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# “Weebles wobble but they also commit to lifelong relationships”: teachers’ transdisciplinary learning in computational play

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## Abstract

**Background:** Computational approaches in STEM foster creative extrapolations of ideas that extend the bounds of human perception, processing, and sense-making. Inviting teachers to explore computational approaches in STEM presents opportunities to examine shifting relationships to inquiry that support transdisciplinary learning in their classrooms. Similarly, play has long been acknowledged as activity that supports learners in taking risks, exploring the boundaries and configurations of existing structures, and imagining new possibilities. Yet, play is often overlooked as a crucial element of STEM learning, particularly for adolescents and adults. In this paper, we explore *computational play* as an activity that supports teachers’ transdisciplinary STEM learning. We build from an expansive notion of computational activity that involves jointly co-constructing and co-exploring rule-based systems in conversation with materials, collaborators, and communities to work towards jointly defined goals. We situate computation within STEM-rich making as a playful context for engaging in authentic, creative inquiry. Our research asks *What are the characteristics of play and computation within computational play? And, in what ways does computational play contribute to teachers’ transdisciplinary learning?*

**Results:** Teachers from grades 3–12 participated in a professional learning program that centered playful explorations of materials and tools using computational approaches: making objects based on rules that produce emergent behaviors and iterating on those rules to observe the effects on how the materials behaved. Using a case study and descriptions of the characteristics of computational play, our results show how familiarity of materials and the context of play encouraged teachers to engage in transdisciplinary inquiry, to ask questions about how materials behave, and to renegotiate their own relationships to disciplinary learning as they reflected on their work.

**Conclusions:** We argue computational play is a space of wonderment where iterative conversations with materials create opportunities for learners to author forms of transdisciplinary learning. Our results show how teachers and students can learn together in computational play, and we conclude this work can contribute to ongoing efforts in the design of professional and transdisciplinary learning environments focused on the intersections of materiality, play, and computation.

**Keywords:** Computational STEM, Play, Making, Transdisciplinary, Teacher learning

## Introduction

Meaningful STEM learning involves engaging in inquiry that is authentic to the learner and that reflects disciplinary ways of knowing (Engle & Conant, 2002; Warren et al., 2020). Teaching STEM in integrated ways supports learning that is situated within “real-world” contexts that make STEM disciplinary practices more

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relevant to learners (Honey et al., 2014; Takeuchi et al., 2020), such as in STEM-rich making (Calabrese Barton & Tan, 2018). Increasingly, research on integrated STEM teaching and learning illustrates possibilities for transdisciplinary learning where the representations and practices of different disciplines are mutually supportive of meaningful inquiry (Sengupta et al., 2019; Shanahan et al., 2016). Yet, implementing these approaches in K-12 classrooms remains challenging. Students bring multiple ways of knowing and doing to classrooms (Rosebery et al., 2010), and supporting that heterogeneity requires expansive views of how STEM learning is organized and expressed (Bang & Medin, 2010). In turn, integrated STEM education also requires careful consideration of how to support teachers in classroom implementations (Edelson et al., 1999; Ryoo, 2019). In this paper, we build on growing interest in integrating STEM with computing (STEM+C) in K-12 education (Grover et al., 2020) to explore expansive notions of computation that foster transdisciplinary learning within making contexts.

We focus on the relationships between play and computation and argue that together, they support a reimagining of authentic STEM education (English, 2016; Sengupta et al., 2019). Fostering situated and authentic experiences in classrooms requires that teachers engage in similar forms of inquiry as we envision for students (Windschitl, 2003). As such, we present findings from a professional learning program focused on the integration of STEM and computing. Teachers assumed roles as learners, and engaged in *computational play*, where playful, iterative STEM-rich making surfaced opportunities for transdisciplinary learning. We motivate our research within existing conversations about STEM+computing and transdisciplinary learning, and situate it within literature on how STEM learning can be extended through computation and play. We introduce computational making as a theoretical frame, used in the design of a professional learning model and the analysis of teachers' transdisciplinary learning in STEM-rich making.

## Background and motivation: integrating STEM and computing

Computational approaches to STEM education foster creative extrapolations of ideas and conjectures, supported by technological platforms (Gravel & Wilkerson, 2017; Wilensky & Reisman, 2006; Wilkerson-Jerde et al., 2015) that amplify and extend sense-making<sup>1</sup> (Odden &

Russ, 2019; Rosebery et al., 2016; Warren et al., 2001). Computation extends inquiry in both computer-based approaches (Humphreys, 2004; Wagh et al., 2017) as well as computation with physical objects, like in making activities (Gravel et al., 2022). Inviting teachers to explore computational approaches to making—as authentic, relevant, and transdisciplinary—presents new opportunities to study teachers' relationships to inquiry and how they build learning environments that support students' STEM learning (Ketelhut et al., 2020).

Current research on the integration of STEM and computing (see Lee et al., 2020) focuses primarily on computational thinking (CT) frameworks (Grover & Pea, 2013; Yadav et al., 2016), as the “connecting tissue” of STEM and computing (Martin, 2018). Efforts to define CT relative to different disciplinary goals and practices (Malyn-Smith et al., 2018; Weintrop et al., 2016), have generated interest in “CT skills” (Hadad et al., 2020), computational literacy (diSessa, 2001), and the integration of coding and modeling (Dickes et al., 2020; Irgens et al., 2020). Yet, even within the communities studying CT, leaders call for continued research defining CT and its relationships to different activities. Denning (2017) argued that current frameworks for CT offer relatively “vague definitions” (p. 34) of computing in STEM education. Historically rooted in computer science (Li et al., 2020; Papert, 1980), the current interest in STEM+computing offers opportunities to deepen and expand how computation is defined and understood by exploring its roles relative to other fields. For example, computational thinking may be considered more of a complex experience involving discursive, perspectival, and material experiences when situated within integrated STEM education (Sengupta et al., 2018). We might also further explore the “dynamic and contingent” nature of CT as it occurs in activities not led by researchers nor only within STEM (Wilkerson et al., 2020, p. 267). The implications of an expanded sense of computation and its roles in furthering inquiry are significant for teachers grappling with the integration of computation in STEM classrooms.

One avenue for expanding notions of computation includes examining and designing for the intersection of play and computing, namely through the exploration of game environments (Berland & Lee, 2011; Clark et al., 2015; DeLiema et al., 2019) and through the development of playful computing paradigms (e.g., Gaskins, 2020, 2021; Shapiro & Ahrens, 2016; Shapiro et al., 2017). Playful forms of gaming support learners in discovering and

<sup>1</sup> In this paper, we use the term “sense-making” to reflect the varied, heterogeneous, and everyday practices learners use to “figure something out” (Odden & Russ, 2019, p. 192), and to connect to the literature exploring the ways this term can be used to describe learning. Given the nature of transdisciplinary learning, we concede that meaning-making could be interchangeably used, as play and making can be linked to processing of constructing and revision many different meanings. The intricacies of these distinctions are beyond the

Footnote 1 (continued)

scope of this paper, and we select “sense-making” as a term to remain consistent.

exploring rules, collaborations, and roles within the target domains (Gee, 2003; Holbert & Wilensky, 2014; Richard, 2017; Squire, 2013), often in the pursuit of specific disciplinary learning (Barab et al., 2010). Scholars have more recently extended these findings to explore interactive material computing paradigms specifically designed to encourage playful, domain-specific interactions with technologies, often through artistic domains like music production (Horn et al., 2022; Shapiro & Ahrens, 2016; Shapiro et al., 2017) and computational art production (Gaskins, 2020, 2021). In these paradigms, computational expressions link “body and space to sound and imagery” (Shapiro et al., 2017, p. 52). Bodies and movement become resources for engaging with the computational media (Lee & DuMont, 2010), and aesthetics guide the transformation of materials into expressions (Farris & Sengupta, 2016). These forms of creative computing, or computational action (Tissenbaum et al., 2019), highlight the importance of materials and tools in the relationship between computation and play, which is where we seek to contribute to the conversations about integrating STEM and computation.

Given the broad range of definitions for computation across these research paradigms, it is important to name the flexible, generative definition of computation that we adopt in this work. We introduce the working definition here, and expand on it in the theoretical framing. Following others exploring computation from fields beyond CS (e.g., design, architecture), we view computational activity as defining rules for a system, combining those rules to produce emergent behaviors, and revising the rules and their configurations to assess effects on the system’s behaviors (Knight & Stiny, 2015). Computational work involves jointly co-constructing and co-exploring rule-based systems in conversation with materials, collaborators, and communities to work towards jointly defined goals (Gravel & Wilkerson, 2017). This definition highlights the computational nature of rules, materials, and jointly constructed goals and work, and offers opportunities to expand already rich discussions of computation in STEM. It grounds our examination of the relationships between computation and play, in the collaborative context of STEM-rich making.

