All Roads Lead to Computing: Making, Participatory Simulations, and Social Computing as Pathways to Computer Science

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Abstract—Computer science (CS) is becoming an increasingly diverse domain. This paper reports on an initiative designed to introduce underrepresented populations to computing using an eclectic, multifaceted approach. As part of a yearlong computing course, students engage in Maker activities, participatory simulations, and computing projects that foreground the social and collaborative aspects of CS. Collectively, these activities are designed to introduce learners to the growing diversity of what CS looks like in the 21st century. This paper lays out the practical and theoretical motivations for the Computational Thinking for Girls (CT4G) project, specifically highlighting the use of Making through physical and social computing as ways to engage students in CS. A snapshot of one activity from the program is provided—*Wearing the Web*—in which students use open-hardware programmable badges to explore the underlying structure and technology that enables the Internet. Data from the first year of the CT4G program are presented to show the positive effects that this diverse introduction to CS is having on the students with respect to their attitudes toward CS.

Index Terms—Collaborative learning, computer science (CS), gender diversity, high school, making, participatory simulations, underrepresented students, wearable technology.

I. INTRODUCTION

COMPUTER science (CS) is becoming an increasingly diverse field. Whereas engaging in a CS activity once meant printing "Hello, World!" to the screen or implementing a binary search algorithm, the world of CS has grown to include a variety of technologies such as physical computing, social and collaborative platforms, and a rich Internet of Things that students can plug into. With these new contexts come new opportunities to introduce learners to CS and engage diverse populations in computing. This paper presents the Computational Thinking for Girls (CT4G) initiative, a yearlong colloquium course designed to introduce girls to the field by offering a wide range of entry points. Unlike conventional introductory CS courses that focus on programming, or out-of-school initiatives that seek to broaden participation in computing through a single context (like robotics camps or digital storytelling workshops), CT4G strives to introduce historically underrepresented populations to CS by showing the full array of what computing comprises in the 21st century. Unlike one-day or weeklong activities designed to introduce girls to computing, CT4G is viewed not as an intervention, but as an investment in the students and in the computing futures that await them.

Figuring prominently in this approach to computing are technologies and practices critically adopted from the Constructionist and Maker communities with an emphasis on engaging diverse learners [1]–[4]. Throughout CT4G, girls engage with a varied syllabus of computational projects, including activities allowing them to work with physical computing devices, express themselves through 3-D printing, and participate in embodied simulations using open-hardware, programmable badges. CT4G's conception of Making includes not only the individual construction of physical artifacts but also immersive participatory simulations where learners use *themselves*, augmented with technology, as the building material to collaboratively simulate networks, circuits, and other complex systems. Using engaging materials and hands-on activities and exploring, introductory computing topics including big data, Web programming, and agent-based modeling, this course provides a wide array of pathways into computing, introducing learners to powerful computing ideas while aiming to shift perceptions of the field of CS. The goal of this paper is to add to the growing body of literature exploring ways to leverage emerging technologies and innovative pedagogies to broaden participation in computing. The specific contribution of this paper

is to describe how a yearlong course that uses diverse computing activities and technologies can succeed in this larger goal. More concretely, this paper shows how Making, social computing, and participatory simulations can provide a compelling introduction to computing in a high school setting.

This paper begins by reviewing the literature that informs the design of the CT4G program, including recent shifts in computing standards focused on widening the scope of CS, efforts to broaden participation in computing via innovative and engaging software environments, and the growing body of work looking at Making as a context for nontraditional learning [2], [3], [5]. It continues with a description of the CT4G project, including its motivation, learning objectives, and brief descriptions of some of the activities used in the course, to highlight the diversity of the program. It then provides a snapshot of one of the CT4G activities, *Wearing the Web*, which highlights one way that CT4G uses Making, the Internet of Things, and participatory simulations to engage learners in computing. Next, it reports on findings from the first year of CT4G, showing how participants' attitudes toward computing shifted, and documenting their increased interest in pursuing future CS learning. Finally, this paper concludes with a discussion of the strengths and limitations of CT4G and its approach of situating computing in diverse contexts as a way to create multiple pathways into CS.

