BEST DESIGN PAPER AWARD

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Going Deep: Supporting Collaborative Exploration of Evolution in Natural History Museums

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Abstract: We provide an analysis of pairs of children interacting with a multi-touch tabletop exhibit designed to help museum visitors learn about evolution and the tree of life. The exhibit's aim is to inspire visitors with a sense of wonder at life's diversity while providing insight into key evolutionary concepts such as common descent. We find that children negotiate their interaction with the exhibit in a variety of ways including *reactive*, *articulated*, and *contemplated* exploration. These strategies in turn influence the ways in which children make meaning through their experiences. We consider how specific aspects of the exhibit design shape these collaborative exploration and meaning-making activities.

Introduction and Background

Evolution is a central organizing principle of modern biology that accounts for the diversity of life on Earth. Despite its importance, evolution remains poorly understood by the general public, particularly in the United States (Rosengren et al., 2012; Miller, Scott, & Okamoto, 2006). In this paper we present a qualitative analysis of an interactive tabletop exhibit called *DeepTree* that we have designed to help museum visitors explore key evolutionary concepts. The exhibit presents an interactive visualization of the "tree of life" consisting of over 70,000 species that visitors are free to explore through a *deep zoom* interaction technique (Figure 1). We emphasize the idea that life on Earth is not only astonishingly diverse but also related through common ancestry. A key design challenge is to provide visitors with the means to explore a vast information space, instilling in them a sense of wonder at life's diversity while providing insight into evolutionary landmarks

After briefly describing the exhibit, we present a study involving pairs of 9- to 15-year-old children interacting with the exhibit at two natural history museums. Our analysis focuses on three questions related to the use of multi-touch tabletops to support collaborative learning in museums: First, how do dyads negotiate their moment-to-moment exploration of the exhibit? Second, how do dyads negotiate meaning through their interaction? And, finally, how do specific aspects of the exhibit design shape these collaborative activities? Our contribution in this paper is a framework that describes dyadic interaction along with an account of the role of design in allowing visitors to make sense of large *information visualization* exhibits.

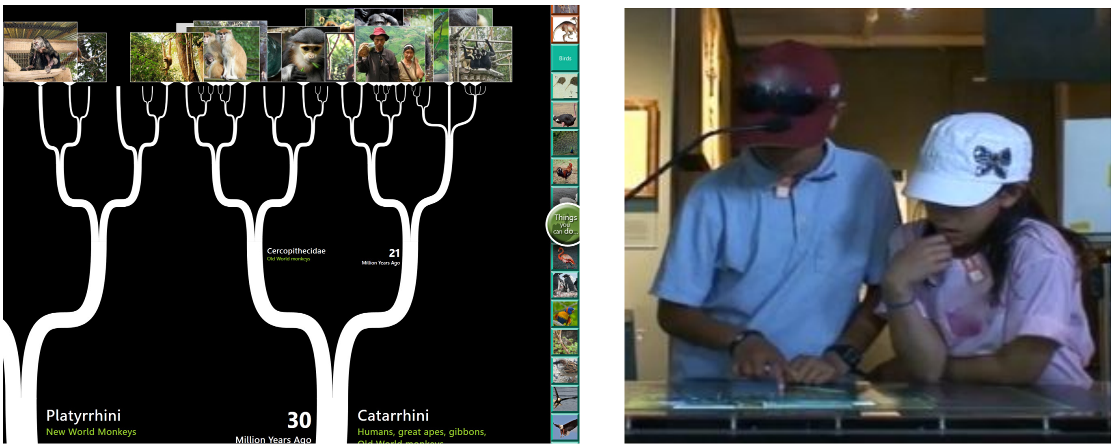

Figure 1: Screenshot from the *DeepTree* exhibit (left). A dyad (Gabrielle and Max) interacting with the exhibit at a natural history museum (right).

Learning Evolution

Studies have demonstrated a variety of challenges that learners face in attempting to grasp core concepts of evolution (see Rosengren, Brem, Evans, & Sinatra, 2012 for a review). These challenges are amplified in museums where engagement times tend to be short and visitors have freedom to move from one exhibit element to the next (Humphrey & Gutwill, 2005). Even depicting the evolutionary relationships of a small number of species can be confusing for learners (Novick & Catley, 2012; MacDonald & Wiley, 2010). While we embrace the usefulness of simplified representations of scientific concepts (Davis, Horn, & Sherin, 2013), it can be difficult to convey the vast scale and dynamic processes of evolution using simplified static representations alone.

