JrnlID 11412_ArtID 9249_Proof# 1 - 24/02/2017

Intern. J. Comput.-Support. Collab. Learn
DOI 10.1007/s11412-017-9249-7

DCLM framework: understanding collaboration in open-ended tabletop learning environments

Mike Tissenbaum[1] **· Matthew Berland**[2] **· Leilah Lyons**[3]

Received: 23 November 2015 / Accepted: 20 February 2017

Abstract There is a growing understanding of the unique ways that tabletops support effective collaboration; however, this research mostly focuses on environments in which learners work towards a single shared goal. Underpinning this perspective, either implicitly or explicitly, is the theory that collaborative learning is a process of attaining convergent conceptual change. However, this model of collaboration may not apply to all scenarios where learners are working together. In particular, informal, open-ended exploratory environments support (and often promote) shared activities where the goal may not be for all participants to emerge with a single, shared understanding. There is increased interest in understanding the efficacy of designs that support (and encourage) learners to collaborate while seeking divergent goals, ideas, and conceptions. This paper advances a framework (Divergent Collaboration Learning Mechanisms - DCLM) for recognizing and coding collaboration and divergent learning in such environments. We apply the DCLM framework to an informal tabletop environment (*Oztoc*) as a means of highlighting how DCLM may reveal new productive interactions environments that support divergent forms of collaboration, mentorship, and learning. Analysis of participants' interactions within *Oztoc* revealed that participants who have non-aligned goals can still productively collaborate, and in many cases can provide insight and feedback that would not be possible in shared-goal activities. We conclude with an examination of how open-ended exploratory environments can support communities of

✉ Mike Tissenbaum
miketissenbaum@gmail.com

Matthew Berland
mberland@wisc.edu

Leilah Lyons
llyons@uic.edu

[1] MIT Center for Mobile Learning, 32 Vassar St., Room 32-386, Cambridge, MA 02139, USA

Q2 [2] Department of Curriculum and Instruction, University of Wisconsin–Madison, Madison, WI 53706, USA

[3] Learning Sciences Research Institute, University of Illinois Chicago, Chicago, IL 60607, USA

practice and legitimate peripheral participation, and the importance of divergent inquiry and divergent conceptual change across a range of learning environments.

Keywords Interactive tabletops · Collaboration · Museums · Informal learning environments

Introduction

There is a growing interest in the learning sciences to understand how interactive tabletops and tangibles can afford new opportunities for people to collaborate and learn (Dillenbourg and Evans 2011; Rick et al. 2009; Tse et al. 2007; Marshall 2007). Tangible and tabletop learning designs span both formal and informal spaces and involve a wide range of activities including browsable collections of content (Geller 2006); collaborative poster and concept map building (Shen et al. 2003; Collins et al. 2012; Martínez Maldonado et al. 2010); math and science experiments (Mercier and Higgins 2013; Yoon et al. 2012); and simulations and games (Jermann et al. 2009; D'Angelo et al. 2015; Lyons et al. 2015). These are all very different types of collaborative tasks, and as such, researchers and designers should be careful about trying to understand "tabletop interaction" as a unified construct. Interaction designs that support one type of shared tabletop activity may fail to apply to other types of shared tabletop activities, and interaction analyses that shed light on one type of collaborative tabletop activity may not expose the most salient aspects of another collaborative tabletop activity. In this paper, we present a perspective for recognizing and understanding an under-recognized form of tabletop interaction, *divergent collaboration,* which is especially salient for open-ended tabletop learning activities.

Most researchers acknowledge that collaboration around a tabletop is complex and, in response, have created frameworks to better (and more systematically) describe how participants interact around tabletops. Most of the frameworks assume that groups will be engaged in joint activities around a tabletop in which participants are pursuing a singular collective goal, such as: using a museum exhibit to co-design how a community manages energy (Antle et al. 2013); negotiating the seating arrangement in a new office (Hornecker et al. 2008); or deciding on how desks should be arranged in a classroom (Fleck et al. 2009). This type of collaborative task can be characterized as having relatively 'tight coupling' (Pinelle et al. 2003; Nova et al. 2007), as the users' inputs are interdependent and the outcome is shared for all users. Due to their shared outcomes, "effective" collaboration in tightly coupled tasks is often characterized, either implicitly or explicitly, by participants attaining convergent conceptual change (CCC, Roschelle and Teasley 1995), meaning that the participants come to a shared understanding of the task, its goals, and what constitutes satisfaction of those goals. However, this model of collaboration does not apply to all scenarios where learners are working together. In particular, informal open-ended exploratory learning environments often support (and promote) shared activities where the goal is not to have all participants emerge with a single, shared understanding. For example, many museums have "maker spaces" where visitors are encouraged to produce their own idiosyncratic creations using supplied materials like circuit components, cardboard, and tape.

Tabletop applications are most commonly designed to support tightly coupled tasks (in which actions by one participant have a direct effect on the work of others), but they can also be designed to support "loose coupling" (i.e., individuals' actions do not necessarily have a direct effect on the actions of others), allowing for independent, parallel task execution (e.g., Sugimoto et al. 2004) and for learners to develop and evolve their own goals for the interactive experience (Lyons et al. 2015). Many early design recommendations for tabletop applications included supporting independent task execution as well as joint task execution (e.g., Morris et al. 2004; Scott et al. 2003), but existing frameworks for describing interactions at collaborative tabletops do not emphasize the role of parallel independent task execution within collaborative activities and can mask the presence of parallel activities.

This paper argues that many open-ended collaborative learning activities (such as those which include tinkering, exploration, building, or iterative design) may benefit from more explicit attention to how independent work can intersect with group work. To that end, we are proposing a new framework called the Divergent Collaborative Learning Mechanisms, or DCLM, framework. DCLM is derived from the Collaborative Learning Mechanisms (CLM) framework proposed by Fleck et al. (2009), which in turn is rooted in the Mechanics of Collaboration (Pinelle et al. 2003), an early way of representing collaborative work scenarios so that they would be amenable to usability task-analyses. While the CLM framework highlights many of the subtle forms of learning and collaboration supported by interactive tabletops (Fleck et al. 2009), it does so within a narrow definition of participant roles and goals. In the design case Fleck et al. analyzed using CLM, and subsequently evaluated, the goal was strictly defined (having a group of students decide where to place tables and students in a classroom), and participants were tasked with jointly achieving the goal (the students had to come to a solution together and only one solution for the group was possible), making it a tightly coupled collaborative activity. While this type of design is valuable, and in many cases desirable, it casts a narrow view on the kinds of learning designs afforded by tabletops. In open-ended, exploratory learning designs, goals are often individualized, idiosyncratic, and fluid, emerging and evolving as each learner interacts with the "curriculum" and his or her peers rather than defined a priori (Lyons et al. 2015). In these open-ended activities, the loose coupling of participant actions opens up a wider range of potentially productive collaborative behaviors. We need a method for documenting these collaborative behaviors that embraces their inherent characteristics.

As such, we claim that extending the Collaborative Learning Mechanisms (CLM) framework to encompass open-ended tabletop collaborations and, more generally, the role of tabletops within a distributed sociotechnical space, will widen the scope of collaborative tabletop activities that can be studied. We introduce the Divergent Collaborative Learning Mechanisms (DCLM) framework as a means for widening the lens on collaborative activities at tabletops to include activities in which learners can shift between solo and shared work, and in which learners are free to define, co-define, redefine, and diverge in their goals. By focusing on cases not captured by the CLM framework, this paper (and the DCLM framework) helps to highlight a broader spectrum of productive collaborative behaviors within open-ended, exploratory activities in which participants can pursue divergent goals.

Background

Frameworks are useful intermediaries between theory and practice in the learning sciences: they encode the theoretically-relevant learner behaviors in a format that allows both researchers and educational designers to witness those behaviors when enacted in context. To set the stage for our Divergent Collaborative Learning Mechanisms (DCLM) framework, then, we need to be specific about the *theories* upon which the framework is built, and the *context*

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within which we propose to witness the targeted the learning behaviors. In this section, we thus review existing theories of collaborative learning and theories relevant to open-ended, exploratory learning. We also review research that sheds light on the context of our learning activity: what we know about how collaborative learning unfolds in informal settings; and what we know about how digital interfaces can shape and influence collaborative learning. Finally, we review existing frameworks for characterizing collaborative activities at digital tabletops, to illustrate the contribution of DCLM.

