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# Computational Practice and Perspectives in the Arts

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# Abstract

Art has been tied to scientific and technological advancements throughout history, providing methods and mediums for communication, expression, and exploration. Art is a dialogic domain that evolves with the technological advances in society–incorporating technology and computational tools to create new genres of art. We live in an increasingly computational and technological society, which is reflected in the emergence of many new tech-based and computational genres of art. Computers and computation have dramatically changed how and what artists can create and what ideas can be explored. Yet is naïve to assume that this is a one-way relationship that computing has changed the arts. In fact, since the advent computation, artists have been leveraging, critiquing, extending, and creating, computational tools as part of their artistic practice. The relationship between the artist and computer is important to people in both the arts and sciences, as well as to society as a whole.

Our increasingly computational world necessitates greater computational literacy. Not only are computers being used in everyday contexts, but the practices in myriad domains are transformed as they incorporate new computational tools and methods. As such, there has been an increased push for computing education and while these efforts have received support from funders and educators, major questions remain unanswered regarding how best to facilitate computing education for all–or for that matter, what computing education should entail. This dissertation seeks to contribute towards these efforts expanding computing for all by pushing on our understanding and exploration of the concept of computational thinking (CT). As we move toward providing all students with opportunities and experiences in computing, it is vital to reflect on how we are representing computational ways of thinking and knowing, in additional to computational practices. Are we, as a field, privileging computing education that is designed to

fill future jobs, or are we representing the diverse ways that computing can be leveraged in real world contexts?

In parallel with other constructionist scholars exploring the intersection of CT and Science, Technology, Engineering and Mathematical disciplines (STEM), this work constructs a situated definition of CT in the arts in order to broaden access to computational and artistic practice as well as to increase the perspectives and epistemologies represented in computing education. We are at a beautiful time in history where computation is relatively young and evolving at a rapid pace. Artists are in the process of incorporating these computational tools, negotiating what computation should mean for society, and sparking new pathways for computational progress. In order to capture these practices, this work leverages methodological approaches of others who have constructed situated definitions of CT in STEM through interviews with practicing computational scientists and mathematicians–exploring the computational art experiences of artists in order to capture their unique perspectives.

This dissertation leverages qualitative methodology, particularly in-depth case studies, to develop an understanding of the computational practices and perspectives of artists. A new theory and associated methodology, called *computational art ecologies,* is explicated and applied to analyze the ten distinct cases and then used to systematically characterize artists' practice within the rich landscape of computational and technology-based art. These cases highlight unique practices, perspectives, experiences, and relationships between computation and art. They also highlight the rigorous computational practices and epistemologies that emerge in computational art. Finally, the practices and perspectives identified through these cases are consolidated to develop an emergent Framework of Computational Engagement and Perspectives in the Arts. This framework advances scholarship around computational thinking, particularly that of constructionist scholars who have worked to develop situated definitions of computational thinking across contexts and domains. This new theory and associated methodology are introduced to allow for a systematic approach to capturing these diverse artistic experiences with computation. Additionally, we contribute to efforts in computing education to identify situated computational thinking and to expand definitions of computing education to reflect the diversity of computational practice in the world.

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# Dedication

“The tree was a tree
with happy leaves,
and I was myself,
and there were stars in the sky
that were also themselves
at the moment
at which moment
my right hand
was holding my left hand
which was holding the tree
which was filled with stars
and the soft rain –
imagine! imagine!
the long and wondrous journeys
still to be ours.”

-Mary Oliver (2003)

This dissertation is for my mother, Patricia Anton. I would not be who or where I am without your curiosity, joy, compassion, and your dedication to teaching and education.

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# Chapter 1: Introduction

I grew up as a quiet, observant child in an extended family of boisterous extroverts. I remember sitting next to my mother at family gatherings, silently watching interactions around me. One aunt would connect to me by telling stories about my namesake going on magical adventures to save mystical creatures and communities. While she told these tales, she would sketch components of the stories on the napkins or scraps of paper around her. As an artist, my aunt would quickly and effortlessly transport me from place to place with her drawings. I loved hearing her craft these alternate realities and seeing her skillfully recreate moments of me vanquishing medusa or escaping danger on the back of a gryphon. I connected with my aunt through the process of expression, giving value to a different way of building relationships with individuals like I had not seen in my loud family before. This simple activity and the relationship I had with my aunt sparked the love of art. Art became a common practice in my life, a powerful medium and tool for self-expression, for communication, and for connection.

In Mindstorms, Papert described his personal connection to gears, describing that his time spent playing with them as a child later acted as a lens to think about the world. He expressed that they allowed him to explore and make sense of the world around him (1980). As this dissertation sits at the intersection of foundational experiences and personal passions, it seems fitting to first introduce and frame art as a domain that has acted as my own personal “gear”. Art has been a prominent element of my life and has allowed me to explore and express myself and my perceptions of the world in personal and professional contexts. I’ve spent my life engaging in various forms of artistic expression and have participated in academic computing fields for the past ten years. As a woman and artist participating in computing fields, I’ve personally experienced challenges associated with holding a differing epistemology within the field.

Throughout my career, I have seen how powerful computing can be in providing disengaged learners new outlets to express themselves and explore their interests. I have also experienced and witnessed many of the systemic barriers that limits retention or prevents entry for underrepresented groups in computing. I have also seen the utility in leveraging an artistic epistemology in my personal work in computing fields. As such, for my dissertation, I focus my study on the intersection of art and computing.

Art has been tied to scientific and technological advancements throughout history, providing alternate methods and mediums for communication, expression, and exploration of new ideas (NRC, 2016; Rush, 2005). As a highly dialogic domain, art evolves with the technological advances in society, incorporating technology and computational tools to create new genres of art. For example, the first manmade glass was an accidental byproduct of ceramic glazing; this discovery went on to support advances scientifically and artistically from electricity and microscopes to architectural design and stained glass, among many others (Macfarlane & Martin, 2002; Warmus, 2012). As computing has such a large impact on the arts, computing can be considered a *restructuration*, or dramatic shift to the underlying representational structures of art resulting in changes to the way knowledge can be explored and expressed (Wilensky, 2020; Wilensky & Papert, 2010). To explain this theory, Wilensky and Papert explore the restructuration of Roman numerals to Hindu-Arabic numerals; Hindu-Arabic numerals made arithmetic and other mathematical thinking more powerful and accessible without substantial education or cognitive power (2010). As such, the use of Roman numerals for mathematics was replaced with the new representational structure, Hindu-Roman numerals.

Computers have significantly changed how and what artists can create (Leavitt, 1976; NEA, 2021). However, the restructuration of computers in the arts is not to the dramatic degree of the example of Hindu-Roman numerals. As computers are protean machines, the have the potential to bring about a more dramatic change in the arts and I argue we are actively in a computational restructuration. Like other technological advancements in the arts, these new computational forms do not replace the traditional but rather expand the potential representational structures and genres possible in the arts. Two of the major changes of incorporating computation in art are the potentials for increased interactivity with the audience and exploration of temporality in art pieces. Not only has the computer impacted the arts but since the advent of the computer, artists have been leveraging, creating, and critiquing computational tools in their artistic practice (Grau, 2016). Early scholars in computer art recognized the reflexive and impactful nature of the arts and computing; “the relationship between artist and computer is important both to people in the arts and sciences and to society as a whole. The union of art and science in computer art is reflective of the times in which we live. Ours is a technological society, one which demands interdisciplinary approaches to problems.” (Leavitt, 1976). As computing is also a dialogic medium that reflects and evolves with society, art has the potential to impact computing as much as computing impacts the arts.

As a technological society, computing education has become increasingly important as computational tools and technology have become more deeply and widely integrated in everyday lives. Not only are they being used in everyday contexts as individuals access smartphones and computers, but the practices of fields are transformed as they incorporate new computational tools and methods. As such, there’s a push for computing education, with a subset driven by economic trajectories that highlight the increasing integration of computing in most domains (Bureau of Labor Statistics, 2021). While these 21$^{st}$ century computing skills have support from funders and educators, major questions are still unanswered in how to facilitate computing education for all or even what computing education should entail.

This dissertation seeks to contribute towards these efforts for computing for all by expanding our understanding and exploration of computational thinking, particularly constructionist approaches. Computational thinking (CT) is largely recognized as "[involving] solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science", a definition put forth by Jeanette Wing (2006, pp. 33). Prior to this widespread appreciation in the 21st century, the term computational thinking first was used by Seymour Papert and was strongly tied to the educational philosophy associated with the constructionist theory of learning (1980). Constructionism states that knowledge building occurs best through building tangible, sharable artifacts, especially with the "protean power" of the computer (Papert, 1980; Papert & Harel, 1991). This theory of learning has advocated for interdisciplinary learning environments that allows learners to explore their personal interests and leverage their prior knowledge to computationally explore powerful ideas, often with creative and artistic practices (Papert, 1980). Contemporarily, CT has an evolving definition, reflecting that computer scientists and constructionists have both picked up the term to advance different types of computational goals and practices for computing education. Computer scientists focus on concepts and practices that are foundational within computer science, like algorithms, abstraction, and automation. Constructionists focus on approaches to meaningfully leveraging computers to engage in *powerful ideas* within and across domains.

For many constructionists, the term *thinking* does not fully capture the myriad ways of engaging computationally. Seymour Papert, who originally coined computational thinking, shifted to the use of computational *fluency*, which better represented the cognitive, social and cultural elements associated with computing. Others, for example Andrea diSessa and Yasmin Kafai, leverage the terms computational *literacy* and computational *participation*, respectively, as different analogies to explain impact and goals of computing education (diSessa, 2001; Kafai, 2016). Constructionists argue these terms capture a broader set of epistemologies, or orientations toward knowledge that impacts practice and engagement with the world. These orientations impact how people engage meaningfully with computing in across disciplines and their everyday lives (Kafai et al., 2020). Epistemologically, this dissertation aligns with a constructionist perspective on CT, arguing that the term computational *thinking* may not capture all aspects and goals of computing education or computational engagement in the real world. Computing within art may entail computational participation and perspectives that may not traditionally fit under the frame of computational *thinking*. However, for this work, I use the term computational *thinking* to engage in conversation with a broader group of scholars exploring and designing for computing education that value a wide array of practices, participation, and ways of thinking (Kafai et al., 2020; Papert, 1980; Weintrop et al., 2016). While I use CT throughout this work, I consider it a term with many layers. I seek to contribute to the theory building and scholarship exploring constructionist approaches and epistemologies of computational thinking, particularly in extending definitions for situated computational engagement and literacies.

Within K-12 education, contemporary initiatives to teach computational thinking have largely been situated in computer science (CS), and more recently science, technology, engineering, and mathematics (STEM) (Grover & Pea, 2013; Merino-Armero et al., 2020; Sengupta et al., 2013; Sengupta et al., 2013; Weintrop et al., 2016; Wilensky et al., 2014). The alignment with CS and STEM exposes learners to CS and STEM epistemologies, and authentic skills and practices within these domains. While these are important to represent in K12 education, the focus on CT and STEM within computing education represents a subset of the epistemologies and perspectives from other domains that learners can bring to their explorations in computing (Harrell, 2013; Kafai et al., 2020; Turkle & Papert, 1990).

As the field moves towards providing all students with opportunities and experiences in computing, it is vital to reflect on how we are representing computational ways of thinking and practices. Are we, as a field, privileging computing education that is designed to fill future jobs, or are we representing the diverse ways that computing can be leveraged in real world contexts? In parallel with other constructionist scholars exploring the intersection of CT and STEM, I seek to construct situated definitions of CT in the arts in order to broaden access to computational and artistic practice and to increase the perspectives and epistemologies represented in computing.

This shift reflects the ideology of early advocates of computing education like Seymour Papert who argued for learners of all ages to leverage the “protean” nature of computers to explore and express powerful ideas through computational constructions (1980). In broadening the definition of computational thinking for this dissertation, I look to the arts. Computational artists can offer new practices, perspectives, and epistemologies on computation. Their engagement with technology and computation, often supporting technological advancements, should be reflected in computational thinking definitions. Moreover, their perspectives can be leveraged educationally to introduce learners to computation in art classrooms as well as extend and bolster constructionist approaches that leverage creative computing.

This dissertation marks the beginning efforts to construct an emergent definition of computational thinking situated within art. This work is influenced by the theoretical and methodological approach of Wilensky, Horn, and the larger CT-STEM team (Peel et al., 2020; Weintrop et al., 2016; Wilensky et al., 2014), who have incorporated computation into STEM fields and created a definitional taxonomy of what computational thinking is in STEM fields, this work seeks to construct a situated definition of computational thinking within the arts through in-depth case studies of visual artists that leverage computational tools and practices in their artistic practice. The CT-STEM taxonomy was developed through interviews with practicing computational scientists and mathematicians. Using a similar approach, this dissertation explores the computational art experiences of ten artists engaging in computational art in order to capture their unique perspectives. To do so, I introduce a new theory, *computational art ecologies,* and associated methodological approach to characterize and compare computational art practice across artists with differing practices and motivations.

## Research Questions

The first research question in this dissertation explores the ways in which the developed *computational art ecology* framework can be used to identify computational perspectives in artists that leverage computational tools and practices in their work. To answer this, I compare three in-depth cases of computational artists using *computational art ecologies* then explore structural patterns across the *ecologies* for all 10 computational artists. The second research question explores the ways that computation has impacted artists by capturing the unique practices and perspectives that they identify as vital to their personal art practice. To answer this, I interpret the structural patterns derived from the 10 *computational art ecologies* into a series of computational practices and perspectives common across the artists. Finally, the third research question is design focused, reflecting on how the identities practices and perspectives from the participating artists can be translated into a design framework to help researchers design and integrate computational art practices in K12 educational contexts. To develop this, the computational practices and perspectives identified as common across the artists are translated to a framework that can be used to make sense of computational art practice and applied to educational contexts. These research questions will be explored more thoroughly in the methodology chapter.

1) In what ways does the methodological lens of *computational art ecologies* add insight into identifying computational perspectives in artists?
2) How do artists conceptualize the use of computation in their art? What computational practices and perspectives are leveraged during the creation of computationally influenced visual art?
3) What is a preliminary framework for computational art practices that could serve as a basis for educational design at the intersection of art and computing?

## Intended Outcomes

These research questions are motivated by three overarching goals of this dissertation, contributing to theoretical and practical conceptualizations of computational thinking. The first goal is to develop a methodology to help holistically capture the perspectives and practices of artists who use computational tools in their art practice. The landscape of computational or technologically influenced art is wide ranging and falls across many genres and sub-genres, making it challenging to capture (Grau, 2016; NEA, 2021). Notably the National Endowment of the Arts publishing the first comprehensive study attempting to capture technology-centered art across genres in 2021. This first goal seeks to create a methodological lens that can provide more consistent characterizations of artists for comparison across these diverse genres. The second goal is to begin to build an understanding of how artists use and conceptualize the use of computational tools in their art practice. In order to capture the practices and perspectives that computational artists are engaging with and expressing in their art practice, systematic exploration and analysis of these artists is necessary. Moreover, there is a dearth of literature expressing the ways that computing impacts and reshapes art practices. By identifying the landscape of practices and perspectives broadly, these can begin to be translated into design for K12 education.

The final goal is to produce an evidence-based recommendation of how computational practices and perspectives can be integrated in K12 education. Like others defining computational thinking in a situated approach (Peel et al., 2021; Weintrop et al., 2016; Wilensky et al., 2014), I seek to provide exposure computational practices and perspectives that occur authentically in the arts. The scholars who have identified situated definitions of computational thinking in science and mathematics argue that these are most effectively used in the science and mathematics classrooms (Weintrop et al., 2016). Differing from the theoretical framing of these scholars, I argue that computational art practices have the potential to impact computing education in addition to impacting art education. Art is highly dialogic and, when integrated in an interdisciplinary or transdisciplinary fashion, can fundamentally shape the experience of other domains while disrupting the hegemonic practices in those domains and society at large (Anton & Martin, 2020; Sengupta et al., 2019). Other constructionist scholars, like Sinclair, extend the philosophical beliefs of mathematicians that aesthetics play a fundamental role in the cognitive and affective development of mathematic knowledge, exploring the positive impacts of aesthetic design for mathematics students (2004; 2001). Moreover, scholars studying the history of art highlight the positive impacts that art has when integrated in domains of practice (Kariuki & Hopkins, 2010; Leavitt, 1976; Malina, 2016). In sum, art has great potential to impact computing education, particularly when identifying the computational practices and perspectives that practicing artists engage in and express. These have great potential to bolster the creative and artistic practices already integrated in many constructionist computing education initiatives.

## Structure of this Dissertation

The remainder of this dissertation is broken into four main sections. The first section is a comprehensive review of the literature informing this dissertation. This covers the landscape of research on computational art practices; the history of computer and new media art; the history of computational thinking, focusing on the constructionist and computer science branches of study; and finally, historical patterns of discrimination and bias across computing and the arts. The next section, chapter three, presents the theoretical and methodological approaches used in this study. This chapter includes the study design, instruments and procedures, description of the data collected, and the primary analytic methods. The third section, including chapter four and five, include the findings from the study. Chapter four focuses on an in-depth comparison of three cases that highlight differing practices and perspectives in the arts (RQ 2) and explores the benefits of using the *computational art ecology* methodological lens (RQ 1). Chapter five consists of a summary of the remaining 7 cases (RQ 2). The next section, chapter six, focuses on characterizing overarching patterns across the 10 cases as identified through *computational art ecologies* and translates these into an emergent framework of computational thinking in art (RQ1, RQ2, RQ 3). The final section, chapter seven, includes a summative discussion and conclusions. This chapter includes a summary and synthesis of research done, a reflection on the use of emergent methodological and design frameworks, and the limitations of this study. It concludes with a reflection on the potential implications and future work still to be done in this area of study.

# Chapter 2: Literature Review

Art is a means for meaning making, expression, and communication (Dewey, 1934; NEA, 2016). As a highly dialogic practice, the arts not only consume, reflect, critique, and advance sociohistorical structures (NEA, 2015). Art has been historically entwined with science and technology, contributing significantly towards the exploration and expression of new ideas in these fields (EPRS, 2019; Kariuki & Hopkins, 2010; Malina, 2016;). With these ties, art has been at the forefront of technological and computational advancements. As expressed by one of the pioneering computer artists, Ruth Leavitt, “the relationship between artist and computer is important both to people in the arts and sciences and to society as a whole. The union of art and science in computer art is reflective of the times in which we live. Ours is a technological society, one which demands interdisciplinary approaches to problems.” (Leavitt, 1976).

Within our current technological society, researchers and educators have advocated for engagement with computation in one way or another for decades. Early computing education visionaries saw a future in which all could express themselves with computer code and could readily access the “protean” nature of computers (Papert, 1980a; Perlis, 1962). For these early thinkers, computers offered a powerful tool to democratize education, explore powerful ideas, and facilitate expression. One of the earliest proponents for computing for all, Seymour Papert, argued that computation, “opens a vast universe of things to do” and holds the power of “concretizing and elucidating” subtle and challenging concepts across many fields (1972).

Another wave of support arose for broad computing education initiatives in the 2000s under the redefined concept of computational thinking, which originated from Seymour Papert and constructionist theory (1980). Though often tied to programming and computer science since the re-introduction, computational thinking is generally understood as a set of concepts and practices that aid in problem solving through the use of computers or other computational tools

(Wing, 2006). Scholars in the field have redefined and characterized computational thinking across many dimensions (Grover & Pea, 2013; Merino-Armero et al., 2020), expanded definitions to intersect and situate CT outside of computer science (Grover & Pea, 2013; Wilensky et al., 2014; Weintrop et al., 2016;), and reframed CT as different epistemological practices (Kafai, Proctor Lui, 2019). The evolution of this term falls under two main camps of thinking. The first camp is rooted in constructionist ideology, a theory of learning originated by Seymour Papert (1980), and largely focuses on the use of computing and computational literacies to support learners' engagement with powerful ideas. The second camp is rooted in computer science, and advocates for learners to engage in the abstract computing concepts and principles that are foundational within computer science.

In thinking about giving all learners access to computing, these two camps have two very different outcomes in the relationships, perspectives, and epistemologies that are formed towards computing. The ways we define and conceptualize computational thinking shapes the educational opportunities and spaces that we design for k12 education. As the field moves towards providing all students with opportunities and experiences in computing, it is vital for self-reflection of how we're representing computational ways of thinking and practices. Art offers the potential for new epistemologies within computing and increases access points to computing education. As historically entwined with science and technology, integrating computing practices and epistemologies from an authentic art perspective within educational initiatives around computational thinking has potential to positively impact computing education.

To fully capture the implications of this effort, in this chapter, I will explore the scholarship surrounding art, art and computing, and computational thinking. First, I motivate the study of art by reflecting philosophical and historical perspectives on the Arts, and contemporary engagement in the field. Next, I document the limited scholarship on the artistic practice of computational or tech-centered artists. To bolster understanding of computation and technology in the arts, I briefly summarize the history of computer and new media arts. These perspectives largely focus on the histories and perspectives of visual arts, though there is a similarly rich history of other artistic fields, like music or performing arts, and computation. After exploring the intersection of art and computation, I shift to capturing the historical and contemporary perspectives on computational thinking. I will first outline the contemporary attempts to define and situate computational thinking in education. Next, I highlight the rich history of creative computing education, and educational initiatives at the intersection of art, creativity, and computing education. Finally, I examine two overarching areas of literature that impact both the arts and computing. I reflect on the discrimination, bias, and underrepresentation that is prevalent across both art and computing fields. I conclude by exploring the theory of restructuration, which describes the dramatic impact that can occur when shifting representational infrastructures within a domain, and how this applies to the intersection of computing and the arts.

## Exploring the Arts

> *"Every art communicates because it expresses. It enables us to share vividly and deeply in meanings… For communication is not announcing things… Communication is the process of creating participation, of making common what had been isolated and singular… the conveyance of meaning gives body and definiteness to the experience of the one who utters as well as to that of those who listen"* (Dewey, 1934).

John Dewey was instrumental in arguing for a new understanding of art that moved beyond an examination of a product, or piece of art, and towards a theory of aesthetic and ecology that captured the social and cultural complexity of the art practice (1934). As Dewey explained, art is a means for expression, communication, and meaning making (1934). The definition of art has long been a topic of interest for philosophers and scientists. In its simplest form, art is a form of communication of ideas, emotions, experiences between artist and viewer. The dialogic nature of art provides important lenses into the cultural, social, historical factors, among others, that influences the creation of a piece of art. The arts not only reflect, critique, and advance sociohistorical structures, they also strengthen communities and provide a means for connection and understanding of others, offering "a continuous, powerful, and resilient source of individual and collective identity" (Burford as cited in NEA, 2015). As expressed by those at the National Endowment for the Arts:

> *The arts matter because they help us see the world from different perspectives. They give us empathy and help us understand people, places, periods of history, and issues with which we may otherwise be unfamiliar. They comfort us in grief and energize us in celebration. They are important because they can act as a catalyst for change…they can start a revolution! The arts ignite something in our brains that I can't explain, but I know it's essential for life.* (Terman as cited in NEA, 2015)

Finally, and critically, art, science, and technology have been historically entwined (EPRS, 2019; Kariuki & Hopkins, 2010; Malina, 2016). Art has promoted "cultural change, triggered the imaginative conscience and community action and acted as a bridge towards scientific understanding and application of sustainable efforts" (Clark & Button, 2010). The advancements that came from the partnerships between art and science showcase that these seemingly "hard" and "soft" approaches are mutually beneficial. Both provide a means to explore of powerful ideas with different approaches. Research suggests that arts and science collaborations have the potential to break new territory and use the respective audiences to inform a broader public (Ghanbari, 2014). Some scholars describe the impact of artists as akin to researchers and educators, "Artists, like researchers, create new knowledge through studio practice. Artists, educators, and cultural objects are significant contributors to our evolution" (Mayo, 2007). For computational art, these ties may be even clearer. Even early scholars in computer art recognized the reflexive and impactful nature of the arts; “the relationship between artist and computer is important both to people in the arts and sciences and to society as a whole. The union of art and science in computer art is reflective of the times in which we live. Ours is a technological society, one which demands interdisciplinary approaches to problems.” (Leavitt, 1976). New technologies have brought opportunities for aesthetics to be leveraged to communicate and express ideas (e.g., visualizations, end-user design, modelers), and scholars suggest artists can make substantial contributions to research, particularly interdisciplinary (Mayo, 2007; Mayo, 2008; Wilson, 2002).

**Engagement in the Arts**

As philosophers and researchers have explored, engagement in the arts has myriad socioemotional, cognitive, and cultural benefits (Eisner, 2002; Ghanbari, 2014; Upitis, 2003). Participation in arts education has similar benefits for learners, both in immediate growth and long-term prospects. Participation in the arts and art education have a positive impact on academic performance as well as a host of other cognitive and emotional competencies in learners (Blatt-Gross, 2010; Burton, Horowitz, & Abeles, 2000; Catterall, 2012; Jeffers, 2009; Lampert, 2006 ). Longitudinal studies suggest that the arts have a long-term impact on college access, academic success, and increased civic engagement later in life (Catteral, 2009; Peppler et al., 2014). STEM and art have been historically entwined (Malina, 2016; Kariuki & Hopkins, 2010). Art has promoted “cultural change, triggered the imaginative conscience and community action and acted as a bridge towards scientific understanding and application of sustainable efforts” (Clark & Button, 2010, pp.43). Advancements from the partnerships between art and science show that the combination provides a means to explore powerful ideas utilizing different perspectives. Moreover, research suggests that art and science collaborations have the potential to break new territory and use the respective audiences to inform the broader public (Ghanbari, 2014). Art fundamentally shapes the experience of STEM and can challenge the hegemonic practices within those spaces (Sengupta et al., 2019). However, historically, the two are often entwined, with many early scientific thinkers engaging in artistic practices alongside the scientific. Art and creativity are recognized as one of the most important emerging competencies for future leaders (Eisner, 2002; IBM, 2010).

Beyond socioemotional and cognitive benefits of the arts, there is a high level of engagement in the arts from laypeople; a 2017 study of adults within the U.S. found that 74% (175 million) adults use electronic media to consume artistic or arts-related content, 54% (133 million) adults attended artistic, creative or cultural activities, and 54% (133 million) adults created or performed arts (NEA, 2017). Moreover, 41 million adults (17%) reported learning art informally and 23 million adults (9.5%) reported taking formal art classes or lessons (NEA, 2017). Within K12 education, Art traditionally attracts populations who are underrepresented in CS and elective STEM courses (DES, 2007; Etherington, 2008). Returning to gendered participation trends, women are the majority within K-12 art education, ranging from 64% – 70% women in varying courses (Etherington, 2008; DES, 2007). Moreover, 25 states have adopted a new set of standards for art education, the National Core Arts Standards, and now require course credits in the arts for high school graduation (Heckinger Report, 2015). All combined, the arts are a fruitful space to explore computation, offering a domain to explore new epistemologies that will bolster engagement in the arts for the more than 175 million adults casually participating in the arts. Lastly, the arts cover a wide range of genres ranging from music to theater to visual art.

While each offers a unique set of practices and perspectives, for the purpose of this work, I will narrow focus on visual arts. In the following section, I explore scholarship capturing the ways artists perceive and engage with computation, and the history and genres of art that intersect with technology, computation, and new media.

**Research on Computational Art Practices**

While there is rich scholarship on art education, there has been little scholarship that captures the role of computation in the visual art process. In one study of how artists differentially create with computational tools and without, researchers found that the use of computational tools changed the artistic process, changing the relationship to the practice (speed, precision, or ease of production) in addition to the products (computational tools often support different forms of production) (Beardon et al., 1997). This early work highlights the early integration of technology in the lives of artists, but focuses more on the day-to-day impact rather than on how it shapes the process of art. Since the Mid 90's, computers and computational tools have become more ubiquitous in life. It can be assumed that computers are more integrated the lives of artists as well. As such, the ease of use and conception of computational tools have likely shifted. However, this piece does highlight tensions associated with computation and the arts. The authors discuss the tension between design and production, terming tradeoffs as "workmanship of risk" and "workmanship of certainty". The artists must use the tools to meet an internal vision or goal and must assess the benefits and risks of using either traditional or computational tools.

There have been numerous studies on the practices of artists, exploring cognitive elements of practice that provide some insight into the features to examine when trying to make sense to computational art. These range from leveraging behavioral to constructivist theories, but primarily focus on the mental structures and abilities that allow artists to represent objects realistically or creatively (Efland, 2002). Others have focused on capturing how individuals interpret or engage with art. For example, Parsons captured a broader evolution of art practice in five stages that reflect the overarching goals and focus of a budding artist (1987). These stages; favoritism, beauty and realism, expressiveness, style and form, and autonomy; reflect how individuals understand art, which is a heavily subjective process laden with assumptions about art, practice, skill, and personal affect relating to the artist and the viewer (Parsons, 1987). More holistic approaches to interpreting and assessing art capture a range of features from skill and style to representation and intellectual challenge to viewer experience (Dutton, 2009).

Lastly, there are artists who have published in anthologies about their personal practice or specific pieces of art that are reflective of a given theme (Leavitt, 1976). Conversely, others have explored the works a given artist or a set of artists on a theme or genre. These are important building blocks for understanding the perspectives of artists but are often limited in scope, particularly due to the complicated nature of the umbrella genre of new media and the many intermixed subgenres. The most cohesive study of new media art comes from the National Endowment of the Arts (NEA) (2021). In this multi-year study, the National Endowment of the Arts conducted an extensive study on the intersection of art and technology in which they held roundtables and town hall events, conducted a literature review and a grant portfolio analysis, conducted 20 field interviews, compiled 9 case studies, and held technical working group meetings with stakeholders to review findings (NEA, 2021). In this report, they sought to answer how artists use technology in their artistic practice, identify career paths or trajectories that are accessible for artists working with technology, and capture ways that artists engage in cross-sectorial or inter-disciplinary partnerships. From this mixed method approach, they found that 1) code, computation, data, and tool-building are fundamental practices for tech-centered artists, 2) the field of tech-centered artists is very diverse and makes it difficult for traditional organizations and funders to access communities, 3) tech-centered artists have established both virtual and physical organizations, hubs, and other communities to aid in social, educational, and economic community-building, 4) career pathways for tech-centered artists are diverse and reflect traditional obstacles that career artists experience and 5) tech-centered artists are poised to engage with larger societal and sectoral challenges (NEA, 2021). Notably, they found that artists leverage their technological knowledge to connect with audiences physically and virtually. Moreover, they found that tech-centered artists commonly explore themes of diversity, equity, and inclusion, and often address racial inequalities and social injustices across arts, technology, and society more broadly. Lastly, they found that many of these artists seek out engagement with local communities to support creative pathways at the intersection of art and computing (National Endowment for the Arts, 2021). This report reflects the first efforts to capture the broader landscape of computational or technology-centered art practice and is foundational for understanding the scope of the field. As reflected in the report, the myriad practices, roles, and classification of artists within this field makes it challenging to fully document the scope of practice, engagement, and perspectives present in the field. This is particularly true for the quantity of tech-based or computational artists; there are no statistics that explicitly capture the number or growth of tech-based artists. Moreover, a large portion of the NEA report focused on economic and financial issues. This dissertation seeks to contribute to this body of knowledge by more in-depth exploration of practice, perspectives, and epistemologies of artists within this space. Lastly, it contributes to the call for artists as collaborators and partners for education; translating these perspectives into situated definitions of computational literacies within the arts that can evolve and grow as the landscape is more thoroughly explored and captured.

## Brief History of Art and Computation

In 1953 short love letters began appearing in the Manchester University computer science department. These letters, addressed to an unnamed other, consisted of flowery adorations and were signed by M.U.C; "DUCK DUCK, YOU ARE MY LITTLE AFFECTION: MY BEAUTIFUL APPETITE: MY EAGER HUNGER. MY COVETOUS LOVE LUSTS FOR YOUR INFATUATION. MY YEARNING ANXIOUSLY CLINGS TO YOUR FELLOW FEELING. YOURS EAGERLY M.U.C." The author, Christopher Strachey, was a computer scientist who created a computer program to randomly generate these love-letters, viewed as a queer critique of heteronormative expressions of love. This program ran on one of the first stored-program computers, the Manchester University Mark 1 computer (M.U.C.), which "wrote" or generated algorithmic love letters based on a list of approximately 70 adjectives, adverbs, substantives, and verbs. (Gaboury, 2013; Montfort & Fedorova, 2012). This program is seen as the first piece of digital literature and one of the first pieces of computational art (Gaboury, 2013). While artistic computer scientists like Strachey were in the minority, where there were new innovations with technology, there were artists exploring how to leverage and distort them for their creative and expressive practices. There is a rich history of artists innovating with technology and computers, often with disdain and critique from society overall (Armstrong, 2015; Burnham, 1979; Nake, 1971; Taylor, 2014).

The earliest computational artists, like Strachey, programmed the computers themselves or partnered with programmers, experimenting with the protean power of computation and translating their ideas into artwork that could be produced with the technological capabilities at the time (Victoria and Albert Museum, 2016). The first art, as mentioned above, featured word processing and computer-generated literature (see Dreher, 2014). As technology advanced to include printers and plotters, these early practices expanded from the 50s to the early 70s to include analog graphics like oscillograms and plotter drawings, densities (Karl Otto Götz), binocular depth perception (Béla Julesz), patterns (Georg Nees), computer graphics (Georg Nees), and random polygon movement (Dreher, 2014) (see Figure 1 and Figure 2 for examples of early computer art). For these first computer artists, experimentation in practice fell within two paths: 1) a visualization of a mathematical formula as an artifact and, 2) the research to find or invent an algorithm for artistic expression (Mohr, 1973). The first two exhibitions of computer art were held in 1965 in Germany and New York, showcasing work by Georg Nees, Bela Julesz, and A. Michael Noll. The first international exhibitions, "Cybernetic Serendipity" in London 1968, "Computers and Visual Research" in Zagreb 1969, represented a broader community of about 20 artists within this genre (Lenz, 2014). These first exhibitions showcased the artwork as "generated pictures" as they were not yet seen as art, and the public's reaction was negative (Burnham, 1979; Taylor, 2014). Even the pioneering artists were conflicted about the use of the computer to make *art*, "I don't see a task for the computer as a source of pictures for the galleries. I do see a task for the computer as a convenient and important tool in the investigation of visual (and other) aesthetic phenomena as part of our daily experience" (Nake, 1971).

Despite the critique, these early artists built complex relationships with computers and were able to explore new ideas with these new thinking partners. Vera Molnar was one of the first fine artists to use a computer as an artistic tool, and her approach to the computer reflects a deeper mindset that was expressed by the pioneers of computer art. While she first used a computer in 1968, she had designed a systematic method for creating art in 1959 on a concept of the 'Machine Imaginaire'; in her words, "I imagined I had a computer. I designed a program and then, step by step, I realized simple, limited series which were completed within, meaning they did not exclude a single possible combination of form. As soon as possible I replaced the imaginary computer, the make-believe machine by a real one." (Molnar as cited in Lenz, 2014). For many of these early artists, the computer was more than a medium with which to express one's thoughts. Computers were thinking partners that pushed their own imaginations and challenged their ways of thinking. The computer helps the artist to perceive in a new way.

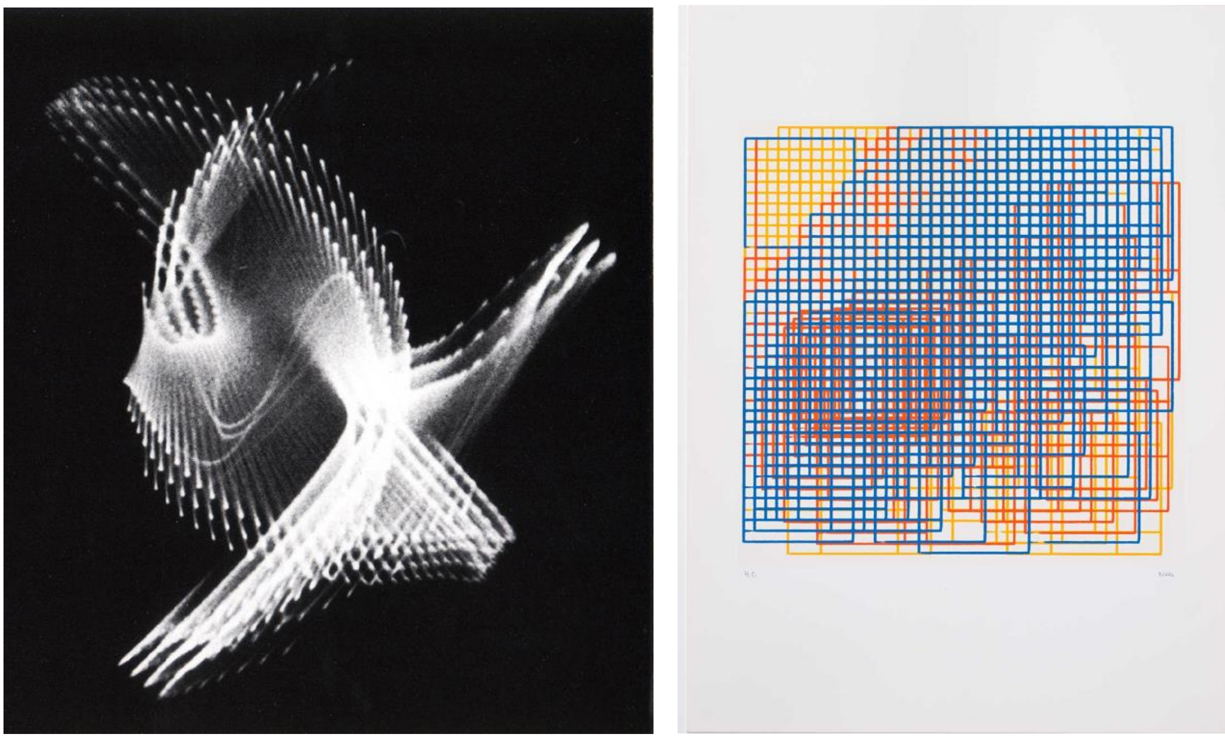

**Figure 1 - On left, Benjamin Francis Laposky: Oscillon Number Four, 1950, photo of an oscillograph's screen. On right, Frieder Nake: Walk-Through Raster, 1972, plotter drawing.**

As described by Mohr, "just the fact that you are working with a machine doesn't make you a technician. I would like to draw, that's my life. The context has changed, become more reflective, clearer, just as my thinking became clearer in working with a machine…the computer is my auxiliary, my partner, but it has nothing to say. I want to make something that brings me further. I want to make something that reflects my thinking." (Mohr as cited in Galloway & Sabisch, 1992). Others, like Howard Cohen, developed longer lasting relationships with computer programs. Cohen explored the question "what are the minimum conditions under which a set of marks function as an image?", observed how children draw, and studied various forms of art, then developed a computer program, AARON, that could draw and eventually make decisions about the design of artwork (Cohen, 1994; Grimes, 2016).

Computer art and computational art after the 70s began to reflect more of the social,cultural, political, and economic themes surrounding technology at the time, including Sputnik Space Wars, Video Games, Star Wars, Cyberpunk, Neuromancer, and many others (Mayo, 2008). Moreover, the 80s saw more widespread integration of computers and technology in everyday life, broadening access to this genre of art (Victoria and Albert Museum, N.D.). As access broadened, computational art evolved to incorporate a wider range of technology and practices, and largely lost its name of ‘computer art’ by the 1990s. During this time, the mediums began to incorporate interactive environments, situating both the artist and the viewers at the intersection between the real and virtual worlds (Lenz, 2014; Rush, 2005).

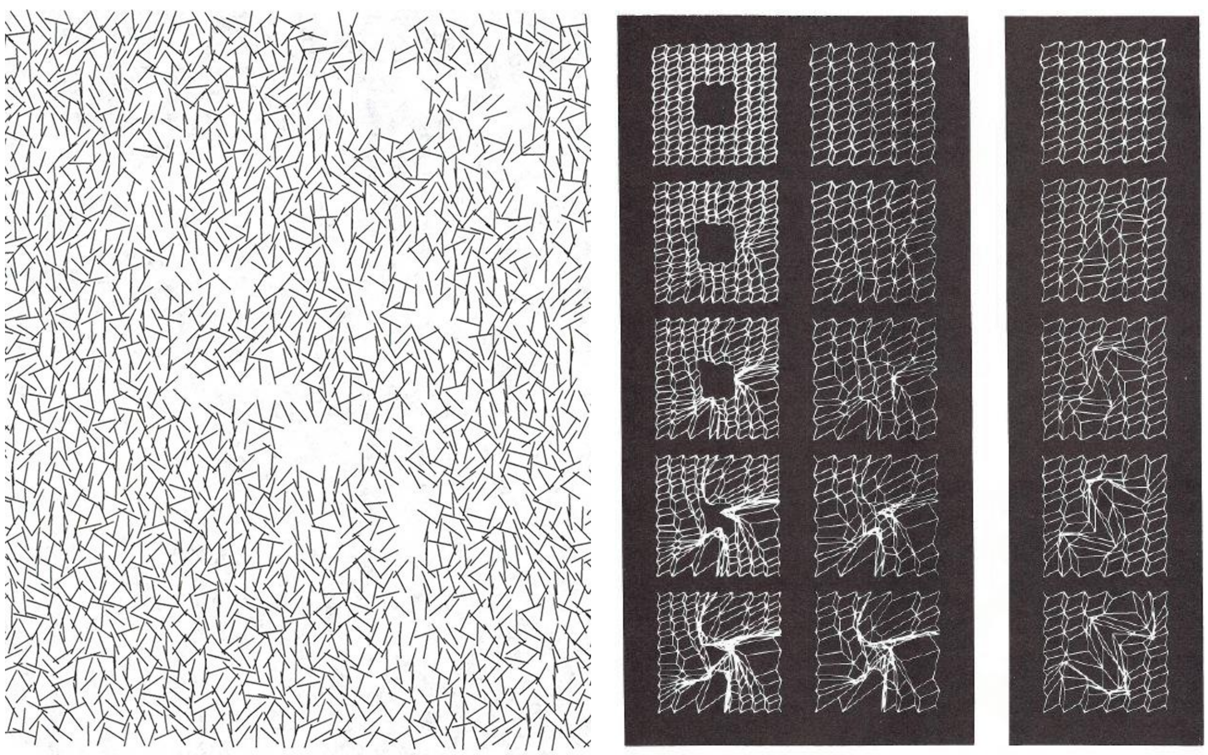

**Figure 2 - On left, Vera Molnar: Interruptions, 1969, plotter drawing. On right, Ruth Leavitt, Diamond Transformations I, serigraph.**

Since these first explorations into computational art, there has been development of new practices, mediums, and perspectives relating to technology and computation. As a highly expressive and reflective medium, advances in technologies are often mirrored in artistic ventures. There are a range of genres and camps that reflect varying perspectives and approaches to incorporation of various technological or computational elements. One umbrella genre that has emerged to capture these is termed New Media art, and includes sub-genres like digital art, computer graphics, virtual art, interactive art, video games, 3D printing, and biotechnology, computer art, new media art, virtual art, internet art, glitch art, bio art, and interactive art, among many others (Grau, 2016). As an important genre in contemporary art, new media art broadly encapsulates art that is produced, modified, or transmitted by means of new and emerging technologies that originate from a scientific, military, or industrial contexts (Grau, 2016). The field struggles to define and identify the boundaries of this genre and its subgenres, as new computational technologies evolve that result in drastically different forms of practice and perspectives on technologies. As described,

> *"The combination of artist and oil paint is, for example, a different statement than that same artist and watercolors. The medium changes the statement. The artist now goes to an art supply store to purchase a given set of tools, whereas the computer artist can create the tools he will use. This is remarkable and allows for unlimited possibilities in the art to be created. Every program functions as a new set of tools. The type and quality of work produced on the computer depend both on the artist who uses the machine and the program."* (Leavitt, 1976)

A consistent theme across new media art is that it "challenges the very foundations of an object-centered understanding of art, in particular with regard to its characteristics of interactivity, nonlinearity, immateriality, and ephemerality, and its intricate interrelation between artist, artwork, and spectator" (Grau, 2016). Moreover, there is a persistent tendency to question the long tradition of painting as the privileged medium of representation (Rush, 2005). There are tensions in characterizing new media art as technology is introduced and retired over time, such as a cassette players or floppy disks, among others. These retired technologies fall under the categorization of new media art, despite being culturally characterized as antiquated in the 21st century. As computational tools and practices are more integrated in art fields, we may see a distinction emerge around how the field characterizes technology and computation or the application of technology and computation in the art process.

The introduction of new media, technology, and computation has resulted in a swift expansion of art practices beyond the traditional, and has increased the inclusion of everyday objects or artifacts into art. As Rush describes, "this inclusiveness bespeaks a central preoccupation of the contemporary artists, which is to find the best possible means of making a personal statement in art" (2005). More importantly, the artists who practice in new media or technology will explore and often subvert both the critical and technological potentials of new media (Rush, 2005; Armstrong, 2015). Within this context, artists often focus more deeply on process than on the artifacts within the works of art (Graham & Cook, 2010). Computational methods add new elements to the user experience, largely potential for interaction with the viewer and in additional sensory features and temporality (NEA, 2021; Wands, 2006). This evolution presents computational artists with interesting decisions as they explore new practices and approaches that can construct relationships between the artist and the viewer. Lastly, as identified by the National Endowment for the Arts, artists who leverage technology or computation in work often do so while engaging in larger conversation or critique of social and cultural contexts, both for personal expression and to spark community engagement (2021).

While the scholarship on artists working with computation is limited, the history of computer and new media art highlights a rich artistic engagement with computing that has featured diverse practices, perspectives, and technology. This vein of computational expertise and the variety of creative and critical perspectives should be reflected in educational practices with computing and computational thinking. To better understand the ways that these artistic epistemologies can be integrated and bolster successes in computing education and computational thinking, the historical and contemporary expressions of CT will be explored next.

## Diverging Approaches for Computational Thinking

Computing education is becoming an increasingly important as technology is becoming more integrated in everyday lives and most fields. Computational thinking, a focus within computing education, seeks to increase access to practices and ways of thinking to effectively leverage computational tools across myriad contexts and towards diverse goals. Originally coined by Papert (1980), computational thinking has been desired outcome for computing education for the last half-century. Computational thinking education was invigorated in 2006, when Jeannette Wing published an influential article arguing for the "universal attitude and skill set" of computational thinking that sparked conversations around the importance of these practices across fields (Wing, 2006). In this article, she defines computational thinking as "[involving] solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science" (2006, p. 33). Abstractly, CT reflects the skillset of thinking like a computer scientist when confronted with a problem, and this computational approach can be leveraged across all contexts (Henderson et al., 2007).

While there is a rich body of literature on computational thinking, the definitions and outcomes of this term are challenging to track, as two camps of scholars have picked up the use in service of two different sets of foundational practices and ways of thinking: one rooted in constructionism and the other in computer science. While both camps seek to support the structures and ways of thinking foundational to their respective domains, the definitions of computational thinking differ significantly across the two. The constructionist approach to computational thinking is rooted in constructionist theories of learning that situate the computer as a “protean” tool with which to explore powerful ideas at the intersection of domains. In this approach, the goal is to develop comfort and fluency at leveraging computation as a tool to explore interests and knowledge, which is enabled and deepened by the power of computation. This approach to computational thinking frames it more as a literacy that is uniquely observed across domains of practice. The computer science camp orients definitions of computational thinking towards the foundational concepts and principles that underly thinking in computing fields, including more concrete structures like algorithms or automation. This approach to computational thinking focuses on the building blocks of communication with computational tools, teaching learners how to think in the structures the computer uses to run programs so that learners can effectively engage with the computer. Both camps view programming as an important practice that allows engagement and interaction with computers or other computational tools, but not the key learning outcome for computational thinking.

In the following section, I outline constructionist theories on computing education and the rich scholarship leveraging creative and artistic computing practices that support computational literacies. Next, I outline the more contemporary definitions and approaches to integrate computational thinking in K12 education emerging from the computer science camp.

## Constructionist Approaches to Computing Education

Seymour Papert, the founder of constructionism, may have been the first to use the term computational thinking in his seminal work Mindstorms, making it an integral part of this theory of learning (1980). Based on his theories, these early constructionist thinkers sought an idyllic world in which all could leverage computers to express, create, connect, and explore with the world around them and the people within it. Since then, constructionist scholars have designed transdisciplinary computational experiences that allow learners to drive exploration of big ideas through their personal interests and passions. These initiatives have directly and indirectly contributed to the characterization of computational thinking rooted in the constructionist camp. Importantly, these scholars encouraged multiple epistemologies and expressions of knowledge (Turkle & Papert, 1991). Below, I explore the history of constructionist computing education to highlight the key practices, perspectives, and epistemologies present in the definition of computational thinking rooted in these theories.

Seymour Papert envisioned a world in which children could readily access the “protean” nature of computers in order explore powerful ideas and express their ideas through computational construction (1980). Papert embraced Piaget’s belief in children as “active builders of knowledge” and worked to make powerful computational tools widely accessible to children as he saw these as powerful, creative tools that could be meaningfully harnessed to explore a wide range of topics (Papert, 1999; Papert, 1988). It was with this motivation that Papert introduced the world to constructionism, a theory that extends the cognitive theory that learners construct their own knowledge structures, arguing that “this [construction] happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it is a sandcastle on the beach or a theory of the universe” (Papert & Harel, 1991).

A primary tenant of constructionism is to put the learner in control of the experience. Rather than seeing the child as a “tabula rasa” that one can fill with knowledge, Papert strongly believed in individual choice and individual interest guiding learning experiences. He lamented the shift away from natural curiosity and inclinations for day-to-day learning into the learning that occurs in formal educational systems, in which participants are taught to be a good student (Papert, 1994; Papert, 1996). By exploring his personal challenge learning flora, he argues the importance for both mathetics, or the art of learning, and multiple pathways to gaining knowledge. This latter idea, encouraging and cultivating many learning pathways, is strongly represented throughout his body of work.

Papert leveraged computation to support more mathetic learning experiences. He argues that computation, "opens a vast universe of things to do. But the real magic comes from when this I combined with the conceptual power of theoretical ideas associated with computation" (Papert, 1972). It has the power of "concretizing and elucidating" subtle and challenging concepts across many fields. Through the development of computationally powerful tools and curricula combined with constructionist principles, "what kinds of innovation are liable to produce radical change in how children learn…computers feature prominently only because they provide an especially wide range of excellent contexts for constructionist learning." (1991). Moreover, Papert and Solomon argued that computers can introduce "*everyone* of whatever age and whatever level of academic performance to programming, to more general knowledge of computation and indeed…to mathematics, to physics and to all formal subjects including linguistics and music" (1971).

This belief that children could learn programming was innovative, especially for the time. This was more so as Papert sought to teach youth the computational practices and ways of thinking to youth so that they could express themselves freely with computers. Papert found young learners engaging deeply with creative mathematic practices through embodied play with Turtles in Logo (Papert, 1980a; Kafai & Harel, 1991). From the success of Logo, others built similar computational constructionist tools that leveraged low threshold, high ceiling designs. As

Abelson said, Logo is “a philosophy of education and a continually evolving family of programming languages that aid in its realization” (1982). From Logo, over 130 implementations of Logo-inspired languages have been designed (Feurzeig, 2007), which have supported learning across myriad domains. Children intuitively explored music and mathematical concepts through TuneBlocks (Bamberger, 1996); represented motion and “reinvented” graphing through Boxer (diSessa et al., 1991); explored and modeled complex scientific phenomenon through NetLogo (Wilensky, 2001; Wilensky, 2003). Notably his approach to computing sought literacy and expression with computation, as he described, “some think of using the computer to program the kid; others think of using the kid to program the computer” (Papert & Solomon, 1974).

One major element of constructionist theory is the design of flexible, meaningful environments that support the exploration of powerful ideas. By situating the learners as the programmers of the computer, or their virtual learning environment, they “embark on an exploration of how they themselves think” and through this, they make personal and epistemological connections with domains of knowledge (Papert, 1980). To Papert, the computer allowed learners to immerse themselves in domains and explore their personal interests and their own thinking. He likened this immersion to language learning, highlighting the different learning trajectories between learning Spanish vocabulary in a classroom compared to moving to Spain to fully immerse oneself in the language and the culture. Based on this metaphor, Papert developed microworlds, a domain specific “incubator” or virtual environment whose deliberate design supports “specific species of powerful ideas or intellectual structures” (Papert, 1980). Others designed frameworks, termed microworld construction kits, to support other researchers in rconstructing these virtual environments to focus learners’ “thinking on particulars of a conceptual domain while providing for self-motivated, free-form manipulation and transformation of the representations and the ideas" (Strohecker, 1999; Strohecker & Slaughter, 2000a; Strohecker & Slaughter, 2000b). Moreover, due to the flexible nature of the computer and these environments, learners with a vast variety of learning styles and needs could gain access to powerful ideas (Weir, 1987). Notable, Weir viewed the computer as an important agent in socially-mediated learning, and argued that the larger constellation of social connections and cultural expressions in the class needs to align with that of the computational learning environment to be most effective for learning (Weir, 1989).

This designed flexibility and space for exploration are key components in early conceptions of computational thinking. As Papert argued, computers are "objects to think with" (1980). The "protean" nature allows users to align computation with their interests and their way(s) of thinking. DiSessa conceptualized a similar idea, computational literacy, as a medium through which other domains could be explored (2001). In this, he differentiated aspects of computation, identifying material, social, and cognitive threads, suggesting that computational "literacy is the convergence of multiple genres and social niches on a common, underlying representational form" (diSessa, 2001, pg. 24). These early proponents frame computation as a malleable tool that can be shaped to fit any context or individual. As Papert mused:

> *"Computers are a domain where everyone expects the analytic to reign supreme, yet this situation makes it especially clear that for certain children, the development of intelligence and programming expertise can reach high levels without becoming highly analytic as well……one in which a program emerges not through planning and subdivision of a problem but through something closer to the way in which a sculptor or painter makes a work of art-a process in which the plan of what is to be made emerges and is refined at the same time as the created object takes form. One might call it more of a negotiation between the creator and the material than an imposition of logical order."* (1991)

This framing stands in stark contrast to many of the concretized, problem-based definitions of computational thinking proposed in the last decade. Computation with this lens is envisioned as a practice with multiple pathways to support diverse epistemologies, both “hard” and “soft” approaches as described by Turkle and Papert (1991). Turkle and Papert advocate for educational environments to accept this framing in order to broaden access to computational practices by countering perceptions of computation as primarily analytic. Rather than discouraging creative or artistic goals in making with computation, constructionists argue that these ventures allow learners to meaningfully combine prior interest and passion to engage with new domains of knowledge (Martin et al., 2000; Papert, 1980a; Resnick, 2006). While constructionist environments are designed with these principles in mind, the broader computer science community struggles with perceptions and practices around computation. Many efforts to attract underrepresented groups in computing education focus on creative ventures that allow learners to explore and construct while learning programming. These theories of learning and computation have continued to impact contemporary scholars and their designs of computing education.

*Computing Creatively and Creative Computing*

Constructionist theories of learning have strongly influenced contemporary approaches to youth-oriented programming and computer science experiences. As Eisenberg reflected, the most compelling aspect of Papert’s ideology of computing education was

> “*a democratizing impulse focused on the relationship between people and technology…[he] envisioned a world in which technological artifacts are designed to make profound concepts understandable and expressive, and he sees the spread of affordable computers as a means toward knitting together disparate intellectual subcultures.”* (2003).

These efforts are present in informing the design of new youth-focused programming languages, curricular lessons and activities, and programs and communities (Blikstein, 2013; Eisenberg et al., 2009; Horn & Wilensky, 2012; Horn, 2006; Horn et al., 2020). A common thread throughout constructionist computing initiatives has been the integration of creative or artistic ventures in computing initiatives to engage youth and encourage positive affective ties to computing education. Importantly, these efforts have often been aligned with efforts to increase access and engagement to computing for underrepresented and underserved communities. The challenges of underrepresentation in both computing and art fields will be explored to a greater extent later on in the literature review. In the following section, I outline the constructionist designs that have been influential in broadening access to computing education for a wide range of learners.

In efforts to lower the floor for computing education, scholars have designed youth friendly programming languages and environments that scaffold learners into computing practices and concepts. The computational ideas can be more accessible if the language itself is shaped to reflect more natural ways of thinking that can scaffold learners to more complex computing concepts (Guzdial, 2008; Kelleher & Pausch, 2005). Youth friendly programming languages like Scratch focus on digital media creation, providing kids an environment to create games, music videos, and other digital art (Resnick et al., 2009). Similarly, studies of youth designing and developing their own games have showed gains in a wealth of literacy and critical thinking practices (Anton et al., 2013; Carbonaro et al., 2010; Peppler, Diazgranados, & Warschauer, 2010; Peppler & Kafai, 2007), and suggest that these facilitate the development of computational thinking skills like logic, debugging, and algorithm design (Berland & Lee, 2011). As other youth-oriented programming and design environments, such as *Alice* (Pausch et al., 1995), *Toontalk* (Kahn, 1996), *AgentSheets* (Repenning, 1993), *NetTango* (Horn & Wilensky, 2012; Horn, Baker & Wilensky, 2020), and *Scratch* (Maloney et al., 2004); these youth oriented languages provide a) a library of media with which learners can use, modify, and extend, b) enable peers to help one another to progress in skill from beginner to expert, and c) create safe spaces to learn to program together without fear of harassment or judgement (Resnick et al., 2009) can be powerful supports for learning to think computationally. These programming environments support the acquisition of computational practices and ways of thinking while encouraging youth to express themselves and their personal interests.

Early advocates of constructionism leveraged computing to allow students to deeply explore creative endeavors. As mentioned prior, early constructionist designs incorporate flexibility for learners to tinker, modify, and create something of their personal interests. In early initiatives, students created artifacts that were expressive of their social and formal interests and knowledge, for example one student created a nail salon that used a sensor to detect hands, gears to and materials to polish nails, and background music to play throughout the experience (Martin et al., 1980). Projects in this vein allow learners to explore their personal interests with computational practices and ways of thinking while engaging in big ideas. Papert and Solomon published an article describing "20 Things to Do with a Computer" that included computational craft and every-day activities like drawing various shapes or scenes, writing poetry, making puppet shows, and playing with and programming robots (1974). Papert sought to bring computation to the learners' hands physically as well; he began to leverage 'floor turtles', a programmable robot, in his computing initiatives (Feurzeig, 2007; Papert, 1980; Papert & Solomon, 1971). Learning programming with these Logo floor robots achieved a dual purpose of making computing more hands-on and accessible, while also providing a body syntonic experience. Shortly after, scholars designed a series of programmable bricks, or handheld computers, that could be integrated in robotic and physical computing projects (Martin et al., 1980). These initial endeavors have been highly influential for creating a culture of creativity within computing education.

Others from constructionist camps have explored new forms of computation, reimagining how learners can engage meaningfully with computational content and tools. One notable scholar in this vein, Michael Eisenberg, explored the role that computation can have in engaging and enriching the world that a child inhabits and sought to expand the mediums of computation to better facilitate engagement (2003). Eisenberg's work was motivated by imagining the ways the traditional computer form, or "box on one's desk", could evolve through the expressive combination of computational and material artifacts (Eisenberg, 2003). He leveraged three primary approaches to do so: 1) the development of software to augment the use of tangible materials, 2) embedding computational capabilities in physical objects, and 3) exploration of new materials with varying degrees of intelligence. His designs seek to make computation an accessible aspect of the lives of youth so they can readily showcase these items in their personal lives and rooms. He and his colleagues reimagined traditional crafting practices, like origami and sewing, as computational activities and encouraged learners to orient towards these as playfully and creatively as with the traditional mediums (Hendrix & Eisenberg, 2005; Huang & Eisenberg, 2011; Leduc-Mills & Eisenberg, 2014; Wrensch & Eisenberg, 1998). One of the first educational softwares for digital fabrication, HyperGami, enabled children to design 3D polyhedra that would be translated to a 2D origami pattern so that explorers could print these on paper to cut out and assemble (Eisenberg & Nishioka, 1994). This design not only allowed learners to explore the powerful ideas associated with geometry but gave them the freedom to express their personal interests through the geometric designs, the tangible materials (colors, textures), and displaying these artifacts in learners' personal worlds. Throughout his educational designs, Eisenberg sought to facilitate the relationship between learning and play, between learners and computation, and between traditional and computational materials (Blikstein, Kafai, & Pea, 2019; Eisenberg & Nishioka, 1994; Wrensch & Eisenberg, 1998).

Others have worked to extend computational into more accessible forms and practices. Leah Buechley and colleagues' work on electronic textiles, or fabric based computational construction kits, has been shown to engage many underrepresented groups in creative computing practices (Buechley et al., 2011). Her work broadly focuses on expanding forms, as construction kits facilitating the creation of technology and their forms "constrain what we build and how we think" (Buechley et al., 2011). Others have explored craft-based applications, like paper or sticker circuits, to engage a broader audience of artists and makers (Hodges et al., 2014; Jacoby & Buechley, 2013; Mellis et al., 2013; Qi & Buechley, 2010). Others have sought to develop creative learning kits that incorporate a mixture of familiar, low-cost traditional and computational materials that can make creative computing more accessible, particularly for those who are underserved (Anton & Wilensky, 2019; Tamashiro, Burd, Roque, 2019). Some of my early work explored the role that the physical size of construction kits might have in increasing access to powerful ideas and socially supported learning (Anton & Wilensky, 2019). The StegaCircuits physical computing kit, a set of dramatically scaled-up electronic components ranging from 10 to 20 times the size of traditional electronic kits, acted as an introductory kit to physical computing with professionally-driven materials. Due to the size and design of the kit, learners could playful social and collaborative exploration of circuitry and introductory ideas to physical computing, while avoiding some common cognitive strains related to technical knowledge (Anton & Wilensky, 2019). These constructionist physical computing and robotic kits have been shown to foster interest in computing, support acquisition of computational practices and ways of thinking, and facilitate new forms of engagement with computing for a wide range of learners (Anton & Wilensky, 2019; Bers et al., 2014; Blau & Benolol, 2016; Blikstein, 2013; Roque, Lin, & Luizzi, 2016).

Many of the scholars focusing on artistic or expressive computing situate their work under an emergent subgenre of computing termed *creative computing* (Yang & Zhang, 2016), *creative coding* (Bergstrom & Lotto, 2015) or *creative programming* (Park, 2016). These initiatives are often situated at the intersection of constructionism, maker spaces, and computational thinking. Instead of technical details of computation, creative computing emphasizes the interests of youth, their vivid imagination, and the realization of their creative potential (Benolol & Blau, 2016; Berland, 2016; Blau, Zuckerman, & Monroy-Hernández, 2009; Kafai, 2016). Moreover, programs within creative computing often leverage traditional non-computational craft, practices, and materials as well as computational craft, practices, and materials (Gomes et al., 2019; Roque, Lin, & Luizzi, 2016).

While many of these constructionist initiatives have leveraged creative and artistic practices in service of explorations in other domains of knowledge, there are other constructionist scholars who sought to leverage the power of computation towards explorations in the arts. Early constructionist scholars Bamberger and Sendova sought to use computation to elevate music and art education, respectively (Bamberger, 1996; Bamberger & Hernandez, 2000; Sendova, 2001; Sendova & Grkovska, 2005). Bamberger's work leveraged computational composition of music, allowing students to construct music from differing primitive sizes and representations (Bamberger, 1996). Sendova's work was situated between math, computing, and art fields, and strongly featured the computational creation of abstract art (Sendova, 2001; Sendova & Grkovska, 2005). In this work, Sendova designed learning experiences in which learners could enrich the study of mathematics, informatics, and art by visually modeling abstract paintings (Sendova & Grkovska, 2005). Across these initiatives, they found that learners used not only used great creativity in making their artistic representations but needed to apply mathematical knowledge and practices (i.e., transformations, rabatment, rule of thirds), observed the world around them with a new perspective, and used mathematic and computational knowledge to gain deeper insight into art compositions (Sendova & Chehlarova, 2013; Sendova & Grkovska, 2005). These early efforts were shown to be successful in engaging children's deep thinking while sparking creative epistemologies in both music and art.

Contemporary scholars have furthered the study of computing in music and art education. Researchers have furthered the study of music and computing, showing the growth of positive relationships to computing while developing fluencies in musical and computational practices (Brown, 2020; Freeman et al., 2019; Horn, Banerjee, & West, 2020; Horn et al., 2020; Manaris & Brown, 2014; McKlin et al., 2021; Quigley & Payne, 2021; Repenning et al., 2020; Payne & Ruthmann, 2019; Wanzer et al., 2020). Computational fabrication, sewing, embroidery, and quilting is another vein of artistic practices that are becoming popular within creative computing. These initiatives leverage a variety of programming languages and computing practices to design and produce embroidered, quilted, and sewn artifacts (Kafai et al., 2021; Gursch et al., 2021; Schneider, Boufflers & Benetos, 2020; Wolz, Auschauer, Mayr-Stalder, 2019; Kafai et al., 2010; Buechley et al., 2011). Once again, these programs have shown a wealth of benefits for computational, artistic, and socioemotional outcomes, particularly in groups of learners who are traditionally underrepresented in computing education (Blau & Benolol, 2016; Peppler, 2010; Lindberg, Fields & Kafai, 2020; Peppler & Kafai, 2007; Zhang, 2017). These creative pathways are important for broadening access into computing education, particularly for groups who are traditionally underrepresented in computer science and elective STEM courses. Importantly, these initiatives allow learners to develop new relationships to computing that are personal, social, and cultural in nature, disrupting the traditional perceptions that many youth hold about computing as being asocial or disconnected from community (Margolis & Fisher, 2010). One challenge to creative computing is the epistemological framing of computational thinking and the perceived goals of these experiences. Within computing education, these programs or tools are often perceived as steppingstones into more serious computational work. This mindset may be epitomized by participants of the Maker communities, which tends to showcase larger, more computationally advanced projects and struggle to support and represent the creations made by underrepresented members of the community (Vossoughi & Bevan, 2014). As such, learners who enter these spaces may not feel validated if they are engaging with non-computational or low-computational materials. Moreover, many initiatives within this space leverage definitions of computational thinking from the broader computing education field, meaning there is an inherent orientation towards the epistemologies of CS (Grover & Pea, 2013). Even the computational tools used in computing education are designed with these epistemologies, and do not widely support computing for all, especially for communities that are underrepresented (Litts et al., 2021).

**Contemporary Approaches to Computational Thinking**

Within the last decade, computational thinking has gained international focus, largely due to a shifting economic landscape that values those with computing skills (NSF, 2014). With the pervasive spread of computational tools across careers, these skills are becoming increasingly valued, and required for adept 21st century workers (Grover & Pea, 2013; Kaczmarczyk & Dopplick, 2014). Within this landscape, computational thinking has grown in popularity with funding and resources going towards supporting these initiatives. In the following section, the varying definitions and contemporary approaches to computational thinking arising from the computer science camp will be explored.

With the reintroduction of computational thinking, scholars have worked to identify the core practices and goals of CT, and what differentiates it from computer science. Proponents built on Wing's definition to incorporate concepts of formulating problems with "solutions [that] can be represented as computational steps and algorithms" (Grover & Pea, 2013). The National Science Foundation (NSF) further characterized CT by characterizing seven "big ideas" of computing, including concepts like computation is a creative activity, defining algorithms, and highlighting the role of digital tools/devices in practices (NRC, 2010). These big ideas and definitions were further concretized into a list of elements that reflected overarching concepts key to thinking computationally, including abstractions and pattern generalization, systematic processing of information, symbol systems and representations, algorithms, iterative/recursive/parallel thinking, structured problem decomposition, and debugging, among others (Grover & Pea, 2013). Overall, scholars in the field have characterized computational thinking into broader categories of concepts, practices, and skills, which capture levels of practice and thinking from smaller actions to ways of thinking.

