❑ Videos about bioeng/microbio/DNA
- ❑ Games about bioeng/microbio/DNA
- ❑ Books about bioeng/microbio/DNA
- ❑ Amino Labs bioengineering kit
- ❑ Bento Lab bioengineering kit
- ❑ BioBuilder bioengineering kit
- ❑ Other bioengineering or microbiology toys: _____________________________________

12. Which of the following materials related to **robotics** or **programming** are present in the child's home?

- ❑ Videos about robots
- ❑ Games about robots or coding

- ❑ Books about robots
- ❑ KIBO robot kit
- ❑ Little bits tangible coding kit
- ❑ ScratchJr programming app
- ❑ LEGO Mindstorms / LEGO robotics kit
- ❑ Other robotics or programming toys: ____

13. Have concepts of genes, DNA, or related biology topics been introduced at home?

- ❑ Yes, thoroughly
- ❑ Somewhat
- ❑ Not at all

If yes or somewhat, please describe what your child explored:

____

____

14. On a scale of 1-5, how much do you think you child is interested in science, technology, and engineering? Circle one:

1	2	3	4	5
Not at all interested	Somewhat uninterested	Neutral (neither interested nor uninterested)	Somewhat interested	Very interested

15. How comfortable would you be if you learned that your child was exploring the following concepts in their learning setting? Please mark selections with an X.

	1 - Not at all comfortable (I would pull my child out of such activities)	2 - Slightly uncomfortable	3 - Neither comfortable nor uncomfortable	4 - Slightly comfortable	5 - Very comfortable (I would actively seek out these kinds of activities for my child)
Learning about genetics					
Learning about how bioengineers change living organisms to solve problems					
Thinking about genetics as a coding language					
Designing their own solutions with genes to solve real-world problems					
Thinking about the impact of humans on natural environments					

16. Do you have any questions, concerns, or feedback for us about this study? (optional)

____

____

____

____

Appendix C. CRISPEE Museum Study Protocol

CRISPEE Testing: Museum Study
Location: Boston Children's Museum

Procedure

Implement a 15-minute activity CRISPEE tool, stuffed animals, & CRISPEE planning sheet

Timeline for each Play-test:

<table>
<tr><th></th><th>Videographer</th><th>Interviewer</th><th>Greeter</th></tr>
<tr><td>1) Prep for session (5 mins)</td><td>Check space on SD card and battery on camera. Switch SD cards and copy files to hard-drive if needed.

Start new notes document.</td><td>Check that all consent is in order.
Start adult on parent survey.</td><td rowspan="6">Welcome families and children. Explain that we are researchers from Tufts and Wellesley conducting studies of new technologies about genes and gene editing. Explain Consent doc and Parent Surveys.

While families are waiting, invite them to:
1. Complete consent forms and parent survey
2. Try the other technology, if available
3. Read CRISPEE storybook with family
4. Plan CRISPEE program using planning sheet (unless being used)
5. Younger or older siblings: play with the toys left out by museum staff</td></tr>
<tr><td>1) Get started (1 min)</td><td>Begin recording and note-taking (note child's name and other necessary info)</td><td>Introduce children to CRISPEE, ask names and get set-up</td></tr>
<tr><td>2) Interview (4 mins)</td><td>Note children's answers or anything interesting</td><td>Lead interview</td></tr>
<tr><td>3) CRISPEE free-play (10 mins)</td><td>Continue notes.
Take pics if possible</td><td>Lead free-play</td></tr>
<tr><td>4) Wrap-up (5 mins)</td><td>Control Bob with phone*</td><td>Lead wrap-up</td></tr>
<tr><td>5) Reset (5 min)</td><td>Stop video, turn Bob off, complete last notes</td><td>Restart CRISPEE, clean and prep table</td></tr>
</table>

***Bob light control:** b = blue ; r = red ; g = green ; c = cyan ; m = magenta ; y = yellow ;
w = white ; o = off

Greeter Script

To family and children: Hello! (Speaking to child and parents) My name is _____, what are your names? Nice to meet you, (child's name)! Do like science and engineering? This might be a fun activiti for you! Let me tell (parent's name) about the games we have and see if they think it's ok to play with us today!

To parent (invite child to color or watch other kids play CRISPEE while you talk): We are student researchers from Tufts University and Wellesley College! We are conducting a research about a toy and a videogame that we developed to teach children ages 5-8 years about DNA and gene editing. You can learn more about it by reading this storybook or by looking at our website (show postcard). Basically, it's just a play activity where we would watch your child and ask some questions about what they're doing. Does that sound ok?

Since it's research, we are asking all families to fill out these consent form, basically saying you agree to let us ask questions and video-record your children.
(Show parent permission page): This page is for you to fill out giving permission and this is the most important page.
(Show child assent page): How old is (child's name)? If they are 7 or older, they are old enough to say themselves whether they want to do the study or not, so we would just need them to write their name here.
(Show image release page): This one is totally optional, but we sometimes use pictures from these studies to promote and recruit for other studies. If you don't mind that we do that then feel free to sign this, otherwise don't worry about it and we won't bother.

CRISPEE Interview Script

1) Introductions	Hi! What's your name? How old are you? Today we're going to play a game with this tool *(motion to CRISPEE)*! What does it look like it could be? CRISPEE is a toy that is based on a real tool that adults use, called CRISPR! We're gonna explore it today! First, we're going to have a little conversation and I'll ask you some questions. And then we can try playing with it!
2) 3-question interview	My first question is – **can you point to something you see that's alive?** How do you know that _______ is alive? *Ask follow-up questions as needed*

<table>
<tr><td></td><td>

If the child gives you a rule, try pointing to something that is alive that doesn’t fit that rule and ask them to try to explain it
If the child only names one thing, ask: Am I alive?

What makes me and _______ different?
Have you ever heard of a gene? What are genes?
Have you ever heard of something called a program in a computer?
If no: Skip this part and go straight to genes
A computer program is a list of instructions that tells the computer what to do.
Just like a computer has a program (continue below)…
Our bodies have genes, which tell our bodies how to grow like how to grow a hand with 5 fingers that can bend this way (demonstrate)
Now I have another question – have you ever heard the word bioengineer?
If yes: What is a bioengineer?
Bioengineers build things that are alive by using the genes we just talked about
</td></tr>
<tr><td>3) CRISPEE play</td><td>
IF BUG OCCURS:
We built this tool CRISPEE, so it’s not like the toys we buy in the store. Since we built this CRISPEE, sometimes it doesn’t work.
This is our friend Bob the firefly!
If we have time, we’ll meet Bob the stuffed animal after our fun experiment!
Have you ever seen a firefly?
What color was it?
Bob has genes just like we do, and today we’re going to use this tool here to create a light for Bob’s genes to tell his body how to glow!
Here’s how we’re going to play with CRISPEE
First, we’re going to check our program (button #1) – this is to make sure CRISPEE understands what we made
</td></tr>
</table>

	Then, after we press #2, it's time to mix our genes back into the rest of the animal's genes And #3 shows us the light that we made How do you think these blocks *(motion to CRISPEE blocks)* fit with this tool? *Allow children to play with blocks, try putting them into CRISPEE, don't correct them* Let's see what happens when we press the 1 button. *Guide their block input accordingly* What color do you think each of these blocks is? Ok, let's try putting these blocks together to build a light program for Bob *Troubleshoot child's attempts accordingly* *If not already addressed, ask what they think the Off blocks do* *Once they've successfully built a light program:* What does each block we put into CRISPEE do to the light here? *Introduce Level 1 placemat after the child has made one light program* Before you change anything I'm going to keep track of the combinations you've made. We know this is one combination that works.
4) Last program with Bob	*Tell other children in line to plan with Level 1 placemat while waiting to use actual CRISPEE* <u>End with Introducing Bob</u> Here's Bob the stuffed animal! Do you want to make one last program of your favorite color? And see it on our stuffed animal version of Bob? *Use Bluetooth to program plushie*
Wrap up-	Thank you for helping us with our bioengineering experiment today! - Sticker, info to parents about where else to see CRISPEE *If child insists they want to keep playing:* I'm so glad you had fun being scientists with us today but we have some other people waiting to play with CRISPEE too! We'll be back at this museum in a month and you can play with CRISPEE then!

Appendix D. Museum Study Codebook of CRISPEE interactions

Code	Definition	Examples	Inclusion Criteria	Exclusion Criteria
Indirect CRISPEE Interactions				
Planning Sheet	Child interacts with CRISPEE planning sheet or paper blocks	Touching/pointing to any of the following: - worksheet-style planning mat - velcro paper blocks - velcro paper light circles	Generally include anytime child is engaging with the planning sheet. Include when researcher is engaging with planning sheet and child is observing or actively participating	Exclude if only researcher is interacting with planning sheet and child is ignoring/focused elsewhere
Exploration	Child interacts with CRISPEE in a way other than building or testing a block program	Touching/pointing to any of the following: - blocks outside of CRISPEE (e.g. building tower, sorting blocks on table) - buttons - platform - other CRISPEE element (e.g. storybook, plushie, etc.) - Touching/pointing to planning sheet	Generally include anytime child is engaging with CRISPEE but not building or testing a program	Exclude if part of building a program or conducting a test
Direct CRISPEE Interactions				
Build Program	Child interacts with CRISPEE to build a block program	- Adding new blocks to CRISPEE - Emptying CRISPEE of all blocks - Changing/swapping same blocks in program (i.e. same program in new sequence) - Changing/swapping different blocks in program	Generally include anytime a child is adding or removing blocks from platform	Exclude if child is building with blocks outside of platform. If building alternative construction (e.g. upside down blocks, in-between slots) code as building program and testing alt. construction