Information Visualization and Large Data Sets

Scientific organizations are actively compiling databases intended to describe all known species inhabiting the Earth today. Current estimates put the number of eukaryotic species around 8.7 million with additional millions of prokaryotic species (Mora, et al., 2011). These organizations face unprecedented challenges related to the processing and visualization of information on such a massive scale. To meet these demands, researchers across scientific disciplines are developing advanced computational methods to visualize information in order to find unexpected patterns and anomalies (Fayyad et al., 1996; Frankel & Reid, 2008). These methods will increase in importance as the capacity for data collection, storage, and communication expands. Due to this importance and utility, educators are beginning to find ways to leverage these tools to visualize large scientific data sets for public consumption in museums.

Interactive Tabletops

As information visualizations become increasingly important for scientific practices, they are slowly beginning to appear in museums in the form of interactive exhibits (e.g. Hinrichs et al., 2008). In particular, we argue for the utility of *interactive tabletops*—surfaces that allow direct touch interaction with a computational environment for multiple users. In recent years, interactive tabletops have moved out of research labs and into classrooms, museums, and public spaces. Preliminary research on the use of interactive tabletops to support collaborative learning has found that tabletop environments can promote physical engagement, reflection, and collaboration (e.g. Harris et al., 2009; Piper & Hollan, 2009; Rick et al., 2011; Shaer et al., 2011; Schneider et al., 2012). Furthermore, researchers have documented some of the interactional arrangements (Hinrichs & Carpendale, 2011) and group dynamics (Rick, Marshall, & Yuill, 2011) that shape interactive tabletops as collaborative forums. Because tabletops support multi-user interaction, they seem remarkably well suited for use in museums. However, while many tabletop museum exhibits now exist (e.g. Geller, 2006; Hornecker, 2008; Antle et al., 2011), few have been rigorously evaluated. In previous work, we have attempted to define measures for successful interaction with multi-touch tabletops and use these measures to evaluate our own design for a table-base evolution exhibit (Horn et al., 2012). In the current study we expand on this previous work to develop a more in-depth qualitative analysis of dyadic interaction around an interactive, information visualization exhibit.

DeepTree Design

The *DeepTree* exhibit is an interactive visualization of the tree of life showing the ancestral relationships of 70,000 species starting from the origins of life some 3.5 billion years ago (see Block et al., 2012, for more detail). *DeepTree* currently runs on a multi-touch Microsoft PixelSense™ surface. The exhibit was designed around five related learning goals: (1) All life on Earth is related; (2) biodiversity is vast; (3) relatedness is derived from common descent; (4) species inherit shared traits from common ancestors; and (5) evolution is ongoing and happens over very long periods of time.

The design has three major components (see Figure 1). The main display area allows visitors to zoom and pan through the entire tree of life using standard multi-touch gestures. Pulling the tree down from the top of the screen allows visitors to zoom in to reveal more information, starting from the root of the tree to its canopy, displaying individual species. Touching and holding an image of an organism causes the display to automatically "fly" through the tree to the selected species. The tree uses a fractal-based layout algorithm so that branches emerge as the user zooms in or out. Unlike static depictions of trees that simplify information by limiting the number of species, the fractal design allows for the depiction of every species in the tree of life while still reducing visual complexity.

The second component is a scrolling image wheel along the right side of the screen containing a subset of 200 species representing important evolutionary groups. Visitors scroll through the images to select and pull out any species onto the main display. When an image is held, a transparent chord points to the species' location in the tree and the system automatically flies toward it. Holding two images points toward both species' location, allowing visitors a glimpse at both species' relative positions on the tree of life.

The final component is an action button centrally located on the image wheel. When pressed the action button reveals a *relate* function that allows visitors to select any two species from the image wheel and the tree automatically highlights their shared lineage and flies to their most recent common ancestor. Once there, the tree prompts the learner to press an icon to initiate an embedded learning activity. This activity presents a simplified tree depicting the two species' shared lineage and highlighting major evolutionary speciation points. These points can be activated to reveal further information about common ancestors and major traits.

We developed *DeepTree* through an iterative process of design and evaluation with a team of computer scientists, learning scientists, biologists, and museum curators. Over the course of a year, we implemented and evaluated twelve prototype designs with 250 visitors in a large natural history museum.

Research Design

In order to evaluate the design, we placed a tabletop surface running *DeepTree* and another interactive design (called *FloTree*, which we discuss in Chua et al. 2012) in two prominent natural history museums in the United States (one in the Northeast and one in the Midwest). We recruited 250, 9- to 15-year-olds (M=11.56, SD=1.68; 126 females, 124 males) in dyads and randomly assigned them to one of four conditions. In condition A, participants interacted with both *DeepTree* and *FloTree*. In condition B, participants interacted with *DeepTree* only. In condition C, participants watched a 10-minute video about the tree of life[1]. This comparison group was meant to reflect common, non-static museum exhibit design. Finally, condition D was a control group that received no intervention. For 10 minutes each dyad (except those in group D) freely interacted with one of the tabletop exhibits or watched the video. We video recorded children's physical and verbal interactions in order to capture discourse, behavior, and collaboration.