This paper examines how teachers engage with the integration of STEM and computation within their own professional contexts. We build on a tradition of research on supporting teachers to integrate disciplinary practices in their classrooms. A significant body of literature in science and mathematics education punctuates the importance of inviting teachers to engage in learning disciplinary knowledge and ways of thinking as instrumental to their professional learning (Blank et al., 2007; Carpenter et al., 1989; Jaber et al., 2018; Li & Anderson, 2020;

Loucks-Horsley et al., 1998; Maeng et al., 2020; Porter et al., 2003). It not only deepens their understanding of critical disciplinary ideas and practices (Grossman et al., 2001; NGSS Lead States, 2013; Shulman, 1986), it also enables them to better understand and hear students’ ideas (Pappas & Tucker-Raymond, 2011; Rosebery et al., 2016; Warren et al., 2001) and it supports development of professional vision (Ball & Hill, 2009; Ball et al., 2008).

Schools remain organized by content area, and there is a push to transform learning in these areas to look more like disciplines (e.g., in mathematics, Boaler, 2002; in engineering, Cunningham & Kelly, 2017; in science, Ford, 2008), with clear emphasis on inquiry, problem-posing and solving, and sense-making practices. We share an interest in fostering meaningful and authentic inquiry, and build on the work of others who call for more integrated STEM learning that fosters *transdisciplinary* learning<sup>2</sup> (Honey et al., 2014; Shanahan et al., 2016; Takeuchi et al., 2020). Transdisciplinary perspectives note the generativity of deeper integration of knowledge-building practices that transcend the boundaries of traditional disciplines (Mejias et al., 2021; Sengupta et al., 2019). Transdisciplinary learning captures the sense-making that learners demonstrate when they are engaged in playful STEM-rich making; where knowledge and practices from science (e.g., understanding phenomena), mathematics (e.g., noticing and defining patterns), engineering (e.g., iterating to optimize material selections), and everyday life are cooperatively applied in sustained inquiry. Making as a playful integration of STEM and computing centers personal, contextual, and material interactions, situating problem-solving and sense-making within the rich heterogeneity of human learning experiences (Rosebery et al., 2010). Transdisciplinary perspectives, thus, support the project to expand the possibilities for integrated STEM and computing for K-12 classrooms. Continued examination of the dynamics and contexts that support teachers in re-making their relationships to disciplinary practice has larger implications for how they re-make their relationships to students and the diverse forms of sense-making, play, and linguistic practice they bring to science learning (Warren & Rosebery, 2011). We examine teachers’ engagements with playful computational approaches to transdisciplinary learning to illuminate possible pathways for re-making relations by

<sup>2</sup> We acknowledge the persistent discussion and debates involving descriptions of disciplinary, interdisciplinary, and transdisciplinary learning. As noted, we utilize transdisciplinary to point to where “multiple disciplines meet and coexist” (Sengupta et al., 2019, p. 3). Our intention is to challenge the potentially harmful adherence to strict disciplinary boundaries (Mignolo, 2009), and point toward a more generative, decolonial future for meaningful integrated STEM education (Takeuchi et al., 2020).

articulating the interactive nature of computation and play in integrated STEM learning.

This paper expands the discussion of computational possibilities in STEM learning by presenting findings from a design-research project focused on a professional learning model that involves *transdisciplinary computational play*, where teachers engaged in *making* as a form of exploratory learning that supports STEM-rich inquiry (Gravel et al., 2022). The paper draws on data from over 60 h of teachers' participation in a professional learning model, where they engaged in computational making with their colleagues and with students as co-learners and co-makers. Fieldnotes and video recordings capture teachers' explorations of how computational making and STEM work together. The paper expands on the intersections of play and computation through a case study of three teachers making "Cupid," a spin-the-bottle inspired edifice that became the substrate for exploring transdisciplinary STEM questions. We then present an analysis that characterizes the relationships between play and computation. Specifically, we examine how computational play surfaces forms of transdisciplinary learning, and how both definitions of play and computation are mutually supportive when asking teachers to renegotiate their relationships to disciplines, tools and materials, and their students.

### Prior research on play, computation, and making in STEM

This paper contributes to research at the intersections of play and computation in STEM by illustrating their complementary natures. We review literature on extending STEM learning through play, computational modeling, and STEM-rich making to motivate the present focus on how computational play gives rise to transdisciplinary learning.

#### Extending STEM learning through play

Through play, humans reconfigure the world to suit their needs (Huizinga, 1949; Sutton-Smith, 1997). Play as activity involves "imaginings and trial action" where "anything is possible" (Chazan, 2002, p. 19); our relations to different aspects of the social and material world are actively constructed through play. Foundational research on play focused on subject-object interactions in young children (Fromberg & Bergen, 2015), for example how play supports symbolic development (Piaget, 1951/2013), social development (Vygotsky, 1978), physical development (Pellegrini, 2011), and even how play supports explorations of materials (Forman, 2015). While prior research largely focused on children's play, we explore the nature of play's primacy as a human activity (Bergen,

1988; Huizinga, 1949), irrespective of age, to articulate possible relationships between play and learning.

Through play, humans "learn to extend the limits of human experience and to develop the capability to deal with the unknown" (Ellis, 1998, p. 31). While centrally positioned in conversations about learning and being, clear definitions of the functions of play in precise descriptions of learning remain elusive (Zosh et al., 2018). Bruner (1972) named risk-taking and exploring combinations of behaviors as two distinct features of learning through play. Play creates space to explore configurations, examine new roles and authority structures, take risks in patterns of action or with materials, and explore variations of the familiar (Bruner, 1972; Pellegrini, 2011; Rice, 2009). The re-examinations found in play are means for "deconstruction of the world in which [we] live." (Sutton-Smith, 1997, p. 166). Deconstruction, or decomposition, involves breaking down the world into essential components—building blocks—that can be explored, assessed, and used to perform improvisations (Levi-Strauss, 1962). Building up from these deconstructions brings one's cultural repertoires of practice into conversation with other objects and individuals (Gutierrez & Rogoff, 2003; Nasir et al., 2006), which we view as a process of continual relation making. Examining essential or foundational components of the world—e.g., materials, roles, phenomena—through play contributes to making and re-making of relations in our worlds, offering means of understanding how play can extend learning (Nasir & Hand, 2006). Even though it is central in children's development and learning (Elkind, 2008), play remains understudied in adults (van Leeuwen & Westwood, 2008), despite consistent calls for its importance in supporting STEM learning in computational environments for people of all ages (Rieber, 1996).

Hawkins' (1965) notion of "messing about" captures the importance of exploratory and playful interactions with materials and situations as fundamental to how we learn in science. In this initial phase of doing science, learners are "given materials and equipment-things and are allowed to construct, test, probe, and experiment without superimposed questions or instructions" (Hawkins, 1965, p. 1); Hawkins calls it "work," but acknowledges that other researchers see it as play. Within careful attunements to the material world, Hawkins describes how questions emerge that give rise to science disciplinary activity. Historical accounts of play and imagination in scientific discovery (Keller, 1984) establish play as an element of disciplinary learning in science, and offer insights into how play supports STEM learning.

Considering recent discussions of the importance of uncertainty in science learning (Manz, 2015; Manz & Suárez, 2018; Watkins et al., 2018), ideas of risk-taking,



reconfiguring, and exploring different roles and variations in play seem well-aligned with evolving views on STEM learning. Ellis (1998) positioned play as the “basis for adaptation to the unpredictable future” (p. 31); thus, play opens space for engaging with uncertainty. Bergen (2009) notes the intersection of STEM and play—specifically constructive play involving materials and physical objects (Forman, 2015)—leads learners to attend to the “physical world and the laws that operate” to produce phenomena that they find interesting (p. 418). Thus, regardless of age, “messing about” in play with materials can produce phenomena that captivate our attention and lead us to begin making sense of the behaviors demonstrated in what we make. The notion that play *extends* humans’ curiosities, continually developing relationships to materials and phenomena in the world, is further complimented in the literature on computational modeling.

### Play in computational modeling

The role of play in computational science has received some attention, focused primarily on playful engagements in computing contexts such as designing simulations (e.g., Sengupta & Clark, 2016). Considering computational constructions as a form of learning through play, we see how activities like computational modeling (Wilensky & Reisman, 2006; Wilkerson-Jerde et al., 2015) and building computational games support STEM learning (Tucker-Raymond et al., 2019). Our focus on computational play emphasizes open-ended explorations and “messing about” in ways less-emphasized in conversations about science and engineering practices (NGSS, 2013). Modeling, for example, is a science and engineering activity that develops entities with explanatory and predictive power (Wagh et al., 2017). Modeling also promotes attending to rules, iteration, and refinement with a focus on constructing coherent explanations of phenomena that drive learners’ future inquiry (Gouvea & Passmore, 2017; White & Frederiksen, 1998). Computational play focuses less on developing explanations and more on constructing artifacts, where attention to rules of a system and rapid iterations support learning through making, and re-making, projects.