Witness Bug	A bug or malfunction in the technology occurs while child is using CRISPEE	Typically this is a false-negative red feedback light in the third slot, but could be any kind of bug in feedback lights or incorrect color light as a result of a tested program. CRISPEE should only light up red in two cases: 1) empty slot, and 2) double-block colors.	include any time a tech malfunction occurs while child is using/looking at CRISPEE. Include this no matter who debugs the malfunction.	Exclude if child completes a functional program but changes the blocks partway through. Even though the light will look incorrect, this is not a bug as CRISPEE cannot interrupt a test once it has started. Instead, code this as exploration.
Debugging	Troubleshooting resulting from bug in the technology	rearranging blocks in program (e.g. spinning, pushing in harder) to resolve a bug in the technology (e.g. false-negative feedback light)	Include only if technology shows bug and children actively try to troubleshoot it. This can be mimicking adult troubleshooting behaviors or trying their own idea	Exclude if they are testing a non-functional program (i.e. tech is not buggy) Exclude if only adult is debugging.
Testing Functional CRISPEE Programs				
Test Functional Program	Child tests any functional program in CRISPEE	Child presses buttons 1-3 to test any functional R-G-B program for the first time	Include every time child completes steps 1-3 of testing a functional program.	Do not include if child does not complete a test and see resulting light color. Do not mark multiple time intervals if the test of a single program spans more than one 15-second time-sample interval; the end total of codes should be the exact number of functional programs the participant tested.
Testing Non-Functional CRISPEE Programs				
Test Double-Block Program	Child tests non-functional program with two blocks of	Child presses button 1 to test programs like the following: R-r-G	include and double-code with other non-functional programs	Do not include if child does not press button 1. Do not mark multiple time intervals if the test of a single

	same color in CRISPEE	B-r-b G-g-_		program spans more than one 15-second time-sample interval; the end total of codes should be the exact number of double-block programs the participant tested.
Test Missing Block Program	Child tests non-functional program with 1 or 2 blocks missing from CRISPEE	Child presses button 1 to test programs like the following: G-g-_ _-B-_ R-_-b	include and double-code with other non-func. programs	Do not include if child does not press button 1. Do not mark multiple time intervals if the test of a single program spans more than one 15-second time-sample interval; the end total of codes should be the exact number of missing programs the participant tested.
Test Empty CRISPEE	Child tests non-functional program with all 3 blocks missing from CRISPEE	Child presses button 1 to test the following program: _-_-_	include and double-code with other non-functional programs	Do not include if child does not press button 1. Do not mark multiple time intervals if the test of a single program spans more than one 15-second time-sample interval; the end total of codes should be the exact number of empty CRISPEE programs the participant tested.
Test Alternative Construction	Child tests alternative CRISPEE/program construction	Child presses button 1 to test any of the following "programs": - upside-down blocks - blocks in between slots - blocks stacked in a tower	MUST double-code with other programs. include and double-code even if some blocks in program are functional and correct (e.g. correct R-G-B	Do not include if child does not press button 1. In this case, double-code as "build program" and "exploration". Do not mark multiple time intervals if the test of a single program spans more

			program in slots, with non-functioning r-g-b blocks between block slots, balanced on other blocks, or elsewhere on CRISPEE).	than one 15-second time-sample interval; the end total of codes should be the exact number of alternative construction programs the participant tested.
Social Interactions				
Turn-based talk or gesture* *Pair-work only	Children verbally or physically declare "turn" boundaries, specifically individual turns Applies to entire tests (Steps 1-3)	- pushing partner's hand away - saying "it's my turn", "your turn is over", or something similar - moving the CRISPEE to face themselves or partner - using body/arms to prevent partner from touching or working with CRISPEE - removing other child's program from CRISPEE - taking turns creating their own start-to-finish test	Include if children interrupt their partner's test to do a different gesture (e.g. taking block out of CRISPEE when partner is trying to test) Children give directions to partner to request them to stop activity	Exclude if they are collaborating on a single test using role-based turns
Collaborative/role-based talk or gesture* *Pair-work only	Children verbally divide up "jobs" or specific tasks up by child for a single test Children use gestures to prompt, remind, or help each other in their role Applies to steps within a single test	- announcing roles ("I'll be the button-pusher", "you need to add the blocks," or something similar) - children respond to partner's prompts (e.g. child 1 says "push the button" and child 2 pushes it) - Take turns completing steps within one test - Arranging blocks on table for partner to insert into CRISPEE	Include if children verbally describe roles or give directions to partner to solicit their help with a test Include if children non-verbally divide jobs (e.g. pausing and waiting for partner to finish action before moving on)	Exclude if children interrupt a test to begin a separate test of their own Exclude if it's too subjective and you can't tell about children's intentions while working

Researcher Prompting	Researcher volunteers information or prompts with questions or gestures (i.e. children did not ask for help or clarification)	Individual Codes: - prompting questions ("What do you think this blocks means?") - prompting to assist behavior/actions ("Did you want to try this block?") - offering information ("Can I share something with you about this CRISPEE?")	Include if: - Researcher interrupts testing/planning process to provide information - Researcher draws children's attention away from CRISPEE - Researcher explains CRISPEE is a prototype, or interrupts coding session to debug CRISPEE - Researcher prompts children to explain the function of CRISPEE or CRISPEE parts	Do not include if: - Researcher offers simple validation or comments on children's activity - Child requests researcher involvement

Appendix E. CRISPEE Camp Study Protocol

CRISPEE Testing: Camp Study
Location: Eliot-Pearson Children's School

Pre and Post Procedure

Implement a 20-minute semi-structured interview about genes and bioengineering

In small groups (3 children at a time with 1 researcher), invite children into a quiet section of the room that has been closed for testing. Complete the following interview structure:

1. Show video of **natural non-glowing zebrafish:** https://www.youtube.com/watch?v=yRmLwKqg5d4. Leave video running during children's conversation. Prompt them with the following conversation starter:
    a. What do you notice about these fish?
    b. Follow-up children's thoughts with informal prompts, e.g. "can you tell me more about that", and "what do you see that gives you that idea?"
2. When it seems like children are ready to move on, show video of **bioengineered glowing GloFish:** https://www.youtube.com/watch?v=RmHnKfTLgNw . Leave video running during children's conversation prompt them with the following conversation starter:
    a. What do you notice about these fish?
    b. How are they different from the fish in the first video we saw? How are they similar?
3. When it seems like children are ready to move on, prompt them with the following script:
    a. Can I share something that I know about these fish? They are both Zebrafish, but special scientists called *bioengineers* did something that made them look different from each other. Do you have a guess what they could have done?

Post-only Follow-up

Once children have completed their conversation, bring the CRISPEE kit to the table. Ask the children if they recognize this tool. After their conversation, ask if they would like to try to use CRISPEE to try to create a light on the CRISPEE zebrafish, Zoe. They may try to recreate one of the colors they observed in the GloFish video if they like. After they have completed several tests, you can prompt them to complete their last program and transition out for the next group.

Appendix F. Table of all Museum Study Participant Child Ideas

See below a table with all children's ideas during first and second half of each CRISPEE play session. See Chapter 8 for a description of each idea.

ID	Partner ID	Age	Gender	MINS 1-5	MINS 5-10
BCM05	None	4(9)	M	D	D
BCM120	None	5(0)	M	D	D
BCM63	BCM91	5(0)	F	D	D
BCM113	BCM129	5(2)	F	D	C
BCM32	None	5(3)	M	A	C
BCM29	BCM98	5(4)	M	D	D
BCM30	BCM22	5(5)	F	D	C
BCM114	BCM100	5(6)	M	A	B
BCM100	BCM114	5(7)	F	A	B
BCM08	None	5(9)	M	A	C
EPCS92	EPCS35	5(9)	F	A	C
EPCS03	EPCS67	5(9)	F	A	B
BCM116	BCM106	5(9)	F	D	D
BCM123	BCM122	5(10)	M	D	D
BCM35	None	5(11)	M	D	B
EPCS29	EPCS11	5(11)	M	A	D
BCM12	BCM88	5(11)	M	C	C
BCM108	BCM115	5(11)	F	D	D
BCM03	None	6(0)	M	B	B
BCM19	BCM75	6(0)	M	D	D
BCM57	None	6(1)	F	C	C
BCM99	None	6(1)	M	B	C
BCM121	None	6(1)	M	A	D
BCM124	BCM112	6(1)	M	B	A
BCM79	None	6(2)	M	D	D
BCM66	None	6(3)	M	C	C
BCM82	BCM60	6(4)	M	C	C
EPCS67	EPCS03	6(4)	F	A	C
BCM02	BCM06	6(4)	M	D	D
EPCS35	EPCS92	6(5)	M	A	C
EPCS11	EPCS29	6(5)	M	A	A
BCM103	BCM110	6(9)	F	B	C
BCM71	None	6(10)	F	C	C
BCM98	BCM29	6(10)	M	D	D
BCM122	BCM123	6(10)	M	D	D
BCM60	BCM82	7(0)	F	C	C
BCM97	None	7(2)	F	A	C
BCM91	BCM63	7(2)	F	D	A
BCM75	BCM19	7(4)	M	D	D
BCM106	BCM116	7(4)	F	D	C
BCM48	None	7(5)	F	C	C
BCM33	BCM89	7(6)	F	C	C
BCM13	None	7(8)	F	B	C
BCM129	BCM113	7(8)	F	D	C
BCM88	BCM12	7(10)	M	C	C
BCM59	None	8(0)	M	A	C
BCM112	BCM124	8(0)	F	B	A

BCM102	None	8(2)	F	C	C
BCM105	None	8(3)	M	C	C
BCM125	None	8(4)	F	C	C
BCM110	BCM103	8(4)	M	A	C
BCM115	BCM108	8(4)	F	D	D
BCM111	None	8(9)	M	A	C
BCM26	None	8(11)	F	C	C
BCM39	BCM70	9(0)	F	D	C
BCM70	BCM39	9(0)	M	D	C
BCM22	BCM30	9(3)	F	B	C
BCM101	None	9(5)	M	B	A
BCM89	BCM33	9(6)	M	C	C
BCM45	None	9(8)	F	C	C
BCM16	None	9(11)	M	A	D
BCM06	BCM02	9(11)	M	A	C