II. LITERATURE REVIEW

A. Broadening Participation in Computing

Concepts and practices from computational fields are becoming essential for all learners in an increasingly digital world. Despite its growing importance, CS education has historically struggled with attracting female and minority students [6]–[9]. Among the factors contributing to these trends, researchers have identified lack of interest and confidence [10], limited visibility of positive role models [11], [12], and lack of positive experiences with CS [13], [14].

Efforts to increase enrollment among both female students and students from historically underrepresented groups take a number of forms, including new national curricular efforts, the design of new programming environments that emphasize creativity and collaboration, and a wide array of out-of-school programs oriented toward engaging a diverse set of learners.

In response to the shifting nature of computing in society, and the need to attract a larger and more diverse student body into computing, a range of major curricular and standards efforts have been undertaken. As part of their decennial effort, the IEEE/ACM Joint Task Force on Computing Curricula introduced a number of new components to their recommended CS curriculum [15]. Central to this revision is a "big tent" view of CS, explicitly welcoming computing in all its varied forms into the discipline. Similarly, there are efforts designed to make students aware of the broad applicability of CS, as well as to emphasize the importance of "soft skills," such as teamwork, communication, and an appreciation for diversity, in professional computing contexts.

Within schools, curricular efforts with the explicit goal of reshaping introductory CS classrooms are also underway. For example, the exploring CS (ECS) curriculum is designed to broaden participation in CS by emphasizing aspects of computing such as Web design, data analysis, and robotics, and by foregrounding the human and social aspects of the domain [16]. While programming is still a component of the ECS curriculum, it is not the main focus, as has historically been the case in introductory CS coursework. Furthermore, ECS is designed to emphasize inquiry, culturally relevant curricula, and equity-oriented projects [17]. A second curricular example can be seen in the recently approved AP CS Principles course [18]. Like ECS, this course frames computing as a creative endeavor, highlighting the broad applicability of the concepts, practices, and skills that learners develop in studying CS. Finally, a third approach to reaching a broad range of learners with foundational CS ideas that is also gaining attention is to embed these concepts into existing mathematics and science courses [19], [20] or across the broader K–12 curriculum [21].

There are also a growing number of learning environments, technologies, and programs being designed to address diversity issues in computing. Low-threshold programming environments such as Scratch [22], Alice [23], and Pencil Code [24] have emerged, which use novel programming interfaces that make it easier for novices to program with little or no prior experience. Across these and similar environments, programming is framed as a creative activity, allowing learners to develop games, interactive stories, and websites that can easily be shared with others. Such efforts have indeed been shown to attract diverse learners who are historically underrepresented in CS [25], [26].

Along with software initiatives, a growing number of camps, workshops, and after-school programs are turning to physical computing as a way to draw learners into CS. For instance, the Lego Mindstorms robotics kit has been found to engage learners from low socio-economic communities [27]. A second example is the Lilypad Arduino, designed for use with conductive thread to create responsive and interactive electronic textiles, which have been found to engage girls in historically male-dominated aspects of CS [3].

B. Making in Education

Emerging from roots in constructionism [28], the Maker movement emphasizes digital fabrication and supporting learners in creating personally relevant artifacts, while leveraging important STEM tools and practices [1], [29]. As Vossoughi and Bevan [29] suggested, Making can be categorized in terms of three themes: 1) entrepreneurship; 2) pathways into STEM fields; and 3) inquiry-based practices. At its heart lie the practices of ideation, design, and production of physical and virtual artifacts—drawing inspiration from hackers, designers, and innovators. Advocates claim that Making and "tinkering" blend professional practices at the intersection of science, technology, engineering, art, and mathematics (STEAM) [30]. Research conducted on Maker Spaces and similar learning environments suggests that inquiry-based

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Making fosters a wealth of educational and sociocultural benefits [29], particularly when adopted critically [2]. To better understand this movement, one must examine its educational lineage.

Though the movement leverages many of the newest technologies and practices, it also mirrors some of the earliest modern theories of education and human activity. Theorists like Dewey, Froebel, Montessori, and Papert argued that learning should be physical, playful, self-directed, and reflective of everyday practices [1], [31], [32]. Maker Spaces foster sociocultural learning that emphasizes collaborating, sharing tools and ideas, helping and providing feedback to peers, and communicating openly about projects [31], [33], [34]. Computational Making emerged from the Constructionist approach to learning and design [28], [32]. Constructionist environments empower learners to take charge of their own learning by creating personally meaningful public artifacts.