Despite efforts to clearly define the practices and goals of computational thinking, there is not yet a clear consensus on what CT is. Moreover, arguments for CT education often overlap with arguments for computer programming initiatives. Many scholars advocate for widespread educational initiatives to teach fundamental computational skills and can more easily measure, track, and teach the concrete programming practices (Guzdial & Soloway, 2003). These moving definition and nuanced goals bring tension into computational thinking research. As CT overlaps with most fields, there are theoretical disputes regarding the rigidity of the term, with many computer scientists arguing greater alignment with the foundational structures and concepts within computer science while other proponents arguing that there are more general problem-solving skills or ways of thinking that do not require explicit use of programming. For those aligning CT with programming, outcomes and learning can be tracked more concretely, however it can be hard to isolate the specific computational thinking aspects or ways of thinking. For those arguing for CT as disconnected to programming, ways of thinking unique to CT are in the forefront, however these are more challenging to track. As such, progress can be hard to gauge, and it can be difficult to build on the successes and failures of those in the field.

Scholars argue that computational thinking is impactful for all fields, despite the varying definitions that may or may not be situated within computer science. Until recently though, CT has been largely taught in computer science classrooms for several reasons. There is conceptual overlap between computational thinking and programming; coding is often viewed as an important practice for deeper computational thinking practice and ways of thinking effectively about are seen as necessary for more beautiful or more efficient code (Grover & Pea, 2013). As such, curricula can be more easily adjusted to emphasize CT elements compared to non-CS classes. On a practical front, teachers in computer science are already proficient at computing education, making computer science classrooms logistically the easiest space to enrich and explore computational thinking in K12 classes (Guzdial, 2019).

Due to this educational overlap, many computational thinking initiatives experience the same structural obstacles and fundamental image problems as computer science (Grover & Pea, 2013; Margolis & Fisher, 2003). Firstly, there is a limited infrastructure for computer science courses within K12 education. At a state level, only 35% of high schools in the US teach computer science courses, with a subset of 15 states requiring high schools to offer CS (State of

Computer Science, 2018). Of these, only 50% of these provide funding for teacher professional learning in computing. Moreover, within these schools, the number of CS teachers are declining (Guzdial, 2019). The US does not yet have the infrastructure to support scaled computing education.

*Computational Thinking in STEM*

Partially responding to issues of access within the computing field, proponents of computational thinking have more recently argued for the integration of CT in educational domains beyond computer science (Schanzer et al.2013; Peel et al., 2020; Weintrop et al., 2016; Wilensky et al., 2014). Beyond accessibility, these scholars argue for integration of CT in science and mathematics in order represent authentic computing practices and to broaden epistemologies reflected in computational thinking education. These scholars have provided rich theoretical contributions to the field in efforts to define and situate computational thinking beyond computer science. As a primary goal of these efforts is to increase access to computing, both branches of computational thinking are reflected in the scholarship.

Researchers have begun to situate abstract CT principles in concrete practices used in STEM careers. These scholars design K-12 CT curriculum based on the computational tools and practices that experts commonly use in STEM careers (Barr & Stephenson, 2011; Weintrop et al., 2016; Schanzer, Fisler, & Krishnamurthi, 2013; Yadav et al., 2014; Aslan et al., 2020; Bain et al., 2020a; Bain et al., 2020b; Dabholkar & Wilensky, 2020; Swanson et al., 2019). Computational methods are increasingly leveraged in STEM fields and allow new questions to be asked about the world around us as well as supporting new venues for exploring answers. Within education, this approach to integrating CT is built on the premise that computational thinking practices are meaningfully leveraged in STEM careers. The integration of this type of

CT content within STEM courses exposes learners to authentic scientific practice and engagement with real-world CT. Studies of student learning and engagement in STEM courses with integrated CT elements have been shown gains in computational practices and scientific knowledge (Basu et al., 2013; Gendreau Chakarov et al., 2019; Levy & Wilensky, 2009; Papert & Harel, 1991; Schanzer et al., 2015; Swanson et al., 2017; Swanson et al., 2018;  Wilensky, 1999; Wilensky & Papert, 2010; Wilensky & Reisman, 2006). Incorporating computational elements, particularly agent-based modeling, in STEM curricula reflects an embodiment of core scientific and mathematic practices with contextualized representations that make it easier for students to learn programming (Sengupta et al., 2012). As STEM credits are required for high school students, these initiatives work to broaden access to computational education opportunities to all students, while providing learners with valuable skill-based practice for future careers (Wilensky et al., 2014). Moreover, by engaging students in authentic practices that allow them to deeply explore disciplinary content, students may form new perspectives and relationships with computing that could disrupt other negative notions about computing and STEM fields. These ventures are vital for not only building concrete, cohesive educational experiences but also for broadening access to these important computational practices.

Theoretically, these efforts have been vital for broadening definitions of CT outside of computer science, which allows others to design for and situate these practices in external domains more effectively. Notably, Wilensky and colleagues have developed a CT-STEM taxonomy that situates computational thinking practices in science and mathematics (Weintrop et al., 2016). They constructed the taxonomy based on interviews with experts in the field, practicing STEM professionals who use computational methods. Unique to many of the frameworks for CT in the field, the CT-STEM taxonomy captures a set of practices (including data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices) and sub-practices within each, ranging from using to constructing computational tools towards those broader practices. Outcomes from the CTSTEM research team broadly show the benefits of this situated approach for CT; researchers have found that students and teachers are exposed to new epistemologies, engage in authentic practices, and can gain deeper domain knowledge (Arastoopour et al., 2020; Dabholkar et al., 2018; Dabholkar et al., 2020; Peel et al., 2020; Swanson et al., 2019).

Broadly, these efforts to integrate computational thinking in STEM courses are paving the way for more extensive computing education. The positive outcomes in content, affect, and practices in CT integrated STEM courses is a step towards CT integration in classes more broadly. Moreover, as scholars work to build domain situated definitions of CT, we can further broaden access to computing education.

*Computational Framings and Epistemologies*

In addition to broadening access to computing education and computational thinking, some scholars are more critically examining the epistemological framings associated with computational thinking initiatives. These advocates of computational thinking seek to expand the definitions of CT, arguing that the term thinking captures only a subset of the diverse computational practices, perspectives, and epistemologies that appear in the world (Guzdial, 2019; Kafai, 2018; Kafai et al., 2021). While important for providing exposure to authentic skills and practices, the alignment with CS and STEM constrains the epistemologies and perspectives that learners can bring to their explorations in computing (Harrell, 2013; Kafai et al., 2019; Turkle & Papert, 1991). As Kafai and her colleagues argue, the term computational thinking should be defined not only by concepts and practices but also values, biases, and histories associated with computation in myriad fields (2020). This epistemological shift opens the door to new expressions and modes of computational engagement.

In efforts to unpack these perspectives and social factors associated with computation, Kafai and colleagues have made theoretical efforts to introduce a new type of computational engagement, called computational participation, and have characterized the field's framing of computational thinking (Kafai & Burke, 2014; Kafai et al., 2021). Kafai and Burke proposed that *computational participation* may be a more effective approach for situating computational practices within 21st century communities and technologies, as it focuses on the types of interactions, sharing, and engagement commonly practiced with technologies (Burke et al., 2016; Kafai & Burke, 2014). Moreover, Kafai and colleagues captured the primary framings of CT seen in the field: *cognitive*, *situated*, and *critical* (2020). The *cognitive* framing aligns with early descriptions of CT; the focus largely is on providing students with an understanding and competency of key concepts and practices useful for future careers. The *situated* framing seeks to encourage the development of computational fluency through the design and programming of artifacts, and to support self-expression and connection to peers through practice. This situated approach overlaps with Kafai and Burke's concept of computational participation (2014). Lastly, the *critical* framing emerges from the tradition of critical pedagogy, and emphasizes engagement with political, moral, and ethical challenges in the world through the critique, creation, and sharing of artifacts or content. Broadly, this expanded framing of computational thinking supports new epistemologies and types of engagements with computing that are authentic and relevant across a broader range of disciplines and practices. Moreover, by recognizing these framings, researchers and designers can more effectively share and strengthen the educational initiatives within these spaces.

As the field moves towards providing all students with opportunities and experiences in computing, it is vital to reflect on how we are representing computational ways of thinking and practices. Are we, as a field, privileging computing education that is designed to fill future jobs, or are we representing the diverse ways that computing can be leveraged in real world contexts? This shift reflects and extends the ideology of early constructionist advocates of computing education like Seymour Papert, who argued for learners of all ages to leverage the "protean" nature of computers to explore and express powerful ideas through computational constructions (1980).

While important for providing exposure to authentic skills and practices, the alignment with CS and STEM represents a vital but limited set of epistemologies and perspectives that learners can bring to their explorations in computing (Harell, 2013; Sengupta et al., 2019; Turkle & Papert, 1991). Contemporary scholars are also exploring the epistemologies and ontologies of computing, suggesting that expressive epistemologies are leveraged for subjective computing purposes (Harell, 2013). Moreover, researchers in this space reflect that the design of computational media works for artistic and subjective purposes pose different challenges than for scientific and engineering agendas (Harell, 2013). Beyond providing a different epistemological context, art allows students to leverage experience from their own lifeworlds and provide more critical and personal contexts while disrupting hegemony across domains (Sengupta et al., 2019).

The ways we define and conceptualize computational thinking shapes the educational opportunities and spaces that we design for K12 education. As the field moves towards providing all students with opportunities and experiences in computing, it is vital for self-reflection of how we're representing computational ways of thinking and practices. I seek to extend the successes of these prior efforts in creative computing within the domain of art. While my ultimate goals are towards access to computing education, we first need to understand the ways that artists are engaging with computational tools in order to bring authentic practices and perspectives into the classroom and more adequately support creative epistemologies. Like others constructing situated definitions of CT (Weintrop et al., 2016), I argue this work can be further supported by capturing the computational practices and perspectives that appear when "experts" engage in artistic practice with computing. Artists have a rich history of critical engagement with technology and computation that should be represented within the epistemologies supported in our K12 computing education.

## Bias, Discrimination, and Underrepresentation within Computing and the Arts

This review has highlighted the role of computational epistemologies within computational thinking education and suggested the need to further expand these to represent authentic, real-world practices and engagement with computing. Before moving on to explore the approaches to capture these new perspectives within the context of visual art, it is important to reflect on how bias and discrimination within both computing and art fields also impact access to knowledge and space to voice or express themselves. Historically, both computing and the arts have experienced underrepresentation of women and people of color due to bias and discrimination. As such, each field has primarily represented the voices of and supported white males disproportionately to other genders, races, and ethnicities. In the following section, I briefly summarize the bias and underrepresentation present in computing fields and then the arts.

### Underrepresentation in Computing

Computing fields face ongoing underrepresentation of women and other racial and ethnic groups (Margolis & Fisher, 2003). Within computing, women were involved in all stages of the earliest computers, including designing and programming, and were often stereotyped as being the ideal candidates for programming (Gürer, 2002). Moreover, the very word "computer" was associated with women and women's work at this time (Gürer, 2002). However, the computing field became masculinized and largely white, which resulted in women and people of color getting forced out of computing and their participation in the history being overshadowed by men (Frenkel, 1990; Gürer, 2002; Lenz, 2014).

Now, computing has a "fundamental image problem," preventing those underrepresented in computing from choosing computing careers as a pathway (Martin, 2004). A large body of scientific research indicates that there are significant social barriers preventing women from freely choosing computer science pathways (Ceci et al., 2009). Cheryan, Master, and Melzoff argue that many of these social barriers are directly related to stereotypes, acting as gatekeepers to the field (2015). Proponents argue that inaccessible pedagogy, white male dominated culture, and a lack of mentors are responsible for rates of attrition within the CS education pipeline (Lagesen, 2007). For those who do enter the field, discrimination often prevents equally qualified women from receiving the same opportunities as their male counterparts (Moss-Racusin et al., 2012). These social pressures build up, forcing women out of the field and into others with more refined social and cultural engagement.

Underrepresentation of females perpetuates future underrepresentation (Murphy et al., 2007), with stereotypical views trickling down and influencing middle and high school students on their beliefs on what it means to be a computer scientist. This "fundamental image problem" prevents girls and other underrepresented groups exploring courses (Martin, 2004). Scholars have found that computing fields are perceived as difficult or boring (Yardi & Bruckman, 2007), overly "geeky", solitary, or isolated (Margolis & Fisher, 2003), and dissociated from communal goals, like helping society (Diekman et al., 2010; Hoh, 2009). These perceptions mediating participation in computing prevent underrepresented groups from gaining important computational practices traditionally taught in those spaces (Martin, 2004). High school computer science advanced placement (AP) test taking provides a measure of participation within the field overall. The most recent statistics from the college board that are undisturbed by impacts of COVID-19 reflect patterns of underrepresentation prevalent throughout K-12 and higher computing education. Only 24% of AP computer science A and 31% of AP computer science principles students are women, with all AP CS students reflecting less than 2% of total AP students across all subjects (College Board, 2018; Ericson, 2019). In 2018, computer science was tied as having the lowest representation of females across all AP exams. These patterns of underrepresentation remain consistent within undergraduate majors as well (Myers, 2018). Bachelor's degrees in Computer Science and Information Science highlight the underrepresentation of people of color within this field. In the US, statistics of bachelor's degrees conferred by postsecondary institutions in 2020 show that graduates were 49% white, 8.3% black, 10.9% Hispanic, 17.6% Asian, .2% indigenous, 3.8% two or more races (NCES, 2021). These statistics show that in 2020, graduates were 78.6% male and 21.3% female (NCES, 2021). For those advocating for widespread computational thinking, overcoming these perceptions entails tackling pervasive challenges associated with the computing field more broadly.

**Underrepresentation in the Arts**

Within the arts, there is a distinction between participation in artistic endeavors or art education and fine art, regarding historical issues with underrepresentation and voicing. While earlier statistics from the National Endowment of the Arts show that most adults in the U.S. engage with artistic practices or art related content (2021), the fine arts have historically seen challenges with representation and voicing. Art has historically represented the works of white men at proportionally higher rates compared to women and people of color, with only 8% of artist represented in histories of Western art as women and less than 1% were women of color (Davies et al., 2014). Another indication of this underrepresentation can be found in museums. Historically, artists in U.S. museums have been predominately white males (Topaz et al., 2019). Topaz and colleagues conducted the first large-scale study of diversity in U.S. museums by scraping the online catalogs of 18 major museums for 9,000 unique artists (2019). Then using crowdsourcing and a survey designed to guide participants through online searches of demographic information, they were able to infer the genders, ethnicities, geographic origins, and birth decades for artists within the sample (Topaz et al., 2019). From this pool of artists, 12.6% were women (87% men), 85.4% white, 9.0% Asian, 2.8% Hispanic/Latinx, 1.2% Black/African American, and 1.5% other ethnicities (Topaz et al., 2019). The four largest groups represented across the sampled museums were white men (75.7%), white women (10.8%), Asian men (7.5%), and Hispanic/Latinx men (2.6%) (Topaz et al., 2019). From these statistics, it is clear that white men are the predominant voices in classical art spaces in the United States.

Trends of artist representation in art galleries showcase not only underrepresentation but also divergent economic outcomes. McAndrew has studied representation in galleries, finding that women accounted for only 16% of the established artists from 3,050 galleries on Artsy’s database, an online repository of the world’s best galleries and art marketplaces (Carlos et al., 2019; Shaw, 2019). This number rises to 36% for unestablished female artists, or those whose work that has not sold at auction. In another study of 820,000 exhibitions across public and commercial sectors in 2018, only a third are by female artists (Shaw, 2019). Data shows that the more successful a female artist is, the less likely she is to find gallery representation. These studies show that women are undervalued and underrepresented, due to discrimination and cultural biases (Carlos et al., 2019; Shaw, 2019). Moreover, as women age, they earn progressively less than their male counterparts, data showing that artists aged 55-64 earn only 66 cents for each dollar earned by men (NEA, 2019). In sum, the fine art community is also dealing with its own history of discrimination, bias, and underrepresentation that challenges who gains access and success in the arts.

Within the early computer art scene, these trends were more pronounced as art merged with computer science. As Grace Hertlein, one of the early artists in computer art, spoke about representation in exhibits, reflecting that she was the only woman present at many of the first exhibitions for computer art. These early female artists, including Vera Molnar, Grace Hertlein, Katherine Nash, Sylvia Roubaud, Lillian Schwartz, Sonya Rapoport, Ellen Sandor, among others, are comparatively hidden from history (Lenz, 2014). While computer artists generally had to struggle against dismissive or technophobic attitudes towards their art, the female pioneers had to additionally grapple with gendered politics related to computing due to its history rooted in military and engineering, and then the masculinization of the field in the decades after the 60s (Lenz, 2014). As Lillian Schwartz described, ‘I had a reputation in the arts before I got involved in these areas but when I started using computers, my fellow artists began to look on me as a prostitute. I haven’t been able to find an artistic circle where I can discuss the aesthetics of my work.  I've had to replace my artist friends with computer scientist friends.’ Women in these spaces were alienated from traditional art fields as well as computer art fields. Despite these challenges for women and people of color within the arts, their participation has been formative and formidable in expanding, challenging, and theorizing about computer and new media art practices (Lenz, 2014). This perspective about the public access to art and computational art practice is reflected:

> *"The impact of computers on art in the future will be greater because more artists will have access to machines. I have no doubt that the public shall also have access to computers and certainly more leisure time. If computer art is to become 'the public art' it will not be because graphics can be produced cheaply and en masse as some have predicted. It will be 'the public art' because the public will be generating works of art with programs that artists have created."* (Leavitt, 1976)

The patterns of discrimination and bias across computing and the arts highlight differing challenges that need to be overcome across both fields. Moreover, the intersection of computing and the arts may compound the challenges traditionally faced in each field independently. As computing and art field both face issues with representation and voicing, artists at this intersection may have to engage with both fields independently, experiencing the associated discrimination and biases, as programs, communities, and the associated social and cultural norms of these spaces are developed. As these spaces at the intersection of art and computation are understudied and in development as the field adapts to incorporate new computational tools, mediums, and practices, this is an empirical question that can be studied in the future. While many of these trends emerge from systemic barriers in society at large, awareness of these trends can support researchers and designers in addressing access and relationships to these domains within education.

## Restructurations

The last body of literature informing this dissertation deals with the ways that people connect to domains of knowledge and how the representations and tools within those domains can impact access. A common thread throughout computing education is the idea that computing has dramatically changed our lives, including the practice and ways of thinking across most domains. Motivated by expressing the impact of computing on domains, Wilensky and Papert developed a theory to help characterize dramatic changes, termed *restructurations* (2010). They explain that disciplines have *structurations*, or a representational infrastructure that is used to express and encode knowledge (Wilensky, 2020; Wilensky & Papert, 2010). The original structurations can be disrupted when a new one is introduced, resulting in changes to the ways that people encode knowledge within that domain. Their seminal example of a restructuration is the shift from Roman numerals to Hindu-Arabic numerals in mathematics. Division, for example, was originally a lengthy process that required an expert to complete when using roman numerals. With the introduction of Hindu-Arabic numerals, this mathematic process became more accessible cognitively and socially.  This Hindu-Arabic restructuration led to better numerical relationships compared the previous representational infrastructure, roman numerals.

Wilensky and Papert outline five properties of structurations for use in evaluating and identifying restructurations: power properties, cognitive properties, affective properties, social properties, and diversity properties. These properties are present across any structuration and may be impacted differently given a new restructuration. Power properties describe restructurations that do at least but ideally more than what could be done before with the original representational forms. For example, the restructuration of Hindu-Arabic numerals provides the ability to represent large numbers in small (logarithmic) length with place value properties that supports easy construction of algorithms for multiplication and division. Cognitive properties indicate describe restructurations that are more easily learned compared to the original representational forms. The introduction of Hindu-Arabic numerals shifted access mathematical knowledge, allowing it to be accessible for laypeople to learn and practice arithmetic. Affective properties describe restructurations that can make knowledge more or less engaging or likeable. The affective property for Hindu-Roman numerals is challenging to gauge, as there aren't clear measures for changes in the affective relationships regarding these numerals. The restructuration of agent-based models with NetLogo, the agent-based modeling environment developed by

Wilensky (1999), highlights the affective property. Wilensky and Dabholkar have shown increases in interest and engagement in science through the integration of computational agent-based models in science curricula (Dabholkar et al., 2018; Dabholkar & Wilensky, 2020; Wilensky, 2020). Not only did students explore the scientific content more deeply, but they expressed increased interest and enjoyment of the scientific practice when learning with these agent-based models. Social properties describe restructurations that spread in an evolutionary manner through a society. Hindu-Roman numerals spread throughout society, replacing Roman numerals in practice. Important to note, this social process is slow; the shift to Hindu-Roman numerals took 500 years. Finally, diversity properties describe restructurations that can support more diverse backgrounds and epistemologies. Returning again to the restructuration of science with agent-based models, Dabholkar and Wilensky have shown that learners of diverse backgrounds can explore a variety of approaches to using agent-based models in the science class, and that these models support varying ways of thinking about science (Dabholkar et al., 2018; Dabholkar & Wilensky, 2020; Wilensky, 2020). Again, these properties are present across all restructurations but may be impacted in different ways given the restructuration.

Wilensky and Papert argue that the advent of computers acts as a restructuration, or the change in the representational infrastructure to another, across domains. In science, for example, the use of computational tools and questions in computational research has changed not only the common practices and methods of the domain but, significantly, also the types of questions that can be asked. Within the constructionist camp of computational thinking research, these restructurations underlie approaches to integrating computational thinking within STEM classes (Peel et al., 2020; Weintrop et al., 2016; Wilensky et al., 2014). The developments in computing are still ongoing and evolving. We have yet to realize and leverage the power of computation. As such, the full impact of computation in varying domains is yet to be seen.

Art has integrated technological advances throughout the years with resulting shifts in practices, mediums, and genres. Historically, advances in science have followed with artistic applications and explorations of those advances. For example, the scientific discovery of glass enormously accelerated change in the world both scientifically (spawning new tools, architecture, and electricity, to name a few) and artistically (sparking the creation of glass vessels and stained glass) (Macfarlane, 2002). Moreover, the earliest man-made glass appears to have originated from artistic practice. Archaeologists theorize that early glass was a by-product of advances in ceramic design, particularly new approaches for glazing vessels and artifacts (Macfarlane & Martin, 2002; Warmus, 2012). For a more contemporary example of the ways that technological advances have impacted art, in the 19$^{th}$ century, French chemists developed low-cost pre-packaged and synthetic pigments, like ultramarine which had previously been made from ground lapis lazuli (AIC, 2003). With these new pigments, emerging impressionist artists like Monet and Seurat could explore the physiological, psychological, and phenomenal effects of color, light, and perception through their paintings, which often leveraged these pre-packaged synthetic paints (AIC, 2003). As such, synthetic paint was a democratizing advancement in the arts that lead to the emergence of new genres, like Seurat's technique of Pointillism (AIC, 2003). Reflecting on the close ties between art and science, one contemporary artist reflected, "there is no more distinction between art and technology. Artists have always used the medium that is available to them (Paula Gaetano-Adi as cited in Clifford & Waldorf, 2017).

Computing may act as a more dramatic restructuration of the arts than other technological advances in the past. This restructuration is in its early stages, so we cannot yet say how dramatically it will impact the arts. The first computer and computational tools were developed less than a century ago and personal computers were only popularized in the 90's. This is the start of a restructuration that will see larger impact as computation evolves and becomes more integrated with society. However, the initial impact can already be observed through examination of the properties of computation in the arts. There are impacts of these restructurations on artists and audiences alike, which will be explored next.

First, in reflecting on power properties, computers allow artists to create the same artifacts as traditional methods, for example graphics software, like Adobe Photoshop, allow artists to create digital art with myriad brushes that reproduce the effects of other mediums like paint, pencil, or charcoal, among many others. Moreover, other computational tools, like 3D printers, allows for computational creation of ceramics or other sculpture. Computing further allows for new types of practices and interactions, particularly with the audience; for example, artistic games or virtual reality experiences allow the audience to make decisions that impact the works of art they're experiencing. The *Immersive Van Gogh* exhibit reflects a popularized approach for integrating technology in the arts, where classic paintings are reimagined through digital manipulation and animation, are projected on the walls and floors of a large space, then paired with music to create an immersive experience where the audience can experience the classics in a new way (Siccardi, 2018).As explored by the National Endowment for the Arts, these interactive properties of technology and computation are a draw for many tech-centered artists, as they leverage capabilities of technology and computation to engage with their audiences more deeply (2021). At this time, computation has varied impact the cognitive properties, as computational tools add complexity to learning artistic practices while allowing for greater tinkerability. While there are programs that are designed with "low-floors" or easy entryway for novices, most computational tools require artists to learn how to effectively manipulate complex tools and software in addition to understanding the artistic craft. That said, online resources, guides, and communities can support budding artists' acquisition and practice of skills. Moreover, computational tools also allow artists to tinker with their art in ways that one cannot do in traditional mediums. For example, artists using drawing software can layer their digital canvas so that they can easily resize, recolor, or remove elements of a piece of artwork. With computational tools, the artist can tinker, take risks, and explore new techniques without fear of ruining a piece of art.

Socially, computational art practices are integrated in domains widely, as seen in graphic design, UX/UI design, game design, and film, among others. The pervasive nature of computing is not as central in fine arts currently. Fine arts have historically valued and privileged traditional practices and have been slow to accept new traditions or genres that depart from those. As such, the field has not fully embraced computation, particularly as it has the potential to disrupt or replace many of those traditional practices. Computing does engage many affective and diversity properties in the arts, which I cluster as the impact overlaps across these properties. As mentioned before, computational art supports greater possibilities for interactions and engagement with the audience (NEA, 2021). This has potential to change the perceptions of and engagement with art for those consuming, and now interacting, with art. Technology and computation can also democratize art, making these practices more accessible for people to learn and practice. There are many free or low-cost software and tools that support general entry into artistic practice, cutting down the cost of traditional materials like canvas, clay, and paints since these are accessible computationally. Moreover, there are myriad online sites with guides, tutorials, courses, and forums that provide access to artistic practices that would commonly be in traditional formal art education. As such, the general population has greater access to artistic practice and knowledge. While there are many lost-cost options, computational art can be an expensive and resource intensive practice. Physical computing, 3D printing, virtual reality, and other high-tech practices require expensive materials (e.g., microcontrollers, sensors, printing filament) and expensive technology (e.g., 3D printers, virtual reality headsets, subscription to software), making high-tech genres less accessible for artists. Beyond artistic practice, computing democratizes art socially and economically. As described in the section on discrimination and bias in the arts, women and people of color are underserved and underrepresented in history and in exhibits (Carlos et al., 2019; NEA, 2019; Shaw, 2019; Topaz et al., 2019). The internet and social media give artists the freedom to showcase, advertise, and sell their artwork outside of traditional exhibit and museum spaces. Moreover, computational artists create engage in their own communities through Instagram, Twitter, and other social media sites, allowing them to support each other and to share practices and bodies of work outside of the traditional structures within the art field (NEA, 2021). Across these factors, it is clear computing impacts the affective and social properties of arts for practicing artists, potential artists, and art audiences.

While these restructurations to art are dramatic, they have not replaced the traditional styles of art. With the current state, computing shapes new practices, genres, communities, and connections in art. As the restructuration is in early stages, it is yet to be seen whether this will be a full restructuration that replaces other noncomputational mediums. These restructurations impact many properties of the arts, and additional research needs to be done to understand the depth of these changes. Moreover, as suggested at the start of this section, art has impacted technological developments historically and, as scholars suggest, continues to do so with computing (Ghanbari, 2014; Leavitt, 1976; Macfarlane & Martin, 2002; Malina, 2016; Warmus, 2012). I argue that the integration of computational art practices and epistemologies in computing education may act as a restructuration by impacting affective and social properties of computing and may attract and engage a more diverse audience of learners than traditionally seen in the field. However, given fine art's history of valuing traditional practice and craft, I theorize that computing in art will increase in practice but will not fully replace traditional mediums. This dissertation begins to explore the impacts of computing in the arts and the potentials of art in computing by documenting the practices and perspectives of computational artists.

This concludes the review of the various literatures that have informed the design of this dissertation. To briefly summarize and reflect on the intersection of these bodies of literature, the history of computational art showcased a rich relationship between art and computing that begin with the development of the first computers. Since then, art has continued to consume, extend, and create computational tools and methods. As expressed by the artists and the scholars, computing and computational tools dramatically changed the practice and ways of thinking within those genres of art. In this way, computing can be considered a restructuration within art, and additional research needs to be conducted to explore the ways that computing has impacted the perspectives and epistemologies within these computationally enriched genres of art. However, these perspectives and epistemologies should be leveraged in an interdisciplinary fashion to bolster the definitions of computational thinking originating from the constructionist camp of scholars. Those within this camp believe computing education should leverage computers and other computational tools to explore powerful ideas while constructing personally meaningful artifacts. This work seeks to contribute to this constructionist characterization of computational thinking through the exploration and identification of computational art perspectives and epistemologies. In the next chapter, I layout the theoretical framings and study design used to answer the stated research questions and introduce the methodology and analytic approach.

# Chapter 3: Methodology

The heart of this dissertation is a series of case studies of a sample of artists who are engaging in artistic practice with computational tools and methods (George, 2019). These case studies are windows into the computational art epistemologies and perspectives that are present in the larger new media or technology-centered art field. These cases act as first steps towards more thoroughly documenting the field, and in understanding the ways in which computing impacts the arts and how art might impact computing. Building upon the theoretical work of Wilensky, Horn, and the larger CT-STEM team (Wilensky, Brady & Horn, 2013; Weintrop et al., 2016; Peel et al., 2021), I interview practicing artists who use computational tools and mediums in their artwork in order to identify the authentic computational perspectives and practices within the art field. The analysis of this work is grounded in Dewey's theory of *art ecologies*, or positing that art is a social and cultural dialogue between artists and audiences (1934). I extend the art ecology theory to develop a new methodological lens termed *computational art ecologies* to account for the impact of computation within this dynamic. This lens suggests that the use of computation necessitates social and cultural engagement with the computing field, in addition to the pre-existing engagement with the art field that Dewey previously outlined (1934). In the following section, I showcase the theoretical frameworks grounding this work, namely the *CTSTEM taxonomy* (Wilensky, Brady, Horn, 2014; Weintrop et al., 2016; Peel et al., 2021) and *art ecologies* (Dewey, 1934). Next, I establish *computational art ecologies* as a theory and associated methodology. I then introduce the participating computational artists. Finally, I present the data sources and approaches for analysis.

## Theoretical Frames

### CT-STEM Taxonomy

The methodological and theoretical framings of the CT-STEM research team are foundational in the design of this study. The CT-STEM team, led by Wilensky and Horn, have developed a situated definition of computational thinking in science and mathematics, extending the constructionist branch of computational thinking scholarship (Weintrop et al., 2016). While this work was referenced in the literature review, more of the theoretical grounding and methods for developing their taxonomy will be explored in this section.

| Computational Modeling and Simulation Practices | Computational Visualization Practices | Algorithm Practices | Computational Data Practices | Programming Practices | Computational Problem-Solving Practices |
|---|---|---|---|---|---|
| Using computational models to understand a complex phenomenon | Using a computational visualization to understand a phenomenon | Using an algorithm to solve a problem or understand a phenomenon | Using computation to collect and create data | Reading and understanding code | Choosing effective computational tools to solve a problem |
| Using computational models to hypothesize and test predictions | Using a computational visualization to identify and predict trends | Selecting an appropriate algorithm to solve a problem | Using computation to transform, manipulate, and clean data | Modifying code | Using a computational tool to solve a problem |
| Using a computational tool to understand a system's components and dynamics | Assessing computational visualizations | Assessing algorithms | Using computation to analyze data | Writing elegant, readable, and maintainable code | Preparing problems for a computational solution |
| Using a model to understand how positive and negative feedback function and impact a complex system | Modifying a computational visualization to better fit a phenomenon/ data | Modifying an algorithm to better address a problem | Using computation to explore and draw insight from large data sets | Debugging programs | Decomposing complex problems into smaller solvable pieces |
| Assessing computational models | Designing and constructing computational visualizations | Designing and constructing algorithms | Modifying a computational approach to better fit data | Developing modular solutions and abstractions | Systematically troubleshooting a solution |
| Modifying a computational model to better fit a phenomenon | | | | Iteratively designing and testing programs | Modifying a computational tool to solve a problem |
| Designing and constructing computational models | | | | | Creating a computational tool to solve a problem |

**Figure 3 - The CTSTEM Taxonomy, defining computational thinking as situated practices in STEM fields**

The CT-STEM taxonomy is an important shift in representing computational thinking practices that are identified based on their use in domains of practice, rather than abstracted concepts (see Figure 3). This approach emphasizes the important epistemological shifts and restructuration that takes place when computing is integrated in domains; computing not only adapts the practices within the field, but fundamentally changes the types of questions that can be explored (Wilensky et al., 2014; Wilensky & Papert, 2010). They argue that integrating this within K12 education has additional implications for supporting restructurations in both STEM and computing (Wilensky & Papert, 2010; Wilensky, 2020). Learners gain access to real world science and mathematics practices, ways of thinking, and inquiry practices. The computational elements allow learners to engage in the science content in new ways that aren't possible without the use of computation; for example, a computational model teaching gas laws may allow learners to see and interact with particles while constructing an intuitive understanding of the relationship between pressure, volume, and temperature (Levy & Wilensky, 2005; Wilensky, 2003). Computational models and tools integrated in the classroom can provide experiences that support restructurations of content along four factors of scale: time, size, number, and repeatability (Bain & Wilensky, 2021).

In order to identify these practices and ways of thinking, they interviewed scientists and mathematicians that leverage computational tools and methods in their practice (Weintrop et al., 2016). These interviews dug into the tools used, the practices engaged in, and the ways of thinking of these experts while using computing in their domains. To analyze the data, they leveraged codes grounded in computational thinking definitions and identified emergent codes unique to their interviews. From this, they developed a CT-STEM taxonomy 1.0, which consisted of four overarching practices (data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices). Within each of these, twenty-two sub-practices were identified, reflecting a hierarchy of skills and processes related to the overarching practices. Since this first taxonomy, the team of researchers revised the taxonomy, merging categories of practice, adding in two additional overarching practices (algorithm practice and programming practice) and a series of sub-practices, to clarify and streamline implementation in educational contexts (Peel et al., 2020). Importantly, while some of these practices may overlap with computing practices or even apply to nonSTEM domains generally, these do reflect the computational perspectives important in STEM, and have great potential to change learners' relationships to STEM domains and computing.

Within this dissertation, I extend these theoretical and methodological approaches used by the CTSTEM team to the arts. I seek to construct a situated and emergent definition of computational thinking from the arts, specifically visual art. A subtle difference between the CTSTEM approach and the present scholarship lies in the intended application of the taxonomy. The CTSTEM taxonomy is intended to be used primarily in STEM courses and with occasional implementation in computer science or other computing courses. However, in this work, I argue that there is a reciprocally beneficial and impactful relationship between art and computing. As explored in the literature review, these two domains have been entwined since some of the first models of computers, as programmers tinkered with and expressed artistic sentiment while learning (e.g., Christopher Strachey and his computer-generated romantic poetry) (Dreher, 2014; Gaboury, 2013; Montfort & Fedorova, 2012). Both domains are highly dialogic, communicative, and reflective of social and cultural contexts. As such, the intersection gives rise to advances in both domains. Moreover, computing education has leveraged creative and artistic practices since early constructionist educational initiatives (Papert et al., 1971; Upitis, 1989), and many of the contemporary introduction courses feature this type of expressive practice. As such, there is fertile space within computing education to concretize and enrich the creative and artistic practices already being used to engage and teach computing concepts. As such, I seek to identify computational perspectives from practicing artists in service of a CT in Art framework that can be applied to either art education or computing education.

**Art Ecologies**

I leverage Dewey's theory of *art ecologies* as a theoretical framework to conceptualize how artists engage with computation in their art practice (1934). In this theory, Dewey attempts to shift the characterization of art as a product or as a singular piece of art to a view that art is a process fundamentally intended to create an "experience". These artistic experiences, or aesthetics, are entwined with both the artist's and the audience's social and cultural lives. In this theory, the piece of art becomes expressive language, or a dialogic artifact, connecting the artist to the audience. With the artwork, the artist expresses his or her ideas about those shared social and cultural factors in the world. The audience then receives these, and has their own dialogic experience and reflections based on their interpretations of the artifact. This theory is influential, as he was the first to shift focus away from an isolated piece of art. Rather, Dewey focuses on the process and the larger art ecology that influences the creation of a piece of art and the aesthetic experience it provides others. More simply, Dewey's art ecology captures the idea that a piece of art reflects a broader social context and is a line of communication between the artist and the audience.

There are more contemporary theories that represent the systems in which artists practice. Becker's *art worlds*, construct models of art fields that are more complex, containing the participating agents (e.g., artists, buyers, audience), institutions (e.g., exhibits, museums, schools), and tools (e.g., mediums, materials) in art fields (2008). This ecology, however, represents a more traditional engagement with the arts that entail many agents that contemporary artists may not interact with in a professional capacity (for example, museums or exhibits). As such, I extend Dewey's theory of *art ecology* as it represents the engagement that takes place socially and culturally in the arts but does not impose a traditional artistic practice or pathway.

The model is adaptable and can holistically capture the unique agents, institutions, and factors relevant to an individual artist, as not all are participating in the same type of art world.

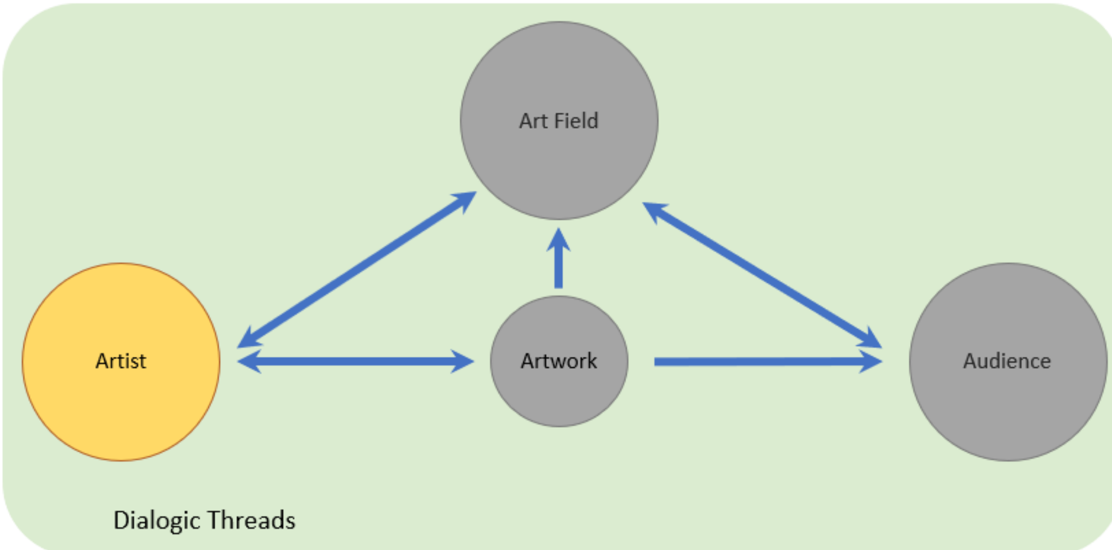


**Figure 4 - A simplified representation of Dewey's theory of art ecologies, in which key agents are represented by nodes and connected with bi-directional links.**

The core elements of *art ecologies* could be represented visually in a model as a series of nodes and bi-directional arrows (see Figure 4). In this model, the key agents become an artist, the audience, a piece of art, and the larger art field, all represented by a node. The piece of art has a directional arrow leading into the art field and the audience, as each individual piece contributes to the larger field and can be received by the audience, respectively. The impact of the art field on emergent art can be captured through the bi-directional arrows connecting the art field and the artist. The audience is connected to the art field as well with bi-directional arrows, as the audience reception to art can influence larger trends and the art field can impact the audience. Lastly, these nodes are all enclosed by the green dialogic threads element. The dialogic threads are meant to represent a dialogue between the artist and something of importance to them, for example their identity, their culture, technology, among others. This is a way to represent the broader social and cultural factors that are influencing an artist's work while constraining it to the factors that an artist is attending to and in dialogue with throughout their art practice.

## Introducing the Computational Art Ecology Theory

As expressed in the literature review, the art field is dramatically changed with the introduction of computing; computing acts as a restructuration that allows both artists and audiences to express, engage, and interact with art in substantially new ways. Moreover, the history on computer and new media art suggests that this relationship is mutually impactful. The first manmade glass, for example, was a byproduct of new ceramic glazing practices (MacFarlane & Martin, 2002; Warmus, 2012). As described in the NRC report, the impact of art on computing, specifically, can be harder to trace historically as the scientific or technological impacts are traditionally more strongly highlighted (2003). However, there is great influence on the design and usability of technology and computational tools from the artist or aesthetic perspective (NRC, 2003). Art has the potential to influence computing, and computing education as much as computing influences the arts. As such, when engaging with computational tools, the computing field must also be represented in an ecology to fully capture the social and cultural factors that are at play during the artistic practice. Moreover, computing adds a dynamic element, as a piece of art can interact with the computing field after it is completed, given communication supported with computing. As described in the literature review, new media art is expansive and representative of myriad computational approaches to art practice. Due to this, the addition of computation adds more variance to the potential agents and connections that may be present for a given artist. For example, an artist using photoshop as a computational tool may have less interaction with the computing field compared to an artist who is making art experiences in virtual reality.

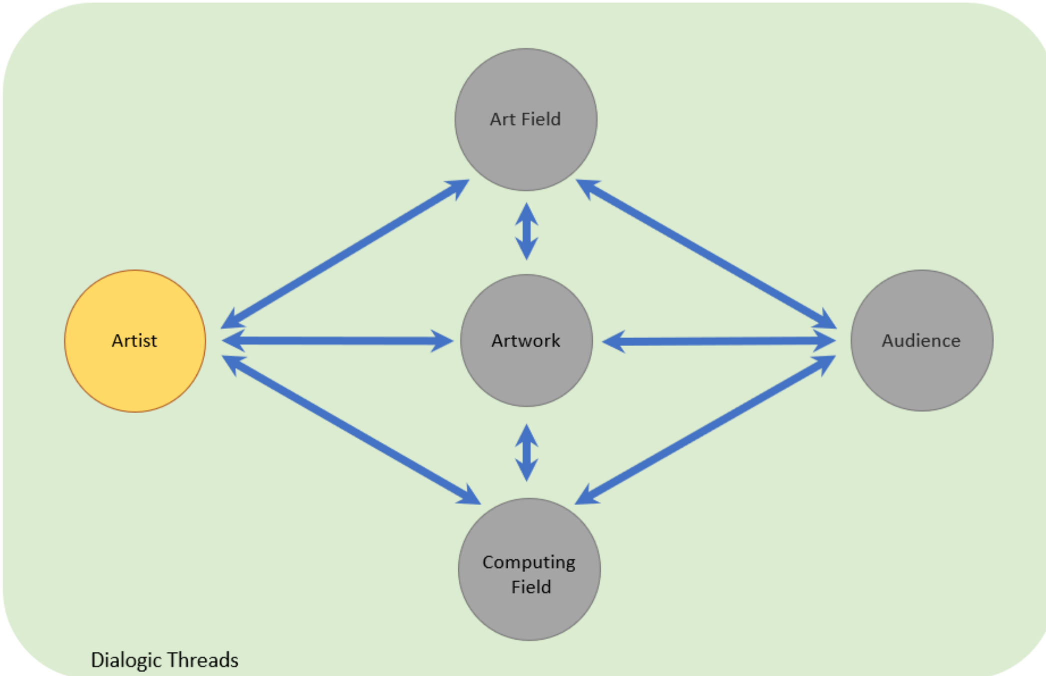


**Figure 5 - Diagram representing the computational art ecology, extending Dewey's theory of the art ecology to a computational context.**

As such, I propose extending Dewey's theory of *art ecologies* to incorporate computing in the art practice. As I will demonstrate, computing in art is a radical shift that necessitates a new approach to exploring and characterizing the experiences of artists leveraging computation in practice. This new theory, *computational art ecologies*, takes account for the restructuration that occurs when computing is introduced to art. The intent is to visualize and characterize the computational nature of artists' practice while recognizing and representing that practice occurs in a complex system with other participating elements. This theory and methodology was developed after interviewing the participants in order to create shared language and structure in analyzing the artists who expressed participation across differing genres and schools of thought. This theory remains largely the same, reflecting that art is a social and cultural process and entails communication between the artist and the audience through a work of art. In the *computational art ecology* model, the role of computing is recognized as a significant influence in the process, potentially impacting the artist, the audience, and the work of art. To define the theory of *computational art ecology*, computational art is a dialogic process that entails communication between the artist and the audience through a work or works of art created with computational tools. These computational artworks communicate and cue engagement with social and cultural factors for both the artist and the audience of both the computing field and the art field. While these social and cultural factors may differ for each artist, all practice is inherently in dialogue in some way with the social and cultural factors for both fields. As computing is dialogic, transdisciplinary, and integrated so deeply in everyday life, its impact on artistic practice may be more varied for each artist as compared to artists who practice in traditional arts.

This theory can be represented visually, to communicate the unique ecologies for individual artists or a general artistic practice that represents multiple artists (see Figure 5). In this model, the artist is represented as a node, reflecting that the model is constructed for a specific artist or group of artists and is not generally applicable to all artists. An artist’s artwork is represented as a central node, connecting the artist and the audience. As these models are constructed from the perspective of the artist, the audience experience is communicated as the artist’s perception of their interactions with the audience and the intended goals of their artwork, as related to the audience. Both the art field and the computing field are represented as nodes. These reflect the engagement with the art and computing communities, respectively, for the artist and the audience. For an artist using traditional mediums, the types of community engagement may be more predictable. For example, community engagement for a traditional artist may entail leveraging the historical practices, situating in art genres, showcasing work in exhibits, attending traditional art classes, among others. The computing field brings another set of social and cultural factors, tools and practices, and history that artists can engage with and leverage in practice. At the intersection of these two communities, we may see varying forms of engagement across these two communities. The links between the nodes in the ecology represent how these elements impact each other. Computational tools and mediums add in potential for new types of interactions, particularly with the audience. In this generic ecology, the bi-direction links connecting all nodes represents the most extreme potential of computing impacting an art practice. In unique ecologies for artists, the directionality of the links will vary with their computational engagement and practices. Finally, artists engage in dialogue with personal, social and cultural factors in the creation of their artwork. The most salient factors for the artists, as they self-identify, can be documented. Within the ecology, this is termed dialogic threads, and represent a dialogue in their art between the artist and something of important to them, for example their identity, their culture, technology, among others. This framing allows the representation of a smaller subset of the social and cultural factors that influence an artist's practice. It is important to note, again, that this representation does not intend to capture all of the social and cultural factors that impact artists, solely the ones they identify as significant in their art practice. This theoretical lens seeks to reflect the impact of computation in the art practice. This may be useful in characterizing emergent "types" of computational artists, which is a research question within this dissertation. These models of art ecologies may support a richer conceptualization of computational thinking in art that can then be translated to education as authentic practices, especially as we work to characterize and build out a landscape of computational practices, perspectives, and goals unique to this space. In the following section, I'll use the *computational art ecology* theory to inform a methodological approach with which these ecologies can be identified for artist.

## Methods and Analysis

As described by the foundational study on tech-centered artists by the National Endowment of the Arts, artists that use computation or technology in their art practice come from a variety of schools of thought, genres, and practices (2021). The overlapping nature of these genres and subgenres makes it challenging for comprehensive studies on the ways that artists use computation in artwork (Grau, 2016; National Endowment, 2021). The identification of artists and the type of work they create is complex and varied, representing the schools of thought in which they were trained. In this dissertation, I refer to participating artists as computational artists, distancing from the name of any one of the myriad genres related to technology, new media, or computer art. This name is useful theoretically to honor individual artist's characterization of their practice while describing the common use of computational tools and practices seen across genres. Additionally, for the purpose of narrowing the population of artists being studied, I focus on artists that primarily create artwork within the visual domain. Again, this term is used to distance characterization away from specific genres within art. Visual art is a genre that not all artists would characterize themselves as participating within; as such, within this dissertation, we explore artists that engage in work that is accessible visually, though it may also have physical, auditory, temporal, or interactive features that would sway artists from characterizing it as traditional visual art.

Artists creating artwork in the visual domain were recruited through cold contact via email or direct message on listed social media accounts to participate in an interview on their use of computational tools and practices in their artwork. I searched for top art and design programs in the United States then identified those with computational or new media programs. I additionally identified colleges and universities in near geographic proximity to Northwestern

University. I focused on a subset of these top and local institutions that included student and faculty biographies on their program websites. Recruitment took place at Cranbrook School of Design, School of the Art Institute of Chicago, Rhode Island School of Design, School of Poetic Computation, and Colombia College in Chicago. From these schools, I identified pools of potential artists from student and faculty biographies. I sought to find an array of enrolled students and faculty to represent different perspectives on technology. Within these schools, the student and faculty directories in the computational and technological related art majors were searched to identify artist profiles that specifically referenced computational tools, practice, or mediums. For example, one recruited participant described her practice as, "[creating] strange and horrible new technologies to explore questions of identity and alienation". Another described himself as, "a hybrid media artist whose diverse range of works include installation, performance, printmaking, video, sculptural objects, handmade paper, artist books, code, net.art, and projections." Artists received recruitment messages via email or Instagram direct message, depending on the contact information provided. Some participating artists volunteered the names of peers with similar computational, technological, or new media backgrounds for snowball recruitment. To protect the creative property of the artists, the consent form included an optional waiver of anonymity. All participants in the dissertation waived their anonymity.

A total of 10 artists participated in the study (7F, 3M; 4 white, 2 East Asian, 2 multi-racial, 2 declined to report). The artists leverage a variety of tools, software, and mediums, including hardware, electronics, kinetic sculpture, live coding, 3D printing, 3D modeling, virtual reality, physical computing, robotics game design, engineering, and videography, in addition to more traditional mediums like performance, painting, and sculpture. One additional artist was interviewed and excluded from the current study due to the characterization of himself as a project manager more than an artist. Due to the nature of recruitment, all participating artists have some experience with higher education in an artistic field. Five artists received bachelor's degrees in an artistic field. Two participated in a degree-less commercial experience in computing and the arts. Six were either actively enrolled in or had graduated from a master's program in the arts. Three were faculty in an arts program at a college or university. Beyond gender, which was inferred through language in profiles, demographic information was an optional component of the study. A subset of the artists reflected on their gender and race in relation to their art practice. A demographic survey was sent to artists after interviewing in order to supplement the demographic information of those who didn't reference in the interview.

**Situating the Participating Artists**

As the intersection of art and computation has not been thoroughly documented, recruitment of participants was conducted to capture breadth of computational practice within a subset of formally trained artists. After recruitment, the National Endowment for the Arts released a report *Tech as Art: Supporting artists who use technology as a creative medium* (2021). This report reflects the multi-year research of the "lived experiences of working artists engaging with technology through formal and informal arts settings." As this reflects the most intensive research across the variety of tech-based or computational art, the report was used to validate the sample of participants in this study and was used as a guide for the recruitment of two additional participants to broaden the sample of artists in this study. In the following section, this report will be explored in more detail and then will be used to situate the artist within this study.

The NRC collected data from four in-person round tables with a total of 66 practicing artists from major US cities, a virtual town hall event with 104 practicing artist, 20 field interviews, 9 artist case studies, a grant portfolio analysis of 150 recent NEA grant awards, and 3 meetings with a tech working group to explore the findings. The report itself is broken into two major themes, 1) ways that artists use technology as a creative medium and, 2) sources of support for these tech artists. The first focus, ways that artists use of technology, acts as a basis for validating recruitment for this dissertation project. They identify that code, computation, data, and tool-building are fundamental to the "tech centered" artistic practice. Moreover, they find that this thread of tool-building "expands access to software and computational thinking, and [supports] the creativity of other artists through an open-source ethos." While the report does not attempt to fully capture the array of practices within tech-centered art, they do note that these practices do tend to bridge virtual and physical spaces, and requires new distinct approaches to presentation, public engagement, and accessibility. They found that tech-centered artists often focus on diversity, equity, and inclusion as themes guiding practice and often focus on engaging communities or audiences in addressing social issues. The report doesn't detail if this is a focus that is more common in tech-based fields, rather that many tech-based artists report this as a motivation. This idea will be explored in more detail in the discussion of this manuscript, developing and situating hypothesis in the reflections of the artists within the smaller sample of this dissertation.

They found that artists in tech-based art field are deeply collaborative and often work across traditional disciplinary boundaries. This trans-disciplinary work can reflect applied artistic fields like graphic design or video production. It also captures genres of fine arts that are merging with STEM or social sciences, for example art-based research, a more contemporary genre of art that leverages creative and artistic approaches to answer research questions in other fields. Finally, the genres of tech-based art are emerging and evolving, often situating artists at the intersection of multiple genres. For example, generative art and computer art are two similar and overlapping genres in the art field that leverage computer programming to create randomly or procedurally generated artwork. However, both have a slightly different practices and associated schools of thought that influence how an artist thinks about their practice, tools, and motivations. Others may question whether the addition of computational practice shifts the engagement in another field; an artist creating impressionist styled virtual reality worlds, for example, may not feel fully represented by only characterizing themselves within painting or new media art. This trans-disciplinary nature translates to challenges characterizing their practice in relation to existing academic or artistic disciplines. These artists are often trans-, multi, or post-disciplinary and work across programs and genres, as described above. They identify that funders and art organizations struggle to accurately assess tech-centered artists, as it requires additional infrastructure and understanding of the computational aspects. Finally, they reflect that tech-centered artists can be invaluable partners for policymakers, educators, and practitioners in art and non-art sectors, as these artists have unique trans-disciplinary expertise and often orient towards social issues around them.

This report provides some validation for the participants recruited in this study and offers a basis from which I can build and extend scholarship on “tech-centered” or computational artists. First, I will situate participants in the findings from the NEA report. I found that all participating artists engaged in some form of coding, though the expertise differs across the artists. A subset of the artists engages with tool-building (3/10) while the remaining artists leverage software and tools in unique ways. One reflected on the use of data in their practice. All engaged with computation in some form, which was a requirement for participation. One participant was excluded as he engaged in more managerial work rather than active computational art practice. Finally, nine of the participating artists situate themselves in relation to multiple genres (including art and technology, new media art, glitch art, sculpture, music, performance, print making, among others) and disciplines (including biology, computer science, engineering, literature, and design, among others), reflecting the NEA finding that tech artists are trans-, multi-, post-disciplinary. While this report provided a thorough and rich examination of tech-based arts, there is space to extend and deepen the research presented by the NRC. There are two primary ways that this dissertation contributes to and extends the scholarship on the intersection of art and computation. First, the report provides an overview of the technological practices of artists in their sample, primarily focusing on the mediums or tools that are leveraged, such as use of coding or virtual reality. This dissertation extends that landscape by examining how and why computation is used in the art practice, capturing the perceptions, beliefs, and motivation guiding practice. As computation is a protean tool, the underlying perceptions and intent for its use in art is vital to fully understand and characterize the intersection of art and computation. Second, the report reflects that engagement with community and creating new interactions with the audience is a common element of tech-based art. This dissertation further extends this by capturing varying motivations and approaches for interacting with and engaging the audience. Broadly, this dissertation seeks to deepen understanding of the relationships and perceptions that artists form towards computation through case studies. Additionally, this dissertation proposes a new theory and associated methodology to help characterize and compare computational engagement in the arts across genres and disciplines. This approach may help bridge the varying schools of thought, genres, and disciplines with shared language and structure so that broader patterns of practice can emerge. As computation is protean and can be used in myriad ways, there's more significance of the intent guiding the use of technology and computation in a work of art or body of work. With traditional art, the expression or language of a work of art may shift (e.g., differences between expressionism and abstract painting) but largely the structure of the communication remains the same. With computation, the structure of the communication and language itself can change dramatically when comparing something like digital painting to virtual reality. Genres like digital painting align more closely with the practices and outputs of traditional art. Emerging technologies like virtual reality may become a performance, video game, interactive experience, immersive painting, among many other potential forms, each requiring different skillsets and perspectives and resulting in different audience interactions.

**Data**

Prior to introducing the data sources leveraged in this dissertation, it is important to note that this research project was conducted during the COVID-19 pandemic. A number of modifications were made to the research plan and methodology to adapt to the constraints of a quarantine and a pandemic. The original research plan entailed on-site studio visits during which observations and interviews would take place. This was important to situating practice for the participating artists. It also included a design and implementation portion in which the computational practices and perspectives in art would be applied to the design of lessons for K12 courses. These lessons were planned to be implemented and assessed based on engagement in and learning of computational and artistic elements. With the pandemic constraints, the plan shifted to focus on the perspectives of artists, which could be more easily conveyed through virtual interviews. While the design of a learning environment could still be completed, this research element conceptually pairs with the educational implementation. Observations of practice and implementations in educational settings are delayed for future work. While this change in research plans shifted the outcomes of the dissertation, it ultimately allows for more in-depth exploration of ways the participating artists are conceptualizing computation in their practice and in the art field more broadly.

The primary data for this study are semi-structured interviews. Interviews were conducted primarily through video-conferencing software and were between 25 and 130 minutes in length, with an average of 67.2 minutes. The interview protocol covered a range of topics meant to elicit deeper reflection on art practice and engagement with computation, and the ways that the two might impact one another. The primary research questions guiding the design of the interview were: How do artists conceptualize the use of computation in their art? What computational practices and perspectives are leveraged during the creation of computationally influenced visual art? These questions guided the design of the interview questions. The participating artists were asked to reflect on themes including experiences with art, experiences with computing, characterizing personal practice, contrasting traditional and computational practices, interaction with other artists or designers, and sharing art with others. These categories and questions were developed to capture deeper perceptions and connections to art, computing, and practice. Artists were asked to reflect on each field independently before exploring the intersection, in attempt to capture nuance in how computation may act as a restructuration in art. For each, artists were asked to reflect on formative experiences with each field, capturing informal and formal training in each field, their personal history in each field, and interest in and impact of the field. After exploring both fields, the artists were asked to characterize their art practice, describing tools and materials, intent, and produced artifacts. Next, artists were asked to explicitly reflect on the role of computation in their practice and how it compares to their experiences with traditional art or traditional computing. The artists were asked to frame these themes in relation to one or more pieces of their art to contextualize their reflections. In this portion of the interview, artists were asked if they could share their art in the moment, either by sharing their screen, showing a video, or by physically showing it to the camera. A subset of artists requested to schedule a second interview to show their work. This allowed conversation to be grounded in a shared artifact to elicit deeper reflection on the use of computation in practice. Moreover, it helped shift conversation away from vague generalizations about art practice and remind the artist of fine-grained detail about their experiences. As the field is evolving and emerging, artists were asked to reflect on engagement in art and computational fields.

The semi-structured nature of the interview allowed for unique questions to be developed for each artist based on their personal websites and biographies prior to the interview. These additional questions often focused more deeply on computational tools and mediums referenced, unique professional opportunities, or teaching experiences. This was meant to draw out unique perspectives on computation and art for each artist, and to help illuminate any external factors that may shape perceptions or engagement with computation for each artist. Finally, unique follow up questions were asked during the interview to account for in-the-moment responses from each participant. The interview protocol can be found in the appendix. Interviews were recorded then transcribed using an Artificial Intelligence transcription tool, named Descript. After AI transcription, the interviews were reviewed and corrected for accuracy.

The secondary data source for this study are analytic memos (Charmaz, 2006; Glaser & Strauss, 1967). These are evolving memos that I wrote to document interactions with and perceptions of the participating artists. Prior to interviews, I would copy their institutional biography and professional biography to the analytic memo then examine their professional websites or Instagram pages, noting observations about their practice and artwork. These were used to generate artist-specific interview questions about their practice. After each interview, the analytic memo was updated about the emergent themes for the interviewed participant. These memos included a summary section that captured key information discussed by the participant, like career, educational history, overview of art practice, artistic and computational tools and practices used. The memo also included a section about the artist's connection to broader art and computing communities. Lastly, general interviewer reflections and interpretations were noted, including connections or similarities across participants, personal reflections on the connection between the interviewer and the interviewee, and connections to emergent overarching themes. These memos were updated throughout the transcription and analysis process as a reflexive practice on my evolving understanding and reflection of these artists and their practice. As described by Herz,

> *"Researchers must become aware of their own positions and interests are imposed at all stages of the research process – from the questions they ask to those they ignore, from who they study to who they ignore, from problem formation to analysis, representation, and writing – in order to produce less distorted accounts of the social world" (1997).*

As I am seeking to develop definitions of computational thinking that emerge within these communities, these reflexive practices allow me to document and reflect on any biases pre-conceptions that I bring to this area of study. An example of this analytic memo can be found in Figure 6.

The final data source is the collection of artifacts from public websites and Instagram pages for the participating artists. These websites act as a lens into how artists frame their practice and their artwork for public display. Prior to interviewing, these public domains were used to orient to an individual artist's practice and develop a subset of personalized interview questions based on how they frame their practice and specific pieces of artwork. After interviewing, these sites were used to capture images and, for some, more detailed information about the process of creating certain pieces of artwork. Images were downloaded and saved in corresponding folders for a specific artist. Text from the site was copied and saved in the corresponding analytic memo for an artist. Artifacts and text from these sources were used to support, expand, and triangulate themes covered in the interviews.

**Data Analysis Approach**

There are two goals of this research, with differing methods for each goal: 1) rich exploration of the experiences of computational artists through thick case studies, and 2) development of an approach, *computational art ecologies*, to summarize and compare computational art experiences across artists. Respectively, these differing goals can be viewed as providing a rich account of computational engagement in an individual artist and a succinct, high-level picture to compare across artists. These two methodological approaches interact within this dissertation but meet two differing goals and answer different research questions, which will be explored below.

This dissertation leverages case studies to explore the computational practices and perspectives that are present for practicing artists in a structured approach that allows for focused comparison (George, 2019). I translate the *computational art ecology* theory to a corresponding analytic lens to construct these ecologies for comparison. The findings of the dissertation are structured to first outline three in-depth cases that reflect similar yet distinct computational engagement in the art practice (Chapter 4). These three cases aid in richer understanding of the relationships that artists form with computation when it is integrated in their art practice. Moreover, the cases showcase the utility of the *computational art ecology* theory and methodological approach for capturing and comparing the unique experiences and perceptions of computation for artists. Following that, I present a summarized case of all 10 participating artists, once again structured as *computational art ecologies* (chapter 5).

**Analytic Memo**

**Participant**: Meimei Song

**Professional website***: https://www.onfailedsystem.com*

**Practice***: cyber companion plant, how to walk with plants; appears to intersect nature and computing (pre-interview);* intersection of art and science, reflecting on politics

**SAIC biography***: Meimei Song is a second year graduate student from Guangzhou, China. Her work takes form in performative art tour and speech. Through engaging the site with installation, performance, and videos she explores the poetic parallel between virtual and real, human and non-human.*

**Date of interview***:* 7/22/2020

**Education**: BFA studio art @ SAIC; masters Art and Tech @ SAIC; school in China through middle school then high school in the US

**Career**: Artist

**General Summary:**

Meimei sees herself at the intersection of biology and art. She mentioned the use of technology as a medium but when asked later, she said it was more than just a medium but another perspective. Her interests in tech are around the human, everyday aspects of it. The professors call her low tech – but this reflects a broader/less in-depth approach to the use of technology. She does a lot of performative art that incorporates different mediums and satirical aspects/critiquing concepts in science/environmental science. She says that she wants to bring art into science – not just as a visualization or to make science more accessible but to provide a different perspective and the use of narrative. She was able to screenshare to show some of her work and sent a portion of her thesis work (video "Work example_MS_carp").

**Connection to Broader Communities:**

She comments that technology and art is very political; she describes her program as white male heavy and with recent uptake with international students from China and from Korea. Mentioned power dynamics are present in the field because she is an international student and most of her teachers are white men. Moreover, there are challenges with using "low tech" in her program. As such, she feels misunderstood.

Rather than connecting with the computing fields, she seems to connect more with science communities. Computing is one of many tools that she leverages. The "low tech" aspect and perspective of the SAIC on tech seems to impact how she orients towards the computing community.

**Interviewer Reflection:**

- Didn't mention technology a lot without explicit prompting from me. The focus in her work seems to be more of the narrative/intersection of art and science.
- Cares about giving her audience a different experience/perspective
- Reflects that technology has a communal effect – many traditional mediums are very solitary, but tech creates space for community
- *Art and tech may mirror the dynamics of computer science fields. I wonder if this is more so related to the normative vs. non-normative approach to exploring this space. E.g. would students from school of poetic computation have a different approach/reflect different communities compared to those at a prestigious art program?*

**Notes from Processing Transcription:**

- Reflection on purpose of art, focusing on concept of capturing and sharing experiences that are "deeply human":
    - 14:53: "So, so, so like something that's deeply human, like curiosity, right? Like how do you make that into art?"
- Intersection of politics, humanity, art:
    - 15:32: "capitalism kind of, uh, you know, constructs or made things make objects in a way that kind of dehumanize people. So if you're kind of working as part of a machine, um, and a lot of the time art is trying to rediscover the humanist and to embrace that…"
- On finding balance of using technology in her artwork. Reflects on issues of power and accessibility to tools and human/expert support
    - 20:48: "everyone has their own balance. And, uh, I think I am still figuring out my, um, and, and you know, it's not just technology is not just technique and concept it's also about power…."
- Programming experience: Learning to code but so she can "navigate" and use software and computational tools more efficiently and easily.
    - 28:55: "So you need to have some basic knowledge about programming sometimes to do small adjustments. Uh, I mean, you can also rely on the existing stuff that other people, uh, write in code, but if, you know, like the basic it's really helpful…"
- *Researcher Reflection: Recurring theme across interviews appears to be that the cost and access to technology creates a lot of barriers in art. This is unsurprising, as this is the case for pure tech fields. However, some artists seem to struggle with what it means to engage with these tools that have so many barriers, especially related to power structures and privilege (36:43) (i.e., ann, Janell)*
- *Researcher Reflection: "low tech" versus "high tech" – term used within, at least, the SAIC community to describe technological and computational practice in art*

**Figure 6 - A selection from the analytic memo written for the artist Meimei Song.**

Broad patterns identified across these cases are highlighted and interpreted. In the following section, I outline the analytic lens associated with the *computational art ecology* theory. I next outline the approach for identifying structural patterns across these ecologies.

To ‘identify the universe’, or context that these cases reflect (George, 2019), I formally outline the phenomenon of study and the research objective for these cases. First, the phenomenon of interest for these cases is that of computational engagement in the arts. As mentioned previously, I look towards a population of artists characterized as computational artists that practice in the visual domain. Given recruitment methods, these participants are from a population of artists who have experienced formal higher education within the arts. Second, the research objective for these cases is to provide exploratory breadth for the ways that artists are conceptualizing and leveraging computation in their art, and the ways that computation can impact practice. Moreover, the three in-depth cases were identified as they reflected computational art ecologies that were thematically similar but engaged in very different computational engagement. Finally, these cases are in service of identifying a breadth of computational practices and perspectives emerging from artists who have engaged in formal educational training in the arts.

Interviews were coded deductively (Miles, Huberman, & Saldana, 2014), with codes derived from the *computational art ecology* (CAE) model. Interview episodes were coded to capture the artist’s *relationship with computing*, *relationship with art, relationship with audience*, and *intersection between art and computing* reflecting the key elements in the *computational art ecology* introduced earlier in the chapter (see Figure 5 for computational art ecology model; see Table 1 - The codebook for the *computational art ecology* methodological lens.for codebook). The code *relationship with computing* reflects the artist’s engagement with the computing field, as described in CAE. Operationalized, *relationship with computing* details the socioemotional or cognitive interactions with technology, computers, computational tools, or computing communities. The code *relationship with art* reflects the artist's engagement with the art field, as described in CAE. Operationalized, *relationship with art* details the socioemotional or cognitive interactions with art, design, creative and artistic practices, or artistic communities that do not entail use of computation. The code *relationship with audience* reflects the artist's engagement with the audience node, as described in CAE. Operationalized, the code *relationship with audience* details the design, reflection, or perception of audience interactions with the artist. The representation of the audience is through the perception of the artist, as this study does not entail any examination of audience perception or reaction to a given artists' work. This is fertile space to explore in future iterations of this research. The code *intersection between art and computing* reflects the potential overlap between the art field and the computing field, namely how the artist conceptualizes this overlap for their personal practice. Operationalized, *intersection between art and computing* details the ways in which artistic or creative practices co-exist with practices related to technology, computers, computational tools, or communities. The intersection can represent practice, or affective and cognitive reactions. After using these codes to characterize an artist's interview, these episodes were examined within a code category to identify the significant themes and experiences relevant for each participating artist. These emergent themes were qualitatively described and then synthesized across each code to develop a case study for each artist. The social and cultural factors significant to each artist were identified through the synthesis of these five codes. These are holistically determined through an examination of the cases and the elements that are discussed frequently by the artists.