### STEM-rich making

Since 2013, there has been a marked increase in research on the learning potential for STEM in *making* (Rouse & Rouse, 2022). The Maker Movement in education focused attention on activity that fosters STEM-rich learning when students are engaged in making things (Blikstein, 2013; Calabrese-Barton & Tan, 2018; Halverson & Sheridan, 2014; Martin et al., 2018; Peppler et al., 2016). The multimodal and transdisciplinary nature of making (Tucker-Raymond & Gravel, 2019) offers an

expansive context for STEM learning. There are numerous approaches to making, including project-based engagements (Gravel & Svihla, 2021), textile and crafting activities (Kafai et al., 2014), design-thinking approaches (Kijima et al., 2021), engineering-focused design (Gravel et al., 2021), and also tinkering, which Resnick and Rosenbaum (2013) define as “a playful, exploratory, and iterative style of engaging with a problem or project” (p. 164). Making constitutes a playful form of STEM engagement, known to foster engagement, intentionality, and innovation (Bevan et al., 2015; Petrich et al., 2013). Compelling stories of making situated within the lived experiences of youth highlight how making provides opportunities for meaningful STEM learning (Calabrese Barton & Tan, 2018), and showcase the potential for engaging in computing through making to further STEM pursuits (Dixon et al., 2020; Fields et al., 2018; Wilkerson et al., 2020). Here, we build from theory and research at the intersections of play, computation, and making to design learning environments for teachers and to guide analysis of how transdisciplinary STEM learning unfolds.

Weaving together research on play, computation, and making, we propose a theoretical frame where an expansive definition of computation, situated within STEM-rich making, structures analysis of how teacher’s play can support their transdisciplinary learning.

### Theoretical framing: computational making

The rise in computational approaches to STEM opened debates about how computation relates to, shapes, and extends practice (e.g., Humphreys, 2009). Similar to extant understandings of play as generative and enriching contexts for extending human experience, Humphreys’s (2004) *Extending Ourselves* describes computational science as an “epistemic enhancer” (p. 3). Imagine for a moment we are not describing computational models in physics but rather young children trying to balance blocks like a seesaw. The learner’s initial placement can be considered a kind of conjecture of how balance may be obtained in the specific situation, and when the blocks are not balanced, adjustments to its placement constitute revisions to the system. As the learner iterates the block placements, rules emerge regarding where the fulcrum should be placed underneath the block. As blocks with different characteristics are encountered, rules are adjusted to account for weight distributions and relative proportions of the block on either side of the fulcrum. The materials extend the learner’s explorations, supporting the construction of a sense of balance in the specific context (Karmiloff-Smith & Inhelder, 1974). The block system serves as a template for exploring forces and equilibrium in tangible and manipulable ways. This example

illustrates playful interactions with materials that possess computational qualities.

Humphreys argues that computational approaches offer “access to features of the world we are not naturally equipped to detect” (p. 4) through augmentations (e.g., adjusting the blocks positionings). As with play, computation offers opportunities to extend ourselves into new spaces of exploration to explore objects and phenomena that might otherwise remain hidden. Humphreys (2004) describes the construction of computational templates which operate as translations of theoretical ideas—which he considers “too large and too abstract to be useful” (p. 59)—into analytical descriptions that guide explorations of theoretical ideas within specific contexts. These templates propose relationships about how the world works, and when run on computers, they offer complimentary and possibly illuminating stories of what empirical data may reveal. Humphreys adds that these computational templates almost always require a “correction set” (p. 78), which adjusts the template to account for differences between the computational model and the empirical data. In computational modeling in science, these adjustments are often predicted by the modeler in response to scenarios such as “if the model predicts this, we might have to adjust it like that.” In the block example, as learners become familiar with the system they make slight adjustments to the block’s placement before releasing them, anticipating imbalances based on the rules emerging from their interactions. These adjustments amount to forms of conjecturing which we argue has parallels to playful, iterative, and creative learning with objects.

We theorize making as an activity that structures engagements with materials in the playful manners we have described (Honey & Kanter, 2013). Making offers opportunities to re-examine one’s relationship to tools, materials, and transdisciplinary learning (Gravel et al., 2022). Making is a learner-centered activity, where people explore, design, and produce objects of interest, both alone and together (see Peppler et al., 2016). Computation figures prominently in many popular forms of making, from digital fabrication (Blikstein, 2013), to augmented reality environments (Holden et al., 2014; Litts et al., 2020), and with specific physical systems like electronic textiles (Lui et al., 2020). Previous examples involve coding as a primary form of computational activity (Fields et al., 2018). Similar to “unplugged” activities, we wonder where computation happens without computers, where the focus is on the “process of problem-solving rather than a product ... not necessarily involving a computer” (Caeli & Yadav, 2020, p. 4).

We revisit the definition of computation introduced above. Drawing from design studies, Knight and Stiny (2015) offer an expansive notion of *computing with*

*objects*, which they define as developing rules for how those objects interact, assembling them in particular ways, and observing the results. They define making as “doing and sensing with stuff to make things,” arguing that “when we make things with stuff, we usually engage multiple ways of doing and multiple modes of sensing” (Knight & Stiny, 2015, p. 13). Framing making by reducing it to fundamental actions with objects—“doing and sensing with stuff to make things”—offers means of connecting making with computation at the level of rules and their configurations. The maker, thus, can adjust rules and configurations to evaluate changes in the system’s behavior, noticing patterns, relationships, and even constructing representations to capture these observations. This form of *computational making* has a performative element, where the maker engages dialogically with materials, tools, and things they produce (Knight, 2018). We define computational making as a blend of play and computation, where combinations of familiar craft and art materials and tools, physical programming systems (e.g., Micro:bit), and digital fabrication are used to produce artifacts of personal interest that can be iteratively refined. This permutation of computation *with things* embodies Humphreys’ (2004) vision of computational extensions, and offers a way to analyze how thinking with objects can extend and deepen inquiry. Furthermore, it brings a relational perspective to conversations about STEM and computing, allowing us to see how people relate to and make sense of the materials and phenomena in making.

Computational making, as we describe, generates moments where learners “bump up against the world” (Bransford & Schwartz, 1999, p. 93). When objects do unexpected things, learners can initiate a response or reconciliation. Pickering (1993) described the “dialectic of resistance and accommodation” (p. 567) whereby messing about with familiar materials produces opportunities to make accommodations in terms of one’s sense-making. However, this framing suggests the world is doing the pushing, and it is the learner’s responsibility to pay attention to where the world conflicts with expectations. Alternatively, we position the learner as *actively pushing on* the world, probing the world’s phenomena with novel uses of tools and materials through play. In this way, materials and learners are jointly exploring configurations and phenomena expressed in the processes of making. Adjustments to these artifacts amount to forms of conjecture about how the materials will behave, initiating cycles of revision and attention. The dialectic Pickering (1993) describes can be understood as learners making bids with materials and listening to the ways those materials offer response. This perspective supports our claim

that making is a computational approach to exploring the world with materials.

Within that larger conception of computational making—which encompasses the digital forms of production, directed at particular purposes or project goals, as well as work with materials, crafting, and the arts—we call this specific kind of playful engagement with making things *computational play*. We argue it is computational because of the focus on rules, iterations, and extending inquiry; it is play because it involves risks, reconfigurations, and variations. In this paper, we explore these relationships between making, play, and computation, guided by the following research questions: *What are the characteristics of play and computation within computational play? And, in what ways does computational play contribute to teachers' transdisciplinary learning?*

## Methodology

This paper draws from a design-research project (Collins et al., 2004) exploring shifts in teachers' relationships to disciplines, tools and materials, and students when they integrate computational making into their STEM classrooms. We designed a four-phase professional learning model anchored in critical relational theories on learning and computational making. We describe the research context and design of the model, data collection, and analytical processes. Crucial to this research on play and learning is our commitment to positioning teachers as learners, engaging jointly with colleagues and students.

## Research context and design

The larger design study took place in three cities in Northeastern United States, inviting teacher participants from three different school districts and eight different schools. Each of the districts serve racially, linguistically, and socioeconomically diverse student populations; however, the majority of teachers in these districts identify as White. This paper focuses on data from one of the districts, where participating teachers taught grades 3–12. Standard processes for Institutional Review Board approval were followed, and consent was obtained from all participants, including the use of photographs in research publications. An interdisciplinary team of scholars from the learning sciences, critical multiliteracies, computational physics, computational mathematics, engineering, computing, and critical STEM studies co-designed a series of workshops totaling more than 60 h. These professional learning sessions took place in two different making spaces located in the school district's high school, both initiated and cultivated through partnerships between the district and the first author.

The primary theories grounding the design of the professional learning workshops included heterogeneous

ways of knowing (Cole, 1996; Nasir et al., 2006; Rogoff, 2003), teacher collective inquiry (Pappas & Tucker-Raymond, 2011), and computational making practices (Gravel et al., 2022). Human sense-making is fundamentally diverse, comprising wide-ranging constellations of practice rooted in historical and cultural values (Nasir et al., 2006) and repertoires (Gutierrez & Rogoff, 2003). To engage these diverse ways of being and knowing, we developed a framework of computational making practices that guided how learning arrangements and activities were designed. The workshops built on principles of teacher learning, including teacher learning as disciplinary inquiry (Ball & Bass, 2000) and reflection (Pappas & Tucker-Raymond, 2011), and fostering interpretive power (Rosebery et al., 2016). Each phase of the design invited teachers to explore their relationships to learning, tools and materials, and their students, in ways that deepened and complicated existing content-area pedagogies.