The constructive act, along with the process of learners publicly sharing and discussing their constructions, can support learners in refining and reorganizing their ways of thinking [28], [32]. For a learner, Making offers a unique opportunity to investigate personally relevant ideas with diverse tools and practices, supporting the development of interest, identity, agency, and expertise [29]. Practices involved in Making foster conceptual understanding, STEM skills, scientific exploration, and connections to real-world science practices [35], all of which can further support critical thinking, reasoning, and innovation [36]. Making is often situated in a community of like-minded learners with diverse interests, which helps to facilitate positive relationships among learners, with new practices, and with STEM content, while cultivating flexibility, initiative, and metacognition [36]. As Tai *et al.* [37] suggested, young learners feel a greater connection to a community they are working within when they are interested and when they perceive an alignment between the activities and their sense of self. Making can thus have great implications for the ways that learners identify with a domain, partly predicting whether they will later pursue a career in that field [37]. On one hand, Making has historically attracted white males [29], and there are legitimate concerns about some connections of some elements of the movement with commercial and culturally dominant ideologies. On the other, the growing breadth of Making activities, including projects like the e-textiles work discussed above, has made great strides in broadening participation. The CT4G program is informed by a critical adaptation of this paper, sharing many of the goals and practices of the Maker movement, including interest-driven investigation, expressive construction and fabrication, and an environment that fosters a community of active, collaborative learners. CT4G also seeks to leverage other successful practices that may support a deeper understanding of CS concepts.

C. Embodied Social Simulations

A third body of research that informs CT4G, and its design of activities to broaden participation in computing, concerns Participatory Simulations, or PartSims [38], [39].

PartSims involve classroom groups in enacting scientific phenomena through coordinated role-play. In a PartSim, students behave and interact according to the roles of the components they are playing, while the classroom as a whole experiences systems phenomena and behaviors as they emerge. PartSims thus can offer "firsthand" experiences of important phenomena that exhibit both micro- and macro-level behavior. Moreover, they establish key shared experiences among the group of learners.

The historical roots of PartSims reach back to early work by [40] that involved groups in simulations of social and economic systems without the support of computational tools for representations or networks for communication and data aggregation. In the late 1980s and early 1990s, Resnick and Wilensky [41], [42] began building on Logo to construct environments for groups of learners to engage with and reasoning about complex systems with many agents. PartSims in this tradition were deployed at conferences and in educational settings in the mid-1990s, where participants played the role of systems agents, moving and exchanging "messages." They could then witness global patterns emerging from their local interactions, which were aggregated in illuminating visualizations of the simulated system as a whole. With the creation of NetLogo [43], both researchers and learners could model multiagent complex systems using personal computers. Wilensky and Stroup created the HubNet module of NetLogo a platform that enabled virtual PartSims to be easily developed in a distributed computing setting [39], [44].

1) Connections With Research in Wearable Computing: In developing activities for CT4G, an opportunity was identified to combine PartSims as enabled by HubNet with the programmable, hardware-hackable microcomputer technology that has partly driven the Maker movement. To explore this hybrid opportunity, a programmable badge was developed in collaboration with a corporate partner (Fig. 1). This enabled a connection between the social learning typical of the PartSims tradition and prior work in wearable computing.

Wearable smart tags first appeared in the corporate sector as a means to provide tracking information about people and objects of interest [45]; it was not until later that researchers began to incorporate more symmetric (peer-to-peer) and active (versus passive) communications technologies and apply wearables to learning. MIT researchers introduced Thinking Tags [46] to take this step and to explore wearables' potential to facilitate interactions between people. These tags were deployed at conferences, where participants could configure them by "dunking" them in electronically instrumented containers that corresponded to responses to multiple-choice questions. When two tags interacted, they would exchange information and flash a pattern of LEDs, reflecting matches in their wearers' responses and thus supporting and stimulating meaningful social interactions. MIT's Meme Tags advanced this trend further by making tags more easily programmable and by aggregating, analyzing, and displaying social media data (e.g., the participant with most interactions) in public displays that acted as "community mirrors" [47].

2) Wearables and PartSims: This wearable computing research intersected with the PartSims research above, including uses of the MIT tags for PartSims in high schools, where students were found to draw heavily on prior experiences, knowledge, and interests [38]. In the late 2000s, work in this tradition continued using Palm Pilots and other handhelds [48], but PartSims with wearable computers did not receive sustained attention. This was in part due to the emphasis on developing the easily programmable microcontroller platforms needed for the Maker movement, and in part due to an approach to computing that foregrounded individual versus collective constructions.