Following the interaction, all participants (group D included) were interviewed individually. Each interview lasted roughly fifteen minutes and involved open-ended and closed-ended questions about participants' ideas and understanding of evolution. To assess children's breadth of knowledge, we asked about common descent, common ancestry, natural selection, biodiversity, and the on-going nature of evolution. Parents completed a demographic form that included questions on their children's interaction patterns and a survey on their understanding of evolution. There were no significant differences between conditions in parent completion/non-completion of college, parents' or children's self-reported knowledge of evolution, religiosity, or compatibility of evolution with their religious beliefs.

The focus of this paper is on a qualitative analysis of dyadic interaction with the exhibit. Briefly, however, an analysis of close-ended responses revealed that dyads in both tabletop conditions were more likely than those in the control group to agree that humans, other animals, plants, and fungi had ancestors in common, a long time ago. Furthermore, dyads in condition B (*DeepTree* only) were most likely to interpret a tree of life graphic accurately and agree that all living things share DNA ($ps < 0.05$). All were multi-question measures (Evans et al., 2013). A full description of these results is forthcoming.

Descriptions of Interaction

As stated earlier, three research questions drive our analysis:

1. How do dyads negotiate their moment-to-moment exploration of the tabletop exhibits?
2. How do dyads negotiate meaning making through their interaction?
3. How do specific aspects of the exhibit design shape these meaning-making and exploration activities?

In order to begin the process of answering these questions, we adopted the frame of *interaction analysis* (Jordan & Henderson, 1995) that uses video as a primary data source and involves repeatedly viewing data in order to provide a deep analysis of the interactions that shape thought and behavior through talk, nonverbal cues, and artifacts. Based on this approach, we first created *content logs*—rough descriptions of the action with annotations of particularly compelling sections—of the videos. These logs guided analysis, in which we co-viewed the videos and discussed the *micro-level* interactions in order to isolate more general patterns of interaction. This analysis is ongoing and a fully representative account of interactions is beyond the scope of this paper. Nevertheless, in the following sections we describe preliminary interaction analysis using examples from three dyads representing differing levels of successful interaction with the table.

Negotiating Exhibit Exploration

Our first question concerns the ways in which dyads negotiate their exploration of the exhibit from moment-to-moment. Large tabletop displays support collaborative interaction that is potentially much different from other electronic devices. Without the constraint of a single input device (like a mouse or a keyboard), individuals are free to interact at any time, and, as is the case of the *DeepTree* exhibit, individual actions often affect the state of the entire system. For example, if one child decides to zoom or pan the display, the picture that the other child happens to be looking at can disappear. So, individual actions can work at cross-purposes, forcing dyads to frequently negotiate their exploration of the exhibit. This negotiation could be as simple as saying "wait" or physically grabbing the other's hand. We observed the formulation and execution of goals at different levels of granularity lasting from a few seconds to over a minute. An important dimension seemed to be whether or not

[1] http://archive.peabody.yale.edu/exhibits/treeoflife/film_discovering.html

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goals were articulated and agreed upon. Based on our preliminary analysis, most dyads' collaborative exploration seemed to take one of three forms—*reactive*, *articulated*, or *contemplated* (Table 1). These forms do not necessarily describe the overarching pattern of interaction, but rather a moment-by-moment analysis—a single dyad may employ one or more forms during their interactions.

Types of Goal Negotiation	
Reactive	Independent, moment-to-moment actions in response to the tabletop and other people
Articulated	Short-term goals are expressed (physically or verbally) and agreed upon
Contemplated	Longer-term goals that are articulated and verbally elaborated
Patterns of Meaning Making	
Serendipitous	Chance discovery through exploration of exhibit content
Making Connections	Drawing parallels between outside sources and exhibit content
Goal-oriented	Meaning making directed by the pursuit of overarching goals

Table 1. Forms of dyadic interaction in goal-negotiation and meaning making.