Phase 1 of the workshops invited STEM teachers to explore materials and tools in playful and exploratory ways by making things in response to simple prompts like, “make something move”. The prompts were carefully designed to promote computational approaches to playing with materials, which we describe in detail elsewhere (Gravel et al., 2022). It is important to note that facilitation continually emphasized playfulness, encouraging teachers to try new ideas, to explore new tools and technologies, and to disregard concerns about pedagogical practicalities in this phase. Phase 1 engagements were around 30 h for each teacher participant. Phase 2 involved teachers inviting students to join them as co-learners and co-makers. They continued to play with materials, build small projects, and deconstruct old technologies (e.g., VCRs, camcorders) all comprising different forms of joint activity intended to disrupt traditional hierarchies (Vossoughi et al., 2021). These activities culminated in a 30-h week-long project-based workshop designing and constructing projects that addressed local issues that the participants identified.

## Researcher positionality

Responding to a broader call to more carefully attend to the positionality of researchers (Secules et al., 2021), we describe that of the design and authorship team. The first author, Gravel, identifies as a White male with a background in engineering and STEM education. The second author, Millner, is an African-American male with a background in Computer Science. The third author, Tucker-Raymond, identifies as White male whose research focuses on creating expansive learning environments at the intersection of STEM and literacy. The fourth author, Olivares, identifies as a first-generation Chicana with a background in ethnic and cultural studies. And the fifth

author, Wagh, identifies as a Brown scholar with a background in STEM education. The diversity of identities, backgrounds, and foci found in the composition of this research team is instrumental in our shared commitment to designing for the (re)negotiating of relationships to disciplines, tools and materials, and students. The ability of our team to design for expanded relational possibilities is grounded in the experiences we bring to design, analysis, and writing (Collins et al., 2004). The multi-disciplinary composition of the team lends trustworthiness to our methodological approach, further established in how we describe the context, offer citations that elaborate the design, and describe the ways the findings emerged from the data (Shenton, 2004).

### Participants

Participants included teachers and the students they invited to participate in the co-learning phase of the project, all from the focal district. Teacher participants included five mathematics teachers, four science teachers, and three “STEM” teachers. Teachers’ professional experience ranged from 3 to 10 years of classroom teaching. All participants voluntarily participated in the project. Teachers invited students from their classroom with whom they had complicated or curious relationships (see Ballenger, 1999). We encouraged them to invite students they wanted to learn more about and with through co-learning and co-making. Student participants in Phase 2 of the project came from grades 6 through 9, including four girls, and four boys, all of whom identified as people of color.

### Data collection

Prior literature on play research punctuates the importance of microgenetic study and analysis (Forman, 2015). Drawing from video research approaches from the learning sciences (Derry et al., 2010), we captured video and audio recordings of all participants throughout 60 h of engagement. At least two cameras were focused on each group of participants, supplemented with voice recorders. Additionally, a roving cameraperson captured interactions as participants moved through the spaces, as well as photographs of people at work (Jordan & Henderson, 1995). Ethnographic fieldnotes were produced by research team members based on observations during each of the sessions (Emerson et al., 2011). These were reviewed weekly in research team meetings, where emerging themes were noted. Research team discussions of early sessions with teachers during Phase 1 noted a strong presence of laughter and playfulness in workshop sessions (e.g., “laughter. Group engages in team building by laughing together and deciding to begin documenting funny phrases as they arise from their group

work”, Fieldnotes, 02/13/18). This developing theme led researchers to pay greater attention to moments of playfulness and joy in the fieldnotes, consistent with grounded theory (Charmaz, 2006). The total data corpus includes 60 h of recorded observations and 20 associated fieldnotes.

### Analysis

*Data selection.* The emergent theme of *laughter*, noted in fieldnotes and discussed at length among the research team, catalyzed our initial identification of moments for further analysis. All references to laughter, joy, and play in the fieldnotes were accumulated for review. These are generally agreed upon essential indicators of play (Bergen, 2009) within the play research community (Fromberg & Bergen, 2009). However, we realize play does not necessarily involve laughter or normative expressions of joy, and this was merely a place to begin the analysis. From this collection, potential episodes from the workshops were nominated for review by the research team to initiate the identification and refinement of more robust themes.

*Initial analysis.* The research team selected one episode from the nominated collection for initial descriptive analysis to begin clarifying potential themes. Building from interaction analysis (Jordan & Henderson, 1995), we engaged in repeated viewings of the episode, and conducted cycles of memo writing (Charmaz, 2006). Our research questions and theoretical positions focus on transdisciplinary learning and computational play, thus the initial analysis focused on mapping moments identified as transdisciplinary—where “multiple disciplines meet and coexist” (Sengupta et al., 2019, p. 3)—with emerging characteristics of computation and playfulness. This initial mapping drew from established CT frameworks (e.g., Grover & Pea, 2013) and descriptions of play (Pellegrini, 2011) to name specific themes. This first set of themes, which had computational elements and play elements, served as an initial structure to guide specific analysis of transdisciplinary inquiry surfacing in one selected episode (Gravel et al., 2019). We established a two-cycle process for refining the themes through each lens, computation and play. This allowed us to explore how play contributed to computation in one cycle, and where in computational activity we observed characteristics of playfulness in the second cycle. The composite analysis was built into a case study presented below. The resultant themes were further analyzed using the episodes selected from our previous review of fieldnotes. The identification and selection of additional episodes, from the larger data corpus, resulted in a final agreed upon collection of episodes used to home the themes and develop descriptions of the characteristics of computational play.



**Table 1** Identified episodes of teachers and students engaging in computational play

Episode	Description	Duration
"Cupid" (spin the bottle)	Three teachers built a spinning object called "Cupid", exploring the relationships between rubber bands, tensions, friction, and momentum	3 sessions, 270 min
Playing with LEDs	A college professor, middle school students, and teachers try to determine how strings of LEDs work in order to embed them in a bicycle car wash	1 session, 45 min
Thunkable & Micro:bits	A teacher tries to get an app programming platform to "talk" to the Micro:bit for a larger project focused on distributing sports equipment for free to youth in the city	2 sessions, 360 min
Conductive Fruit	Two students and a teacher explore whether fruit is conductive and what rules govern that	1 session, 30 min
4-bar Linkage-Llamas	One teacher systematically examines different 4-bar linkages to animate a llama riding on a sailboat	3 sessions, 270 min
Micro:bit Tales	Two teachers explore the features of the Micro:bit by narrating stories showing icons of happy and sad faces on the LED array	1 session, 90 min
Round and Round	Two teachers built a planetary gear system powered by a simple hobby motor	3 sessions, 360 min

**Secondary analysis.** We identified 7 episodes that included transdisciplinary computational play (Table 1), each varying in duration and participant configurations. Repeated viewings of video data with transcript analysis allowed us to refine and hone the themes of play and computation. We identified three central themes for computation observed within playful activity, and five central themes for play within computational activity. Discussions of each theme included constructing descriptions of the dynamics of how the designed environment, focused on play, contributed to transdisciplinary learning. Our findings offer rich description of the dynamics of how computational play contributed to STEM learning, illustrated with a case study, and the presentation of characteristics of computational play drawn from across the data.

## Results

We present findings in two parts: first, a detailed case of one group of teachers engaging in computational play to illustrate, with texture and specificity, how transdisciplinary inquiry surfaces in this activity; and second, we present the characteristics of computational play, derived from the analysis of the seven selected episodes, by first mapping those to the case study. We expand on the characteristics of play within computational activity, and computation within play, noting where transdisciplinary learning surfaced in each of the episodes.

### "Weebles wobble"—making cupid spin

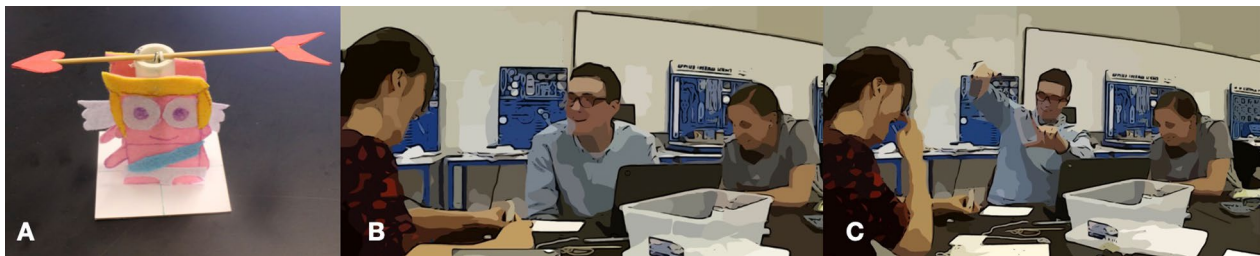
In response to the first prompt of Phase 1, "Make something move", three of the teachers, Liz, Mike, and Melissa, wanted to build something that would spin.