PartSims in CT4G thus revives a research tradition, using new, open technologies to explore hybrid physical-virtual learning environments [49]. The CT4G context is particularly suited to this approach, emphasizing community and resonating with the perspective of [50] that wearables should connect physical and virtual experiences through "augmentation," rather than reinforcing a separation between them. CT4G's social emphasis also plays a pivotal role: Whereas wearable technologies like Google Glass or Oculus Rift augment the *individual's* experience of an activity, badge-based PartSims augment the *interactions between* human participants. In terms of the network of human participants in an activity, wearables like the Rift enhance the experience for the individual network *nodes*, while wearables like the badges enhance the nature of participant interactions—the *links between* nodes. Furthermore, by offering both public and private displays based on those communications, badges enable the shared experience of an *augmented social reality* to emerge. Wearable computing in general has recently taken a social turn and moved away from individualistic uses of technology [51], and CT4G's take on PartSims represents a particularly strong emphasis on the social dimension of wearable technologies.

III. COMPUTATIONAL THINKING FOR GIRLS

This paper argues that a promising way to engage students from historically underrepresented populations in computing is by offering an array of computing activities that invite participation and highlight the diversity of the field. To explore this hypothesis, the CT4G program was adapted as a *colloquium*, or hands-on seminar, at a selective-enrollment, urban public high school in the Midwestern U.S. It was open to students from 7th to 12th grades and held once a week in 100-min sessions. The girls-only context was made possible with the support of the school administration, which had identified increasing the diversity of students engaging in computing as a priority. Activities were orchestrated and facilitated by the second author, drawing on ongoing design research projects of a diverse set of researchers from the Center for Connected Learning and Computer-Based Modeling (CCL) at Northwestern University. These were structured in a series of short units (from one to four weeks long) designed to engage the girls in different aspects of CS through innovative and socially relevant computing activities.

The CT4G name invokes "computational thinking" (a term created by [52] and popularized by [53]). Using this name serves a number of purposes, including: 1) distinguishing the course from existing CS courses that focus on programming; 2) aligning its goals with other computational thinking initiatives (e.g., the Next Generation Science Standards use the same term); and 3) highlighting the broad applicability of ideas treated in the class. Throughout the class, links between computational thinking and CS are stressed.

The course design and philosophy also draw on principles and classroom culture from learning by design [54]. Project activities are designed to allow students to explore complex concepts and problems without prior introduction, while working individually or in small groups, through open discussion and manipulation of materials and devices used to complete the project challenges. Students are guided through iterative cycles of designing, testing, explaining, and redesigning to refine their understanding and project products.

Throughout the year, students engage in social computing activities, PartSims, agent-based modeling, and an array of physical computing and Making activities, including using wearables, programming Arduino-compatible hardware, and creating 3-D printed artifacts. One of these activities is described in detail in Section III-A; it is representative of the larger curriculum in how it engages learners with fundamental computational ideas in a hands-on, innovative way, bringing together wearable technology, Making, and PartSims to provide a new pathway into CS.

A. Design of the Wearing the Web Activity

The *Wearing the Web* activity offers a snapshot of CT4G, illustrating some of the key design themes of the program. It is a PartSim that engages a group of learners in collectively simulating and reasoning about the network communications that enable instant-message (IM) applications. While doing so, students encounter foundational CS ideas including abstraction, data representation, and dimensions of human–computer interaction. The activity also introduces learners to tangible computing through the use of the CCL-Parallax programmable badge (Fig. 1). These badges were co-designed by the CCL and Parallax, Inc., for the CT4G program and other similar research projects; the activity as described below was the first-ever classroom implementation of the badges. The badges offer a low-threshold entry point to physical computing, coming equipped with various sensors, input ports, a 128×64 pixel display, and an infrared transmitter and receiver, allowing them to communicate with each other. Using these badges, computing activities can become mobile, social, and collaborative, as well as inviting tinkering and customization on both hardware and software fronts [49].