Appendix G. Camp Study Qualitative Codebook

Themes (shaded) and Codes	Description	References	Example
CRISPEE	Interaction with or about the CRISPEE prototype	145	*Children are playing with CRISPEE kit* Yash: Now, which one [color] do you wanna make, Henry? Henry: Let's make, uh, blue… [makes program with GREEN, green, blue] Yash: It needs to, cause if it's green and then no green that makes no sense right? [touching GREEN and green blocks] Which one do you want? Henry: [changes blocks, makes program with GREEN, RED, blue] Researcher: What color are you trying to make? Yash: Blue? That one will make yellow Henry: Shake it! [Shakes platform]
Attitudes (CRISPEE, Camp)	General attitudes or opinions about the kit or intervention	29	
Block Functions	Function of CRISPEE block(s) in creating a light	18	
Meaningful Colors	Colors that children have special connection with	19	
Roles-social	Dividing turns, assigning roles, or other social negotiation while playing with CRISPEE	30	
Sequence, Order	Investigating whether order of CRISPEE blocks impacts light output	6	
Visual Pattern	Using blocks or other elements of CRISPEE to create an aesthetic pattern	5	
Design Process	Any creative expression of design planning, ideating, creating, and/or iterating; referencing the design process	159	*During a Circle meeting, children discuss biodesign:* Researcher: Could there be a reason that cyan might not be such a good color for fireflies? Samantha: Because Bob might want, the fireflies might laugh at him after a while so he could make Pam turn him a different light Researcher: Might not be a popular color for him? Melody: He could get, there's a way he could get lost, if he has cyan he could camouflaged as a river and the other part a leaf Researcher: So he could camouflage differently, he could blend in differently with his surroundings. Then they still wouldn't be able to find him even though he has a light. So we have to think about
Biodesign	Design process specifically involving genes/animals/bioluminescence	82	
Consequences	Considering the positive, negative, or neutral effects of some biodesign choice	38	
Ecosystem-Context	Consequence related to the animal's natural habitat or species	7	
Environmentalism	Consequences related to a larger context of earth-stewardship and eco-preservation	10	
Social-Story	Consequences related to an imagined	10	

Themes (shaded) and Codes	Description	References	Example
	scenario, such as assigning human motivations to biodesigned animal		all these consequences when we make our design. Samantha: Wait wait, if he fell into the river and the fireflies saw him, they might be like why is that part of the river lighting up? And the others might be like that's Bob!
Design Journal	The CRISPEE bioengineering design journal used in the intervention	27	
Change Genes	Children describe design step of changing genes	11	
Take-Give Genes	Children describe design step of taking, giving, or swapping genes	7	
Hardware-Debugging	Any reference to building or repairing human-made hardware, parts, or machines	25	*Children are playing with a malfunctioning CRISPEE kit* Caroline: And I can tell how all the other lights come on. See? Researcher: Yeah! Krista: The wires over there. Carlos: No guys watch, watch back here. Look. See what happens? Caroline: What are you doing? Krista: Whoa! Caroline: Wow! He's shaking the wires! Caroline: Hey! When you press number button, number one this little contraction goes down. Caroline: We're finding many cool stuff in CRISPEE.
Construction-Engineering	Building human-made hardware (machines, electronics, computers)	16	
CRISPEE Debugging	Debugging a CRISPEE hardware malfunction (not a coding or block order challenge)	22	
CRISPEE Malfunction	Malfunction in CRISPEE prototype (unrelated to block coding error)	13	
Robots-Programs	References to specific robotics kits or programming environments (excluding CRISPEE)	11	
Life Science	Exploring/Investigating nature or properties of living things	353	*Children are at Nature Observation Center* Samantha: This ones my favorite type of shell. Researcher: Why? Samantha: Because there's two holes. Samantha: But my hypothesis is that had a part that stuck out of the Earth Kevin: They're actually lobsters. Researcher: They're lobsters? Researcher: That's a really good hypothesis!
Asking Questions	Questions to solicit more information, to determine "reality" or "facts"	34	
Attitudes	General attitudes or opinions about life science	14	
Bioengineering	The science of gene editing through bioengineering, work of professional bioengineers	14	

Themes (shaded) and Codes	Description	References	Example
Bioluminescence	Naturally glowing living organisms	94	*Researcher is reading aloud a storybook about bacteria* Researcher: There's other bacteria that I had never even heard of in this book so let's take a look. "They're everywhere, in the dirt, in the air, although they can't be seen, on walls and doors, on chairs and floors and cracks, there in between." They're all over the place! Child off-camera: I'm stepping on them right now. Kevin: Me too! Amanda: You're stepping on them right now, maybe they're even in your hair, maybe they live on your hands. Samantha: Bacteria–[inaudible] Child off-camera: I'm sitting on them right now! Child off-camera: They're inside our tongues!
Adaptive Function	Purpose/function of bioluminescence for specific animals	10	
Animals	Animals that luminesce	36	
Color Mixing	Exploring the ways that colors mix in solids and light	25	
Genes	Genes as the material that bioengineers use to change living things	58	
Code-Instructions	Genes as a programming language	8	
Family-Related	Genes as a connection between related living organisms	3	
Natural Resource-Building Blocks	Genes as a finite resource that can be harvested from living organisms	13	
Hypothesis-NOS	Proposing some new knowledge or guess, or considering how scientists form knowledge or guesses	23	
Observation-Senses	Using experiential senses to gather information	49	
Picture Books	Using picture books to gather information	26	
Mental Model	Children's attempts to understand or explain differences between bioengineered and non-engineered animals, or to generally explain luminescence in living and non-living thing	150	*Researcher is showing videos of glowing and non-glowing fish* Researcher: So they aren't glowing anymore, even though the water is dark. So something is different about these fish. Do you think- Zora: Oh I might know another reason. Researcher: What's another reason? Zora: Because if you think of fish like humans. There are many different types of humans, there are girls,
Analogy	Comparing a phenomenon to something else (related or not)	5	
Anthropomorphic Animals	Assigning human-like motivations to biodesigned animals	12	
Concrete-Descriptive	Using experiential knowledge to explain	52	

Themes (shaded) and Codes	Description	References	Example
	phenomenon		there are boys, there are Indians, there are Americans. There are lots and lots of different types of humans, which means that there could be lots and lots of different types of fish, and also zebrafish too. Researcher: That's a good hypothesis! *Children are reading picture book about genes* Kevin: You know at the doctor's when they open, um, when they give you open heart surgery? They open your body and see your genes Researcher: You can see genes then when you're looking inside your body? Kevin: But you obviously they do it when you're sleeping Researcher: Oh, because it would hurt a lot if you weren't sleeping. I think that makes sense too. Kevin: Because they have a knife and they cut you open by heart
Glowing (Non-living)	Distinguishing bioluminescence from other sources of glowing light	12	
Itchy	Children's words to describe non-living glowing objects	2	
Sunlight	As source of glowing light	3	
Make Light (Put, Give, Go On)	Non-explanatory models to describe glowing phenomenon	6	
Evolution-Species	Explanation using family/species relationships	8	
Health-medical	Explanation using health/medical references	11	
Image	Explanation using visual depiction (e.g. double helix for DNA)	11	
Microbiology	Explanation referencing tiny, invisible, or microscopic objects	13	
Story-Narrative	Explanation involving characters, human-like motives, or a fictional plot	24	
Play	Playful moments (Role, Dramatic, Silly) during structured intervention activities (e.g. storytime) or while using CRISPEE	48	*During Nature Observation Center:* Zora: I'm a unicorn! Samantha: It feels smooth. Researcher: Mm-hmm! Oh! So that's a really interesting texture that you noticed! Zora: I'm a goat. Samantha: And can you see these little lines on [crosstalk 00:12:15] Kevin: I am a walrus!
Prior knowledge	References to prior experience (e.g. through children's media, anecdotal experience, picture books) as a way to explain or ask	100	*During CRISPEE play* Caroline: I want to be a scientist when I grow up. Researcher: You do?

Themes (shaded) and Codes	Description	References	Example
	questions related to the intervention		Krista: Me too. Caroline: I saw a commercial about, I saw something on the news about it and so that's why I want to be one.
Teacher Impressions	Feedback from teacher (Katie) who was present during intervention and had prior relationships with many of the campers	151	*During Follow-up Interview with Teacher* Teacher: Yeah the call themselves bioengineers so much. Researcher: Do they really? Teacher: They, Caroline and Samantha do, yeah […] I don't want this to stop though because especially, not to be bringing up feminism but women, they never have as much STEM opportunities as they should, or they're never going to be as competent in it as they should. *During Follow-up Interview with Teacher* Teacher: The biggest thing for me is that we have math groups in class and we have literacy groups. We have no science groups. So this is clearly a spot that me and [another teacher] struggle in because we don't even have groups for it. I don't even know how we would separate them because science isn't something where you can be like, "This kid is ..." well you can but we just haven't even began to start it and I feel like that's not okay. Researcher: Well what would science mean to you? Teacher: Science could mean anything. Technology we don't do anything with. Researcher: Right. Teacher: Like not enough KIBO is, we're starting but it's still not enough. But also even just the nature aspect of it, like the bioluminescence I think that's why we can't do science groups because it's so big.
Age of Students	References to age of campers (e.g. age-appropriateness, age recommendations)	4	
Camp Intervention-Materials	Reference to materials and activities that comprised intervention	38	
Activities-Centers	Center activities offered during intervention	11	
Activity Structure	Level of structure during center activities	5	
Child-Directed	Child-directed nature of activities	2	
Importance-Impact	Importance of designing/curating intervention activities and materials	11	
Light Table	Color-mixing light table offered during intervention	5	
Picture Books	Original and curated children's picture books offered during intervention	7	
Classroom Management	Designing and organizing activities to maximize learning and minimize behavior outbursts	53	
Behavior Management	Specific children's behavior challenges during intervention	14	
Children Social Dynamics	Relationships among children, and impact on intervention activities	6	
Familiarity with Students	Teacher's personal experiences with children, or generally with importance of	19	

Themes (shaded) and Codes	Description	References	Example
	having consistent educator/caregiver during interventions		Researcher: Right, it's pretty big. Teacher: Science is, like you said, an umbrella term it could literally mean anything. But we've got to start somewhere. So even them wearing the lab coats, they loved that. They felt so official and cool with their goggles.
Gender of Students	Experiences of boys vs girls during intervention	4	
Intimidation-Low Interest	Teacher's perspective on chidlren's low performance or engagement during intervention	11	
Learning Domains	Teacher's ideas about learning domains explored during intervention	10	
Transition	Extended transition interactions (longer than a minute or two). Generally unrelated to intervention, but occurring before or after camp activities	24	*Children are getting seated in circle* Henry: Carlos, Carlos sit right here. Yash: That's mine. Carlos: That's mine. Yash: No. That's yours (points to spot on rug)…Carlos is taking my seat! Teacher: This is Carlos' chair. You can have it tomorrow. Okay? Yash: No. That was his. Teacher: We just need to get through these last 15 minutes (pulls on bean-bag chair). If you don't let go, neither of you are getting this, guys. This is ridiculous. No more bean bag. Samantha: [crying] I was saving that seat for someone [talking to Henry]. Could you please move? Henry: [gets up, crying] Carlos: Henry, you can sit in my seat. Teacher: Carlos, that is so nice of you!
Vocabulary	Children using, exploring, or defining new vocabulary introduced during intervention	48	*During Follow-up Interview with Teacher* Teacher: Yeah the call themselves bioengineers so much. Researcher: Do they really?