1. *Melissa: Want to make a thing that winds up?*
2. *Mike: That also involves hearts cause it's nearly Valentine's Day?*

3. *Melissa: I want to make it wind up, and then it goes.*
4. *Mike: I agree with the idea. I am scared of my ability to execute it.*
5. *Melissa: Me too!*

Beginning with an idea for a particular behavior (turn 1), they agreed to an exploratory approach while admitting some skepticism (turns 4–5); they were taking risks. Together they explored a website (papermech.net) that offered animations of simple mechanisms, Melissa said, "I kinda don't wanna, I kinda want to just, like try it, is that annoying? I kinda just want to go for it, and if it fails, just figure out." Melissa proposed setting aside the models offered on the website, and instead engaging with the materials and following emerging ideas about what to make. This embrace of the playful nature of the task was marked by laughter as they recounted a variety of things that spin. The group chose to visit the materials table to further their ideation and explore the material options provided as part of the workshop. There were small wind-up toys on the table, offered as further provocations of playful ways of thinking about movements. As they played with these toys, the laughed at some of the absurdity of clumsy wind-up walking toys. Ultimately, Melissa brought a rubber band twisted around a thin wooden skewer back to their table to continue exploring spinning possibilities. Their collective stance was exploratory, uncertain, but also fun and joyful:

*Mike says "That's how the fairies work" referring to the toy—the group finds, "That's how the fairies work" funny and laughs. Someone suggests keeping a quote log. <Laughter. Group engages in team building by laughing together and deciding*



**Fig. 1** A Cupid; B Mike, Melissa, and Liz expressing joy and excitement as the initial Cupid rubber band construction spins (Image reproduced with permission from participants); C Mike's expressive gesture in response to their project performing, albeit with "wobbles". (Photos: Gravel)

*to begin documenting funny phrases as they arise from their group work*<sup>3</sup> (Fieldnote, 2/13/18).

Jokes and laughter were hallmark features of their work. In this observation, the teachers' move to document phrases is significant. It suggests they noticed a pattern of recurring funny quips, something that was different, enjoyable, and novel about this experience, and thus decided to memorialize it. As Melissa said, "I find this PD to be incredibly relaxing!"

Back at their table, Melissa demonstrated a mechanism for spinning to her group mates, winding up the rubber band around the middle of the long wooden skewer, borrowed from another's suggestion of a wind-up propeller on toy balsa wood airplanes. The materials were familiar to her, but she configured them in such a way that these familiar objects demonstrated unfamiliar behaviors.

*Melissa: What I don't know is, what would you have to do ... OH! [expressed with surprise as the rubber band unwound spinning the skewer] ... like that... It twists this way then, which is not what I expected. [Turning to Liz] What I figured out, if you do this, and you twist this, that'll twist this way. That sounds like it was not very colossal, but it felt colossal.*

The rubber band-skewer mechanism did not behave as Melissa expected and she was surprised by the direction of the skewer's rotation (as indicated by her "OH!" as she demonstrated it). Melissa said the surprise behavior felt "colossal", indicating how messing about with familiar materials while playing with the idea of spin produced an opportunity to notice something unexpected. We argue her playful making began a process of attunement to the wonderment of how rubber bands behave.

Their first iteration of the project, in response to the original "make something move" prompt, used the mechanism that Melissa demonstrated: a rubber band twisted

around a wooden skewer on one end, passed through a small piece of PVC pipe, and held tenuously on the bottom by a paperclip (see Fig. 1A). The device was relatively unstable, and Mike joked, saying, "I suggested a dowel [for stability, instead of the paperclip] to Melissa, and it was a harsh neg." They all laughed. Melissa tested the device for the first time by twisting the wooden skewer affixed to the rubber band and releasing it to let the skewer and band unwind.

1. *Mike: Hey, look at it! [Smiles with wide eyes]. Woo, ho ho! Hey! [Waves his hands in the air]*
2. *Melissa: It's just at the end that I feel like it's so, meh.*
3. *Liz: What do you think? It has to slow down eventually!*
4. *Melissa: No, I don't like that it wobbles.*

Mike's exuberance—expressions of joy, smiling, and gesturing excitement (Fig. 1B, C)—illustrates the playful tone of their work (turn 1). Melissa smiled too, but expressed disappointment (turn 2). Liz questioned Melissa's discontent (turn 3), which prompted Melissa to specify her expressed judgment, naming the behavior she did not like—"it wobbles" (turn 4). Disapproval of the "wobbles" focused their attention on the materials, and possible ways to remedy the undesired behavior.

1. *Mike: I think part of the weirdness now is that, now it's [the rubber band] not taught. It's not taught because if you pull this up [the wooden skewer on top of the PVC] there is no tension until like here [the skewer is about 1 cm above the rim of the PVC].*
2. *Melissa: I don't think so. I think it's because this top part [of the twisted rubber band] is not as thick ... as what this was [points to thicker rubber band they tried previously]. Once this is figured out, we can just make cupid... I think this is hilarious.*
3. *Mike: It wobbles... Weebles wobble but they also commit to lifelong relationships.*
4. *[laughter]*

<sup>3</sup> Sections of fieldnotes within brackets marked by <> denote a convention for marking laughter, joy, and play in the participants' activity.

As they played and interrogated the behaviors of their little cupid, the group demonstrated transdisciplinary approaches: sharpening the focus of their inquiry on the performance of the rubber band and characteristics of the material. Mike argued that the rubber band's lack of tension was causing the wobble (turn 1). Melissa disagreed, pointing to the thickness of the rubber band as a possible problem (turn 2). Their efforts to make sense of the behaviors they observed raised questions about the material configurations of Cupid, deepening their attention to the mechanism driving Cupid's performance. Their questions reflect a transdisciplinary "what kind of problem is this?" disposition (Davis et al., 2019), combining questions of *why* the wobbles were happening with questions about *how* the configuration could be altered to achieve the desired behavioral effects. In these moments of design, it is notoriously challenging to maintain sustained and deep scientific inquiry (Berland, 2013). Yet, we see the beginnings of how playful engagements with relatively frivolous projects opens new spaces for fluid ways of knowing (Markauskaite & Goodyear, 2017). During this moment, Mike continued to joke about their device (turn 3), further punctuating the sustained playfulness of their work.

As the group explored possible solutions to the "wobbles", they developed different ways of configuring the system to achieve the desired behaviors. They contemplated how they could constrain the top of the device to stabilize the spinning skewer. They proposed placing the skewer tightly against the rim of the PVC to solve the "wobbles". One solution was tightening the rubber band such that it behaved more like what they observed with a previous iteration using a thicker rubber band (turn 2). Rapid iteration—involving reconfigurations and variations—in response to the observed behaviors allowed them to improve their device's function. The iterative attunements to material behaviors and the rules of the system reflect a computational approach to making. This process also contributed to deepened transdisciplinary learning, where the teachers worked to understand phenomena by making material conjectures in response to their queries. After resolving the "wobbles" issues, Melissa shared, "But wait, now does it, now does it spin backwards?" She noticed that when twisted a certain amount, the skewer unwound past where it had started, or "backwards". This observation proved pivotal in their sustained examination of Cupid's behavior.

The teachers' initial brainstorming and iterative construction of Cupid involved noticeable patterns of play and computational activity. They began working from familiar materials to explore new and unfamiliar arrangements, some of which produced very

unexpected behaviors. We see evidence of the kinds of risks teachers took, as Melissa said "I kinda just want to go for it, and if it fails, just figure out." Entering into uncertain and unknown spaces through making allowed them to consider different material configurations and variations. They explored tension, and ultimately assumed roles as learners as they played. These characteristics of play and computation contributed to their transdisciplinary inquiry with materials.

As the group gathered on the second day of making, Mike played with the finished device and wondered, "I feel like there's a great probability thing here." Their observations surfaced a new question, which Mike elaborated:

*Mike: One thing I'm thinking about ... here's it's flat... let's do 1 rotation. Let's do 1,000 trials of 1 rotation. I bet for the most part, for 1 rotation, it'll go to the same place.... I have a feeling that the more you spin it, the more it would be different from like your starting place.*

Mike's curiosity built from Melissa's observation about where the skewer stopped. He proposed a probabilistic model for Cupid's performance, seeing probability as a means to study why the spinner went "backwards", or performed differently based on the number of spins. His response to Melissa's noticing of the "backwards" behavior reflects his mathematical perspective on the problem space, using probability and repeatability as lenses for interrogating the material's behaviors—an example of transdisciplinarity, as he drew from different disciplinary actions to make progress on the project at hand.