There are three distinct roles, with corresponding badge types: 1) network endpoints; 2) data packets; and 3) routers. Each student fulfills one of these roles, interacting with others through the badges' infrared communications. Collectively, the group simulates a network that supports messaging. In the process, they build intuitions about network behavior and see firsthand how CS underpins technologies they use every day.

Students acting as network endpoints play the role of human users of the IM application. Their goal is to send and receive

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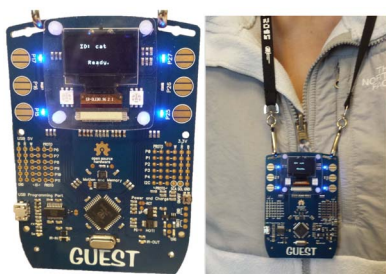

Fig. 1. CCL-Parallax programmable badge.

messages over the system; they are stationed at computers that are connected to badges and offer a simple IM interface. To send a message, a network endpoint chooses a recipient and establishes a data link via infrared communications with a student playing the role of data packet. The IM message is sent via the badges' infrared communications, in a bundle containing the logical address of the recipient and the encoded message payload.

The problem that the IM application as a whole must solve is to locate the physical address of the recipient, based on the logical address. The information needed to solve that problem is distributed among the routers in the network.

On receiving a message from an endpoint, a student in the data packet role enters the network and proceeds to the nearest available router participant. When a data packet interacts with a router, her badge "beams" the logical address of the message it is bearing. Router badges have partial lookup tables that match *some* of the logical addresses in the network to physical addresses. Thus, the router may or may not know the physical address of the destination, depending on whether the entry is in her table. However, if she does not know the physical address, the router does know the location of another router to which she can refer the data packet.

After a data packet goes through several "hops" (a count is displayed on her badge), she is finally directed to an endpoint. Arriving there, she transmits her message, and if the logical address is a match, the payload is transmitted and decoded, and its contents are shown on the endpoint's terminal screen, successfully delivering the IM message.

In the first round of this PartSim, the collective goal is simply to create a functioning IM application. After the group has stably achieved this goal, the activity is interrupted for participant discussion. Each student's experience contributes to shared understandings of the network, building ideas such as "bandwidth" and "congestion."

In a second round of the activity, a wrinkle is added: The router participants are given a budget of *lies*, allowing them to data packets to other routers if they choose. The effects of this new rule on message transmission are detectable both qualitatively and quantitatively. For routers and data packets, the network becomes noticeably more congested. Network endpoints notice that messages can take much longer to arrive. Moreover, the data packets' hop counters begin to show counts of 4–6, whereas in round one the counts higher than 3 were rare. After several minutes of running messages through this network, the activity is again interrupted to allow students to discuss the experience. Again, the different perspectives contribute to shared understanding. Routers can connect their particular misdirections to local network effects. Data packets report that often no routers were available for them and that they had to queue up for access. Participants noticed congestion and stopped bodies in the middle of the room, yet it is also true that the data packets did eventually get through, indicating a degree of robustness in the network.

B. Outcomes of the Wearing the Web Activity

This activity illustrates how learners engage with powerful computing ideas in an embodied, social manner in CT4G. First, the PartSim is grounded in a social technology context of which all of the participants have firsthand experience: communicating with friends (whether through texting, instant messaging, or on social media platforms). The social aspects of CS are thus highlighted, drawing a direct link between the domain and their daily experiences. Second, the inherently collaborative nature of the PartSim activity, and the fact that each individual is dependent on others to accomplish the shared goal, highlights the collaboration emphasized in CT4G and essential to much work in CS. The activity directly confronts the misconception of CS as a solitary activity and more realistically paints the field as a collaborative, social endeavor. Third, by making their own network, CT4G students develop an understanding of how the Internet works as a distributed system, and how its decentralized nature is responsible for some of its greatest strengths (including robustness, reliability, privacy, and security). In this way, students collectively engage with powerful ideas of computing by simulating a familiar application. Finally, through the use of the CCL-Parallax programmable badges, the activity introduces learners to tangible computing, highlights different capabilities of such devices, and lays the groundwork for various Making and tangible computing activities that follow in CT4G. This further aids in reshaping their perceptions of CS to include tangible computing and the Internet of Things as contexts in which to engage with CS ideas. As a snapshot of the program, *Wearing the Web* illustrates CT4G's approach of drawing on tangible computing, emphasizing social interactions, and connecting to the digital lives of today's learners to create new and engaging pathways into computing. The activity also mirrors features of CT4G as a whole, positioning girls as a group of Makers engaging collectively with core CS concepts.