Grounding DCLM in theory

Collaborative learning theory

Collaborative learning has been defined in any number of ways both before and since it became a field of study in its own right (Dillenbourg 1999), but it is generally understood to include any activity where two or more learners attempt to learn something together. Because this definition is so broad, educational designers must be precise about characterizing learning scenarios that they wish to support, and learning researchers must be highly sensitive to how they frame collaborative learning and associated activities. Some researchers have made distinctions between types of collaborative learning by differentiating cooperation from collaboration (Dillenbourg 1999; Stahl et al. 2006). In this division, cooperation represents a process where individual learners engage in separate subtasks and later assemble their products into a whole. By contrast, when learners are engaged in collaboration they are engaged in the joint and sustained co-construction of shared knowledge. This latter definition of collaboration leans heavily on Roschelle and Teasley's (1995) theoretical characterization of collaboration as a process of convergent conceptual change, meaning that as learners collaborate with one another, their individual conceptions of the problem space and problem solution evolve to be more similar to their learning partners' conceptions (this can be either a unidirectional or a mutual process of evolution). The CLM framework was based in part on Convergent Conceptual Change (CCC), with the assumption that the goal of the learners' collaboration is to come to a mutual understanding.

The concept of CCC is grounded in both situated and distributed theories of cognition, which in turn are derived from earlier sociocultural-historical theories of human activity (Leont'ev 1978; Vygotsky 1930/1978). This strand of learning theory stresses the importance of society, culture, and context in shaping what individual learners can do. Situated cognition posits that knowledge is "inextricably a product of the activity and situations in which [it is] produced. A concept, for example, will continually evolve with each new occasion of use, because new situations, negotiations, and activities inevitably recast it in a new, more densely textured form" (Brown et al. 1989, p. 33). Hutchins' (1995) model of distributed cognition posits that knowledge is contained not within people's heads, but within a system of people and artifacts found within a scenario. This theoretical grounding has significant implications for any research into CCC: researchers wishing to frame collaborative learning using a convergent conceptual lens must attend to the nature (and activity) of the artifacts in the space and characterize (or at least attend to) learning at the grain size of the group (Stahl et al. 2006).

Via the CCC lens, communication is seen as evidence of the state of the group's learning (i.e., their convergence). The persistence of divergent ideas in a group's conversation may be then seen as a marker of poor collaboration. In exploratory and open-ended learning settings, however, divergence in ideas can actually increase opportunities for learning, as differences press learners to elaborate and define their creations (and goals) in juxtaposition to the creations (and goals) of others (Turkle and Papert 1990). As this paper illustrates, circumstances in which learners move *away* from a shared goal via adaptation and differentiation are potentially very fruitful for learning – albeit individual learning in a group setting. A CCC lens suggests examining the state of artifacts for additional evidence of convergence, with the implication that when learners' artifacts are more similar to one another, learning has occurred. Once again, DCLM suggests the opposite tack – through a more open-ended, exploratory lens, divergent artifacts provide learners with the opportunity to learn new approaches and adapt them to their own ends. In exploratory collaborative settings, divergent artifacts provide opportunities for learners to seek help from one another and recognizing when another learner is doing something that they have not. The presumptive mutuality of CCC poses other challenges for characterizing the collaborative learning in informal, free-choice learning settings, as the next section will review.

Constructivism and constructionism: theories relevant to hands-on, open ended tinkering

The dominant pedagogical approach found in free-choice science and technology museums is what is often called "hands on" learning activities. Loosely grounded in constructivist learning theory, "hands on" learning activities have learners physically manipulate learning materials with the intent to both increase engagement and support personal knowledge construction. Hands-on learning pedagogy thus often overlaps with other design-based learning frameworks. Design-based learning frameworks (such as constructionism, Papert and Harel 1991, or learning-by-design, Kolodner et al. 1998) broadly suggest that making, tinkering, and other creative technical work are excellent learning opportunities for groups (Vossoughi and Bevan 2014), disciplinarily authentic for science and engineering (Berland et al. 2013; Berland 2016), and encourages divergent thinking (Turkle and Papert 1990). The focus on the building and refinement of artifacts, through tinkering (Gutwill et al. 2015), messing around (Ito et al. 2010), remixing (Ito et al. 2010), echoing (Wielgus 2015), or creative exploration (Peppler et al. 2016) has been shown to support learning disciplinary practices. There is a growing recognition that in order to support learners in learning about STEM topics, we must support the development of disciplinary practices in addition to domain content (Berland 2016; Daskolia and Kynigos 2012; Whitman and Witherspoon 2003; Wilson 1996). Constructivist theories of knowledge suggest that in order to develop disciplinary practices, learners must be contextually engaged in those practices (Bransford et al. 1999). In particular, work on disciplinary practices in open-ended creative learning has suggested that tinkering, with its cycles of design, construction, evaluation, and redesign, can provide learners with a set of practices that both mirror those of domain experts (Wang and Agogino 2013) and prove useful on their own (Berland et al. 2013). Additionally, the work of Horn and Jacob (2007), Gutwill et al. (2015), and Lyons et al. (2015) suggest that tinkering is a useful learning practice that is particularly well-suited to the museum context, as it is informal, low-stakes, and involves rapid, often visual, feedback about activity from fellow learners and from the artifacts themselves. A proper frame is needed, though, to attend to the mechanics of informal open-ended learning activities like tinkering.

Prior work suggests that to understand how people learn via open-ended, hands-on activities, we need to attend to individual learners' understandings, social interactions, social goals, and how they co-evolve with both the material affordances of learners' environments and the other learners' experiences. Tinkering enables learners to iteratively revise their understandings and goals as they revise their creations, but, by definition, it does not force convergence on a common goal (Lyons et al. 2015). Individual tinkering in a shared context is precisely the kind of collaborative behavior that we hope to capture through an analytic framework, but the processes and mechanisms of tinkering have not been historically well characterized by collaborative museum learning frameworks focusing on CCC.

Grounding DCLM in context

Collaborative learning in informal, free-choice learning settings

Not all researchers use Convergent Conceptual Change (CCC) as the major marker of collaboration (Baker et al. 1999; Mäkitalo et al. 2001; Elbers and Streefland 2000). While CCC is a parsimonious concept, it may not be the most appropriate goal for many real-world collaborative learning scenarios. In life outside of school, people are not (as) often called upon to deeply engage in joint problem-solving – most shared tasks involve some degree of specialization, bringing the activity closer to the "cooperative" end of the spectrum of joint effort. This is certainly true in the work world, but it is also arguably true in interest-driven free-choice informal learning environments like museums, where visitors have the freedom to engage with exhibits in ways that suit their own unique perspectives and agendas (Falk and Storksdieck 2005). Free choice learning is most evident in educator-led informal institutions like hands-on science and technology museums (as opposed to more traditional curator-led institutions like art museums or natural history museums) (Roberts 1997).

The majority of visitors to science and technology oriented museums are groups containing adults and children (Korn 1995), so much of the learning that takes place in such museums occurs within these social groups. One might argue that the type of social learning in these groups is not collaborative, owing to the innate power and knowledge asymmetries (cf. Dillenbourg 1999). In some family groups, parents play the role of teacher or tutor, sometimes even at the expense of a child's ability to participate in the full breadth of the learning activity (e.g., Schauble et al. 2002). Even when parents are not in possession of more prior knowledge about the current exhibit than their children, the family members do not necessarily leave the exhibit with a shared set of concepts – the learning outcomes can be quite different for each participant (Crowley and Jacobs 2002), as each visitor is likely approaching their shared experience with different goals and thus is playing a different role from their companions (Falk 2006; Zimmerman et al. 2008).

While the collaboration in free-choice museums may not follow CCC models, it is not necessarily cooperative either (Dillenbourg 1999); rather than pursuing parallel paths, families often explore museum content together and engage in highly dialogic processes when doing so (Ash 2003). In fact, studies have shown that conversations between parents and children, despite the power differential, are often more mutual (in terms of participation in the conversation) than peer groups, where one party tends to dominate (Crowley et al. 2001). Even when children are relegated to executing "simpler" portions of an informal learning activity, parents often do monitor their children's task execution and use that to inform their own task execution and conversation (Schauble et al. 2002). In order to document the shared learning processes in informal settings, then, one must attend to both the conversational moves and the physical actions taken by individuals in the space, as well as the ways in which those choices affect group dynamics. Moreover, room must be left to acknowledge that learners may have differing personal subgoals within the shared learning interactions.