Appendix H. Transcript Examples from Camp Study

Transcript Conventions.

For all transcripts in which children are using CRISPEE, the following conventions will be used. All-caps colors (e.g. RED) refer to CRISPEE's ON blocks, and lower-case colors (e.g. red) refer to OFF blocks. Platform refers to the area of the CRISPEE prototype where programs are constructed. Slot refers to the specific hole in the platform that contains a block. Slots are labelled 1, 2, 3 from left to right on the platform. All names presented are psuedonyms.

Pre-Interviews

Transcript Examples: Prior Knowledge	Analytic Memo Interpretation
Group 1 Amanda: This is a different video of some zebrafish. Samantha: Once I caught a fish that was...what's your name? Aman-- Amanda: Amanda. Samantha: Amanda and once at summer camp, I remember catching a fish, I think it was about this big. Amanda: Whoa, that's a big fish. Did you ever see any fish like this at camp? [shows glowing zebrafish] Samantha: Wow! All: Wow! Samantha: No I didn't! Amanda: What are these? Samantha: I don't know, they look like some kind of tropical fish.	Samantha recalls a recent experience she had with fish, during a fishing trip at her summer camp The children all express surprise at seeing a bioluminescent fish Despite being surprised by their appearance (suggesting she has never seen GloFish before), Samantha identifies a habitat known for brightly colored animals and fish.
Group 2 Zora: Zebrafish! They start with a Z like me.	Zora connects with a personally meaningful letter in the new animal vocabulary word

Amanda: Why do you think they're called zebrafish, Zora? Zora (?): Because it has stripes for zebras.	She also connects the name of the fish with the visual similarity to another animal she knows about
Group 3 Amanda: Can I tell you something else about these fish? These are also Zebrafish. Henry: What?! Yash: Oh my god... Amanda: Do you think you can look really closely and see the stripes on them? Yash: Yeah, I see some stripes. Amanda: You see little stripes? Yash: Why is there so many? Amanda: There's so, so many, I guess they just like to be with their friends. Kevin: Yeah, I see the stripes Yash: And the bubbles are the most important cause that's the breathing. Henry: That's the oxygen. Amanda: Oh, so we know something else about these fish. So they need oxygen to breathe, and bait to eat. But, how come some of these zebrafish are glowing and some are not? That's so funny. Henry: [Watching video] That's the oxygen	Children express surprise, perhaps at the compound name of the fish. Yash engages in observation of the video and wonders aloud about their schooling behaviors. Kevin joins in on the observation. Yash recites information he must have learned about how fish breathe underwater. Henry offers the science vocabulary word "oxygen" to validate Yash's observation. I recall some of the observations the children have made, and remind them of the prompt about bioluminescence Henry remains focused on the connection of his word "oxygen" to Yash's observation in the video.

Transcript Examples: Mentions of Genes	Analytic Memo Interpretation
Group 1 Melody: And every one of us said something about genes. Amanda: That's right, you all mentioned genes. Do you think it was because of that story that we just read that reminded you of it? Did you guys already know about genes before?	Near the end of the interview, Melody recalls that they had discussed genes earlier. Amanda asks whether the CRISPEE storybook inspired them to consider genes, and asks if they knew about genes before.

Samantha: Yes Amanda: Sort of, maybe? What do you think that genes are again? Samantha: Genes are the building blocks of stuff Melody: They're not jeans. Amanda: They're not our pants, they're building blocks of stuff. Is that everything Carlos, did we Figure out everything about genes? Carlos: No. Amanda: No? What else do genes do? What are they for? Carlos: Genes die at some point. Amanda: They die? They can die?	Samantha answers yes, but it is unclear which question she is answering. Amanda prompts for a definition of genes. Samantha replies with the answer “building blocks of stuff”, similar to the definition offered in the CRISPEE storybook: “the building blocks of living things” Melody affirms again that they are not denim jeans. Carlos, who has not engaged much with the genes conversation, offers his idea that “genes die at some point,” perhaps connecting to the concept that genes are somehow related to living things.
Group 2 *[Amanda has prompted about why some fish are glowing]* Caroline: In my book! It's like, there's a book about it and it's like you and a zebrafish share, uh like, share *this* of your genes. Amanda: Of your genes? What are genes? Caroline: This is like *my* genes, it’s like a “my genes” book. Amanda: What is genes? Caroline: A genes is something that makes you you. Amanda: Where does it go? Where is it? Caroline: Inside your skin. Anywhere!	Caroline is very excited to share about the book she has at home. She emphasizes that “you” (humans) and zebrafish share specific elements of genes. I prompt for elaboration. Caroline explains that the book teaches you about your own genes. She defines genes as “something that makes you you”. She thinks of genes as things “inside your skin”, but then offers a more open-ended answer

Pre-Interview Transcript Examples of References to Genes

Transcript Examples: Concrete/Descriptive Mental Models	Analytic Memo Interpretation
Group 1 Melody: They're tropical zebrafish.	Melody suggests that the glo-fish are a “tropical” kind of zebrafish

Amanda: How did you know they're zebrafish? Melody: Because they have stripes! Amanda: They have the same stripes... Carlos: I already knew that. Melody: They're just different colors cause they're tropical	 She uses observations to explain why the glo-fish are still zebrafish She emphasizes that the zebrafish are all the same, but that glowing fish are a tropical variant
Group 2 Amanda: What's your idea Zora? Zora: Because the water on the other video was not dark. Caroline: Yea Amanda: The water wasn't dark and that's in the other video? Caroline: Yeah. […] Zora: They're [glowing fish] covered in algae.	 Zora suggests that the bioluminescent fish only seem to glow because they are against a darker background Caroline supports this idea, despite her previous idea that it the difference is caused by genes Later, Zora amends her idea to involve glowing algae, suggesting that the fish aren't different at all, but perhaps are costumed
Group 3 Amanda: Okay. So, Yash can you tell me your best idea of why those glowing and striped fishes look so different? Yash: Cause they have different colors, that's all. Amanda: That's the only different, cause they had difference colors. Yash: And the colored ones can glow and the other ones cannot.	 I prompt Yash to describe his idea Yash points out a visual difference between the fish, and concludes that the difference is superficial. He clarifies that the different colors are the cause of the glowing light.

Transcript Examples: Human Analogy and Evolution/Species Mental Models	Analytic Memo Interpretation
Group 1	

Amanda: Why do you think that some of these fish glow and some of them do not? […] Carlos: So first, maybe some of them are nocturnal. And some of them might be genes. And also maybe, some of them have see in the dark Amanda: Wow. […] I heard Carlos say that maybe they can see in the dark because the water is so dark. Maybe their genes somehow make them glow.	Carlos offers multiple suggestions, including a difference in genes (although it is unclear what he thinks genes are), and also listing hypothesized traits of the glo-fish (e.g. nocturnal sleep patterns, night vision). This suggests that he thinks glo-fish are zebrafish that have adapted to a night-time environment.
Group 2 Amanda: So something is different about these fish. Do you think- Zora: Oh I might know another reason. Amanda: What's another reason? Zora: Because if you think of fish like humans. There are many different types of humans, there are girls, there are boys, there are Indians, there are Americans. There are lots and lots of different types of humans, which means that there could be lots and lots of different types of fish, and also zebrafish too. Amanda: That's a good hypothesis! […] Zora: Well [the fish] are the same species, it's just they're different, so there are all of these groups of animals and they are called families, like snails and slugs are in the same family. Amanda: Okay, are fish, do you think the fish might be in the same family? Zora: Yeah, so basically they are all a little different. Like we're all over different from each other.	Zora has already guessed that algae and dark water are the cause for glowing, but she offers a new idea She draws on her prior knowledge of human differences of sex and ethnicity, and extends this diversity to the zebrafish, suggesting her idea that the glo-fish are simply a different type of zebrafish I use a science vocabulary word to validate her idea Zora offers the word “species” to group the fish, then defines the biology vocabulary word “family”, perhaps to offer a sub-categorization to separate the fish I ask a clarifying question about “families” Zora confirms that she thinks zebrafish might be the same species, but they are from different families so they are all different. Again, she likens this to how humans are different from each other

Caroline: Some people don't like look alike. Zora: Except in some cases they are the same, so that could be the reason why they are glowing.	Caroline agrees and takes up the analogy of human diversity Zora clarifies that sometimes people or fish are the same, and concludes that the differences and similarities within a species could account for the glowing
Group 2 Amanda: [repeating a child's words] "The stripes have light." But we saw other zebrafish and we know they don't normally have that. Caroline: Because they're different type. Amanda: They are different types? Caroline: And they have different genes. […] Caroline: They might have different. The genes to the fish is different because the fish have genes and we have genes, so I think the zebrafish that we saw and these other fish got separated from each other because they have different genes. Like we have genes in our skin, but we just can't see them.	Caroline suggests different "types" of fish. I prompt for more information. Caroline responds that the different types have different genes as well. She explains that both types of fish have genes, likening them to human genes. She goes on to day the fish "got separated from each other", perhaps referencing a model of evolutionary selection for different traits. She concludes by reminding me that humans have genes but they are invisible.

Transcript Examples: Genes Mental Model	Analytic Memo Interpretation
Group 1 Samantha: I saw in the first zebrafish video that the scientist did take some of the fish into a second tank. Amanda: So he was moving them from tank to tank? So you think that might have been something that was happening about changing glowing and non glowing? Samantha: I think they took that fish away and put genes in it that made it glow.	Samantha uses observations from the video used in the interview to infer that scientists are working on the glo-fish When prompted, she guesses that the scientists "put genes in" the fish that resulted in bioluminescence.