**Table 1 - The codebook for the *computational art ecology* methodological lens.**

| Code | Definition | Example topics | Example Quotes |
|---|---|---|---|
| *Relationship with computing* | Detailing the socioemotional or cognitive interactions with technology, computers, computational tools, or computing communities. | • Describing experiences in computer science education<br>• Describing interactions with computers throughout childhood<br>• Describing emotional responses to the tech industry | • "I think it's important or worth noting that I am the child of a computer programmer. So that's very deeply a part of me." (Anna Christine)<br>• "I think more so I am thinking about technology as how it impacts people's life or how it changes us. And there's also a lot going on we could dig into like the technicality aspect of technology. But I think I for me, I'm mostly interested in the way, similar to how like electricity or industrial revolution changes our society or how agriculture changes humans, like how technology nowadays is changing human." (Meimei)<br>• I, the moment I felt like computer science was something that was knowable to me was when I took a class in SFPC with Ramsey, when he explained how compilers worked, basically… And that was when I was like, Oh, this isn't magic. You know, computer languages written by idiots, just like us. We can totally do this and that moment that it became knowable and opened the whole kingdom up. Cause then I was like, Oh, it's not impossible. (Sarah) |
| *Relationship with art* | Detailing the socioemotional or cognitive interactions with art, design, creative and artistic practices, or artistic communities that do not entail use of computation. | • Describing experiences in art education<br>• Describing childhood creative practices<br>• Describing engagement with art communities, like exhibits | • "I know people that are successful as I'm sure you do too, in the gallery scene. And that notion that you're, 'Oh, you're the person that makes the so and so's and you sort of make that' that essential example. And they're doing variations on that for a long time. That just sounds so boring to me that it's not that I've been offered that opportunity, but that's what I tell myself at least." (Taylor)<br>• "I've always liked art ever since I was a kid, I had always liked draw and sketch and, you know, just like very traditional - oh, it's in traditional mediums, just like sketching on your pads and drawing with a pencil and things like that. Always really enjoyed world-building" (Iva)<br>• "For me, art is working on like a more critical conceptual level. Um, like there's more abstraction there." (Cody) |
| *Relationship with audience* | Detailing the design, reflection, or perception of | • Describing goals for art that focus on audience engagement | • "So like a lot of people have always been like for pricing, my work is really difficult |

| | | | |
|---|---|---|---|
| | audience interactions with the artist. | • Describing types of interactions or responses received from the audience<br>• Describing uncertainty with addressing the expectations or needs of the audience | because they're like, 'you didn't make it, you clicked print'." (Cody)<br>• "But I think for the virtual reality I think it's different with, it can help people. It seems like they can enter a different, so world and this world they could explore these virtual worlds by themselves so they can make the choice which parts they were most interested in and which parts they will focus on. So I think it's different because when the people see something different people will have different opinion or they can have, hmm, they can get the different information." (Yimin)<br>• "I do feel like I have a little bit more control over saying, like, I want this thing to evoke this particular feeling, but it's a little less of my focus. Like I feel like if I put a feeling into it then maybe people will get that one out of it and maybe they'll get something else that's important to them. But like, I'm always just so pleased if people are paying attention and willing to engage that, like, whenever you get out of it, man." (Sarah) |
| *Intersection between art and computing* | Detailing the ways in which artistic or creative practices co-exist with practices related to technology, computers, computational tools, or communities. The intersection can represent practice, or affective and cognitive reactions. | • Describing first experiences using a computational tool while creating art<br>• Describing the challenges of marketing computational art<br>• Describing the goals of artistic practice that entail both computing and art | • "If I do have the tech in my art. I try not to make it like, I guess, the word I keep thinking of, like, just make it quieter. Like it's not too flashy." (ann)<br>• "I took more of a poetic approach maybe in my senior year when I was starting with like data bending which is like most people's first foray into glitch art. You can add text into the characters. So, I would type in secrets… And I loved that I could like produce that in an image, have a result from it. And then someone could look at it, see what I was saying, but not know that they were seeing it. I thought that was really fascinating." (Anna Christine)<br>• "I think for artists, who's working on art and science or art and technology like intersecting both subjects, they are also exploring certain kinds of narratives that you know, that's like maybe something art can bring to the table." (Meimei) |

*Constructing Computational Art Ecologies*

After synthesizing the *computational art ecology* codes into a summary or in-depth case, a unique computational art ecology model was created for each artist. Each ecology represents the unique practice of an individual artist. To create these unique ecologies, the nodes and links can be modified, which will be explained in more detail next. The nodes can be added to represent significant elements in the artist's practice. For example, if an artist engages with the science field in addition to art and computing, an additional code can be added to the model to represent this participatory element. Other artists may collaborate in their practice, necessitating additional nodes to represent those agents. The nodes can be increased or decreased in size to represent how large of a role they play in the art practice. For example, an artist who makes artwork for themselves would have a smaller audience node compared to someone who explores computational approaches to support interactive audience experiences.

Next, the links reflect the relationships or influence between the nodes in the ecologies. As mentioned previously, the links shown in the template computational ecology reflects an extreme version of the impact of computation in the art practice. The links can be modified in three ways, First, the directionality of the link indicates influence or impact between two nodes. For example, an artist may not intend for the audience to think about or engage with ideas from the computing field, so the link between the computing field and the audience could be removed. Directionality of the links suggest the origins of impact or influence. For example, in traditional visual art, the audience members primarily view or consume the artwork. Depending on the artist, some may adapt their artwork for their audience, which would entail a bidirectional like. It is more common that there is bidirectionality from the art field to the artist, accounting for critics or curators, among other roles, that may influence what an artist creates. This could be modeled with a one directional arrow leading from the artwork to the audience. Bi-directionality suggests a mutual impact influence. Returning to the link between the artwork and the audience, an artist may create a piece of artwork that is interactive and changes its output based on audience input. In this situation, the audience is influencing the artwork and changing it dynamically while the artwork is influencing the audience, warranting a bi-directional link. Second, a solid or dotted link represents whether there is always a connection or if there is an occasional connection. For example, an artist may sample from a variety of traditional and computational tools, only using the computational tools in their artwork a portion of the time. This engagement would warrant a dotted connection between the artwork and the computing field. Third, the weight of the link represents the significance of the connection for the artist, with a smaller weighted link representing less significance and a larger weighted link representing greater significance. Given the small sample size and necessity to identify measurements for significance across many elements, the weight will not be adjusted in the analysis for this dissertation. Additional research will need to be done to identify measures that can capture and represent significance meaningfully across artists and across elements of their artwork.

The last component of the *computational art ecology* that can be modified is the dialogic threads element that surrounds the links and nodes. This can be adjusted to represent the unique factors that an artist attends to and engages with throughout their practice. Each is meant to represent a dialogue between the artist and something of important to them, for example their identity, their culture, technology, among others. The dialogue showcased in the ecologies are not intended to be fully representative of all the potential dialogues or factors influencing the social and cultural worlds in which the artists reside. The dialogue represented captures the subset that the artists identify and reflect on throughout their interviews. The artist intent, or the broader motivation for their artwork, is used to label the dialogic threads element. The element itself is reshaped to represent the nodes that the artist primarily engages in dialogue with through their artwork.

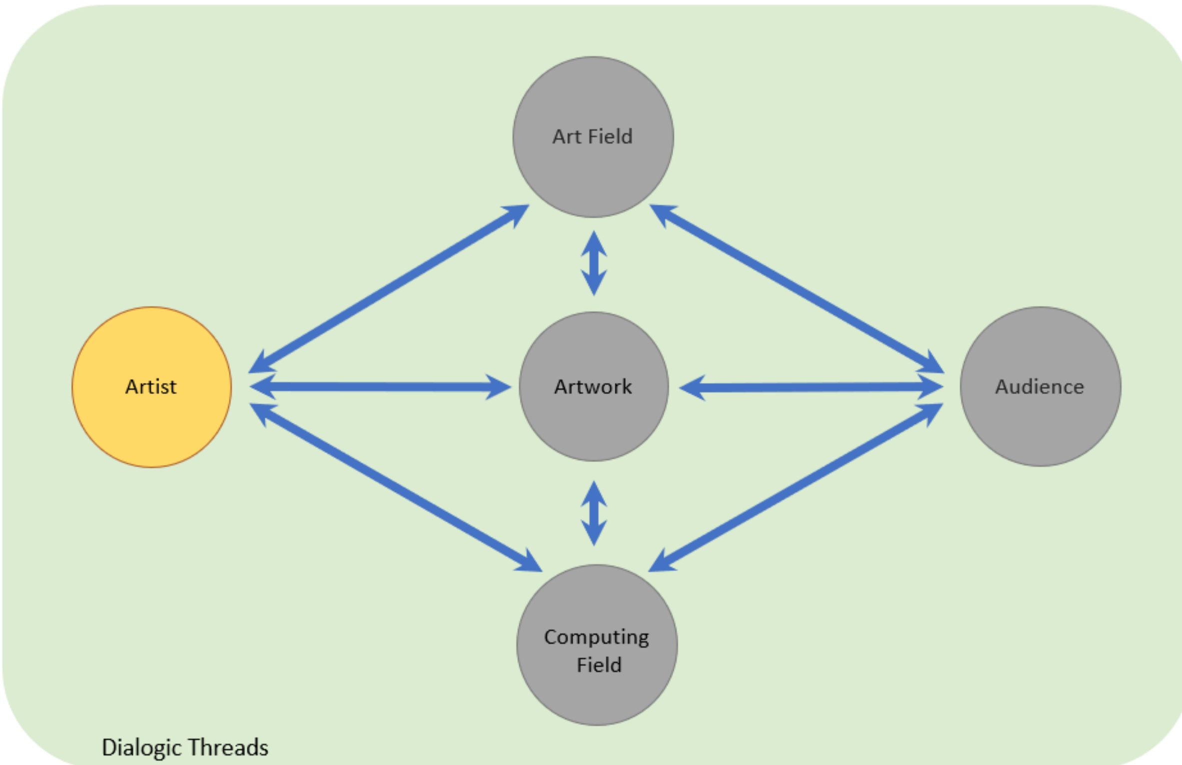


**Figure 7 - Generic computational art ecology**

To visualize how these are constructed, I present a brief hypothetical case of an artist and then create the *computational art ecology* for their practice. Clara spent her childhood dancing, attending formal classes and performing regularly. Her dance practice dropped off after going to college, but she remained passionate about dance. In a computing elective, she realized she could combine computational measurements and visualizations with movement from dancers to generate visual artwork. She sewed microcontrollers and sensors into some of her clothes and collected motion and acceleration data while she danced. After collecting the data, she explored various approaches for translating the raw sensor data into visual artifacts that could represent the beauty of dance in new ways. She decided to make a series of videos that show how the data changes over time and translated the sensor data into visual elements (e.g., hue, shape, distortion, etc). She then showcased these in an art exhibit at her college.

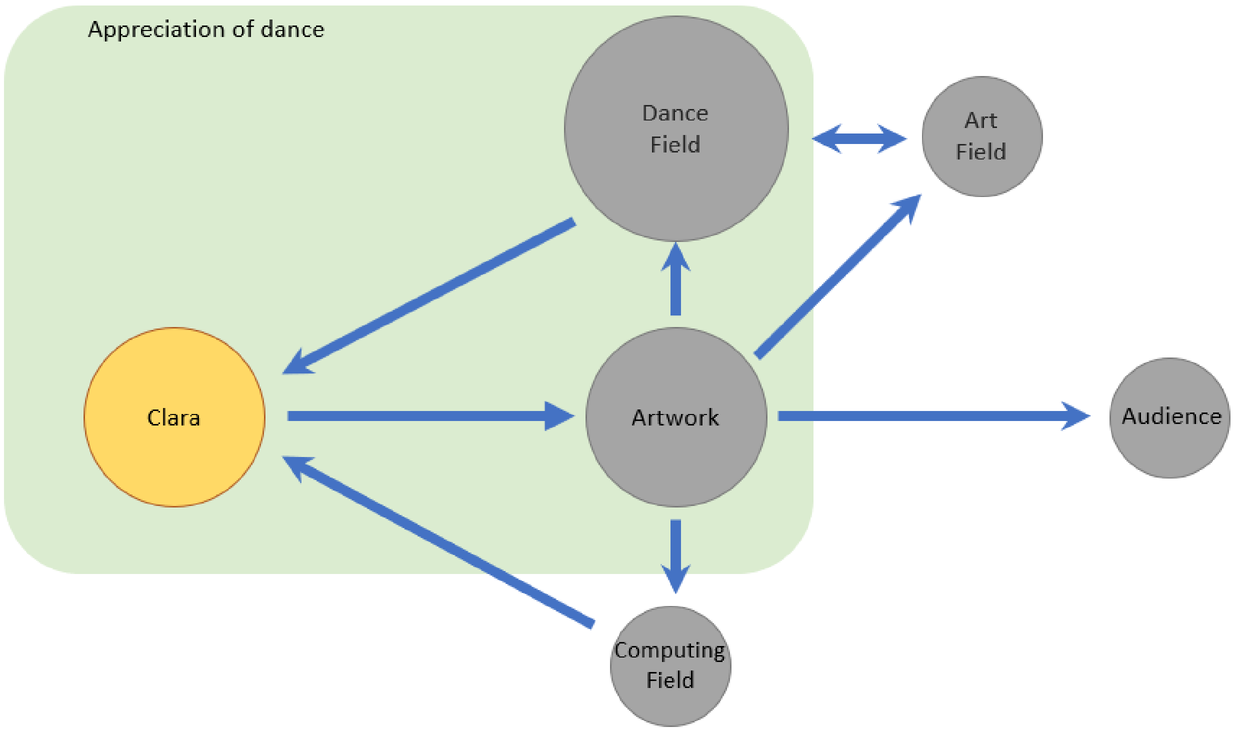


**Figure 8 - A computational art ecology constructed around the hypothetical case of Clara.**

Based on this hypothetical case, a *computational art ecology* was created for Clara (see Figure 8) that can be compared to the generic ecology (see Figure 7). In this, there are differences to the nodes, links, and the dialogic threads element compared to the generic ecology. First, as Clara is primarily interested in dance, a dance field node was added to the ecology and was increased in size to reflect the role in her practice. Again, node size reflects the significance of the element in the art practice more broadly. Next, both the computing field and the art field nodes were reduced in size as she did not seek to engage with these communities directly but intended to deepen her engagement with dance. The audience node was also decreased in size, as she was engaging in the practice primarily for her own interests and not in service of engaging the audience. Compared to the generic model, the links have changed significantly. Primarily, there are more one-directional links connecting the nodes, as this practice is not particularly self-reflexive. A one directional link starts from the computing field leading to Clara, as interaction with the tools in the field inspired her to begin this artistic practice. The connection between Clara, the artwork, and the audience is all one directional starting with Clara and leading to the audience. Clara did not use the practice to inform her thinking about computation or dance nor did she iterate and create variations of her artwork, warranting a one-directional arrow rather than bi-directional. The artwork is showcased in an exhibit without any interactive features, meaning that the audience consumes the artwork in a more traditional manner. Moreover, Clara doesn’t intend for the audience to engage more deeply with the art, dance, or computing fields, so there are no links connecting these elements. The artwork contributes to expanding both the dance field and the computing field by adding to a body of scholarship related to both, reflecting the one directional links leading from artwork into both fields. Finally, the dialogic threads are adjusted to reflect the focus on Clara exploring her personal expression of dance, as such this element frames Clara, the dance field, and the artwork nodes. Finally, it is labeled appreciation of dance, as this motivates her practice. This very simplified case highlights the process of modifying the *computational art ecology* to represent the unique practice of an artist. This process for developing ecologies will be explored in greater detail in the following chapter through a comparison of three artists’ practices.

*Identifying Overarching Patterns of Practice*

After constructing the computational art ecologies for each artist, the ecologies were compared to identify structural patterns that might characterize types of computational artistic practice. To do so, the ecologies were clustered based on differences in node sizes, the types of links in the model (i.e., one-directional or bi-directional), and the orientation and positioning of the dialogic threads element. The theme characterizing each cluster was identified through grounded thematic coding of the cases and were iterated on to determine the connection to the structure of the ecologies (Charmaz, 2006). Three major structural patterns were identified and used to characterize ecologies that fall under a broader category I call *computational participation in the arts*. This reflects ways that artists leverage and engage with computational tools and systems throughout their broader artistic practice. Within *computational participation in the arts*, the codes *computational tool use*, *computational community*, and *computational reflexivity* were identified as three major spectrums of computational participation in the arts. The first two codes relate to the horizontal and vertical positioning of the dialogic threads element in the *computational art ecologies*. The dialogic threads element, again, is adjusted to frame the elements that the artists intents to engage in dialogue with during their art practice. As such, this element is placed to frame differing nodes for each artist, depending on their artistic intent. The orientation of this dialogic threads element can be conceptualized as falling along horizontal and vertical axes like (x,y) coordinates. The varying horizontal and vertical orientations will be detailed below.

The horizontal orientation of the dialogic threads element is how the dialogic threads element falls along the X-axis of the ecology (see Figure 9). This element can orient on a spectrum from the left to the right side of the ecology. Within the art practice, this structural orientation is associated with *computational tool use*, which is a spectrum of how artists interact with the computational software, machines, and methods within their art practice. This ranges from a focus on engagement with the tools themselves (left leaning) to a focus on the application of tools in new contexts (right leaning) (see Figure 10).

The vertical orientation of dialogic threads element can also shift across individual ecologies, framing the top to the bottom of the ecology (see Figure 11). Within the art practice, this structural orientation is associated with *computational community*, which a spectrum of how artists use computation to engage with certain groups connected to art and computation, among others. This ranges from a greater focus on engaging with the art field (top) or the computing field (bottom) (see Figure 12). Additionally, a central placement suggests limited engagement with either field while a placement spanning from the top to the bottom suggests equal engagement across both fields. This structural orientation of the dialogic threads element can be interpreted as the ways in which computation supports an artist's engagement in and across fields. The final structural pattern used to analyze cases was the directionality of the links in ecologies. These structural patterns illuminate some approaches for computational practice that occurs in the arts.

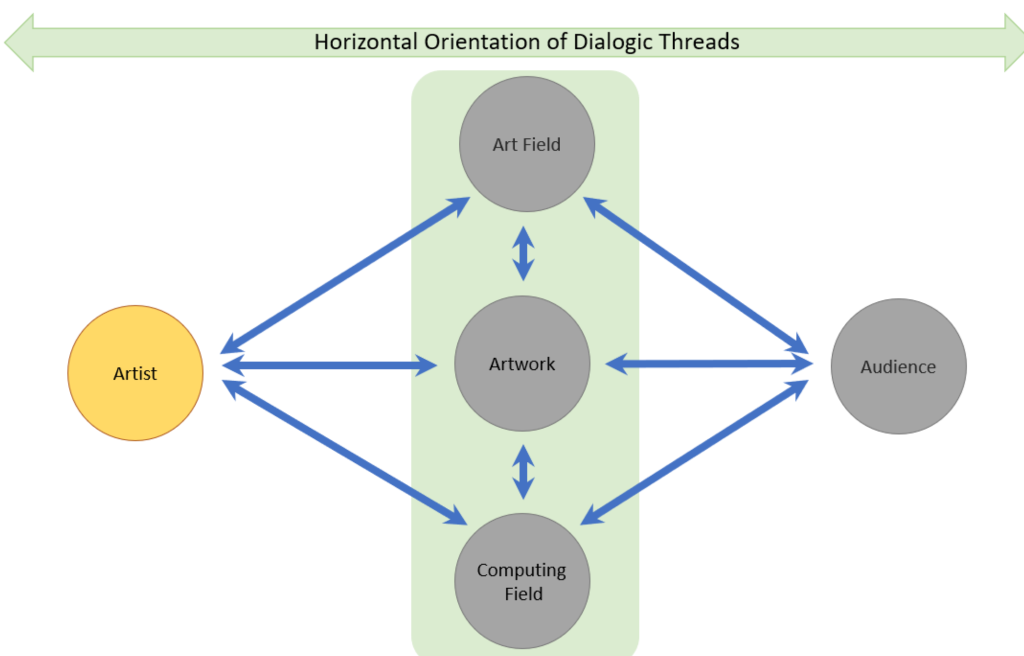


**Figure 9 - The generic computational art ecology with the horizontal orientation of the dialogic threads element highlighted.**

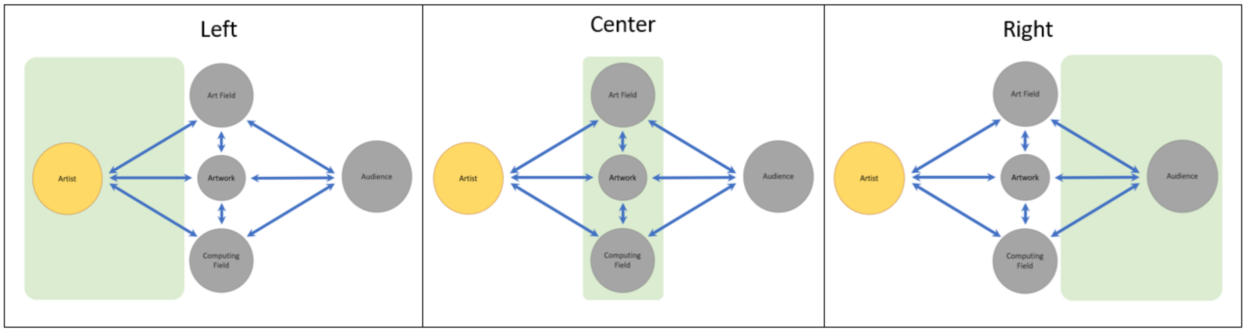


**Figure 10 - The spectrum of horizontal orientations for the dialogic threads element from left to right leaning in the ecology.**

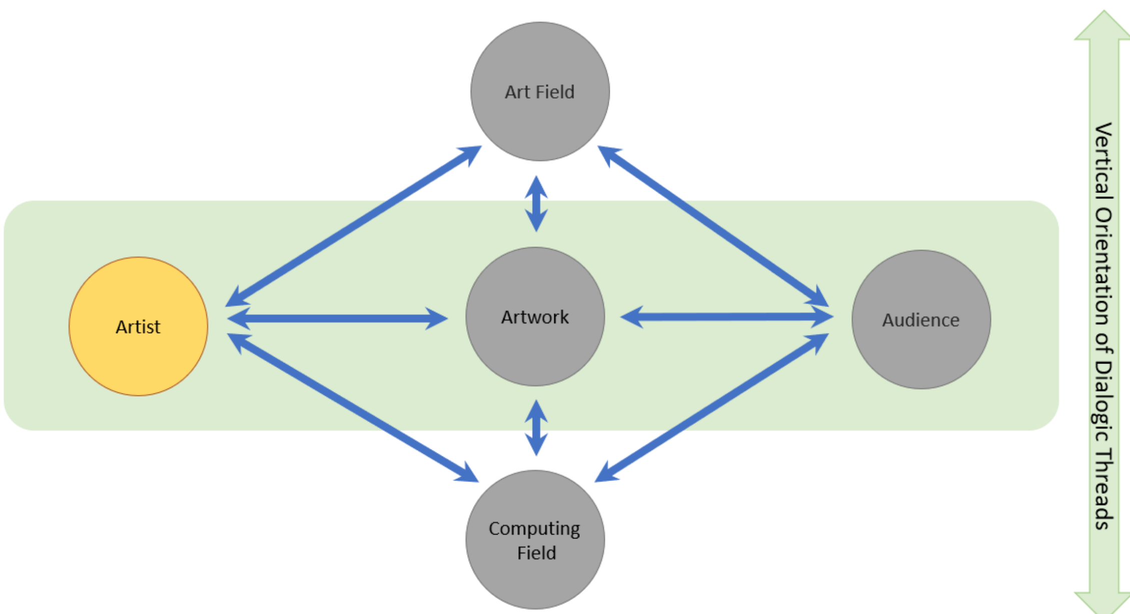


**Figure 11 - The generic computational art ecology with the vertical orientation of the dialogic threads element highlighted.**

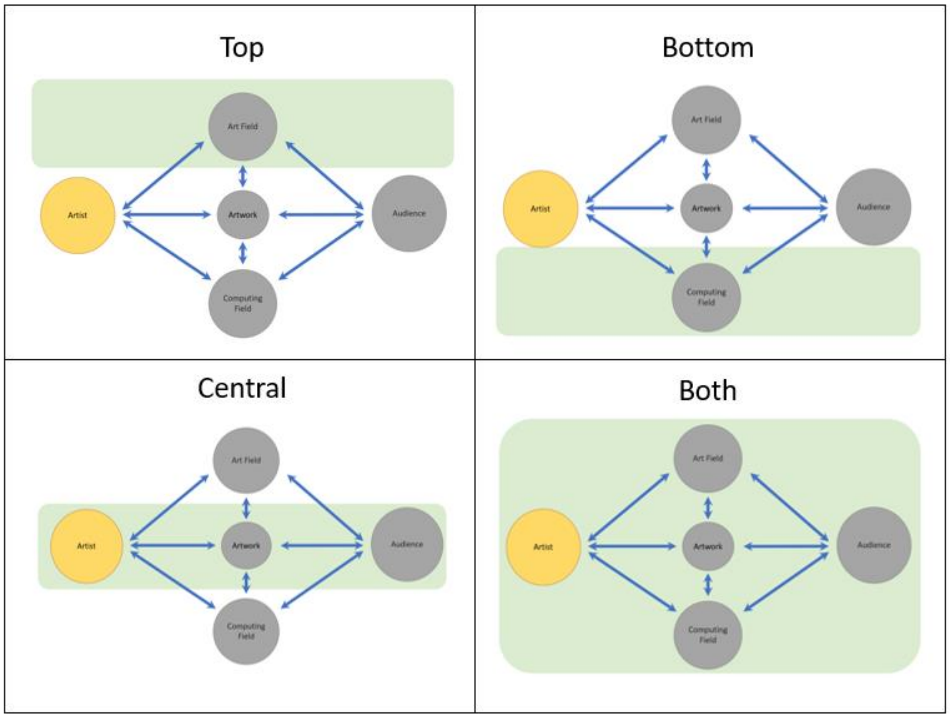


**Figure 12 - The spectrum of vertical orientations for the dialogic threads element from top to bottom of the ecology.**

After exploring the patterns of practice, emergent coding was used to characterize themes overarching the motivation and *intent in computational arts*. These emerged from characterization of cases, rather than looking at the structures of the ecologies explicitly. From this, five types of intent were identified: 1) *computational expression*, 2) *computational inquiry*, 3) *computational connection*, 4) *computational critique*, and 5) *computational subversion*. *Computational expression* entails the creation of art that focuses on communicating and sharing ideas or experiences through computational tools or systems.  *Computational inquiry* entails the creation of art that focuses on exploring phenomena or experiences related to tools or systems. *Computational connection* entails the creation art that focuses on building or breaking relationships related to computational tools or systems. *Computational critique* entails the creation of art that focuses on evaluating or critiquing computational tools or systems. Finally, *Computational subversion* reflects the creation art that focuses on breaking, manipulating, or modifying computational tools or systems. A richer description of these patterns and themes will be described in detail in chapter 5. Together, the patterns captured by looking at these computational art ecologies represents central engagement and perspectives leveraged during computational art practice. Moreover, they contribute to a budding understanding of the epistemologies that appear within the computer and new media art fields.

**Research Questions**

With these data sources and analytic approaches, three research questions are answered.

4) In what ways does the methodological lens of *computational art ecologies* add insight into identifying computational perspectives in artists?
5) How do artists conceptualize the use of computation in their art? What computational practices and perspectives are leveraged during the creation of computationally influenced visual art?
6) What is a preliminary framework for computational art practices that could serve as a basis for educational design at the intersection of art and computing?

All research questions are explored through the examination of cases and *computational art ecologies* that are constructed using the interview data, artifacts from public websites, and supported with analytic memos. The first research question in this dissertation explores the ways in which the developed *computational art ecology* framework can be used to identify computational perspectives in artists that leverage computational tools and practices in their work.  To answer this, I compare three in-depth cases of computational artists and construct unique *computational art ecologies* for each. I show the process for using this analytic lens to construct unique ecologies then compare the artists using both the cases and the structural similarities and differences in their ecologies (chapter 4). In the following chapter (5), the remaining seven artists are introduced using abbreviated cases structured with *computational art ecologies*. After introducing these artists, the overarching structural patterns of the ecologies are explored in more depth as the experiences of artists are used to expand the spectrums of computational participation (chapter 6). The second research question explores the ways that computation has impacted artists by capturing the unique practices and perspectives that they identify as vital to their personal art practice. To answer this, I connect the two broader code categories *computational participation in the arts* and *intent in computational arts* to the unique experiences of artists, building out a deeper conceptual understanding of the role of computation in the practice and intent.  Finally, the third research question is design focused, reflecting on how the practices and perspectives from the participating artists can be translated into a design framework to help researchers design and integrate computational art practices in K12 educational contexts. To develop this, the defined practices and perspectives associated with *computational participation in the arts* and *intent in computational art* are abstracted and reframed for design purposes. These are compiled in a table that intersects the forms of participation and the artistic intent.

This chapter presented the foundational frameworks, the *CTSTEM taxonomy* (Weintrop et al., 2016) and the *art ecology* (Dewey, 1934), that ground this dissertation theoretically. A new theoretical framework building on the work of Dewey, *computational art ecology*, was motivated and introduced (1934). The data sources, methods, and analytic approach were explained. In the following chapter, we explore three case studies that showcase unique computational perspectives and engagement within art and highlights the utility of leveraging *computational art ecologies* for constructing an understanding of computational artists.

# Chapter 4: Constructing Computational Art Ecologies

In the previous chapter, I proposed the theory and associated methodological lens, *computational art ecologies* (see Figure 13), to characterize the unique ways that artists are thinking about and engaging with computation and technology. To explore the utility of this theory and methodology, I present three in-depth cases of artists who leverage varying mediums and computational approaches in their art practice to further humanistic perspectives of computation. These artists were selected because they reflect similar intent in their computational art practice but apply tools and associate with the art and computing fields in differing ways. As such, these three provide meaningful commonalities and differences that can be easily compared in their *computational art ecologies*. First, I present the case of Janell Baxter, who engages in computational art practice through the programming of generative art bots. Next, I present the case of ann haeyoung, who engages in computational art practice with a variety of mediums to directly critique the technology industry. Finally, I present the case of Cody James Norman, who leverages 3D printing and robotic and analog production methods to create objects and vessels at the intersection of art and design, or fine design. For all three artists, I will summarize their art practice, their engagement with arts and computation, then construct a model of their individual computational art ecology. Finally, I compare the ecologies across both artists to suggest ways in which these cases differ meaningfully in their engagement with computation and argue that the use of *computational art ecologies* provides a systematic approach to characterize varying art epistemologies regarding computation and technology.

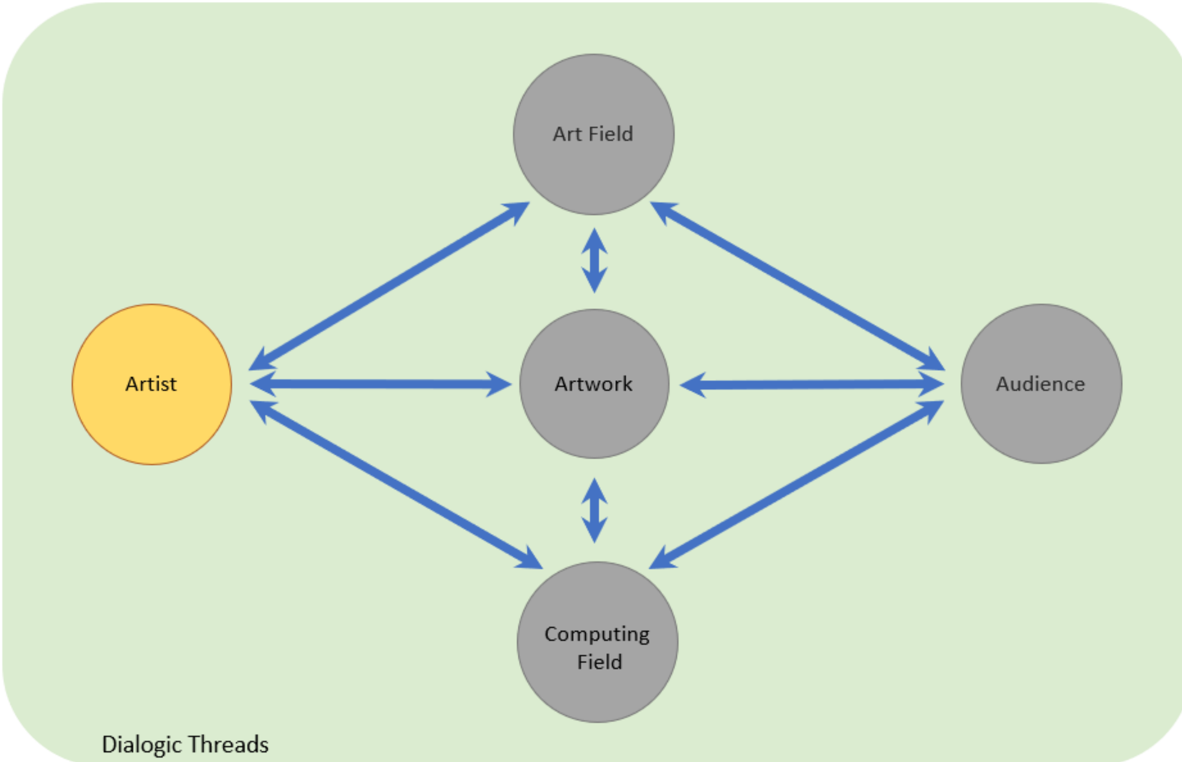


**Figure 13 - Diagram representing the computational art ecology, extending Dewey's theory of the art ecology to a computational context.**

## Janell Baxter: Case of Computation for Inquiry

Janell Baxter is faculty and Associate Chair of the Interactive Arts and Media Department (IAM) at Columbia College Chicago. She obtained a Master of Science degree in Computer Science from the University of Chicago and a Bachelor of Fine Arts in Studio Arts from the University of Illinois. In her biography, she describes herself as "exploring the synergies between programming, design, and art". At this intersection, Janell designs simulations, creates games and game-like experiences, and builds apps that work towards engaging users in interactive, meaningful, and relevant experiences. At Columbia College Chicago, she explores these goals through her classes covering emergent and adaptive systems, interactive application development, and simulations and serious games.  In her personal art practice, Janell focuses on the creation of generative art bots, which are artificially intelligent (AI) programs that output random images or "artwork" based on the inputs they're given. She programs these artificially intelligent bots to create their own artwork after interpreting libraries of visual or textual artifacts that she creates or compiles. Janell explores a theme, like the meaning of consent or conception of self, in each version of the generative bot that she translates into language and rules for the bots to use. Importantly, while these bots are AI, she considers them to be unintelligent because of the biases and limitations implemented in creating them. As Janell describes about her bots, “it has a process and this process makes logical sense, but it’s being used in a completely inappropriate way to how humans find meaning in images...It’s meant to be part of [the design] as a commentary.” This perspective on her bots and AI being unintelligent will be explored in her case more thoroughly. It is this approach to Janell’s artwork that is particularly compelling and reflective of a unique perspective of computing in the arts; as will be explored below, Janell uses these bots to explore and make sense of the world around her, using the unintelligence of the bots to highlight social concepts and constructs.

**Art Practice**

Janell’s art practice centers on the creation of generative art bots that she uses to explore social constructs, like consent or the meaning of self. She programs these bots in varying programming languages to achieve different outcomes associated with her explorations. She has created dozens of versions of these bots since her first show in the late 90’s, exploring collaboration, professional impressions, randomness and order, and consent, among others. To explore some of these themes, I’ll introduce a number of her bots and their intended purposes.

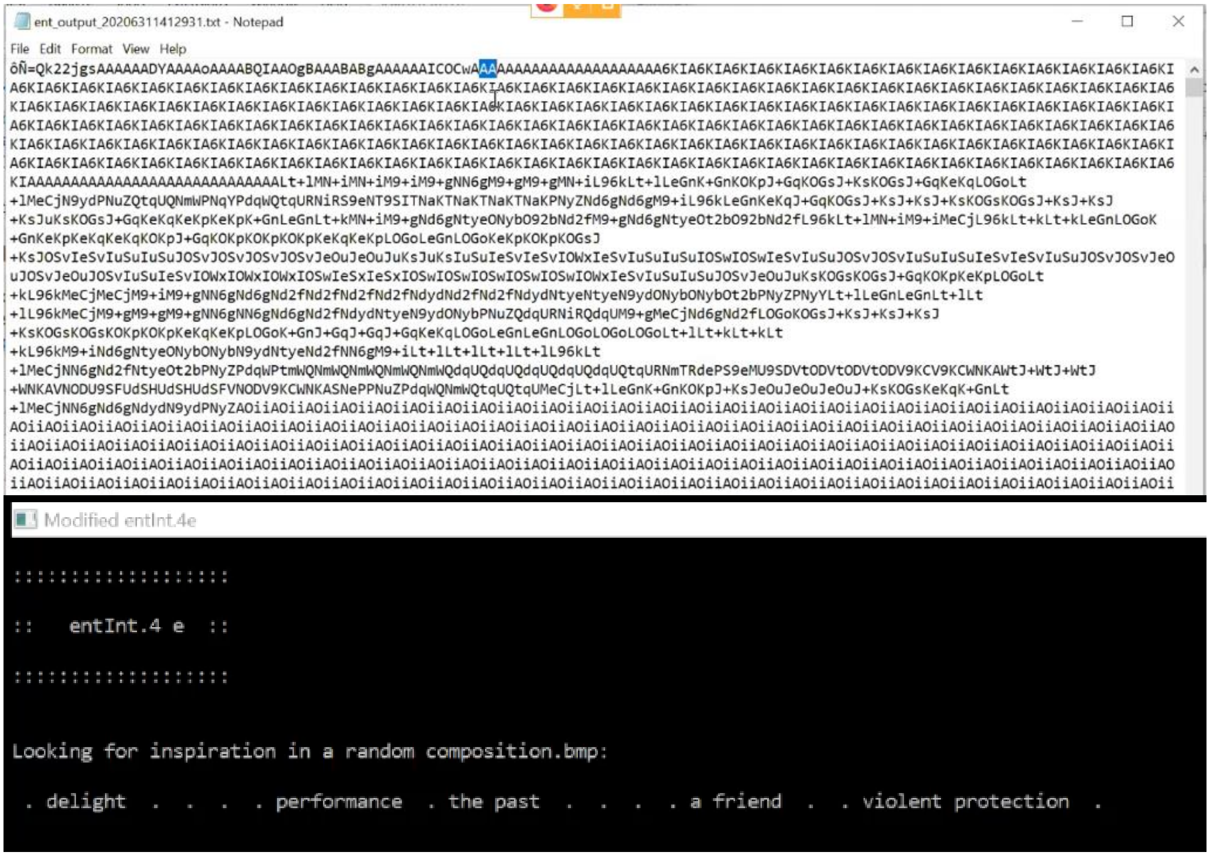


**Figure 14 - On top, entInt.4 program translates an image into base-64 text, that can be searched to identify "known" words. On bottom, entInt.4 program searching for inspiration, or "known" words, in base-64 text based on 'a random composition'.**

One of the series of bots, the ent. series (short for entity) reflects Janell's ongoing exploration of the meaning of consent across seven bots. I will illustrate the typical process of her bots through the description of one of her bots from this series, *entDFP*, that creates its generative work based on 'its interpretation of whether an image holds "consent"' (see Figure 14; Baxter, 2004). The *entDFP* bot is programmed to process a library of images, which are photographs taken by Janell. The bot coverts these images into a string of base-64 text, a group of binary-to-text encoding schemes that translates data into standard ASCII text, using a base-64 encoder primitive (see Figure 14 top for example). The bot creates a new text file for each image with the translated base-64 text, that is the underlying data in the file. This can be translated back and forth between the text and an image without losing any elements in the image. Once the text files have been created, the bot will search through each image, one-by-one, to identify recognizable "words" within the program. For example, the bot might have been "taught" (a.k.a. given a library of words) that the string 'eWVz' in base-64 means 'yes'. Janell creates a matrix of words that each bot is "taught". The bots look through the base-64 text for each word within each image, counting the number of instances for each word identified. For *entDFP*, the more occurrences of "yes" within an image, the more "artistic license" the bot will take in generating a visual response that Janell calls the bot's artwork. If *entDFP* does not identify any of the words that Janell has given it, the bot will not create a work of art based on that image. Janell interprets this as the bot finding the image "nonconsenting".

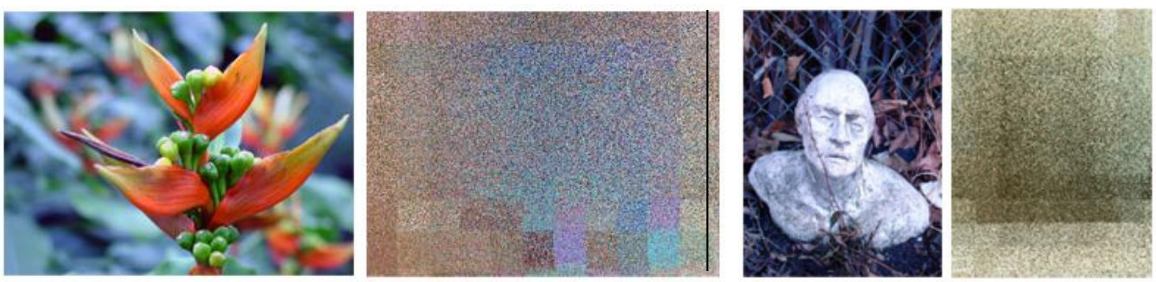

**Figure 4.3. Figure 15 - Two paired examples of entDFP's interpreted images and corresponding generative art (Baxter, 2004). In each pair, the left is a photograph taken by Janell and put into the library of images to be converted to base-64 text. The right image of each pair is the result of the bot searching through the text for "known" words.**

Janell explores nuances of the theme of consent within each of her bots. Janell applies this process across bots that generate their unique artwork based on visual inputs. For each bot, Janell creates a matrix of words to "learn" and how these relate to the themes of interest. This matrix includes the human word and the translation to base-64, 'yes' paired with 'eWVz'. In another example, the bot *entInt.4* will search for inspiration in a library of images and will create a somewhat random work of art based on the themes it identifies in each image (see Figure 4.2; Baxter, N.D.d). In this example, Janell highlighted that the string 'AA' means 'lava', which contributes to the theme 'violent protection'. Janell has the creative freedom to "teach" her bots as many words as she wants but artistically restricts these for each bot. *entInt.4* is more complicated than the *entDFP* bot, that only searched for words associated with consent, like ‘yes’. In *entInt.4*, Janell clusters the taught words into themes that the bot uses in creating the tone and coloration of the art it produces. The output for each image is based on styles of art that Janell associates with themes of interest or with the bots themselves. In figure 4, one can see the input image, ‘a random composition’, inspired *entInt.4* to “think” about performance, and two randomly generated outputs show similar art styles and colors with randomness incorporated to create unique pieces of art. Janell expressed that she gives each bot its own style and then interpretations are based on the scaffolding she provides for thematic interpretation and genre of art, like how an impressionist painter would depict differing subject matter with the same artist’s hand. Her more contemporary bots are built in processing, a java programming language designed for art and design communities (Fry & Reas, 2001), so that they have interpretive power to identify the color of selected pixels for use in creating a color scheme. Each programming language enables Janell to create bots that can connect, interpret, and create in different ways, and she selects them purposively.

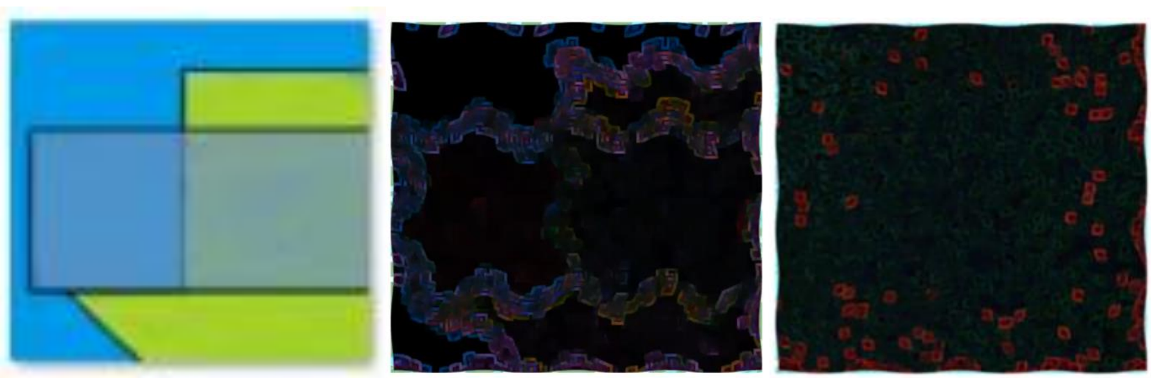

**Figure 16 - On left, an input image named ‘a random composition’. On right, two outputs based on interpretation of the image named ‘a random composition’, identifying performance as the inspiring theme. In this interpretation, ‘performance’ results in produced art that reflects similar geometric structure but with a darker color scheme.**

Beyond her series on consent, Janell has explored other social constructs through her bots. The bot *Self* creates self-portraits of itself, based on what "it understands about itself" through evolving parameters and data, including the history of self-portraits it had created previously (Baxter, N.D.e). The bot *CoLab* is more socially oriented, taking art submission from collaborators, then rating these based on a range of factors, including whether the artwork contains meaning or if the submission consents to be used for inspiration (Baxter, N.D.c). The bot will use the highest rated submissions to create a new work of art. The bots *bios* and *bios.02* both translate biographical data into visual artifacts (see artwork from these bots in Figure 17; Baxter, N.D.a; Baxter, N.D.b). As Janell described, the "misguided but perhaps well intentioned" bots look through biographical data found online to determine an impression of the person (e.g., whether a person was smart or interesting), then would translate these interpretations into a visual (Baxter, 2021). Again, the algorithms guiding the bots were so simplistic that they misinterpret typos or other cues in the biography as interesting or smart because the bots didn't recognize those in the libraries of words they 'know'; "So if someone was smart, it was because the biography would use words that my bot didn't understand. But if he misspelled a word, which on the human side would sort of indicate that, well, maybe you're not that smart, but my bot, I think you were really smart because, 'oh, there's so many words I do not understand.'" *yen* and *yen (Burning Life)* both explore Japanese culture, particularly shrines (Baxter, 2008; Baxter, N.D.f). The former, *yen*, explores order and randomness by iteratively reproducing photographs of Japanese shrines and gardens, while balancing the introduction of random elements at each iteration that are intended to disrupt the process (Baxter, N.D.f). The latter, *yen (Burning Life),* is an interactive virtual sculptural tree exhibited in an online art festival called Burning Life, an online recreation of the Burning Man festival within the game Second Life, that adds branches to the virtual tree with the names of users who interact with the physical tree (Baxter, 2008).

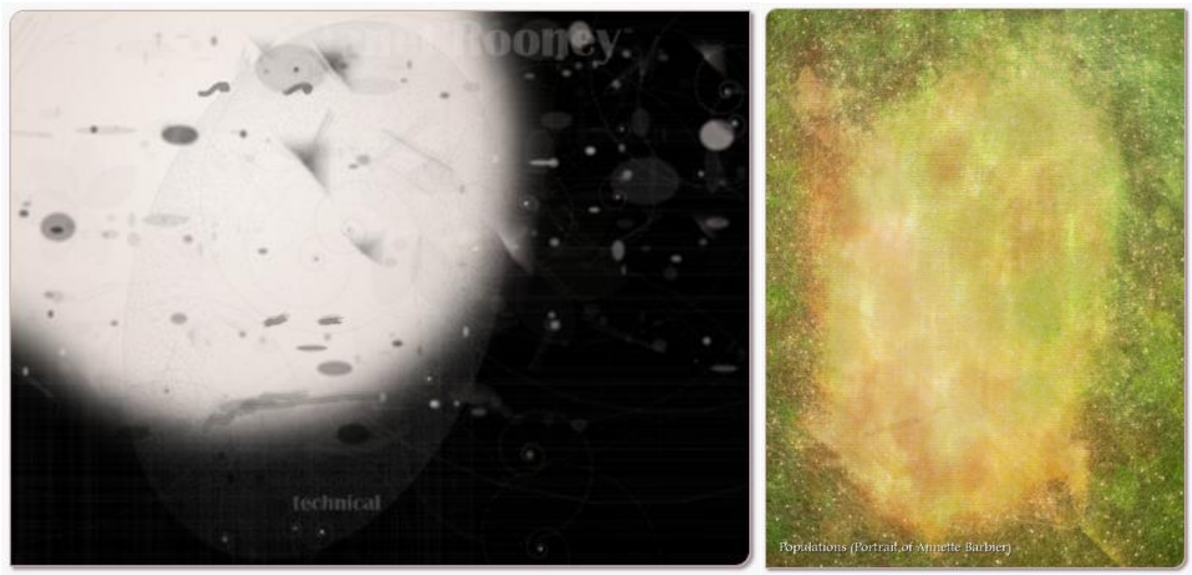


**Figure 17 - On left, art generated by bios. On right, art generated by bios.02. (Baxter, N.D.a; Baxter, N.D.b; Baxter, 2021)**

Her more contemporary work has not been showcased or exhibited. She is beginning to explore networks, or “posse” as she refers to them, of bots that can each provide a service to each other. In these networks, depending on the project, Janell leverages the bots she has created or more intelligent AI found on the internet. As she describes,

> *“One little bot will do something like it'll come up with a topic or it'll create an image and it will pass it to another bot and then that bot will do something and then that'll pass it to another bot. Then the big GaN networks do free processing now. So I can send them a link to one of my images and it will tell based on huge data set training, what they think that image is, and that is like in stark comparison to this like very misguided based 64 and coding way that I'm doing here. So that juxtaposition between like a real trained AI and this very untrained AI approach so you can see them together. You could see like this little ent, I call it an entity, thinks it's this and a lot of humans who help train this bigger dataset think it's this”*

With these, the bots can explore different roles and types of collaborations to create their knowledge and their generated art. Janell can explore nuances in artificial intelligence by comparing the outcome of her bot's interpretation of inputs and the interpretation of AI that has been trained by humans to act more humanistic.

In order to understand the relevance of this approach to designing bots, it's vital to explore Janell's relationship with the arts and with computing. In the following section, I explore Janell's experiences and relationship to art throughout her life to build towards this picture.

**Relationship with Art**

Janell expressed an early interest in art that continued throughout her undergraduate studies, where she obtained a Bachelor of Fine Arts in Studio Art from the University of Illinois. She described herself as a creative individual who engaged in artistic practice through her childhood. In the interview, she answered many questions with a focus on the computational aspects of her interests in art, reflecting on her relationship with computing rather than her engagement and experiences with art. Midway through the interview, the interviewer voiced this observation and asked Janell to speak on what drew her to art originally. She replied,

> *"It was the best way for me to express myself and to communicate. And, I had a really difficult time communicating with other people and expressing myself. I had a lot of terrifying things happen to me when I was a child. It was a sort of therapeutic way of working through issues with artwork… to sort of work through all of my issues and try…to understand them better through working with them, with ideas visually"*

Janell's relationship with art is highly personal and allows her to make sense of and communicate about experiences in her life. As such, her artwork often focuses on social themes that she can explore in new ways. While she didn't intend to go into art for undergraduate studies, originally focusing on German, she returned to the arts where she explored traditional practice like painting and sculpture. She described the benefits of her art program,

> *"I felt like I got to a really good point where I could technically draw things and they would look like what I wanted them to look like. But the really valuable part of that, in the school, was the thinking about why are you choosing to make this a*

> *drawing and not a painting? Or why are you choosing to do it in color and not black and white? Like all that thinking behind it, for me, turned out to be really valuable. And not sort of like technical skills or sort of the trade skills of being good at rendering."*

Again, she found value in the ways the art program shaped her critical thinking in her practice. When asked how this program influenced her exploration of generative art bots, she reflected that the program was foundational for how she interrogated ideas and themes; "What's the concept behind what you're making…and the choices that you make rather than thinking about your technical skill with what you're creating… you would put something up in a critique and they would be very interested in all aspects of it. Why did you choose a screwdriver instead of a nail to hang it? Like, even like those small details and they were really interested in what, what are you thinking behind this."

She explained that she had not planned to continue with art professionally after her undergraduate program. She shifted into museum work where her curiosity and passion for computing was sparked once again when she began to run statistical analyses. Interestingly, her interest in practicing art flourished during and after her master's program in computer science. For Janell, her art practice appears to be personally reflective and expressive, helping her to make sense of both internal and external factors that emotionally impact her. Moreover, her art education shaped her to thoroughly explore and critique concepts in both computing and art practices. In the next section, I explore the experiences with computing that were foundational for Janell.

**Relationship with Computing**

Janell described a rich relationship with computing that started when she was a young girl. When asked to describe herself and how she got where she is today, the first question in the interview, she opened by telling a story of observing an early computing course that her mother attended. In this, Janell describes an early digital computer that uses punch cards, which are stiff pieces of paper that hold digital data represented by the presence or absence of holes. In this, she uses emotional language and makes analogies to religious experiences, imbued with mystery and secret knowledge, when relating to the computational process.

> *"When I was in third and fourth grade, my mother went back to college and one of the classes she took was a class that involved computing. And at the time, they would build these very, very small apps, but it was a stack of cards. If there was an error in their app, they had to redo the entire stack of cards… it was so interesting to me cause I had no idea what was going on, but I knew that these cards were really important. And they would stand in line and they would come up to this small window and they would sort of offer up this offering of these cards. It would be very hopeful, almost praying, right? That, that these cards would be accepted. And it, and it seemed almost religious sort of, this idea of submitting to this window…I would take them out of the trash, and I would draw on them. And for me, I had no idea what all the little holes in the punch cards meant, but I knew that…it had meaning…and I just didn't know how to access it."*

She reflects on her experience watching her mother and the other students "offer up" the coded cards, "almost praying" for them to be accepted within the program. Throughout the story, she mentions "secret meaning" and hidden "information," reflecting on the desire to access this power that she observed. She explained that this was also her first experience mixing art and computation through the act of drawing and adding her own meaning to the cards. Again, knowledge exploration is an important lens in how Janell conceptualizes this interaction with computation. She explains, "I was creating my own artwork in a sense, even though I didn't know that's what I was doing. And I was trying to put my own sort of ideas on this thing that had some secret meaning." Notably, the use of "in a sense" understates the act of drawing as art and suggests that Janell views the practice of art as engaging with the ideas and meaning within the cards. The religious themes in this first experience with computing continue throughout her engagement and conceptualization of computation and artwork throughout her career, which will be explored later in this section.

From an early age, Janell was curious and emotionally drawn to computation. She cited her family, primarily her mother and her uncle, as significantly influencing her unusually early and positive exposure to computing and computation, compared to others her age. Beyond observing her mother's programming courses, her uncle gifted her a TRS 80, a desktop microcomputer that used a cassette tape drive for program storage, when she was in junior high school and would send her Xeroxed zines with pages of code that she would carefully type up to run apps. She described this as a huge advantage over everyone else her age, and particularly her gender at that age; "Nobody else had a computer. Nobody else was thinking along those lines. And I know my cousins at the time, they had game stations like an early Atari and that's what they had. And the difference between them playing games that they bought and me making my own games at that time." She reflected that she felt lucky that she was exposed to computation "in such a way that it made it feel fun and easy, and it was low stress, and it was something [she] could do on [her] own."

Despite her early experiences with computing, Janell went years without engaging in other computational practices, artistic or otherwise. This was due primarily to limited access to computing courses and the cost of computers. After she graduated from her undergraduate program in Studio Art, she took a job at a museum and began to use an old version of Windows 3.1 for statistical analysis and, as she describes, "it just all came back like how easy that was for me and how connected I felt to it. And so, I dove in, got an early Mac and started exploring computer stuff again and tried to mix my computer interests with my art interests." She went back to graduate school at the University of Chicago for computer science, where she studied programming in a program with a rigorous mathematics focus.

This program taught her many of the foundational concepts and practices of computer science and programming. However, she found the program itself was lacking a diversity of perspectives within computing, particularly humanistic approaches which she believes is important to computer science. For her personal interests, she explains that the graduate program was very conceptual, focusing on mathematics, “business, efficiency, and optimism”, among other concepts. She reflected on the design of the program and how it didn’t intersect with her personal goals with computing,

> *“One of the big threads in [the graduate program] was how do you get, how do you choose algorithms that run faster than other algorithms and the math behind that? And, and it was really interesting to me because I did not care about that at all. That efficiency or that optimization wasn’t the most interesting part of programming for me. For me, it was more interesting to think about what are the types of decisions that the bots would make. Like, what is, what does it mean for something to be better or worse in terms of like an interest for my bot? Like when it's looking at a bunch of images in a folder, why would it choose one image to base an artwork off of that it would make, rather than another image? Like what, what is that about? And to me, like, if it takes, you know, 10 minutes to do it, or 40 minutes for me, that's not the important part. The underlying sort of thinking behind the decision making is more important to me. So I'm sort of anthropomorphizing my bots rather than making them like the finely tuned, fast, optimized, efficient machines that they could be. So it's more about this human side, rather than this more technical side.*

Janell expressed appreciation for learning these foundational ideas and concepts, reflecting that they made her more aware of the computer science community and practices, and enable her to better support her students who are seeking technical positions. However, the types of applications and explorations within the program limited her personal growth. She reflected on the difficulty she had in connecting with the framing of the program as the “human” perspective was missing in the education. Her “passion” within programming focuses on this human side; “How does programming sort of sit in this larger world and where is it going? Which is really important now because so much of our lives are impacted by algorithms and algorithms have the bias of whoever made it…if I make an algorithm, it has inherently my biases in there, and my worldview may be entirely different from someone else's worldview." She reflected that the program more generally should include this perspective, as the design decisions of traditional computer scientists have more consequences, "in the financial world, like who gets to decide whether or not you get a loan or you don't get a loan? Algorithms that make those decisions are made by people with very specific backgrounds, and that can have a huge impact on so many people who are…not the same as who made the algorithm."

Throughout these computational experiences in life, Janell has consistently focused on using computation to explore new knowledge and express herself. These perspectives and experiences with computing are foundational to Janell's Art practice more broadly. In the next section, I will explore how art and computation interact in her life and personal practice.

**Intersection of Art and Computation**

Janell's conception of art and computation are strongly tied, her practice focuses on the conceptual inquiry of personal and social themes, and she considers her artistic products the code underlying the bots. She first began to explore the creation of these bots in 2004:

> *"I was invited to this show…and the topic was this idea of the goddess. I didn't feel connected to that topic… so what I did at that time was I developed this small little application that would make its own artwork. And so in trying to figure out how to address the idea of goddess, I sort of became like a God in that form. And I made something that would then make something and that's how I could connect to it."*

While this show focuses on religious themes, Janell found a connection to the idea of goddess by finding herself the god in the analogy. With her computational power she brought "life" into existence in the form of a generative art bot, identifying how it thinks and the world in which it resides. This complements her first experiences with computing, where she conveyed a sense of mystery and power related to the computer and the programs running it. Aligned with this perspective of the power and mystery of computing, she displayed her code in a book on a pedestal, almost like a holy book. Throughout her work, Janell continues to find parallelism between the protean power of the computer and God or religious themes. This is a key element in her conceptualization of computation in her work.

Janell's relationship to the code and her bots have shifted over the years. While she has consistently highlighted the code in exhibits, the role, perceptions of, and purpose of the bots have changed. In describing how these bots function, Janell likened them to Jack Skellington, the main character of the animated film the *Nightmare Before Christmas* (Selick, 1993). In the film, Jack, the king of "Halloween Town", discovers and becomes obsessed with "Christmas Town" then attempts to create his own interpretations of the traditions of Christmas, which are morbidly dark and twisted. Comparing her bots to Jack, she calls her bots "messy, inaccurate, and way off base" then explains,

> "*it created something that was kind of similar, but…it got different meanings from [the images]. This idea of meaning, how do we interpret meaning? how do we perceive meaning? … it's really like the Jack Skellington trying to do Christmas. It's like, it's trying to find meaning, but it's so off base about how it's doing it. It has a process and this process makes logical sense, but it's being used in a completely inappropriate way to how humans find meaning in images. So just want to make sure I remind that there, cause I'm not trying to say that this is logical. In terms of like how humans see it that sort of weirdness or inaccuracy was meant to be part of it as a commentary."*

As expressed, Janell knowingly explores how the logic of these bots is counterintuitive to the social practices of assessing consent, of finding inspiration, of building perceptions, or any of the other social or creative themes she explores in her practice. She does this meaningfully to explore different facets of herself and of others she has difficulty connecting to in the real world. She described that these simple logical processes highlight her own and other biases in the world. Following these rules and biases but in a new context highlights their impact. For her own thinking, Janell will make bots when she is exploring new areas in her life, like a series of "teaching" bots she developed when she became faculty and started teaching at Columbia College Chicago, or when she is making sense of emotional issues, like interpretations of self or others. In creating bots that reflect different ways of thinking, she describes,

> "*I really do kind of feel like they have their own sort of little personalities and little, you know, … I anthropomorphize them. They're little people … they're almost always male cause I'm always struggling and trying to understand how they think so differently. For me. I know that's probably like a bad, stereotypical thing to say, but I do kind of feel like it's, it's a shift to try to sometimes put myself in there, but then again, I'm always trying to like force them to think like me too… because in one way they are alien. They are different. They do think differently and there is kind of a distinction."*

This anthropomorphism is central to exploration of these personal and social themes within her work. With this, Janell can more easily explore personal and social themes in her work.

Janell thinks of development of bots the same way as she thinks about painting, that her traditional artistic training shapes her conceptualization of programming. As she describes, she starts her paintings with a gesture sketch then she roughs out the basic form, which is the early framework. Then she goes in and does another layer of detail, which is like going into programming again to refine, refactor, and iterate. "You're doing that sort of rough, rough first pass at it. And then you go in and add more detail and more detail, and then it gets to this point where it's sort of done, right? And you're sort of finished with it." She again reflected on her distance from traditional computer science, indicating that unlike most developed software that goes through user testing and design iterations, Janell develops her bots until she feels they are done and then displays them or their outputs. The iterations in her bots, like in her *ent.* series, concentrates on her personal conceptual iterations of themes rather than incorporating any external feedback.

Throughout her practice, she has maintained the perspective that her code is the art. Others have critiqued or expressed confusion about her work, saying, '"Oh, well the code is just a tool, or the computer is just a tool." Or, you know, "this part of your medium, like the code is your medium."' Janell's unique perspective at the intersection of art and computation allows her to create unique artworks but results in a disconnect from her broader communities. She participates in both art and technology communities and finds her work has not been fully understood across either. As she describes,

> *"[Artists] don't get what I'm doing, because it's so abstract, it's not tangible. And then all out on my tech friends, look at what I'm doing and say, well, that's not logical because that's not really artificial intelligence. I'm like, I know, but that's the point! And so it's kind of this space between those two. And so a lot of times I have a hard time trying to communicate why I think this is important. Why I think this has value because, cause it kind of mixes the two in a way that not a lot of people are familiar with, I guess."*

For Janell, her work bridges the fields of art and computation in a meaningful way, leveraging artistic practices and computational structures to explore and critique the social world. However, she continues to struggle with framing and situating this work in a way that resonates with her peers across both fields.

**Relationship to the Audience**

Janell's art practice is heavily self-motivated. Her purpose for creating artwork impacts her relationship with the audience, in that she creates these bots for herself with no desires or attempts to sell the bots or the artwork the bots create; "making these things that are kind of silly, kind of ironic, but you know what? It's for me. And it's more like my expression." The shows she has participated in have largely been to reach professional goals, and she's participated less in these outward showcases since her tenure at Columbia College Chicago. Throughout these shows, she's continued to showcase her bots' art while wanting to engage the audience around the “beauty of the code, “It's been 16 years now. But along the way I had a lot of the finished works in gallery shows... that's always been the way that I can show people like what it is rather than let's talk about the code and let's talk about the beauty in the code.” She feels disconnected from the bots’ artwork, put on display so the audience has a more traditional art experience, and continues to showcase her code in appropriate shows. Interestingly with this setup, the audience is in a position of having easy access to the code, but without the expertise or support to reveal its hidden secrets, much like Janell’s first experience with computing. Moreover, given her interest in the beauty of the code and the nuances of creating simplified computational entities, potential conversations are either too technical for those outside of computing communities or overly simplistic for those inside of computing communities. At this intersection, she struggles to connect with communities of practice and audiences. Due to these tensions, she likens her practice to Buddhist monks creating sand mandalas, “It’s kind of that idea of just making it as enough. You know, that you see those people who make those very intricate, amazing sand designs, and then they sweep it away. There’s something about that to me, which is really interesting. It’s like, let’s write the code and run the code and then it’s done kind of a thing. And it can kind of go away because it just bringing it into existence in me thinking about that.” Again, she frames herself as the creator bringing these entities “into existence” and highlights that the important element of this practice is her conceptual engagement with the themes underlying the bots.

Now that she has tenure, she is contemplating how *she* wants to interact with an audience. In attempts to make her bots more relatable, she is considering designing physical forms for her bots so “people sort of see what [she’s] doing in a different way.” For her, it is important for people to see her practice as important and engaging in conceptual inquiry, more than just the silliness of the simplified bots. This tension in her work, creating for herself but wanting her work to be understood, leads her into questioning the value in her practice. She was particularly thoughtful about this during her interview, which took place summer 2020, during the COVID-19 pandemic and during the peak of the George Floyd or Black Lives Matter protests. She became very emotional and reflected,

> *"It's just the last couple of weeks have been really hard and trying to get some motivation to work on this thing, which normally for me is super exciting and interesting. But right now, it just sort of pales in comparison. Like maybe I should be doing something more relevant to what's going on in our country…Maybe I will change it up and do something different based on COVID and the protests and everything. Maybe try to find something that would resonate more with how I'm feeling about living here in this country, and have me in this brand of American, which I am not happy having right now."*

Janell is motivated to engage in a broader dialogue related to public health, racism, and patriotism to connect with others and to make sense of her own emotions and ideas related to COVID-19 and the protests. Moreover, she reflected on her identity as a white woman, expressing concern about the impact of her practice and desire to engage more explicitly with these issues through her work. This orientation to conversation and engagement with others is a new approach within this work, which has primarily been introspective for Janell.

**Computational Art Ecology**

Janell uses art as a process for self-reflection, communication, and expression as she makes sense of her experiences and the social world around her. From an early age, she had positive exposure to and experiences with computing that made her want to explore its power and mystery. Leveraging this power, she creates bots that generate their own artwork, complete tasks, communicate with other bots, and make interpretations about people or artifacts. She has a unique relationship and perspective on her bots, largely that the bots are unintelligent, anthropomorphized 'entities' that she brings to life. She frames herself as a creator, "god", teacher, and curator of the bots. With a background in computer science, Janell knowingly explores unintelligent artificial intelligence, explaining these bots reflect different perspectives and ways of thinking. Her practice explores how meaning is generated or perceived in the world around us as her bots interpret libraries of art, images, and data to find its own distorted meaning. As she describes, she gives the bots a process, which makes logical sense, but is applied in an inappropriate way to how humans engage with the world around them. Importantly, Janell explains that the code and bots are her art, and she does not have ownership of the art the bots create. This practice is important as it sits firmly between art and computing. She leverages her background in the arts to critically design the bots. She leverages her background in computing to knowingly bend the practices of artificial intelligence. Lastly, this process is motivated completely by her desire to explore her own conceptions and questions about herself and the world. This relationship and set of experiences can be translated into a *computational art ecology* that highlights connections between these elements and translates them into a concise representation of her unique perspective on and practice with computation, which will be constructed next. The original model for the *computational art ecology* is included in Figure 18, as reference.