Liz arrived a bit later, and she proposed recording data in a table about the relationship between winds and unwinds. For the first two trials—1 and 2 winds—they noticed the skewer spun back about 1/4 turn less than originally wound. Following this pattern, they continued for 3 and 4 winds. When it got to 5 winds, they had trouble counting as the arrow rotated quickly, so they used the slow-motion camera feature on Liz's phone to video the phenomenon. As they watched the video for 5 winds, Liz counted:

1. *Liz: 1, 2, 3, 4, yeah this is better, fi-ive, 5 and a half.*
2. *Melissa: What? No!*
3. *Liz: Why is that wrong?*
4. *Melissa: Everything I know is wrong. Because how can you twist more and it spins more?*
5. *Liz: Oh yeah, f#\$%.*
6. *Melissa: Science! [yelled, shaking her fists in the air]*

**Table 2** Characteristics of computation in playful activity, and characteristics of play in computational activity, with examples from the identified episodes

Computation in PLAY	Working definition	Example from episodes
Familiar to unfamiliar	Beginning with familiar materials, or algorithms, to find new and unfamiliar behaviors or relationships	From <i>Playing with LEDs</i> : building circuits with wire, then extending to explore copper tape, noting the advantages and frustrations of this adhesive yet delicate material
Modularity	Breaking larger problems down into discrete sub-tasks, with attention to repeatability	From <i>Playing with LEDs</i> : exploring voltage requirements of different LEDs prior to designing a string of them to implement in their project
Abstractions	Identify rules for elements of a system, exploring the behaviors they produce, creating representations of those rules and emergent behaviors	From <i>Round and Round</i> : discovering the relationship between diameter of a gear and number of gear teeth when the size of the teeth is fixed
Play in COMPUTATION	Working definition	Example from episodes
Risk	Exploring and assembling materials without knowing the results to observe the resulting behaviors	From <i>Playing with LEDs</i> : attaching different color and voltage LEDs without knowing what will happen
Reconfigurations	Rearranging the elements of a system to explore alternative configurations and resulting behaviors	From <i>Round and Round</i> : teachers explore different ways of attaching a motor to the driver in a planetary gear system—from underneath, from the top, etc
Roles/Shifting Authority	Exploring different roles, distributing authority in unfamiliar ways	From <i>Playing with LEDs</i> : a middle-school student informs a college professor of the importance of voltage limits when combining LEDs
Variations	Trying multiple ways of solving a problem or enacting some desired behavior	From <i>4-bar Linkages</i> : a teacher explores card stock, chip board, and different fasteners to build variations on a linkage system driven by a motor
Obsession	Fixation and extreme concentration on a task; an unwillingness to stop doing what you are doing	From <i>Playing with LEDs</i> : two participants sit next to each other focused on trying to wire LEDs in series, neither stopping for more than 40 min

Having believed a pattern was emerging—for each wind, the skewer unwound 1/4 less turn—the behavior for 5 winds was unexpected. Liz noted 5 spins in one direction resulted in 5.5 spins in the other direction (turn 1). This was a phenomenon that Melissa noticed earlier, but here it clearly frustrated her as she yelled “science!” across the room (turn 6). We interpret her reaction to be an expression of the observations not making immediate sense, and her recognition that perhaps reconciling this confusion would require more sense-making. Indeed, this moment drew the attention of four other teachers, and for the following 10 minutes, a vigorous debate about elasticity, energy, and momentum emerged. The teachers drew comparisons to yo-yos on a string unwinding further than originally spun. They arrived at some agreement that the rubber band caused the spin, and the friction between the arrow and the top of the PVC pipe contributed to its slowing down. This culminating discussion is evidence of their emerging transdisciplinary learning and forms of obsession, illustrated by the vigorous debate that transpired among them, where making sense of Cupid’s peculiar behavior drove their continued engagement.

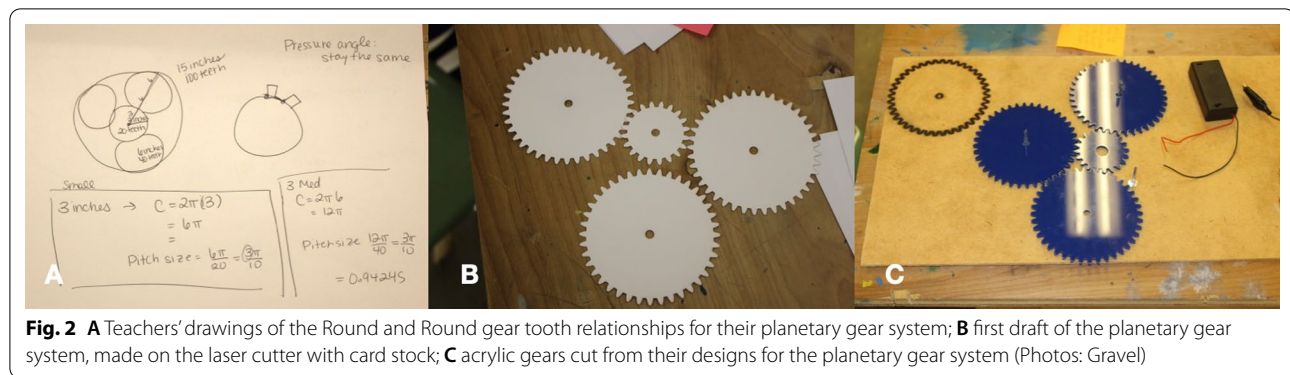
With the Cupid group, understanding the rubber band’s behavior was both a matter of interrogating the materials and using simple mathematical techniques, like recording

the number of spins in a table, to examine a conjecture. The teachers engaged deeply with the materials through play, exploring different configurations, carefully observing and documenting behaviors, and noticing things that were unexpected about how their device behaved. As they made and remade their project, their attention was drawn and focused on elements of their playful project. Embedded within this sustained, iterative play, they combined multiple representational forms (e.g., tables, drawn diagrams) and modeling approaches (e.g., material conjectures, collecting empirical data with a slow-motion camera) that crossed STEM disciplinary boundaries; combinations of representations have been identified as a core feature of transdisciplinary learning in computational STEM activities (Dickes & Farris, 2019; Sengupta et al., 2018). Co-constituted play and iterative making gave rise to transdisciplinary questions and actions, offering a rich case of how computational play supports transdisciplinary STEM learning.

#### Characteristics of computational play

The Cupid case narrates teachers’ making in ways that highlight characteristics of the generative intersection between play and computation. Our analysis of the identified episodes, including the Cupid case (see Table 1), revealed specific characteristics of computational play





that contributed to participants' engagement in transdisciplinary learning (Table 2). The episodes all contain evidence of transdisciplinary activity, from teachers recording data on Cupid's spins in a table, to teachers and students arguing about the "conductive juiciness" of different fruits they used in LED circuits. The episodes present moments that are both playful and computational, at times leaning more one way than the other.

Within activity that we consider to be playful, certain computational characteristics emerged that we term *Familiar to unfamiliar*, *Modularity*, and *Abstractions* (Table 2), each described here using examples from the identified episodes. Activities like computer programming often require repeated use of sections of code that do specific things, where one can deploy these familiar elements to attempt unfamiliar tasks (examples can be found in literature on "remixing" in creative computing; Flath et al., 2017; Vasudevan et al., 2015; or relating to "use-modify-create" paradigms; Lee et al., 2011). Building from familiarity to extend out into unfamiliar spaces was a pattern we observed in participants' making. For example, the Cupid group used a rubber band as part of their mock spin-the-bottle device. They explicitly chose the rubber band after one group member described familiar wind-up propellers on toy balsa wood airplanes. Rubber bands were useful in this example as ways of storing forms of energy that could produce motion. The opening prompt was "make something move", and as the teachers shared familiar ideas like the wind-up propellers on toy airplanes, others responded with, "Oh yeah!" That expression signaled familiarity with the particular mechanism, and also with the twisting properties of a rubber band. However, after playing some with this rubber band, they discovered the twisting was more complex and unfamiliar than they expected. Melissa admitted this to her group as she was messing about with the materials, "That sounds like it was not very colossal, but it felt colossal" With materials that are present in many aspects of one's life, like rubber bands, paper, wooden sticks, we observed

participants extending from familiarity into situations that were less familiar, and even surprising, "colossal" or otherwise.

*Modularity* is a well-documented feature of computational work across platforms and paradigms, focusing on the development of steps or components that can be "reused, repurposed, and debugged" (Weintrop et al., 2016, p. 139). Modular approaches are linked to how computational challenges are broken down into constituent elements, such that more precise and specific functions are identified for possible reassembly in different kinds of projects. One such mode of modularity is identifying specific processes used within a particular computational activity. We observed participants creating protocols for different material manipulation. For example, in the Round and Round project (see Fig. 2), the teachers worked to determine the possible combinations of gears for their planetary system by discovering the ratios of gear sizes expressed in terms of gear teeth.

If the chassis (i.e., the outer gear ring) was 100 teeth in circumference, then composite gear circumferences, measured by the number of teeth, had to sum to 100 teeth. One option was for two 20-tooth gears and one 60-tooth gear, fitting across the ring in a line. Determining ratios of how the constituent gears fit together into an outer chassis constitutes a form of modularizing the system under consideration to determine a structure that governed its function. Using this rule, they were able to adjust the design files they built to cut gears out of different materials on a dye cutter and a laser cutter. Repurposing the same design files, modifying them slightly to meet the particular needs of specific materials or tool commands, constituted a move to modularize their play with materials as they built their planetary gear device.

As participants continued to playfully engage with their projects, new discoveries often prompted them to create representations of what they learned. These representations constitute *abstractions*, a feature of computational activity emphasized by Papert (1980), and included in



**Fig. 3** **A** Luanne explores different configurations and variations of the LEDs; **B** LEDs arranged around a coin-cell battery; **C** the circular LED array that came from playing with different configurations of LEDs (Photos: Gravel)

subsequent CT frameworks (Grover & Pea, 2013; Wing, 2011). In the case of the Round and Round group, teachers discovered a fixed ratio between a gear's diameter and the number of teeth, if the teeth dimensions remained constant. They recorded this rule in their notes, alongside their discovery of the chassis-to-composite-gear ratio, to remind them as they moved between materials and tools of this newly discovered relationship. In the Thunkable & Micro:bit project, managing translations between two software environments led teachers to create new representational codes—e.g., strings of text that serves as signals between the two devices—in order to pass information between the two systems. And with Cupid, we saw the teachers record the number of winds and unwinds in a table as they attempted to reconcile the odd observation that the skewer spun “backwards” at certain points. These *abstractions*—the discovery and recording of particular rules for the systems the teachers built—ranged in purpose and form, but remained a consistent characteristic of how computational activity emerged as participants continued to play with materials and ideas.