Collaborative learning at digital tabletops

A major way technology mediates collaborative processes is by how tightly coupled users' actions are in the interface design (Dewan and Choudhard 1991). Coupling can fall into two categories: output coupling describes how an interface supports awareness of the effects of one another's actions with the technology; input coupling describes how much interdependency the interface imposes upon their actions (Lyons 2009). Interfaces with both tight input and output coupling tend to "enforce" collaboration (i.e., they essentially force participants to work together), while relaxing the coupling can produce interfaces that encourage (but do not enforce) collaboration, and relaxing the coupling further still can produce interfaces that enable (but do not necessarily encourage) collaboration (Benford et al. 2000). In practice, tightly coupled interfaces would tend to privilege CCC approaches, whereas loosely coupled interfaces would tend to privilege more divergent approaches.

Tabletops, in particular, are one form of WYSIWIS (What You See Is What I See) interface (Stefik et al. 1987), which have tight output coupling, meaning that users have full (and identical) access to shared system output. For many existing collaborative tabletop applications, the input coupling is also fairly tight, meaning that the input actions of users are interdependent to some degree – what a user does affects, or is affected by, other users' inputs to the system (e.g., Jermann et al. 2009; D'Angelo et al. 2015; Block et al. 2015; Antle et al. 2013; Zufferey et al. 2009), thus enforcing collaboration. There is nothing inherent to the tabletop form factor that demands tight input coupling, however. In fact, early tabletop interfaces were often designed specifically to take advantage of loose input coupling (i.e., individuals' actions do not necessarily have a direct effect on the actions of others), to allow users to move in and out of collaborative modes of use (e.g., Sugimoto et al. 2004), as time for solo work or independent reflection was deemed helpful for group work (Scott et al. 2003; Sugimoto et al. 2004).

Current frameworks for characterizing tabletop collaboration assume both tight input and tight output coupling, but this perspective would miss the important shifts between individual and solo work that a loosely-coupled interaction design allows. To support analysis of a broader range of open-ended collaborative activities on tabletops, what is needed is a framework that can be applied to loosely-coupled tabletop activities. The framework needs to acknowledge when learners cross the boundary between solo and joint work, both in the input coupling sense (which we dub "boundary spanning actions," which occur when learners engage in solo or shared task execution) and the output coupling sense (which we call "boundary spanning perceptions," which occur when learners shift their visual attention to different parts or to the same part of the interface).

Current approaches for characterizing collaboration with tabletops

Students working toward common goals around tabletops have been extensively researched, resulting in the development of a number of frameworks for characterizing collaboration. For instance, Hornecker et al. (2008) developed a series of verbal and physical indicators to help researchers evaluate participant awareness during collaborative tabletop tasks, classifying awareness into three areas: negative awareness indicators (showing a lack of awareness of others), positive awareness indicators (reacting and assisting each other without an explicit request for help), and awareness work (monitoring and displaying actions). The implicit foundation of these categories is the theory of collaborative grounding – the idea that participants should be aware of one another's actions in a collaborative scenario (Baker et al. 1999). They asserted that increased awareness of the actions of others would lead to more fluid collaboration, and that this form of analysis provided a more comprehensive set of measures of collaboration than would have been discovered by simply analyzing automated log files. While this approach was profitable for unpacking how this particular design increased participants' awareness of each other, Hornecker et al. (2008) acknowledge that for other kinds of co-located tasks or interface set-ups different patterns of the awareness indicators could emerge. We argue that this is especially true in open-ended and exploratory environments, where individuals' tasks are not tightly aligned and may have divergent goals. In these scenarios the tabletop's interaction design is likely to be loosely coupled, which allows participants to shift between parallel and collaborative work, and to be free to enter and exit the activity at will. In these settings not only will patterns change, but they may also overlap or interweave, creating more complex relations between individuals' and groups' awareness and collaboration.

Not all researchers have assumed that participants have common goals, even though they might have a common task. Falcão and Price (2011) developed a framework for characterizing how groups responded when participants interfered with one another's actions with tangibles on a shared tabletop activity. Building on a framework developed by Weinberger and Fischer (2006) to describe argumentative knowledge construction, they described three modes of consensus-building in the face of interference: quick consensus-building (where some learners voluntarily gave up their independent activity and followed the activity of a partner), integrative consensus-building (which involved reflection on the conflict), and conflict-oriented consensus building (where participants took action to undo or redo actions without the consent of others). The activity in this study, a digital re-creation of the sort of prism-based light table often found in hands-on science museums, featured moderately tight input coupling. While participants were free to move and manipulate the individual tangible blocks representing mirrors and prisms, there was only one simulated beam of light that would "bounce" between tangibles, meaning that the "outcome" (where the light would travel) was highly contingent on the actions of others. Although some participants attempted to work in parallel at times, because they ultimately needed access to the shared resource (the light beam) to test their arrangements, this parallel work was not well supported by the interface (Falcão and Price 2009). Indeed, this tight input coupling enforced collaboration and was thus the source of the interference studied by Falcão and Price. The framework they developed reflects the assumption of tight input coupling, thus positioning consensus as the crux of the collaborative activity.

Fleck et al. (2009) advanced the Collaborative Learning Mechanisms framework (CLM - Table 1) as one approach for evaluating the efficacy of collaboration around a shared tabletop by analyzing verbal and physical interactions. CLM proposes two main mechanisms to evaluate collaboration around a tabletop: (1) Mechanisms for Collaborative Discussion, which includes making and accepting suggestions, and negotiation among participants; and (2) Mechanisms for Coordinating Collaboration, which (similar to Hornecker's et al.'s framework, 2008) includes joint attention and awareness, and narrations (verbalizations that enable others to monitor you). Their selection of categories was motivated by findings from prior collaborative learning research and position papers, including Convergent Conceptual Change work (Roschelle and Teasley 1995). Specifically, the Negotiation and Narration categories rest on assumptions that learners are working towards developing the same shared understanding of the same, shared goal.

Table 1 The collaborative learning mechanisms framework (Fleck et al. 2009)

1. Mechanisms of collaborative discussion
a. Making and accepting suggestions
b. Negotiating
2. Mechanisms for coordinating collaboration
a. Joint attention and awareness
b. Narrations

When attending to collaboration around the tabletop, CLM highlights the importance of both verbal and physical (such as pointing and manipulating) interactions. By examining student groups' interactions around a tabletop, Fleck et al. (2009) were able to show not only was the tabletop productive in supporting student learning and collaboration, but that these gains were more subtle and only revealed as part of the learning process rather than in the outcome alone. They were able to detect and describe a number of behavioral markers for their framework categories, and interestingly, several of the physical negotiation markers they found paralleled the markers of conflict-oriented consensus building described by Falcão and Price (2011). These conflicts clearly arise from scenarios that not only have shared goals, but also rest on tightly coupled interfaces to support the shared work. While in principle, this framework could be applied to loosely-coupled interaction designs where learners lack a single shared goal, the framework obviously has some embedded assumptions owing to its origins (e.g., that parallel work, a perfectly valid mode of use in multi-goal scenarios, would count as a "negative" awareness indicator).

As such, there is a general lack of frameworks that investigate divergent learners moving between individual, parallel, and collaborative interactions while using a loosely-coupled interaction design. This poses significant challenges to being able to "see" and, in turn, evaluate the kinds of collaboration taking place, and generally limits the kinds of conclusions that can be reached to generic evaluations of collaboration in general. To this end, there is a need to better document the mechanics of collaboration within designs that allow for individual or divergent goal setting. Doing so will aid researchers in effectively identifying different collaborative phenomena and understanding how different designs do or do not support effective collaboration. As there is significant disagreement and little common framework use, we are somewhat hesitant to introduce yet another new framework, but, as we see, the current frameworks overlook some features key to open-ended learning activities on tabletops, especially those of an exploratory and tinkering nature. Our intention is to make two contributions with this work: a useful framework for documenting open-ended collaborative activities, complete with examples; but, perhaps more importantly, a call for the research community to focus on what has been overlooked in the current discourse on collaboration.