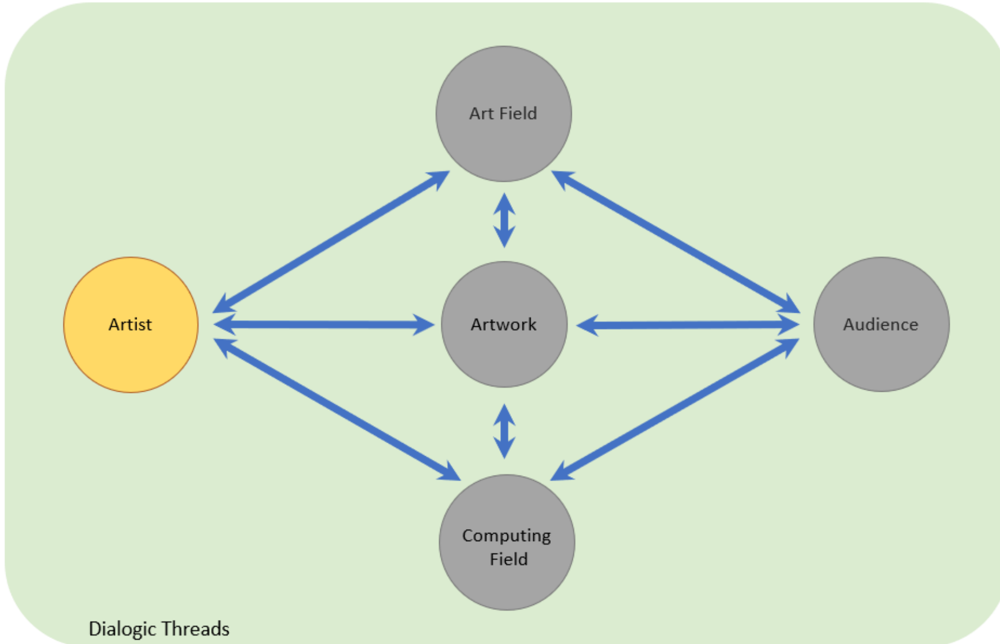


**Figure 18 - The general model for computational art ecologies that can be modified to reflect individual artist's experiences and engagement with computation in their art practice.**

We will begin the construction of Janell's unique *computational art ecology* (see Figure 19 for final ecology) with a description of the nodes. First, the artist node is changed to Janell, as this ecology focuses on her experiences as an artist. Next, the artwork node has been adjusted to represent Janell's perception of the bots as her artistic product. As the bots create their own artwork, an additional node has been added to reflect this in her ecology. As Janell reflects that she does not particularly care about the bots' generated art, the node size has been reduced. Similarly, Janell reflects that she has largely engaged in exhibits and showcases to further her tenure case, so the audience node has also been reduced in size to reflect that the audience is not a particularly significant actor in her art practice. Finally, the nodes for the computing field and art field are unchanged. Janell reflected on positive and negative experiences with both fields throughout her interview. Both are significant fields that influence her work and that she contributes to with her practice. As neither was expressed as being more influential, or as unimportant, they are unchanged.

Now, we will shift to constructing the links between the nodes in Janell's *computational art ecology*, as these reflect the relationship and impact between the elements described above. The weights of the links will not be adjusted in the ecology, but I will reflect generally on the perceived significance for Janell and suggest where this could be incorporated in future iterations. As Janell's practice is highly self-reflective, there are bi-directional links connecting her node with the art field, the computing field, and her bots/artwork. In justifying this bi-directional link with the art field, she described that the training throughout her Bachelor of Fine Arts shaped and refined her design thinking and practice that she uses throughout her engagement with computing and art practice. Moreover, she has influenced the art field by actively participating in art communities, designing for shows and exhibits, collaborating with peers, and sharing practice. The computing field has been influencing her throughout her life, as reflected in the stories she told about her first experiences with computing as a child, throughout middle and high school, then in her master's program in computer science. In her early experiences, she gained a sense of wonder and awe at the power of computation, which she explores thematically in her practice. She was influenced by her CS program's focus on algorithms and efficiency, which made her reflect on the intersection of humans and computing. In approaching artificial intelligence in an unintelligent manner, her bots highlight the bias she brings to the design and, generally, the bias of algorithms when applied to human contexts. This engagement and critique of the field contributes to the larger social and cultural context of the computing field. Finally, we shift to exploring the bidirectionality between Janell and her bots. She engages in active practice in creating and coding these artworks, warranting a link leading from Janell to the bots. As she explored throughout the interview, the bots are reflections of questions she has about herself and about the world around her. Their actions give insight into those questions, which she iterates and explore in series of related bots. She will also create bots that act through challenges in her life and provide her insight into how to engage, for example in creating a series of teaching bots when she became a teacher.

Focusing on the links with the bots themselves, we include bi-directional links from the bots to the computing field and the art field. As Janell situates her work between art and computing, the work she produces contributes to the larger scholarship in both fields. They influence her work actively, as her bots will interpret libraries of images and take recommendations for their art creation. She will also construct networks of bots, drawing on the "intelligent" expertise of AI found online to teach or support her unintelligent bots. In this, the art and computing fields actively impact the outcomes of her bots and her artwork. We have included a one-directional link leading from the bots to the bots' art node. Janell has created a couple bots that will use their artistic output as new data for future work. For example, her bot *Self* engages in iterative self-portraiture based on information given to it, including previous self-portraits created by the bots in earlier iterations. However, most of her bots produce artwork without iterating on it again. As she currently envisions it, her future work focusing on networks of bots that support each other to meet their individual goals has potential to shift this link to bi-directional. Finally, a dashed one-directional link leads from the bots' art to the audience node. As explained throughout the interview, Janell has largely seen her audience interact with the bots' artwork, despite showcasing the code at exhibits. As she does not perceive ownership of the art created by the bots, she does not care about audience interactions with these outputs. Moreover, since obtaining tenure, she has stopped participating in exhibits and showcases, since she feels pressure to present traditional artistic artifacts for the audience. This strained connection with the audience was significant for Janell. She expressed feeling like her art, these anthropomorphized entities, was misunderstood. As such, the weight of this link could be increased, as it is a significant relationship to Janell, and one she is actively thinking about as she moves into her future work. Finally, throughout her interview, Janell reflected that her practice acts as a tool for self-reflection and social reflection as she makes sense of the world around her. These are largely framed in computational terms and relate to the intersection of Janell's thinking, her bots, and the computing field. Translating this to the social and cultural themes that are significant for her practice, we identify the self and social practices, which she explores primarily through making parallel computational entities. As such, in the ecology, we adjust the green social and cultural factors to frame Janell, her bots, and the computing field, labeling it 'self' and 'social practices'.

The final *computational art ecology* is represented in figure Figure 19. In this, one can observe that the model is heavily connected for Janell and her bots. The dialogic threads element also frames Janell and the computing field. In the following section, a case of a contrasting artist, ann, will be explored and used to construct another *computational art ecology.* After introducing her ecology, both will be compared to highlight the utility of this lens in capturing and characterizing computational perspectives in the arts.

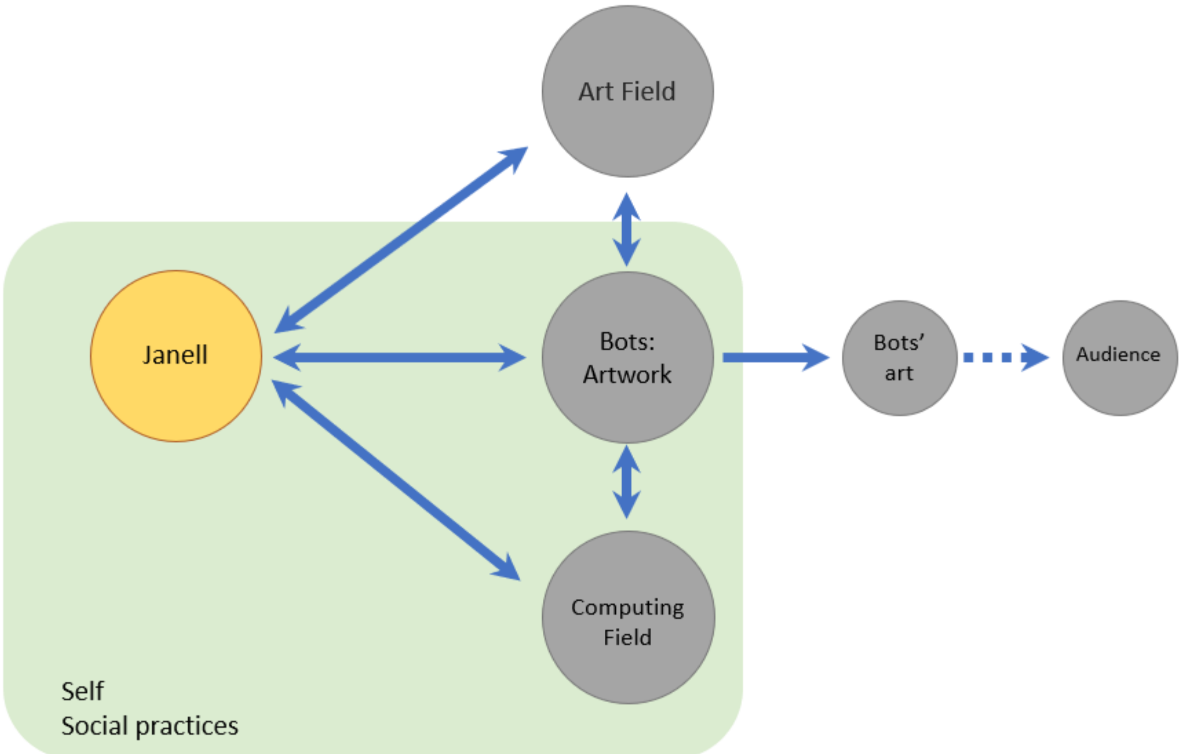


**Figure 19 - The unique Computational art ecology of Janell Baxter.**

## ann haeyoung: Case of Critiquing Technology

ann haeyoung is a media artist using video, sculpture, and performance to explore questions around technology, identity, and labor. She received a Bachelor of Art in International Relations and Visual Art from Brown University, where she focused on technology used for social mobilization. These interests led her to working in the tech industry, where she quickly became disillusioned and left to get educational experiences in computer science and in formal art. She is currently an MFA candidate at the University of California, Los Angeles exploring her artistic critiques of technology in an Interdisciplinary Studio program. Despite describing her own work as situated at the intersection of technology, she expressed hesitation throughout the interview at being described as a “tech artist.” The interview with ann highlighted tensions within the broader art community regarding genres of art and schools of thinking. ann expressed feeling mischaracterized and uncomfortable at the thought of being considered a “tech artist” and, at one point, she directly asked why she was considered for the study. Her perspective reflects a way of thinking about technology and computation that falls outside of these institutional approaches. Moreover, this tension suggest the need for studies such as this one that examine artists across genres and schools of thought to better understand the landscape of computational practice across the arts. Since the interview, there has been additional communication via email. This ongoing communication positively impacted the researcher participant relationship, leading to ann waiving anonymity so her work could be represented more fully. Despite her initial hesitations for engaging in deeper reflections of her practice, her perspective on technology and the rationale behind her hesitation to participate is important to represent in the landscape of computational artists. Her work reflects a more fluid and critical approach to using computation in practice, and actively pushes against the sociohistorical structures underlying computing and technology fields. Moreover, as expressed throughout the interview, ann feels like she fits outside of the community of artists who leverage computation in their practice. As the goal underlying this dissertation is to capture the full landscape of computational engagement in the arts, this case is important to highlight and explore. In the following section, we’ll explore how she uses technology to critique the tech industry and how this focus emerged from her experiences with art and computation.

**Art Practice**

ann’s art focuses on a critique of technology, primarily around the social and cultural biases throughout the tech industry. Her work leverages a variety of tools, mediums, and practices to critique these constructs including media (incl. video, digital photography, animation), high tech tools (incl. robotics, microcontrollers, 3D printers, laser cutting, and machine learning), organic matter (incl. blood, mushrooms, teeth, and hair), and traditional mediums (incl. cloth, resin, thread, and wood), and often feature live or recorded performances to construct narratives. For ann, the juxtaposition of these materials allows her to craft narratives that "counteract dominant narratives of technological progress." She often goes to specific physical locations in or related to the tech industry for her performances, which are often ritualistic and surreal to critique or satirize the dominant narratives. Often her work is deeply personal, expressing her identity as a multi-racial woman and often highlighting intersectionality in the themes and contexts she explores. To explore how these materials and approaches intersect, I'll introduce a variety of art pieces from her early and current practice.

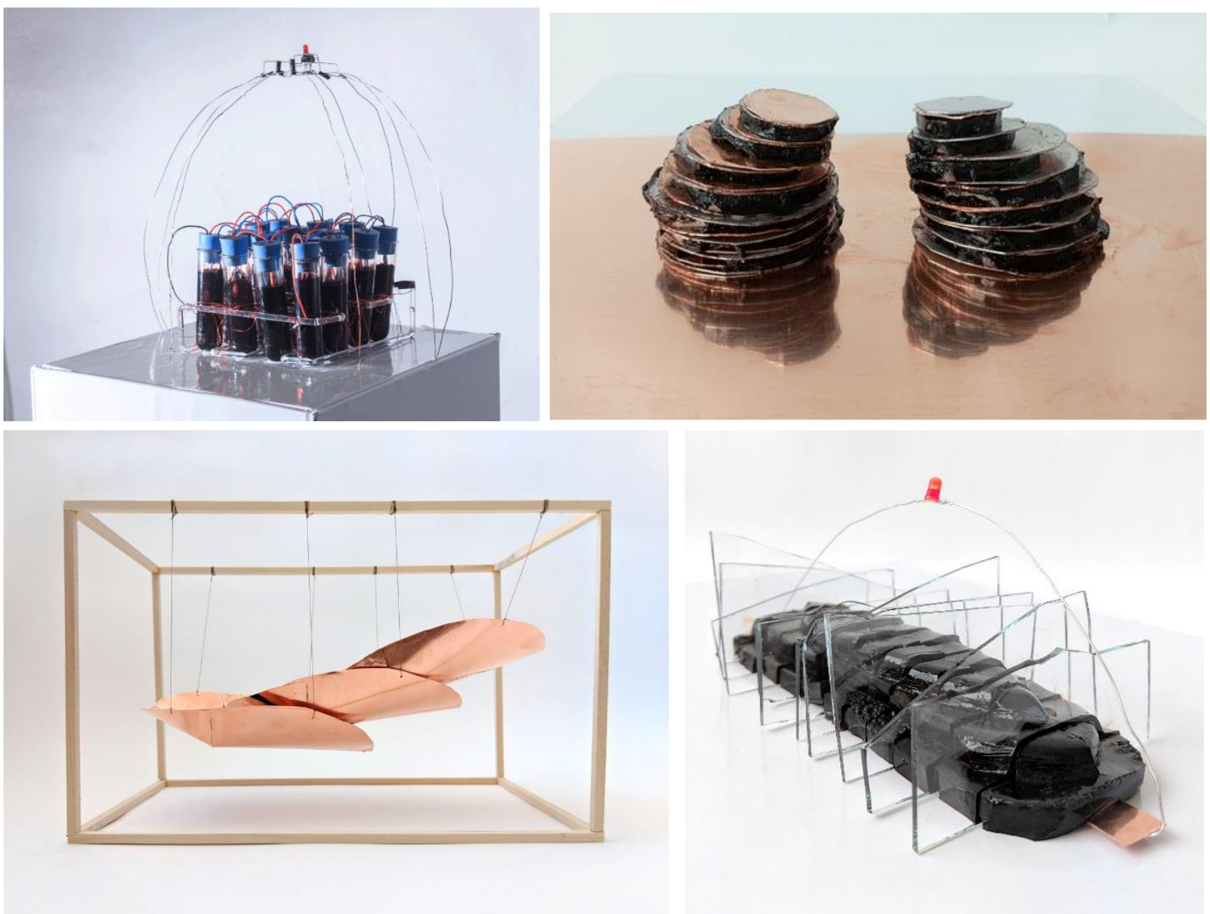

**Figure 20 - Four sculptures from *Blood batteries* (haeyoung, 2017-2018). On top left, *Who will feed us when you're gone?* [blood, glass, wires, electronic components, LED] (haeyoung, 2017). On top right, *family portrait* [blood, gelatin, electrodes, LED] (haeyoung, 2018d). On bottom left, *armor* [blood, gelatin, electrodes, thread,**

**wood] (haeyoung, 2018a). On bottom right, *jjambong* [blood, gelatin, glass, electrodes, LED] (haeyoung, 2018c). (haeyoung, N.D.).**

In one of her early series, titled *Blood Battery*, ann explored socially and culturally constructed identities and whether electronic systems could take on these identities (haeyoung, 2017-2018). She created a series of sculptures that were each a functioning battery made with copper, zinc, or aluminum electrodes, her own blood, gelatin, and simple electronic components (like LEDs). Each unique sculptural battery consists of alternating slabs of blood gelatin and sheets of electrodes, with a single red LED positioned to connect to two sides of the sculpture, creating an active circuit (see Figure 20). These sculptures take on various forms, representing differing mentality towards familial blood ties. As she describes, many cultures represent familial or cultural connections with blood and belonging. With this work, she asks whether these electronic systems take on the same identities as the blood "that was giving them 'life'" and whether we should feel kinship with these structures.

In another piece extending this line of work, *Building a large blood battery in front of the Tesla Gigafactory in Sparks, Nevada*, ann constructed a large blood battery in front of the Tesla Gigafactory in Sparks, Nevada as a film performance piece (haeyoung, 2018b). In this, a camera is positioned on top of a hill overlooking the Gigafactory. On the hill, five large electrodes (appearing to be approximately 2'x3' in size) are connected in a circle with a covered bowl placed nearby. A woman walks up to the circle wearing a disconcerting mask, which is a machine generated composite of many faces hydrodipped onto a 3D printed mask (see Figure 4.9). Once there, the woman takes off her mask and begins to construct the battery, slowly dipping large sheets of white cloth into a bowl of human blood and covering the electrodes. Once fully connected, the battery powers the movement of a tiny, motorized finger placed in the center of the circle. This work was performed outside of a worksite known for poor working conditions and abuse of workers. The mask worn in the video represents the loss of identity and culture that workers experience in the tech industry, and in critiquing who is represented in databases or in the design of technology. As ann reflected "who, or which faces are being curated to be put into these databases that then generate these algorithms that are going to be producing faces, and then, you know, thinking about what that means and who gets to be part of that conversation of creating that technology". Moreover, the machine itself, the tiny moving finger, is "inefficient and has no apparent purpose." The underlying narrative is that the woman is a worker from the Tesla Gigafactory who is "motivated by anti-productivity and de-optimization", represented by creating the "inefficient" battery running a purposeless machine, and causes the worker to turn away from the workplace behind them. This video can be viewed at ann's personal website https://a-tbd.com/tech-rituals.

Other critiques of the tech industry leverage video mashups and timelapses to create narratives about technology and society. In one piece, *Jewel at Playa Vista*, ann juxtaposes the sound from a news recording of a tour of an apartment in a luxury housing complex in Silicon Beach, which is a tech hub of Los Angeles, with the recording of a plant suspended in a glass orb (see Figure 22 right; haeyoung, 2020a). Throughout the video, a woman with a large diamond ring on her finger gestures as if she is revealing and showcasing features in an apartment and occasionally mists the outside of the bowl with water, while the video gets increasingly blurry. While ann does not include an explanation of this piece, my interpretation, based on themes from other pieces, is that these luxury apartments are created to highlight the successes of the tech industry but isolate workers residing there and devoid them of their basic needs while putting on a show to support them. This film can be viewed at https://a-tbd.com/video-scrapbook/.

**Figure 21 - Images from *Building a large blood battery in front of the Tesla Gigafactory in Sparks, Nevada* (haeyoung, 2018). On left, an image of the mask worn in the first portion of the video, created using machine learning and 3D printing. On right, ann haeyoung (performer in the short film) lays next to her blood battery and robotic finger.**

ann often leverages botany throughout her narratives and a common theme in her work is the connection between societal or technological advances throughout history, Western narratives of colonialism, and botany. In a more recent piece titled *They were shipped in wood and glass cases*, ann uses archival imagery from Western botanists and timelapses of a plant cutting removed from an office to create a video mashup or collage representing the connection between contemporary workplace aesthetics and the history of colonialism (see Figure 22 left; haeyoung, 2020b). In the mashup, a timelapse of a monstera plant sits at the top of a pyramid of archival images of botanists that have been animated to repetitively move (i.e., leaves moving, arms stroking plants, people shifting). In the description, ann explains that the plant trade surged in the mid-1800s with the creation of a terrarium like box, called the Wardian case, and allowed colonists to smuggle rubber plants, tea plants, and Cinchona plants (a derivative of quinine, an anti-malarial drug), among others, out of their native habitats. Connecting this back to contemporary offices, she explains that most indoor plants are native to the tropics and originated from these colonial practices. While they were historically displayed in Western houses to represent wealth and class, office plants today represent the success and desirability of a company, and to increase productivity in the office. This piece; and other shorts, video mashups, and timelapses; can be viewed at https://a-tbd.com/video-scrapbook.

**Figure 22 - On left, screen capture of *They were shipped in wood and glass cases* (haeyoung, 2020b), featuring the juxtaposition of archival imagery of western biologists and a plant cutting from ann's office. On right top and bottom, screen captures of *Jewel at Playa Vista* (haeyoung, 2020a), featuring sound from a local news tour of an apartment in a luxury housing complex in Silicon Beach. (haeyoung, N.D)**

As will be explored in the following sections, ann uses technology strategically throughout her practice when it is important for the narrative and critique of a given piece of art. To understand more deeply how and why ann sees utility in these computational art practices, we'll explore her experiences with art, computation, and the larger goals of her practice.

### Relationship with Art

ann spent most of her childhood engaging in artistic practices like drawing and painting. Her family did not engage in any artistic ventures and largely have been disconnected from her professional and artistic ventures throughout life. Professionally, she did not consider art until after her undergraduate program and experience in the tech industry. She attended the School for

Poetic Computation (SFPC), a hybrid school focusing on the intersection of art, code, design, hardware, and theory. SFPC is a hybrid school, residency, and research group that positions itself as a technical bootcamp to teach "writing code like creative writing – focusing on the mechanics of programming, the demystification of tools, and hacking the conventions of art-making with computation" (SFPC, N.D.). Moreover, this school often teaches courses that focus on a Critical Theory perspective on the technology and computation involved. Despite attending with the goal of gaining more programming and computation skills, she began to realize her identity as an artist. She describes her motivation as "critiquing the tech industry", and she reflected throughout the interview that she uses the tools and mediums required to effectively make her critique. She reflected that she has recently engaged with more traditional mediums, like paints, and has been questioning the use of computational elements since the revival of this practice. Broadly, while ann is passionate about her artistic practices, particularly in voicing critiques, she doesn't express any interest in engaging with the social or cultural trends in the arts nor does she situate her artistic practice outside of excluding herself from tech artists. As art is a more recent professional practice, it appears that she is still identifying her place within the broader art community. Since this interview, she's changed her biography on her personal website to identify as a media artist.

**Relationship with Computing**

ann's family does not have interest or professions in the technology industry or any computational fields, nor have they shown much support in her professional ventures in computational areas. ann's interest in computation started when she was in undergrad, where she focused her studies on the ways new technologies could be leveraged for social mobilization and other political practices to organize, mobilize, or protest. She took a sociological approach to exploring these themes and didn't have any exposure to programming or other computing courses. After graduating, she sought to continue work within this area. She first worked at the Ministry of Science and Technology for an Asian country, a department of the government that coordinates and explores how science and technology can be integrated in life and education for the country. She did not feel connected with the work or that she had upward mobility in the department, so she transitioned to a non-technical job at a large tech company, Google. She reflected that she didn't know what it meant to work in tech before she was hired at Google, expressing:

> *"I didn't know what engineering was, I guess, to put it most simply, like, I didn't really understand how these technologies were created. I just understood how they were used. And even, even then, I don't know if I fully understood how they were used. But I was curious about it and … I was just interested in like new interfaces, new ways of communication, things like that."*

She explains she became interested in working at the tech company to learn more about new technology for communication, extending her undergraduate work. However, once there, she expressed becoming disillusioned and frustrated about how technology was being created, like many others working at these large companies. Working at these companies sparked her interest in learning programming and she spent several years teaching herself programming before "[getting] more serious about learning to program". She took a sabbatical and began to read more theory about technology, particularly critical historical perspectives, and enrolled in courses to study programming. She attended the School for Poetic Computation, which is an artist-run school in New York that focuses on creative and expressive computational art and design, where she was able to explore new computational approaches, perspectives, and practices. Afterwards she worked at a startup that did work with machine learning.

When asked to describe what it meant for her to be more critical of technology, she explained the motivation for the ‘aggregated’ face mask used in Gigafactory blood battery video, described above. She explained that there are questions around whose faces are being curated, what algorithms are used to produce these new faces, and who is making them. She asked what does that process look like and “who gets to be part of that conversation of creating that technology?” She further explained that she’s very interested in the workers within the tech industry who are the ones creating the technologies that broadly influence society, “Those are human beings. Those are the workers that are creating these technologies that are making those decisions. So I'm really interested in looking at those like workers and like how they are kind of part of the system.” ann’s critique of the tech industry uses computational materials and mediums to draw out the biases and inequalities within the field. She mentions that she “[uses] technology as intended, [with the] critique coming from the way it is used, opposed to using it itself.” In this, she references a self-identified subset of computational or tech-based artists that focus on modifying or subverting technology as intended in the original design of the technology so new processes or outcomes can be produced. She specifically distances herself from this subset of artists who subvert, modify, or create new technologies as she leverages these tools as intended in their original designs. This use and engagement with technology is a tension for ann, as she struggles to make sense of engaging with tools and mediums that come from the fields that she finds problematic, which we will explore in more detail in the following section.

**Intersection of Art and Computation**

ann integrates technology into her art in ways to downplay any high-tech aspects. She creates props that leverage different high-tech practices or tools that she will then use in performances or videos. For example, she used machine learning and 3D printing to create the "aggregated" face mask used in the Gigafactory blood battery video, as described in the art practice section, and in other performance pieces. She described finding images from another artist of "aggregated faces", compiled 2D images created from many photographs of individuals. She wanted to create a mask of these faces, as they lost their individual uniqueness in the process of aggregating the images. She found a machine learning program online that turned 2D images into 3D objects. With this, she did not gain expertise in the program or the underlying computational mechanics. She created a model of the face then 3D printed it. After printing the face, she used hydrodipping to deposit the details and color onto the structure of the face. ann draws a distinction between the use of high and low technology, feeling comfortable with making simple electric machines (e.g., blood batteries or motorized finger) and the use of photo and video editing or manipulation. However, the use of the higher tech materials makes her reflect on her practice and question whether she wants to be called a tech artist. She defends this by explaining that "If I do have the tech in my art. I try not to make it like, I guess, the word I keep thinking of just make it quieter…if you're not looking that closely or if I don't point it out, you might not notice [the technology]." For ann, this seems to balance some tensions with the use of technology in her work, though continues to see it as a conflict.

Despite engaging deeply in conversations about technology and participating professionally in computing fields, ann is conflicted about her use of these mediums throughout her artwork. She draws a distinction between traditional camps of "tech artists". In her perception of the field, there are some artists using cutting edge or immersive technologies and others who engage in building or subverting tools, and she sees herself as external to both camps. At one point in the interview, she paused to ask me why I wanted to interview her about the use of computation in artwork. She reflected, "When people want to describe me as using technology with my art, cause it doesn't really feel like I do that…recently I've been… kind of wondering like how I want to have tech in my art…I guess it doesn't feel like something that's necessary. When it makes sense to integrate it, then I will. And if I want to." She views the use of technology as another tool that she can leverage when it best fits the purpose and critique of a given project, "It's just another tool in another medium. I'm not sure in the way that I'm using it, that it brings anything thing really special."

When asked to explain in more depth about how and when she decides to use technology, she spoke about three primary concerns. First, she tries to create integrated, non-"flashy" technological aspects in her artwork. ann mentioned that often art with more complex computational aspects breaks or need adjustments in an exhibit, which takes the audience out of the experience. As will be seen in the case studies in chapter 6, other participating artists view these flashy computational elements as a way to bring their audience more deeply in to the art world. However, ann views this as a detriment as the audience may become more focused on the technology, rather than the underlying message or critique of the artwork. Second, she tries to limit the cost of and time engaging with technology in the design of a piece of art. She reflects that because she hasn't trained to become a developer, when she engages in computational practice with more high-tech elements, she can spend significant time and energy researching and debugging the technological or computational elements,

> *"When I'm using these things, they…just take up all my time and energy. I have to research it and then, you know, start trying to dig into the code base… when I'm running into questions, I have to be looking at forums and trying to figure everything out and stuff…I realize I've just spent a week trying to solve this technical problem and I haven't considered the meaning of the piece, then I'm like, okay, now it's time to step back and think about if this is really necessary or in a way that is not adding to the piece".*

ann seeks to spend the majority of her practice engaging in ideas motivating a piece of art. For her, the debugging and research practices related to computation often pull her out of that experience of creating art. Moreover, these practices are financially expensive, which is a huge barrier for other tech artists. She reflected that it isn't easy to find free access to tools and that she was lucky to have free access to computational tools and machines through the tech companies where she was employed and her art programs. Finally, ann leverages technology in her artwork when it assists in starting a conversation with the audience about the ideas and critiques of a piece of art. She mentioned the primary goal is to "open a discussion of the technology" and that at times the use of technology is needed to do so. Ultimately, she remains conflicted on the use of technology in her practice, saying "If you told me you're never allowed to use technology again in your art, I would be like, okay, I can figure that out. I guess that's a little sad, but it's okay."

**Relationship to the Audience**

The primary goal of ann's practice is to engage her audience in conversations about the tech industry. As mentioned previously, her goal is to start a discussion or conversation about the tech field and the associated culture and practice rather than focusing on the specific technology in the artwork. She sees utility in leveraging computation in her practice, as audiences are drawn to these elements. She finds it vital to balance subtle and flashy integration,

> "*this is something I'm thinking about as an artist is if it's so subtle that you have to read a big wall text, like, what does that mean?... I guess my hope is that people are interested because they see something visually interesting and then once they, you know, take a step closer and look at it a little closer and read a little bit about it, then they're like, 'Oh, there's many layers and I can kind of keep digging into it'."*

Again, the integration of technology is a useful element to attract and intrigued the audience but can distract from the purpose of her artwork. She struggles with finding balance and accepting the use of technology. She related this to a piece of artwork that she created using a Raspberry Pi, a tiny and affordable single-board computer. The piece of artwork was a sculpture with a tiny screen embedded in it that, when picked up, would play a video. She explained that people were very excited and reactive to the piece, but this excitement was focused on the video element, rather than the message. She expressed, “I felt like it became a little gimmicky. And so I was like, I'm not sure if I really want this. But, I mean, that doesn't mean there isn't a way to [use raspberry pi]. Well, I just don't think I did it well in that piece, so I would need to think about it more.”

Beyond the audience of laypeople, she struggles with situating herself in computing and art fields, reflecting people in the tech industry or tech artists are not very impressed with her artwork since “it is not very complicated or flashy or interesting.” When pressed, she reflected that a subset of people in the tech industry, particularly ones who are also disillusioned with the field tend to connect with her artwork. Traditional artists that she’s interacted with tend to view computational art as more gimmicky and spend a lot of time asking about the process for integrating the computational elements rather than on the critique or non-technical aspects.

**Computational Art Ecology**

ann uses her art to critically examine and openly critique technology and computing fields. As mentioned throughout her interview, she places focus on the artwork and leverages a variety of tools, both traditional and computational, to accomplish her goals. Notably, she is hesitant about her use of computation in her art practice, as it can shift focus away from the underlying ideas for her and her audience. She is conflicted about engaging with the tools that were created from the field she finds so problematic. The technology field extends a history embroiled with colonialism, exploitation, and theft from native populations, themes she explores throughout her work. These tools reflect the biases and dominant narratives of the field. Moreover, given their price points, higher tech tools are a privilege that many cannot access. However, these tools do provide means for new forms of communication and can attract audiences to engage them with new ideas. ann uses these computational tools as they were intended; she doesn't attempt to modify or subvert their functionality. She does apply the products of these tools in ways that subvert and critique narratives of the field, particularly bringing to focus the problematic design and development in industry. This complex relationship and set of experiences can be translated into a *computational art ecology* that highlights connections between these elements and translates them into a concise representation of her unique perspective on and practice with computation. Once again, the original model for the *computational art ecology* is included in Figure 23, as reference.

We will begin the construction of ann's unique *computational art ecology* (see Figure 24 for final ecology) with a description of the nodes. First, the artist node is changed to ann, as this ecology focuses on her experiences as an artist. Next, ann spoke in detail about the consideration of and concern about the types of tools she uses in her practice. She spends a lot of time reflecting on the impact and implications of the various computational tools she uses. As such, a 'tools' node is added between ann and her artwork. Here, I'll note that while tools and mediums are inherent in practice for all artists, not all artists engage in the critical ideation and reflection of the various tools used for a piece of art. Some artists, for example, never change the tools used (e.g., paint, paintbrushes, canvas, etc.) but refine their practice, skill, and expression. As ann leverages a variety of tools and specifically critiques herself on their use, this is a significant feature in her *computational art model*. Next, the node for the computing field is increased in size as ann largely engages with themes related to the tech industry. The node for the art field is decreased in size, as she did not position her work in relation to the art field, except to say she sees herself as operating outside of traditional tech or computational art genres. For example, she doesn't connect to the work of others or the practices and techniques of art genres. As her primary artistic practice was self-taught and she focused on personal expression throughout her childhood, she is not connected to the institution or history of art. Finally, the nodes for artwork and audience are unchanged, as ann didn't reflect on these as particularly unique features for her practice.

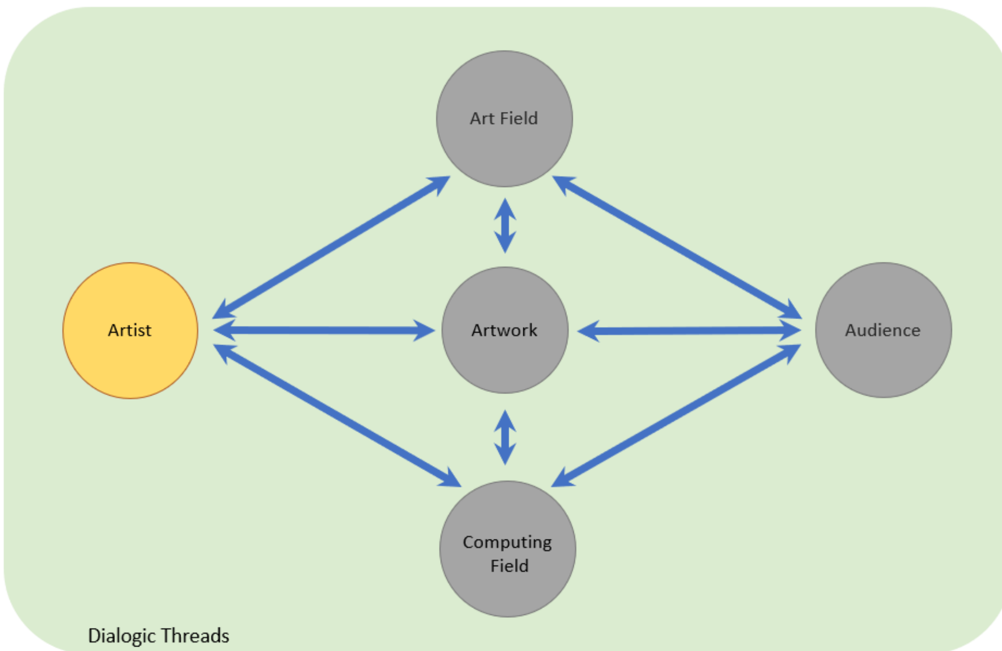


**Figure 23 - The general model for computational art ecologies that can be modified to reflect individual artist's experiences and engagement with computation in their art practice.**

Now, we will shift to constructing the links between the nodes in ann's *computational art ecology*, as these reflect the relationship and impact between the elements described above. The weights of the links will not be adjusted in the ecology, but I will reflect generally on the perceived significance for ann and suggest where this could be incorporated in future iterations. I've included a one-directional link leading from ann to her artwork, as she expresses herself through the creation of works of art.

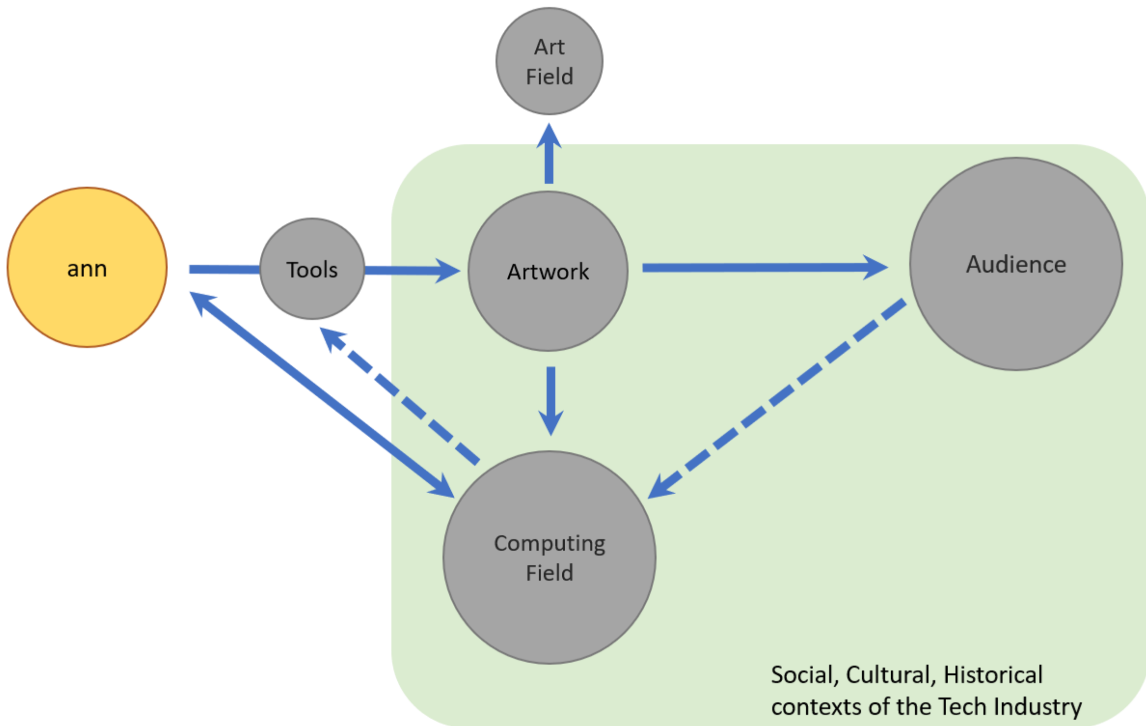


**Figure 24 - The unique computational art ecology for ann haeyoung.**

While she does think critically about the tools she uses in her practice and how these engage with a broader conversation on technology, she remained consistent and focused in her perspective on the arts and on the tech industry throughout her interview. As such, the artwork she creates does not influence or change her thinking in a significant way, translating once again to a one-directional link. As the practice itself was a focus and appeared to be a significant factor in how ann makes art, this link has potential to be weighted more heavily, particularly as she mentioned stopping or restarting the creation of a piece of art because of computational impacts (i.e., cost, time, distraction). There is a one directional arrow leading from artwork to both the art field and the computing field. Again, ann didn't situate her artwork in the broader art community or reflect on any influence from the art field. Her works of art do contribute to expanding the art field largely, translating to this one-direction link. In connecting her artwork to the computing field, ann critiques the tech industry consistently throughout her practice, contributing to the broader culture of the computing field. The computing field does impact her practice through two ways. First, ann studies the historical and contemporary trends in the tech industry, using this information to inspire and guide the themes of her artwork. ann additionally impacts the computing field through her employment in the field and in voicing her perspectives on the industry in public venues. This translates to a bi-directional link between ann and the computing field nodes, as they influence each other. The second way the computing field impacts her practice is through the computational tools she occasionally uses to create her artwork. As these are not present in every work of art, the relationship is reflected as a dashed one-directional link between the computing field node and the tools node. This is one-directional as ann does not subvert or modify the tools themselves, meaning her engagement with the tools does not directly influence the computing field. The last links relate to the audience node. First, a one-directional link leads from artwork to the audience. Throughout the interview, ann spoke on the goals of engaging her audience in a conversations and critiques about the tech industry and computation. While she occasionally includes interactive features in her art, such as a sculpture that plays videos when picked up, most of her art is consumed by the audience in a traditional manner, translating to this one-directional link. Finally, a dashed one-directional link leads from the audience to the computing field. As ann engages her audiences in critique and ideas, she hopes to shift the perspectives of and engagement with the tech industry and computing fields. As this may or may not be happening, this link is dashed to reflect this ideal state from ann’s point of view. Finally, as expressed throughout the interview, ann engages deeply in the history of technology, particularly related to the colonialism and exploitation from Western countries developing technological advancements. As such, the dialogic threads element surrounding the nodes in the original *computational art ecology*, is shifted here to frame artwork, the audience, and the computing field. It has been labeled as the social, cultural, and historical contexts of the tech industry. This characterization is not intended to represent the entirety of the social and cultural factors that impact ann or her art practice. This was identified as the most salient context as she returned to these themes consistently throughout the interview and in descriptions of her artwork.

The final art ecology is represented in Figure 24. In this, one can observe that the model is heavily weighted towards themes related to computing. Moreover, one can observe more clearly where computing factors impact the larger artistic process. In the following section, our final in-depth case study will be presented.

## Cody James Norman: A Case of Computational Manipulation

Cody James Norman is an artist and designer based in Chicago, Illinois. Cody obtained a Bachelor of Fine Arts with a focus in Designed objects and Sculpture from the School of The Art Institute of Chicago (SAIC) in 2016. He obtained a Master of Fine Art in 3D Design from Cranbrook Academy of Art in 2020. The interview was conducted while Cody was finishing his graduate program and he's participated in informal conversations in 2020 and 2021 about his art and practice. Cody "explores the relationship between chaos and order" by creating objects with robotic 3D printing and a handheld plastic extrusion gun (Noman, 2021). His current practice leverages recycled plastics that he transforms into expressive vessels and objects that change viewers' perception of plastic and design.  He leverages digital fabrication processes as well as traditional, analog processes to create these meaningful objects. As will be explored in more depth below, Cody explores the intersection of computing and the arts in a critical manner that highlights the affordances and unique expressive possibilities of computation. He further experiments with computation in art and design in a manner that amplifies the restructuration of computation within art (Wilensky & Papert, 2010; Wilensky, 2020). While other artists within this dissertation practice at this intersection, Cody reflects a subset of artists who personally explore the meaning of computation within art. Cody further represents a subset of artists who have expertise within computing and view it, largely, as a powerful and positive element. Though he does reflect on social and environmental factors associated with his practice, he primarily focuses on theoretical and conceptual exploration of craft. In the following section, a selection of his artwork will be presented and explored.

### Art Practice

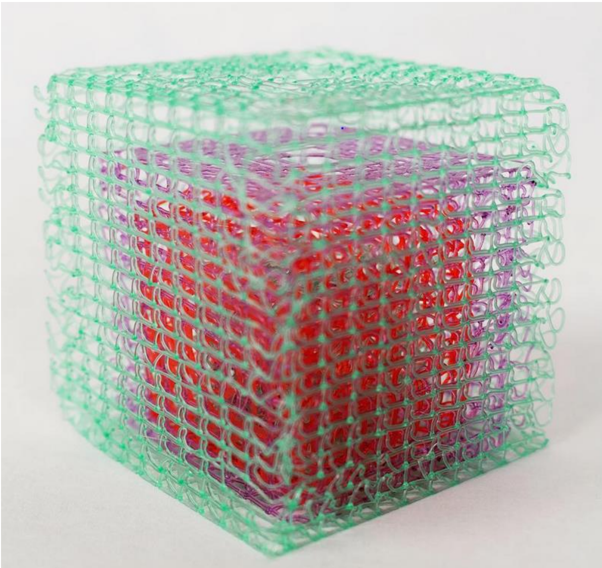


**Figure 25 - On left, *Cube^3* [plastic] a 3D printed object consisting of cubes within cubes (Norman, 2017a). On right, *Jellyfish Lamp* [plastic, electrical] (Norman, N.D. c).**

Cody's artwork focuses on the use of 3D printers, robotic 3D printers, and more traditional, analog processes in the creation of objects and vessels. For this artwork, Cody models objects in three dimensions using software like Rhinoceros 3D, a computer graphics and computer-aided design (CAD) software. He traditionally uses fused deposition modeling (FDM), also known as fused filament fabrication (FFF), the most widely used 3D printing method at the consumer level. In FDM or FFF, the 3D printer functions by extruding filament through a hot nozzle to melt and apply the filament material layer by layer to a build plate until the object is complete. The most common materials used for 3D printing are plastics but additional materials; like wood fill, cork, steel, ceramic, mushroom, and chocolate, among others; are available. After 3D modeling his objects, Cody goes through the process of slicing the object using other applications, like Slicer a free, open-source slicing software. As Cody described in his interview, a 3D model "like a mesh" that the printer needs to build layer by layer,

> *"Each layer has an X and a Y and Z. If I just gave [the 3D printer] the full 3D model, it would just try to print the base and print the top. So basically to get a finished object, it needs to be sliced. I like to tell people, think of like you're going to the deli and you're like, 'I want my slices to be medium thick', that's like a number that you put in and then the slicer. It will slice up your object up into hundreds of layers, and then it'll tell how fast, how hot, all the little settings are a slicer".*

Early in his career, he began creating artistic objects, like *Cube^3* (Norman, 2017a), and vessels, like *Noise #3* (Norman, N.D.c) that disrupt the traditional process of 3D printing. Both pieces of art leverage a style of 3D printing that manipulate the 3D printer to achieve atypical print appearances. FDM or FFF printing for general consumers is a low-fidelity process that results in objects where the layers are clearly visible as ridges along the side of the object. Traditionally these prints also entail a honeycomb or geometric center that provides structural support while limiting resource use. As is seen in *Cube #3* and *Noise #3* (see Figure 25 left and Figure 26), Cody implements printing processes that circumvent these traditional linear printing. In the *Cube^3* series, he leverages a process where each layer has x, y, z, points rather than just x and y points. Due to this additional axis, the mesh-like structure emerges as the filament is placed fluidly along the z axis in each later.

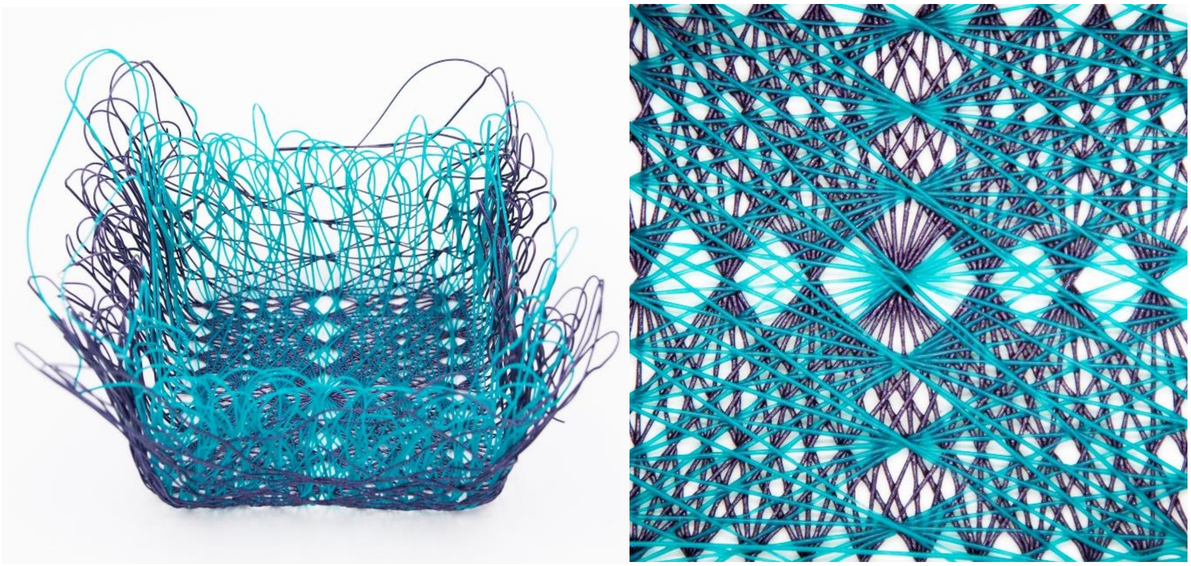

**Figure 26 - *Noise #3* [plastic] a vessel 3D printed using a weaving process developed by Cody J. Norman (N.D.c). On right, a close-up photograph of the woven filament (Norman, 2021a).**

The *Noise* series leverages a novel process developed by Cody wherein he circumvents the slicing process and prints at a constant z axis to weave with the printer. By placing on object like a dowel or a block on the build plate and printing above this object, he leverages the material properties of plastic and gravity to create fused layers of plastics that melt around the object. Cody also leveraged this 3D weaving process in *Jellyfish* to create floor lamps, where the bases are woven and created using industrial robots (see Figure 25 right; Norman, 2020b). This 3D weaving process will be explored in more detail later in his case study. However, these two printing processes reflect his practice of expertly manipulating technical systems, with knowledge of material properties, to achieve new effects in the medium of 3D printing.

Cody's practice has shifted over the time since his participation in the study.  In his career throughout his undergraduate and graduate schools, Cody focused deeply on the role of technology, particularly 3D printing, in art and design. During this period, he described himself as in his biography as

> *"constantly searching for new materials and methods to convey the role that technology plays in our daily lives. Cody's work references the relationships we have with our smartphones and the impact they have on our lives and culture.*

*Additionally, he explores the perceived values of digitally manufactured objects as well as how materials change how these objects are valued in the future."* (Norman, 2017b)

**Figure 27 - Turbulence vessel (Norman, 2020c; Norman, 2021a.) 3D printed using an Industrial robotic arm modified with 3D printing capabilities.**

The case study below largely reflects this mindset towards the intersection of art and computation or technology. While he still explores these concepts with computational tools, he now describes himself as exploring the "relationship between chaos and order", primarily leveraging recycled plastics in his robotic 3D printing and manual production machinery. His work now often leverages manual production machinery, like a handheld plastic extruder he developed to create more "chaotic" pieces, like *Growth*, a piece created using post-consumer, post-industrial, and virgin HDPE plastic (see Figure 28; Norman, 2020a). Much of his current work has aesthetically similar designs to *Turbulence* and *Growth*, where he manipulates 3D printers to create systematically inconsistent layers or abstract depositing of plastics with his handheld plastic extruder (see Figure 27 and Figure 28; Norman, 2020a; Norman, 2020c). Broadly, Cody's journey suggests the utility of longer-term relationships with participating artists, particularly those who are enrolled or recent graduates, as they situate themselves in art and computation fields outside of their programs.

**Figure 28 - Growth [recycled HDPE plastic] an object created using a handheld plastic extruder (Norman, 2020a).**

### Relationship with Art

Cody describes himself as always being connected to making and other creative ventures. His family was supportive of his practice but strongly encouraged him to seek career pathways that were more financially stable than that of an artist. While he told them he would become an architect or an engineer, traditional art, printmaking, and painting drew him to enroll at the School of the Art Institute of Chicago. He describes that he started with the intention of a focus in painting, for which he was given a scholarship, but took one painting class and dropped it the first day because he looked around at everyone's work and felt an urge to create in 3D. He shifted focus to graphic design so that he "could probably get a job" but then realized he wasn't attracted to the 2D elements of graphic design like typography and kerning fonts, which is the spacing between letters or characters. He was intrigued by 3D printing throughout his undergraduate career but explained that the classes teaching 3D modeling and printing were always full, so he only was able to take one his senior year. This class ultimately sparked his interest in computation, which will be explored more deeply in the following sections. His undergraduate career focused on design classes and sculpture classes, looking to explore how foundry could "boldly inform" his sculpting and design practices.

After graduating from the SAIC, he went on to a graduate program at Cranbrook Academy of Art for 3D design. Cranbrook is one of the top-ranked graduate school for the arts and has a rich and experimental history in education. The history and curricular design of Cranbrook is vital to understanding the impact of this school on students. Cranbrook was founded as an experimental artists' colony (Cranbrook, N.D.). George Booth and Ellen Scripps Booth, both within the publishing industry, purchased 319-acres of land in the metro-Detroit area in 1904 upon which to build their family home and public buildings focused on arts and education. The larger Cranbrook campus houses a PreK-12 college preparatory school, Natural History Museum, Art Museum and Library, Institute of Science, and the Academy of Art. The Academy of Art was founded in 1932 by George Booth and Ellen Scripps Booth then brought the Finnish architect Eliel Saarinen to Cranbrook to design the architecture for the campus and to formulate the curricula for the academy of art. Textile designer Loja Saarinen was also brought on to influence the curricular design and founded the textile and weaving programs within the academy. The Saarinen family had lasting influence on the academy, shaping the educational theory leveraged in addition to serving in prestigious roles within the academy and contributing to the rich body of artwork housed in Cranbrook's Museum of Art. With the Saarinen's influence, the school became a community where students learned through experimentation to "envision, create, and understand all aspects of design". Saarinen and the Booths were inspired by the Arts and Crafts movement for aesthetic and moral reasons, hoping that its influence would stop "tasteless, mass-produced goods from American homes" (Cranbrook, N.D.). They implemented an apprenticeship method of teaching, where a small group of students study under an artist-in-residence for the entirety of their curriculum. This model of self-directed learning under the guidance of an artist-in-residence has not changed since its inception. As such, the school is renowned for its practice and considered synonymous with contemporary American design (Goldberger, 1984).

Cody describes Cranbrook as influencing and refining his thinking about art and design. His time at Cranbrook provided him space and support to experiment in his practice. Moreover, as a self-directed program, Cody was able to explore other programs within the academy, diving into the theoretical and conceptual practice surrounding weaving and ceramics, among others. Moreover, within the apprenticeship model, students within the program, including Cody, expressed their expertise in design and critique, building stronger relationships with each other through the process. The 3D department, in particular, attracts a diverse subset of students focused on design of furniture and objects across varying mediums, such wood, metal, glass, and plastic. As will be explored in more depth, the experimental focus of Cranbrook has strongly influenced Cody's practice and conceptualization of art and design.

With the diverse background, he considers himself a hybrid of art and design. He describes that for him, art is making at a "more critical conceptual level" that entails abstraction of ideas and practice. Design is focused more on integration in the world or everyday life, drawing other factors like production, scaling, and user experience into the mix.  He describes his practice as meeting in the "critical" section in the Venn diagram of art and design, where he can operate on a deeper level than either alone. He pulls the critical nature of design into art making and the artistic abstraction into his design. Much of his work entails the creation of artistic objects or vessels that are functional pieces. As Cody focuses largely on design, much of his practice sits at the intersection of art and computation, as will be explored in more depth in the following sections.

**Relationship with Computing**

Cody did not have extensive interaction with computing, nor any notable personal connection to computers or computation throughout childhood. After realizing his interests related to 3D objects and design, he became fascinated with 3D printing's affordances of object production without needing to go to another contractor. Despite interest in taking these more technical courses in undergrad, due to their general popularity, he was only able to enroll in one his senior year. This launched his deeper engagement with computing and with 3D printing. Within this course, the teacher presented the conceptual framing of 3D modeling and design but "had a very hard time communicating" how to use the tools and the programs. As such, Cody learned the technical components of 3D modeling and printing through the internet. This learning process was intensive but rewarding. He described his first experience 3D printing, where he had two days before a deadline,

> *"There was this one broken printer in the classroom cause every other printer on campus was in use…. So I was like, 'well, if I'm going to print them and get my project in by the deadline, I'll have to fix this machine'. So one night I literally was there from seven at night, till seven in the morning in this room with this 3D printer. I'd never fixed or used a 3D printer before. So I was sitting on Google and message boards, just Googling anything I could think of. It was the printer was clogged and then it had this bolt was loose. It was literally like problems solving and troubleshooting from the get-go like that. That's how I've learned 3D printing."*

This debugging and self-teaching is a common practice throughout Cody’s practice with computational tools; “I've printed for thousands of hours now, most of it is literally through problem solving”.  He describes himself an expert now and continues to leverage online resources and communities to broaden his practice regarding computation and technology. At the time of the interview, Cody’s had begun to meet with about industrial robots after "two years translating German PDFs and YouTube and any deep robots and architecture message boards” to understand industrial robotic arms. His engagement in 3D printing and robotics, as well as plastics, requires reading “deep theory” in engineering and other technical fields.

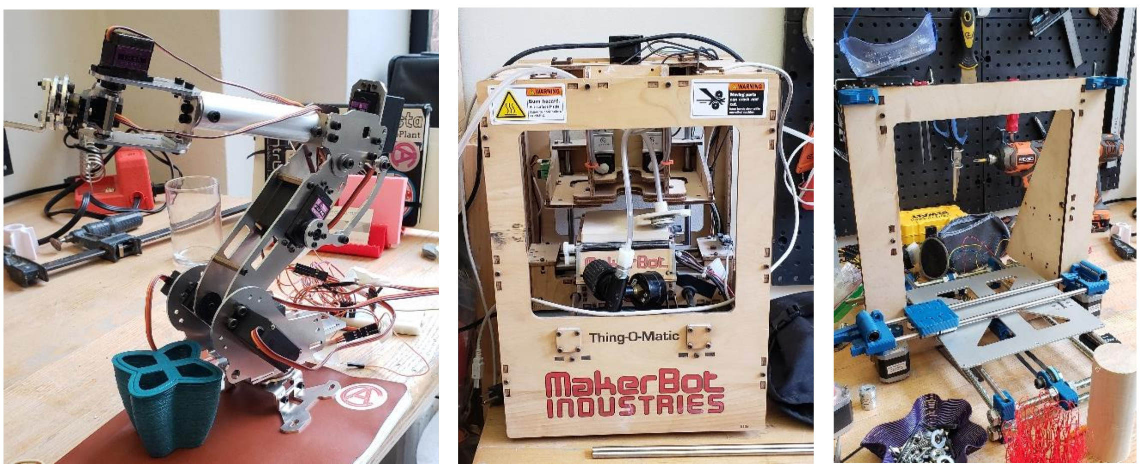


**Figure 29 - On left, a scaled version of an industrial robotic arm built by Cody. In center, the partially constructed 3D printer from the rapid replicator movement. On right, A MakerBot 3D printer used in Cody’s designs.**

Cody often reflects on issues of access within his field. The cost of 3D printers varies from a couple hundred dollars to tens of thousands of dollars, given the type and quality of the printer. Even the design and modeling software can be costly, particularly when multiple software are needed throughout the artistic practice. He carefully chooses the tools to use based on their cost point, limiting the time spent learning new software or machines when he doesn’t have long term access. Due to these issues of access, Cody focuses a lot of his work on finding, fixing, or modifying 3D printers so that he has tools that he can leverage in design and production (see Figure 29 for a subset of his printers). This is a common issue within the Maker community and other communities that leverage 3D printers or production machines. There has been a resulting rise in open-source software and resources to make machines. At the time of the interview, using resources from the rapid replicator movement, he was in the process of 3D printing the pieces of another 3D printer to grow his collection of tools.

Beyond the use of traditional 3D printers, Cody has a deep interest in using industrial robotics in his practice. He's particularly interested in robotic arms that have been used within industry. These large arms have more axes on which to bend or rotate, allowing for the potential of printing large objects. Moreover, these axes afford different potential designs in the objects themselves, as the robotic arms can move in more ways than the traditional x, y, z axes on a FDM 3D printer. At the time of the interview, Cody was modifying a small robotic arm to fit it with an extruder for 3D printing. He had collaboratively built the arm with a CNC professor from his undergrad. He described this machine,

> *"This is my little baby… this is a scaled version of an industrial robot… it has six axes… So this is basically just like my arm. But I want to put on a hot, like a 3D printer nozzle on this and 3D print with this and create like small scale models. And then since this is basically a scale model of a big robot, just take that file, scale it up and have the bigger robot practice this. So, yeah, this is a big step in my process, and I have no experience in robots, robotics. I did not take robotics classes did not compete in robotics in high school. We didn't have that at my school. I wish we did. So this is all self-taught."*

Currently, the low-cost machines for 3D printing trail behind the advances in industrial robotics. His interests in using more advanced machines have brought him into engineering and robotics communities and has motivated deeper learning in these computational fields. Cody grounded his interest in robotics and industrial practices in the rich history of industry within Detroit, where his school is located. In the 20th century, Henry Ford revolutionized automotive manufacturing and mass production in Detroit, and pushing the city into a gilded age of development and prosperity linked to automation. During this time, the city became hub of creative and cultural expression with constructions of renowned architects, the birthplace of music genres (including electronic music or techno), and the founding of the Detroit Institute of the Arts (DIA) (Hill & Gallagher, 2002; Mixon, 2018). However racial tensions and the post-industrial age saw an end to Detroit's prosperity; starting the 60's the city declined, ultimately filing for chapter 9 bankruptcy in 2013 (Davey & Walsh, 2013). Within the last decades, there has been a revitalization in Detroit, and a growing hub of art and design in the city. Cody situates his practice within this rich history, seeking to highlight innovative and creative practices with the industrial machines that once made Detroit famous for production. As will be explored later, Detroit's social orientation to the arts has influenced his practice in addition to its industrial history.  In the time since the interview, Cody had a year-long residency at Ballard International, a robotics company located in the Metro Detroit area, working on repairing a Kuka KR-16F robotic arm then using it in his practice. This residency led him to create *Turbulence*, among other large-scale 3D printed objects and vessels (see Figure 30). He's additionally collected other industrial robotic arms to repair for his work, leveraging online resources and support from his network.

**Intersection of Art and Computation**

Cody's interest in 3D printing focuses on the intersection between art, design, and foundry. His practice entails research in art, design, technology, industrial production, and material science. Though there are many goals of his practice, Cody is motivated by exploring the intersection of computational and traditional mediums while shifting between creating objects that are sculptural art pieces and that are functional objects. These themes and how he engages critically with technology will be explored in more depth below.

**Figure 30 - Photograph of Cody using a Kuka KR-16F industrial robotic arm while in residency at Ballard International. The printing of the *Turbulence* vessel can be seen (Norman, 2020c; Norman, 2021a).**

In his practice, Cody switches between designing for a specific computational tool and exploring a mental image then finding the right computational tool after modeling. This process shifts between traditional mediums and computational mediums as he sketches on paper then translates these images to 3D models. When he first began to 3D print, Cody sought to hide the 3D printed element, trying to make the layers invisible. He described that he was always disappointed, as these layers are impossible hide when printing with Fused Deposition modeling (FDM). After some time, he shifted his approach to "make [the layers] look intentional", by making the layers thicker and thicker. He seeks to create new processes for 3D printing that extends and highlights the affordances of the medium, "I definitely feel like I'm exploring craft right now. I'm trying to use things that only 3d printing can accomplish and explore. What are the affordances of the process? What is something that I couldn't do, a human cannot do?". This process requires Cody to deeply understand each 3D printer and computational tool he uses in his practice. He likens the unique differences of the printing of a 3D printer to an artist's hand,

> *"what's the artist's hand? What does a 3D printers hand look like? So pushing the idea of when it's printing thick, it droops. And in certain movements and certain speeds, it's just like a painter has a brush stroke…Each machine has its own hand. So I come from a painting background. So sometimes I think of 3d printing, like a painter, I think, I hope. So, you have a paint palette, and you have all these different colors. Well, for 3D printing, it's the same. You have all these different plastics and all these different colors and all these different properties. So sometimes it's using the flexibility of one. And the ability to make it really rigid with the other and trying to mix and match those to get to the point where it's conceptually working for me."*

Cody conceptualizes his 3D printers as if they're partners in his artistic practice, rather than simply tools at his disposal. He deeply understands how each printer functions and highlights and amplifies their unique printing styles in his work.

Based on this expertise, Cody's early work focused on the technical affordances of 3D printing through researching new processes that would extend, subvert, and systematically create bugs in the 3D printer. He describes this process,

> *"My stuff looks like it's operating on a different level of the level of 3D printing. A lot of times I have an error and or this happy accident and I'm like, 'Whoa, that effect is amazing. How did that happen?' So then I'm like, 'Oh, the belts were loose and this gear was slipping'. Yeah. Okay. How do I make it do that for seven hours nonstop to get the same effect over and over and over again? So this right here* [ *Expansion* (Norman, N.D.) see Figure 31], *for example, is a totally undesirable effect. This jittery static is something that most people would quit the print, throw it in the garbage and recycle it, then just say this is nonsense. And I was like, 'Whoa, that's actually kind of an interesting feature there that creates'".*

This practice extends and manipulates the 3D printer, systematically creating bugs for new effects in the print. In *Expansion* (see Figure 31), Cody leverages a bug in the print that created a "jittery static" effect then applied it to create an artistic object. He explained his thinking around this piece, "it looked like a sea urchin or something. But then I was like, 'how do I push that?' So then using a castable [polyurethane] foam I was actually able to make it expand and create kind of like a sea urchin alien critter". As the interview was conducted in his studio, he showed other "failed" prints that he was exploring and trying to systematically recreate. These effects emerge from technical issues, such as broken parts in the 3D printer, incorrect printing temperature, incorrect slicing of the print, among many other potential bugs. As Cody alluded to above, these are most often considered failed prints and necessitate debugging to correct. He attempts to systematically recreate these so that he can leverage these bugs to meet goals for his art and design. He has gained mastery over the technical and computational rules underlying 3D printing and knowingly, artistically breaks convention for his practice.

**Figure 31 - Expansion 3D print [plastic, castable polyurethane foam] that highlights Cody's systematic extension of bugs in the 3D print. (Norman, N.D.a). The left photograph taken during the interview and the right posted on Cody's Instagram account.**

In *Expansion* (Norman, N.D.), Cody leverages high-tech (3D printing) and low-tech materials (castable foam). This process of combining "low-tech" and "high-tech" materials is an element of his practice he is exploring in more depth. He explained that his program at Cranbrook School of Design fosters an experimental approach to practice, which he explores through merging older techniques with computational techniques. At the time of the interview, Cody was exploring how weaving could be integrated within 3D printing. He showed early approaches to learning to weave and then weaving together 3D printed blocks (see Figure 32).

He explained that this first attempt was imperfect, and that these pieces should fit together perfectly, rather than being tied together, since he is using technology. Through iteration, he discovered a new process to "literally" weave with the 3D printer. He describes it as a process that bypasses traditional slicing (denoting the layers in a 3D model) and hacks the 3D printer to the fullest extent. He leveraged this process in his *Noise* series, presented earlier in the art practice section (see Figure 26).