IV. FINDINGS

This section reports on findings from the first year of the CT4G project and on preliminary findings from the second-year implementation. As mentioned above, CT4G was adapted as a colloquium in a selective-enrollment, urban public high school in the U.S. This school's population is 72% African-American, 25% Hispanic, and less than 2% each white and Asian, a distribution that is reflected in the CT4G classes. Sixty-seven percent of students in the school are from low-income households. In the first (pilot) year, 13 girls participated in the colloquium. Teachers and administrators

recommended the girls for participation, but enrollment was voluntary. As an elective, CT4G competed with a variety of other colloquia (e.g., fencing, robotics, service to the homeless, sewing, and biology study support) that fell outside the required coursework.

This paper presents the experience and results of CT4G as a pilot program, using a combination of quantitative and qualitative data to show its potential for shifting perceptions of CS and providing meaningful pathways into computing. For the purposes of assessing changing attitudes toward CS and computation, CT4G used a survey instrument shared with a project studying attitude changes among a larger sample of students in the region. Thus, while the 13 pilot students constitute a small sample, the instrument was used in parallel with a larger group that included males and females.

In CT4G, this survey was administered as a pre- and post-measure of the girls' changing attitudes toward CS and STEM, identifying their perceptions of these fields and their interest in pursuing careers in computing or STEM disciplines. The post-survey included additional questions prompting students to reflect on their experience in CT4G. Between pre- and post-administrations, data show a positive trend in the girls' perceptions of computational thinking and CS and a significant rise in their interest in careers related to CS and computational thinking ($z = -2.127$, $p < 0.05$). Moreover, data emerging from CT4G's second year also have suggested a positive trajectory for the approach [55].

In the post survey, when asked to describe the class, one student wrote: "[CT4G] *is a class that is really fun and you [learn] a lot about computers. It really broadened my horizon on thinking.*" Similarly, when asked about how CT4G concepts could help them, 25% of the students explicitly mentioned new ideas about potential future career paths. For instance, one girl who was considering taking computer courses said, "[this class] *sparked my interest even more!*" Another third of the students who responded said the concepts learned would help them with future courses, including both CS and general STEM coursework.

The surveys were augmented with other qualitative data, including transcribed interviews with students, researcher field notes, and participants' digital artifacts. These were collected to identify and study the features of the pilot that resonated with the girls, and have been used to inform CT4G's development and to conceptualize its design principles. Student quotations and vignettes are presented here to describe the CT4G experience, but no claim is made that these data are representative of all students' experiences with CT4G as a whole. Indeed, variability is an important feature of CT4G—different students are engaged by different activities among the variety of pathways into CS that the program offers.

Student projects revealed ways that the girls responded to the CT4G curriculum by personalizing practices of computer scientists. Across the activities, girls incorporated their own interests into the course assignments. For example, as part of a three-week programming-on-the-Web unit, they were challenged to author an interactive website that incorporated iterative logic. One of the girls recreated her favorite Justin Bieber song, "Baby," by writing a program to animate the chorus of the song. She used iterative logic to move through various pictures of babies drawn from the Internet, culminating in a picture of Justin Bieber. When the students in the class were given a chance to share their work, this student eagerly presented her work, getting the class to join in and sing along with her and the program. This serves as one example of how providing opportunities to situate computational ideas in contexts with personal and social relevance can serve as a promising pathway into computing.

Students also created personally relevant artifacts by tinkering with and adapting existing tools they encountered. For example, during an introduction to NetLogo modeling using a model of wolf–sheep predation, one girl ventured to explore the code, making small changes to the shape and color of the agents in the model. Following her lead, other students intervened in models as they were running. For example, they introduced and explored questions about the effects of seasons and natural disasters by changing the color of the "grass" to white (to simulate snow in winter) or to blue (to simulate flooding). The overarching goal of the activity was to explore predator–prey systems, and the girls were able to modify the program and the activity to be more personally relevant and engaging for them, exploring issues that held personal interest. In each case, students who initiated innovative explorations quickly shared their programming findings with peers, provoking collective inquiry. Additionally, this exploratory use of computational modeling software continued to reinforce connections between computing and other STEM fields, emphasizing the broad applicability of CS tools and concepts.