A framework to embrace divergent inquiry: divergent collaborative learning mechanisms (DCLM)

What makes collaboration unique in open-inquiry/tinkering environments is that their goals are not prescribed at the outset; rather, they occur naturally during each participant's arc of inquiry. Unlike in pre-defined learning scenarios, participants' goals are constantly being negotiated and refined, and in some cases may diverge and converge throughout their participation. Further, in open-ended designs, where participants are free to come and go as they please, there are no clearly defined start and end points. Participants will often be at different states of understanding, providing fertile grounds for scaffolding new entrants into the space. And yet, many of the collaborative behaviors identified by existing collaborative frameworks can still emerge, so there is value in building from existing models. We found that the Collaborative Learning Mechanisms (CLM) framework proposed by Fleck et al. (2009) provided a good foundation for documenting divergent collaboration, to which we recommend adding six additional learning mechanisms for supporting divergent collaboration (marked by italics in Table 2, see below for longer descriptions) to form the Divergent Collaborative Learning Mechanisms (DCLM) framework. These six codes were based on prior research into collaboration patterns (Lyons et al. 2015) within the open-ended tabletop exhibit (*Oztoc*, described below) in combination with a grounded approach (Derry et al. 2010) of participants' interactions across two days with the exhibit. We then used interaction analysis (Jordan and Henderson 1995) to iteratively refine our coding scheme.

Note that we do not recommend removing any of the existing CLM categories. Even though we have highlighted that CCC is the foundation of several CLM categories (e.g., negotiation and narration), and previously made a case that CCC does not encompass all the types of collaboration that occur in informal learning settings like museums, there are instances where CCC can and does occur in open-ended learning settings. It is important to note that unlike in many of the other contexts described above, CCC is just one of the many things that could happen in open-ended inquiry environments, rather than a pre-determined desirable outcome. We follow with detailed examples of these learning mechanisms as applied to the evaluation of a specific open-ended, constructionist tabletop museum exhibit.

Extending the mechanisms of collaborative discussion

In extending CLM to support divergent learning environments, two additional learning mechanisms were added: **Clarification** and **Seeking Help**.

> **Clarification**: Clarification focuses on explicit discussion between participants to disambiguate actions by the system or by users. Clarification may take the form of a participant asking a peer how a part of the system works, or what caused a particular system response. During shared-goal activities, participants may require clarification in order to understand how the actions of their peers helps in addressing the overall groups' goals. During divergent tasks, clarification can take on a particularly important role as participants may be trying to do different things (i.e., achieving different goals). In these cases,

Table 2 The divergent collaborative learning mechanisms framework

1. Mechanisms of collaborative discussion
a. Making and accepting suggestions
b. *Clarification*
c. Negotiating
d. *Seeking help*
2. Mechanisms for enacting divergent collaboration
a. Joint attention and awareness
b. *Goal adaptation*
c. *Boundary spanning actions*
d. *Boundary spanning perception*
e. Narrations
f. *Modeling*

clarification can help participants better understand the goals of their peers in order to provide suggestions or support. Similarly, participants can use clarification to better understand the work of their peers towards advancing their own explorations.

Seeking Help: Because participants can freely come and go from open-ended constructionist spaces, it is important to provide means for entrants to learn from the expertise of more knowledgeable members. Throughout exploratory activities, the ability to seek help is a critical means for participants to make sense of and progress their own inquiry/tinkering. The addition of **seeking help** is important in open-ended exploratory environments, as it can highlight moments in participants' exploration where they need to draw on the expertise of others *even if they have divergent goals*. Understanding when and how participants seek help and how others provide help can give us added insight into how participants relate their own learning and exploration to the problem states of others. In this way, **seeking help** (and the resulting exchanges) can give us an important lens into the ways common ground can be established between participants with divergent conceptualizations of the problem space and goals.

Revising the mechanisms for coordinating collaboration to embrace enacting divergent collaboration

While open-ended, tinkering, and exploratory environments can be less explicit in terms of the goals for collaboration, thus removing the strong need for learners to coordinate, there is still a clear need for documenting how collaboration is enacted. In truth, because individual goals are more fluid in these spaces there is a greater need to consider how participants can coordinate their thinking and sense making to support productive collaboration. In response, we changed this section's title to *Mechanisms for Enacting Divergent Collaboration* and introduce three additional mechanisms:

Goal Adaptation: Because open-ended, exploratory activities can allow participants to more freely define their goals (both individually and collectively), it is important that such environments enable participants to understand the larger "learning ecology" in which they are situated, what others are doing, and to define and refine their own goals in relation to this. While in some cases this may involve all the participants orienting towards a shared goal (or achieving CCC), it is not a requisite. This is in contrast to environments in which the UI enforces shared, convergent goals via tight coupling, and instead acknowledges that with a loosely-coupled interaction design participants' goals may or may not converge, and, if they do, it is because the learners chose a shared goal rather than were compelled by some external force. **Goal Adaptations** (moments in the activity when participants expressly change or adapt their goals) serve as important markers of when participants diverge, or converge, in their goals.

Boundary Spanning Actions (BSA): Open-ended tabletop environments offer unique opportunities for participants to directly interact and manipulate the tinkering spaces of others. Actively engaging with other's spaces is unique to parallel tinkering and offers opportunities to tangibly show others your own tinkering practices and/or work out mutual challenges (exhibiting a form of active and intentional ZPD). While these boundary spanning actions have some resemblance to the conflict-oriented actions seen in other work (Fleck et al. 2008; Falcão and Price 2011), considering that learners are Q6 moving or taking the resources of others at the table, in practice, BSA serve as markers of the voluntary input coupling that occurs as learners shift from a more solo/parallel mode of work to a more mutual mode of work. This is why we do not consider BSA to be a form of Negotiation, as Fleck et al. does. Tabletop activities that employ tangible artifacts are particularly fruitful for supporting cross boundary interactions among participants, as tangibles have been shown to provide easier and faster manipulation of objects across the surface than direct touch alone (Lucchi et al. 2010) and a clearer spatial relationship to the object between participants (Scott et al. 2003).

Boundary Spanning Perception (BSP): Having multiple participants working synchronously on similar challenges allows users to simply watch and learn from the tinkering of others, which can serve as a form of "passive collaboration" (and passive, unintentional ZPD – by allowing others to learn through observation of a more knowledgeable peer rather than direct interaction), or as a means for sparking discussion between participants. Well-designed tabletop environments can support this kind of collaboration by allowing participants to clearly see the tinkering of others, relate it to their own tinkering, and refer to it in follow-up discussions. Boundary spanning perception moves mark instances where users voluntarily opt to more tightly couple the output that the tabletop is providing by allowing for these kinds of comparisons. In this fashion, it is similar to the monitoring aspect of the "awareness work" described by Hornecker et al. (2008), but is distinct from CLM's existing Joint Attention and Awareness category, in that the awareness is not about establishing mutual grounding (i.e., one participant can be engaged in surveilling the workspace of another participant without the second participant's attention being simultaneously engaged).

Modeling: Modeling extends Fleck et al.'s concept of narration. With narration, learners are verbally describing their actions or intentions as they execute a task, with the purpose of keeping companions abreast of their current state of activity so as to facilitate group coordination. When modeling, an "expert" explains what they are thinking and doing to others while simultaneously exhibiting it through physical actions (such as manipulating objects on the tabletop) so that novices (or others engaging in BSP) can replicate the actions in their own workspace, without the explainer explicitly engaging with the space or work of their audience.

Investigating productive collaboration patterns for tabletops: applying DCLM

We wanted to understand to how individual visitors naturalistically interact, learn, and collaborate within open-ended tabletop exhibits. As such, the aim of this paper is show how the DCLM framework can highlight productive collaboration among participants' individual and collective tinkering while engaged in divergent inquiry that might otherwise be misclassified using other collaboration frameworks.

Below, we describe one instance of an open-ended exploratory tabletop museum exhibit (named *Oztoc*) and evaluate it in terms of its support for divergent collaboration and conclude with evidence of this collaboration's productive effect on participants' tinkering. We chose Oztoc as our system of choice because prior research into Oztoc revealed productive interaction patterns between participants that were not adequately described by existing collaboration frameworks (Lyons et al. 2015). As such, we felt that Oztoc was an ideal test case for exploring how DCLM could highlight productive interactions that might be missed by other frameworks.

Example exhibit: Oztoc

Our team developed a multitouch tabletop exhibit that is installed at a large urban interactive science museum. The exhibit, named *Oztoc*, situates participants as electrical engineers helping fictional scientists in an uncharted aquatic cave teeming with never-before-documented species of fish (see Fig. 1). The creatures are bioluminescent, and visitors are tasked with designing and building glowing fishing lures to attract the fish so the scientists can better study them. Participants place wooden blocks on the interactive table to create simple circuits (see Fig. 2). In order to catch all the different fish, players must experiment with creating circuits with different colors (red, blue, or green) and numbers (one, two, or three) of LEDs.