Group 1 Amanda: Why do you think that some of these fish glow and some of them do not? Samantha: They have different genes! [...] They have different genes than the last zebrafish that didn't glow Melody: But not, not this kind of jean! [Pointing to pants] Amanda: Not this kind of my pants, jeans? These are different jeans. Carlos: Yeah. Amanda: So what kind of genes do you think they need to help them glow? Melody: They need glowing genes. Amanda: They need glowing genes. Do you think there are genes for other stuff in their bodies? Melody: Yeah! Amanda: Yeah, there's other stuff inside them. Samantha: Like what color they are, what colors they glow, how big they are.	Samantha refers to genes, a topic introduced an hour earlier in the CRISPEE storybook. It is unclear from any transcripts whether she was already familiar with the concept. Melody distinguishes genes from jeans, a point taken in the CRISPEE book. I prompt with a questions about kinds of genes needed for bioluminescence. Melody replies with a direct answer: they need glowing genes. Melody agrees there are other kinds of genes. Samantha lists some ideas about what kinds of genes could be inside the zebrafish
Group 3 Amanda: The reason that those zebrafish glow has something to do with that scientist that you saw in that video. There was a scientist who did something. And now those Zebrafish glow. Henry: Oh, it's the same fish but they have like, a kind of genes. Genes. Kevin: Like Bob's friends Amanda: Like Bob's friend, those other glowing fireflies from the story?	Prior to this question, all three boys in this group have offered a concrete-descriptive explanation of bioluminescence. I now introduce the idea of a human agent who initiated the change to see if they will change their ideas. After hearing the reference to a scientist, Henry suggests that the Zebrafish are the same, but they have different “kind of genes”. Kevin takes up this idea and connects with the CRISPEE storybook plot, in which Bob (a firefly character in the story) cannot glow because he has different genes from other fireflies.

Henry: Yeah, I was just about to say that.	
Amanda: They have those same genes?	Henry agrees with Kevin.
Yash: Yeah!	I ask if the glowing fireflies and zebrafish both have the same genes
Amanda: Oh, so you think that scientist did something with genes and now the zebrafish are glowing?	Yash joins in and agrees that they do. I paraphrase their words to make sure I understand.
Henry: Yeah.	
Amanda: Wow, that's an interesting theory.	
Yash: And they have different colors, too.	Henry confirms my interpretation.
Amanda: What exactly do we mean - I'm just confused what you mean when you say genes. What do you mean by those again?	Yash extends the idea of genes controlling for light to genes controlling for colors as well. I prompt for a definition of genes.
Kevin: Like the genes that make you glow or have a different light.	Kevin clarifies that he is talking about “the genes that make you glow or have a different light”. The word “different” suggests he is recalling the many different colors that CRISPEE can create.
Amanda: They help you glow or have a different light. Does that sound like what you guys are thinking about, too? About genes?	I repeat Kevin’s definition to Henry and Yash to clarify any disagreements.
Henry: Yeah.	Henry confirms that he agrees with Kevin.

Post-Interviews

Transcript Examples: Concrete-Descriptive Mental Models about Bioluminescence	Analytic Memo Interpretation
Group 2	
Amanda: Okay, so we know a lot of things about zebrafish. What about these other fish that-	I prompt children to look at the glo-fish video.
Carlos: The itchy fish?	Carlos asks if they are the “itchy fish”
Amanda: Itchy fish?	
Krista: What itchy fish?	Krista and I are both confused
Carlos: The fishes that always that always itches their ear	Carlos attempts to explain what he means
Caroline: The Glo-fish.	Caroline translates that he is asking about glo-fish.

	Carlos' reference to "itchy fish" is actually from an earlier conversation during the camp, when children were looking at glow-in-the-dark books and they discovered that only "itchy", textured pages glow.
Group 3: Amanda: Now I have a question. How come some of these fish are glowing and the other fish are not? Even though they're both zebrafish	
Henry: Because they have more genes.	Henry guesses that Glo-fish have "more genes"
Amanda: They have more genes? Tell me more about that.	
Yash: Because they're closer to the sun.	Yash's idea is that they are "closer to the sun," perhaps absorbing light to "charge" in the same way that glow-in-the-dark toys do
Amanda: They're closer to the sun? [crosstalk] What do you mean by that?	I ask for more information.
Yash: They're like up in the sea near the sun.	Yash clarifies that the glowing fish are higher in the sea and closer to the sun.
Amanda: So they're just closer to more light and that's why they're glowing?	
Henry: No.	Henry disagrees with Yash's model
Amanda: What's your idea, Henry?	
Henry: Because, it's maybe that the zebrafish without the genes were higher they're nearer to the sun, the other fish are lower Amanda: The other fish are lower? Let's take a look.	He seems to amend Yash's idea, saying that the zebrafish without the genes (non-glowing fish?) are higher and the other fish are lower. Henry may be noticing the dark water background of the glo-fish video, and assuming that darker water is deeper (a concept we discussed in the camps)

Transcript Examples: Defining Genes	Analytic Memo Interpretation
Group 1 Amanda: What are genes? Can someone tell me? Samantha: Genes… Amanda: Yeah?	The children used the word "genes" earlier, so I prompt for a definition

Samantha: Genes are something that makes something unique. Amanda: Make something unique? Like a special hair cut? Melody: Yeah, wait! All: No! Samantha: Genes are things that make you have five fingers.	Samantha explains that they make something unique I offer a non-genetically-encoded trait in humans (a haircut) to scope the boundaries of what "genes" means to her All three children agree that genes do not code for haircuts Samantha offers a genetically-encoded trait in humans (number of fingers) to help me understand
Group 1 Amanda: What do you think is different between regular Zebrafish and these glowing ones? [You said] these have genes. What do the genes do? Samantha: The genes make the - Melody: They're not these (jeans) Samantha: - zebrafish glow. Amanda: They're not the pant jeans Melody: They're not these	 The children used the word "genes" earlier, so I prompt for a definition Samantha explains that they are what makes bioluminescence Melody does not offer a definition for "genes", but explains that they are distinct from "jeans"
Group 1: Melody: That's a zebrafish, that's a zebra! That's a zebrafish. That's a zebrafish. Amanda: So, the Glo-fish are also zebrafish? How do you know? Zora: Because, I forget what it's called ... Melody: There's different kinds of zebrafish. Zora: I forget what it's called but... Samantha: Bioluminescence? Zora: No! The part that changes is the genes. Amanda: Oh. Well, what are genes? Zora: Well, genes [crosstalk]	 Melody identifies fish in the video as zebrafish I ask how she knows they are zebrafish Zora has an idea but can't remember the word she is thinking of. Melody reminds me that there are different kinds of zebrafish Zora continues to think about the forgotten word Samantha tries to help by offering a vocabulary word ("bioluminescence") introduced in the camp Zora insists that she isn't thinking of bioluminescence, but instead explains that the "part that changes [perhaps the difference between the two fish?] is genes" I prompt for a definition of genes

Melody: Is it bioengineer? Amanda: Is bioengineer the person you are thinking of, Zora? Zora: I don't know. Melody: I'm pretty sure its bioengineer. Amanda: You're pretty sure that's the one who does gene stuff? Samantha: Yeah. It is.	Melody returns to the Zora's forgotten word, suggesting another camp vocabulary word (bioengineer) Zora isn't sure. Melody has an idea that Zora must be referring to bioengineers. I ask if she's thinking of the person who works with genes Samantha confirms that bioengineers do work with genes.
Group 2 Amanda: Caroline, what was your idea about genes? Caroline: Well, no one else was before me who knows about the genes in this whole basically entire group. I was the first one about the genes because the second I got that book about them, I have the book we have here ... Amanda: Oh, you already have a book about genes at home? Caroline: The second I bought it, I opened up it…the actual gene book, we have. Amanda: So what did you learn from your gene book? Caroline: And I read it at night time. Amanda: Wow! So what did you learn from your studying? […] Caroline: So there's this girl who has a brother and sister but they totally they don't look like her, and they go on all about the genes. She says, "I love genes!" And she's like, "not jeans, genes!" Amanda: What do genes do? What do they, what are they? Caroline: Genes are the instructions of making you.	Caroline is very proud of the fact that genes were a familiar concept to her because of a book she owned at home She enthusiastically relates how she enjoys her book, sometimes "reading it at nighttime". I prompt for information that she has learned from the book. Caroline describes characters from the book, touching on family relationships and the limits of genes (two siblings "totally don't look like" a third sister). She also brings up the distinction between genes and jeans I prompt for more detail about genes Caroline gives the that genes are the instructions of making you. There is only a slight difference definition she gave during pre-interviews, which is the addition of the word "instructions"

Transcript Examples: Change Genes Mental Model	Analytic Memo Interpretation
Group 1	
Amanda: What's the difference between Glo-fish and zebrafish?	I prompt for the difference between Glo-fish and normal zebrafish
Samantha: The Glo-fish, some of the Glo-fish -	
Zora: They changed the genes!	Zora responds that "they changed the genes," although she does not specify who "they" is
Amanda: They changed the genes that they--?	
Samantha: - some of the Glo-fish are zebrafish but their genes are changed so that they don't seem like it.	Samantha answers that some of the glo-fish are actually zebrafish, but their genes have been artificially changed so they appear different from normal zebrafish. Samantha clearly sees that although they "don't seem like it" Glo-fish and zebrafish as the same "type" of animal, rather than two related sub-species.
Group 2	
Caroline: Genes are the instructions of making you.	Caroline offers a definition for genes: the instructions of making you.
Amanda: Oh. So what does that have to do with our glowing fish here? What do the glowing fish and the zebrafish have to do with genes?	I prompt to relate this definition back to the question of bioluminescence.
Caroline: Because the scientist who cau-, whoever caught the gene, the fishies. Some scientists I feel like went inside of them and got their genes and did stuff and put like different things on it and like they put some like thing on them and that's how they began to light up like that.	Caroline's idea is that someone caught the fish and their genes with it. Then scientists went inside of the fish, took their genes, and somehow added to the genetic instructions, resulting in bioluminescent fish.
Amanda: That's awesome. So maybe they went in and put different genes in and that's how they light up?	I paraphrase her answer, asking if the scientists added different genes to the fish.
Caroline: No. They took out some of the genes from in the fish and then	

made them into like another type of gene. Amanda: They took out the fish's genes and changed them somehow? Caroline: Yeah, to make all these fish light up.	Caroline corrects me, saying the scientists used the *original* genes from the fish, but altered them somehow. I paraphrase again, asking if the scientists removed the fish genes and changed them somehow. Caroline agrees, and concludes that the changed chenges made the fish glow.
Group 2 Amanda: Glo-fish? What are Glo-fish? Carlos: Zebrafish. Amanda: They're also zebrafish? How do you know that? Caroline: Why are they glowing? Amanda: Hmm. If they're also zebrafish, then why are these glowing? Carlos: Because there's genes Caroline: Because they have stripes. Amanda: They have stripes? So that's like a zebrafish then. Krista: They made them. […] They made them glow. Amanda: Who's they? Krista: The people who got them. Amanda: The people who got them made them glow? How did they do it? Krista: They put, new stripes, new stuff in them. Amanda: They put stuff in them? Inside of their mouths? Caroline: No, no. […] Carlos: Maybe it was about the genes, that's how maybe they glow Amanda: What do you mean by genes? What are genes?	 I ask what the Glo-fish are. Carlos answers that they are zebrafish. I ask how he knows that. Caroline asks why the Glo-fish are glowing. I paraphase and ask how Glo-fish can be zebrafish, a fish we know does not glow. Carlos answers my question about glowing, saying "there are genes". Caroline answers my question about how we know they are zebrafish, pointing out their characteristic stripes. I paraphrase Caroline's answer about zebrafish having stripes Krista offers an explanation for my questin about glowing, saying "they made them". Krista explains that "they" are the people who found the fish. She goes on to say "they put new stripes in them", perhaps suggesting that they added glowing stripes to the fish. I probe for more information about where the "new stuff" was put, offering a concrete answer (in their mouths) Caroline says no, that's not where the new stuff was put. Carlos suggests that the "new stuff" was genes that caused the fish to glow. I prompt for information about genes.