> *"I put an object into my printer such as this dowel and I created a three-dimensional pattern. That's slightly above this in the 3d, instead of like printing at the base. Basically, I put this in the center of the printer and I tell it, 'go up above that'. I tell the printer, 'create that pattern', and it just draws around it. And then basically this there's something like this. So basically, um, I'm using the plastics' plasticity and using gravity to pull the plastic around the object. So it's essentially weaving with the 3D printer and then just like really playing up the material properties of plastics."*

In other words, Cody will place an object, like a dowel, on the 3D printing build plate and will tell the 3D printer to start printing above that object. Using modeled shapes that have a spoke-like design, different woven patterns emerge as the 3D printer deposits filament across the object at a constant height and the filament sticks together (see Figure 33). Gravity pulls the hot filament down the sides of the object, creating basket-like sculptures or objects. There are no other processes documented like this 3D weaving and, at the time of the interview, Cody was making sense of how to document and share this process and the associated works. He explained that with 3D printing, it is easy for others to reverse engineer work, so he has been leery of social media, especially after two of his objects were reproduced.

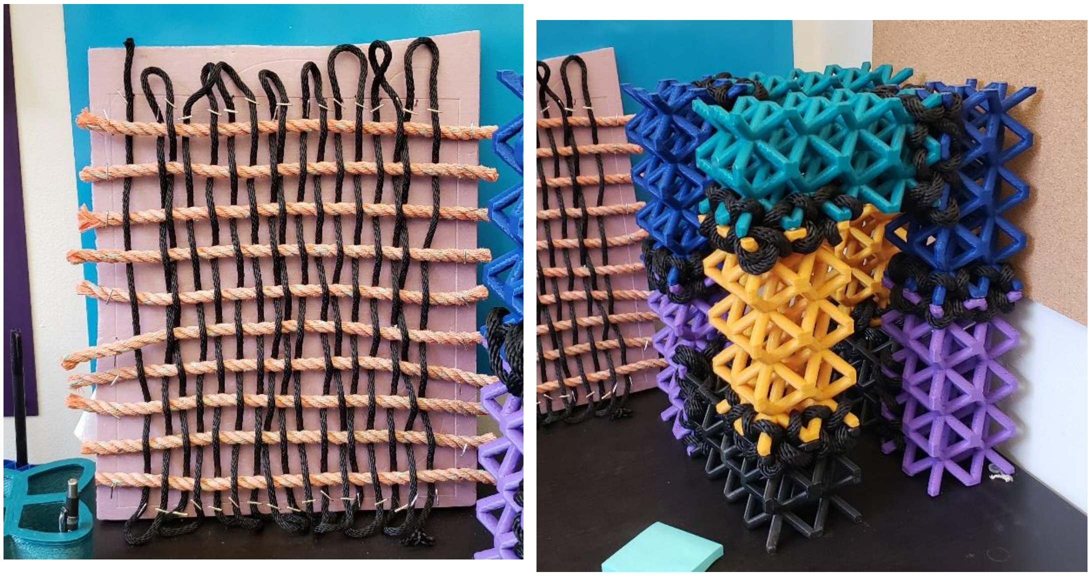

**Figure 32 - Photographs from the studio visit. On left, Cody's exploration of the practice of weaving. On right, a first iteration that combines weaving with 3D printing.**

Cody also leverages online resources in expanding his practice, looking through scholarly articles about design, plastics, technology, industrial production, among many other topics. While he gains exposure to a wide array of research and practice, many articles will redact a subset of the steps needed for the process or hide steps behind a paywall. As such, a lot of Cody's research entails debugging the process, looking at the end product and making informed guesses about the steps leading to it. In one example, Cody found a process about 3D printing mesh in an MIT research paper. Not able to access all of the steps needed for the process, he used a computational generative design software, Grasshopper, to determine that the mesh could be made by moving fluidly in three dimensions to create wave-like lines along a sliced axis. As he describes,

> *"I could take on the surface of a mesh and then break it up into these lines and essentially like connect the dots. So 3d printing is typically two and a half axes where it's just like prints a layer, comes up, prints a layer, comes up. This is actually printing a base line and then it goes up and down. So it's like fluidly moving in three dimensions instead of just doing stairsteps…This is efficient. Time-wise, I can create big objects using this process, uses less material. The one thing it doesn't do so well, it's pretty brittle."*

After experimenting with the mesh process, Cody wove other materials through the mesh sides of his objects to explore how the new materials impact the shape, feel, and utility of the printed object. With the weaving and mesh printing, he drastically lengthened the time it takes to produce an object and felt this raised questions about the benefits or impacts of man in creating art.

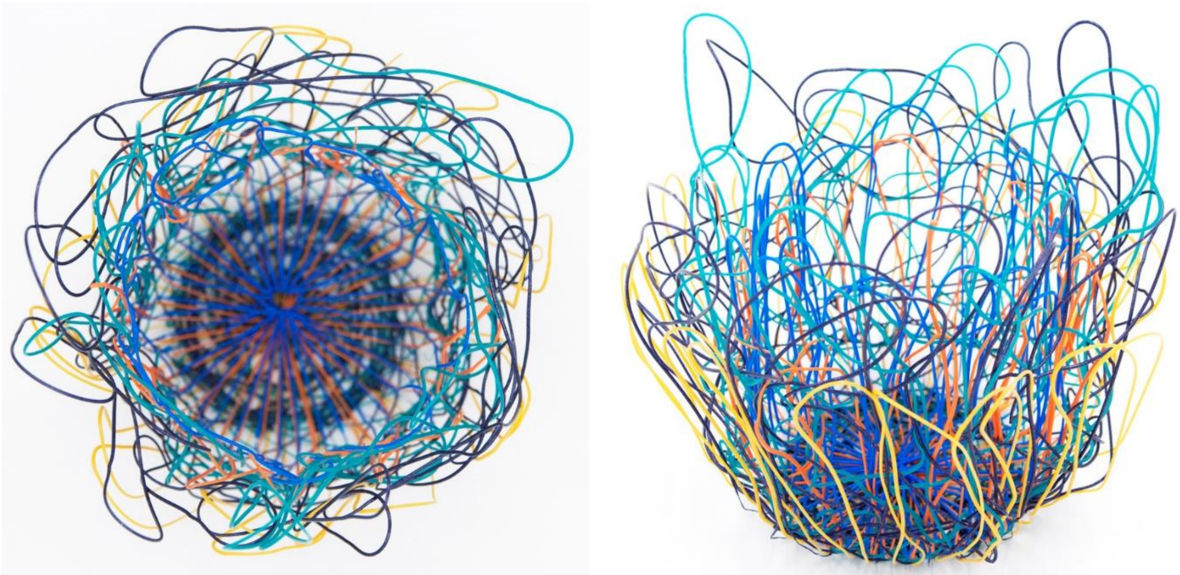

**Figure 33 - *Noise #4* (Norman, N.D.c), a process of weaving with FDM printers developed by Cody Norman. Photographs from Cody's personal website (Norman, 2021a).**

By combining processes completed by hand and my machine, Cody explores the intersection of humans and computation. He brought up the folklore that John Henry, the American folk hero, raced a steam shovel and won the race but died due to physical strain. His thinking about technology and computation often orients around this lore and he is deeply curious about other machine vs. man races and issues. He expressed interest in a race between a 3D ceramic 3D printer and a master potter, noting that the artifacts and process would be completely different between the two. In this, Cody seeks to leverage and highlight the computational hand in the process, rather than using a tool to replicate a human-made design. Moreover, he muses about the various computational tools he might leverage and how these differ from each other and from the human hand, “my goal is to use an industrial robot to print big things and just explore, what does a robot do differently than a 3d printer and what does it do different than my human hand?”

Socially, Cody finds his communities important for deepening exploration of conceptual and material practice in his art and design. Cranbrook, in particular, provided a rich environment for Cody to experiment across materials and genres, “I do think this program, like foster is like an experimental, like try new thing approach. And it's not like you have to really think about how [an object] functions or how it's used. It's more so like the ideas around the process. And I think to explore the craft in 3D printing, this is probably like the perfect program for me.” Moreover, he participated in electives in other departments to explore the ways that they think about design and production of objects. His interest in printing using clay and ceramic materials led him to take an elective in the ceramics program. On this experience, he reflected,

> *“the way they come at a critique is much different than us. [They’re] really concerned that it functions, and it works. And like, what does it live in the outside world? … what's the context that it's used in? They’re looking at the canon of ceramics and the processes and that's their lens to look through. So if I go 3D print there, that's going to be critiqued in a much different way because they're looking at it from ceramics point of view and analog and pottery, what does it mean when you bring a machine into ceramics?”*

Cody’s practice seeks to explore and identify the meaning in using technology in art and design. He digs into the affordances of tools in his repertoire, identifying their unique “artist’s hands” that he can leverage or subvert in order to find new processes for creating art and objects. Moreover, he questions the meaning of art and design at the intersection of technology and various genres, engaging other artists and his audience in practice and conversations about the affordances and perceived value of computational art practice. This unique relationship with his audience will be explored in more detail in the following section, relationship to the audience.

Cody practice is situated within engineering and robotics communities in addition to art communities. These spaces provide him access to technical and computational expertise as well as perspectives on conceptual and theoretical implications of the intersection of art and computation. While he engages in these circles, he explained that some engineers and other technical experts see his work as superfluous or confusing. As he described about his experience discussing his scaled robotic arm with engineers,

> *"I was telling [the engineers] what I do, they were looking at me like, 'who are you?' They're like, 'you speak like a madman. You're going to 3d print what? What's it's use?' They were so concerned with the use of it, and I was like, 'No… it's just pretty. Like maybe this becomes a lamp. I don't know, but why are you so concerned with the use?'... So this idea of using robots and art in architecture is becoming more prevalent, but I still think there's a little kickback, especially when you're working with engineers that are like, 'you want to do what with the robot?' Like I want to draw. Maybe the robot paints for me. And they're like, 'why would you do that?'"*

The intersection of art and these computational or technical mediums requires artists to engage in conversations framed in and by members of each respective field. Cody, like other artists, struggles to engage in the conversation and experimentation with those from more technical fields. As he experienced, there is pushback on the unique applications or manipulations of computational tools from those in technical fields. As he further reflected on his experience talking to engineers,

> *Conceptually, what's it mean when a robot does something? So with [the robotic arm], I've had it draw. I don't have the drawings here, but through pencil and the end of this [pointing to the tip of the robotic arm]. And I would draw something and then put that in illustrator and create code for [the robotic arm] to draw, and it would be the weirdest, clunkiest version of my drawing. And there was something lost there. I'm teaching it to draw essentially as a step to getting to 3d printing theory."*

While the engineers may question the experimentation and process of using industrial robots in art and design, Cody sees this process as vital to building theory around 3D printing and in this genre of art and area of design. Despite initial pushback from engineers, he has since built connections with engineers and others in computing fields, increasing access to industrial robots.

Cody's practice also explores the use of a variety of materials in the creation of objects and artwork. This work is partially an extension of his experimentation and exploration of how 3D printing can relate to other genres of art, like weaving or ceramics. He uses varying materials to explore potential futures of design of objects and furniture. He explained he went on a "composites binge" where he explored cork, wood, bamboo, steel, iron, carbon, and ceramic material for use in 3D printers. In this, he explored the properties and affordances of each material, as well as the environmental impact of each. He further expressed interest in unconventional or short-term materials, like mushroom composite. He mused over the idea of compostable objects that one could use for a year then throw into the garden when they begin to break down. This approach could allow for more stylistic experimentation in the home.

**Figure 34 - On left, a photograph of sorted plastics featuring Rachel Mulder of Thing Thing. On right, cleaned and chipped recycled plastics that can be used in Thing Thing production. (Thing Thing, 2018; Thing Thing, N.D.a).**

While he has explored other materials, his primary material within his work is plastic. Early in his work, he began following plastics designers on social media that focus on developing and extending processes to use recycled plastics in their design. One of these thinking partners identified by Cody is Thing Thing, a manufacturing studio featuring a rotating cast of artists and designers, including Thom Moran, Rachel Mulder, and Eiji Jimbo, that is currently led by Simon Anton. Thing Thing designs processes to work intuitively with materials and methods usually reserved for industrial production (Thing Thing, N.D.). Given the in-person studio visit, I was able to connect with other artists in Cody's studio for informal interviews and discussions about Cody's work and how their practice interacts with Cody's. As Thing Thing was mentioned as an important influence on Cody's process and material experimentation, a brief reflection from Thing Thing designers included to shed more light on Cody's practice and the field broadly.

Simon Anton participated in an informal interview about Thing Thing, the art field, and his interactions with Cody. This informal interview sheds light on the types of practices that are common in the plastics design and showcases some elements that were backgrounded in the interview with Cody. Simon and Cody were both enrolled in the Cranbrook 3D design program in the same cohort and spent a lot of time discussing ideas related to plastics processing, research, and design. Thing Thing's work takes advantage of the material properties of plastic and use plastics in a "painterly way". To do so, they collect post-consumer plastics that are commonly only recycled into industrial sludge for industrial purposes, then clean, sort by color, and shred the plastics into chips that can then be used in artistic production methods (see Figure 34 for process from post-consumer plastic to chipped plastic). Their work features experimental designs that are functional and artistic, featuring narratives that encourage new perspectives on plastic and recycling (see Figure 35 for selection of their work). These works showcase variety in the plastics genre and highlight some of the process related to and methodology within this field.

**Figure 35 - On left, *Rainbro* [hand recycled plastics], a whimsical piece of urban sculpture and a quirky domestic object (Thing Thing, 2012). In center, *Clocks* [hand recycled plastics], a series of clocks created using plastics (Thing Thing, N.D.b). On right, *Pillows 2* [hand recycled plastics], a series of functional pillow shaped lamps created using plastics (Thing Thing, N.D.).**

Simon explained that design with recycled plastics started in the 70's but has only been popularized n in recent years, largely due to more widespread interest in recycling and ecological issues related to climate change. He noted that plastic is a niche material and there is a potential to see competition in development of equipment and processes within the genre. Unlike ceramics, for example, where artists have developed practices and materials for centuries, plastic is a new frontier that is still evolving and developing. Simon explained that artists from all over the world are sharing ideas, materials, and tools but applying these for their own emphasis within plastics. The field itself requires a transdisciplinary approach to practice that leverages art, design, technology, and scientific knowledge. Simon explained that this genre requires a lot of research in order to be successful, 1) Plastics research: multidisciplinary study looking within chemistry and technology to explore material properties and material technology, 2) Plastic production and fabrication: broad and technical area of research exploring how plastic has been used, particularly important for those situated in historically industrial areas of the US like the Midwest, 3) Design research: exploration that removes form and function from the material to explore how plastics have been used in the past, how projects can be made accessible, 4) Craft research: a primary focus within the Cranbrook Academy of the arts, a hands-on approach focusing on identifying new approaches and methods for working with materials and tools (e.g. mixing plastics, testing finishing styles, remelting, cutting, applying new tools), and 5) global practices with plastic: an exploration of the global systems and patterns of engagement with plastics, global waste and recycling systems, and how to situate personal practice within this larger system. On the genre generally, he reflected that production is less expensive, more consistent, and faster with virgin plastics compared to recycled plastics. For those working with these recycled plastics, it takes a lot of education and storytelling to convince others to pay more money for objects created with materials traditionally associated with trash and cheapness.

**Figure 36 - On left, plastic extruding gun in-process picture of the creation of *Plasticus canistraria*. On right, *Plasticus canistraria* (Norman, 2021c).**

At the time of the interview, Cody reflected that the interactions with Thing Thing and other designers and plastics projects were influencing him to explore new production approaches for his own work that could support this shift to recycled plastics. Since the interview, Cody has developed several new approaches for using recycled plastics in his work, including an extruder gun that lets him manually deposit melted recycled plastics onto a form (see Figure 36) and an approach to creating multicolored prints through selection of recycled plastics (see Figure 37). As both Cody and Simon reflected, these informal conversations and sharing of processes were instrumental in supporting the development of personal ideas within their practice. Moreover, as plastics is a small emerging genre, these connections provide conceptual and technical support as the genre evolves in practice and grows in popularity. Finally, this partnership was formed within Detroit, which offers a unique community to engage in artistic practice. As was explored previously, the 'Motor City' provides a rich industrial history in which Cody's work is situated. His artistic practice is further situated in the culture and history of art within Detroit. As he explains, "the most interesting to me right now is seeing the work that's engaging with the city and the community. It's much different than Chicago. There are a lot of social practice works happening in Chicago, but Detroit, I think there's a lot more of that going on. And I think you see that the actual impact of it a lot more here." He described Detroit as a burgeoning community of artists that engage with the community in arts education and public art experiences. While the city is often overlooked in the landscape of major art cities, like New York and Los Angeles, its community is growing and is interconnected in Detroit.

**Relationship to the Audience**

Cody's relationship with his audience varies from project to project, depending on conceptual goals of a given piece. Largely, he presents objects created by computation for his audience to view or use in their everyday lives. Coming from a design background, in addition to art, many of his pieces are artistically functional. While present in the design, the computational aspect of his work does not change the relationship between the audience and the work.

While Cody doesn't design for a specific audience, he does reflect on their perceived value of 3D printed and computationally created objects or art. He expressed that some undervalue objects that are created using 3D printing, expressing that the majority of the work is completed by the machine or computer rather than an artist. At the time of the interview, Cody was still unsure how to price his work. His focus was on experimentation and practice while in school, but pricing was an ongoing concern, “it's been really difficult to price my work. What's the price? I don't have as much “time” sometimes. Where it took me three hours to print the object. *I* wasn't printing it; the machine was printing it. So then I have to think about material cost and energy.” Cody struggles with the perceptions of the process of 3D printing, saying that some will say “’you didn’t make it, you clicked print’” or undervaluing objects made of plastic, as was also reflected in the informal interview with Thing Thing. Early in his practice, Cody engaged his audience in making sense of perception and value of materials. Cody designed a show where he printed the same object in every material he could find then asked the audience to price the work.  He described that “the corks ones would always be like $30 more than the plastic ones. And the steel filament would be worth more than the cork. So people automatically were prescribing a value to that object”. While Cody’s exploration of material value does incorporate interaction with the audience, he primarily expresses his personal goals within art and design when creating new objects.

Finally, Cody is active on social media, particularly Instagram (www.instagram.com/gcody3d). There, he posts a variety of content including professional photography of his designed objects and vessels, information about his exhibits, and documentation of his ongoing practice. This documentation captures engagement with various computational and analog tools, experimentation with plastics and processes, and collaborations with fellow artists, engineers, and others in his broader communities. Moreover, he highlights a subset of his work on his professional website, where he sells products occasionally. Broadly, this community engagement is an important practice in the plastics design genre, as artists share their processes and networks within this niche community.

**Figure 37 - On left, multicolored prints using recycled plastics in an FDM 3D printer (Norman, N.D.b). On right, a piece from the *Metamorphosis* solo-show (Norman, 2021b) that uses the multicolored RDM printing technique in addition to the manual plastic extruding gun.**

## Computational Art Ecology

Cody leverages and manipulates computational tools to explore the future of design. His practice sits at the intersection of art and design but focuses strongly on the meaning and influence of technology across these two fields. He engages with 3D printers and other robotic tools to create an array of objects and vessels. Rather than using these tools as intended, he uses his expertise of the tools to subvert and manipulate their functioning to achieve new outcomes and effects beyond what is traditional. Cody seeks to elevate and showcase the "artist's hand" of these computational tools, systematically recreating bugs and exaggerating the print layers. The original model for the *computational art ecology* is included in Figure 38, as reference.

We will begin the construction of Cody's unique *computational art ecology* (see Figure 39 for final ecology) with a description of the nodes. First, the artist node is changed to Cody, as this ecology focuses on his experiences as an artist. Next, Cody focuses much of his work on tools that he leverages in his practice, both computational and analog. As this is a primary focus, particularly as he gains expertise so that he can extend and manipulate their processes, a tools & materials node is added between Cody and his artwork. As was explained with ann's *computational art ecology*, not all artists critically engage with the tools of their practice. As such, this is a unique node that is added due to the significance of tools in Cody's practice.

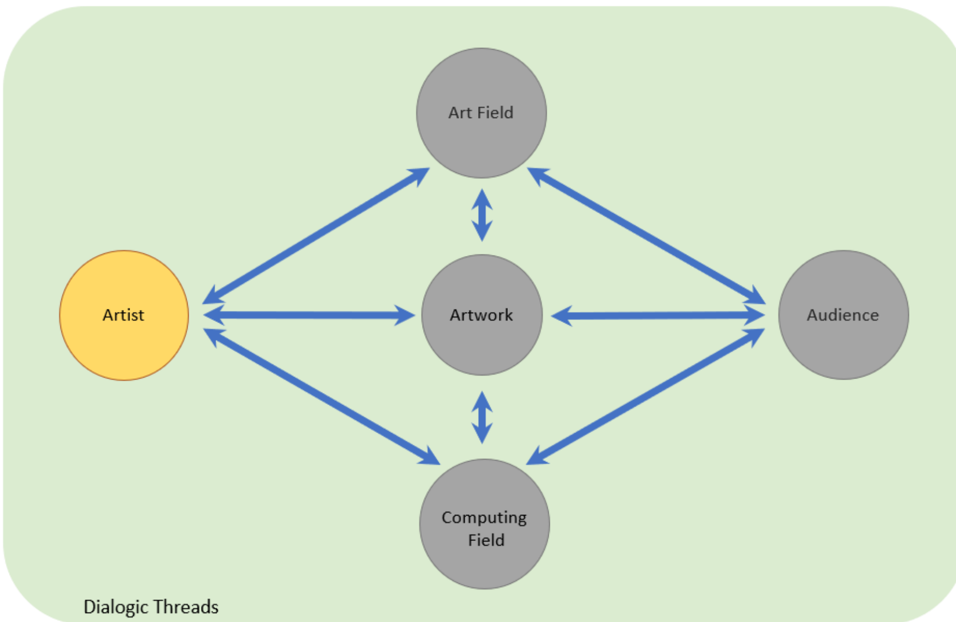


**Figure 38 - The general model for computational art ecologies that can be modified to reflect individual artist's experiences and engagement with computation in their art practice.**

Cody situated his practice at the intersection of art and design, describing his background in classical arts as informing his design approach. Detailed by Simon Anton of Thing Thing in his informal interview, the intersection between art and design has been growing in popularity in the half-century, with various schools of thought identifying various boundaries and subgenres between art, design, and craft as well. Fine design or collectible design are two common terms describing this overlap between art and design, reflecting the design of functional objects or furniture that have are uniquely precious and convey emotional and personal qualities (Macdonald, 2017). This intersection is represented in the *computational art ecology* by replacing the art field node with a fine design node. The computing field node remains unchanged. Future iterations of the ecology could provide more detail about the types of communities in the computing field with which Cody engages, including robotic and industrial engineers, computer scientists, and others. Finally, the audience node is reduced in size, as the bulk of Cody's practice focuses on his personal experimentation and manipulation of tools rather than on communicating with his audience. The design element adds a new level of interaction with the work he produces, as the work is integrated functionally in the everyday lives of his audience. However, most of his exhibits align with more traditional art viewing experiences, as such we include a one-directional link leading from artwork to the audience.

Now, we will shift to constructing the links between the nodes in Cody's *computational art ecology*, as these reflect the relationships and impact between the elements described above. Again, the weights of the links will not be adjusted in the ecology, but I will reflect generally on the perceived significance for Cody and suggest where this could be incorporated in future iterations. A bi-directional link leads from Cody to the tools & materials node, as he engages in deep self-reflection and experimentation around the use of tools and materials in his practice. Moreover, the personification of these machines, perceiving them as having unique "artist's hands" and almost as unique collaborators to bring onto a given project, deepens this connection with his tools and would suggest a more heavily weighted link. His engagement with materials is experimental and iterative. As Cody's practice is generally reflexive and consists of theoretical explorations and experimental iterations, I've included bi-directional links between Cody and the fine design node as well as the computing field node. He draws practice and theory from both the fine design and computing field for his work. Moreover, he is developing new processes and applications of tools and theory for both fields as well. Importantly, Cody modifies and creates new tools that support new theory and practice for both the computing and fine design fields, warranting bi-directional links between tools and each respective field. He is active in sharing process and technical processes that he has developed in order to expand his practice in the plastics genre of art and fine design. Moreover, his collaborations with robotics companies and other industrial companies expands the computing field. I've included a bi-directional link between tools and artwork, reflecting the iterative experimentation that Cody engages in throughout his practice. The bidirectionality of this link is exemplified by Cody's practice of trying to systematically recreate errors or bugs in his prints so that he can achieve new effects. His subversion of the 3D printer to develop a process of weaving also captures this bidirectionality. A link from the artwork node leads into both the 'fine design' and 'computing field' nodes. In this, Cody's practice contributes to expanding the body of work across both fields. His artwork does not adapt or interact with the larger fields. These fields influence his thinking and the process, as they're created with computational tools, but the plastic objects and vessels are not adaptable after being created. Finally, a link leads from artwork node to the audience node, reflecting a more traditional viewing experience with the audience.

To complete Cody's ecology, the dialogic threads element is shifted to frame the tools & materials, fine design, artwork, and computing field nodes. This framing reflects Cody's deep engagement across the intersection of fine design and computing fields, using tools to explore the relationship and differences between the two. His experimentation and theorizing about the nature and implications of computation in art and design reflects an equal engagement across these elements. Moreover, Cody's practice explicitly highlights the restructuration of computing in the arts and in design (Wilensky, 2020; Wilensky & Papert, 2010), as he seeks to identify the affordances and "artist's hand" of his computational tools.  While other artists may inherently engage in practice that reflects this restructuration, Cody seeks to identify these for himself and use his discoveries to further subvert, modify, and expand computation in the arts.

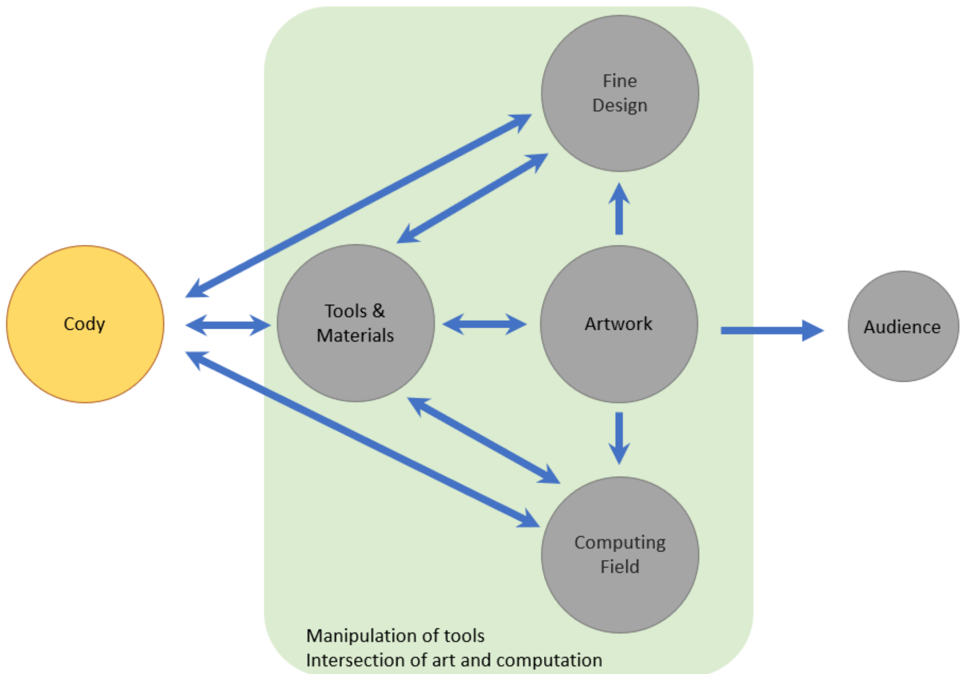


**Figure 39 - The unique computational art ecology for Cody James Norman.**

In the following section, the *computational art ecologies* for Janell, ann, and Cody will be compared to further highlight the utility of this lens in capturing and characterizing computational perspectives in the arts.

## Comparison and Discussion

In the cases above, we've highlighted three artists; Janell Baxter, ann haeyoung, and Cody James Norman; who leverage and engage with computation in unique ways to explore and express personal and social narratives. The three artists engage in critical inquiry and commentary with their artwork but they each took unique pathways through art and computing fields to gain the knowledge, skills, and perspectives that they leverage throughout their practice. The cases highlight the complex relationship each has with the use of computation in their art practice.  In the following section, we'll explore similarities and differences between the three cases through the *computational art ecologies*, particularly in how each relates to computation (see Figure 40 for ecologies).

Janell and ann provide insight into humanistic perspectives on computing that go against mainstream narratives in computing fields. Janell highlights biases in algorithms through the creation of AI bots that explore personal and social themes. Looking at the *computational art ecologies,* we can observe a few differences in their art practice at an ecological level. Janell's model is weighted more heavily to the left, with the nodes for Janell and her bots highly interconnected with each other, and both art and computing fields. Her dialogic threads element frames nodes on the left side of the ecology. ann's ecology, in contrast, is weighted more heavily towards the right. For ann, the computing field node is highly connected to all nodes except for the art field. Her dialogic threads element tends towards the right as well. Lastly, we can identify that Janell has a larger number of bi-directional links between nodes in her ecology compared to links in ann's ecology, suggesting Janell is more self-reflective in her practice than ann. Cody's critical engagement through his art takes the form of experimentation at the intersection of computation and fine design. While Janell and ann focus on a more critical perspective on technology and computation, Cody expresses deep excitement and joy at the premise that computational tools can aid in design and artistic practice. He draws on historical industrial production to inspire and motivate the design practices of the future with new computational tools. Cody's *computational art ecology* in more centrally weighted, with his dialogic threads element framing the tools & materials and artwork nodes in addition to capturing both art and computing fields. Like Janell, Cody's ecology contains primarily bi-directional links, again showcasing his self-reflective and iterative practice. Like ann, Cody's ecology also highlights the tools used, plus the addition of materials in his case, as his computational tools are a central component of his practice. Unlike ann, Cody engages in deep exploration of the computational tools he leverages so that he can extend, modify, and manipulate them to create new outcomes unintended in the design of the tools. As he does create new processes, we can observe his contribution to both art and computing fields from the bi-directional links from the tools & materials node to both fields. We can also observe a difference in the significance of the tools in both artists' practice. ann approaches these tools hesitantly, critically questioning their use in her practice while Cody embraces and highlights their use in his practice. As such, the tools node is smaller for ann than it is for Cody.

Connecting this back to the artists, what can these structural differences in the *computational art ecologies* tell us about differences in practice for Janell, ann, and Cody? For all three, their unique engagement with computation and the computing field is at the forefront in their art practice. Janell consistently creates AI bots. ann critiques the computing fields throughout her artwork, critically leveraging technology to critique the tech industry and showcase its problematic history. Cody leverages and manipulates computational tools to explore the future of fine design while paying homage to a culture and history of industrial production. The *computational art ecologies* reflect this as the dialogic threads element is aligned towards the bottom of the ecology for both Janell and ann, framing more active participation in the computing field, compared to the art field. The links for both of these artists between the art field node and the artist node in both ecologies showcase that there is still community engagement in the art field for both. For Cody, his dialogic threads element frames fine design and computing fields, showing his active participation in both.

In exploring the weight from left to right in the ecologies, we see that Janell's dialogic threads element is more aligned towards the left. ann's ecology is more aligned towards the right while Cody's is centralized. This reflects differing levels of engagement with computational tools. They each leverage computation in the process of creating a piece of art, and the artwork for all three is expressive and critical. In practice, we see that Janell engages with technology in a consistent manner, leveraging a variety of programming languages and connecting to the computing field to leverage AI and other technological advances. These computational mediums are vital to her artistic practice. Without the use of these tools and mediums, Janell would not be able to engage in her art practice. ann leverages technology and computational tools cautiously, considering a series of factors related to cost, time, level of gimmick, and significance for critique before incorporating computational elements in her practice. While she does spend time and energy reflecting on tool use, her primary focus is on exploring how unique applications of these in nontraditional contexts can provide insight on or critique of the tech industry. Cody, like Janell, consistently leverages computational tools and practice in his art and design. His practice necessitates expertise with these computational tools, as he learns how to build, modify, and manipulate them to create new processes. While Cody does leverage analog production processes, like his handheld plastic extruder, much of his work focuses on how computation can shift genres of art and the future of design and production. In shifting to relationships with the audience, ann uses these computational elements to attract and engage audiences into thinking more deeply about the tech industry. For Janell and Cody, their engagement with computational tools is for their personal inquiry and experimentation, and their ecologies reflect this limited engagement with a small 'audience' node. Janell has the least interest in a relationship to the audience, often creating bots for herself without exhibiting them, shown by the dashed link to the audience node.

Finally, we observe that Janell and Cody's ecology contain more bi-directional links compared to ann's ecology. Janell's practice is very self-reflective, and she deeply interrogates how art and computing overlap, particularly as it applies to understanding herself and other humans. Moreover, she continues to draw from and situate herself in terms of art and computing fields. She is actively making sense of how and where she fits at the intersection of these two fields and is currently ideating on how she could incorporate new elements into her work that would allow others to better understand the impact of her practice. Cody seeks to experiment with his computational tools and materials to extend computational practice and the fine design fields. Much of his practice is theoretical, examining texts and practices across both fields and slowly applying and extending them for his personal goals. Moreover, he engages in iterative design as he manipulates the tools and materials he leverages throughout his practice. Conversely, ann engages in ongoing critical and historical studies of the tech field, which she incorporates as themes and critiques in her artwork. For her, computation is another tool that can be leveraged when necessary to accomplish an artistic goal; it's a means to an end. Unlike Janell and Cody, she does not have a reflective or reflexive experience in using the tools, beyond questioning whether it aligns her with the tech industry in ways she may not desire.

Lastly, while not a focus of this study, it is important to note that the identities of these artists may have impacted their participation and experiences across art and computing communities. Each artist brought their personal identities and experiences into their practice. Janell and ann, as women within computing, both focused more deeply on the critical side of computation and its impact on society. Additionally, ann's identity as a multi-racial woman appears to shape her motivation and intent within her art practice, primarily focusing on critiquing dominant narratives within computing and history more broadly. As a white man, Cody's identity aligns more closely with the dominant culture of computing fields. While Cody is a self-taught computational expert, his identity as a white man may have positively impacted his informal participation in these computing communities. As art and computing both have histories of bias and discrimination, these three cases suggest the need to more thoroughly capture artists' identities and how these impact their art practice.

Through analysis of these three cases, we identified unique *computational art ecologies* that capture differing relationships with computation in art. The simplified ecologies capture the important actors, connections, and themes the artists explore in their artwork. They are adaptable and can be easily manipulated through the addition or subtraction of link and nodes to reflect the unique experiences of a given artist. At this abstracted level, artists' experiences and practices can be compared to bridge differences in genres, languages, engagement that might hinder comparison of these artists traditionally. The application of these models to describe Janell and ann's art practice highlights differences in how they situate in their respective art and computing fields, how they leverage tools in their practice, and how deeply they examine the intersection of art of computing. Cody adds more complexity, showcasing equal engagement in both art and computing fields. Moreover, he contributes new tools and processes to both fields in addition to the contribution of his designed objects and vessels at this intersection. Focusing on their practice, these three artists highlight the role of computation for providing a means of critique and inquiry. Janell twists the intended use of computational structures and concepts to create uniquely "unintelligent" AI. ann applies her computational tools in unintended contexts that highlight the social and cultural structures around the computing fields. Finally, Cody experiments with the tools and materials he uses to extend and bolster the role of computation in art fields. These unique perspectives give insight into how computation is meaningfully integrated in art practice.

In the following chapter, the remaining seven participating artists will be introduced through abbreviated cases. Each will be framed in terms of the elements in the *computational art ecologies*, as was done for Janell, ann, and Cody; and unique ecologies will be presented for each. Following these, the features of the ecologies, referred to in the comparison above, will be more rigorously characterized and associated with concepts related to computational engagement and perspectives in the arts in chapter six.

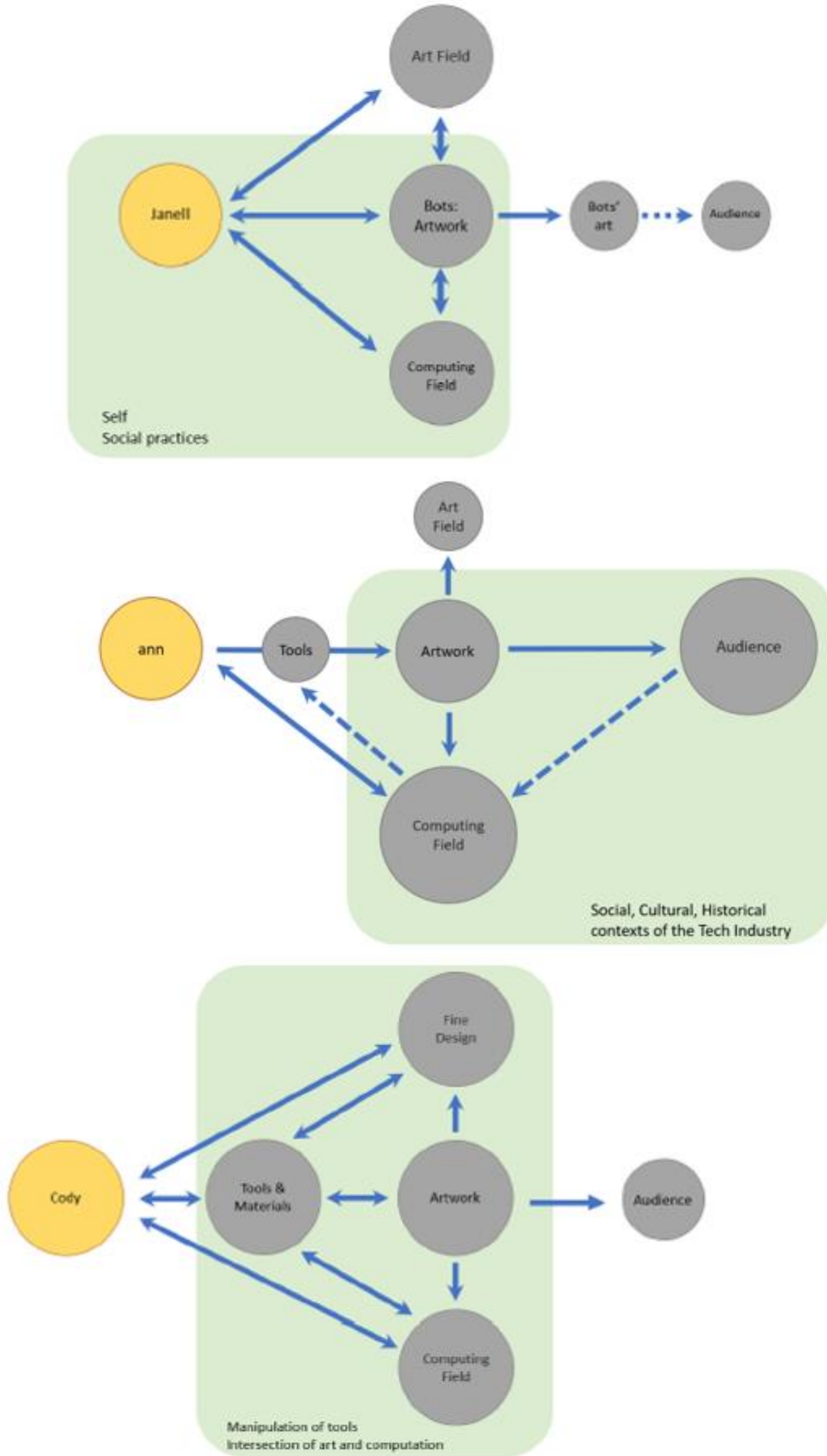


**Figure 40 - On top, the computational art ecology of Janell Baxter. In middle, the computational art ecology of ann haeyoung. On bottom, the computational art ecology of Cody James Norman.**

# Chapter 5: Summary of Computational Cases

In recruiting participants for this dissertation, I sought to capture a breadth of computational engagement in the arts in order to identify significant features in the landscape of computational artists. In this chapter, I present summarized cases of the remaining seven computational artists recruited for this study. These artists leverage a variety of computational and traditional tools to explore a spectrum of ideas and themes in their practice. These can be characterized in many ways, as will be more thoroughly explored in Chapter 6. However, to begin this characterization, the cases are presented in two clusters reflecting the artists' engagement with the computational tools in their practice. First, I present four artists that leverage computational tools as they were traditionally developed: Anna Christine Sands, Iva Bollig, Meimei Song, and Yimin Zheng. Then, I present three artists that leverage computational tools with experimental approaches: Paul Catanese, Sarah Groff Hennigh-Palermo, and Taylor Hokanson. All artists opted to waive their anonymity. This characterization does not privilege one approach over the other but reflects divergent engagement and application of computational tools to achieve rich artistic outcomes across the two clusters of artists. Each case is structured using the key elements of the *computational art ecologies* methodology, including art practice, relationship to art, relationship to computing, intersection of art and computation, and relationship to audience. The unique *computational art ecology* is constructed for each artist and briefly explained to link themes in the cases to the structure of the ecologies. After presenting each case, the theme of computational tool use will be explored and summarized across all participating artists.

## Traditional Computational Tool Use

The following four artists; Anna Christine Sands, Iva Bollig, Meimei Song, and Yimin Zheng; reflect a subset of the participating computational artists that leverage computational and technological tools as intended. ann haeyoung, one of the in-depth cases presented in Chapter 4, is also characterized as using computational tools as intended. Artists in this category assess computational tools based on the affordances and constraints of each tool, selecting and applying the appropriate tool for their artistic goals.

## Anna Christine Sands

Anna Christine Sands is an Art and Tech artist who focuses on digital collage and glitch art. She creates images and GIFs with photo or video editing software and modifies the underlying data of images to create disruptions to the image. She obtained a Bachelor of Fine Arts in Photography from the Art Academy of Cincinnati. She obtained a Master of Fine Arts in Art and Technology from the School of the Art Institute of Chicago.

### *Art Practice*

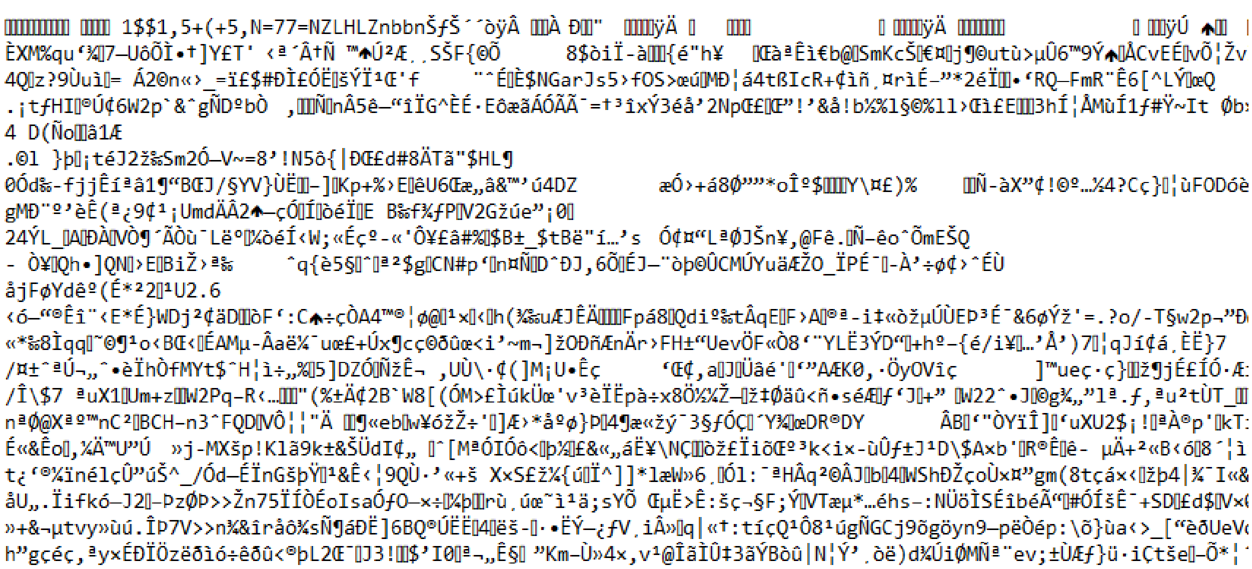

**Figure 41 - An example of the text data underlying an image file, accessed by converting an image file to a text file. Anna Christine manipulates this text data to create glitch art.**

Anna Christine identifies as a practicing artist in art and technology, which is a genre and school of thought focusing on the creative use, misuse, and investigation of technology. Within this area, she explores glitch art and digital collage. She describes glitch art as taking an image or a video and breaking it down to its essential parts, which are the characters and text data underneath the image (see Figure 41 for an example of the underlying data), then causing some sort of corruption through deleting or adding characters. The resulting corruption “is very tangible”, ripping apart the image in some way (see Figure 42 for example from *codex play*, a series of glitch artworks by Sands). In her art practice, she focuses on themes of self and family, leveraging forms of confessional art to represent personal experiences. In her art practice, these confessionals have become more explicit; where once she wrote personal secrets in the underlying data of an image to create glitches (e.g., *codec play*), she now uses digital collage to write these secrets in the forefront of her images (e.g., *HEAVY HEAVY*) (see Figure 42 right; Sands, 2018-2020; Sands, 2021a; Sands, 2021b). Her portfolio can be found at https://www.annacsands.com/ and her ongoing practice is documented on Instagram at https://www.instagram.com/annacsands/.


**Figure 42 - On left, a piece from *codec play* (2018-2020). On right, a piece from *HEAVY HEAVY, NO MISTAKES* (2021) [Digital Collage]. (Sands, 2021)**

*Relationship with Art*

Anna Christine grew up in a family passionate about photography. She began to explore photography to connect with them, though they practiced independently. She went to undergraduate and explored what she knew she was good at, which was art. In her senior year, she was introduced to glitch art and became connected with the intersection of photography and computation. Glitch art is a genre of art that has been practiced since the 1930's that uses digital or analog errors for aesthetic purposes by corrupting digital data or physically manipulating electronic devices; the first glitch art symposium was held in Oslo in 2002 (LLF, 2022; Menkman, 2011). She went on to her master's program to explore this intersection more thoroughly and with the goal of teaching at a collegiate level. At the School of the Art Institute of Chicago, her teachers and peers validated her practice and perspective as an artist and pushed her to be more explicit about the themes she explores throughout her work. She expressed that the art communities in which she participates are significant to her practice, including Facebook groups, Twitter, and Instagram. She reflected that Art and Tech is a small, niche genre that values interconnectedness within their community, as artistic practice within Art and Tech hasn't yet been widely accepted in the art field more broadly.

Her current practice is very personal, exploring themes of self and family throughout her work. She treated her early work "like a journal entry", embedding personal secrets in the underlying data for images and video to create glitch art. Over time, she has made these secrets more visible, engaging in art as a confessional. Confessional art is a contemporary genre that focuses on intentional revelation of the private self and encourages an intimate analysis of the artist or the expressed experiences or emotions (Sage Reference, 2022). She currently explores digital collage and occasionally uses traditional mediums. She describes her motivation as making sense of family relationships and history, mentioning,

> *"And I'm really interested in the images that we take as a family. The archive that we create that most people never look back on. I find it very interesting that family is the first relationship you form and probably the strongest relationships you form…I think a lot of people don't want to acknowledge how ugly it can get or how hard it can be. I think people want to think about family as like a safe place to be in. It usually is for most people. And for those that it's not, it's harder to tell."*

*Relationship with Computing*

Anna Christine has deep, personal connection to computation and computers. Her dad was a programmer and she described that "every room was a computer room" in her house. She expressed, "ever since I can really remember like formative memories, I've been online. And I think, having that space to grow and understand the world through the internet was really, really influential for me and important for me as well". She began to explore this interest with computers through image and video manipulation and digital art tools but mentioned that she doesn't know how to program and isn't seeking to build that expertise.

*Intersection of Art and Computing*

Anna Christine finds it vital to express her connection to computation in her artwork but is still exploring why this is so important to her, "I don't know why it's important for me to express that in my work. I can't really speak to that as of yet but, yeah, I guess it's just a way of me processing my memories and how I grew up…. so when I think about memories, when I think about family, somehow personal computing gets injected into that." As her work focuses on these personal themes related to self and family, the computation is a vital element to represent because it was a foundational component of her childhood. She further expressed an interest in personal computing and how people can make art with the computational tools readily accessible, mentioning that she doesn’t understand hesitation about their use in art, “I don't understand where that fierce resistance comes from, because I mean, computers are such a ubiquitous thing. There's no escaping them. I mean, you have one in your pocket.”

For Anna Christine, technology and computation plays another role in her art practice, namely in community building. She became more confident in her practice through joining Facebook Glitch Artists collective groups, where she connected with “hard hitters” who supported her practice early on. She uses Instagram to post her ongoing explorations, engage with audiences, and connect with peers. She exhibits selected series of artwork on her personal website (https://www.annacsands.com/), where she has a shop with merchandise related to her art themes.

*Relationship to the Audience*

As mentioned above, Anna Christine is very active on social media (i.e., Instagram and Facebook), showcasing her ongoing work and self-reflections of her ongoing practice to audiences in addition to networking with fellow artists. She describes a disconnect between her intent for making the art, which is expressing herself and her family relationships, and the experiences the audience might have. She is happy if she can create conversation or shared emotions with her artwork but that isn’t her goal or a necessary element of her work. She sees the “mystery” around the theme and the technology as a vital and “wonderful” part of her art. Her series integrating her personal secrets highlight this well as she’s hidden ideas in the images and videos that are distorted and disrupted, “I think the first question that I get most of the time is, oh my God, how did you do that? And I mean, it's not like I won't tell. I'll definitely tell my secrets, but I think having that mystery is really interesting. That wonder is really important.”

*Computational Art Ecology*

Anna Christine's *computational art ecology* focuses on engagement in the art field (see Figure 43). While she has a lot of personal relationships with computing, her art focuses more heavily on photography and personal expression than on computational practice. She leverages confessional practice that scaffolds potential thematic connections to the audience. However, her work does focus on more traditional audience interactions in art. Anna Christine's art ecology reflects these patterns, showcasing a more linear connection between nodes and her dialogic threads element centered around the artist, art field, and artwork node.

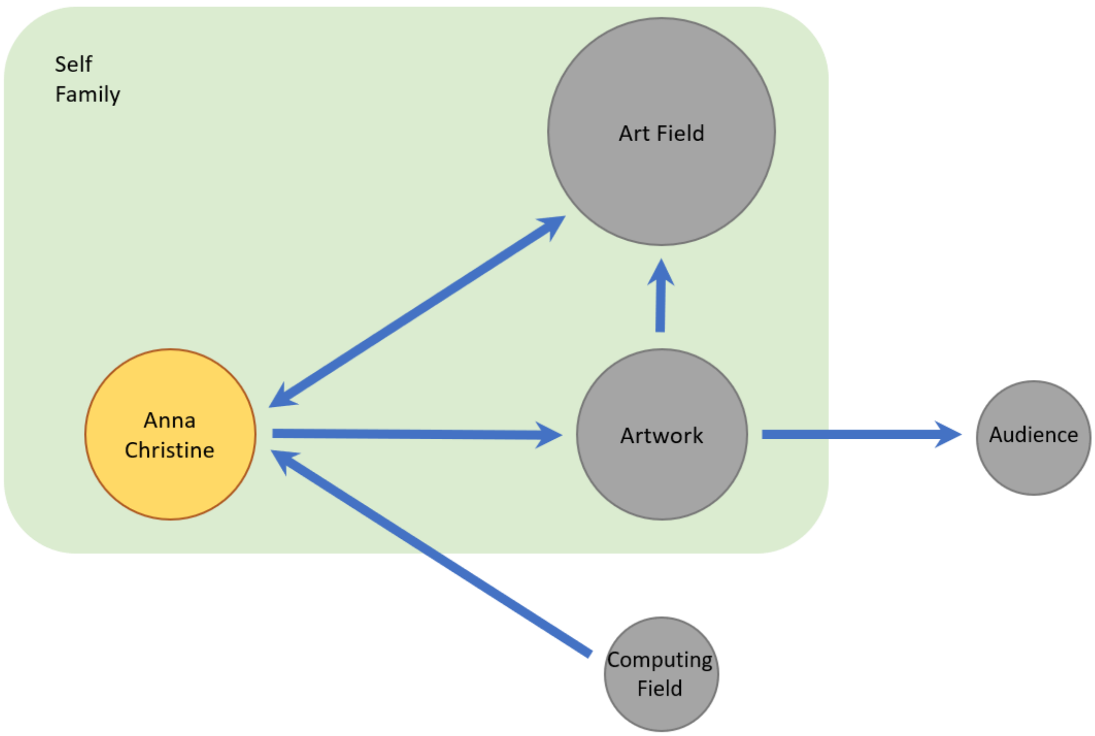


**Figure 43 - The computational art ecology for Anna Christine Sands.**

### Iva Bollig

Iva Bollig is a 3D artist working at Lost Boys Interactive, a game development studio located in Madison, Wisconsin. She obtained an Associate of Arts (AA) degree in Animation from Madison College. Iva is originally from Bulgaria and moved to the US as a child. She became interested in art when she was young and realized her interest in animation in college. In her art practice, she primarily creates environmental art, which is the focus on the indoor and outdoor settings for videogames. Iva was recruited through snowball sampling and represents a perspective of computational arts outside of the fine art and design world. As an artist in the game industry, there are many external factors and constraints that dictate the art she creates.

*Art Practice*

**Figure 44 - On left, a 3D model of a Sperry searchlight. On right, a 3D model of a drafting desk. (Bollig, 2021).**

Iva is an environment artist in videogames, who develops 3D models for games and specializes in creating the indoor and outdoor spaces that are seen in videogames. She is responsible for a range of practices including set dressing (modeling and placing 3D objects into the environments within games), lighting (designing light sources and their interactions with the objects in the environment), and FX (designing the visual effects within an environment, such as fog, clouds, or rain) and Unity Integration.  Additionally, she designs material, UV and texture work, which describes the process of creating 2D skins that are mapped onto 3D objects so that the objects appear to have surface detail. However, she describes herself as a “jack of all trades” within her game development studio, meaning she will complete other 2D, 3D, and technical design outside of environmental design. Examples of her 3D modeling can be found in Figure 44 and an example of her scene design can found in Figure 45 (Bollig, 2021).  Her portfolio can be accessed https://www.artstation.com/ivaivanova.


**Figure 45 - 3D modeled environments, lighting, and assets from Iva's portfolio. (Bollig, 2021).**

Across her projects, she leverages a variety of tools to meet the specific needs of a project, including Maya, 3ds Max, Unity, Photoshop, Substance Painter, Blender, Substance, Substance Alchemist, ZBrush, and Unreal Engine, which are all 2D, 3D, or game engine software commonly used in the game industry.  When creating concept art, she finds reference images and compiles them digitally using photoshop. She will then slowly build out the rough outlines of the structure then refines the aesthetic details, engaging in an iterative process of mapping assets in space then solidifying their aesthetic. Her art practice is also highly collaborative. Her practice entails a "constant back and forth between departments" (e.g. IT & Technical Support, Q/A Testing, Audio, Engineering, Art, Design, etc) as the studio moves from the planning stage to developing a visual look to gameplay mechanics.

*Relationship with Art*

Iva grew up drawing and sketching, mentioning that all of her notebooks and sketchbooks would be completely full of her artwork and doodles. She describes that has always connected with art throughout her childhood. She spent much of her free time sketching and drawing. She described that she also “always enjoyed world building” and would use Legos, constructor-type toys, “anything [she] could find outside and inside and just like build a house out of it… and make little apartment settings out of shoe boxes.” In her youth, Iva thought she would be an architect. However, she hated math and couldn’t get over the prospect that architecture required mathematics. She described herself as “super passionate” about this world building but didn’t realize it could be a career until she randomly picked an animation course in college. She described that the course “completely opened my eyes to what the [game] industry is capable of” and how this industry could incorporate what she has always loved in a professional setting.

Within her professional practice, Iva explains that 3D artists in the game industry need to balance numerous external constraints that dictate how and what they design. Her role in the process of game design typically comes after the pitch of the game and after the general concept has been solidified. She personally likes to start with more significant direction or established look, finding it easier to create with more specifications on the needed environments, characters, or assets. Interestingly, considering her dislike of math, she describes this process of meeting the conceptual framework as solving an equation. For Iva, time is a major factor in her design process. Her art practice is a part of a team that is working to make hard deadlines to get a product in the hands of consumers. As such, she makes ongoing decisions about what is important to spend time on and the correct detail needed or warranted for a project or a component. This also translates into determining when she is “done” with a design. “There comes a point where you're happy with it. It looks great. And it, you know, you've solved the problem…I've filled the need, let's pass it along…there is such a thing as done, but it's never perfect. So at some point you have to be done and like make the deadline, but you're never done.

It's never done. Everything you ever make it, can be improved." Her artistic practice is in full conversation with external agents and goals that shape what she creates.

*Relationship with Computing*

Iva connects deeply with the creative building that she can do with software. She reflected that discovering this passion in her associates degree rekindled her passion for world design that she did as a child, "it felt like I was a kid again…it tapped into some memories that I have, how much joy it brought me to like how passionate I was into like building these little scenes. Like they were everywhere in that house. Everywhere… It just brought out the passion in me". She explained the shift to using the software was hard initially but that after a semester, it became intuitive to navigate the space and she began to develop an eye for the computational aspects of her practice. The largest challenge she finds is learning the software specific components and keyboard shortcuts that allow users to use the full potential of the software more efficiently and effectively.

*Intersection of Art and Computing*

For Iva, computational tools allow her to explore her art practice more deeply and more quickly. Throughout the interview she reflected that the shift from traditional mediums to digital was difficult at first but that she fell in love with the digital process once she become more comfortable using the tools. She explains that "when you first start using a piece of software, when you first started learning it, it feels limitless. And still after two years…it still feels really vast and limitless in what it can do and how much it's simplified the work. Just speeds up the process". The ease of adjusting the size, shape, color, and compositions of her designs gives her freedom to take chances, test theories, and explore aesthetic possibilities without arduous effort that one would see when using traditional mediums like pencil and paper. She leverages tools based on the needs of the projects, assessing the affordances of each software for a given problem. For example, she uses Maya or 3ds Max for the design of mechanical assets and Zbrush for organic creatures and characters because the software construction is more angular for the former software and more sculptural for the latter software. Iva explains that in swapping across software and trying to achieve visions for her designs, she'll very often have difficulty translating her ideas and vision into the software itself. She explains that "people don't necessarily see the mistakes. There's a lot of them. It's hard. I would say you just got to keep attempting at it. Keep finding new references, trying to find a different approach, a different way to think about something".

The process of creating 3D art, specifically realistic art, has impacted how she interacts with and sees the world. She describes that her work requires her to become an expert on everything as she researches and finds references for her art. She explained that she has to understand and interpret the world around her in order to be successful in her field. The medium necessitates a deeper understanding of the functionality and underpinnings of the things around her in order to realistically reproduce them in digital environments. To make her worlds realistic, she has move beyond seeing a tree as a trunk with branches, sticks, and leaves to understanding how a tree grows, why variation in shape and size occurs. This impacts how she interprets the world around her and "rewires" her brain to apply this critical lens to everything. Moreover, it changes how she consumes media, "You can no longer watch a movie or an animation or play a game. It's like all these things are forever ruined for you. You're going to find something you dislike or something you're going to pick at. You're going to see some things that maybe someone else who doesn't, know much about games will never see. Things will be forever ruined for you. Like entertainment forever will be a different experience." Finally, despite designing videogame worlds and character design, she does personally play many videogames. She engages with them like she would with more traditional art, colleting books that showcase the art and design of the games.

*Relationship to the Audience*

There are two relationships Iva has with her audience. The first relationship relates to how her friends and family or others outside of the game industry understand the practices in her career. She described that the younger generations tend to understand more easily but that older generations do not understand the full artistic practice involved with her design work. The second, and more central, relationship relates to the player-oriented nature of the game industry. Games are created to engage players in new interactive experiences, storylines, and worlds. The art Iva creates is in service of audience-oriented goals. Moreover, Iva receives feedback and critique throughout the artistic process from others in her studio including those from the management, art, and design department, including others. These collaborative and audience focused art practices introduce a larger set of external constraints as more agents are introduced to the ecology of practice.

*Computational Art Ecology*

Iva Bollig's practice reflects a more collaborative art practice that hinges on the design decisions and timelines set by external collaborators or clients. While she personally connects deeply with creative and artistic practice, her art is strongly influenced by the video game industry, which inherently weaves together artistic practice and computational advances that focuses on audience engagement. Her *computational art ecology* reflects this more complex practice. Additional nodes (tools, game studio, game, and video game industry) were added to the model to reflect these significant participating agents in Iva's art practice (see Figure 46). It is important to note, like the art and computing field notes, the game studio note reflects a variety of roles and members within that community. At the time being, these are represented as an individual node, but future iterations of this methodology may explore other approaches for more systematically documenting the key members and roles of those communities and representing those diagrammatically. There is a high level of bi-directionality connecting the game studio, the video game industry, the game, and the audience nodes. Largely speaking, the audience influences concepts and designs of games, as the companies are motivated by sales.

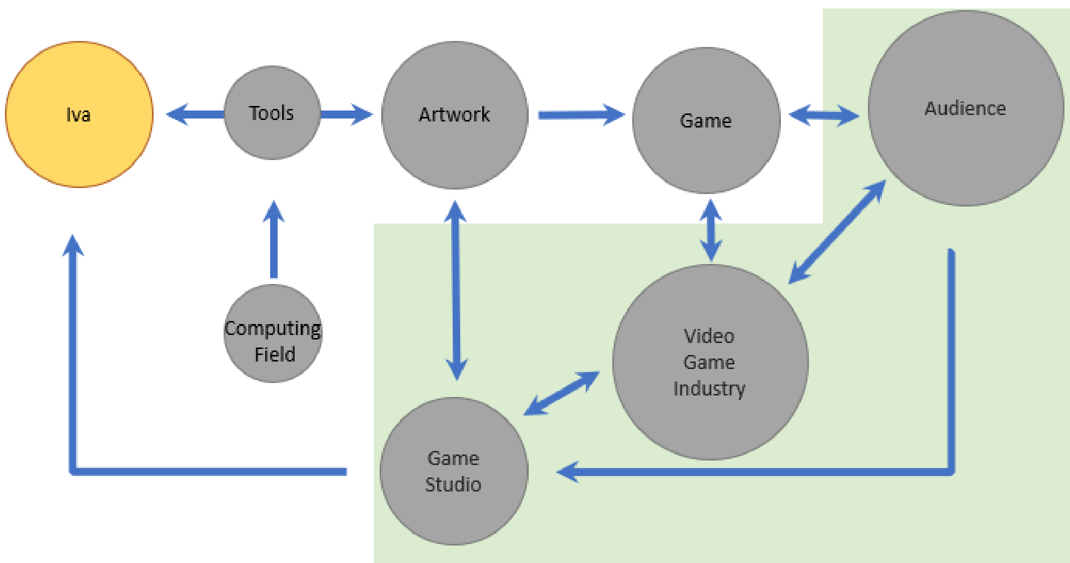


**Figure 46 - The computational art ecology for Iva Bollig.**

Moreover, the player base can influence the design of games, even after releasing titles, through feedback and game patches to provide new content. Iva expressed self-reflection from practicing with computational tools, shifting her perception of the world through a lens of design. As such, there is a bi-directional link connecting Iva to her artwork, through these computational tools. Finally, the dialogic threads element captures the audience, the video game industry, and the game studio nodes, as these are the agents that are guiding artistic direction of games.

**Meimei Song**

Meimei Song is an artist practicing art-based research at the intersection of art, science, and technology, in particular exploring sustainability. She leverages sculpture installation, technology, live plants, social media, and performance to create new narratives about ecological issues. Her work often focuses on the idea of Anthroprocene, which is a proposed geological epoch characterized by human domination in the planetary system (Crutzen & Stoermer, 2000). She lived in China through the end of middle school then moved to the United States for high school. She obtained a Bachelor of Fine Arts in Studio Arts from the School of the Art Institute of Chicago then went on to obtain a Master of Fine Arts in Art and Technology from the same school.

*Art Practice*

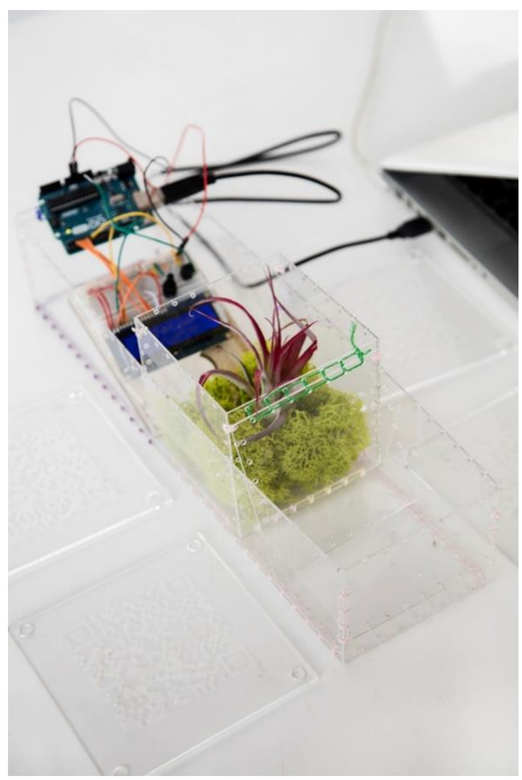

**Figure 47 - On left, an image of *Domestaponic: Stackable Broom Farm* (Song, 2016). On right, an image of *Cyber Companion Plant* (Song, N.D.a).**

Meimei engages in art-based research to create artworks that explore new relationships or narratives within science, particularly ecology. Her early work raised questions about sustainability and relationships to plants by exploring new interfaces between plants and humans. In one work of art, *Domestaponic: Stackable Broomstick Farm*, she constructed a fictional vertical growing system for plants that are integrated on the tools needed for domestic labor (see Figure 47 left) (Song, 2016a). This work explores questions of how household cleaning tools can empower people; how everyday tools can become "radical tools" that reform perspectives on domestic labor, agriculture, and plants; and how plants can impact us when integrated with daily lives (Song, 2017). Another work in a similar vein, extends a scientific discovery that we can interact with plants by "hacking" their electric circuits (Rutkin, 2015). In *Cyber Companion Plant*, she constructed a plant companion system using an air plant, moss, and a microcomputer, in which data about the plant is collected using sensors and an Arduino (see Figure 47 right) (Song, N.D. a). In this work, she similarly explores new approaches to interacting with plants but through the implementation of a more technical system. She extended this series, integrating it in a free interactive walking tour, *How to walk with plants*, where she walks the audience through a sculpture garden featuring these alternative plant systems (Song, 2016b; Song, N.D. b). The website documenting and advertising this tour leverages scientific language and diagrams to situate the audience in the art-based research and describes a goal of understanding how to reconnect and interact with plants through gathering computational information "from the past, present, and future" (Song, N.D. b).

In her master's thesis work, Meimei designed a multimodal performance art piece about the Asian carp. As she described, the Asian Carp is a "foreign immigrant, invasive non-native species" threatening the native population of Lake Michigan. She disagrees with the scientific narrative about this species and the implemented solutions to dealing with this species (i.e., electric "fences" protecting waterways). Her thesis work creates a series of experiences that create new narratives about the carp, particularly drawing on Chinese cultural perspectives on carp. She developed a virtual reality world in which the audience can see ways that the carp are represented and ways that they're celebrated. She describes that she leverages pseudo-scientific language and performs as a satirized governmental authority, "I will twist their language a little bit. I make it sounds kind of hilarious and also kind of scary the way they describe fish". In process design images of the virtual reality world can be viewed in Figure 48. Originally, she intended this piece to include a performance where she eats a prepared carp in front of an audience, but this was disrupted due to COVID.

**Figure 48 - Screen captures of the design of her thesis project featuring carp prepared as a meal and in their natural state.**

*Relationship with Art*

Meimei has always been interested in the idea of art but only realized it as a passion in high school after being introduced to the idea of research-based arts, which is a mode of qualitative inquiry that uses artistic processes to understand and articulate human experience (Barone & Eisner, 2011). She explained she was originally attracted to this genre of art because she considered herself a "biology geek" and she was excited "to combine [her] passion because you know, before that, art seems like these separate things like paintings, sculptures, like their own world, art world and all that." She describes that finding a community of research-based artists exploring the intersection of science and art has helped her to "sustain [her] practice". She enrolled at the School of the Art Institute of Chicago (SAIC) for her undergraduate, focusing on sculpture, drawing, and painting. She continued with a master's program at the SAIC in Art and Technology.