When a circuit is successfully created, a fish will swim up from the depths and head towards it, getting captured and displayed on a large scoreboard screen placed at one end of the multitouch table (see Fig. 3). It is important to note that the scoreboard does not provide a linear scoring mechanism (i.e., the points do not accrue over time), it only displays all fish that participants have individually "captured". The "points" assigned to each fish are randomly generated as a means of showing when a new fish of the same kind is caught. The goal of the scoreboard is to encourage continued exploration and discussion among participants. Mounted along another side of the table is a rear-projection screen, which displays a looping video that introduces visitors to the exhibit's narrative and provides a wordless tutorial on how to manipulate the blocks to form a simple circuit.

In designing *Oztoc*, it was important to ensure that visitors would have some freedom in choosing their own goals (e.g., which type of fish to target) while still providing a common set of materials and processes. The table provides feedback on visitors' circuit building, acting as a layer of augmented reality to support participants' exploration and tinkering.

Methodology and participants

Oztoc is installed in an enclosed exhibit space just off the main floor of a major metropolitan science center. A 'lollipop' sign just outside the exhibit indicates when videotaping will take place, letting visitors decide to enter or to return when data collection was not active. Researchers were present at the edge of the room so that they would not be obtrusive, but were available in the event of equipment trouble. Video data was collected via three cameras unobtrusively placed across the exhibit space, and audio was captured using a boundary microphone near the table. Visitor interactions with the table were logged using the ADAGE system (Owen and Halverson 2013).

Fig. 1 Children gathered around the *Oztoc* exhibit. The large scoreboard can be seen behind the children

Fig. 2 Players assemble virtual circuits using wooden blocks that represent resistors (1), batteries (2), timers (3), and different colored LEDs (4). Participants make circuit connections (depicted as lines on the tabletop (5) by bringing the positive and negative terminals of the blocks (augmentations displayed by the table) in contact with one another. Creating a successful circuit (one that has the correct ratio of resistors, batteries, and LEDs) causes the LEDs to glow and lures the fish attracted to that light

Video data was coded in Inqscribe to indicate times when participants engaged in DCLM patterns. Log data and video data were manually synchronized then programmatically synced to create the graphs supporting the case analysis.

The cases presented here were specifically selected from seven days of data collection to illustrate how visitors engaged in collaborative patterns both within and across groups while engaged in divergent inquiry. We selected groups that represented two important forms of collaboration support: 1) The transition between shared collaborative goals to divergent parallel goals; and 2) collaboration within groups, and collaboration across groups. Neither of the groups used in this analysis had interacted with the exhibit before, and therefore served as excellent cases of how participants explored the space for the first time and set and revised their goals as they explored. Because the exhibit was closed except when we were collecting data, we were able to verify that neither group had engaged with the exhibit previously by reviewing the recorded video.

Table 3 describes the coding scheme for the analyzed discourse. In each excerpt, we included turns of talk, participant gestures directed towards the table, and participant eye gaze. Each turn of

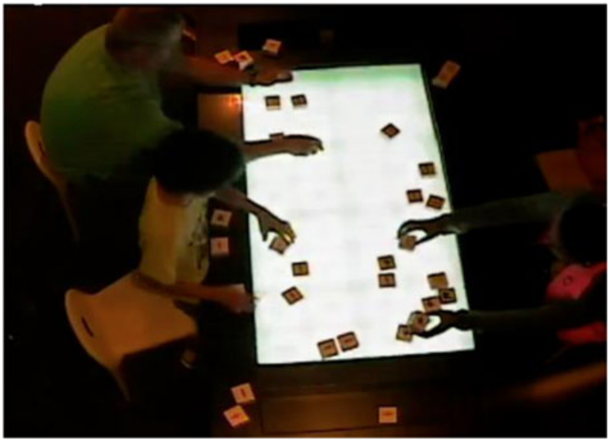

Fig. 3 *Oztoc* participants in case 1, first phase, first interaction

talk, gesture, and gaze change could have multiple codes. Eye gaze, which may relate to Boundary Spanning Perception and Actions, was recorded by the first author to preserve naturalistic interactions in the exhibit (compared to eye-gaze tracking headsets that may impact behaviors). All the codes were assigned using Inqscribe, a popular video transcription and annotation software. An external coder assisted with inter-rater reliability. Across the coded discourse, gesture, and gaze tracking, Cohen's kappa for inter-rater agreement was 0.9339 for 17 of the 68 coded excerpts (40%). Disagreements were resolved through discussion.

Analysis and findings

In the analysis below, we examine two cases of participants engaging with the exhibit in terms of their collaboration around the tabletop while they attempt to accomplish both shared and divergent goals. The groups described below were chosen afterwards during the analysis period. While there were many groups that exhibited elements of DCLM, we chose the groups below because they were particularly excellent case studies for how DCLM plays out. We apply the DCLM framework to identify aspects of their collaboration during both individual and shared goal tasks, and the affordances the tabletop provides to support these collaborative interactions.

Case 1: Transition from collaborative goals to divergent goals

The following case shows how DCLM can document how an exhibit can support users in establishing both shared and divergent goals within the same activity. The participants begin the activity working together but as open exploration progresses their goals become increasingly divergent and individual.

First phase: collaborative exploration

This phase consists of four interactions, wherein the group is using a shared-goal perspective while they are actively trying to deduce what the object of activity should be. There are a few

t3.1 **Table 3** Case study analysis coding scheme

	Descriptor	Code/Explanation/Icon
t3.2	Descriptor	Code/Explanation/Icon
t3.3	Group and Player number	Group members are identified first by their group (e.g., G1 indicates the first group to enter the space) and then an individual speaker notation (e.g. P2 indicates second member of the group), so G1P2 indicates that the second member of the first group is talking
t3.4	Making and Accepting Suggestions	MS or AS
t3.5	Clarification	CL
t3.6	Negotiating	NG
t3.7	Seeking Help	SH
t3.8	Joint Attention and Awareness	JA
t3.9	Goal Adaptation	GA
t3.10	Boundary Spanning Actions	BSA
t3.11	Boundary Spanning Perception	BSP
t3.12	Narrations	NA
t3.13	Modeling	MO

attempts at parallel goal execution, when one member of the group attempts to incorporate a specific artifact into his circuit that his companions do not attempt to use, but the group is largely seeking convergence during these interactions.

First interaction This first interaction involves the group – a boy (G1P1), his mother (G1P2), and father (G1P3) - coming up to the table and collaborating together to understand the interaction space and develop some initial goals, which are largely shared at first (Fig. 3).

G1P1: JA: Hey look, a resistor is connected to another resistor.
G1P1: NA: Alright, this resistor… so I got to put this battery here, next battery there.
G1P2: BSP: Looks at G1P1's space again
G1P2: CL: So you did an LED [and] a resistor?
G1P2: BSP: *[G1P2 starts "mirroring" what G1P1 is doing]*
G1P1: NA: Yeah, I connected the battery to the resistor, so now all I have to do is connect the resistor to battery to the LED. Yep, it's all connecting. So I have two resistors connected to each other, and, uh, one there's of the two resistors is connected to the battery, and the battery is connected to the red LED.
G1P2: CL, SH: What the timer for?
G1P1: NA, GA: There's a timer? I mean I don't, why would you need a timer? Awesome, so this is awesome, because I think you're trying to power a timer, because two resistors and then a battery and then a LED and then a timer, that's what I think it is.

G1P1 starts by getting G1P2 to orient to their space (JA - "Hey look!"), and then proceeds to work through what he is doing out loud ("so I got to put this battery here…"). G1P2 watches G1P1's tinkering and tries to copy him (BSP), while asking some probing questions ("What's the timer for?"). G1P1 attempts to help G1P2 follow his thinking by verbalizing possibilities (NA) and in doing so sets a new goal (GA – "powering" the timer, which counts as a valid goal for G1P2, even though it is not actually a valid task in the game).

Second interaction Once the group got used to the basic mechanics of the exhibit, led by the son, they began to further refine their shared goals by talking about their processes and hurdles (Fig. 4).