Carlos: Genes are the things that make you you. Amanda: Oh. And where do you find them? Carlos: In your body. Amanda: Oh. Is that what you mean, Krista? Or were you talking about something else? Krista: Yea I was talking about that	Carlos explains that genes make you you. He further explains that you can find them inside your body. Krista agrees that she was thinking of the same thing Carlos is talking about.

Transcript Examples: Designing with CRISPEE	Analytic Memo Interpretation
Group 1	
Samantha: We're making nothing.	Group 1 builds a program of all X blocks, and Samantha points out that this will make "nothing", or no light
Melody: We're making nothing. CRISPEE's gonna be so confused.	Melody agrees, and suggests that "CRISPEE will be confused", a term the children used interchangeably to mean a technological malfunction or a non-functional program. In fact, this program was functional, so Melody might actually not understand the block functions, or (given her success rate when building with CRISPEE) she might be saying that using CRISPEE to create an Off light may as well be a malfunction.
Amanda: Uh oh. Wanna push it in again little harder?	I offer a debugging strategy for a true malfunction (blocks disconnected from prototype).
Melody: CRISPEE could be confused.	Melody repeats that X-block program will "confuse" CRISPEE
Melody: That is a lot.	
Amanda: Okay. Let's see. Samantha: Let's see what happens Melody: I'm supposed to press the buttons	CRISPEE reads the block programs, so I suggest that we follow-through on the test.
Amanda: Oops! We'll have to switch again next time. It worked. Who do you think has this color no glow gene?	The program works, and produces an Off light. I prompt the girls to see if they remember a character from the CRISPEE book who has the Off light program.
Samantha: CRISPEE.	Samantha misinterprets my question and explains that CRISPEE currently "has" that program.

Amanda: CRISPEE has it? Do you think that any real fish should have these no glow genes. Samantha: No glow genes are Zoe's. Amanda: Zoe? Does she already have these irregular ones that don't glow? Samantha: She has the regular ones that don't glow right now but, you can program her to- But we can program her genes to make her glow.	I change my question, and ask if there are any real fish that might have that have an Off light gene program. Samantha says that “no-glow genes” belong to Zoe the Zebrafish, the faceplate character that is currently displayed on the CRISPEE prototype, with a non-glowing light. I request more information about Zoe, and term the non-glowing genes “irregular”, slipping into Melody’s mindset that Off gene programs are not typical for CRISPEE Samantha flips my phrasing and calls the Off genes “regular”. She tells me that Zoe has regular Off genes currently, but that “we can program her genes to make her glow”. Samantha clearly holds a model of genes as a programmable language to control for an animal’s bioluminescence. Further she’s identified that zebrafish normally do not glow, but we can make them glow by programming their genes.
Group 2 Carlos: I think, I don't know. Maybe they used CRISPEE. Amanda: Maybe they used CRISPEE? What does CRISPEE do? Carlos: CRISPEE makes things light up? Amanda: Makes things light up!	During a conversation about bioengineers, Carlos suggests that an unidentified “they” used CRISPEE to make Glo-fish He guesses that CRISPEE “makes things light up”, offering a very concrete description of the tool. From his description, it seems that he is connecting CRISPEE broadly to any design process that involves making something glow.
Group 3 Kevin: Or, maybe Pam changed them. Amanda: Maybe Pam changed them? How would Pam have changed them? Kevin: Like they put them into CRISPEE	During a conversation about bioluminescence, Kevin suggests that Pam (a character from the CRISPEE storybook) is responsible for changing normal zebrafish to Glo-fish. I ask how Pam would have done that.

Amanda: Oh! And what would that change? Henry: Their color! Amanda: Their color? How? Is, does the CRISPEE paint things? Kevin: No. Amanda: No? What does it do? Kevin: Um, you make different colors. Yash: How does it make orange? Amanda: How does it make orange? Yash: Maybe, green, red, and blue? Amanda: Oh, are you thinking of the blocks in CRISPEE that would make orange? Henry: Yeah, it also makes yellow!	Kevin responds that Pam might have put them (the fish) into CRISPEE. He is showing a very literal understanding of gene editing using the CRISPEE kit. I prompt to find out what Pam can change with CRISPEE. Henry suggests that CRISPEE can change the fish's color I ask how CRISPEE changes color, asking if it is related to a superficial change like paint. Kevin is sure that using CRISPEE is different from painting an animal. However, when prompted, he has no explanatory mechanism and repeats that CRISPEE makes different colors . Yash asks how to make a specific color (orange) that is not available in CRISPEE, and then thinks aloud about which colors can mix to create an orange light. I prompt to see if he is thinking specifically about the CRISPEE blocks. Henry affirms that he was thinking of the CRISPEE blocks, and lists a color that he knows CRISPEE can make. All three boys seem to be thinking of concepts introduced in the CRISPEE storybook as non-fictional, including characters (Pam) and the machines used by bioengineers CRISPEE) to create bioluminescence. Although they don't say it directly, they seem to agree that Glo-fish are zebrafish whose colors have been altered, rather than a separate type of fish.

Transcript Examples: Ethical Design	Analytic Memo Interpretation
Group 1 Zora: I thought of this thing just when I woke up about genes, and I wanted to talk to you about it. Amanda: Ooh. What is it?	

Zora: Wouldn't it be nice if could just take aloe plants and take its genes then put them to lotion.	Earlier transcripts reveal that Zora has an aloe plant in her home, so perhaps aloe lotion is something she already knows about.
Amanda: Wow! What would that do? What would that give us?	I prompt to find out what genes will add to her design
Zora: It would be nice to get people to not, because maybe people just don't want take from aloe plant. So, maybe they just want to buy a bottle lotion. So, and my aloe plant.	She seems to know that you can break the leaves off aloe plants to extract the juice. Her design seems to be intended to help aloe plants from losing juice/leaves.
Amanda: What's an aloe plant?	
Zora: It's a plant that's very prickly on the outside, from the inside it has acid, which can heal you if have a bruise in it or gives you a scab, and then it will give you the healing power.	Zora has very detailed knowledge about aloe plant applications. Her idea of "healing power" reminds me of research on children's conceptions of life as an energy or force (e.g. Hatano & Inagaki, 1994).
Amanda: Whoa so you think that if we took the genes from the aloe plant and put them inside a lotion we could put that lotion on us?	
Melody: So, what's the consequences of that?	Melody spontaneously recalls conversations from the camp in which we ask about consequences to help us think of ethical reasons for our designs.
Amanda: Hmm. What's the consequences?	
Samantha: That you can take them from all the aloe plants in the world and there would be no aloe plants left with those genes.	Samantha offers a negative consequence, that aloe plants need their genes.
Amanda: Uh oh. So we can't take all the genes cus then aloe plants need some of them.	
Zora: Yea we can't take all of the genes	
Amanda: That's a good consequence. [crosstalk]	
Melody: Not these (jeans)	Melody clarifies that we are speaking of the vocabulary word "genes".
Zora: Except I would say, we would take a couple humongous aloe plants and then use those. Then they'll be a bunch of little aloe plants left. Or, or, another thing to do would be to plant new aloe plants.	Zora offers a counter-proposal to address Samantha's negative consequence. Her idea is to only take genes from large aloe plants, leaving smaller or new ones in their place.
Group 1	

Zora: Blue. Blue of course. Now let's try to make it purple. Amanda: Before we change it, can I ask you a question? Do you think there is a positive consequence to making Zora the Zebrafish bright blue if all her friends are not glowing?	While working with CRISPEE, Zora lists a design goal of making purple Since the girls had already brought up the idea of consequences, I prompt about consequences to a design they are currently working on
Samantha: That they may laugh at her.	Samantha's names a social consequence that seems rooted in a fictional story context, similar to the CRISPEE storybook
Amanda: That's a positive consequence? A good thing to happen?	I prompt to determine if her consequence is positive or negative
Samantha: That they love how she looks.	She offers a positive social consequence, anthropomorphizing the fish.
Amanda: They like how she looks so maybe they'll swim to her all the time? What's a bad thing that can happen?	I prompt for a negative consequence Zora reiterates her design goal
Zora: Try to make it purple. [crosstalk] Samantha: That predators may see her. Amanda: More predators might see her.	This time, Samantha changes from a fictional story context to an ecosystem-habitat one. Perhaps she thinks this more formal science response will appease me and allow her to focus on playing with CRISPEE.

During Camp Transcript Examples:

Sequencing

Transcript 1: Yash's CRISPEE Plan	Analytic Memo Interpretation
Yash: [places On blocks in CRISPEE in this sequence: GREEN-BLUE-RED]	Here Yash uses his actions to indicate a plan for his first program
And then we're going it the opposite way.	
[on table, makes sequence with Off blocks: red-blue-green]	Yash's second program represents a reversed version of the first program. By "opposite", it seems Yash was referring to "opposite sequence"
But we keep blue in the same.	He is clarifying his choice to leave blue in the same location in both sequences

[Picks up red-blue-green sequence and places them on top GREEN-BLUE-RED program that's already in CRISPEE] Like this. Like this.	Yash physically overlays the two programs to clarify how they are similar, but the sequence is reversed.