These brief vignettes show examples of how computing can align with, and leverage, existing student interests and ideas to enable new forms of Making and computational participation. In doing so, CT4G can shift both how learners view the field of CS and, more importantly, how they view their own position relative to computing and participation in computing culture. Other activities in CT4G provided learners with shared learning experiences that introduced the use of tangible computing technologies as contexts to explore key CS ideas. For example, *Wearing the Web* not only emphasized collaborative social interactions enabled through tangible computing, but it also engaged with foundational ideas of networks on the Internet. This activity also illustrated the connections drawn by CT4G between social Making and computational innovation. The fact that this activity was the *first-ever* use of the new CCL-Parallax badges made the experience even more significant to the girls. They were so excited at the prospect of giving input as the first users of the new technology that the early segment of the session was dedicated to discussing what it meant to the girls and how, over the course of the year, they would continue to tinker with some of the newest tangible computing tools available. Beyond piquing their interest for the Making to come in the course, the activity provided girls with a co-constructed understanding of the Internet that they used to reflect on their own online experiences. They applied these networking concepts to other personally relevant contexts, such as how networked printers receive documents and how police are able to search for someone's record after pulling them over (both of these

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links were made by the students). Linking the activities in the course to the real world was viewed as a strength of the class; as one student said, the activities "*were applicable, not just like, here's this random problem that you'll never encounter in your life.*" This was echoed by a second student who said, the stuff they learned in class was "*was like real life stuff too, so that was cool.*" As an example of the CT4G approach, *Wearing the Web* highlights how technology can mediate and support learners in their collaborative exploration of CS concepts, and it demonstrates the broader learning goals and practices that CT4G showcases. In general, CT4G seeks to position girls as collaborators engaged in learning, investigation, and development while still providing a fun environment in which they can explore their personal interests. This collaborative aspect of the class also contributed to the perceived authenticity of the activities, as one student said "*most of it [was] collaboration-based. That's how it is in the real [world] ... you have to work with people.*"

A final piece of data that suggests the success of CT4G is the growth in enrollment from year one to year two of the colloquium. The pilot year consisted of a single section of 13 students. At the request of the administration, a second section was added in year two, when 47 girls participated, with the majority enrolled through teacher or administration nomination. Furthermore, all but five of the students from year one elected to rejoin CT4G in year two. Of the five who did not return, one changed schools and three elected to receive supplementary academic support on a schedule that conflicted with CT4G. Finally, the growth in CT4G enrollment in year two happened almost entirely through word of mouth, as no active recruitment was done at the school by the research team. All these data are consistent with students' having a positive reaction to the CT4G approach and are evidence that students found the course materials engaging and valuable.

V. CONCLUSION

The CT4G environment offers an exciting bridge between formal and informal learning environments. On one hand, it is an interest-based club that is conducted in an informal manner, and with participants choosing to remain in the colloquium after being nominated. On the other hand, it takes place in a computer laboratory of the school during school hours, and attendance is taken. This combination makes CT4G an optimal setting for designing and refining activities that leverage the diverse interests of participants, and yet it also ensures a high degree of continuity and engagement among the group of girls. The girls themselves saw the course as both similar to and different from normal classes, as one student said at the end of the first year: "*it was this really different environment. It was more of a learning environment than a school...walking into CT4G is more like, okay, what we're going to learn today?*" In such a setting, group-level social activities like *Wearing the Web* can thrive, giving the girls the opportunity to think *together* about fundamental issues in CS. At the same time, open-ended individual activities, like the units on modeling and Web programming, provide learners the opportunity to express their own ideas and interests, be it through exploring modeling questions driven by curiosity or writing programs

of their favorite pop stars' latest hits for the class to sing and dance to.

Though the CT4G model is still being refined, the growth in enrollment in the CT4G colloquium, in conjunction with the attitudinal gains identified and the evidence of shifting views on computing observed in course projects, collectively suggest the power of providing multiple pathways into computing. By incorporating Making, tangible computing, and PartSims, along with creative, socially meaningful, and collaborative activities, this paper shows how the growing diversity in the nature and scope of computing in the 21st century can serve as a powerful context to engage historically underrepresented populations in computing. In doing so, learners become better informed about what it means to be a computer scientist and better prepared for the computational futures that await them.

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