Practicing at the intersection of art and science allows her to engage in political debates about ecological issues while looking at science in a more artistic or poetic manner. She describes that artists who practice art-based research focus on "playing and experimenting" and do not have expectations about where their work will go. She described that a lot of art and science is based on the visual understanding of an object, distinguished by divergent approaches to narration. Scientists visualize their data to communicate narratives so that others can access their research, "artist is doing similar things, but when you explain the visual, it becomes a very different story from art and science. Right? So I can make something that looks like a scientific experiment, but I will narrate it so differently".

She believes that art can provide new approaches to visually narrate science but can also "impact and bring out new perspectives in a deeper level". Art acts as a humanizing practice that counters the dehumanizing factors of capitalism, "if you're kind of working as part of a machine and a lot of the time art is trying to rediscover the humanist and to embrace that. So I think art is just deeply human to begin with". She explained that art can leverage affective relationships to connect people around science, "something that's deeply human, like curiosity, right? Like how do you make that into art?" For Meimei, this practice enables her to "find out the things that I'm curious about that I feel like I'm not getting answered satisfied from other field". In much of her work, she identifies “weird” narratives in science and politics then uses satirical performances to “dig into” and “present that weirdness”.

Her art program is very politically charged, which is impacting her identity as a Chinese woman. “I just going to be a rebel after I returned back to China, I am just against everything. That's that's not like Liberal or, you know, or is it deeper that like, I still need to draw more on that, because again, I don't have that much time and space for that question-these questions when I'm in my program.” She describes that “our world is still centered around white male and white straight male”, and even though the program is generally open to exploring diverse issues from around the world, she doesn’t have the bandwidth to explore these naturally as she is also trying to gain proficiency in coding and other engagement with computational tools.

*Relationship with Computing*

Meimei was not interested in technology throughout her childhood and only became interested in it through art. She sees it as an important element of her work, as technology is the driving force of cultural change and ecological change,

> *“technology, it's a big word. Right? And I think more so I am thinking about technology as how it impacts people's life or how it changes us. And there's also a lot going on we could dig into like the technicality aspect of technology. But I think I for me, my I'm mostly interested in that the way, similar to how like electricity or industrial revolution changes our society or how agriculture changes humans, like how technology nowadays is changing human.”*

Finally, she reflected feeling discouraged by the ways that computer scientists think and react to her work, “if you care about the human approach or like this aesthetic approach, those factors are kind of looked down upon within computer science often”. She thinks differently than a computer scientist, describing their approach, “you have to practice being structural and the more you do it, the more you'll become a more rational, structural person. It's hard to come back. Like I almost don't want to go there”. However, she desires the “freedom” that comes with being able to use computational power. Within her program, she has gained basic knowledge about programming but largely relies on existing materials, assets, and frameworks from others online. She describes that she is “not trying to be prolific or anything, but to, you know, navigate those kind of 3D fabrication or 3D rendering software better, basically”.

*Intersection of Art and Computing*

Meimei used differing metaphors and framing to describe the role of computation in her artwork. The primary focus of her work is on the intersection of art and science, but computation plays an integral part as her medium and in representing computation’s role in culture and society. It as an important medium that she can leverage critically to deepen her research and exploration of questions of sustainability and ecological decline. She struggles to balance the larger conceptual goals of her artwork and the technicality of her practice, describing that the motivation for technological use and the time takes to engage in technological practices can distract from the larger vision. She explained,

> *“I have seen work from artists who's very, very good at programming. And still that doesn't, to me, it doesn't seem as free as if you were using a more traditional medium, like a piece of clay or, you know, like a paint and a pen brush, paint brush. And so I think I have to still adjust my mindset a little bit and expect something that's more realistic in terms of working with technology. Because often times my expectations are not realistic at all. Like I want to become this thing. It's not going to get there without like five supercomputers.”*

Moreover, the cost and access to these computational mediums and materials are restrictive for practice. Her thesis work was significantly disrupted due to loss of access to resources at the School of the Art Institute of Chicago during the COVID pandemic and quarantine. She finds that her experience practicing at the intersection of art and science has been more positive than her practice at the intersection of art and computation, noting that artists practicing in Art and Technology are strongly tied to the technology and that participants are less open to diverse ways of thinking about that intersection. With art and science, she describes that people are open to diverse ways of thinking and characterizations of science.

More broadly, she struggles to situate her work within the Art and Technology program and field. She was characterized as a “low-tech” artist within her program and found a disconnect with many of her “high-tech” peers and teacher. This terminology capturing varying depths of engagement in technology. She also describes her program and the Art and Technology genre as very politically engaged. As a Chinese woman in the United States, the political, social, and cultural topics that interest her are not always understood by those in her program, which is largely centered around politics within the United States. While her program has been primarily white and male, she does recognize a growing population of Asian students who are pursuing art and technology. She described art and technology is growing in popularity for Asian youth.

*Relationship to the Audience*

Meimei seeks to engage the audience in new narratives about science. She describes that performance is an important factor in humanizing these scientific and technological topics, reflecting, “I also like to bring me, or, or like any other performer, in art and technology related work, because I like to embrace that kind of human being like they engage quite literally with us.” She leverages technology situationally when it allows her to deepen her exploration or strengthen her narrative. While she does use technology that increases the potential audience interaction, this isn’t the primary goal of its use for Meimei.

Finally, she finds that her work is not well understood by traditional artists. She explained that traditional artists will question whether her work is art, 'how is this different than like science?' I mean, to me, of course, having talked to folks who work in science, I realized that like, I am really making art, like I'm not trying to do some kind of scientific research in any sense, but for like artists with more traditional practice, they will be confused." Despite this, she is passionate about bridging art and science, believing that art can deepen understanding of science and ecological issues.

*Computational Art Ecology*

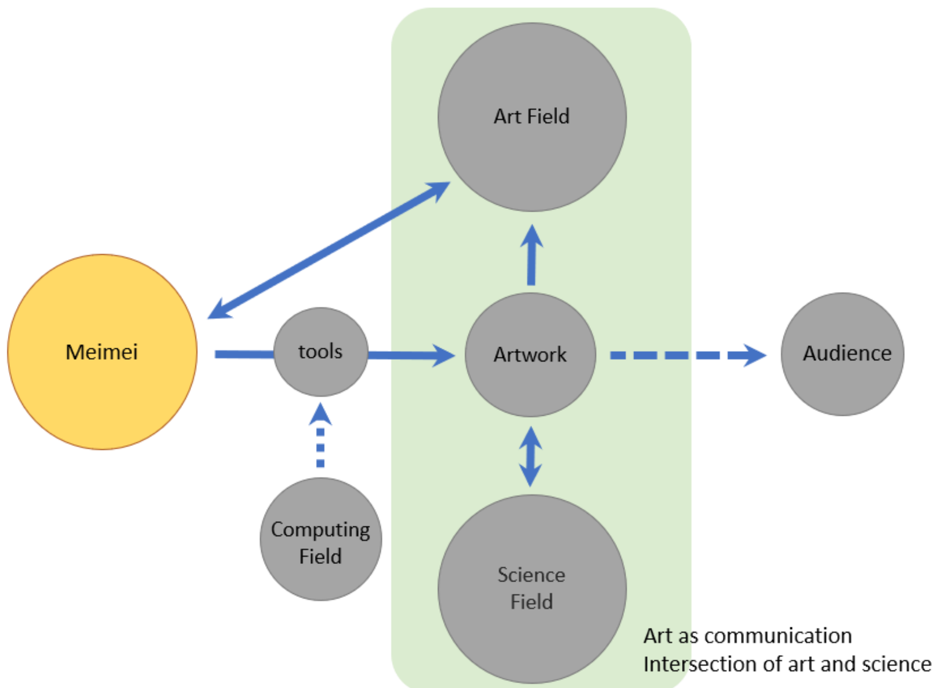


**Figure 49 - The computational art ecology for Meimei Song.**

Meimei Song's art practice largely focuses on the intersection of art and science, mediated by technology as a medium for practice and sociocultural change, as reflected in the structure of her computational art ecology (see Figure 49). The art and science nodes are increased in size to reflect their significant role in her practice, whereas the computing field is decreased in size to reflect the unstable role in her practice. Moreover, she leverages noncomputational tools in her practice, using computation as appropriate for a given project. Her artwork is in dialogue with the science and art communities, as well as interactive for the audience. As such, these nodes are bi-directionally linked. Finally, her dialogic threads element frames the art field, artwork, and science field nodes, as her exploration of sustainability engages these agents.

**Yimin Zheng**

Yimin Zheng is a Chinese Contemporary artist who is currently practicing in Chicago. She obtained her Bachelor of Fine Arts in Public Art from China Academy of Art in the People's Republic of China then went on to the School of the Art Institute of Chicago, where she obtained a Master of Fine Arts in Art and Technology Studies. Her artwork explores historical, social, and futuristic narratives surrounding her personal culture and the ideas of anthroprocene. To explore these themes, she leverages computational and traditional approaches and materials while creating physical, virtual, or augmented reality experiences.

*Art Practice*

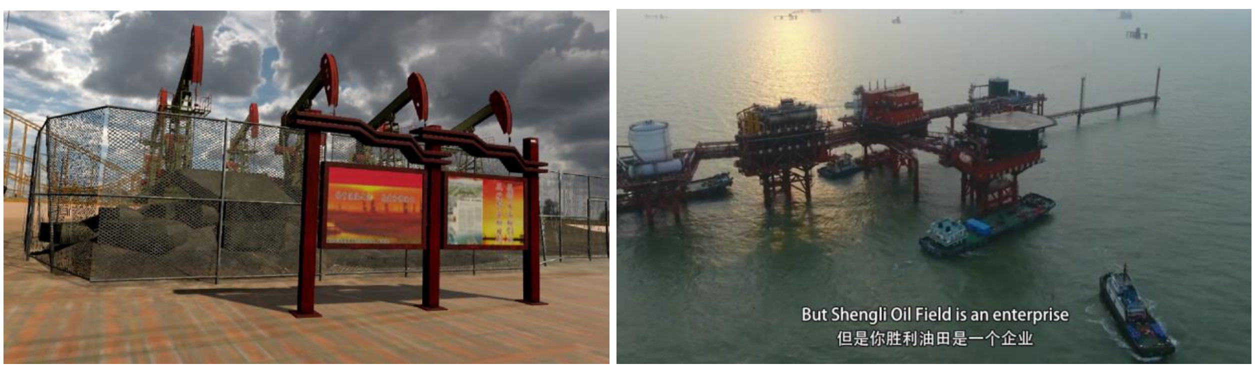


**Figure 50 - Two screen captures from Twin City (2020), a project giving voice to the collective memory of those who lived in Shengli Oilfield in the People's Republic of China. On Left, a screen capture of the virtual reality world depicting scenes from Shengli. On right, a screencapture from the documentary video in the artwork with interview quotes overlaying found video footage of Shengli.**

Yimin creates kinetic sculpture and interactive installations, primarily with virtual reality (VR), to explore the intersection of machines and humans. Her VR work explores and expresses social and cultural themes that are personally relevant to her. The kinetic sculptures she makes mirror both real and fantastical biological creatures as well as futuristic architecture. Her artwork combines these virtual and physical spaces, tying together multiple mediums within a single work of art. Her recent project, *Twin City*, reflects these primary themes and mediums (see Figure 50; Zheng, 2021). *Twin City* is a series consisting of multiple works, including virtual reality, embodied physical kinetic sculpture, and a collection of photographs, videos, and found objects related to Shengli Oilfield. The work gives voice to the collective memory of those who lived in the oilfield. The oilfield itself is the second largest oilfield in China and was hugely impactful for early state building, particularly from the 1980-2000 (Zheng, 2020b). Since this golden age, there has been an economic decline in the city causing social problems and relocation to other areas of the country. Yimin asks, "Will it become an empty city like other resource cities or will there be a new turn? …When a city inevitably declines, where should the people living in the same period go? What's become of their lives?". She uses narrative and juxtaposition of scenes to create a virtual space where the past, present, and future experiences of Shengli coexist. She constructs a virtual reality world where significant geographic locales, including an abandoned amusement park called Shaoniangong and oil platforms, can be viewed in their present and imagined future states. She additionally captures the collective history of the people residing in Shengli through interviews she conducted that are overlayed onto historic video and photographs of the region. In the virtual reality, the users walk through these moments of time and geography to create a non-linear narrative about the region. She describes,

> *"This work was built from three levels. One is the real world part which tries to restore the actual scene. The second part is the world of the surface. This world is divided into the past and the future. The third part is the inner world, the space of consciousness, floating in outside space. The audience shuttles between the real world and the surface and inner worlds."*

Her earlier work explored the intersection of humans and technology through a combination of traditional and computational mediums that often leverage sculptural forms. *Sound of Nature* comments on the prevalence of electronic instruments through wearable sculptural instruments made of bamboo that naturally produce original music (see Figure 51 left; Zheng, 2016). A more technological early piece, *Travelogue*, explores the role of personal technology imagined in the future with a prototyped self-motored suitcase; made with an Arduino, raspberry pi, and processing; that collects and displays information about the environment around it (see Figure 51 right; Zheng, 2015).

**Figure 51 - On left, Sound of Nature (2016) [bamboo, bamboo hat, timber, hemp] a set of instruments to contrast modern electric ones for their natural materials and original tunes. On, right, Travelogue (2015) [Arduino, raspberry pi, processing] a self-recognized storage space that can collect environmental data while moving.**

*Relationship with Art*

Yimin spent her childhood drawing and painting. She went to art school for drawing and painting for her undergraduate degree but quickly became disinterested. She explored sculpture but found it unexciting and overly traditional in practice for her taste. During this time, she saw an exhibit on New Media art that had computational and kinetic sculpture and felt compelled by the artwork on display, sparking her shift to public art, which focused on technological and computational approaches. She described the focus was on the tools themselves, working on ways to create engaging and compelling experiences for audiences. She expressed that her artistic voice was underdeveloped until she started her master’s program at the School of the Art Institute of Chicago. She began to think more critically about what she wanted to say and express in her artwork. She expressed that in the past the topic of her work was related to fancy technology or some emotion that wasn't central or important to her. "my background or my experience or my hometown or this kind of personal, emotional, personal experience is very important for myself because, because I can make myself to know my identity…this part, I think I want to build my work to have a connection with my real life or my experience". Through this experience, and the experience of traveling back to her home in the Shengli, she began to find her voice in capturing and reflecting the history that was being lost in that region. She expressed,

> *"every year when I came back to my hometown, I have different feelings for that because when I saw the city was empty and the more people leave for the city. I think maybe it seems like a disappoint or something. So I want to do something for the city. And so I think I wanted to share these memories from the city and from this group because I think this group is very important because it's not just only in China. I think maybe all of the industrial society, we will always have this it's kind of things that maybe they have a different reason."*

Within her program, she finds that other artists from non-technical programs are very interested in the work of art and technology students but are unable to engage critically with the ideas or provide meaningful feedback on the artwork, as they lack the computational understanding. Moreover, she felt her personal perspective as a Chinese woman wasn't well understood in her program.

*Relationship with Computing*

Yimin did not have experience with computation before going into her program in Public Art. She expressed that she didn't realize it would focus so strongly on technology and computational. In her work making kinetic sculpture, she did not find the programming aspects very difficult, but found conceptualizing and planning the complex mechanical aspects more challenging. She described that for artists who are beginning projects with new technology, they might think that they'll experience 10 or 11 problems but will find that they'll have "more than

100 problems to solve" as they go through the art practice. With computing, she acknowledged that more time would be spent dealing with technological challenges, and that it is likely to experience "stupid" or "crazy" bugs or malfunctions with the technology.

*Intersection of Art and Computing*

Yimin describes cultural differences between China and the United States that have influenced and changed her practice. In China, "we focus on technology, not about the art". She described the use of technology in China as a way to attract larger audiences and younger audiences to museums and cultural exhibits. In this way, the practices in China at the intersection of Art and Technology put technology and aesthetically pleasing or intriguing experiences at the forefront. She applied to a master's program in the US because she learned a lot of mediums and how to use a lot of different technology in China to create new media art but then did not feel like she had a reason to do it and wanted to focus on her own expression/topics rather than just making something "cool". She described her experience in China at that time, "I didn't feel very clear for what I want to use that medium or why I tried this technology in the art to get something. So I'm not very clear from that. It seems like I just said, 'Oh, it's so cool so I want to do that'… I will feel it's very empty for myself because my work, I cannot find very powerful or very strong reason." She described a major shift to her conception of art when she moved to the Unites States to complete her master's program at the School of the Art Institute of Chicago. At the SAIC, professors pushed her to motivate the use of technology in her practice, arguing that each design decision should align with her motivation and be justified in its use in her artwork. the interview, she expressed feeling like she was still figuring out where she wanted to take her art practice and how she wanted to use technology.

Yimin perceives a large disconnect between the process for creating her traditional artwork and the process for creating the technology focused work she does now. She views the technological aspects as important and central for her work but reflected that it adds a lot of time and problems to the process. Moreover, working with technology requires her do to extensive work to translate her conceptual idea or mental image of a piece of work to the physical or virtual model, often times making conceptual concessions for practical reasons. She expressed that she struggles with some of the technical factors in her artwork and leverages online communities, forums, and resources to support this practice.

*Relationship to the Audience*

Yimin creates interactive experiences that invite her audience into historical and futuristic perspectives of the world around them, and most often of China. For her, it is important to express and provide connection to these lived experiences foundational to her culture. She stated, "I think the technology is very important to, for me. I just want to try different or some new technology to help people to understand my work better or how people should explore the new the new ways the audience can feel all, can express your work". She expressed challenges presenting and expressing her perspective in both China and the United States. Her current work, focusing on historical and future narratives of China, cannot be exhibited there due to the political environment. She also expressed challenges at exhibiting her work to audiences in the US. Her program distilled a political perspective to art and technology, but she finds that her personal political perspective, as a Chinese woman, is not well understood or received within the United States.

Lastly, she expressed the process of creating art and technology was more "severe" than traditional mediums, as there are more questions about what tools and mediums an artist leverages within art and technology. Within this landscape of rationale for tool use, she looks for audience's interpretation as a guiding element. She reflected that she may have an understanding and relationship with the concept and the technology that is perceived and experienced in a completely different manner for the audience. She takes this audience experience into account, changing the computational tools or approaches of expressing ideas in order for her perspective to be clearer to the audience. She describes her motivation for using virtual reality,

> *"it can help people. It seems like they can enter a different, so world and this world they could explore these virtual worlds by themselves so they can make the choice which parts they were most interested in and which parts they will focus on. So I think it's different because when the people see something different people will have different opinion or they can have, hmm, they can get the different information."*

*Computational Art Ecology*

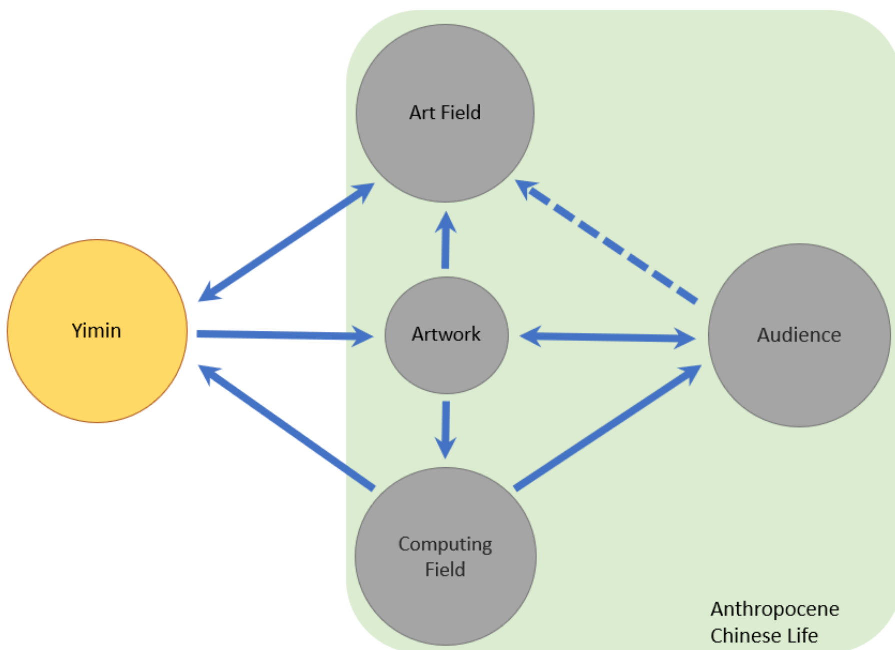


**Figure 52 - Computational art ecology for Yimin Zheng.**

Yimin's art focuses heavily on the audience, creating interactive experiences where they can explore new worlds related to her personal life and the life of those living in the People's Republic of China. Her *computational art ecology reflects* this orientation, with her dialogic threads element framing the audience, the art field, and the computing field (see Figure 52).

When she implements computational tools in her art, the technology is at the forefront; the computational aspects are visible, used to attract audiences, and leveraged in their traditional forms. Yimin cares less about her audience situating her work in a larger field of art, instead hoping they explore new worlds and perspectives.

## Exploration of Computational Tools

The following three cases; Paul Catanese, Sarah Groff Hennigh-Palermo, and Taylor Hokanson; reflect artists that leverage computational tools in experimental approaches. Janell Baxter and Cody James Norman, cases presented in Chapter 4, are also characterized at engaging with computational tools in experimental ways.

### Paul Catanese

Paul Catanese is a hybrid media artist, blurring the lines between fine, performing, and media arts. His artwork reflects a wide variety of practice, “including installations, performances, videos, sound installations, projections, net.art, and print media”. Paul is known for his innovative work on groundbreaking post-digital techniques to integrate computer controlled industrial tools, like laser cutters and CNC routers, with traditional printmaking (Catanese & Geary, 2012). He is currently a professor and director of the Graduate Study for Art and Art History at Columbia College Chicago. He served as the President of the New Media Caucus, a non-profit association formed to promote the development and understanding of new media art, from 2009-2014. He obtained a Master of Fine Art in Art & Technology from the School at the Art Institute of Chicago (SAIC) in 2000 and a Bachelor of Art in Theater at State University of New York at Geneseo in 1997.

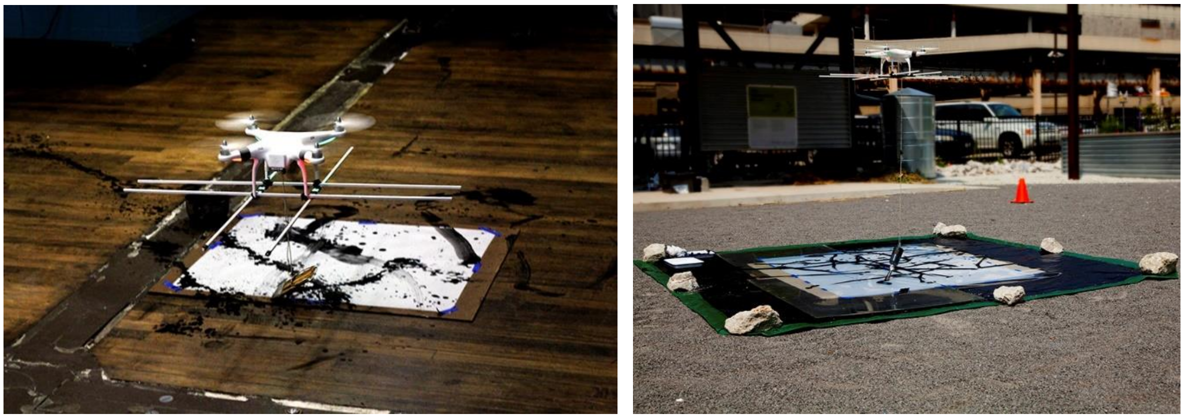

**Figure 53 - *Stones & Drones* (2014) is a set of experiments conducted by Paul Catanese with David Jones and Chris Flynn that extend another art piece, *visible from space.***

*Art Practice*

Paul is a hybrid media artist and leverages a variety of computational and traditional mediums in his practice. He characterizes two outcomes of his practice in the arts: experimentation and artworks (Catanese, N.D.). Experimentation consists of experiments and studies he conducts with computational and traditional mediums that explore significant themes of interest (see Figure 53). These often are not framed for consumption, but the process and findings are documented. In one example of this, *Stones & Drones*, Paul partnered with two colleagues, David Jones and Chris Flynn, they suspended various objects (e.g., stones, paint brushes) from a drone to create drawings that were later used for printmaking (Catanese et al., 2014).

His artwork is the application of these experiments that are prepared for showcase or public consumption. The distinction between these two outcomes will be explored in more depth in the following sections. His body of artwork is difficult to summarize concisely, as he has explored a range of themes, techniques, and tools throughout his practice. He identifies two major themes that spark his impulse to create and explore ideas. First, he has explored intimacy through 2D modalities. These include browser-based installations, programming collections of artifacts that can be explored on game boys, and print making (see Figure 54). All have very different outcomes but reflect this similar “impulse” of exploration of intimate spaces. His second major theme is the exploration of a spatial modality, reflecting the work he has done with installations, theater, and opera. These works of art focus on ephemerality and “special, magical moments” that only exist in that single time and space, as they’re co-created and shared with those in attendance and Paul. Lastly, overarching both modalities, Paul has returned to the phenomenon of vision and of consciousness throughout his body of work. His experiments and artwork can be found on his professional website http://www.paulcatanese.com/index.html.


**Figure 54 - Misplaced Reliquary (2005) commissioned by rhizome.org. It is a handheld curiosity cabinet containing relics collected by an eccentric curator. These relics are contained virtually in the form of GBA ROM, can be “played”, and downloaded with the correct transfer hardware. (Catanese, 2005).**

*Relationship with Art*

Paul grew up as a very creative person, using a variety of traditional and technical materials to tinker and explore the world around him. Looking back on this practice, he sees a continuation of this experimentation in art in his current practice. At the time, he didn’t recognize this as art, he reflected, “I didn't know I was an artist. I wasn't one of those people who knew it growing up. I did a lot of things and I had a lot of creativity and activity. But no one ever said to me, Hey, maybe this is art.” His creativity and art practice focuses on deep inquiry exploration of the world around him. His natural interrogation of the world seems to have led him to philosophy in undergrad, where he realized his academic interests aligned more with the arts. He obtained his undergraduate degree in theater and then applied to a variety of art schools that could help deepen his explorations at the intersection of art and technology.

In his master's program, Paul began to experience the political side of the arts. After he graduated, he came to realize the role of art programs in pushing schools of thought that privilege and teach certain approaches and ways of thinking about practice. He intentionally characterizes himself as a hybrid media artist to distance himself from these schools of thought that cue epistemological approaches to thinking about the intersection of art and technology. He explains, "I always been a traveler between worlds. It's always been an itinerant sort of thing. … you're able to bring beginner's eyes to things. You're able to see things that others can't." He sees this interdisciplinary practice as a challenge to disciplines and their colonial approach of thinking. Being outside of these explicit genres and schools of thought gives him freedom to flexibly experiment and explore while also exhibiting his epistemological stance on these historical trends in art.

Paul's creative work is heavily tied to experimentation and philosophical exploration of the world. He describes part of art practice as "gestures" or "impulses", which are like the buds of creative thinking where you may experiment with ideas, mediums, and techniques. He calls these "gestures" the poetry of the art process. They're pure in form and reflect a natural artistic and creative expression that he argues can get squashed when trying to "artify" these gestures for consumption. This concept of art as thought experiments or a process of inquiry is a significant role in his art practice. When pressed to explain his motivation for art, he struggled to identify it,

> *"what motivates me? I don't know. It must be some sickness because it hurts to make work and it hurts to be lost. And yet you kind of still do it…I occasionally wonder, is this a type of poetry that I am just trying to sort of express through any*

> *means necessary? Through any form necessary? I can't tell where art begins and thought ends."*

*Relationship with Computing*

Paul has always been interested in technology from a creative standpoint. He reflected that he "was obsessed" with computers as a child but that his family couldn't afford one. He made friends with peers who could program and picked up knowledge informally. He finally took a course in high school where he, "learned enough to be dangerous". Reflecting on this, he said, "I don't know that I learned enough to really be, you know, good. But enough to make what I wouldn't have called art then. But what I might say as some kind of poetry." Again, he associates his explorations and learning as poetic, which underlies his conceptualization of art. As the program didn't have classes in the artistic approaches for computing, he informally learned additional computational skills and knowledge throughout college from friends and online, "going on FTP sites, downloading Ray tracers, reading, everything I could about that topic and, and being like, kind of lost about actually learning a bunch of it". He explained that Technology "definitely provides [him] with a way of thinking about how to integrate different materials and modalities." This approach of informally learning and exploring new technologies and computational tools has continued throughout his career. He described multiple projects that required him to learn and refine his knowledge during experimentations and practice.

*Intersection of Art and Computing*

As expressed throughout his interview, Paul has deeply engrained curiosity about technology that began when he was a child. Throughout his childhood, he engaged with technology and computation in a creative, experimental manner. Interestingly, Paul backgrounds the technological aspects when describing his work. His artwork reflects a focus on curiosity as Paul leverages and extends computational tools and technology to express himself and his philosophical examination of the world around him. In his perspective, expertise in a technology may hinder the art practice and prevent an artist from "asking the actual questions that ought to be answered". While the technology is a vital component for him, he highlights the impulses, the gestures, and the poetry of his practice. Moreover, he pushes the characterization and use of technology, "*the appropriation of technology is about rethinking its use, creating hybrids that are not so easily contained, explained or pigeonholed. This is precisely what is attractive about working on hybrids to me: they defy classification and must be met on their own terms". Within this experimentation in technological use and form,* he reflected that many of his experiments were "total failures from a technical and practical point of view, but they were beautiful poetry".

Extending this idea of failure to the broader field, he equated technology in art to theater, describing well known works of art in which the technology conceptually works but does not functionally work. For the performance and showcasing, the technological aspect was acted out. Engaging this idea in existential questioning, he asks,

> *"They're interested in the idea about the work or the idea that the work is? So then it's like, and so thus my thought before about this gesture, why make anything? Like you know, how do you know that half of the technology projects out there actually exist? Does it matter? Because if the idea was getting the idea and helping people notice things, if you can make an instrument, if you can imply a universe without having to create a universe, is that then human scale?... I think that your part of what you're doing as an artist is you're implying something in another person's head."*

Finally, he expands this idea of the meaning of technology and technology-based art and questions their lasting influence in history. These works "are tied so temporarily to the [technological] infrastructure and their poetics are a reflection on a cultural shared understanding of that, that later [in time] …you're only ending up looking at sort of a style or a mode as opposed to truly a poetics." He comments that these artists, including himself, need to be more critical and rigorous in thinking about their staying power in the art field. As technological systems and infrastructures become outdated, will these works survive?

*Relationship to the Audience*

In reflecting about his relationship with the audience, Paul expressed that his primary goal is "to work through a set of what [he's] noticing at that moment". He also seeks to share these noticings with others to evoke emotional responses. He explains,

> *"if I can create something that a few of these other thought bodies out there, meaning people, will also be attracted to in some way and notice the noticing then maybe that was it. That's what we get in this go around. I don't know. I'm not going to be able to witness it anyway. I can't witness another person's feelings. I mean, externally can, but I can't be inside them. And I think a lot of what I'm trying to do with the type of work is you know, hope that I was here… is intimacy of proof of that? I don't know. But if I can, if I can put something out into the world that another person can pause upon, I think that's great."*

As he is comfortable not knowing whether someone has experienced those emotions or understood that noticing, he focuses his practice on his own inquiry and experimentation. As such, he does not like to repeat his work or practice for the sake of making money or expressing the same ideas repeatedly.

*Computational Art Ecology*

Paul Catanese engages in exploratory and inquisitive art practice that orients towards an engagement with the art field. While computation is an ongoing interest, his practice focuses on using artistic expression to explore philosophical ideas. His practice is very self-reflective, with great focus on his personal intent through creative utterances. Moreover, Paul engages in the design of tools that intersect these two fields and allow him to explore larger questions about the world around him. This complex relationship is reflected in his *computational art ecology* through bi-directional links that connect the artist, art field, computing field, artwork, and tools (see Figure 55). He only occasionally engages the audience in his experimental and artistic practice, leading to a dashed line connecting the audience node. Finally, his dialogic threads element frames the artist, tools, artwork, and art field nodes, once again reflecting his orientation to artistic expression about ephemerality and expressing his philosophical noticings.

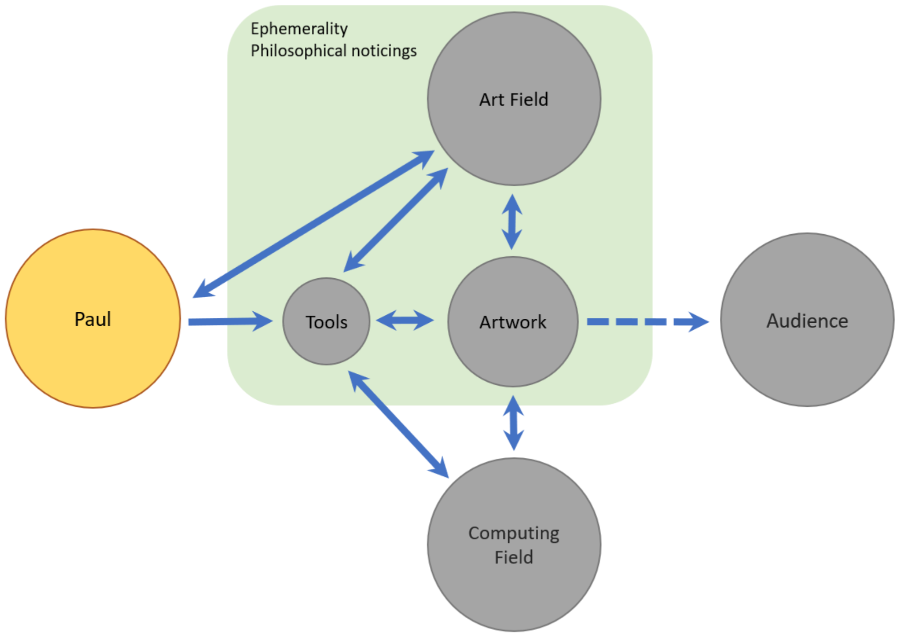


**Figure 55 - The computational art ecology for Paul Catanese.**

## Sarah Groff Hennigh-Palermo

Sarah Groff Hennigh-Palermo is an artist, programmer, and former data designer. Her artwork focuses on large-scale abstract works that leverage video editing software and computational tools. She additionally performs as the visualist for Codie, a livecode collective featuring the musical talents of Kate Sicchio and Melody Loveless. Livecode is an international movement based around algoraves, or experimental multimedia nights where music and visuals are produced through coding live (Algorave, N.D.). In addition to her artistic practice, she is employed as a senior frontend engineer for GitLab. She obtained a Bachelor of Arts in Modern Culture and Media from Brown University, where she focused on literary and critical theory and creative writing. She obtained a Master of Science in Integrated Digital Media from New York University, where she explored the intersection of art and technology. She also is an alumna of the School for Poetic Computation, a hybrid school, residency, and research center that explores the intersection of art, hardware, and theory; and the Recurse Center, an independent educational institution and retreat for computer programmers.

*Art Practice*

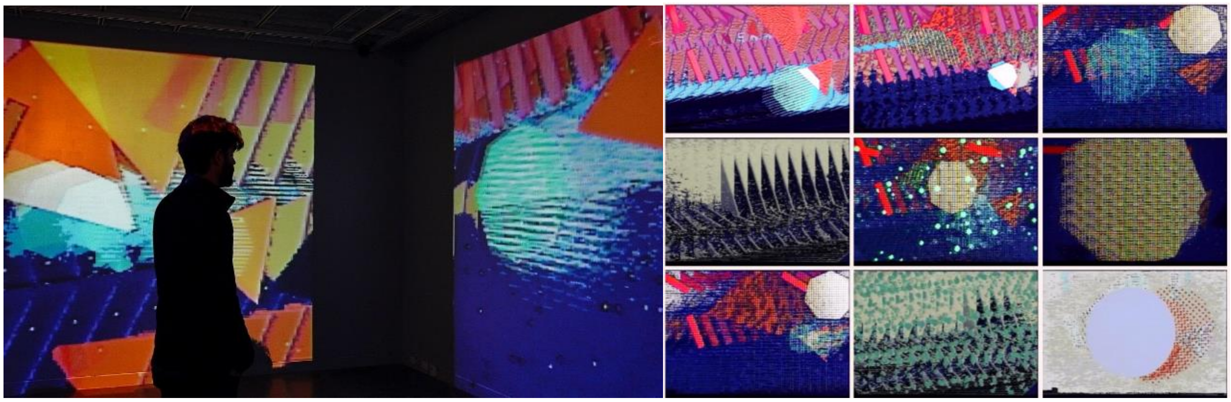

**Figure 56 - Images from *Jets to Codie* (2019), a variation of earlier projects in which Fairlight CVI was used to create variations on her animations that depict Codie music. On left, photograph of the installation. On right, a series of screen captures of visuals from the performance. (Groff Hennigh-Palermo, 2019; N.D.).**

Sarah primarily practices with digital and video to to create improvisational, immersive performances and installations. In her recent work, she's focused on leveraging the digital medium to explore abstraction, movement, and transitions (see Figure 56) (Groff Hennigh-Palermo, N.D.; Groff Hennigh-Palermo, 2019). To explore these concepts, she developed her own custom animation framework that she uses for her practice. She additionally leverages video processing tools that have been created since the 80s, such as the Jones frame buffer, which offers digital processing with analog control; the Fairlight CVI (Computer Video Instrument), an early video synthesizer developed that is associated with the "iconic" MTV aesthetics of the '80s; and variety of modern video editors. Her work focuses on computational tools and expertise, exploring the ways engagement with these tools can create imperfect outcomes in her visual displays. Her earlier work more often leveraged elements from physical computing, augmented reality, and computer vision, like *Smell-o-gram* [openFrameworks, scents from I Hate

Perfume, paper-mache], which was an investigation into sharing memories through smell (2016). In this, whenever a user lifted an object to their nose to smell, the screen showed a representative icon and a "less-representative" abstraction capturing a memory state. These artworks and projects were across a range of themes that center around modifying or introducing new representations of human experiences.

She also performs live with Codie, a livecoding collective. During Sarah's performances with her collective, she acts as the visual artists, projecting her abstract, moving animations while also showcasing her programming IDE where she programs live to change the animations (see Figure 57). A more complete body of work, including performance with music and visuals can be viewed at https://art.sarahghp.com/works/.

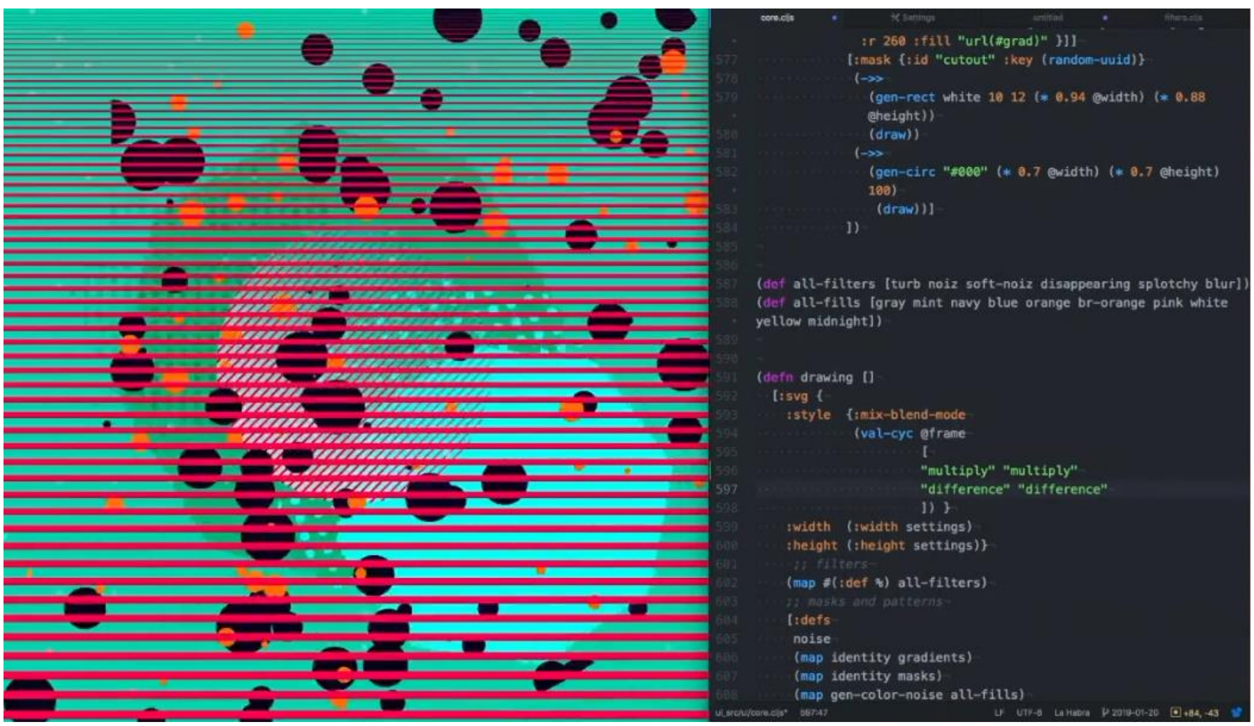


**Figure 57 - Screen capture of the visual elements (visual display and programming IDE) from the recorded performance of *Codie at Noiseberg*. (Groff Henning-Palermo, N.D.)**

*Relationship with Art*

Sarah grew up loving art but feeling like she didn't have the skill needed to be an artist, "art was a lot harder. I really loved art when I was a kid and I had these terrible art traumas." She described an experience when she was eight where her class was collaboratively reproducing a painting, and she couldn't "figure out how to look at the painting" and translate what she was seeing to paper. She said she "couldn't figure [art] out" and felt like it wasn't for her because it didn't come to her naturally, like other domains did. It took twenty years before she returned to the idea of art, realizing "no, actually I can make it". Sarah went into literature, specifically literary and creative theory, for her undergrad and was hired as an editor at a small publisher after graduation. She began to explore more visual creative works after seeing data visualization art then developed more of an identity as an artist after attending the School for Poetic Computation. This practice deepened when her thesis advisor in her master's program convinced her to perform with her in Codie, the live coding collective.

She draws inspiration and parallels from previous art movements, including suprematism (focusing on fundamentals of geometry), pop art (reflecting popular and mass culture), and color field (highly simplified abstract compositions focusing on the expressive power of color detached from figuration or line). She describes that she is on the "mystical end of art" that attempts to construct and share "states of being", like "sunlight looked when I was eight and reading in our house in California" or the experience of water in a pool on a hot summer day. She describes her emotional reaction to standing in front of these large color field or suprematism works of art, like from Mark Rothko or Agnes Martin,

> *"I just stood in front of them. And I felt this thing. That was a thing that I haven't felt in other contexts. Right. And it's a sort of falling away of time and feeling connected to other people in this attenuated like threaded fundamental way that's not about being like, you're sitting next to me and we're the same, but we have*

> *access to some universal that makes sense to all of us. And I think that that universal is rendered through specifics, and even when people don't hear it, sort of rendering those thoughts, visible, interactable with other people is really important."*

She reflected that her creative practice in literature and in visual arts are both motivated by a larger goal to be seen in the universe. She explores these common, nostalgic themes that bridge and connect periods of time. As such, temporality is a primary focus of her work. She explained, "I was talking before about connection and a lot of about that is about nostalgia, right? That feeling, that attenuated feeling is partly a connection of yourself in the past. And then you get all these layers of time, all built up together. And so, I think I'm interested in time in that sense too, that we move through this thing we can't ever really go back, right". For Sarah, these creative ventures are her way of attempts of telling the "universe that you're here… And like, hopefully people hear it. And even when people don't hear it, sort of rendering those thoughts, visible, interactable with other people is really important". Finally, she expressed that her perception of art has shifted over time. While she focused on the technical practices when she was younger, she now sees art as "an interface to culture and the world" and her dynamic, temporal art is her way of engaging with the world.

*Relationship with Computing*

Sarah became interested in computing after her undergraduate program, as she was working as an editor. She moved into project management in the tech industry because it paid better and realized her interest in user experience design. While working at this small tech company, she decided she should learn how to program. Sarah explained that she "came into computer science at odds with it". Her first exposure to computer science was through friends of friends who gave her a negative impression of the field through his description and the work required of the program, "it was late nineties and I knew nothing. And I'm just like, 'what is computer science?' And he was just like, 'it's too hard'… by the time I finally got to learning, I was already, I'm not one of you and I don't have to be one of you this isn't my community." Even as she explored the possibility of learning to program while employed at a tech company, her coworkers discouraged her by telling her it is really hard. She described that she realized she could become a computer scientist after realizing the human side and imperfection of programming languages, "this isn't magic. You know, computer languages are written by idiots, just like us. We can totally do this and that moment that it became knowable and like opened the whole kingdom up. Cause then I was like, 'Oh, it's not impossible'". She took more courses, joined communities, and began to express herself through data visualization art, in which she would represent her written works in artistic data driven ways. She applied to a hacker school in New York City then went to the School for Poetic Computation after being declined from the first. After, she went to graduate school at New York University for Integrated Digital Media in the engineering department then went into a career as a software engineer.

She perceives and critiques computation and the computing field through a lens constructed in her literature program and from her intersectional identity as a multi-racial woman. She sees similarities in the structures and norms of programming and literature but feels more confident as an "outsider" to critique computer science.

> *"And so much of that writing code is about making a structure that makes sense so that someone else can read it and they can figure out what in that structure is important content and what that structure is, connective content and how do they logically fit together? And how do I find the thing that I need to find? And all of that is what you do when you write or you make a book or you lay out a book and you think about those logical interactions. And the fact that these words are directions to computers is not particularly important"*

She expresses that the practices for writing code and constructing computational systems that privilege and set ideals based on computation rather than on humans are deeply flawed, "I find this cultural drive in the technical sector for perfection, or the idea that you can with enough effort, make something unbreakable to be absurd and to lead to, I think, toxic cultural assumptions. So I'm really interested in the other side, but I'm like, 'how do you make software resilient?'" Moreover, she is aware of and highly critical of the history of computing, reflecting on histories of oppression in the computing field. She expressed, "computer history is inherently violent. Computers were developed as tools of war and surveillance, and only entered the private sphere when corporate interests began to comprehend the power they afforded" (Groff Henning-Palermo, N.D.). In the interview, she further connected this history to a piece of her identity as a black woman, framing her engagement in the field as a step towards improving the culture and application of computing. She additionally created a number of applications and IDEs to support her own creative computing explorations as well as others. She describes the tools she creates as, "[generating] work that explores the materiality of the digital… not smooth and continuous, but crunchy and unsteady (Groff Henning-Palermo, N.D.). Through her work, she critiques the "positivist, perfectionist assumptions" that underly code and the computing field.

*Intersection of Art and Computing*

Sarah's position in art and computing is unique, considering she constructed an identity as someone who could not make art and who does not fit into the computing field. She describes that it was "harder to decide that I could call myself an artist than it was to call myself a programmer because being a programmer felt like, 'can you do this thing? Can you read this code and can you make the computer do the thing?'" As mentioned earlier, Sarah really connected to art once she shed her prior conceptions of traditional art and began to explore states of being and temporality. She described, "these persons' work make me feel these like big, vast feelings that pools make me feel and books make me feel, and we can all do that. And so what I want to do is be like, 'okay, well, how do I use video synthesis, the kind of work I do …how can I use that and repetition and size to induce those feelings of expansion in other people?'" Sarah engages with computational art because it allows her to manipulate and express time, calling back to nostalgic experiences and transporting the audiences to new states of being. It also gives her agency in making positive changes to the narrative of computer science,

> *"I feel like computers could be so much more than weird business buying war machines that culturally that made it that thing. … I think I sometimes hope to envision it as a way of splitting off that computer science history…it's my tiny drop in the ocean, but I do think that's a lot of why it's important for me to use computers and even older hardware to make art."*

Sarah sees her engagement in live coding and building systems as a disruption to the computing field, "the code is part of that, is a critique. And it really gives me a chance to explore a world structured by other goals". While the majority of the coding in these performances is done in the moment, she brings a theme or palette, a loose narrative or "state" she wants to convey, and some pre-coded building blocks (e.g., "I can make a shape and say how big it is and where it should go, and which frames it should appear in") that she uses to shape the performances. The dynamic experience programming is an important for her in creating art, and she will delete and start fresh with new building blocks after using them for some time. As she is passionate about the live component of the performances, each performance requires balancing her artistic and computational visions with speed and risk of new programmatical elements. She noted that others who live code or do similar video-based art will program systems, or larger "building blocks", that front-end most or all of the programming. She explained that while these support more complex animations and automatic responsiveness from the music, they front-end the programming; "I don't want to do that. I am not interested in doing that because it feels too close and that feels not creative enough to me. That gives other people too much power… it feels not active enough for me".

Finally, in reflecting about the broader field of art and the intersection of computation, she identified several groups of artists: artists who engage in "just in time" programmatic or computational learning to achieve a desired outcome, those who are using "code to make art that fits within contemporary art", and developers or computer scientists who are making generative art with code. She draws a distinction between these groups of artists and those that she describes as "native computer artists", those who aren't oriented towards either art or computational fields. She identifies as one of these "native computer artists" who engages in new art practice that expands both the art field and the computing field.

*Relationship to the Audience*

While Sarah personally sees her practice as an active critique against the history and culture of computing, these goals are not explicitly visible to the audience. She does provide some computational hooks for her audience with the hope that they can understand the basics of the programming behind her live coding performances, "I do name things and named functions and stuff so that people watching them, even if they didn't code could presumably get a little bit out of it, like 'generate circle', 'do freak out', right? Just little things where it's like, 'okay, you saw this little bit, know what it meant'. However, her primary goal with the audience is to communicate and share states of being and new experiences that connect moments in time. Sarah seeks to expand the viewer's experience with light, color, and time. She does this with her immersive experiences that wash over the audience in waves of color, motion, and shape. These experiences are challenging for her to convey outside of her performances or exhibits, as much of the immersion is done through large screens placed around the room (see Figure 56). She extensively documents her perspective about art, computing, and the intersection of art and computing in personal essays on her website. Moreover, she invites others to participate in her creative use of computation by providing free access to applications, software, and frameworks that she's developed in her artistic practice. She recently began to experiment with selling prints of screen captured visual elements, not including code.

Finally, in reflecting on the reception of her work by other artists and computer scientists, Sarah explained that "programmers are way more excited about the art than the artists are about the programing". She described that many artists are "just in time" computational learners so they do not have the full understanding of how she is creatively using her code. Developers can appreciate the art both from the visual side and from the disruption of computational norms and practice.

*Computational Art Ecology*

Sarah Groff Henning-Palermo's art practice weaves together the art field and computing field, advancing and exploring both through her aesthetic and programmatic expression. She situates herself as a "native computer artist" who artistically explores computation and computationally explores art. This relationship is reflected in her *computational art ecology* through the overlapping code and artwork nodes that are bi-directionally connected to both art and computing fields (see Figure 58). In addition, Sarah engages in self-reflective practice about the nature and norms of art and computing fields, reflected in the bi-directional links between her and those respective nodes. Her participation in her live coding collective is represented by a new collaborating musicians node. This is bidirectionally connected to her artwork and code artifacts, capturing the collaborative and interactive process of creating a live emergent performance. Finally, the dialogic threads element frames the entirety of her ecology, as she intends to engage all agents in reflection on computational norms and in sharing states of being.

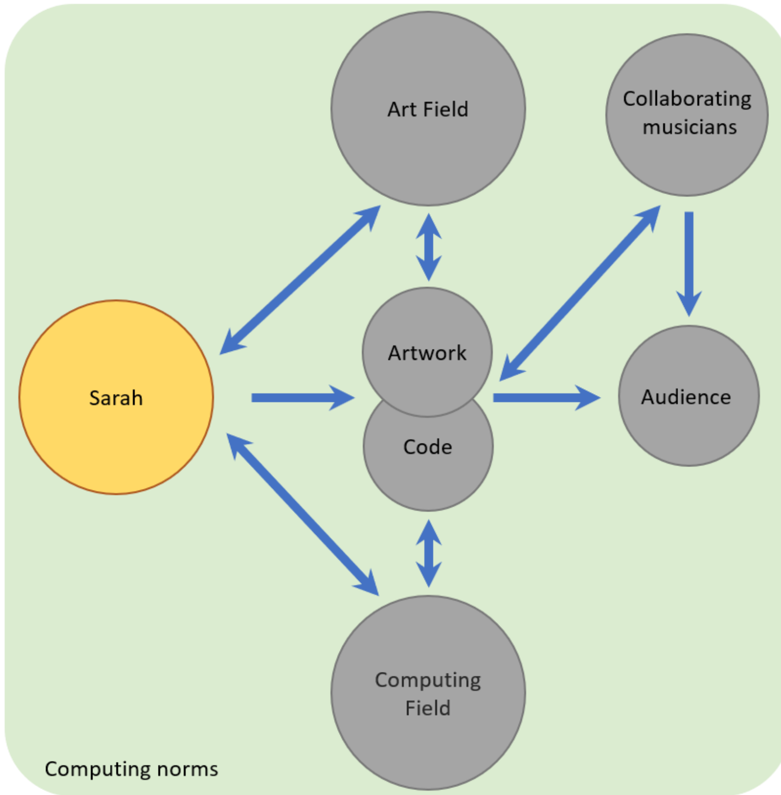


**Figure 58 - The computational art ecology for Sarah Gross Hennigh-Palermo.**

### Taylor Hokanson

Taylor Hokanson describes himself as an artist, engineer, educator, and noted tall person. He was an early participant in the Maker movement, a movement EXPLAIN. He investigates the promises and the problems of uncritical technology consumption in the post-digital world, focusing on human-computer interaction, computer-aided fabrication, and new models for collaborative authorship. He obtained a Bachelor of Fine Art in Sculpture from Washington University in 2000. He obtained a Master of Fine Arts in Studio from the School of the Art Institute of Chicago in 2004. He is an Associate Professor of Art History at Columbia College Chicago. He is co-host of the podcast *Opposable Thumbs* with Rob Ray, where they assign themselves and a guest a creative challenge every two weeks then debrief about the challenges and discoveries in their design process (accessible at https://www.opposablepodcast.com; Hokanson & Ray, 2017- present).

*Art Practice*

Taylor orients his practice around the ideas of connections and access, exploring projects that leverage technology to allow people to do new things and make more connections. In describing his work, he uses language of design, more often than traditional language of “artwork”. One subset of his practice is the investigation and creation of new computational systems. One example of this is his work exploring 3D printing with light. In exploring how light could be “3D printed”, he created a machine, *Horror Vacui*, that that can move a television with computer-controlled precision to effectively print in layers of light when paired with long-exposure photography (see Figure 59 left) (Hokanson, 2019a). His first series of images from this machine were extensions of protoscientific studies in which he represents molecular structures of various artifacts (i.e., hyacinth, cinnamon, mothballs) (see Figure 5.19 right) (Hokanson, 2019b). These themes of protoscientific or philosophical explorations are common throughout his more recent creative ventures and motivations of computational systems he designs.

**Figure 59 - Images from *Horror Vacui* (2019 - ongoing) [photography, 3D printing with light]. On left, a studio shot of the Horror Vacui 3D light printer. On right, *Hyacinth (Highest Occupied Molecular Orbital)* (2019), a 3D printed light photograph.**

Another thread of practice reflects a more "traditional" art practice, emerging from his background in Sculpture and metalworking. He creates large structural objects use size and form to question social and cultural norms and practices. *Ingot*; made of stone and iron, cast from secondhand jackets; comments on the historical practices of using iron ingots as currency and the rationale for the popularity of the "oxhide" shape, that looks like animal skin (see Figure 60 left). This piece is both sculpture and currency, and uses it's form (conceptual shift from animal skins to human bodies) to speak on "speaks to a cultural and environmental moment where the consumption of resources, and the relentless pursuit of capital, has put all of our lives at risk" (Hokanson, 2019c; Hokanson, 2019d). He also creates computational interactive sculptures. His *Sledgehammer-operated Keyboard*, is a fully functioning keyboard, though without the backspace or delete keys, that is dramatically increased in size, requiring the use of a mallet or other physical exertion to communicate (see Figure 60 right; Hokanson, 2019e). In this piece, Taylor disrupts the normal engagement with and communication practices of a keyboard by making it "absurdly" difficult to use. He describes the piece as fostering an "exuberant environment, prompting the audience to author a collaborative document that is equal parts heartfelt, thought-provoking, and profane" (Hokanson, 2019f).

**Figure 60 - On left, *Ingot* (2019), an iron and stone sculpture. On right, *Sledgehammer-operated Keyboard* (2005 - ongoing), a dramatically large keyboard requiring physical force to type.**

*Relationship with Art*

He grew up in midwestern states, largely post-industrial river towns, which inspired his practice and approaches to thinking about art. He described, “I started out in a much more blue-collar sensibility with welding and bronze fabrication jobs and hurt my body a lot that way as a young person.” He has always been interested in process-oriented, industrial, and high-tech practices. In his undergraduate program, he was more interested in the “essential stuff” like foundry, casting, welding, and other metal working. After graduating from his undergraduate program in sculpture, he went on to work at a company that made life-size or larger than life bronze sculptures then to a commercial sculpture shop that leveraged carved high-density foam. He described these jobs as having numerous dangerous and physically strenuous working conditions that left him feeling exhausted and experiencing chronic injuries. With these challenges, he decided to go to graduate school to explore art and technology.

When asked about his motivation that led him to sculpture, he expressed an interest in conveying his experience as “a really enormous person”. He reflection, “I think the physicality of big objects that I can relate to as my size or larger, you know, strikes me as really interesting. And I like how sculpture takes up space in a way, like it demands more from the viewer because it can't be, you know, kind of placed safely against the wall or something… [big objects] require again, a relationship.” He compared this relationship with these large objects to the relationship formed when collaborating with peers and the connectedness of the internet. His work explores the social and cultural impacts and potentials of technology, often creating objects that are “physical, functional, and absurd” in order to reevaluate or problematize core societal norms associated with technology.

*Relationship with Computing*

Taylor grew up with computers in his home and access to computing courses in his elementary school, though he remembers only taking one at that time. He began exploring computer science and computational tinkering after graduating from undergrad in 2000. He described that he didn’t have access to digital control but would pick up technology or computational tools that were discarded or broken to take apart and put back together. He explained, “I was doing stuff like taking the timers out of washing machines and then hooking wires up to the, you know, so you'd like, you'd set the timer and you just have a way of turning switches on and off and so forth. And it was, it was so kind of aimless. I mean, I didn't really know what I was doing at all.” When he reached his physical breaking point with his sculptural work, he realized he could explore the intersection of art ad technology to make artifacts without the physical demands. He began to shift his research into questions of “what would happen if artists get ahold of [computational] tools and they weren’t just restricted to industry where you really have to think about economics of scale”. He expressed that he is interested in technology for what it allows people to do. He explained,

> *“I don't really regard like this part of the practice as technology and the previous part is non-technology. But just to make a nod to the fact that, you know, digital technology is kind of regarded in a separate space…the original computers were just people. And I think I like seeing it on a continuum where it's just more about the*

> *connections that lets you make. It's about people for me and so forth as opposed to the sort of, 'does it have to be on a computer?' No."*

He quickly began making accessible computational tools for himself and others to leverage to meet their own goals. One of the major projects in this vein, *DIYLILCNC,* is a partnership with Chris Reilly, of the School of the Art Institute of Chicago, to develop a free and open-source set of plans for an inexpensive, fully functional 3-axis CNC mill that could be built with access to basic shop skills and tool access (accessible at: www.diylilcnc.org; Hokanson & Reilly, 2009). CNC devices are fabrication devices that can create objects with a high degree of precision and feature a mounted cutting tool (like a router), all controlled by a computer that translates the digital design into movement of the tool. In another computational project inspired by the computer hacker conference DEFCON, he and a fellow hacker Nick Bontrager developed an open-source simple electronic conference badge, *CAAint*,  that non-engineers, "noobs, artists, and the interdimensionally-curious" could program and make their own (accessible at: https://github.com/TaylorHokanson/CAAint; Hokanson & Bontrager, 2019). He described his motivation for this work aligned with the "large effect" he explored in sculpture, "I tried to sort of start this this ripple that other people can pick up and jump off of and I can have the satisfaction of knowing that it wouldn't have gone forward without me participating, but I don't have to be at the top of the Hill to make that work".

*Intersection of Art and Computing*

In the interview, Taylor focused on describing and discussing his computational system design, mentioning a divide or disconnect between that practice and "conventional" art practice. He expressed hesitation at calling his practice art, despite labeling himself as an artist on his professional websites, attending art school, and teaching in an art program at the collegiate level. This hesitation appeared to be associated with the products of his practice rather than the process itself. He expressed that his motivation and the process across his artistic sculptural work and computational or technological work are very aligned, saying,

> *"there's just a lot of little, sort of, process things that you had to have all kind of floating in your mind in order to accomplish the thing that you want. And then sometimes your mold could like limp across the finish, but it would still work. And then sometimes it would be super tight… I think that all those skills feel completely applicable to working with coding or whatever it happens to be."*

For his art, design, and computational practice, he finds continuity in the organization of the processes and in imagining physical objects as a final product, even when creating computational systems. More specifically, his approach to engaging in this process-oriented practice is in service of questioning these tools and contexts in how they relate to and impact social and cultural norms,

> *"what if I subverted a part of the process that is- has been established to be correct? …what if we went back to some of those things that have been so well established that they're no longer regarded critically and then change them in a way to sort of pull the rug out and to get us thinking more expansively about other things that we no longer think about too carefully?"*

Finally, he is expressive and collaborative in his practice. In his interview, Taylor reflected on the issues of underrepresentation in computing, commenting that he sees them but has not experienced much discrimination as a white man. Despite aligning with normative culture of computing fields, his work largely focuses on expanding access and giving voices wto those who may be underrepresented or struggle to find space within computing. In additional to his work developing open source technical systems, his podcast, *Opposable Thumbs*, with Rob Ray reflects some of this critical design thinking oriented towards community and communication (Hokanson & Ray, 2017). This podcast spans his artistic and computational practice by exploring creative and technical design challenges with guests who are traditionally underrepresented in the Maker movement and computing fields, such as women, people of color, and gender nonconforming individuals.

*Relationship to the Audience*

In his artwork, Taylor invites the audience to experience new physicality and relationships to objects. As he is deeply inquisitive about the world and the implications of technology in everyday life and academic research, these projects represent a variety of topics that aren't at the forefront of audience experience while interacting with the artwork.

Taylor exhibits his work frequently and repeatedly at differing art and maker events. He is active in sharing his art practice with others, documenting his thinking, explorations, and projects in a blog on his public website (https://taylorhokanson.com). He also posts resources to help others access materials, technology, and courses.

*Computational art Ecology*

Taylor has two *computational art ecologies* that reflect his art practice, as he strongly described a dichotomy between is more "conventionally" artistic sculptural work and his practice in developing computational systems. The first ecology, $Taylor_{1}$, captures his more conventional art practice (see Figure 61). In this practice, he primarily focuses on his personal expression, not situating within either the art field or computing field in a significant way. This practice occasionally uses computational tools but does often leverage more traditional mediums, like metalworking. As largely sculptural, this artwork is more often displayed in a traditional manner where the audience views it, though there are exceptions, like his *Sledgehammer Keyboard* (Hokanson, 2019e). The dialogic threads element frames Taylor and his artwork as this practice is largely self-reflective and often times expresses his lived experiences as a very tall man.

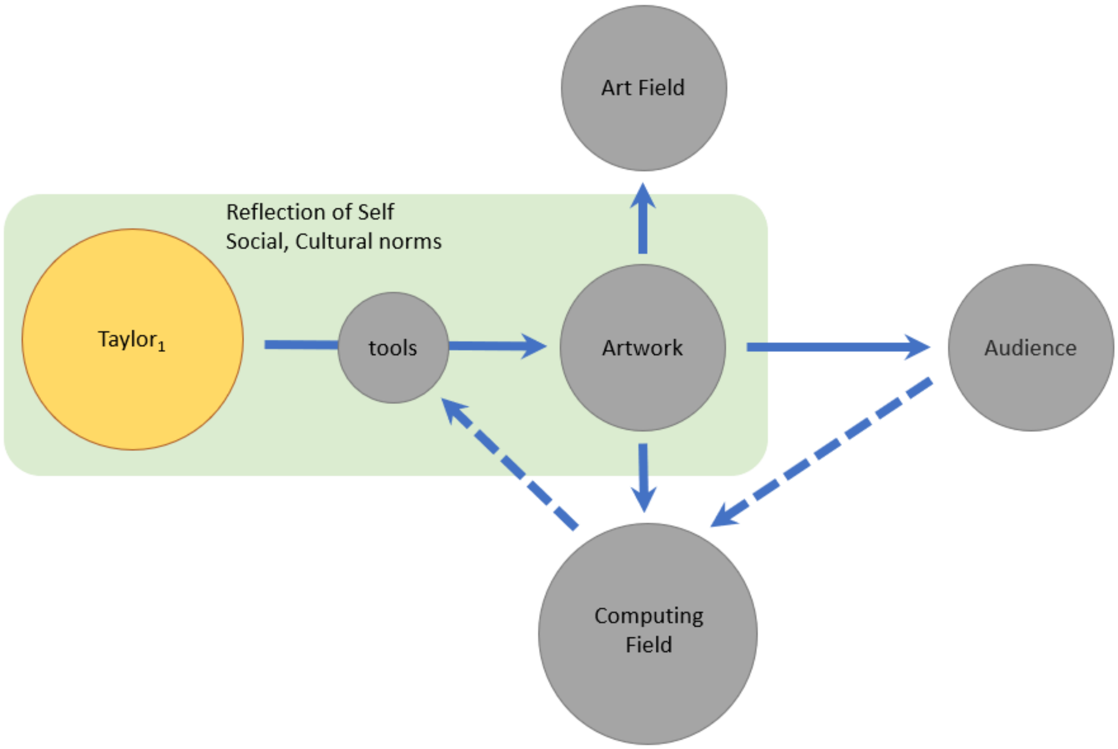


**Figure 61 - The first computational art ecology for Taylor Hokanson, reflecting his more traditional artistic practice.**

His second *computational art ecology* reflects his engagement with modifying and developing computational systems primarily for others to use in their practice (see Figure 62). In this, the role of the art field is reduced, as the primary focus is on the computational systems. However, Taylor reflected that the users of his machines and systems do create their own artwork, that he perceives a “ripple” of his own practice, warranting links between the audience, art, and the art field. Most of the focus in this practice is on changing forms of connection in the computing field, particularly around access and collaboration. Taylor gets inspiration from engagement in the Maker movement and in computing fields, where he contributes while observing social and cultural norms and community needs. As such, there is bidirectionality in the links between Taylor, the computing field, computational systems, and the audience. Finally, the dialogic threads element frames these nodes as he engages in dialogue on these themes within computing with participants both inside and outside of the computing field.