G1P3: JA, NA: Look at this, a battery to a resistor, to 2 LEDs!
G1P1: Oh, it's not a computer.
G1P2: SH: Well, I don't have the line…
G1P1: CL: What, yeah if you have the line, then you made a connection.
G1P1: NA, GA: Um, timer, I'm going to connect the timer to another LED, it's going to be weird.
G1P1: NA: I connected the timer to another LED, I have the other…
G1P2: CL: I have the LED and a resistor.
G1P3: BSP, BSA: *[G1P3 looks over to G1P2's space and gestures.]*
G1P3: CL: The problem is that the "power thing".
G1P1: NA: Alright, there we go, resistor connects to…
G1P3: CL: What kind of rule?
G1P2: CL, SH: Do we put the timer in there?
G1P1:*[Inaudible]*
G1P1 and G1P2: BSP: *[Starts looking at G1P3's table]*
G1P3: JA: Well look at that…

Fig. 4 *Oztoc* participants in case 1, first phase, second interaction

We begin with G1P3 describing the product of his tinkering to the rest of the group and trying to draw their attention to it (NA, JA). G1P2 then seeks help (SH) from G1P1, and G1P1 explains to her why she doesn't see the connection lines that he does. G1P1 attempts another approach to figure out what is going on (GA). G1P3 and G1P2 continue to work together to figure out what isn't working. G1P3 gets his circuit working and both G1P1 and G1P2 notice and stop what they are doing to watch G1P3's playspace (BSP). G1P3 gets his group members to focus on his circuit once he gets it to work (JA).

Third interaction Once G1P3 figures out how to make the circuit, G1P1 figures it out soon after, and they begin to work together to bring G1P2 up to speed (Fig. 5).

G1P1: NA: So that would mean resistor and LED.
G1P3: Cool!
G1P2: NA: I have that…
G1P1: CL: Yeah! Battery, resistor…
G1P2: NA: I have 'battery'.
G1P1: CL, MO: Mom, you're doing it wrong then, because it's like this… uh, positive to negative like that and then…

G1P1 talks about his circuit out loud to walk through his tinkering process (NA). G1P2 asserts that she had the same thing as G1P1 (NA), but G1P1 explains that she must be doing it wrong (CL), and then shows her the difference by modeling it in his space (MO).

Fourth interaction After the group sees G1P3 successfully make his first circuit they think this is the main goal (because it takes about 20 s for a captured fish to swim into the "light lure"); however, when G1P3 captures the fish the group learns this is one of the core "achievements" in the game and reorient themselves to figuring out how to catch fish (Fig. 6).

G1P1: BSP: *[G1P1 starts looking at G1P3's space]*
G1P2: BSP: *[Starts looking at G1P3's space]*
G1P2: JA: Look! Look!
G1P3: Whoa!
G1P1: NA: That was on my side!
G1P2: CL: But G1P3 has that connected and then right there, what was that?

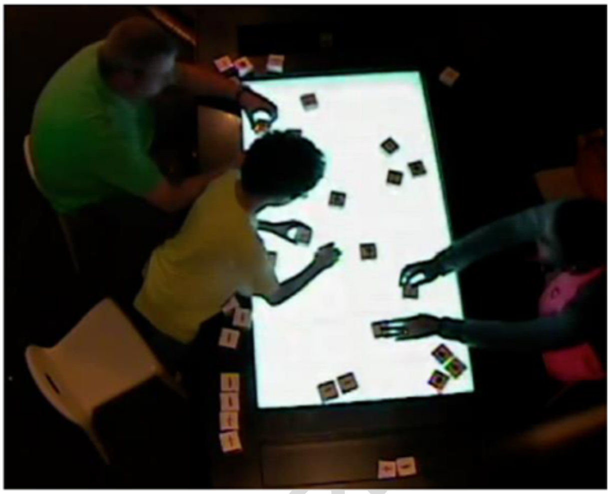

Fig. 5 *Oztoc* participants in case 1, first phase, third interaction

G1P1: CL: What was that?
G1P2: CL: What is that?
G1P1: I don't know actually…
G1P2: JA, BSP: Looks at G1P1's space: Oh look at that!
G1P1: Wow!
G1P2: MS: Get this thing Derrick!

As the fish swims across the table (starting at G1P1's area of the table), G1P1 and G1P2 watch the fish (BSP) until it accelerates out of G1P1's zone and gets captured by the circuit in G1P3's area (which is brought to the group's attention by G1P2 - JA). All three members try to make sense of what happened, during which time G1P1 makes his own circuit and attracts his own fish to get captured. When the second fish appears G1P2 suggests G1P1 try and capture it (MS).

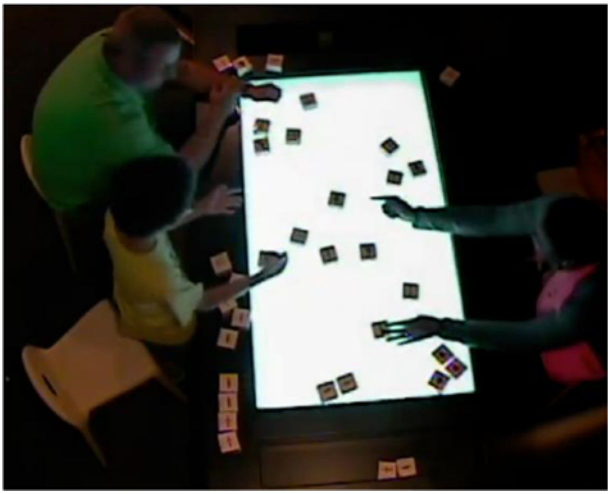

Fig. 6 *Oztoc* participants in case 1, first phase, fourth interaction

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Second phase: diverging goals

Once all the group members figured out the core mechanic of the game, they began to branch out and try to make different circuit types on their own, and to establish their own metrics for success (Fig. 7).

G1P3: NA, JA, BSP: I'm player one look!
G1P2: NA, BSP: I'm player 3!
G1P1: JA, BSP: I have 9 you have none!
G1P2: NA, BSP: You got none…
G1P1: NA, BSP: No, I have 9!
G1P2: NA, JA: Oh look I got one!
G1P1: NA, BSP: I have 10, got 10!
G1P2: NA: Come thing come back over to me…
G1P3: NA, JA: You have no points.
G1P1: JA Yeah, you have no points mom.
G1P3: That's cool!
G1P2: GA: I don't need points.
G1P1: CL, SH: What happens if you have two batteries?
G1P3: NA: I got one!
G1P1: CL, SH: What happens when you have two batteries?
G1P1: GA: I want to see what happens when you have two batteries.

G1P3 orients all three group members to look at the scoreboard (JA, BSP) and they all discuss (BSP) their individual "scores" (values assigned to the fish they captured). After some back and forth, G1P2 declares that she "doesn't need points," thus setting her own goal as different than P1 and P3. After some additional tinkering P1 starts wondering what would happen if he tried different circuit configurations (SH, CL) and after not getting any feedback, he decides to set his own goals distinct from those of the other group members (GA).

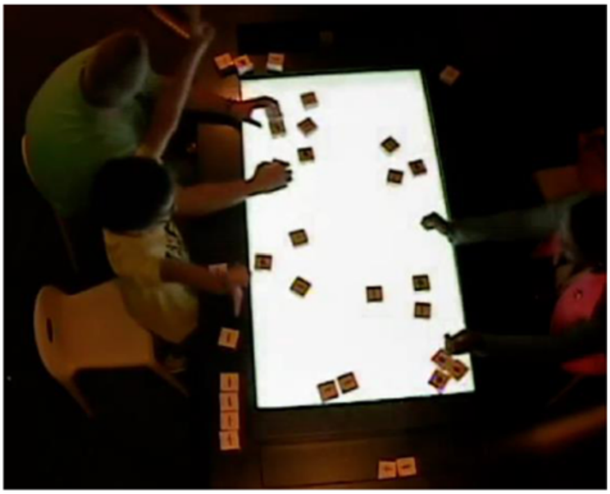

Fig. 7 *Oztoc* participants in case 1, second phase

Key behaviors revealed in case 1 using DCLM

In the case described above, we see several instances in which participants move between shared and divergent goals during their investigations. Under other existing frameworks, the divergent moments of exploration would be often classified as unproductive. However, by highlighting the BSP and BSA events, we see how participants can leverage these independent events for productive collaboration. In both the first and second interactions, the group members are advancing their own largely independent explorations, but come together when a member achieves an important event (e.g., creating a working circuit). We also see how these events can the trigger new divergent goal setting, such as when G1P1 attempts to figure out what happens when he uses two batteries in phase 2. The DCLM framework reveals the nuanced connections between these events that may have been backgrounded otherwise.