We call the first type of interaction *reactive* negotiation, because it seems driven by reciprocal reaction to immediate individual actions on the tabletop. This is especially evident in the dyad of Diego and Anna's (both 12) interaction with *DeepTree* (Figure 2). Diego and Anna seldom spoke while interacting with the exhibit and most of their moment-to-moment goals seemed independently construed. They appeared to learn how to use various aspects exhibit by watching each other, but their actions also frequently came into conflict, forcing momentary episodes of spontaneous negotiation. For example, at one point Diego begins resizing images of species using a two-finger spread and pinch. Anna is observing this, but not touching the screen. Anna notices the action button pulsating, points to it over Diego's arms and says, "Oh look." Diego pulls his arms back, looks at the action button, moves his hand towards the button as if to touch it, then looks back toward the main display while moving his arms back over Anna's, and continuing to resize the images. In this instance, Diego's goal—independent of Anna—is the manipulation of the images. When Anna notices and draws Diego's attention to the action button, through both a gesture and an utterance, she introduces a new goal. Diego momentarily considers this goal, employing a pointing gesture, before he wordlessly rejects it via a gesture that actively suppresses Anna's previous gesture. This is an example of two divergent goals clashing and requiring a negotiation between the actors, which takes the form of a brief consideration followed by cursory dismissal or acceptance. Throughout Diego and Anna's interaction we see a cycle of parallel goals conflicting when both require simultaneous use of the table and fleeting negotiations wherein one goal overrides the other, only to start the cycle anew. This arrangement of goals and negotiation is apparent in many of the dyads.

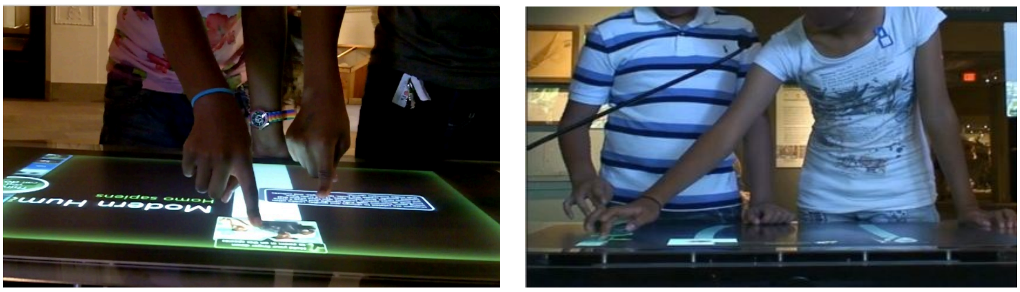

Figure 2: Dyads interacting with the DeepTree exhibit: Anna and Diego (right) and Chloe and Braden (left).

At other times the dyads actively *articulate* their goals through speech or gesture. *Articulated* negotiations generally involve less independent interaction than the *reactive* and sometimes result in mutual agreement on the goal. At one point, Chloe (9) and Braden (11) both begin tapping on images. Their taps result in the image enlarging and Chloe says, "Yeah, let's try that." They both then zoom in and out of the images together. Likewise, Leo (13) and Hope (9) begin their interaction with Leo explicitly asking, "Where do you want to start?" And Hope moving her hands over the table while saying, "Let's start... uhhhhh… here," and pointing at an image. Leo and Hope then work together to discover the deep zoom function of the tree. These kinds of articulations result in more joint action, even when both parties do not adopt the articulated goals. For example, Chloe and Braden are engaged together with a joint action of panning and zooming on individual images. After zooming in on a particular organism, a block of text appears with a description of the species.

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When this happens, Chloe begins to read the text, thus introducing a new goal. Braden does not adopt her goal and instead continues to pan and zoom. Chloe says she can't read the text and Braden moves his hand away so the words are no longer obscured, however he continues to pan and zoom the image. In this case, their goals are independent, but they are able to simultaneously achieve their articulated goals, without the strong conflicts or dismissals seen in reactive negotiations. In these interactions, previously articulated goals seem to prevent some level of conflict and support mutual table use.

Occasionally dyads will vocalize explicit overarching goals for their explorations and then negotiate or refine these goals through relatively smooth verbal exchanges. We call this *contemplated* negotiation. *Contemplated* negotiation is similar to *articulated* negotiation*,* but instead of just being a moment-to-moment goal setting, it involves the setting of larger goals that result in more directed interaction. The dyad of Gabrielle (12) and Max (14) (Figure 1) frequently demonstrate this type of negotiation. Less than two minutes into their interaction with the table Gabrielle says, "Let's try…" then glances at the pulsating action button, points at it and finishes, "let's go to things you can do." Max then presses the button and chooses the *relate* function (Figure 3). Gabrielle then says, "Ok, relating to…? What could we relate to?" In this exchange they have quickly negotiated an overarching goal of "relating to" for their activity, and for the rest of their interaction they only use the *relate* function. Because they have established this higher order goal, they only need to negotiate the specifics of its enactment. After trying several different relations, the following exchange takes place:

Gabrielle: Let's try… Maybe something that you would think would be the total opposite. See, if, some—somewhere that you think would be the total opposite that you think would never relate.