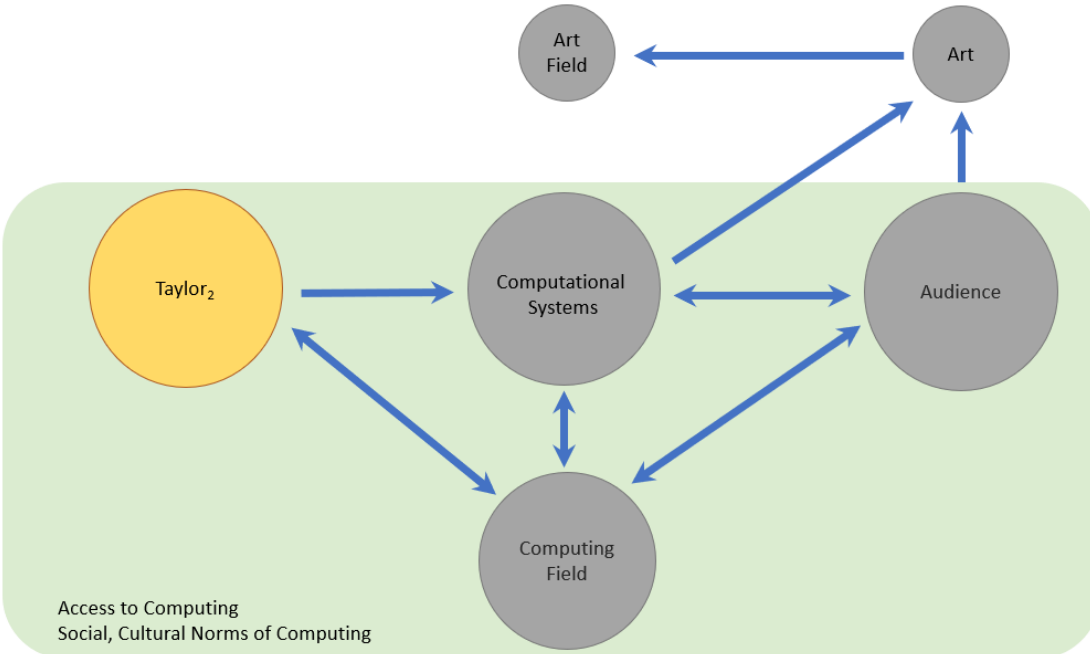


**Figure 62 - The second computational art ecology for Taylor Hokanson, reflecting practice developing computational systems for artistic and creative work.**

## Emergent Themes at the Intersection of Art and Computation

The cases explored in this chapter and in chapter four reflect a subset of the breadth of computational art practice taking place at this time. These artists can be characterized across numerous elements, which will be explored in more detail in the following chapter. To make sense of how these artist experiences give insight into computational perspectives in the arts, the following section will highlight emergent themes and perspectives common across these computational artists.

Tool usage and perceptions of computational tools was a common distinguishing feature identified by the participating artists. As was expressed through many of the interviews, these subcommunities at the intersection of art and technology or computation are commonly characterized by the epistemological stance towards computational tools in practice. For those recently graduated from the School of the Art Institute of Chicago; like Meimei, Yimin, and Anna Christine; artists in the field can be distinguished based on the computational intensity of their practice. As they characterized, “low-tech” artists that engage in surface level practice with technology and “high-tech” artists that focus deeply on a technology or computational practice of interest. Others described the camps of artists based on programming expertise and computational fluency, on distance from other traditional art genres or practice, forms of social critique, or extension and disruption to technology. Largely, these conceptualizations of the field are based on the epistemological stances of the programs in which these artists were trained. They provide important landmarks in characterizing the varying perspectives represented in the field broadly. However, given the isolation of these schools of thought and the ever emerging and evolving practice with computation, these institutionally derived perspectives may not fully represent the ongoing practices at the intersection of art and computation. As such, this work seeks to characterize computational practice in the arts across many factors so the complexity of this population can be represented more authentically. As reflected in the clustering of cases in this chapter, rather than characterizing a low- or high-tech dichotomy, artists’ engagement with computational tools can be characterized based on whether the computational tools are leveraged for their designed affordances or if they are used in experimental approaches. Artists like Anna Christine, Meimei, Yimin, Iva, and ann all show expertise in gauging the affordances of computational tools and applying them towards varying artistic outcomes in their practice. Artists like Paul, Sarah, Taylor, Janell, and Cody represent artists who extend, subvert, modify, or create new computational systems that engage in experimental approaches to either art or computing.

Artists across this characterization referred to tensions between the goals of art and computation in their practice. All artists referenced issues of access within the field, describing that cost of materials and resources prohibited participation in the field. Moreover, a subset of artists raised concerns about the hidden cost of time when leveraging computational tools in practice. Still learning programming and other computational proficiencies, these artists reflected that the use of computational tools can take up extensive time in the art practice, requiring debugging and problem solving that can detract from the purpose of a piece of art. Others reported feeling a disconnect between their conceptual ideas of technology or computation and what they practically could implement given constraints in resources, computational power, and time, among other factors. A subset extended this concern, explicitly referencing power dynamics that further limit access particularly for underrepresented groups in art. This topic is captured by Meimei's reflection on her personal struggle finding space within the white male dominate culture in the arts that intersects with limited epistemological stances imposed by computer science. Janell described her discontent in her computer science courses, seeking humanistic perspectives when efficiency and algorithms were at the forefront. Sarah's experience documents explicit moments where members of computer science sought to gatekeep and discourage entry into the field. Moreover, she passionately speaks and writes about the inherently violent and capitalistic history of computing. Like ann, she argues this is a larger societal issue and uses her art to try to express new narratives and pathways for computing.

This sociocultural, political orientation in the arts is common, but may be particularly at the forefront of computational art. Most participating artists reflected on the commonality of art exploring these themes within art and technology. Many of the artists described motivations to explore these themes due to the prevalence of technological integration and interaction in all facets of human life. Yimin and Meimei comment directly on this, citing the role of technology in the Anthroprocene and fueling ecological issues in our world today. Sarah and ann reflected similar perspectives on needing to shift narratives and perspectives on the role of technology and tech companies in our everyday lives, cautioning against a continued blind trust of computation and tech companies. These broader sociocultural and historical factors mediate engagement with computing for the participating artists to varying degrees. However, across the majority of participating artist, these diverging epistemological approaches to computation offered hope for and potential of future world that interact with technology and computation in vastly different ways. Artists like Taylor, Paul, and Meimei express their beliefs that art can expand and uncover new knowledge through unconventional methodology. These artistic narratives, perspectives, and epistemologies offer pathways for science and humanity more generally to grow and evolve.

Despite thematic trends at the intersection of art and computation, another common theme within this group of artists is a struggle to find their identity and to situate their work in the broader landscape of art and computational practice. It is important to note that the personal histories and identities of artists impact this struggle to find their identity in the field in differing ways. To summarize some of these perspectives, many reported feeling that traditional artists could not make sense of or engage with their computationally influenced work. For a subset, their computational practice was overlooked in computing fields for lacking technological mastery. Moreover, the field of art and technology is advancing and evolving, meaning there is limitless potential for artists practicing at this intersection. However, this freedom also can be isolating for artists exploring new frontiers in computational art. As expressed by a subset of artists, finding one's voice can be challenging with those around you lack shared experiences, skills, or interests. The participants within this dissertation reflect a subset of computational artists that are largely fine artists situated in the Midwest or Eastern coast of the United States. The current sample is lacking global representation in engagement at the intersection of art and computation. Meimei and Yimin offer perspectives from Asia, describing that art and technology is a rising trend in Asian countries. In these countries, there is hope that art and technology can entice younger generations back to museums and other cultural experiences. As Yimin described, the technology-centered art education in the People's Republic of China orients artistic goals towards aesthetically innovative or creatively interactive and engaging works of art that pique the interest of new audiences. Both Meimei and Yimin reflected feeling disconnected from their art programs in the United States. They noted political orientation of these programs, but that they couldn't find space and validation to fully explore sociocultural and political themes important to their experiences growing up in China.

Finally, many artists reflected that online communities gave them a place of belonging that they lacked in institutional pathways and more traditional communities described above. Anna Christine spoke extensively on her experiences finding communities of practice within the glitch art genre. These communities provide vital support structures as artist seek out others with shared practice, mediums, and interests. These online communities shift the power dynamics of the art world, giving artists more agency to advertise and showcase their work to audiences outside of institutional spaces like exhibits. Moreover, online spaces allow artists to disseminate resources and materials that allow others to engage in creative practice. Taylor, Sarah, and Janell all use their personal websites to share documentation and software that allows others to engage in computational artistic practice on their own. For those advocating for new perspectives and pathways in computer science, these online spaces are vital. Finally, these online spaces give artists the freedom to communicate and commiserate over shared experiences related to their art practice, as well as their perspectives on the world.

In this chapter, we've documented the experiences of seven artists as they find their voices at the intersection of art and computation. Through these cases, we've explored the experiences and challenges that shape art practice that this intersection. These cases highlight nuances in the field that should explored in greater detail in future studies that are able to represent larger and more diverse populations of computational artists. In the following chapter, the *computational art ecologies* will be compared to further characterize the practices and perspectives of artists at the intersection of art and computation. These lead the design of an emerging framework for computational thinking in the arts.

# Chapter 6: Patterns of Computational Engagement and Perspectives in the Arts

The ten cases presented in the last two chapters represent a breadth of computational experiences in the arts. As was seen throughout these cases, each artist had unique experiences and relationships with art and computing fields that led them to engage in computational art practices. The cases highlight the importance of personal exploration through computational arts, which was expressed in varying engagement with tools, practices, and genres across the artists. While the sample is limited in size, we can more systematically characterize the computational engagement and perspectives that emerge within this group of artists.

In this chapter, these broader patterns will be explored, using *computational art ecologies* as a framework to characterize artistic practice across artists. To do so, the structural orientation of the dialogic threads element and the bidirectionality of links within the ecology are used to characterize artists. As was described in the methodology chapter, the dialogic threads element can be used to identify general computational practices and engagement through its horizontal and vertical orientation (see Figure 63). Finally, each artist can be characterized by themes that capture the computational intent of their practice.  Finally, these structural and thematic characterizations can be used towards the development of a framework that captures computational thinking as it appears in the arts. The chapter concludes with this initial framework, called Computational Engagement and Perspectives in the Arts, and a discussion of how to further strengthen and expand it.

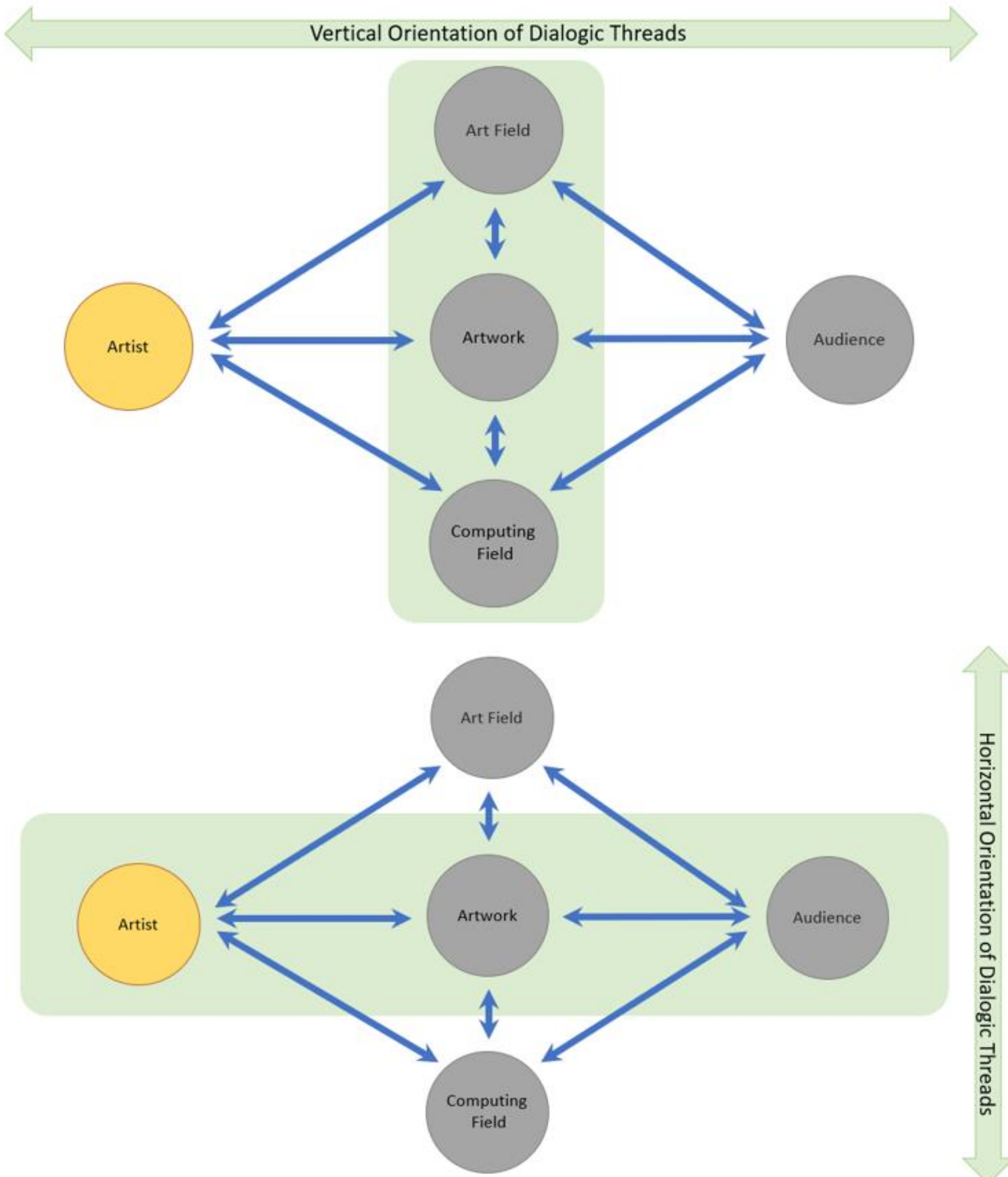


**Figure 63 - On top, the generic computational art ecology with the vertical orientation of the dialogic threads element highlighted. On bottom, the generic computational art ecology with the horizontal orientation of the dialogic threads element highlighted.**

## Computational Participation in the Arts

Computational participation for artists can be represented in many ways as artists have diverse expressions of their practice. The case studies revealed complex relationships with computing fields and computational tools that mediate what artists create. One approach to characterizing this participation emerges from the structure of the *computational art ecologies* for each artist. We first begin characterizing artists based on the orientation of the dialogic threads element in the ecology. Again, the dialogic threads element is the green structure that frames nodes within the ecology. The dialogic threads element represents a dialogue between the artist and something of importance to them, for example their identity, their culture, their technology, among others. This is a way to represent the broader social and cultural factors that are influencing an artist's work while constraining it to the factors that an artist is more closely attending to and in dialogue with throughout their art practice. The vertical and horizonal orientation of this element reflects a spectrum of participation regarding computational tools and computational communities, respectively. These patterns emerge from characterization of structural patterns that are compared to the cases to identify the themes these patterns describe. As this methodology is emergent based on the 10 cases in this dissertation, this process of identifying meaningful structural patterns is iterative and interactive with the cases. The potential for using these ecologies independently to characterize computational practice in artists increases with a larger sample of artists. These elements are best captured using spectrums, rather than binary categories, as art is a fluid practice. The artists in the sample highlight this fluidity, particularly around the use of computation, which is varied and evolving for artists as they make sense of the role of computation in their work. Below, these spectrums of computational participation in the arts will be outlined and situated in relation to artists from the sample.

**Computational Tool Use**

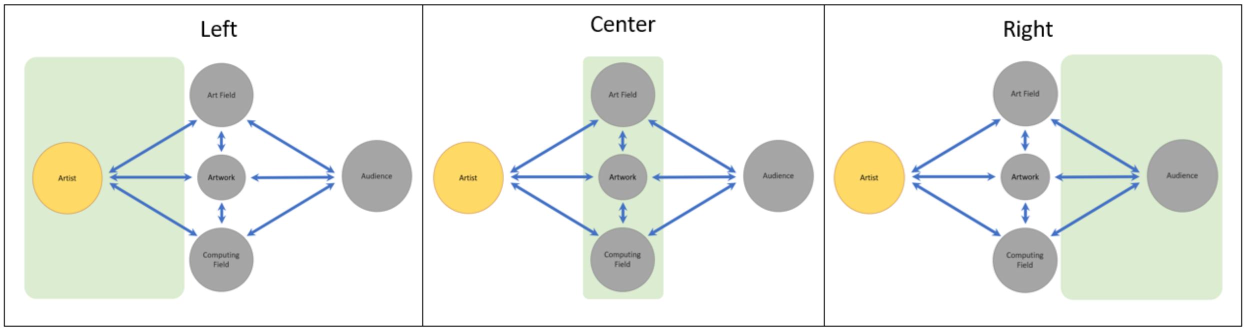


**Figure 64 - Spectrum of vertical orientations for the dialogic threads element from left to right.**

Artists use a variety of computational tools to meet their artistic needs. Within this sample of participants, these tools included: programming languages (C, Processing, R, Python, etc), 3D printers and CNC machines, industrial machines, electronic devices (Game Boy game consoles, Televisions, drones, etc), circuitry and robotics, and design software (Rhino, Zbrush, CAD, Photoshop, etc). Each artist expressed different perceptions of the role and engagement with these tools throughout their practice. Some, like Meimei and Alex, occasionally use computational tools in their practice, critically assessing if the goals of the piece align with the computational elements. Others, like Iva and Yimin, frequently use computational tools in their practice, carefully selecting and applying them based on their affordances. Others, like Paul and Taylor, use a wide variety of computational tools in their practice but create, modify, and extend each beyond their intended affordances. Finally, artists like Sarah, Janell, Cody, and Anna Christine leverage a smaller selection of computational tools in their practice, gaining expertise in their tools of choice so they can apply them more meaningfully. This engagement is important in characterizing computational thinking and practice in the arts.

While cases reveal intricacies in the role of computation in practice, the structure of *computational art ecologies* can help to characterize this engagement with tools. As was described in the methodology section, the vertical orientation of the dialogic thread element from left to right in the ecology captures a spectrum of tool use. Computational Tools Use is a spectrum of how artists interact with the computational software, machines, and methods within their art practice. This ranges from a focus on engagement with the tools themselves (left) to a focus on the application of tools in new contexts (right) (see Figure 64). Below, each side of the computational tool use spectrum will be explored.

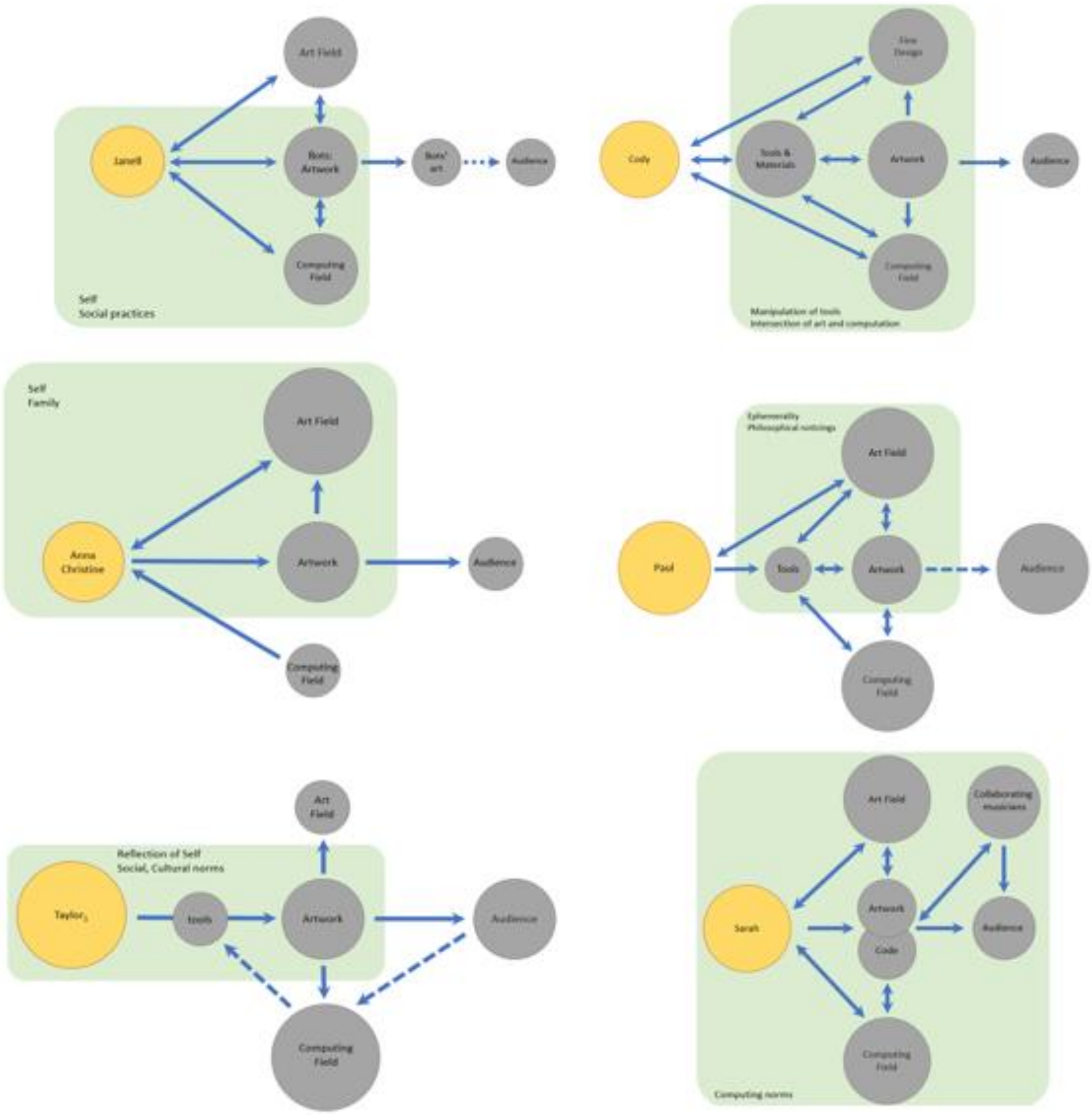


**Figure 65 - Artists that are characterized as having deeper engagement with computational tools, as highlighted by left-alignment of the dialogic threads element in their computational art ecologies.**

*Engagement with Computational Tools*

Artists that are characterized as having a deeper engagement with computational tools are observed through computational art ecologies with dialogic thread elements that orient towards the left side of the ecology. Janell, Anna Christine, Taylor[1], Cody, Paul, and Sarah all fall within this characterization of a deeper engagement with computational tools, as reflected in their ecologies (see Figure 65). It is important to note, those that have dialogic threads that frame central nodes or the complete ecology, were characterized as falling to either side of the spectrum based on interpretations of their case studies. With the current sample, there isn't enough variation across the spectrum to tease apart meaningful characteristics with individuals who fall in between. However, those that span categories tend to leverage practices across types of tool use.

Artists within this category expressed expertise or desire to learn the inner mechanics or functioning of the computational tools that they leveraged throughout their artistic practice. Artists on this side of the spectrum often explore affordances of computational tools for their practice and may engage in knowledge building that goes further than what is necessary to complete a given work of art. For some, this entails creating new computational tools or extending, modifying, or subverting existing tools. For others, this means deeply exploring and leveraging computational tools within their practice. This approach to integrating computation in practice is exemplified by perspectives from Cody James Norman and Paul Catanese. Cody's case highlights the importance of expertise and close personal relationships with computational tools leveraged in practice. With these, he extends the possibilities and practices of 3D printing,

> *"[this practice] is most exciting for me because this technology is still in its infancy and people are doing things with it, but there's an opportunity to do something that's compelling and it hasn't been done before. I think that's the most exciting thing about 3D printing to me is that there's still a lot of room to do*

> *weird stuff that somebody else hasn't done before. It's the forefront of the avant-garde of 3d printing."*

For artists, computational tools stray from the conventions associated with centuries of artistic practice. While artistic sentiment and schools of thought remain, there is great freedom in exploring the application and potential of these computational tools for art. Moreover, artists reflect on the benefits of approaching these tools as relative outsiders to the computing field, as they can overlook conventions in computational practice as well. While Paul also extends the boundaries of practice as was reflected by Cody, he does so to explore philosophical questions and ponderings about the world and how we collectively experience it, "Some poetry occurs to me, some meaning some way of twisting or pivoting a technology occurs to me as a way to make a thing to notice… and I tried to arrange them and give people a perspective". Importantly, Paul also spoke on the role of computational knowledge and expertise in the art practice. After explaining building expertise in computational printmaking, he reflected, "maybe sometimes knowing how it works isn't the best, you know? Maybe knowing too much stops you from asking the actual questions that ought to be answered". As other artists have commented on the tension they've felt between artistic and computational epistemologies, these varying levels of expertise and perspectives at the intersection will only help to expand the field's use of computation and disrupt normative approaches across both fields. As was observed throughout the sample of artists, knowledge building is often self-directed within computational arts. Varying levels of expertise is seen not as a limitation but a way to introduce important perspectives on computation and the integration of computation in arts and other fields.

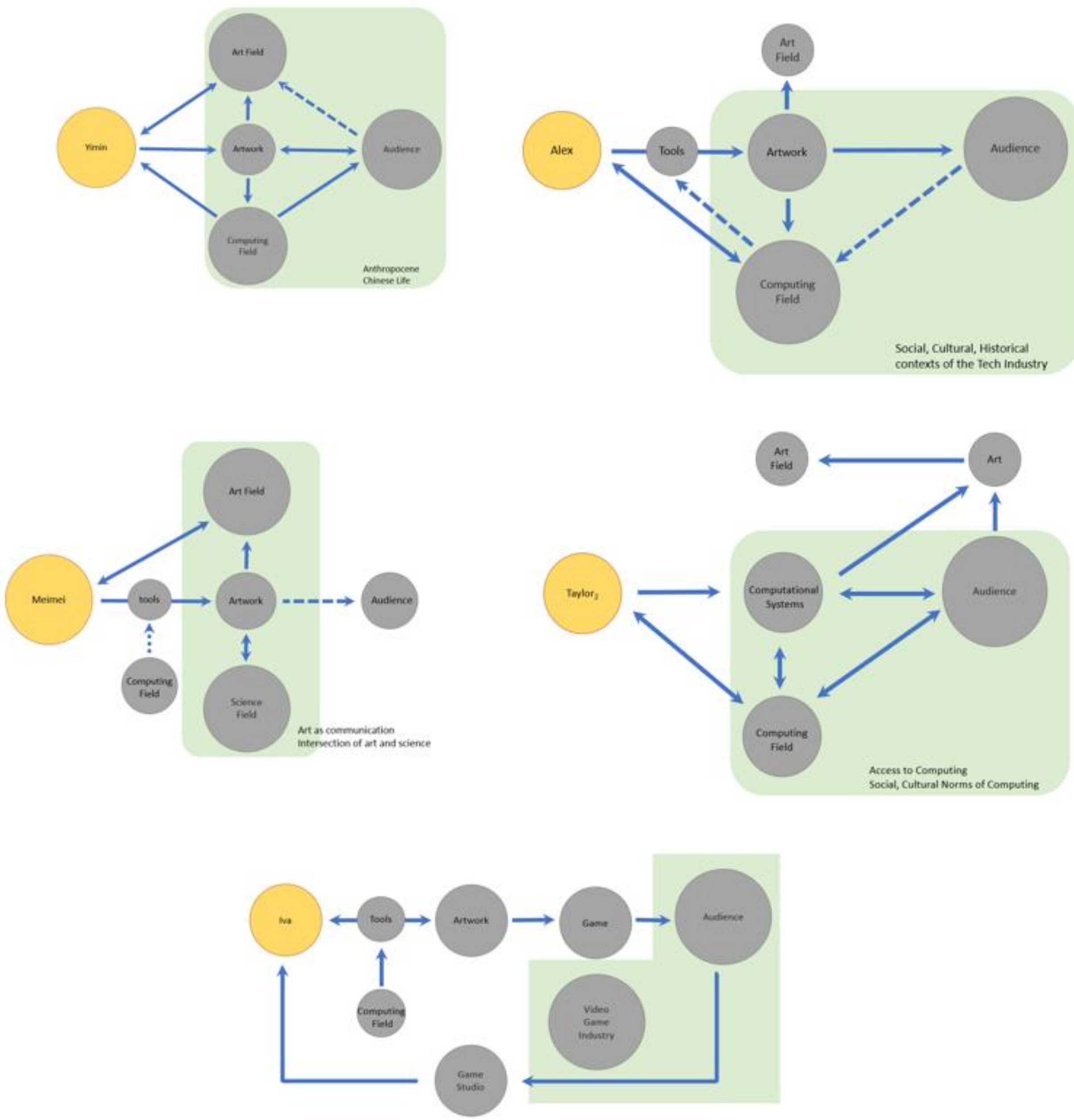


**Figure 66 - Artists that are characterized as exploring applications of computational tools, as highlighted by the right- alignment of the dialogic threads element in their computational art ecologies.**

*Application of Computational Tools*

Artists that are characterized as exploring the application of computational tools are observed through computational art ecologies with dialogic thread elements that orient towards the right side of the ecology. Alex, Iva, Meimei, Taylor$_2$, and Yimin all fall within this characterization of exploring the application of computational tools, as reflected in their ecologies (see Figure 66). Again, artists that fell in the center of the spectrum have been characterized at either end based on their practice. For application of computational tools, Meimei has the only centrally oriented ecology and she has been characterized as leaning towards this end of the spectrum due to her occasional computational tool use, reflected by the dashed link between the computing field and the tools node. Artists within this category expressed a general interest in computational tools and technology in their practice but didn't seek expertise in the tools or computational fields. They often described the benefits of leveraging computation in their practice as benefiting new forms of communication or interaction with the audience. They also broadly reflected on the necessity of using technology to comment on social issues in the increasingly technological world. More often, artists in this category engaged in 'just-in-time' learning where they explored online resources to gain enough knowledge about the tools to apply them to achieve a desired outcome in their practice. Computational learning often took place within the creation of a new piece of art. Moreover, many of the artists in this category reflected that they needed to adjust their artistic vision to align with the constraints of technology.

This approach to integrating computational tools in practice is exemplified by perspectives from Alex and Meimei Song. Alex is critical of the use of computation in her work, expressing that the computational elements should support the narrative of her art without overshadowing it. She describes that when her art practice focuses too much on debugging and problem-solving or researching computational elements, she pauses to consider if the computation is the right choice for that piece of art. She expressed that technology can start conversations around the tech industry or computational field, "I do think, with the example of using the mask, I could've made that mask as a sculpture, but … using the machine learning and

3D printing like that was to open a discussion of the technology… there are spaces where it seems important to use technology in order to have the discussion around it". Other artist who are characterized at this end of the computational tool use spectrum express similar approaches to integrating technology, seeking to use it to engage the audience in discussion, share experiences, or more immersive experiences. Meimei expressed another common concern held by this subset of artists concerning using computational tools. She perceives the need to have expertise to manipulate tools or apply tools in the ways she imagines, however she wanted to maintain her non-computational thought processes. She reflected,

> *"I don't think the way a computer programmers think when I do coding, so it's hard to get used to the thought process and but to the end of the day, I just want to have the freedom to play around things. But, I feel like you have to reach certain maturity in terms of skill to be able to do that. And still that doesn't, to me, it doesn't seem as free as if you were using a more traditional medium, like a piece of clay or, you know, like a paint brush. And so I think I have to still adjust my mindset a little bit and expect something that's more realistic in terms of working with technology."*

Others at this end of the spectrum expressed feeling dissonance between artistic and computational epistemologies inherent at the intersection of art and computing fields. Regardless of these differences, these artists uniquely apply these computational tools to deepen their artistic practice. Moreover, these artists explored the implications of computation on the experience of the audience or on society more broadly.

**Computational Community**

Another form of computational participation is represented by the communities or fields in which artists orient towards as they create their artwork. The case studies revealed a range of experiences and relationships with art and computing fields across artists. All of the artists in the sample reflected that art and/or computing were central to their early development in life. However, this sample is limited in the diversity of childhood experiences expressed by artists, namely most within the sample expressed informal and formal training in the arts that eventually lead them into computational experience later in life. As is highlighted by the history of computer art, traditionally the field has attracted computer scientists towards art in addition to artists towards computer science (Leavitt, 1976). Despite early experiences, each artist situated themselves in relation to these two fields. As was described in the methodology chapter, the orientation to these fields is captured in the structure of the *computational art ecology*. While the size of the nodes and the links between these nodes highlight the experiences and interactions with art and computing fields, for the purpose of this dissertation, we examine the horizontal orientation of the dialogic threads element in each ecology.

The horizonal orientation of this element reflects a spectrum of how artists use computation to engage in and speak to certain communities. This ranges from a greater focus on engaging in dialogue with the art field (top), the computing field (bottom), both fields (top to bottom), or neither (central) (see Figure 67). Broadly, this spectrum reflects the ways in which artists use computation to engage in and across fields. It is important to note that these categories reflect the field in which the artists situate themselves more deeply. Each artist has experience and exposure to art and computing fields throughout their practice and their personal histories. This category reflects the intent of artists to engage in dialogue with those from certain communities and fields. Below, each category will be outlined and situated in relation to artists within this study.

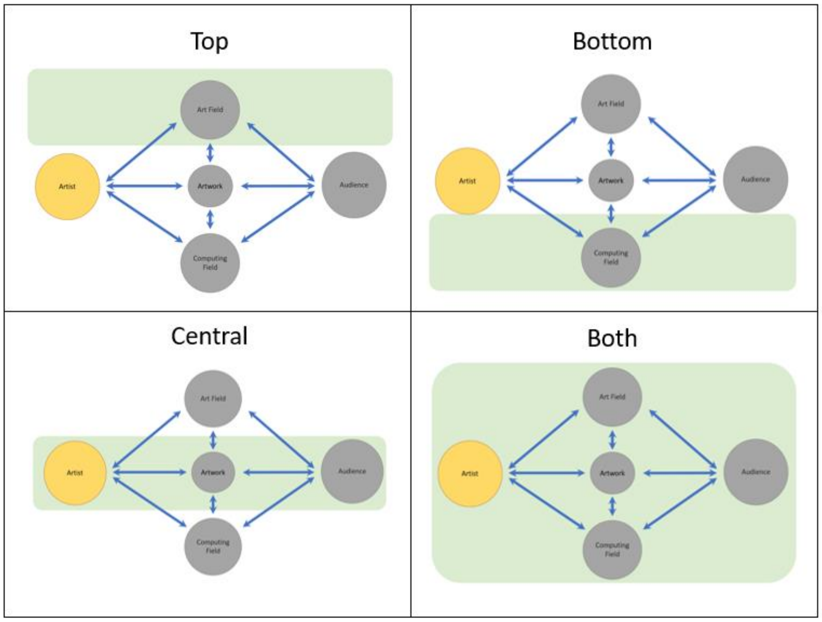


**Figure 67 - The spectrum of horizontal orientations for the dialogic threads element from top to bottom of the ecology.**

*Engagement in the Art Field*

Artists that express the intent to engage more deeply with the art field or art communities as they practice and produce art are characterized by a top-oriented dialogic threads element. Anna Christine Sands and Paul Catanese are characterized as more deeply engaging in the art field (see Figure 68). These two artists situate their practice in histories of art and tech-based art. While they engage in computational practice, they express limited intent towards attracting those from computing fields. Both have strong conceptions of the computational art genres. Anna Christine situates herself within the glitch art and Art & Technology genres. Paul defines himself as a hybrid media artist, a way of situating himself in relation to the broader landscape of art genres while positioning himself outside of any concrete school of thought. Both expressed the use of computation to advance their artistic visions.

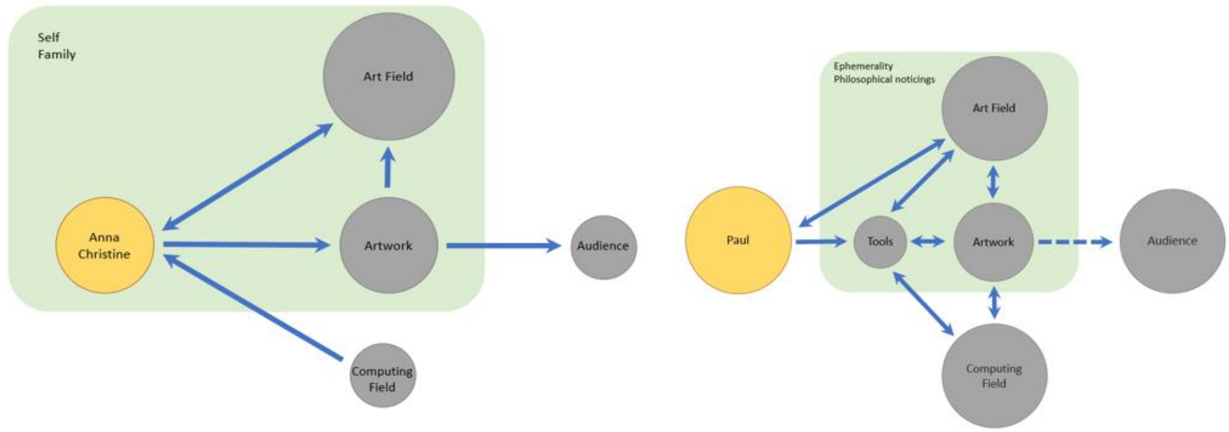


**Figure 68 - Artists that are characterized as having deeper engagement with the art field as captured in the alignment of the dialogic threads element in the top of their computational art ecologies.**

*Engagement with the Computing Field*

Artists that express the intent to engage more deeply with the computing field or computing communities as they practice and produce art are characterized by a bottom-oriented dialogic threads element. Janell Baxter, Iva Bolig, Alex, and Taylor Hokanson's computational system practice all fall under this category of engagement (see Figure 69). These four artists situate their practice in terms of computational communities or fields. The distinction between Alex and Janell has been explored in depth in chapter 4; again, both engage in commentary on humanistic approaches and concerns to computing but leverage computational tools in differing ways. Iva and Taylor are unique, as both fall outside of traditional fine art practice. Both are focused on understanding and extending computational systems to create new experiences for their audiences. Taylor leverages his artistic knowledge and knowledge of the maker community to create new computational systems that enable his audience to express themselves with accessible computational tools. Iva leverages knowledge about software and computational design to efficiently create artistic elements for videogames. All four artists express intent towards engaging computational communities in dialogue or engaging in dialogue about computational themes.

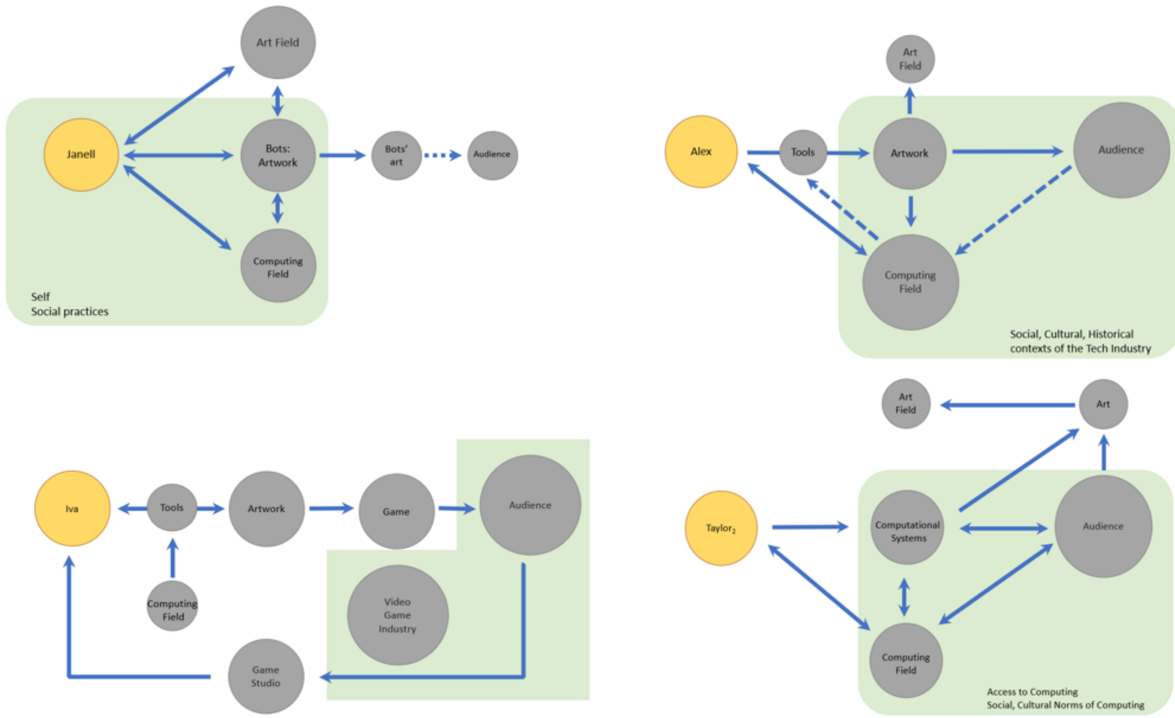


**Figure 69 - Artists that are characterized as having deeper engagement with the computing field as captured in the alignment of the dialogic threads element in the bottom of their computational art ecologies.**

*Engagement across Art and Computing Fields*

Artists that reflect the intent to engage more deeply with both art and computing fields and communities as they practice and produce art are characterized by a dialogic threads element across the top and bottom of their computational art ecologies. Cody James Norman, Meimei Song, Sarah Groff Hennigh-Palermo, and Yimin Zheng reflect this engagement across both fields (see Figure 70). It is important to note, Meimei's community engagement is situated across art and science fields with computation as a medium of expression mirroring the integration of technology in science and society. Artists within this category position their artwork and practice as at the intersection of fields and seek to engage in dialogue with both. They engage in ongoing learning in both fields. Cody and Sarah both reflect art forms that emerge from the full integration of art and computation; their art forms would not be possible without the role of computation. Meimei and Yimin both engage in computational practice and themes, particularly about the Anthroprocene, or the role human activity on the climate and the environment.

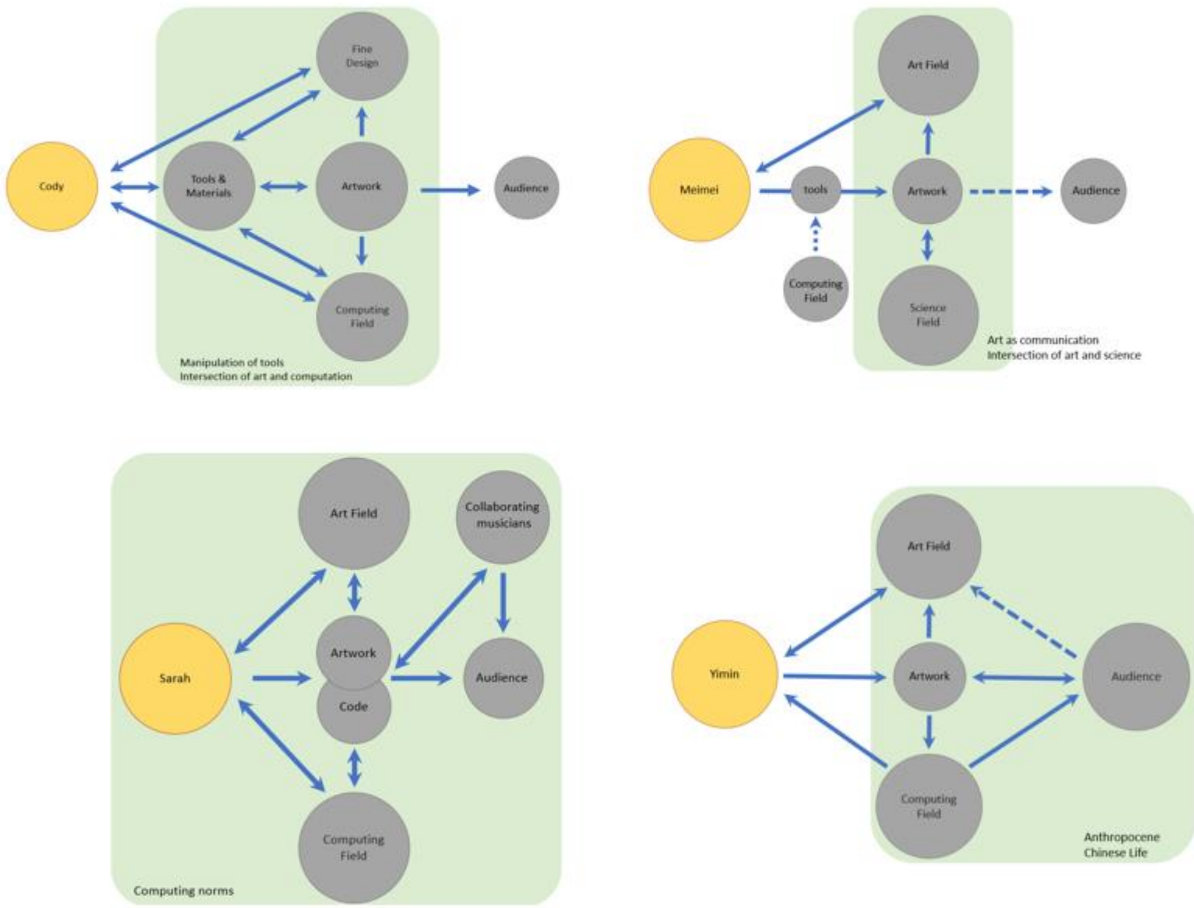


**Figure 70 - Artists that are characterized as having deep engagement with both art and computing fields as captured in the alignment of the dialogic threads element across the top and bottom of their computational art ecologies.**

As technology is highly integrated in human life and culture, their work focuses on technological themes and leverages computation to deeply engage in conversation about it. However, both expressed hesitation about how they perceive the role of computation in their work. All four artists within this category highlight unique computational practice that seeks to engage both fields in dialogue.

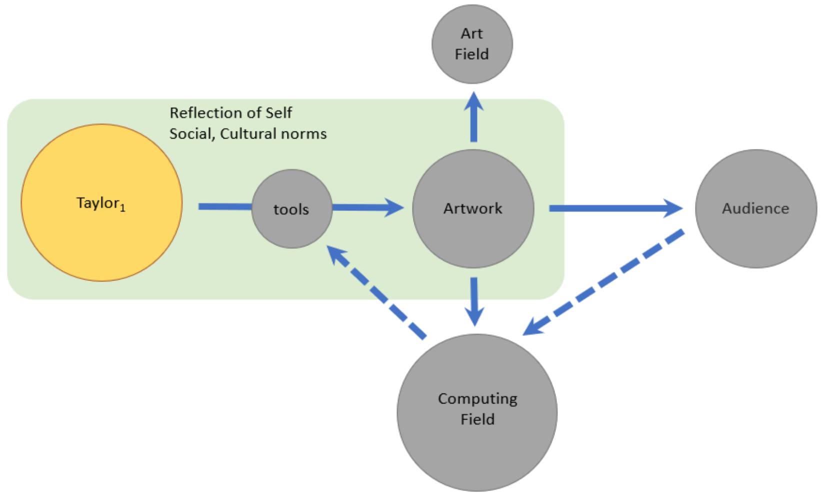


**Figure 71 - Artists that are characterized as detached from communities as captured in the alignment of the dialogic threads element in the center of their computational art ecologies.**

*Detachment from Communities*

Artists that express detachment from both fields as they practice and produce art are characterized by a centrally oriented dialogic threads element. Within this sample, only Taylor Hokanson's more artistic practice falls within this category (see Figure 71). Again, Taylor is the only artist who characterized himself as having two distinct practices, one considered more artistic and one focused on the development of creative computational systems. He expressed hesitation at characterizing himself as an artist, distancing himself from traditional art practice. When pushed to explore his more traditional artistic practice, he described the purpose as expressing himself and reflecting his experience as a large man. It is important to note that this characterization does not mean that Taylor has had no interactions with art and computing fields. As he reflected, he has had formal training in the arts and in tech-based or computational art fields. This characterization reflects Taylor's disinterest in engaging in active dialogue with art and computing fields and communities when creating more traditional art pieces. Future work will explore this category to better understand the computational art practice of those who are detached from art and computing communities and fields.

In this section, computational participation was characterized for artists based on the structural differences in their computational art ecologies. The orientation of the dialogic threads element conveys types of engagement with computational tool use and computational communities. These are building blocks in more thoroughly capturing the rich computational engagement across the diverse field of computational arts. In the following section, the intent of the artists will be characterized based on common themes identified in this sample of artists.

## Intent in Computational Arts

In the previous section, general forms of computational participation were explored through structural differences in artists' *computational art ecologies*. Across each category of participation, the intent of the artist was used to further situate their engagement with tools and with communities. This artistic intent is a vital component to understanding and characterizing computational artists. Artistic practice within each category can appear very different from others within the same category due to the range of computational intent. In order to characterize common themes of computational intent across artists, the expressed motivations, goals, and intents of artistic practice were emergently coded across all artists then collapsed into common themes. These emerged from characterization of cases, rather than looking at the structures of the ecologies explicitly. From this coding, five types of computational intent were identified: 1) *computational expression*, 2) *computational inquiry*, 3) *computational connection*, 4) *computational critique*, and 5) *computational subversion*. Artists' general practice was characterized using these themes. It is important to note that artists may approach their practice with multiple intents, as such, some artists are coded with multiple themes. Below, each computational intent will be defined and situated within the practice of artists.

### Computational Expression

Computational expression entails the creation of art that focuses on communicating and sharing ideas or experiences through computational tools or systems. Seven of the artists' (Paul, Cody, Taylor, Janell, Anna Christine, Meimei, Yimin, and Iva) practice within the sample falls under the theme of computational expression. While this category may appear to represent all art, as art is expressive in nature, *computational expression* focuses on the intent of leveraging these computational systems to create a shared experience, idea, or feeling. Sarah Groff Hennigh-Palermo's perspective on art exemplifies this theme. She described the magic of art in communicating and immersing the audience in a new experience. As Sarah expressed, "the thing that's interesting to me about [art] is the way you can access states and share them with other people in ways that don't involve talking to people… And it's a sort of falling away of time and feeling connected to other people in this attenuated, threaded fundamental way… like, 'we have access to some universal that makes sense to all of us". Others mirrored this sentiment in their interviews, reflecting that computational tools allow them to make shared magic or shared experiences more powerful for the audience.

**Computational Inquiry**

Computational inquiry entails the creation of art that focuses on exploring phenomena or experiences related to computational tools or systems. Paul Catanese, Cody James Norman, Janell Baxter, and Taylor Hokanson are characterized as engaging in computational inquiry in their artistic practice. These artists explore or apply computational tools to gain deeper understanding or new perspectives on the world around them. Paul, Cody, and Taylor describe their practice using language that reflects their deeply inquisitive practices. All three engage in artistic experimentation that they use to refine their computational and theoretical perspectives in art and computing. Additionally, all three build diverse collaborative relationships with artists and computer scientists that allow them to extend their thinking with partners in practice and thought. Janell's inquiry is more internalized. Her practice explores personal questions that help her work through negative experiences and conceptions about society. All four artists use computation to deepen their inquiry, often using computation to explore new perspectives or lenses on the world.

**Computational Connection**

Computational connection entails the creation art that focuses on building or breaking relationships related to computational tools or systems. Taylor Hokanson, Yimin Zheng, and Iva Bolig are characterized as engaging in computational connection in their artistic practice. These artists view computation as a powerful tool for building or breaking relationships. Taylor constructs computational systems that supports community growth within computing and artistic fields. Moreover, his artistic practice focused on building computational tools intends to showcase new interactions or relationships that the audience can have with computation. For example, his sledge-hammer keyboard changes the physical relationship between a user and the keyboard in addition to highlighting the impact of actions within those systems. In another approach, Yimin seeks to computationally save the community and relationship to the city and region where she was raised in China. By recording and giving life to the stories of those from her home town within virtual reality worlds, she supports the audience in building relationships to the people and the region. Moreover, she maintains the collective history and relationships of those individuals she interviewed. Finally, Iva's art goes into the design of games that are intended to encourage community engagement. Broadly, artists within this category orient towards using computation in their practice to foster or break relationships and community.

**Computational Critique**

Computational critique entails the creation of art that focuses on evaluating or critiquing computational tools or systems. Alex, Meimei Song, and Janell Baxter are characterized as engaging in computational critique in their practice. Alex's practice is strongly oriented towards critiquing the technology industry and colonial histories related to the culture and evolution of technologies. Though not all works of her art leverage computation, or "high-tech" elements, all are constructed as commentary on these themes. As was described in the computational subversion section, Meimei's practice seeks to subvert political narratives within science. In addition to this subversion, she critiques political narratives, social engagement with technology, and scientific use of technology as solutions to politically charged environmental issues. These critiques are often non-computational and performative while her subversive practice more often leverages computational elements. Finally, Janell engages in critiques of computer science and programming practices through her creation of "unintelligent" artificially intelligent bots. She implements knowingly biased rules to guide the bots' interpretations of the world around it to highlight the biases that are inherent in artificial intelligence. All three artists engage in practice with computational tools or explore computational themes to critique systems around them.

**Computational Subversion**

Computational subversion reflects the creation of art that focuses on breaking, manipulating, or modifying computational tools or systems. Cody James Norman, Sarah Groff Hennigh, and Meimei Song are characterized as engaging in computational subversion in their art practice. Cody's practice engages in modification and extension of 3D printers and other industrial machines to create new processes for production within fine design. His subversion focuses on the tools in his practice, which he expertly modifies mechanically. Sarah engages in manipulation of computational systems at two levels: tools and community. Her practice adapts technology to create or convey shared states of being. Her larger intent in practicing is to subvert the norms within the computing field by performing and coding live. She perceives her practice as disrupting the norms of the field and encouraging new relationships with computational tools and technology. Finally, Meimei applies computational tools to subvert and modify culture and conceptions within the science field. Her use of computation in art-based research allows Meimei to amplify and twist the narratives within science, particularly regarding politically charged solutions to scientific problems and environmental issues. All three artists integrate computation within their work with the intent to disrupt and modify normative practice, perceptions, or culture.

## Framework of Computational Engagement and Perspectives in the Arts

One of the goals of this dissertation is to develop an initial definition of computational thinking within the arts, specifically the visual arts. I characterize this theoretical contribution as a framework rather than a definition. While the case studies of ten participants reveal rich narratives of computational engagement and nuances in the perspectives of and relationships with computation in the arts, it does not provide the necessary breadth to construct a definition. To construct this framework, we leverage the patterns of computational engagement and computational intent identified through structural patterns in the *computational art ecologies* and the thematic characterization of cases. This framework extends the Constructionist camp of computational thinking (Kafai et al., 2020; Papert, 1980), particularly building on the work of scholars who have constructed definitions of computational thinking based on meaningful practices and perspectives of computing situated within disciplines (Peel et al, 2021; Weintrop et al., 2016; Wilensky et al., 2014).

**Table 2 - Framework of Computational Engagement and Perspectives in the Arts.**

| | | Computational Participation in Art | |
|---|---|---|---|
| | | **Computational Tool Use** | **Computational Community** |
| Computational Intent in Art | **Computational Expression** | Using computation in art to focus on creating, communicating, and sharing ideas or experiences through computational machines, software, or mediums. | Using computation in art to focus on creating, communicating, and sharing ideas or experiences through communities. |
| | **Computational Inquiry** | Using computation in art to focus on the exploration of phenomena or experiences related to computational machines, software, or mediums. | Using computation in art to focus on the exploration of phenomena or experiences related to communities. |
| | **Computational Connection** | Using computation in art to focus on building or breaking relationships related to computational machines, software, or mediums. | Using computation in art to focus on building or breaking relationships related to communities. |
| | **Computational Critique** | Using computation in art to focus on evaluating or critiquing computational machines, software, or mediums. | Using computation in art to focus on evaluating or critiquing communities. |
| | **Computational Subversion** | Using computation in art to focus on breaking, manipulating, or changing computational machines, software, or mediums | Using computation in art to focus on breaking, manipulating, or changing communities |

In order to capture the interacting elements within artistic practice, computational participation and computational intent in art interact to create a matrix of definitions. These definitions, found in table 1, reflect the ways that computational tool use and engagement in computational communities can be applied towards varying artistic intent. As a larger number of participants are interviewed and observed, this matrix can be extended to capture specific practice and perspectives that emerge within the field and situate within the categories of computational engagement and computational intent.

## Discussion

In this chapter, computational participation in the arts was characterized based on computational tool use and orientation towards computational communities. As was shown, the structure of the computational art ecologies can be used to distinguish these types of participation in the arts. As these patterns are emergent and based on the sample of participants, we are limited in generating a larger set of meaningful structural patterns due to the small sample size. We can theorize that patterns related to node size and links position will emerge with a larger sample size. The goal is that deeper thematic patterns can be identified based on interactions between these structural elements. While this is not within the scope of this dissertation study, the diversity of ecologies within this sample highlights the potential of these types of models for characterizing computational art practice, particularly across practices, genres, schools of thought, and fields. To characterize artistic computational practice more deeply, the computational intent of artist was coded using emergent themes from the case studies. Computational intent and computational participation are elements of practice that intersect, expressed by unique artistic practice for individual artist. These categories are used to construct the initial framework of Computational Engagement and Perspectives in the Arts, intended to capture the emergent definition of computational thinking as the perspectives and experiences of a larger population of artists are captured.

In the following chapter, the limitations and future directions for this dissertation will be explored. Final thoughts on the implications for this work will be detailed.

# Chapter 7: Discussion and Conclusion

In this concluding chapter, I reflect on the limitations and ways they can be addressed in future work. Next, I move to summarize findings, synthesizing what we have learned about computational engagement and perspectives in art. Throughout, I make suggestions for future work towards further understanding computational elements in art and how these can be drawn into educational contexts.

## Limitations

As with any large research project, there are a number of limitations to this work. First, as was reflected in the methodology presented in Chapter 3, this study was largely conducted during the COVID19 pandemic and quarantine. While the study design was reshaped to focus on the data most safely collected, the study still suffers from the limitations of virtual interviews and participant communication. The difference between physical interviews and the virtual interviews is highlighted by the depth of information gathered from Cody James Norman, who was the only participant that was able to participate in an in-person interview at his art studio. As was suggested in his case in Chapter 4, the physical environment, particularly his studio, sparked deeper conversations about the nuances of practice, the tools leveraged, and his experimentation with 3D printing. One of Cody's workspaces can be seen in Figure 72 and photographs from another studio of Cody's collaborators and peers can be seen in Figure 73. These spaces give insight into process and practice, and the ways that studio-mates can impact or influence ideation or design. Figure 73 captures a shared artist studio located in Detroit, Michigan. These photos capture the myriad tools, materials, and art present within studio spaces. The studio was a somewhat revolving space for emerging artists, including Thing Thing (Plastic Designers; https://www.thingthing.us/) , Ellen Rutt (Painter; https://www.ellenrutt.com/) , and Patrick Ethen

(Light Artist; https://www.patrickethen.com/), among others, and included a broad spectrum of including plastic design, painting, light art, carpentry and woodworking, and textiles. Interviews and data collection within the artists' personal studio space gives depth into understanding the daily practice and influences on their work. Moreover, it provides opportunities to conduct informal interviews with collaborators or fellow artists within those working spaces to enrich the understanding of the focal artist. Future work, when safe to do so, will shift interviews into the studio once again.


**Figure 72 - A photograph of a portion of Cody James Norman's studio space at Cranbrook.**

Extending the importance of studio visits, the study lacks observation of artistic process during the creation of a work of art. While some of the artists in the sample were able to screenshare to showcase their work and the underlying computational elements, broadly the understanding of process is limited from the interviews. The types of computational practices and perspectives are at a high level, characterizing broader forms of engagement and thinking rather than nuances in interacting with tools or computational ideas. As such, the Framework of Computational Engagement and Perspectives in the Arts, introduced in Chapter 6, is limited in scope, particularly compared to the computational thinking definitions and frameworks that are leveraged in computing education. Future work will incorporate observation of process in order to build a deeper understanding of computational impact and practice at this fine-grained level.

**Figure 73 - Photographs from a shared artist studio located in Detroit, Michigan. These images showcase the myriad tools, materials, and art present within studio spaces.**

Another limitation of the study is the small sample of artists recruited. This number of participants is adequate for the methodological approach of case studies to gain rich understanding the of experiences and perspectives of computational artists. However, this small sample limited the exploration of the computational art ecology methodology and associated pattern identification. The dialogic threads element was able to be used to identify two structural patterns that connected to underlying computational participation. The nuance in structural differences related to nodes or links is lost given the sampling method of breadth over depth in artistic representation. While there are some similarities across nodes and links in the ecologies, the sample is too small to identify any emergent patterns. Moreover, this theory and methodology was developed after interviewing the participants in order to create shared language and structure in analyzing the artists. This methodological approach may have utility in characterizing larger populations of artists, facilitated by surveys with questions targeting elements within the art ecologies. Given the scope of this dissertation, this more in-depth assessment of the computational art ecology methodology will be conducted in future work. With a larger sample and more targeted survey responses, it will be possible to conduct interrater reliability to rest the efficacy of this methodology for other scholars.

Another main limitation deals with the representation of artists within this sample. The recruitment method focused on first finding breadth of mediums and computational tool use. After initial recruitment and interviewing, additional artists were recruited to balance gender and age representation in the study. As the initial recruitment was conducted prior to the start of the COVID19 pandemic, the majority of the schools used to identify potential participants were located in the Midwest, where I could travel to interview and observe. At the start of the pandemic, this was broadened to capture other top universities with computational programs, reaching into the East and West coasts of the US. Despite this, the participants within this dissertation reflect a subset of computational artists that are largely fine artists situated in the Midwest or Eastern coast of the United States. Moreover, most of the participants within the study are students or recent graduates of the program, with only 3 artists who have been practicing for decades. Paul Catanese reflected on the importance of capturing a breadth of ages in participants,

> *"Talk to people from different of different ages… it's super important that you connect with some of the pioneers who are still around. I think that they're just as important to talk to as you know the whippersnappers that are in the mix because there's just -it's hard to describe. There was no going to school for new media art when, even when I went to school. … I'm just, I'm astounded by the audacity of leaping into that void. You know, I think art practice is a leap into the void, but the void that those folks were leaping into is just totally fascinating. It's like, there's no scale. Now we're surrounded. … We are literally surrounded, on a screen. We drown in this technology. And so of course, it's like, 'I'm going to make art with technology'. The idea that you would do that in the fifties or sixties or to dream up machines that didn't exist. It's visionary…That's belief."*

The early computer artists and new media artists were disrupting norms within art and computing fields by exploring the use of computers and other computational tools or technology in their art practice. As Paul expresses, this effort is a "leap into the void" and entails a different approach to thinking about the intersection compared to young artists who grew up surrounded by computational tools. Returning to the sample in the dissertation, I've succeeded in capturing a breadth in tools use and mediums, but I am lacking representing the experiences of a more diverse and representative population of artists. This representation can be captured along education, ethnicity, race, gender, background experiences, types of art (e.g. fine versus applied) among other individual characteristics. These themes were reflected by other artists in addition to Paul; Meimei and Yimin both reflected on their experience interacting with computational art in China and other Southeast Asian countries, indicating that computational art practice is explored and taught in differing ways with differing goals globally. In order to fully capture the landscape of computational art, a larger sample of artists that are recruited more critically is necessary.

Finally, this dissertation highlighted rich pathways into computational art, with artists often reflecting on the impact that their personal backgrounds and identities had on the art they make now. This is particularly evident in the contrast between Janell Baxter, ann haeyoung, and Cody James Norman, whose gender and racial identities shape their perspectives on computation and their approaches to integrating computation in their practices. The abbreviated cases further highlighted the ways that economic standing, birth countries, and family relationships impact the development of artistic and computational interest. After analysis, a body of scholarship around learning ecologies and life paths was introduced to me. These theories apply to the cases and pathways identified in the dissertation and may give insight into further developing the computational art ecology theory. I will briefly introduce the theory of learning ecologies here and suggest ways that it can be used as a lens to more deeply explore this work in the future.

The theory of learning ecologies is built on socio-cultural theories of learning, such as communities of practice or activity theory (Wenger, 1998; Engestrom, 2000), arguing that all learning is socially and culturally constructed and technology can be considered a mediating artifact within this social learning process (Maina & Garcia, 2016; Sangria et al., 2019). As described by Maina and Garcia, learning ecologies was first discussed by Nardi and O'Day (1999) in terms of information flow within local environments or organizations then was expanded by Lemke (2000) to account for temporal and spatial dimensions, or the ways that the past and present interact (2016). More recent studies on learning ecologies or pathways highlight the individual learner's perspective within the ecology. Barron's work with ecologies has highlighted the ways that learning takes place across settings and contexts, identifying ways that these contexts may support or challenge learning, and capturing the role of technology in this process (Barron, 2006; Barron, 2004). Barron's work highlights the ways that intersectional identities impact learning in technological or computational contexts and argues that identities should be more finely detailed in the learning process (2004). These theoretical perspectives focus on the individual experiences and identities of learners. These perspectives can help to further identify ways to capture and represent intersectional identities and experiences of artists who practice at the intersection of art and computing. Moreover, scholars examine the role of technology within these ecologies, identifying the ways that computation connects differently across intersectional identities. Related to this concept, artists within my dissertation, particularly ann haeyoung, expressed nuanced experiences and perspectives with computation. This body of literature may provide new avenues into more critically examining these perspectives on computation and how it connects to practice.

While there are limitations to this study, the results still highlight important elements of computational practice and perspectives in art and can be used to advance understanding of the intersection of art and computation. In the following section, the findings will be synthesized within each chapter and linked to the three research questions guiding this work.

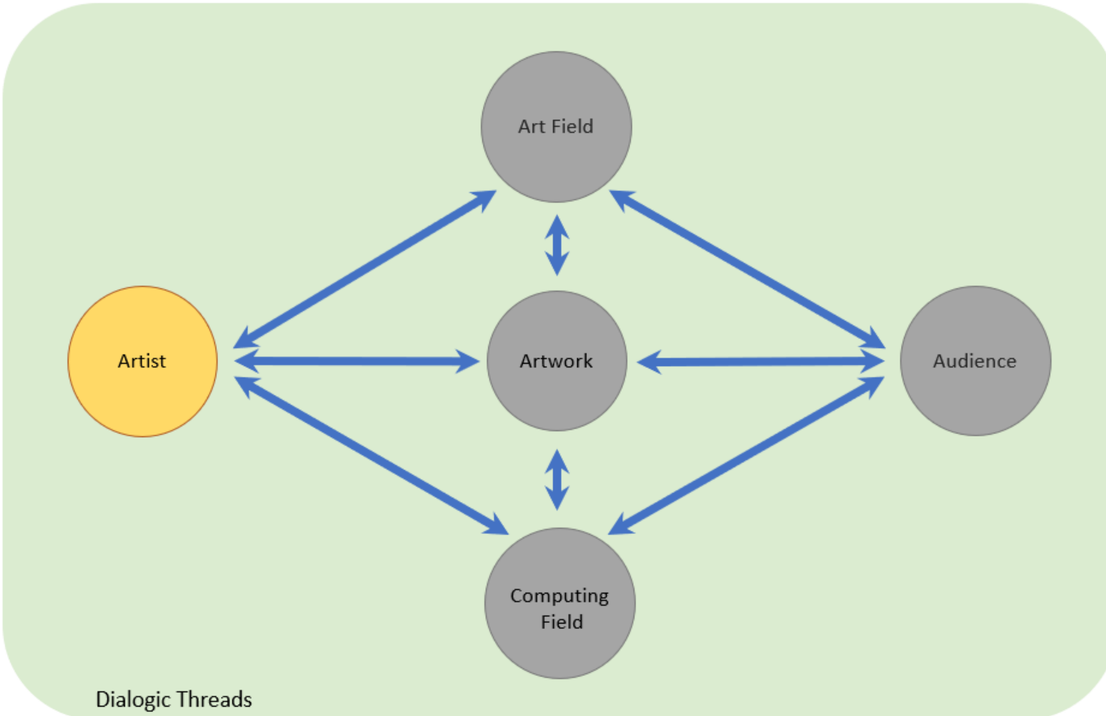


**Figure 74 - Diagram representing the computational art ecology, extending Dewey's theory of the art ecology to a computational context.**

## Synthesizing Results

There are three overarching goals for this dissertation regarding theory, research, and design. The first goal is to develop theory and associated methodology to help holistically capture the perspectives and practices of artists who use computational tools in their art practice. The second goal is to begin to build an understanding of how artists use and conceptualize the use of computational tools in their art practice. The final goal is to produce an evidence-based recommendation of how computational practices and perspectives can be integrated in K12 education.