From the perspective of computation in making, which we defined above as attention to rules, combinations, and behaviors (Knight & Stiny, 2015), we found playful attributes in participants' computational activities, specifically: *Risk*, *Reconfigurations*, *Roles/Shifting Authority*, *Variations*, and *Obsession* (Table 2). We share an example of the group Playing with LEDs to further elaborate on these characteristics.

During Phase 2, one of the project teams was working on a playground structure design featuring a bike carwash with lights and sound. The group consisted of two teachers, two students, and a university math professor who had joined the summer workshop to learn more about making. In the episode we identified from this larger project arc, the group worked together to explore LEDs as part of their larger playground project. The participants

admitted that none of them had used LEDs before. They had wires, copper tape, LEDs, and coin-cell batteries laid out on the table as they tried lighting different colored LEDs. The college professor, Peter, and one of the middle-school students, Luanne, sat next to each other, each with a battery and LED in hand. Peter noticed, “Only one way works”, meaning the LEDs had to be placed in one configuration on the coin-cell to light up. Luanne tried it, but it did not work. Peter said “It's not working? Maybe try it another way?” In that moment, Peter and Luanne were collaborating to explore different *reconfigurations* of the system to understand its function. Their exploration also constitutes a kind of *risk*: they did not know what would happen, but they tried anyway. This kind of loose experimentation is characteristic of how play serves to extend curiosity and explorations of materials. For the LED group, after determining that there was a “correct” configuration—the negative end of the LED must touch the negative terminal of the battery—they began playing with different colors of LEDs. They had blue, green, red, and yellow LEDs at their disposal, and they explored different arrangements of these colors to discover what worked and what did not. They also played with alternative conducting materials like copper tape, learning of its limitations, and eventually turning to conductive thread to explore that option as well. The exploration of a range of materials organized around a loosely formed goal of getting LEDs to light up constitutes what we call *variation*, where the group played with multiple ways of achieving some desired behavior with the materials.

As they continued to play, Peter tried to string together a few LEDs around the battery, as Luanne too played with different LED configurations (Fig. 3A), but failed to get them to work. Luanne said, “I don't think the two can light up at the same time because they have different voltages.” Peter replied, “What did you say?” When Luanne repeated herself, Peter said,

“Ohhhh! That’s why it wasn’t working. So, we need two of the same one?” Luanne noticed that different colored LEDs have different voltage requirements—information obtained from a card with voltage figures inside the container of LEDs—and those with different requirements did not light up in the current configuration. Peter positioned Luanne, the middle-school student, as an expert in this situation. This is an example of exploring new kinds of *roles and authority* structures, where the middle-school student became the expert on these materials, teaching the college professor about the rules that govern behaviors of LEDs. Finally, the episode lasted more than 45 min, an example of focused *obsession* with the task, which eventually produced an unexpected yet captivating example like the array of LEDs encircling the coin-cell battery (Fig. 3B, C). This brief description illustrates how computational play supported the participants to discover rules about how LEDs work, rules for how to combine them, and ultimately their discovery of how the system of materials could be used in their larger project.

The examples from the LED episode resonate with our description of the Cupid group’s process. Melissa’s charge to the Cupid group to venture into unfamiliar space with familiar materials constituted a form of risk-taking. She encouraged the group to “just go for it” and “if it fails, just figure it out”, signaling the acknowledgement of some risk involved, even if it appears minimal. Their play involved different material solutions for repeating the same spinning process, reflective of reconfigurations, variations, and modularity. Their roles as learners and players distributed authority over the process, and it supported their obsession with the Cupid project, evidenced by the nearly 4 h they spent building and exploring the device. Finally, their attempts to understand the “backwards” behaviors led them to abstract this process using a table of numbers gained from their slow-motion smartphone camera. Taken together, the entirety of their computational play and making supported transdisciplinary learning, as we observed in other episodes as well. Our analytical decision to parse play and computation in service of identifying and refining the characteristics we present supported efforts to name specific aspects of computational play that support learning. However, the examples we present suggest a more fluid tacking between and among the set of characteristics of play and computation within these making activities. We argue it is useful to identify specific characteristics, which build from the literature, reflected in our data of computational play such that we can advance discussions about how play, computation, and making are supportive of transdisciplinary STEM learning.

## Discussion

This paper illustrates how transdisciplinary STEM learning manifests in computational play using a case study of teachers having fun making a frivolous and whimsical “Cupid” during a professional learning program. The dynamics of their engagement signal particular computational approaches to inquiry and the emergence of questions from their observations and iterations. The characteristics of computational play that we propose (Table 2) support furthering a collective understanding of the emergence of transdisciplinary learning within making. In the story of Cupid, framing the design activities as play encouraged exploration, and we found that teachers took up that frame as they explored configurations and variations through sustained and focused iterations. We described a computational approach to playing with materials: altering arrangements produced new behaviors and authentic lines of inquiry where transdisciplinary STEM learning emerged, which we call computational play. Our findings address two central research questions: *What are the characteristics of play and computation within transdisciplinary computational play? And, in what ways does computational play contribute to teachers’ transdisciplinary learning?* We offered an initial description of the characteristics of computation and play in this form of making activity, and here, we discuss three aspects of computational play that contribute new perspectives on how making can support transdisciplinary learning: familiarity supporting risk-taking and reconfigurations, shifting roles and authority structures, and the re-making of relations through computational play.

Playful forms of making center and amplify one’s familiarity with materials (e.g., rubber bands, skewers), which is supportive of teachers’ risk-taking as they explored new ideas and processes. For the Cupid group, we observed familiarity with the materials at hand in the teachers’ inquiry, which heightening their attention to unexpected or surprising behaviors (e.g., spinning “backwards”). We argue this familiarity invited them to engage in ways that contributed to the enactment of transdisciplinary sense-making. The teachers in the Cupid case study shared that they were all relatively new to making, and embracing new and unfamiliar activities amounted to a form of risk-taking. However, it was clear that their experiences with materials in the world were resources in the initial “make something move” project; for example, they mentioned wind-up toys with rubber bands that they played with in the past. They manipulated skewers and PVC with comfort and ease. They knew how to work with these simple craft materials, and they held expectations about how they performed under certain conditions. We can imagine these expectations were like rules for components of



the system. They were able to use those prior experiences with the materials as resources for inventing and playing with new configurations. Assembling the familiar in unfamiliar ways, prompted with the simple mission of making something that moves, opened space to revisit and build from their histories with these materials. From the standpoint of computation (Table 2), building from familiarity—with materials and simple mechanisms—is a resource for exploring new arrangements, which we observed across the range of identified moments (Table 1).

As learners engage in making activities like “making something move”, this familiarity supports attunements to the rules of the physical system, which opened authentic lines of inquiry. We frequently observed teachers enacting different processes of deconstruction and modularization among different projects. For example, the LED group was interested in stringing lights together, but as they play with the materials their focus shifted to understanding the battery–LED–wire relationships. They played with wires, copper tape, and conductive threads as different materials to connect a circuit, and they explored different LED sequences. They encountered the idea of forward voltage for LEDs which helped them make sense of why certain LEDs play nicely with others, and explored this through making the circular array (Fig. 1C). Reconfigurations and variations such as these constitute processes of *re-familiarization*, building from familiar objects or forms (LEDs may be new, but lightbulbs and circuits were familiar) to explore new less-familiar arrangements. Refamiliarization processes make the rules of a system more salient, drawing attention to particular material behaviors within the context of what the teachers made. Computational play supports this kind of attunement—identifying, defining, and representing different rules are moves we observed teachers making. The Cupid group’s inquiry into spins illustrates how willingness to venture into new corners of somewhat familiar material space cues attention to the rules of the system. Refamiliarization surfaces when teachers take risks in exploring new configurations and variations, and feed their obsessions for making their projects work in the ways they imagine. Within this space of refamiliarization, modularization and abstraction support building from observation to decipher and encode certain rules. Documenting and working to understand the “backwards” phenomenon is an illustration of refamiliarization contributing to naming and defining rules for how materials behave. Rules function as a kind of tool for refining one’s descriptions of what they observe (see Duckworth, 2006). Comforts with the range of materials and creative freedoms in making encourage risk-taking, reconfigurations, and variations, which we found support transdisciplinary

STEM learning. Yet, the characteristics of play and computation within these activities appear most productive for transdisciplinary learning when we also consider the roles individuals adopt.