Case 2: Collaboration with and across groups

In the following case we see an important contrast to the group discussed above. In this case, one member of the group (Group 2 or G2) quickly figures out how to make a successful circuit and works with his group members to help scaffold their tinkering and goal setting. Unlike in the first group (G1) where they did not interact with any other participants outside their group, in this case a second group (G3) joins the table and begins to tinker alongside G2. As G3 struggles in their tinkering we see a member of G2 engage with them and help them understand the task and set their own goals.

Within-group collaborative constructionist scaffolding

We first examine a situation in which two members of the same group (G2) engage in collaborative discussion to help one of the members progress past their initial roadblock (unable to successfully complete a circuit that attracted a fish) (Fig. 8).

G2P2 SH: Why does this not fit?

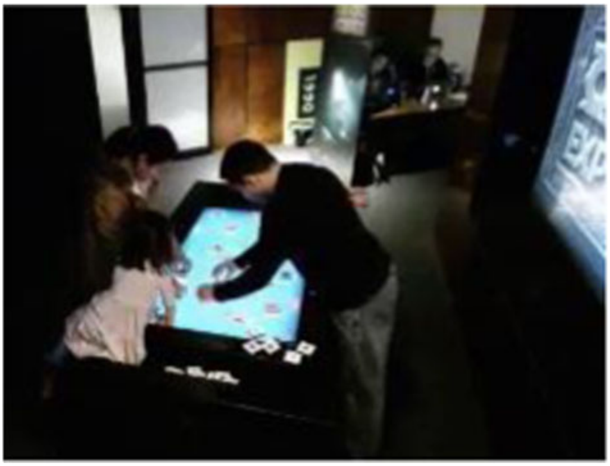

Fig. 8 *Oztoc* participants in case 2, within-group collaboration

G2P1: BSA:*[Reaches over to G2P2's space and helps her build a circuit.]*
G2P1: NA: So positives, negatives.
G2P1 MS, NG:Let go.
G2P2: CL: These?
G2P1: CL: Oh, that's because you need a battery and a resistor.

In this case the G2P2 is struggling to make a complete circuit and seeks help (HS) from G2P1. G2P1, having already figured out how to complete a basic circuit, reaches across the table (BSA) to help G2P2 complete her first circuit while also explaining the components she is missing (and asks her to let go of the blocks so he can work with them – MS, NG). Once her error is explained to her G2P2 is able to advance in her tinkering. This shows how G2P1's ability to see and interact with G2P2's space was instrumental in developing a common collaboration space to allow G2P1 to scaffold G2P2's work, and how DCLM allows us to capture this collaborative interaction.

Cross-group collaborative constructionist scaffolding

The second analysis involves the same group (G2) as they synchronously tinker with another group (G3) that arrives a few minutes after them. Below, we examine four successive interactions between the two groups.

First interaction

G3 BSP:*[Enters Room]*
G3P1: SH, GA: So how do you play?
G2P1: CL: So basically there was a little instructional video that says… it literally (inaudible) you take a battery, a resistor, and an LED to create a complete circuit, so by creating the circuit it attracts some kinds of fish…

A new group (G3) walks up to the table and starts by watching what others are doing (Boundary Spanning Perception - BSP) to get a sense of the community of practice (Fig. 9). After a minute one of them (G3P1) engages in Goal Adaptation (GA) and Help Seeking (SH) with the other participants to orient themselves to the activity. G2P1 responds with a Clarification, summarizing the goal of experience and the process for attaining that goal as he has come to understand it (CL).

Second interaction

G2P1: NA, BSP, BSA: There are rules to follow, so you gotta be careful, too much electricity it might overload the circuit, so once you get it working you light up the LED, and it will attract it, it will attract the fish.
G2P1: NA, MO: So like mine, I don't have enough battery, so let's take away an LED.

After a few minutes of tinkering in his own space G2P1 looks at G3 (BSP) and notices they are still struggling to make a complete circuit, draws their attention to a specific part of the circuit he is currently building (BSA) and offers additional information about his progress (NA) and models a solution (MO) (Fig. 10).

Fig. 9 *Oztoc* participants in case 2, cross-group collaboration, First Interaction

Third interaction

G2P1: MS, BSP: Yeah, but see, you're missing a power source.

G3P1: SH, GA CL: Oh so we need more power?

G2P1: MS, CL, BSP: You need more power.

G3P1: (To G3P2): AS, MS: Oh put your battery, battery, put your battery in. Maybe over here.

G2P1 looks at G3's space again and sees they've gotten close to making their first circuit (BSP), and describes the current state of their circuit building, noting that now they still need a power source (MS) (Fig. 11). G3P1 picks up on G2P1's suggestion and ask for help about what they should do next (SH & GA). G2P1 answers them by making a suggestion to add more power (MS, CL) after looking at their workspace (BSP). G3P1 accepts G2P1's suggestion (AS), then suggests to G3P2 (who is tinkering on the same circuit as G3P1) where to put the battery (MS).

Fourth interaction

G2P1: GA, MS, BSP: The other trick is if you want a bigger fish put the same color LEDs.

G3P1: Ok

G2P1: CL: A bigger fish, because it attracts a bigger.

G3P1: Ok

Fig. 10 *Oztoc* participants in case 2, cross-group collaboration, second interaction

Fig. 11 *Oztoc* participants in case 2, cross-group collaboration, third interaction

G2P1: CL, MS, GA: So if you've got two reds you'll get two times the size.
G3P1: CL, JA: Ok, you saw that [G3P2]?
G2P1: BSA MS: So just replace one of your LEDs with the same color. *[G2P1 points to one of G3's LED blocks]*
G2P1: AS: Right the same color
G2P1: CL, GA: So you'll get twice the size fish

G2P1 once again looks at G3's space (BSP) and sees they have some errors in their circuits – in this case they have increased the number of LEDs in their circuit, but they are all different colors (in order to capture a larger fish the LEDs must all be of the same color). G2P1 points to their circuit (BSA) and suggests they replace one of their LEDs with the same color (MS), clarifying the way the number of LEDs affects fish size (CL) while simultaneously helping G3 to form a new Goal Adaptation (GA - catch bigger fish) (Fig. 12).

Key behaviors revealed in case 2 using DCLM

In Case 2, we see the use of DCLM in exposing the ability of BSP and BSA to allow participants engaged in parallel, divergent goals to still engage in productive collaboration. In the *within-group* interactions, G2G1 was able to see how his fellow group members were struggling with their exploration and to provide timely support to help them make progress. Similarly, G2P1 was able to engage with G3 when he recognized their struggles in making

Fig. 12 *Oztoc* participants in case 2, cross-group collaboration, fourth interaction

sense of the exhibit. As a result, G3 was able to overcome their initial struggles and progress to new, more complex, goals (Fig. 13). In both cases, the participants were engaged in divergent goals; the DCLM framework highlights ways in which divergent participants engage in productive collaboration. In addition to the lack of a shared goal, when applied to the case above, DCLM reveals how collaboration is not limited by the lack of shared input coupling, rather it reveals a range of new opportunities for participants to engage in discourse around open-ended, exploratory learning environments.

Discussion

This work advances a new way of recognizing collaboration in environments that support participants in exploring goals and solutions that may diverge from their co-located peers. Similar to the work of Nathan et al. (2007), which recognized the potential for divergent views to help middle school students engage in intersubjectivity, divergent inquiry offers a contrast to the generally accepted notion that movement towards convergent conceptualization is always the desired goal for collaborative learning activities. As shown in the cases above, allowing learners to both explore their own paths and to set their own divergent goals can provide new ways of understanding the learning context in ways that provide benefits for all participants. In the cross-group scenario, G2P1 was able to apply his understandings of the problem space, gained from his own explorations, to the exploration being done by G3, *even though they were working on very different goals* (e.g., trying to get their first circuit working versus the more complex tinkering being enacted by G2P1).