In Chapter 3, I developed theory and associated methodology to help holistically capture the perspectives and practices of artists who use computational tools in their art practice. I introduced a new theory, *computational art ecologies*, extending Dewey's (1934) theory of art ecologies to incorporate the restructuration of computing in art. To define the theory of computational art ecology, computational art is a dialogic process that entails communication between the artist and the audience through a work or works of art created with computational tools. These computational artworks communicate and cue engagement with social and cultural factors for both the artist and the audience of both the computing field and the art field. This new theory takes account for the restructuration that occurs when computing is introduced to art. The intent of this theory is to visualize and characterize the computational nature of artists' practice while recognizing and representing that practice occurs in a complex system with other participating elements (see Figure 74). Within this chapter, I also introduced an associated methodology to characterize individual artist's unique computational art ecologies. A series of codes were developed to reflect the key elements within the computational art ecologies, including *relationship with computing*, *relationship with art*, *relationship with audience*, and *intersection between art and computing* (see Table 3 - The codebook for the computational art ecology methodological lens.). These are used to code interviews with artists and then interpreted to represent individual artist's computational practice in art in a diagrammatic form. The goal of this theory and associated methodology is to characterize and compare computational experiences across artists. Associated to this goal is a research question intended to assess the utility of this framework: *In what ways does the methodological lens of computational art ecologies add insight into identifying computational perspectives in artists?* This research question was answered with data presented in chapters 4-6, as will be synthesized below.

**Table 3 - The codebook for the computational art ecology methodological lens.**

| Code | Definition | Example topics |
|---|---|---|
| *Relationship with computing* | Detailing the socioemotional or cognitive interactions with technology, computers, computational tools, or computing communities. | • Describing experiences in computer science education<br>• Describing interactions with computers throughout childhood |

| | | |
|---|---|---|
| | | • Describing emotional responses to the tech industry |
| *Relationship with art* | Detailing the socioemotional or cognitive interactions with art, design, creative and artistic practices, or artistic communities that do not entail use of computation. | • Describing experiences in art education<br>• Describing childhood creative practices<br>• Describing engagement with art communities, like exhibits |
| *Relationship with audience* | Detailing the design, reflection, or perception of audience interactions with the artist. | • Describing goals for art that focus on audience engagement<br>• Describing types of interactions or responses received from the audience<br>• Describing uncertainty with addressing the expectations or needs of the audience |
| *Intersection between art and computing* | Detailing the ways in which artistic or creative practices co-exist with practices related to technology, computers, computational tools, or communities. The intersection can represent practice, or affective and cognitive reactions. | • Describing first experiences using a computational tool while creating art<br>• Describing the challenges of marketing computational art<br>• Describing the goals of artistic practice that entail both computing and art |

In Chapter 4, I presented the rich cases of three artists who express differing relationships and experiences to art and computing while leveraging computational tools with differing intents in their practice. Janell Baxter, ann haeyoung, and Cody James Norman highlight the ways that personal experiences and perspectives on technology can influence the integration and use of computational tools in practice. Janell and ann both expressed curiosity and interest in technology and computing but experienced negative social and cultural impacts of those fields. As a result, they chose to challenge and critique the computing field through their artistic practice. Janell integrates her critique into the code of her “unintelligent” artificially intelligent bots that generate artwork, designing them with strong biases in their code that impact how they interpret data or “perceive the world”. Her practice is applied to introspective themes, as she explores social constructs to help overcome personal challenges and traumas. ann expresses her critique in the themes and final products of her art, often creating artwork about the negative impacts of the tech industry or colonialism throughout history. She carefully applies computational tools when their integration aligns with and is backgrounded to the message or theme of a piece of art. Comparatively, Cody expresses a more positive perception of computation, reflecting on the potential good that computational tools can do in the production of fine design of the future. Despite no formal training in computing fields, Cody gains expertise in computational tools and their related fields (like engineering) so that he can subvert their traditional functionality to create new processes for 3D printing. Cody engages in experimentation around the processes and applications of computational tools to explore two primary themes, the restructuration of computing in art and the future of fine design; these themes are backgrounded in Cody's artwork and not explicitly conveyed in the produced objects and vessels.

Chapter 4 additionally showcased the methodology of creating unique computational art ecologies for individual artists. A unique ecology was created for Janell, ann, and Cody that reflected the ways that each engages with significant elements in their art practice, including art and computing fields. Moreover, this process highlights the differing goals of the methodologies implemented in this dissertation. The cases showcase the rich perspectives and experiences related to art and computation, capturing important nuances in artists' practice. The *computational art ecologies* are a simplified version of the artistic practice that abstracts these experiences to highlight general elements and interactions through nodes and links, respectively. While there are many potential approaches to identifying and characterizing patterns in computational practice and engagement in art, this approach is intended to use an ecological perspective on practice to help identify commonalities between artists that may relate to the interaction of elements significant to their practice.

In Chapter 5, I presented summarized cases of the remaining 7 participating artists, presented within the computational art ecology framework. This chapter contributes to answering research question 2: How do artists conceptualize the use of computation in their art? What computational practices and perspectives are leveraged during the creation of computationally influenced visual art? The cases, presented within the computational art ecology framework, document and convey varying conceptualization of computation and the ways that relationships to art and computing fields impact art practice. Moreover, the chapter synthesizes these cases to identify overarching themes of interest for the artists pertaining to the intersection of art and computation.

The seven artists were qualitatively characterized based on their engagement with computational tools as either leveraging computational tools as intended or using computational tools in experimental approaches. Throughout the interviews, artists characterized the art and technology genre or other genres of computational art based on the perceived depth of engagement with computational tools. For some, this was described as low-tech versus high-tech, for others it was described as just-in-time learners versus experts. The characterization presented bridges these ideas, focusing on the intended purpose of computational tools in practice rather than perceived expertise or classification of tools. Like Chapter 4, the artists presented in this chapter highlight the diverse pathways that lead artists to practicing at the intersection of art and computation. To synthesize these cases, I documented common themes expressed by participating artists about computational art. Beyond the characterization of the field based on perceptions of tool use, artists reflected on challenges of using computation in their practice. These challenges included increased time and financial costs of using computational tools, imbalance in artistic versus computational focus while creating, and discordance between artistic and computational epistemologies.

This tension between art and computing fields was expressed as more severe for the female artists in the sample. They reported more negative experiences in computing fields, which aligns with ongoing research on experiences of women and other commonly underrepresented groups in computing fields (Margolis & Fisher, 2006). This theme will need to be more thoroughly studied in future work, as both art and computing fields have histories of bias and discrimination with unknown effects at the intersection. These cases did highlight the associated challenge of finding one's identity and situating practice at this intersection, particularly for those who are exploring new processes and practices within art. It was also noted that artists at the intersection of art and computation often focus on sociocultural or political themes in their work. It is important to reflect here again on the limitations of the sample. The schools of focus for recruitment have programs that focus on more critical and social engagement within their computational art programs. Other schools may orient towards different practices or themes in their programs. This is supported with Yimin Zheng and Meimei Song's reflection on the differences between art programs in the US versus China and other Southeast Asian countries. Again, they characterized the programs in the US as promoting the critical use of computation towards social or political commentary while programs in China and other Southeast Asian countries promote exploration of aesthetic outcomes of computation that will attract new and larger audiences to participate in art.

For these artists, online spaces have become vital to their practice in a variety of ways. Artists who expressed difficulties finding their place or identity at the intersection of art and computing reported that networking and connections built through social media have been integral in advancing their artistic practice. Artists frequently use personal websites and social media sites; particularly Instagram, the photo and video sharing social networking service; to share artwork, commiserate around challenges, document ongoing processes and experiments, advertise events or shows, and sell their artwork. Artists additionally use this space to find and build collaborative relationships with other artists and professionals in other fields related to their practice, including computing fields. Particularly related to the computational elements, artists often leverage online resources, communities, and forums to build knowledge and extend their practice. These online spaces disrupt the traditional dependency that artists historically had on exhibits or showcases for their success and sales. Moreover, these online spaces bring the artist to the forefront compared to the opportunities for interacting with art or artists historically. On social media, artists are expressing their process, sharing their challenges, celebrating their successes, communicating their goals, and highlighting the individual behind the art. These spaces also allow artists to build ongoing relationships with their audiences. Some even reflected that these social platforms allow them to connect with the communities in their cities and support art education or social and cultural growth in those communities.  While the trend of using social media within the art practice is not soloed in computational arts, the artists in the sample reflected that these online spaces are more significant for computational artists because they struggle to find physical communities that welcome or can support their computational practice.

Finally, the 10 cases presented across Chapter 4 and Chapter 5 highlight the varying ways that computation has shifted artistic practice, acting as a restructuration in art (Wilensky, 2020; Wilensky & Papert, 2010).  Artists like Cody James Norman and Taylor Hokanson explicitly reflect on the impact, engaging in experiments to compare computational processes to human processes. Others highlights subtle computational impacts in art, reflecting on dissonance between artistic and computational epistemologies and practices that require creating new epistemologies or approaches for practice. Other artists reflected on the ways that computation has shifted traditional artistic processes, for example, challenges associated with preserving computational art, as many works of art are based on systems that will be lost or discarded as computing fields evolve and time progresses. Others reflected on the duality of the computational art experience; there is great freedom and potential for innovation when applying a protean machine in their practice, particularly as these emerging genres are untethered from traditional artistic norms. However, this freedom comes with isolation and struggle in marking new artistic or computational territory. The restructuration of computing in art can be more thoroughly studied, particularly with observations of practice and studio visits that can highlight the ways that computation has impacted artistic process in addition to epistemologies.

In the literature review, I explored some of the ways that computation acts as a restructuration within art and suggested the potential influences of art within computing. For a subset of the artists in this study, art is viewed as a potentially revolutionary lens to disrupt external fields and their associated norms. ann haeyoung engages in ongoing artistic critique and commentary to expose the systems of oppression within the tech industry. Artists like Janell Baxter and Sarah Groff Hennigh-Palermo engage in personal inquiry and disruptions to computational systems, hoping that these small acts of defiance lead to larger shifts in norms within the computing field. Other artist who engage in art-based research or similar inquiry-based art; like Meimei Song, Taylor Hokanson, and Paul Catanese; imagine a future where art can more significantly inform and create new perspectives within scientific, computational, or social research. Other artists like Cody James Norman and Taylor Hokanson use artistic lenses to extend and subvert the functioning of computational tools and systems, contributing to the expanding the existing computational resources and practices that are used in both art and computational fields. Again, these ideas can be more thoroughly studied in future work by recruiting artists that situate themselves more deeply in computing fields to capture the range of artistic perspectives they bring to computing fields.

In Chapter 6, the structure of the computational art ecologies was used to identify overarching patterns of computational engagement and perspectives in art. This chapter extended the synthesis of themes that emerged across artists within Chapter 5, identifying more concrete categories and spectrums of engagement that can be used to systematically characterize computational artists. The results presented in this chapter addresses all three research questions. In the following section, the results from Chapter 6 will be summarized in relation to each research question.

I will first discuss the implications for research question 1: *In what ways does the methodological lens of computational art ecologies add insight into identifying computational perspectives in artists?* The computational art ecologies were leveraged in exploratory characterization of computational practice and the use of two structural elements, the horizontal and vertical orientation of the dialogic threads element, were successfully used in identifying varying approaches to engaging with computational tools and in computational communities (see Figure 75 - On left, the generic computational art ecology with the vertical orientation of the dialogic threads element highlighted. On right, the generic computational art ecology with the horizontal orientation of the dialogic threads element highlighted.). The vertical orientation reflects the computational tool use, a spectrum of how artists interact with the computational software, machines, and methods within their art practice. This ranges from a focus on engagement with the tools themselves (left) to a focus on the application of tools in new contexts (right). The horizonal orientation of the dialogic threads element captures a spectrum of how artists use computation to engage in and speak to certain communities. This reflects the ways in which computation supports an artist's engagement in and across fields. This ranges from a greater focus on engaging with and speaking to the art field (top), the computing field (bottom), both fields (top to bottom), or neither (central). While only two structural elements were explored, this approach suggests the utility of clustering similar structural patterns within the ecologies to identify underlying computational practice and perspectives. Moreover, this structural approach focuses on the ecology or system of practice rather than isolated elements, incorporating potential interactions with tools, communities, and audiences. The methodological framework applied to cases also provides a structure to help identify the potential impacts that computing has in practice, as relationships and experiences to each field is explored independently before examining the intersection. As this theory and methodology emerged from the analysis of these cases, these methods and analysis are preliminary and will evolve as additional artists are studied. The analysis and characterization of these 10 participating artists shows potential for this methodology but lacks the power to explore emergent patterns across other structural elements, like nodes or links, that varied across artists to a greater degree.

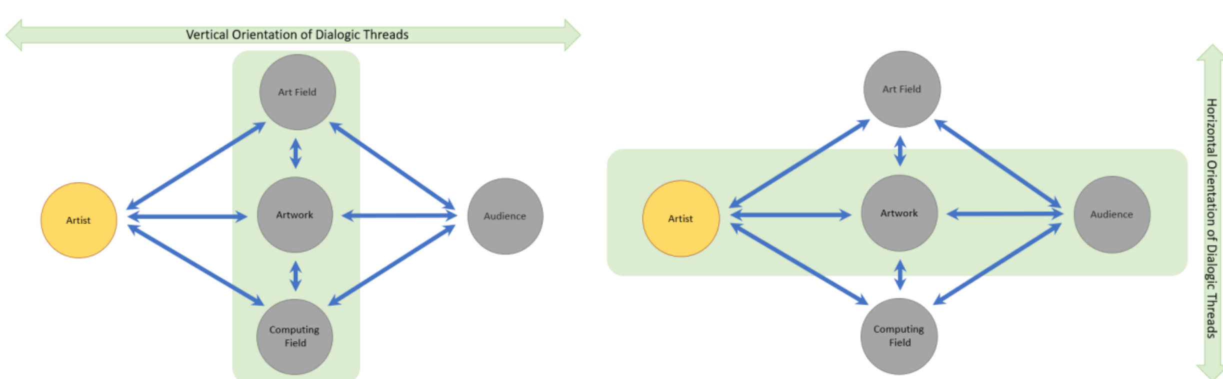

**Figure 75 - On left, the generic computational art ecology with the vertical orientation of the dialogic threads element highlighted. On right, the generic computational art ecology with the horizontal orientation of the dialogic threads element highlighted.**

Chapter 6 contributed further to answering research question 2: *How do artists conceptualize the use of computation in their art? What computational practices and perspectives are leveraged during the creation of computationally influenced visual art?* The spectrums of computational participation provides a window into the ways that artists conceptualize the use of computation in their practice and how they use computation to orient to art and computing fields. In computational tool use, artists (6/11) that are characterized as having a deeper engagement with computational tools are observed through computational art ecologies with dialogic thread elements that orient towards the left side of the ecology. Artists within this category expressed expertise or desire to learn the inner mechanics or functioning of the computational tools that they leveraged throughout their artistic practice. Artists on this side of the spectrum often explore affordances of computational tools for their practice and may engage in knowledge building that goes further than what is necessary to complete a given work of art. At the other side of the spectrum, Artists (5/11) that are characterized as exploring the application of computational tools are observed through computational art ecologies with dialogic thread elements that orient towards the right side of the ecology. Artists within this category expressed a general interest in computational tools and technology in their practice but didn't seek expertise in the tools or computational fields. They often described the benefits of leveraging computation in their practice as benefiting new forms of communication or interaction with the audience. They also broadly reflected on the necessity of using technology to comment on social issues in the increasingly technological world. Again, artists are characterized across these categories as Taylor Hokanson differentiates his more artistic practice from his practice that focuses on computational art systems.

The structure of the computational art ecology additionally highlights the artists' computational community participation. Termed computational community, the horizontal orientation of this element reflects a spectrum of how artists use computation to engage in and speak to certain communities. This ranges from a greater focus on engaging in dialogue with the art field (top), the computing field (bottom), both fields (top to bottom), or neither (central). Within these categories, artists fall under the given categories: engagement in the art field (2/11), engagement in the computing field (4/11), detachment form communities (1/11), and engagement across art and computing (4/11). Again, it is important to note that these are meant to characterize the community that the artist orients most significantly towards and is not meant to communicate a complete absence of engagement in other communities.

Finally, I developed categories to capture the overarching goals and intents expressed by artists. Each artist was characterized with one or more of these intents in computational art. Five types of computational intent were identified: 1) *computational expression*, 2) *computational inquiry*, 3) *computational connection*, 4) *computational critique*, and 5) *computational subversion*. Computational expression entails the creation of art that focuses on communicating and sharing ideas or experiences through computational tools or systems (7/10 artists). Computational inquiry entails the creation of art that focuses on exploring phenomena or experiences related to computational tools or systems (4/10 artists). Computational connection entails the creation art that focuses on building or breaking relationships related to computational tools or systems (3/10 artists). Computational critique entails the creation of art that focuses on evaluating or critiquing computational tools or systems (3/10 artists). Computational subversion reflects the creation of art that focuses on breaking, manipulating, or modifying computational tools or systems (3/10 artists). Artistic intent is a vital component to understanding and characterizing computational artists. Artistic practice related computational tool use and computational community engagement can appear very different from others within the same category due to the impact of computational intent.

| | | **Computational Participation in Art** | |
|---|---|---|---|
| | | **Computational Tool Use** | **Computational Community** |
| **Computational Intent in Art** | **Computational Expression** | Using computation in art to focus on creating, communicating, and sharing ideas or experiences through computational machines, software, or mediums. | Using computation in art to focus on creating, communicating, and sharing ideas or experiences through communities. |
| | **Computational Inquiry** | Using computation in art to focus on the exploration of phenomena or experiences related to computational machines, software, or mediums. | Using computation in art to focus on the exploration of phenomena or experiences related to communities. |
| | **Computational Connection** | Using computation in art to focus on building or breaking relationships related to computational machines, software, or mediums. | Using computation in art to focus on building or breaking relationships related to communities. |
| | **Computational Critique** | Using computation in art to focus on evaluating or critiquing computational machines, software, or mediums. | Using computation in art to focus on evaluating or critiquing communities. |
| | **Computational Subversion** | Using computation in art to focus on breaking, manipulating, or changing computational machines, software, or mediums | Using computation in art to focus on breaking, manipulating, or changing communities |

Finally, Chapter 6 answers the third research question, *what is a preliminary framework for computational art practices that could serve as a basis for educational design at the intersection of art and computing?*, through the creation of an emergent Framework of Computational Engagement and Participation in Art. This framework reflects the computational elements that are significant to artists in their computational practice, as expressed in interviews and translated into diagrammatic form in analysis. This framework combines the spectrums of computational participation, computational tool use and computational communities, with the computational intent in art category in a table (see Table 4 - Framework of Computational Engagement and Perspectives in the Arts.). Each cell reflects a new definition of the integration of computational intent with computational tool use or computational community. This framework is intended to capture emergent practices and perspectives from the small sample while providing structure and space to expand when additional participants are recruited. As this framework develops, it can be translated into the designs of educational initiatives that focus on practice across these elements.

**Table 4 - Framework of Computational Engagement and Perspectives in the Arts.**

## Summary of Contributions

In this dissertation, I have contributed an emergent theory and associated methodology, advancing the identification and characterization of the landscape of artists who leverage computational tools, and theoretical contributions to the study of computational thinking. I have developed the *computational art ecology* theory and associated methodology to help characterize the landscape of computational or technology-based artists. As was reflected in the recent report on Tech-Based Artists released by the National Endowment for the Arts, artists that leverage computational tools or technology in their practice participate in a broad landscape of emergent and overlapping genres of art that are understudied and often intersect with other fields of domains (2021). The *computational art ecology* theory and methodology was developed to capture the breadth of practice and perspectives for artists across schools of thought, genres, and the landscape of computational art. I further contributed to beginning to characterize this landscape of computational art through the rich cases of 10 computational artists. These cases highlight unique practices, perspectives, experiences, and relationships to computation and to art. These cases highlight the rigorous computational practices and epistemologies that emerge in computational art. Finally, I contributed a framework that begins to characterize these computational practices and perspectives that are emergent from this field. This framework advances scholarship around computational thinking, particularly the constructionist camp of scholars who have worked to develop situated definitions of computational thinking across contexts and domains (Kafai et al., 2019; Peel et al., 2021; Weintrop et al., 2016; Wilensky et al., 2014).

There is a long way to go before fully understanding and characterizing computational practices and epistemologies that emerge in art. We are at a beautiful time in history where computation is relatively young and evolving at a rapid pace. Artists are in the process incorporating these computational tools, negotiating what computation should mean for society, and sparking new pathways for computational progress. As such, it will take time to understand the impact of computation in art and the potential impact of art in computation. For now, future work can more thoroughly document the computational practices within art and seek to bring these expressive and creative computational practices into art education and computing education.

# References


Abelson, H. (1982). *Apple Logo*. United States: Byte.

Aho, A. V. (2012). Computation and computational thinking. *The computer journal*, 55 (7), 832–835.

Algorave. (N.D.) “About”. *Algoraves*. Retrieved from: https://algorave.com/about/

Anton, G., Harris, S., Ochsner, A., Rothschild, M., & Squire, K. (2013). Patterns of play: Understanding computational thinking through game design. In Williams, Ochsner, Dietmeier, & Steinkuehler (eds.) *Proceedings of the Games, Learning, and Society Conference (Vol. 3)*. (pp. 61-68).

Anton, G. & Martin, K. (2021). Computational art practice in transdisciplinary contexts. In E. de Vries, Y. Hod, & J. Ahn (Eds.). (Eds.). (2021). *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. Bochum, Germany: International Society of the Learning Sciences. (pp. 1079-1081).

Anton, G., & Wilensky, U. (2019). One size fits all: Designing for socialization in physical computing. In *Proceedings of the 50th ACM Technical Symposium on Computer Science Education*. (pp. 825-831). Association for Computing Machinery, New York, NY, USA.

Anton, G. & Wilensky, U. (2020). Computational art ecologies. In E. de Vries, Y. Hod, & J. Ahn (Eds.). (2021). *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. Bochum, Germany: International Society of the Learning Sciences. (pp. 701-705).

Arastoopour Irgens, G., Dabholkar, S., Bain, C., Woods, P., Hall, K., Swanson, H., Horn, M., & Wilensky, U. (2020). Modeling and Measuring High School Students’ Computational Thinking Practices in Science. *Journal of Science Education and Technology*, 29(1), 137-161.

Armstrong, K. (Eds.) (2015). *Art and disruption*. New Forms Art Press. https://www.academia.edu/18456402/Art_and_Disruption

Art Institute of Chicago (AIC) (2003). The enduring relationship of science and art. *On Science of Art & Technology*. Retrieved from https://archive.artic.edu/sciarttech/2a1.html

Aslan, U., LaGrassa, N., Horn, M., & Wilensky, U. (2020). Code-first learning environments for science education: a design experiment on kinetic molecular theory. In B. Tangney, J. Rowan Byrne & C. Girvan (Eds.). *Proceedings of the 2020 Constructionism Conference*. Dublin, Ireland.

Bain, C., Anton, G., Horn, M., & Wilensky, U. (2020). From “authentic tools” to authenticity: Using CT to enable discovery in statistics classrooms. In E. de Vries, Y. Hod, & J. Ahn (Eds.). (Eds.). (2021). *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. Bochum, Germany: International Society of the Learning Sciences. (pp. 1115-1117).

Bain, C., Anton, G., Horn, M., & Wilensky, U. (2019). Position: Building Blocks for Agent-based Modeling Can Scaffold Computational Thinking Engagement in STEM Classrooms. In *2019 IEEE Blocks and Beyond Workshop (B&B)* (pp. 1-4). IEEE. Bamberger, J. (1996). Turning music theory on its ear Do we hear what we see; Do we see what we say?. *International Journal of Computers for Mathematical Learning, 1*(1), 33-5

Bain, C., & Wilensky, U. (2020, February). Vectors of CT-ification: Integrating Computational Activities in STEM Classrooms. In Proceedings of the 51st ACM Technical Symposium on Computer Science Education (pp. 1361-1361)

Bamberger, J. (2003). The development of intuitive musical understanding: A natural experiment. *Psychology of music*, 31(1), 7-36.

Bamberger, J. S., & Hernandez, A. (2000). *Developing musical intuitions: A project-based introduction to making and understanding music*. Oxford University Press.

Barron, B. (2004). Learning ecologies for technological fluency in a technology-rich community. *Journal of Educational Computing Research, 31*, 1–37.

Barron, B. (2006). Interest and self-sustained learning as catalysts of development: A learning ecology perspective. *Human Development, 49*(4), 193-224.

Barone, T., & Eisner, E. W. (2011). *Arts based research*. Sage.

Barr, V., & Stephenson, C. (2011). Bringing computational thinking to K-12: what is Involved and what is the role of the computer science education community?. *Inroads, 2*(1), 48-54.

Basu, S., Dickes, A., Kinnebrew, J. S., Sengupta, P., & Biswas, G. (2013, May). CTSiM: Computational Thinking Environment for Learning Science through Simulation and Modeling. In *CSEDU* (pp. 369-378).

Beardon, C., Gollifer, S., Rose, C., & Worden, S. (1997). Computer use by artists and designers: some perspectives on two design traditions. *Computers and Design in Context*, The MIT Press.

Becker, H. S. (2008). *Art worlds: updated and expanded*. University of California Press.

Bergstrom, I., & Lotto, R. B. (2015). Code bending: A new creative coding practice. *Leonardo*. MIT Press.

Berland, M. (2016). Making, tinkering, and computational literacy. In K. Peppler, E. Halverson & Y.B. Kafai (Eds.). *Makeology* (pp. 196-205). Routledge.

Bers, M., Flannery, L.P., Kazakoff, E.R., & Sullivan, A. (2014). Computational thinking and tinkering: Exploration of an early childhood robotics curriculum. *Comput. Educ., 72*, 145-157.

Blatt-Gross, C. (2010). Casting the conceptual net: Cognitive possibilities for embracing the social and emotional richness of art education. *Studies in Art Education*, 51 (4), 353-367.

Blau, I. & Benolol, N. (2016). Can designing self-representations through creative computing promote an incremental view of intelligence and enhance creativity among at-risk youth? *Interdisciplinary Journal of e-Skills and Life Long Learning*, 12, 267-278. Retrieved from http://www.informingscience.org/Publications/3577

Blikstein, P. (2014). Digital fabrication and 'making' in education. In J. Walter-Herrmann & C. Büching (Eds.). *FabLab* (pp. 203-222). Transcript Publishers, Bielefeld, Chapter 1, 1-21.

Blikstein, P., Kafai, Y., & Pea, R. (2019). Mike Eisenberg: A One of a Kind Pioneer in the Learning Sciences. *Journal of the Learning Sciences* 28:4-5, 678-684, 28:4-5, 678-684,https://doi.org/10.1080/10508406.2019.1684751

Bollig, I. (2021). "Portfolio". *Iva Bollig*. Retrieved from https://www.artstation.com/ivaivanova

Brown, A. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of Learning Sciences*, *2*(2), 141-178.

Brown, A. R. (2020). *Scratch Music Projects*. Oxford University Press.

Buechley, L. (2018). Celebrating Art, Craft and Computation. In *Proceedings of the Conference on Creativity and Making in Education*. (pp. 1-2). Association for Computing Machinery, New York, NY, USA.

Bureau of Labor Statistics. (2021, September 9). Occupational Projections and worker characteristics. Retrieved September 9. From https://www.bls.gov/emp/tables/occupational-projections-and-characteristics.htm#top

Burnham, J. (1979). Art & Technology, the Panacea that Failed. *Audio Archives of Canada*.

Catanese, P. (2005). *Misplaced Reliquary*. [Online, Browser-Based Artwork, Physical Installation with Gameboy Advance (GBA), Handbook]. Rhizome. Retrieved from http://www.paulcatanese.com/artwork/misplaced/index.html

Catanese, P. (N.D.). *Paul Catanese*. Retrieved from http://www.paulcatanese.com/

Catanese, P. & Geary, A. (2012). *Post-digital printmaking: CNC, traditional and hybrid techniques.* A&C Black, London, UK.

Catanese, P., Jones, D. & Flynn C. (2014). *Stones & Drones*. [Printmaking with Drones]. Paul Catanese. Retrieved from http://www.paulcatanese.com/experiments/stones_drones/index.html

Carbonaro, M., Szafron, D., Cutumisu, M., & Schaeffer, J. (2010). Computer-game construction: A gender-neutral attractor to Computing Science. *Computers & Education*, *55*(3), 1098-1111.

Carlos, McAndrews, C., Schiff, L. & Shaw, A. (2019). Women Artists on the Market. Panel presented at *Talking Galleries*. Barcelona, Spain, Jan 21-22

Catterall, J. S. (2009). *Doing well and doing good by doing art*. Los Angeles, CA: Imagination Group I-Group Books.

Catterall, J. S. (2012). The Arts and Achievement in At-Risk Youth: Findings from Four Longitudinal Studies. Research Report# 55. *National Endowment for the Arts*.

Ceci, S. J., Williams, W. M., & Barnett, S. M. (2009). Women's underrepresentation in science: sociocultural and biological considerations. *Psychological bulletin*, *135*(2), 218.

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. Thousand Oaks, CA: Sage Publications.

Cheryan, S., Drury, B., and Vichayapai, M. (2013). Enduring influence of stereo- typical computer science role models on women's academic aspirations. *Psychology of Women Quarterly(37)*,72–79.

Clark, B., & Button, C. (2011). Sustainability transdisciplinary education model: Interface of arts, science, and community (STEM). *International Journal of Sustainability in Higher Education*, *12*(1), 41–54.

Clifford, M. & Waldorf, S. (2017, August 21). 5 Cutting-edge innovations in art history tech. *The Iris*. Retrieved from https://blogs.getty.edu/iris/5-cutting-edge-innovations-in-art-history-tech/

Cohen, H. (1994). The further exploits of AARON, painter. *Stanford Humanities Review*

College Board. (2017). Program summary report 2017. Retrieved from https://research.collegeboard.org/programs/ap/data/participation/ap-2017

Crutzen, P. J. & Stoermer, E.F. (2000). The "Anthropocene." *Global Change Newsletter* (41): 17–18.

Dabholkar, S., Anton, G. & Wilensky, U. (2018) GenEvo - An emergent systems microworld for model- based scientific inquiry in the context of genetics and evolution. In J. Kay & R. Luckin (Eds.). *Proceedings of the 13th International Conference for the Learning Sciences (ICLS),* London, UK

Dabholkar, S., Arastoopour Irgens, G., Horn, M., & Wilensky, U. (2020). Students' epistemic connections between science inquiry practices and disciplinary ideas in a computational science unit. *Proceedings of the 14th International Conference for the Learning Sciences (ICLS),* Nashville, USA: ICLS.

Dabholkar, S. & Wilensky, U. (2020). Designing computational models as emergent systems microworlds to support learning of scientific inquiry. In K.K. Mashood, T. Sengupta, C. Ursekar, H. Raval & S. Dutta (Eds.). *Proceedings of EpiSTEME8 International Conference to review research in Science, Technology and Mathematics Education*, Mumbai, India.

Davies, P.J.E., Hofrichter, F.F. Jacobs, J., Roberts, A.M. and Simon, D.L. (2014) *Janson's Basic History of Western Art (9th ed.)*. Boston, MA: Pearson

Department for Education and Skills (DEA). (2007). *Gender and Education: The evidence on pupils in England*. Published by the Department for Education and Skills on behalf of HM Government.

Dewey, J. (1934). *Art as experience*. New York: Minton, Balch, and Company.

Diekman, A. B., Clark, E. K., Johnston, A. M., Brown, E. R., & Steinberg, M. (2011). Malleability in communal goals and beliefs influences attraction to stem careers: Evidence for a goal congruity perspective. *Journal of Personality and Social Psychology, 101*(5), 902–918. https://doi.org/10.1037/a0025199

diSessa, A. (2000) *Changing minds: computers, learning, and literacy*. MIT Press, Cambridge

Dreher, T. (2014) *History of Computer Art*. IASLonline.

Dutton, D. (2009). *The art instinct: beauty, pleasure, & human evolution*. Oxford University Press, USA.

Efland, A. (2002). *Art and cognition: Integrating the visual arts in the curriculum*. Teachers College Press.

Eisenberg, M. (2003). Mindstuff: Educational technology beyond the computer. *Convergence*, *9*(2), 29-53

Eisenberg, M., Elumeze, N., MacFerrin, M., & Buechley, L. (2009, June). Children's programming, reconsidered: settings, stuff, and surfaces. In F. Garzotto (Ed.). *Proceedings of the 8th International Conference on Interaction Design and Children* (pp. 1-8). ACM.

Eisenberg, M., & Nishioka, A. (1994, November). HyperGami: A computational system for creating decorated paper constructions. In K. Miura (Ed.). *Proceedings of the Origami Science Meeting*, Otsu, Japan. doi:10.3168/jds.S0022-0302(94)77044-2

Eisner, E. (2002). *The Arts and the Creation of Mind*. Yale University Press.

Engstrom, Y. (2000). Activity theory as a framework for analyzing and redesigning work. *Ergonomics*, *43*(7), 960-974.

Etherington, M. (2008). How girls' achievements in school art are undermined by boys' rejection of the subject: An investigation into gendered attitudes towards art and design education or why schoolboys drop art. British Educational Research Association Annual Conference, Heriot-Watt University, Edinburgh.

Ericson, B. (2019) AP CS Report for 2018. Blog posted on Computing for Everyone. Retrieved from: https://cs4all.home.blog/2019/02/28/ap-cs-report-for-2018/

European Parliamentary Research Service (EPRS) (2019). The historical relationship between artistic activities and technology development. Report for *Panel for the Future of Science and Technology* doi: 10.2861/961315

Feurzeig, W. (2007). Toward a culture of creativity: A personal perspective on Logo's early years, legacy and ongoing potential. In I. Kalaš (Ed.). *Proceedings of EuroLogo*

Freeman, J., Magerko, B., Edwards, D., Mcklin, T., Lee, T., & Moore, R. (2019). EarSketch: engaging broad populations in computing through music. *Communications of the ACM, 62*(9), 78-85.

Frenkel, K. A. (1990). Women and computing. *Communications of the ACM*, *33*(11), 34-46.

Fry, B. & Reas, C. (2001). Processing [Computer Software]

Gaboury, J. (2013). "A queer history of computing". Rhizome. org.

Galloway, D. & Sabisch, C. (Feb./Mar. 1992) Interview with Manfried Mohr. In *NIKE Nr. 41*

Gendreau Chakarov, A., Recker, M., Jacobs, J., Van Horne, K., & Sumner, T. (2019, February). Designing a middle school science curriculum that integrates computational thinking and sensor technology. In Proceedings of the 50th ACM Technical Symposium on Computer Science Education (pp. 818-824)

George A.L. (2019). *Case Studies and Theory Development: The Method of Structured, Focused Comparison*. In: Caldwell D. (eds) Alexander L. George: A Pioneer in Political and Social Sciences. Pioneers in Arts, Humanities, Science, Engineering, Practice, vol 15. Springer, Cham. https://doi.org/10.1007/978-3-319-90772-7_10

Ghanbari, S. (2014). Integration of the arts in STEM: A collective case study of two interdisciplinary university programs.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. New York, NY: Aldine de Gruyter.

Gomes, C. A., Gomes, H., Rego, B., Sousa, B., Loureiro, M., & Rocha, P. (2019, November). Smart City Kids Lab: Creative Computing in Primary School. In *2019 International Symposium on Computers in Education (SIIE)* (pp. 1-6). IEEE.

Graham, B., & Cook, S. (2010). *Rethinking Curating: Art after New Media*. Leonardo Books. The MIT Press.

Grau, O. (2016). New Media Art. *Oxford Research Bibliographies*. DOI: 10.1093/obo/9780199920105-0082

Grimes, W. (2016, May 6). “Harold Cohen, a pioneer of computer-generated art, dies at 87”. The New York Times. Retrieved from https://www.nytimes.com/2016/05/07/arts/design/harold-cohen-a-pioneer-of-computer-generated-art-dies-at-87.html.

Groff Hennigh-Palermo, S. (N.D.b). “Installation views, mixed media, and some full videos of my most recent works”. *Sarah GHP*. Retrieved from https://art.sarahghp.com/works/

Groff Hennigh-Palermo, S. (2016). *Smell-o-gram*, Spring Show, NYU MAGNET 2005 Misplaced Reliquary. Rhizome 2004/05 Commissions Showcase at New Museum of Contemporary Art New York, NY (June 28). Retrieved from https://sarahghp.com/projects/smell-o-gram.html

Groff Hennigh-Palermo, S. (2019). *Jets to Codie: Trails*. Retrieved from https://art.sarahghp.com/contact-sheets/jets-trails

Groff Hennigh-Palermo, S. (2021). *Sarah GHP*. https://art.sarahghp.com/

Grover, S., & Pea, R. (2013). Computational thinking in K–12: A review of the state of the field. *Educational Researcher, 42*(1), 38-43.

Gürer, D. (2002). Pioneering women in computer science. *ACM SIGCSE Bulletin, 34*(2), 175-180.

Gursch, S., Krnjic, V., Urak, K., Herold, M., & Slany, W. (2021, June). How to Encourage girls to code Through Embroidery Patterns?. In E. Pereira, C. Costa, Z. Breda (Eds.). *ICGR 2021 4th International Conference on Gender Research* (p. 122). Academic Conferences and Publishing Limited.

Guzdial, M. (2008). Paving the way for computational thinking. *Communications of the ACM: Education Column. 51*(8), 25-27.

Guzdial M. & Soloway, E. (2003) Computer science is more important than calculus: the challenge of living up to our potential. *SIGCSE Bulletin 35*(2), 5–8

Harrell, D. F. (2013). *Phantasmal media: An approach to imagination, computation, and expression*. MIT Press.

Hechinger Report. (2015). *The push for standards is seeping into arts education*. Retrieved from: http://educationbythenumbers.org/content/arts-education-data_2636/

Henderson, P. B., Cortina, T. J., Hazzan, O., and Wing, J. M. (2007) Computational thinking. In I. Russell, S. Haller, J.D. Dougherty, S. Rodger & G. Lewandowski (Eds.). *Proceedings of the 38th ACM SIGCSE Technical Symposium on Computer Science Education (SIGCSE '07)*, 195–196. New York, NY: ACM Press.

Herz, R. (1997). Introduction: Reflexivity and voice. In R. Hertz (Ed.), *Reflexivity and voice* (pp. vii-xviii). Thousand Oaks, CA: Sage Publications.

Hodges, S., Villar, N., Chen, N., Chugh, T., Qi, J., Nowacka, D., & Kawahara, Y. (2014, April). Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In S. Greenberg, S.E. Hudson, K. Hinckley, M. Ringel Morris & D.R. Olsen Jr. (Eds.). *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* (pp. 1743-1746). Association for Computing Machinery, New York, NY, USA.

Hoh, Y. (2009). Using notable women in environmental engineering to dispel misperceptions of engineers. *Journal of Environmental and Science Education, 4*(2), 117-131.

Hokanson, T. (2021). *Taylor Hokanson*. https://taylorhokanson.com/

Hokanson, T. (2019a). "3D Printing with Light". *Taylor Hokanson*. https://taylorhokanson.com/2019/03/26/3d-printing-with-light/

Hokanson, T. (2019b). *Horror Vacui.* Taylor Hokanson. https://taylorhokanson.com/2019/05/28/horror-vacui-historical-context/

Hokanson, T. (2019c). *Ingot*. [Iron, Stone]. 2019 Hot Metal Artist. Franconia Sculpture Park. Shafer, MN.

Hokanson, T. (2019d). "Ingot". *Taylor Hokanson*. https://taylorhokanson.com/2019/09/17/ingot/

Hokanson, T. (2019e). *Sledgehammer Keyboard* [silicone, wood, computer, projector, Arduino Leonardo]. https://taylorhokanson.com/2019/09/19/sledgehammer-keyboard/

Hokanson, T. (2019f). "Sledgehammer Keyboard". *Taylor Hokanson*. https://taylorhokanson.com/2019/09/19/sledgehammer-keyboard/

Hokanson, T. & Bontrager, N. (2019). *CAAint*. GitHub repository, https://github.com/TaylorHokanson/CAAint

Hokanson, T. & Ray, R. (2017 – present). *Opposable Thumbs*. https://www.opposablepodcast.com/

Hokanson, T. & Reilly, C. (2009). *DIYLILCNC website.* Retrieved from www.diylilcnc.org

Horn, M. S. (2006). *Tangible programming with Quetzal: Opportunities for education* [Doctoral dissertation, Tufts University].

Horn, M. S., Banerjee, A., & West, M. (2020). Music and Coding as an Approach to a Broad-Based Computational Literacy. In *Non-Formal and Informal Science Learning in the ICT Era* (pp. 83-97). Springer, Singapore.

Horn, M., Banerjee, A., West, M., Pinkard, N., Pratt, A., Freeman, J., Magerko, B., & McKlin, T. (2020). TunePad: Engaging learners at the intersection of music and code. In *Proceedings of the 14th International Conference for the Learning Sciences (ICLS)*, Nashville, USA: ICLS.

Horn, M. S., & Wilensky, U. (2012). NetTango [computer software]. Center for Connected Learning and Computer-Based Modeling and the Tangible Interaction Design and Learning Lab, Northwestern University, Evanston, IL.

International Business Machines Corporation (IBM) Media Relations. (2010). "IBM 2010 global CEO study: Creativity selected as most crucial factor for future success". Retrieved from http://www03.ibm.com/press/us/en/pressrelease/31670.wss

Jeffers, C. S. (2009). Within connections: Empathy, mirror neurons, and art education. *Art Education, 62*(2), 18-23.

Kaczmarczyk, L., Dopplick, R., & EP Committee. (2014). *Rebooting the pathway to success: Preparing students for computing workforce needs in the United States*. Education Policy Committee, Association for Computing Machinery. (ACM, New York, 2014). http://pathways. acm. org/ACM_pathways_report. pdf.

Kafai, Y. B. (2016). From computational thinking to computational participation in K--12 education. *Communications of the ACM, 59*(8), 26-27.

Kafai, Y. B., & Harel, I. (1991a). Children's learning through consulting: When mathematical ideas, programming knowledge, instructional design, and playful discourse are intertwined. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 85–110). Norwood, NJ: Ablex

Kafai, Y., Jayathirtha, G., Shaw, M., & Morales-Navarro, L. (2021, June). CodeQuilt: Designing an Hour of Code Activity for Creative and Critical Engagement with Computing. In *Interaction Design and Children* (pp. 573-576).

Kafai, Y. B., Peppler, K. A., Burke, Q., Moore, M., & Glosson, D. (2010, June). Fröbel's forgotten gift: textile construction kits as pathways into play, design and computation. In *Proceedings of the 9th International Conference on Interaction Design and Children*. (pp. 214-217). Association for Computing Machinery, Inc (ACM)

Kafai, Y., Proctor, C., & Lui, D. (2019, July). From theory bias to theory dialogue: Embracing cognitive, situated, and critical framings of computational thinking in k-12 cs education. In *Proceedings of the 2019 ACM Conference on International Computing Education Research.* (pp. 101-109). Association for Computing Machinery, Inc (ACM)

Kahn, K. (1996). ToonTalk: An animated programming environment for children. Journal of Visual Languages and Computing. Kelleher, C., & Pausch, R. (2005) Lowering the barriers to programming: A taxonomy of programming environments and languages for novice programmers. *ACM Computing Surveys, Vol. (37)* 83–137.

Kariuki, P., & Hopkins, B. (2010). The Effects of an Interdisciplinary Program on Secondary Art Students Participating in an Interdisciplinary Chemistry-Art Program and in an Art Only Program. *Online Submission.*

Kelleher, C., & Pausch, R. (2005) Lowering the barriers to programming: A taxonomy of programming environments and languages for novice programmers. *ACM Computing Surveys, Vol. (37)* 83–137.

Knochel, A. D., & Patton, R. M. (2015). If art education then critical digital making: Computational thinking and creative code. *Studies in Art Education, 57*(1), 21-38.

Lampert, N. (2006). Critical thinking dispositions as an outcome of art education. *Studies in Art Education, 47*(3), 215-228.

Leavitt, R. (Ed.). (1976). Artist and computer. Crown Publishing Group (NY).

Lemke, J.L. (2000). Across the scales of time: Artifacts, activities, and meanings in ecosocial systems. *Mind, culture, and activity, 7*(4), 273-290.

Len Lye Foundation (LLF). (2022). "As an Artist in England". *The Len Lye Foundation*. Retrieved from http://www.lenlyefoundation.com/page/as-an-artist-in-england/4/69/

Lenz, M. (2014). "Cataloguing change: Women, art and technology". *V&A Online Journal. Issue No. 6 Summer*. Retrieved from http://www.vam.ac.uk/content/journals/research-journal/issue-no.-6-summer-2014/cataloguing-change-women,-art-and-technology/

Levy, S. T., & Wilensky, U. (2005). An analysis of student patterns of exploration with NetLogo models embedded in the connected chemistry environment. In *The annual meeting of the American Educational Research Association*, Montréal, Quebec, Canada, April (pp. 11-15).

Levy, S. T., & Wilensky, U. (2009). Students' learning with the connected chemistry (CC1) curriculum: Navigating the complexities of the particulate world. *Journal of Science Education and Technology*, *18*(3), 243-254

Lindberg, L., Fields, D. A., & Kafai, Y. B. (2020, May). STEAM maker education: Conceal/reveal of personal, artistic and computational dimensions in high school student projects. In *Frontiers in Education* (Vol. 5, p. 51). Frontiers.

Litts, B. K., Searle, K. A., Brayboy, B. M., & Kafai, Y. B. (2021). Computing for all?: Examining critical biases in computational tools for learning. *British Journal of Educational Technology*, *52*(2), 842-857.

Macfarlane, A., & Martin, G. (2002). Glass: a world history. University of Chicago Press.

Maina, M. & Garcia, I. (2016). Articulating personal pedagogies through learning ecologies. In B. Gros, Kinshuk, & M. Maina (Eds.), *The Future of Ubiquitous Learning: Learning Designs for Emerging Pedagogies* (pp. 73-94). Lecture Notes in Educational Technology. Berlin Heidelberg: Springer. doi: 10.1007/978-3-662-47724-3

Malina, R. F. (2016). Art-science: An annotated bibliography. *Art Journal*, *75*(3) DOI: 10.1080/00043249.2016.1234202

Maloney, J., Burd, L., Kafai, Y., Rusk, N., Silverman, B., & Resnick, M. (2004) Scratch: A sneak preview. In *Proceedings of Creating, Connecting, and Collaborating through Computing*, 104–109

Manaris, B., & Brown, A. R. (2014). *Making music with computers: Creative programming in Python*. CRC Press.

Margolis, J., & Fisher, A. (2003). *Unlocking the clubhouse: Women in computing*. MIT press.

Martin, C. D. 2004. Draw a computer scientist. In *Working Group Reports on Innovation and Technology in Computer Science Education (ITiCSE-WGR'04)*. 11–12.

Martin, F., Mikhak, B., Resnick, M., Silverman, B., & Berg, R. (2000). To mindstorms and beyond: Evolution of a construction kit for magical machines. In *Robots for kids: Exploring new technologies for learning* (pp. 9-33)

Mayo, S. (2007). Implications for art education in the third millennium: Art technology integration. *Art Education, 60*(3), 45-51.

Mayo, S. (2008). The prelude to the millennium: the backstory of digital aesthetics. *The Journal of Aesthetic Education, 42*(1), 100-113.

McKlin, T., McCall, L., Lee, T., Magerko, B., Horn, M., & Freeman, J. (2021, March). Leveraging Prior Computing and Music Experience for Situational Interest Formation. In *Proceedings of the 52nd ACM Technical Symposium on Computer Science Education*. (pp. 928-933). The Association for Computing Machinery.

Menkman, R. (2011). *The Glitch Moment(um).* Margreet Riphagen. Amsterdam, Netherlands. Retrieved from https://networkcultures.org/_uploads/NN%234_RosaMenkman.pdf

Merino-Armero, J. M., González-Calero, J. A., & Cózar-Gutiérrez, R. (2020). Computational thinking in K-12 education. An insight through meta-analysis. *Journal of Research on Technology in Education,* 1-26.

Miles, M. B., Huberman, A. M., & Saldana, J. (2014). *Qualitative data analysis: A methods sourcebook.* Thousand Oaks, CA: Sage Publications.

Mohr, M. (1973). Artist's Statement, London. In *Bulletin of the Computer Arts Society*

Montfort, N., & Fedorova, N. (2012, May). Small-scale systems and computational creativity. In International conference on computational creativity (Vol. 82).

Nake, Frieder. 1971. There Should Be No Computer Art. *The Bulletin of the Computer Arts Society* 18 21

National Endowment for the Arts (NEA) (2015). *The arts in early childhood: Social and emotional benefits of arts participation.* From https://www.arts.gov/sites/default/files/arts-in-early-childhood-dec2015-rev.pdf

National Endowment for the Arts (NEA) (2016, Sept 23). *Why the Arts Matter*. Retrieved from: https://www.arts.gov/art-works/2015/why-arts-matter

National Endowment for the Arts (NEA) (2017). *Survey of Public Participation in the Arts.* From https://www.arts.gov/sites/default/files/US_Patterns_of_Arts_ParticipationRevised.pdf

National Endowment for the Arts (NEA) (2019). *Artists and other cultural workers: A statistical portrait.* From https://www.arts.gov/sites/default/files/Artists_and_Other_Cultural_Workers.pdf

National Endowment for the Arts (NEA) (2021). *Tech as art: Supporting artists who use technology as a creative medium.* Retrieved from https://www.arts.gov/sites/default/files/Tech-as-Art-report-062921.pdf

National Research Council. (2010). *Committee for the Workshops on Computational Thinking: Report of a workshop on the scope and nature of computational thinking*. Washington, DC: National Academies Press.

National Research Council. (2003). *Beyond productivity: Information technology, innovation, and creativity*. National Academies Press.

National Center for Education Statistics (NCES). (2021). Bachelor's degrees conferred by postsecondary institutions, by race/ethnicity and field of study: 2018-19 and 2019-20. Integrated Postsecondary Education Data System (IPEDS). Retrieved from https://nces.ed.gov/programs/digest/d21/tables/dt21_322.30.asp

Oliver, M. (2003). Last night the rain spoke to me. In *What Do We Know: Poems And Prose Poems*. Da Capo Press. Retrieved from http://famouspoetsandpoems.com/poets/mary_oliver/poems/15850

Papert, S. (1972). Teaching children thinking. *Programmed Learning and Educational Technology, 9*(5), 245-255.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* Basic Books, Inc.

Papert, S. (1988). The Conservation of Piaget: The Computer as Grist. *Constructivism in the computer age*, 3-14.

Papert, S. (1994). *The children's machine: Rethinking school in the age of the computer*. Basic books.

Papert, S. (1996). A word for learning. *Constructionism in practice: Designing, thinking and learning in a digital world*, 2-24.

Papert, S. (1999). “Papert on Piaget”. Time magazine, p 105.

Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism*, *36*(2), 1-11.

Papert, S., Solomon, C., Soloway, E., & Spohrer, J. C. (1971). Twenty things to do with a computer. In *Studying the novice programmer* (pp. 3-28). Lawrence Erlbaum Associates, Inc..

Park, N. (2016). Development of computer education program using LOGO Programming and fractals learning for enhancing creativity: Focus on creative problem-solving. *International Journal of u- and e-Service, Science and Technology*, *9*(2), 121-126.

Parsons, M. J. (1987). *How we understand art: A cognitive developmental account of aesthetic experience*. Cambridge University Press.

Payne, W., & Ruthmann, S. A. (2019). Music Making in Scratch: High Floors, Low Ceilings, and Narrow Walls. *Journal of Interactive Technology and Pedagogy*, *15*.

Peel, A., Dabholkar, S., Anton, G., Wu, S., Wilensky, U., & Horn, M. (2020). A Case Study of Teacher Professional Growth Through Co-design and Implementation of Computationally Enriched Biology Units. In *Proceedings of the 14th International Conference for the Learning Sciences (ICLS),* Nashville, USA: ICLS.

Peel, A., Dabholkar, S., Wu, S., Horn, M.S., Wilensky, U. (2021). An Evolving Definition of Computational Thinking in Science and Mathematics Classrooms. In C.K. Looi, B., Wadhwa, V. Dagiene, P. Seow, Y.H. Kee, L.K. Wu (eds.) *Proceedings of the 5th APSCE International Computational Thinking and STEM in Education Conference 2021*, (pp. 119-122).

Peppler, K. (2010). Media arts: Arts education for a digital age. *Teachers College Record, 112*(8), 2118-2153.

Peppler, K., Diazgranados, A., & Warschauer, M. (2010). Game critics: Exploring the role of critique in game-design literacies. *E-learning and Digital Media, 7*(1), 35-48.

Peppler, K. A., & Kafai, Y. B. (2007, July). Collaboration, computation, and creativity: media arts practices in urban youth culture. In J. Uhomoibhi, G. Costagliola, S. Zvacek & B.M. McLaren (Eds.). *Proceedings of the 8th international conference on Computer supported collaborative learning* (pp. 590-592). International Society of the Learning Sciences.

Peppler, K. A., Powell, C. W., Thompson, N., & Catterall, J. (2014, October). Positive impact of arts integration on student academic achievement in English language arts. *The Educational Forum, 78*(4), pp. 364-377). Routledge.

Pereira, L. (2017). "Why is it so difficult to define New Media art?" In Widewalls. Retrieved from: http://www.widewalls.ch/new-media-art-definition/

Perlis, A. (1962). The computer in the university. *Computers and the World of the Future*, M. Greenberger.

Qi, J., & Buechley, L. (2010, January). Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction.* (pp. 121-128). Association for Computing Machinery, New York, NY, USA.

Quemin, A. (2020, December). What Does Developing a Ranking of Leading Contemporary Art Galleries Unveil about the Importance of the National Factor? An Analysis of Art Basel Art Fair. In *Arts 9*(4) (pp. 105). Multidisciplinary Digital Publishing Institute.

Quigley, M., & Payne, W. (2021). Toneblocks: Block-based musical programming. In NIME 2021. https://doi.org/10.21428/92fbeb44.46c0f6ef

Repenning, A., Zurmühle, J., Lamprou, A., & Hug, D. (2020). Computational Music Thinking Patterns: Connecting Music Education with Computer Science Education through the Design of Interactive Notations. In *CSEDU* (1) (pp. 641-652).

Resnick, M., Bruckman, A., & Martin, F. (1996). Pianos not stereos: Creating computational construction kits. *interactions, 3*(5), 40-50.

Resnick, M., Ocko, S., Papert, S. (1991). Lego/Logo: Learning through and about design. In I. Harel, Papert, S. (Ed.), *Constructionism*. Norwood, NJ: Ablex.

Roque, R., Lin, K., & Liuzzi, R. (2016). "I'm Not Just a Mom": Parents Developing Multiple Roles in Creative Computing. In C.K. Looi, J. Polman, U. Cress & P. Reimann (Eds.). *Proceedings of the 12th International Conference of the Learning Sciences (ICLS) 2016, Volume 2*. Singapore: International Society of the Learning Sciences.

Rush, M. (2005). *New media in art*. London: Thames & Hudson.

Rutkin, A. (2015, Nov 20). "Cyborg rose has electric circuits running through polymer veins". *New Scientist*. Retrieved from https://www.newscientist.com/article/dn28528-cyborg-rose-has-electric-circuits-running-through-polymer-veins/

Sage Reference. (2022). "Confessional Art". In R.L. Jackson II & M.A. Hogg (Eds.) *Encyclopedia of Identity*. Retrieved from https://sk.sagepub.com/reference/identity/n45.xml

Sands, A. (2018-2020). *codec play*. Retrieved from https://www.annacsands.com/codecplay

Sands, A. (2021a). *Anna Christine Sands.* https://www.annacsands.com/

Sands, A. (2021b). *HEAVY HEAVY, NO MISTAKES*. Anna Christine Sands. Retrieved from: https://www.annacsands.com/heavy-heavy-no-mistakes-2021

Sangrá, A., Raffaghelli, J.E., & Guitert-Catasús, M. (2019). Learning ecologies through a lens: Ontological, methodological and applicative issues. A systematic review of the literature. *British Journal of Educational Technology*, *0*(0), 1-20. doi:10.1111/bjet.12795

Sapsed, J., & Tschang, F. T. (2014). Art is long, innovation is short: Lessons from the Renaissance and the digital age. *Technological Forecasting and Social Change*, *83*, 127-141.

Schanzer, E., Fisler, K., & Krishnamurthi, S. (2013). Bootstrap: Going beyond programming in after-school computer science. In *SPLASH Education Symposium*.

Schanzer, E., Fisler, K., Krishnamurthi, S., & Felleisen, M. (2015, February). Transferring skills at solving word problems from computing to algebra through Bootstrap. In A. Decker, K. Eiselt, J. Tims & C. Alphonce (Eds.). *Proceedings of the 46th ACM Technical symposium on computer science education* (pp. 616-621). Association for Computing Machinery, New York, NY, USA.

Schneider, D.K., Boufflers, L. & Benetos, K. (2020). Computerized embroidery for identity building. Demo presented at the *9th Annual Conference on Maker Education (FabLearn'20)*. Association for Computing Machinery, New York, NY, USA.

Selick, H. (Director). (1993). The nightmare before Christmas [Film] Touchstone Pictures.

Sendova, E. (2001). *Modelling creative processes in abstract art and music*. na.

Sendova, E., & Chehlarova, T. (2013). Studying fine-art compositions by means of dynamic geometry constructions. *Scientia iuvenis, Book of Scientific Papers, Scientific guarantee: prof. RNDr. Ľubomír Zelenický, CSc. Slovak republic, Constantine the Philosopher University in Nitra*, 495-502.

Sendova, E., & Grkovska, S. (2005). Visual modeling as a motivation for studying mathematics and art. *Educational Media International*, *42*(2), 173-180

Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework. *Education and Information Technologies*, *18*(2), 351-380.

Sengupta, P., Shanahan, M.-C., & Kim, B. (2019). Reimagining STEM Education: Critical, Transdisciplinary, and Embodied Approaches. In P. Sengupta, M.-C. Shanahan, & B. Kim (Eds.), *Critical, Transdisciplinary and Embodied Approaches in STEM Education* (pp. 3–19). Springer International Publishing. https://doi.org/10.1007/978-3-030-29489-2_1

Shaw, A. (2019, Jan 25). Gallery representation dwindles for 'established' female artists, new research finds. *The Art Newspaper*. Retrieved at https://www.theartnewspaper.com/news/gallery-representation-dwindles-for-more-established-female-artists-new-research-finds

Sinclair, N. (2001). The Aesthetic" Is" Relevant. *For the learning of mathematics, 21*(1), 25-32.

Smith, G. W. (2019, June). An Interview with Frieder Nake. In *Arts, 8* (2), p. 69). Multidisciplinary Digital Publishing Institute.

Song, M. (2016). *Domestaponic: Stackable Broomstick Farm*. [broomstick, plexiglass, vinyl tubing, rubber, clay, pebbles, kidney seeds and plants]. Retrieved from https://cargocollective.com/songmeimei/Domestaponic-Stackable-Broomstick-Farm

Song, M. (2017). "Domestaponic: Stackable broomstick farm". *Meimei Song*. Retrieved from https://cargocollective.com/songmeimei/Domestaponic-Stackable-Broomstick-Farm

Song, M. (N.D.a). *Cyber Companion Plant.* [plants, Arduino, circuitry]. Retrieved from https://cargocollective.com/songmeimei/Cyber-Companion-Plant

Song, M. (N.D.b). "Cyber companion plant". *Meimei Song.* Retrieved from https://cargocollective.com/songmeimei/Cyber-Companion-Plant

Strohecker, C. (1999). Construction kits as learning environments. In *Proceedings IEEE International Conference on Multimedia Computing and Systems*, pp. 1030-1031 vol.2, doi: 10.1109/MMCS.1999.778647.

Strohecker, C., & Slaughter, A. (2000a). A Framework for Microworld-style Construction Kits. *TR2000-19, Mitsubishi Electric Research Lab, Cambridge, MA.*

Strohecker, C., & Slaughter, A. (2000b). Kits for learning and a kit for kitmaking. In *CHI'00 Extended Abstracts on Human Factors in Computing Systems*. (pp. 149-150). Association for Computing Machinery, New York, NY, USA.

Swanson, H., Anton, G., Bain, C., Horn, M., Wilensky, U. (2019). *Introducing and assessing computational thinking in the secondary science classroom*. In Computational Thinking Education (pp. 99-117). Springer, Singapore.

Swanson, H., Irgens, G. A., Bain, C., Hall, K., Woods, P., Rogge, C., Horn, M. & Wilensky, U. (2018). Characterizing computational thinking in high school science. In J. Kay & R. Luckin (Eds.). *Proceedings of the 13th International Conference for the Learning Sciences (ICLS),* London, UK.

Tamashiro, M. A., Burd, L., & Roque, R. (2019). Creative Learning Kits for Physical Microworlds: Supporting the making of meaningful projects using low-cost materials. In *Proceedings of the 18th ACM International Conference on Interaction Design and Children* (pp. 514-519). Association for Computing Machinery, New York, NY, USA.

Taylor, G. D. (2014). *When the machine made art: the troubled history of computer art*. Bloomsbury Publishing USA.

Turkle, S., & Papert, S. (1990). Epistemological pluralism: Styles and voices within the computer culture. *Signs: Journal of women in culture and society, 16*(1), 128-157.

Upitis, R. (1989). The craft of composition: Helping children create music with computer tools. *Psychomusicology: A Journal of Research in Music Cognition, 8*(2), 151.

Upitis, R. (2003). Making art, making connections. *Journal of the Canadian Association for Curriculum Studies, 1*(2).

Vossoughi, S., & Bevan, B. (2014). Making and tinkering: A review of the literature. *National Research Council Committee on Out of School Time STEM*, 1-55.

Victoria and Albert Museum (2016). *History of computer art*. Found at: http://www.vam.ac.uk/content/articles/a/computer-art-history/

Wands, B. (2007). *Art of the digital age*. Thames & Hudson.

Wanzer, D. L., McKlin, T., Freeman, J., Magerko, B., & Lee, T. (2020). Promoting intentions to persist in computing: an examination of six years of the EarSketch program. *Computer Science Education*, *30*(4), 394-419.

Warmus, W. (2012). “A brief history of glass”. Art Alliance for Contemporary Glass. From https://contempglass.org/2012-celebration/info/a-brief-history-of-glass

Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. *Journal of Science Education and Technology, 25*(1), 127-147.

Weir, S. (1987). *Cultivating minds: A Logo casebook.* Harper & Row, Publishers, Inc., 10 East 53rd St., New York, NY 10022.

Weir, S. (1989). The computer in schools: Machine as humanizer. *Harvard Educational Review, 59*(1), 61.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity.* New York: Cambridge University Press.

Wilensky, U. (1999). GasLab—An extensible modeling toolkit for connecting micro-and macro-properties of gases. In *Modeling and simulation in science and mathematics education* (pp. 151-178). Springer, New York, NY.

Wilensky, U. (2001). Modeling nature’s emergent patterns with multi-agent languages. In *Proceedings of EuroLogo* (pp. 1-6). Linz, Austria.

Wilensky, U. (2003). Statistical mechanics for secondary school: The GasLab multi-agent modeling toolkit. *International Journal of Computers for Mathematical Learning, 8*. 1-41. Kluwer Academic Publishers, Netherlands.

Wilensky, U. (2020). Restructuration theory and agent-based modeling: Reformulating knowledge domains through computational representations. In N. Holbert, M. Berland, & Y. Kafai (Eds.), *Designing Constructionist Futures: The Art, Theory, and Practice of Learning Designs*. Cambridge, MA: MIT Press.

Wilensky, U., Brady, C. E., & Horn, M. S. (2014). Fostering computational literacy in science classrooms. Communications of the ACM, 57(8), 24-28.

Wilensky, U., & Papert, S. (2010). Restructurations: Reformulations of knowledge disciplines through new representational forms. In Clayson, J. & Kalaš, I. (Eds.). *Constructionism 2010*, Paris, France.

Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, 49(3), 33-35.

Wolz, U., Auschauer, M., & Mayr-Stalder, A. (2019). Code crafting with turtlestitch. In *ACM SIGGRAPH 2019 Studio* (pp. 1-2). Association for Computing Machinery, New York NY, United States.

Wrensch, T., & Eisenberg, M. (1998, November). The programmable hinge: Toward computationally enhanced crafts. *Proceedings of UIST 98* (pp. 89–96). Association for Computing Machinery, New York NY, United States.

Yadav, A., Mayfield, C., Zhou, N., Hambrusch, S., & Korb, J. T. (2014). Computational thinking in elementary and secondary teacher education. *ACM Transactions on Computing Education (TOCE), 14*(1), 1-16. Association for Computing Machinery, New York, NY, United States.

Yang, H., & Zhang, L. (2016). Promoting creative computing: Origin, scope, research and applications. Digital Communications and Networks. doi:10.1016/j.dcan.2016.02.001

Yardi, S., & Bruckman, A. (2007, September). What is computing?: bridging the gap between teenagers' perceptions and graduate students' experiences. In *Proceedings of the third international workshop on Computing education research* (pp. 39-50). Association for Computing Machinery, New York, NY, United States.

Zhang, L. (2017). *Foundations of research in creative computing* [Doctoral dissertation, Bath Spa University].

Zheng, Y. (2020a). *Twin City*. [virtual reality, embodied physical kinetic sculpture, videos, photographs, found objects]. Retrieved from https://www.yiminzheng.com/copy-of-twin-city-2020

Zheng, Y. (2020b). "Twin city". *Yimen Zheng*. Retrieved from https://www.yiminzheng.com/copy-of-twin-city-2020

Zheng, Y. (2016). *Sound of Nature*. [bamboo, bamboo hat, timber, hemp rope]. Retrieved from https://www.yiminzheng.com/sound-of-nature

Zheng, Y. (2016). “Sound of nature”. *Yimin Zheng*. Retrieved from https://www.yiminzheng.com/sound-of-nature

# Appendix A – Semi-structured Interview Protocol

Semi-structured interview

*Participants*: Self-identifying artists engaging in active creation of visual art with use of computational tools and elements

*Length*: Approximately 60-90 minutes

*Location*: Participants' studio or another location of their choosing

**General Introduction**

1. Tell me about yourself. Can you give me a history of how you got here?

**Experiences with art**

2. How and when did you first get interested in art?
3. Have your interests in art been supported by other around you?
4. What formal training do you have in art?
5. What informal training do you have in art?
6. Do you draw on these experiences for how you currently practice? In what ways?

**Experiences with computing**

7. How and when did you first get interested in computing?
8. What formal training do you have in computing?
9. What formal training do you have in computing?
10. What informal training do you have in computing?
11. Do you draw on these experiences for how you currently practice? In what ways?

**Characterizing personal practice**

12. You engage in art and design practice – how would you describe what you do and what you make?
13. What tools and mediums do you use in your practice?
14. What are your goals in creating art?
15. How do the mediums you use help you to accomplish your goals?

**Contrasting traditional and computational practices**

16. What are your goals for creating art with computational tools/mediums?
17. Are there tradeoffs to using traditional or computational tools/mediums in practice?
18. How does your thinking change about art practice when using traditional or computational tools/mediums?
19. How does your process change when using traditional or computational tools/mediums?
20. Could you talk me through the creation of the last piece of art you created?

a. What challenges did you encounter? Related to traditional practices? Related to computational practices?

**Interaction with other Artists/Designers**

1. Can you tell me about how you interact with other artists and designers? How often?
2. How often do you interact with other artists or designers who use computational tools in their work? In what ways?
3. How often do you interact with other artists or designers who use traditional tools in their work? In what ways?
4. Can you describe the communities you interact with around your art practice? Do you feel like you're an active member in these communities?

**Meaning Making**

5. How do you frame/explain your practice to others? Does this change when you're with others who use traditional or computational tools? How does this framing change when you're participating in different communities?
6. Have you experienced any challenges in using the tools/mediums that you do? When does this happen? How do you react or adjust to this?