Play offers opportunities for people to adopt new roles, and salient in our findings is the consistency with which teachers embraced the role of *learner*. Teachers infrequently experience opportunities to play the role of learner in their professional lives (Feiman-Nemser, 2012). Rarely are they afforded unbounded time and space to learn without specific directives set forth by policy or professional needs, yet this kind of play seems crucial for supporting emergent and authentic inquiry. A playful orientation to the role of learner opens space to embrace risks, uncertainty, and unknowns as opportunities to reconfigure the world in personally meaningful ways. These characteristics of how play extends and enhances one’s inquiry with materials reflect computational approaches in science (Humphreys, 2004). Computation supports asking “what if” questions, and similarly with play, we observed teachers exploring materials by “acting to see if something might happen” (Bergen, 2009 p. 418). Play encourages open-ended, exploratory orientations to learning while making, which in turn contributes to evolving inquiry and captivating tangents (e.g., the LED group’s circular array). Through playful activity, we saw teachers shed the pressures that come with solving problems or getting it right, in favor of “messaging about”, which affirmed their stance as learners. Furthermore, operating as learners, computational play appeared to foster moments where teachers reached for tools to extend their inquiry, just as computational tools serve to extend the bounds of human perception (Humphreys, 2009). Liz’s use of the slow-motion camera supported the group’s collective inquiry and uncovered a “resistance”, or unexpected event (Pickering, 1993) in Cupid’s behaviors. Noticing curious behaviors and using tools to extend lines of inquiry reflects the teachers’ stance as learners in that situation, in ways consistent with how computation is described as a tool for developing knowledge in STEM fields.

Our findings support the argument for a centrality of play in teachers’ intellectual journeys as they participate in the cultural activities of inquiry in STEM (Rogoff et al., 1993). The designs for our professional learning program are grounded theoretically by the notion of computational making, and include simple structured playful engagements like the “make something move” prompt. Coupled with the social arrangements of participants, where teachers and students were invited to engage as co-learners and co-makers, the program was built to support teachers in renegotiating their relationships to materials, tools, disciplines, and each other (Gravel et al.,



2022). As Hawkins (1965) noted, “messing about” in science—or playing with materials to explore phenomena—establishes play as a legitimate form of transdisciplinary STEM. In our data, play supported teachers’ efforts to attend to different relationships with materials, tools, and expanded notions of STEM learning as transdisciplinary. We demonstrated how mathematical ideas and tools came together with scientific questions around consistency and expectations of material behaviors. Mike joked with his group that “weebles wobble, but they also commit to life-long relationships.” In so doing, he affirmed the “wobble” phenomenon that Melissa noted, which became the object of their transdisciplinary inquiry. His joke also characterized the nature of the work, near Valentine’s Day, as joyful construction of a frivolous project: a spin-the-bottle device that looked like Cupid. We read this move as subtly signaling the relational nature of the work in front of these teachers. While he may have been making a joke about love and friendship, the notion of “lifelong relationships” transports us to wondering about the importance of relationality within these making activities. Melissa commented that the “PD was incredibly relaxing.” She related to this work differently than other professional contexts. The teachers laughed, joked, and reconstructed their relationships to each other and different ways of characterizing learning within the context of computational play.

Extending this wondering to the LED case, we see forms of traditionally powered relationships, for example between students and teachers, flattened and reformed in ways others researchers have noted as important to larger equity projects (Vossoughi et al., 2021). Making fosters shifts in participation and deliberate engagement (Dixon & Martin, 2017), whereby the forms of modularity, deconstruction, exploring variations and reconfigurations, and taking risks that we describe operate to re-make constellations of relations (Nasir et al., 2006). We witnessed students and teachers not only learning together, but laughing and playing together. The atmosphere of active and continual remaking of relationships opens new space for participation, and in our case, participation in STEM learning. If we understand learning as a shift in relations (Nasir & Hand, 2006, 2008), then computational play is a context ripe for it. We demonstrated with Cupid how transdisciplinary learning unfolds in this context, but we also have evidence to suggest that the benefits of computational play can be extended when thinking about the nature of the problems that makers are addressing. Phase 2 of our design focused teachers and students on addressing issues, problems, and phenomena in their communities. As co-learners engage community needs, or social movements (Curnow & Jurow, 2021), we support the remaking of relationships

toward more equitable forms of participation and possible learning gains for the young people who participate (Pinkard et al., 2017, 2020). The findings we present, theorized through notions of computational making and the importance of play for supporting transdisciplinary learning, contributes to the evolving discussions of the relational nature of learning in STEM (see Warren et al., 2020).

Through re-casting play as we have done here, the larger frame of computational making functions to transform our understanding of play and its possibilities for teaching and learning. By the same token, computational making functions to transform our understanding of computation and its possibilities for teaching and learning. Neither computation nor play remain unchanged through the course of participants’ engagement, they are mutually constituting. As the field continues to define the computational nature of STEM, exploring the characteristics of play and computation that contribute to transdisciplinary activity has implications for the design of learning environments and notions of participation in computing more generally (Ryoo, 2019). Our emerging framework offers insights into how computational making can transform the relationships teachers have to inquiry in ways that will expand the possibilities they see in their students’ practices.

### Conclusions, implications, and limitations

We conclude with implications for research, practice, and their intersection. There are theoretical and research implications related to the design of professional learning focused at the intersections of making and transdisciplinary learning. We also conclude that our results have implications for teachers’ professional experiences around play and continual remaking of relationships. Finally, we describe how partnerships between researchers and teachers might continue to advance how theory and practice inform each other.

Computational making folds together ideas from computational science, making, and perspectives on the computational manipulation of “things” (Knight & Stiny, 2015). As a theoretical tool, computational making seeks to strip away specific technological systems and paradigms (such as coding) to understand core facets of how computation supports inquiry. We acknowledge this is still a very early articulation, and deeper expansions of the forms that rules can take, the structures of their combinations, and the ways in which emergent behaviors are seen and used are needed. Research on computational modeling (Sherin et al., 1993; Wilensky & Reisman, 2006; Wilkerson-Jerde et al., 2015) has provided important insights into computational possibilities for supporting science disciplinary learning. Of new concern is

how those computing architectures are intertwined with aspects of the physical world. Bifocal modeling (Blikstein, 2014) offers promise in this space, yet we encourage additional research that points at the intersections of computation and playful making that open and expand pathways for learners to engage in modeling, and other explicit scientific disciplinary practices, within the context of transdisciplinary STEM learning.

Following from the notion that play is an underappreciated and understudied aspect of how learners enter transdisciplinary activities, we argue this paper has significant implications for the design of teacher professional learning programs. Teachers need space for playful engagements as they work to re-make their relationships to STEM. Designing for co-making and co-learning, where teachers enact this playful work alongside students, is consequential for re-making relations toward more just, equitable, and ethical learning arrangements (Madkins & McKinney de Royston, 2019; Vossoughi et al., 2020). We shared data from a design-research project focused on teachers who expressed interest in this kind of work. It remains an open question how effective these kinds of designs might be for stimulating similar responses from teachers and students less inclined to these exploratory and constructive forms of learning. We view this as a structural issue: schools as institutions and definitions of success constructed and maintained within those institutions deny many the opportunity to embrace play as a valuable, substantive, and humanizing experience. Furthermore, the continued siloing of content areas that adhere to traditional disciplines constrains the space of imagination for where computation can be integrated into STEM work. Until we address these deep structural issues, the true reality of how play supports new and expansive forms of transdisciplinary learning will remain underexplored and underappreciated.

Finally, the implications of this research for the intersections of research and practice point toward the importance of more participatory ways of designing, analyzing, and iterating professional learning experiences. Design research implies iteration, and this research leads us to wonder how researchers might analyze the experiences of participants *with them* to provide further insights into the questions guiding this kind of work. We are exploring dimensions of participatory analysis with youth and teacher participants from this project (Tucker-Raymond et al., in preparation). Translations of experiences like what we present here to classroom experiences for students and teachers hinge on these forms of participatory analysis and iteration. Teachers adopting roles as learners has supported efforts to re-make relationships to tools, disciplines, and others. We imagine a trajectory where this

relational work is amplified by the analysis of experience, deepened by theory, and informing of new ways of building meaningful, authentic, and equitable STEM learning environments.

The limitations of this study relate to the relatively narrow scope of the work and the manifold ways in which ideas of play are conceptualized both by researchers and practitioners. As designers of the workshops, we can say “play with materials”, yet we cannot know the many ways in which teachers and students may interpret that encouragement. As we note, play has been both a prominent and elusive theoretical construct. We hope that mapping play and computation contributes to efforts to understand how transdisciplinary STEM learning may emerge in the intersections. At the same time, there are likely playful experiences within computational making where specific disciplinary questions do not emerge. What contributes to emergence or absence? Given the facilitators of this work were present and encouraging of play all along, it is hard to answer that kind of question with the present research. It is important to acknowledge how participants might not experience activities like this as playful. The ways power flows through space significantly shapes the forms of participation and the ways learners enact them. Play can encourage risk-taking, assuming new roles and authority structures, and exploring variations and configurations, yet, participants must feel supported in enacting these practices. Certain conditions are required for participants—teachers and students alike—to enact forms of creative inquiry found in computational play: learners’ epistemic rights must be honored, their identities respected and reflected, and shared spaces of intellectual humility (Olivares et al., 2020). We offer this study as a start in a hopefully larger path of exploring different relational configurations in STEM learning.

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#### Author contributions

BEG is the PI on the project, leading design, data collection, analysis, and writing; AM was a major contributor to theoretical and analytical developments for the manuscript; ETR and MO contributed to data collection, analysis, and writing; AW contributed to data collection, theoretical developments, analysis, and writing. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Declarations

### Competing interests

The authors declare that they have no competing interests.

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