Transcript 2: Zora's CRISPEE Center Debugging	Analytic Memo Interpretation
Zora: [Inserts green-BLUE-red blocks into CRISPEE. She pushes the Test button and sees red lights under slots 1 and 3.] [Zora switches blocks 1 and 3, new program reads red-BLUE-green. She pushes the Test button. Now the red light is under slot 2.] [Zora switches blocks 1 and 2, new program reads BLUE-red-green. She tests program, again a red light under slot 2.] [She switches blocks 2 and 3, new program reads BLUE-green-red. She tests the program and this time there are all green feedback lights. She shakes the platform and pushes the Check Light button to reveal a blue shining light on her firefly.]	There must be some kind of faulty connection in CRISPEE, this is a functional program. Instead of changing her program and adding or removing blocks, Zora debugs her program by changing the sequence of the blocks.

Figure #. Transcript 2, Zora's CRISPEE Center Debugging

Design Process

Transcript Example: Samantha's Cyan Light	Analytic Memo Interpretation
During Circle Time Amanda: Do you guys think we can look at the story of Bob the firefly and	

think about, what's the problem in this story? Kevin: That Bob doesn't have a light! Amanda: Bob doesn't have a light, and what's a consequence of Bob not having a light? Kevin: He can't find his friends Amanda: That's right, something that happened because Bob doesn't have a light is that he can't find his friends. So that's one possible consequence of his problem. So when he met Pam, they thought about a plan, the best way to solve his problem. What was Pam's solution? […] Samantha: She created a gene program and so it would make him, this beautiful cyan light and cyan is a special blue that only appears in light *[about 1 hour later]* *During CRISPEE Center time* Samantha: When I- Last time I saw it [CRISPEE] doing it [shining], it was Cyan [touches CRISPEE light]. The first time I saw it doing this it was Cyan. [Timer sounds] Samantha: [Places BLUE and GREEN in slots 2 and 3 (_-BLUE-GREEN) and puts hands in the air] Katie (Teacher): We're going to clean up and go to the rug, please. Samantha: [Frowning] But I just want to do one more CRISPEE! [Adds red to slot 1. Program reads red-BLUE-GREEN. Presses button 1, all green lights. Presses button 2, shakes platform] Melody: [Runs up next to Samantha, looks at CRISPEE]	During a circle conversation, I prompt the children to consider the plot of the CRISPEE storybook As part of this conversation, I also prompt children to consider the problem that the story characters face, and the solution that they design to solve this problem. Samantha remembers key plot points I referred to, and volunteers another piece of information from the story: Bob chose to make his light cyan, a blue color made by mixing light waves. Clearly this color left an impression on her, and she recalls it as a key plot point from the story Samantha again references the cyan light from the CRISPEE storybook. Samantha builds part of her CRISPEE program, then puts hands in the air to listen to the teacher's announcement Katie, the school's teacher, calls children to the carpet Samantha does not want to transition away from CRISPEE until she has finished coding her cyan light.

Samantha: I want to see it make Cyan. [presses green button, and the light turns cyan] Both: Cyan!! [Both girls cheer and dance]	Melody comes to check on Samantha and her CRISPEE design. Samantha explains her goal – to make a cyan light – and finishes her test. Both girls are delighted to see Samantha's successful cyan light design.

Figure #. Transcript Example, Samantha's Cyan Light

Transcript Example: Design a Biosensor Game	Analytic Memo Interpretation
During Circle Time	
Amanda: I have a question for you, my friends. We're going to pretend [there] is a toxin in the forest. To the animals in the forest, it's invisible. They don't know how to find it. They don't know where to go to look for it. They don't even have a machine to help them find it. So, what can we do?	I present the design challenge of an invisible toxin in a forest that is harming the animals.
Melody: Let's bring it to them.	Melody suggests simply moving the toxin.
Amanda: Bring it to them? But remember it's toxic. They want to get away from it.	
Carlos: We could use a dispenser that makes stuff that gets rid of it.	Carlos suggests a machine that dispenses some toxin-neutralizing agent.
Amanda: Something that dispenses, or puts out something, that gets rid of it? […]	
Amanda: Do you guys remember in the story we read about a jellyfish that works like an alarm system?	After some conversation, I remind the children of a natural biosensor animal they learned about in one of the storybooks offered in the camp.
Samantha: The Atolla jellyfish. Amanda: The Atolla jellyfish. What does it do? Samantha: It has this light, and when it's attacked, it lights up in hope that something that's the predator of its predator will come and eat the predator. Amanda: So, it uses lights to communicate that there's something scary	Samantha remembers and describes the animal I'm thinking of.

happening. What about, there was another fish we learned about that changed color when water was warm or cold? […] Melody: I think that maybe Angie [the anglerfish] can help. Amanda: You think Angie can help us find the toxin? Melody: Because, what if there's a stream of water for under the ground? Amanda: So, she can swim in the water! […] Caroline: Bob is actually flyable. And if there's a river, when he's flying, he just has to keep on flying. Amanda: He's "flyable," so he can fly and he just needs to keep flying. [crosstalk] Can you guys help me put Bob [the firefly faceplate] onto the CRISPEE? Caroline: Yeah. Samantha: Maybe he should glow aquamarine when he senses the toxins. Amanda: What do you guys think about that idea? Should we have him glow, what was that? Aquamarine. Melody: I can make it.	I paraphrase her explanation, then prompt again to remind them of different biosensing animals they've learned about. After some discussion, Melody suggests using CRISPEE's anglerfish character She justifies her idea by saying the toxin might come from an underground water source. Caroline suggests using Bob the firefly instead, arguing that he can fly so he can detect airborne toxins and can fly over water as well. The children agree to use a firefly, so we begin to program a firefly on the CRISPEE Samantha suggests a light color (her favorite, cyan or aquamarine) to be the indicator for sensing the toxins. Melody begins to program this color into CRISPEE.

Figure #. Transcript Example, Design a Biosensor Game

Hardware/Software & Debugging

Transcript Example: Debugging with an Engineer	Analytic Memo Interpretation
Caroline: One. We pressed the one. Press two, shake and nothing happens! Clarissa: That's so weird, huh? Caroline: It used to [inaudible]. Clarissa: Hmm. Alright, let's ...	Caroline has identified a malfunction in CRISPEE. She remembers what it should do when working properly.

Caroline:	That's funny.	
Carlos:	It never did that.	Carlos affirms the malfunction.
Clarissa:	I'm gonna try turning it off and turning it on again. […]	Clarissa narrates her debugging process.
Amanda:	Did that work? […]	
Carlos:	No.	As she runs tests, the children watch and offer helpful observations.
Clarissa:	Oh, I see. I see what's wrong.	Clarissa identifies the problem.
Carlos:	What? What's wrong?	Carlos wants to know what she sees.
Amanda:	Want to go see what Clarissa's gonna fix?	I invite the children to look inside the back of the CRISPEE, where Clarissa is working
Carlos:	What's wrong?	
Clarissa:	So, do you see this wire is loose? […]	Clarissa explains the issue and begins fixing it while the children watch.
Caroline:	I'm sorry CRISPEE. I know you're hurt. […] I can tell how all the other lights come on. See?	Caroline notices the interior light fixtures in CRISPEE.
Clarissa:	Yeah.	Krista looks and notices the wires.
Krista:	The wires over there.	Carlos shakes the CRISPEE platform and invites everyone to watch the action from the back of CRISPEE.
Carlos:	No guys watch, watch back here. Look. See what happens?	
Caroline:	What are you doing?	Krista and Caroline are excited to see the wires shaking.
Krista:	Whoa!	
Caroline:	Wow! He's shaking the wires!	Caroline begins trying other interactions to see how they look from behind. She is enthusiastic about this new way to play with CRISPEE.
Caroline:	Hey! When you press number button, number one this little contraction goes down. We're finding many cool stuff in CRISPEE.	
Clarissa:	Isn't it cool there?	
Carlos:	How do you turn it back on?	Carlos asks specific questions about the CRISPEE hardware.
Clarissa:	I have to put all those wires in one by one.	
Caroline:	So you made CRISPEE?	Caroline wants to know if Clarissa made CRISPEE.
Clarissa:	I made CRISPEE, yeah.	
Carlos:	You invented it?	
Clarissa:	Yeah I did.	Carlos asks twice to confirm that Clarissa is the “actual” inventor of CRISPEE.
Carlos:	You actually did?	
Clarissa:	Okay, let's see ...	
Amanda:	Yeah she actually did.	The children continue to watch and narrate while Clarissa repairs the CRISPEE.
Clarissa:	... so this says ...should be	
Caroline:	Wow. which one?	
Clarissa:	Well, we're gonna see.	
Amanda:	She looks like she's working really hard to concentrate.	

Caroline: Let's watch.	