Cross-group collaboration has been seen as an effective means for supporting problem solving among groups who are engaged in different, but similar problems in online problem-based learning environments (Lou and MacGregor 2004). By providing a shared context for the groups to solve their problems, we can create an environment that is analogous to

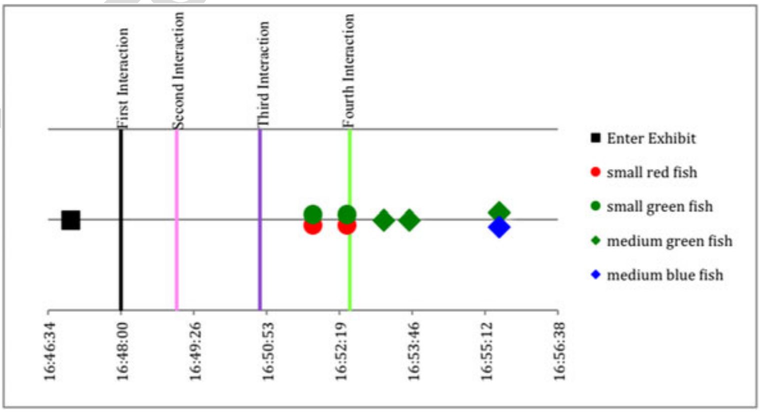

Fig. 13 The four interactions between G2P1 and G3. This shows how G3 was unsuccessful in luring a fish until the third interaction where G2P1 helped correct an error in the design (more power was needed). Less than a minute after G2P1's help G3 successfully lured their first fish (two fish were lured simultaneously because their circuit had both a red and a green LED). G3 made the exact same circuit 30 s later, which prompted G2P1 to intervene a fourth time letting G3 know they could make a larger fish (instead of two small ones) if they switched one of their LEDs (so the circuit only contained one color of light). About one minute later G3 successfully lured a larger (medium) fish

"communities of practice" (Lave and Wenger 1991). While the work of Lou & MacGregor was effective, their designs still focused on the notion of in-group convergence around a common goal and the between-group collaboration was largely asynchronous. In the *Oztoc* cases shown above, we use DCLM to show how divergent goals can still be productive within groups, and how the ability to engage in boundary spanning perception (BSP) can provide fruitful opportunities for real-time support and collaboration. In the within-group collaboration we see each member in the group relating their own tinkering and exploration to that of the rest of the group, talking through the different feedback they receive from the table, and making suggestions.

Offering multiple paths to multiple goals is challenging, but voluntary learners (such as museum visitors) are often working at multiple levels of understanding toward multiple goal states. Many exhibits enable "prolonged bystanding" which can have mixed results and often serves to alienate or exoticize complex content (Heath and Vom Lehn 2008). By enabling creation at multiple levels, newcomers can "see" the ladder towards becoming more central "community" members. This, in turn, can support spontaneous scaffolding through boundary spanning – other learners at the table will provide natural scaffolds both by example and through explicit boundary spanning actions where possible (and where motivated by the exhibit itself). It is important to allow participants to set individual and collective goals (as seen in Case 1) – interactive tabletop activities that are intended to support this kind of boundary spanning need to allow participants to reflect on their work and that of others in order to define and refine these goals. Boundary spanning also provides unique opportunities for more advanced tinkerers to see how and when others are struggling and to offer help. In the third interaction in Case 2, we saw G2P1 use the ability to engage in boundary-spanning perception to notice G3's challenges, diagnose the problem, and offer the targeted advice that G3 needed more power to get their circuit working. Then working together, G3 correctly built their first circuit (see Fig. 13 above).

Within open-ended environments, participants are often free to come and go, providing opportunities for them to pass on their gained knowledge to new entrants. Making each group's tinkering visible and accessible via BSP provides quick entry into the knowledge community - as seen in the second interaction where G3 was able to watch the exploration and tinkering done by G2 and to ask questions before attempting any circuit building of their own. Visibility of the larger group's collective tinkering can allow bystanders to watch those engaged in the activity and act as legitimate peripheral participants (Lave and Wenger 1991) before engaging with the exhibit, while offering reasonably low overhead to move from bystanding to creating (as exemplified in the first interaction above where G3 watches from the periphery for ~30 s before engaging).

Allowing participants to interact with other groups' spaces (Boundary Spanning Actions – BSA) provides opportunities for co-tinkering and physically scaffolding the work of peers – even when their respective goals are different. We see this when G2P1 reached across the table to help G2P2 build their first circuit. The ability for participants to both see and engage in others' spaces provides unique instances for engagement based on their states in real-time. Within groups, this can include orienting strategies, resources, and goals. Across groups this can include giving advice, orienting them to one's own work, or modeling actions. In the forth interaction in Case 2, we saw G2P1 help G3 orient to a new goal by observing what they were currently doing and making suggestions on how to adjust their tinkering (i.e., make all their LEDs the same color). This is especially important in environments where individuals may have different goals or participants may come and go at different times, as it provides a fertile ground for more "advanced" participants to take an active role in supporting the tinkering of "novices" (making it an ideal state for supporting successive and evolving states of ZPD).

We acknowledge some limitations to this study, including the need to hand code participants' gaze and gestures. While it is critical to maintain the exhibit's naturalistic setting, as argued above, we envision future research that uses unobtrusive technological approaches (such as placing Microsoft Kinects around the exhibit) for fully automated data capture. We also recognize the setting described herein is only one example of an open-ended exploratory learning environment. We would be interested in investigating how DCLM highlights divergent inquiry that takes place within other open-ended tabletop systems with different constraints and affordances. We also anticipate further research into how the DCLM framework can be effectively applied to non-tabletop learning environments. Makerspaces are particularly interesting, as learners are often making different things with different goals (e.g., different Minecraft mods or Arduino projects) at the same time in the same space. Of particular interest is how learners' use of Boundary Spanning Perception and Boundary Spanning Actions in makerspaces can support divergent collaboration and inquiry.

Conclusion

Supported by the case studies described here, our goal with the DCLM framework is to provide an expanded set of collaborative behaviors for designers to consider when developing and evaluating open-ended learning activities. In learning environment designs with a clear beginning and end to the learning activity, learners "following a linear path" or orienting around a "shared goal" are likely just a result of the nature of the learning environment design. However, when we start evaluating the tinkering and goal trajectories of learners in more open-ended scenarios, we start getting closer to the kinds of authentic and emergent possibilities for learning envisioned by much of the computer-supported collaborative learning and learning sciences communities. Though existing frameworks do not focus on these behaviors, in many cases this is exactly what we want – learners are naturally diverse, and we want to support them in capitalizing on their strengths as they engage as a rich community of practice (Lyons et al. 2015). It is also important for us to foster learners' abilities to recognize and capitalize on opportunities to spontaneously learn from and teach their peers. By expanding the CLM framework we open up new possibilities for understanding how divergent goals can, rather than being a marker of "poor" collaboration per the convergent conceptual change definition, provide significant and diverse learning opportunities, and we can recognize and design for productive interaction patterns for open-ended and constructionist learning. For this reason, while we acknowledge that DCLM and its codes can be applied to interactions that happen during tightly coupled and convergent collaborative inquiry, they are nonetheless of special utility to divergent inquiry. In truth, while these interactions often transpire in CCC situations, they are particularly fruitful for highlighting, and in many cases are required, to understand divergent collaborative inquiry.

DCLM allows us to show how participants who are simultaneously engaged in divergent (or non-convergent) goals can still effectively scaffold each other and engage in productive collaboration. Because tabletop exhibits reduce the barriers to establishing shared grounding and sensemaking, even when individual goals are not tightly coupled, they offer unique opportunities for participants to collaborate with peers. Unlike in many shared-goal activities, the manipulation of artifacts that reside in others' spaces is not necessarily a sign of conflict or negotiation, but instead may be indicative of a fruitful moment of authentic and spontaneous ZPD scaffolding (an outcome that many educational designers hope for but struggle to achieve). This is particularly critical in informal environments in which joining or exiting the 'community' is fluid – such as museums exhibits or other open-ended environments such as makerspaces – as expertise can be passed down through successive cycles of participants' entry and exit, potentially accelerating the 'scaling-up' of their competency in the domain.

It is this ability to observe, relate to, reflect on, and interact with the tangible ideas and tinkering of others that is the heart of our introduction of boundary spanning perception and actions. Within open-ended and constructionist environments there exist the potential for many simultaneously occurring 'idea spaces,' in which individuals or small groups are working on challenges that may profit from an outside peer's insight or knowledge. By making the work of individual groups visible and accessible, as exemplified by the tabletop exhibit described in this paper, educational designers can reduce the friction for these kinds of productive interactions. In turn, this brings into play need to carefully consider the design of the physical space itself in order to support the visibility and interaction between groups. Before DCLM, we lacked frameworks that could embrace and reveal the different collaborative interaction patterns that emerge in these settings.

In the end, the goal of our work – among many others – is to support students as they learn collaboratively. By creating a framework that helps designers see new modes of productive collaboration, we hope that people will be able to engage in a more informed exploration of the design space of open-ended, creative learning environments.

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