Sensemaking

Transcript Example: Kevin's Storybook Questions	Analytic Memo Interpretation
Amanda: [Holds up CRISPEE storybook] Kevin: Is he real? [pointing to Bob the Firefly on the cover of the book] Yash: Yeah he's real, he's real. Kevin: So there's a real firefly outside? Amanda: Do you think there's a real firefly outside? Maybe we can read the story and decide. *Bob's favorite part about the forest is getting to fly around with his friends. But Bob's friends look a little different from him. Even they're all fireflies.*	Kevin is interested in how factual the information in the storybook is. Yash seems sure the firefly is real. Kevin probes for more information I introduce the main character of the CRISPEE book, Bob, a firefly who does not look similar to his glowing friends.
Children: [crosstalk] Amanda: Yeah they have purple [light]. You already noticed they kind of have purple. […] Does anyone have a guess why they look different?	The children notice the differences between Bob (whose body is shaded grey to indicate he does not glow) and his friends, who glow with a magenta light. I ask for ideas about why the fireflies look different. This question is similar to the pre/post interview task.
Caroline: Because Bob is different? Henry: Because they're a different type of firefly	Caroline suggests that Bob is simply different. Henry offers the "different types" hypothesis, signaling he may hold an Evolution-Species mental model about Bob and his friends.
Amanda: Maybe they're a different type of firefly where he's kind of grey and they're purple. There's a page here that sort of talks about why. *They look different because their genes are different from Bob's.* Do you think they mean these? [points to jean pants] Many children: No!	I introduce the vocabulary word "genes" and compare to the homophone, "jeans" Some children seem sure that jeans are not genes Caroline recalls a book about genes that she owns at home

Caroline: I know what a gene is I have a book about it! Amanda: What's a gene? Carlos: It's a thing in you like in your head	I prompt for a definition. Carlos suggests it's a "thing in you, like in your head". Could he be thinking of thoughts?
Kevin: It helps you grow when grow when you're not supposed to	Kevin thinks genes "help you grow when you're not supposed to." This makes me wonder if he has experience with human growth hormone therapy.
Amanda: It helps you grow. Is that what you think a gene is too?	
Yash: Like the thing in your head!	Yash reiterates Carlos' idea, that genes are "like the thing in your head"
Amanda: Something in your head, something inside of you. What else do we know about genes?	I repeat some of the answers and prompt for more.
Melody: I have no idea	Melody admits she has no idea.
Amanda: You've never heard of a gene? That's okay because we're going to talk about them a little bit now	
Yash: [pointing all around] This is a gene, that's a gene	Yash has made a game of naming things "gene"
Amanda Oh are you ready to hear? I think you guys have a lot of good ideas about genes because listen to this: *Genes are the building blocks of all living things-*	I introduce a definition from the storybook: Genes are building blocks of living things.
Caroline: Yeah!	Caroline emphatically agrees. Perhaps this is similar to the definition from her book at home.
Amanda: *-and they contain many instructions.*	The definition also mentions "instructions"
Henry: [pointing to book] That's a gene! That's a gene!	Henry points to the image of a double-helix in the storybook and is certain he recognizes the image of a gene.
Amanda: You think this is a gene, a picture of a gene right here? [Holds up book, displaying picture of double-helix]	
Kevin: You know at the doctor's when they open, um, when they give you open heart surgery? They open your body and see your genes.	Kevin shares an idea that surgeons can "open your body and see your genes". The children consistently agree that genes are something inside living bodies.
Amanda: You can see genes then when you're looking inside your body?	

Kevin: But you obviously they do it when you're sleeping. Amanda Oh, because it would hurt a lot if you weren't sleeping. I think that makes sense. So we also heard that genes contain many instructions. I wonder what these instructions are all about? Kevin: Because they have a knife and they cut you open by heart	He clarifies a practical point – surgery only happens when you're sleeping.
Amanda: *There are genes for the color of your eyes*	I list some traits that genes encode for
Melody: Oh!	Melody seems surprised by the fact that genes control the color of your eyes
Amanda: *For the length of a dog's fur, and for all sorts of other traits.* All sorts of other things that make us unique.	
Kevin: Did you write this story? Amanda: Should I tell you at the end who wrote it? You can take a guess.	Kevin is now curious about the book itself as a source of information
Kevin: You Yash: You	He and Yash are both convinced that I wrote the story.
Amanda: *Many genes together make a program to build our bodies.* What's a program?	I liken gene instructions to a program that builds living bodies. I then prompt for a definition of a program.
Henry The ABC song! [crosstalk]	Henry suggests the ABC song. He may be focusing on the sequencing aspect of programs, since the alphabet must follow a specific order
Caroline We're in a program!	Caroline offers another definition of program, a structured set of activities, such as a camp.
Yash Something like… like KIBO and you put the blocks down and then you scan them [and KIBO's] like okay! I'll do it	Yash recalls the KIBO robot he uses in his classroom, and describes how to build and upload a program for KIBO.

Transcript Example: Yash's Virus Story	Analytic Memo Interpretation
Amanda: [reading from book] "If they [bacteria] find something that's yummy that they'd like to eat for lunch, the multiply so quickly – "	

Yash: Yeah they multiply in the cells! Amanda: What's multiply, Yusuf? Yusuf: I'm just telling you something about how they multiple. Amanda: Oh how do they multiply? Amanda: Oh, how do they multiply? Yash: They go on top of the cell and then they tell the brain that sense a message to the brain to make more viruses and then after that it makes more viruses and then when it's full it bursts out. And that's how it happens. Amanda: Whoa, so it goes onto the brain then the virus tells the cell to make many more of itself and then it bursts? Yash: No and then after it holds so much that it bursts. And then one of them just goes to another cell and multiply and then multiply. Amanda: That sounds to me a lot like a virus, is that what you learned about? Virus? Kevin: Yeah it is. […] Zora: So let's say you had pink eye and you take as much medicine as you need to so it was all gone but then you still need to finish the dosage off even though it was all gone. Amanda: You still need to finish it even though it's all gone? Zora: Yeah and then all of the sudden there's just one tiny one left and it multiplies and it multiplies.	Yash is very excited about multiply, and introduces the word "cell" He offers quite a thick description of how a virus spreads at a microbial level He's very certain and specific about this model he has in his head of how viruses multiply Kevin either recognizes the description, or recalls that Yash used the word "virus" earlier Zora brings up what seems like a personal experience with pink eye and finishing the medicine I think here she is connecting the idea of "finishing medicine" to stopping the spread of disease. When she says "one tiny one", does she mean one cell? One virus? One unit of pink eye?

Debugging

Transcript Example:	Analytic Memo Interpretation
At CRISPEE Center	

Samantha: [00:55] [Samantha builds Program 2: r-B-r slowly, from left to right] Melody: It'll be confused, it won't work, because CRISPEE's gonna be confused Samantha: [Pushes buttons 1, 2, and 3, (red feedback light under slot 1) then shakes platform, tries to push blocks down] Melody: [reaches over Samantha and mashes button 1 again] Annie (T): [Pushes down block 3, pushes button 1 again] Melody: Samantha- [pushes down blocks 1 and 2] Samantha it's confused Samantha: [pushes down on blocks 2 and 3 with both hands] Melody: [emphatically] It's con-*fused*! Samantha: How do I make it not confused? [Before Melody can respond, removes r from slot 1] Oh its confused, no wonder it's confused [giggles, begins to place b in slot 1. Program would read, b-B-r] Annie (T): Why is it confused? Melody and Samantha: Because it has 2 reds! [Zora, Henry, and Yash, working quietly at the same table, all stand up to watch Samantha work on CRISPEE] Samantha: [Removes b from slot 1] Uh this will make it confused. [Puts g in slot one, makes Program 3: r-B-g, presses buttons 1, 2, and 3 in a row. Feedback lights are green.] Yash: [off-screen] No, that won't make it confused. Annie (T): Think this'll fix the problem? Melody: Yeah!	Samantha attempts to build her first program. Melody explains that the program will be nonfunctional because "It'll be confused" Samantha tests the program anyway. It is non-functional Melody assists her second test. Annie (a research assistant) assists a third test. Again it is non-functional. Melody tries again to explain that "it's confused" Samantha attempts to troubleshoot by pushing blocks in more firmly Melody insists that CRISPEE is confused. Samantha asks how to repair her program, but on her own discovers the source of CRISPEE's error. Annie asks Samantha what she discovered Although no one has explained this rule, Melody and Samantha answer in unison that CRISPEE cannot have 2 blocks of the same color Other children at the table become curious about Samantha's program. Samantha builds a new program that meets her new rule: CRISPEE cannot have 2 blocks of the same color. Yash says approvingly that this new program will not make CRISPEE confused Annie asks Melody what she thinks. Melody agrees that Samantha's new program should be functional.

Ethical Design

Transcript 5: Henry's Cheetah Design	Analytic Memo Interpretation
Yash: [chewing] What are you writing, Henry?	
Henry: [hunched over his worksheet, frowning] I'm trying to think what I should say.	Henry's face and posture indicate that he is thinking really hard about this problem.
Yash: [looking at Henry's design journal] You're trying to kill him?	Yash is confused about Henry's design.
Henry: Yeah	
Yash: But he's too fast?	
Henry: Yeah, why cheetahs are getting killed. Yash: Oh! Yeah, yeah!	Henry explains that he is concerned about cheetahs getting killed, and Yash seems to understand his design in a new way.
Henry: So that's why they need more genes to run away	Henry explains that his design is about protecting cheetahs by enhancing their speed with "more genes to run away"
Yash: You're right, you're right. Katie: [walking over to snack table, she touches Henry's worksheet] This looks so good!	Yash and Katie affirm Henry's work.
Henry: Look at all these bullets [draws something on his worksheet] Katie: I want to cry because it's so good. Why are cheetahs your favorite? Henry: Because they're so fast and I like things that are fast.	Henry may be adding these to emphasize how fast his design will make cheetahs, or to show how they are being hunted?
Yash: They're really endangered, that's why they need [incoherent] Katie: Yeah, they are really endangered	Yash volunteers a new piece of information, that cheetahs are "endangered"
Caroline: [looks up from a different snack table] Well how are they really endangered? Yash: Because people are trying to kill them! Henry: Yeah	Their conversation sparks curiosity from other children. Caroline seeks more information about "endangered"

Transcript 5: Melody’s Turtle Design	Analytic Memo Interpretation
Naomi (Teacher): What’s the animal that you made?	Naomi asks Melody to explain her problem.
Melody: Turtle, wait the one that helps itself with the problem of turtles? Naomi (T): Either one, tell me about it all.	Melody seems to have two problems in mind, so Naomi requests information about whatever she chooses to share.
Melody: So I’m going to solve the problem of turtles with fox.	Melody explains that she’ll use “fox” to “solve the problem of turtles”
Naomi (T): So you used a fox to help turtles? How?	
Melody: I give the genes of the fox’s sniff smell into the turtle.	She wants to give turtles the fox’s ability to smell.
Naomi (T): Really? Why does the turtle need to smell?	Naomi tries to understand why a turtle needs to smell
Melody: ’Cause. Naomi (T): How does that help it?	
Melody: ’Cause it can smell jellyfish.	Melody explains that with the fox’s sense of smell, the turtle can smell jellyfish. Earlier in the activity, she explained to the whole group that turtles confuse plastic bags with jellyfish.
Naomi (T): Oh [incoherent] so they can smell it’s a jellyfish instead of a plastic bag? Oh, that sounds like a really good solution, I bet that would save a lot of turtles	Naomi now understands her idea and validates its ethical merit by saying, “I bet that would save a lot of turtles”.

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