Max: So something with four legs, or no legs.

Gabrielle: Yeah.

Max: So, let's try a fish.

Gabrielle: Against a four-legged animal, ok.

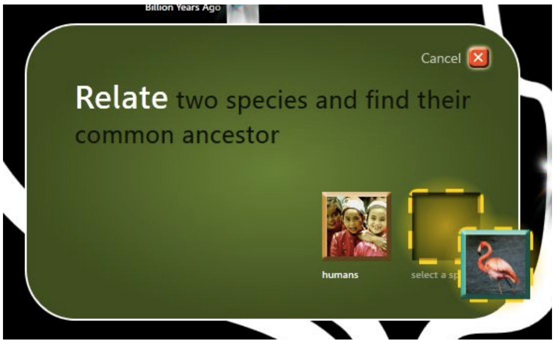

Figure 3: The *relate* function compares two species.

In this exchange, we can see that they are still working under the "relate to" goal, but Gabrielle suggests a refinement on their goal, and one that she seems to think will have surprising results. Max agrees and proposes a more specific comparison to work from. Gabrielle then agrees, Max suggests an animal, and Gabrielle offers a comparison. This dialogic agreement and back-and-forth building of a goal allows them to demonstrate that they both understand and can engage the new task. Furthermore, it shows that even though one actor suggested the new goal there is no "leader" in the task and they must work together. We argue that their setting of the higher order goal in the beginning guided the moment-by-moment exploration and allowed it to run smoothly. In other words, having an overarching activity in place puts them both on the same page, so the possible space of sub-goals is constrained and easier to articulate when small disagreements arise. While *reactive* and *articulated* goals generally seem to correlate with an undirected exploration of the table, *contemplated* goals appear to lend themselves to experimentation. In the above exchange, Gabrielle's sub-goal is presenting an implicit hypothesis—opposites are not related. All of their sub-goals seem like mini-tests of their hypotheses about relationships. Do these collaborative goals actually help the dyads make sense of the content of the exhibit? In the next section, we discuss the patterns of meaning making that we see in the interactions.

Negotiating Meaning

Our second question focuses on how the dyads collaborate to make meaning from the content presented by the exhibit. It has been argued that an important aspect of collaboration is *convergence*—how people construct shared meaning through their interactions (Roschelle, 1992). For surface level understandings convergence may be quite easy to achieve. One person reading a label out loud and another person overhearing and applying the label in order to name an animal is a relatively simple convergence of meaning (and one that is common in museums). However, working towards deeper conceptual change involves progressively more complex systems of convergence. Convergence is also pragmatic—meaning that individuals develop specific strategies moment to moment as they negotiate the meaning with one another and the exhibit. Across our dyadic interaction data we identified three broad patterns in the way children construct an understanding of the content: through *serendipitous discovery*, by *making connections* with prior experiences, and through cooperative, *goal-oriented discovery* (Table 1).

By *serendipitous discovery* we mean that children gained insights about evolution by chance exploration. For example, as part of the exhibit's design when a player holds her finger down on a picture of a species the screen zooms in for a closer and closer view of that species' location in the tree of life. This "fly-through" motion zooms past more distantly related species before homing in on the closest relations. This whole process can take between fifteen and thirty seconds—a seemingly long period of time in the course of interaction. However, during that time players catch a glimpse of hundreds of related species and gain an appreciation for the diversity of species in the tree of life. It is common for players to express their surprise and excitement at seeing so many species fly past. For example, at the start of Chloe and Braden's interaction, Braden holds his finger down on the "modern human" picture. After a few seconds of zooming, he says, "wow," followed shortly by "hey, how far is this?" After twenty-five seconds of zooming in, Braden and Chloe finally land on "modern human"—having seen hundreds of other species along the way. Braden expresses his appreciation for that huge number by saying, "that was a lot!" Chloe agrees with this, saying, "Yeah!" We consider this type of discovery to be serendipitous because it is not intentional. Braden's goal was to find out what would happen if he zoomed all the way in on the species "modern human." Braden and Chloe converge on an understanding of the great biodiversity of the tree of life directly related to the design of the exhibit.

Chloe and Braden also offer an excellent example of the second pattern of meaning making: *making connections* with prior experiences. In this example Chloe verbalizes a connection she makes between a concept she encounters on the table and at another exhibit in the museum. The other museum exhibit is a working laboratory where museum scientists study DNA. Visitors can look through a glass panel and watch the scientists at work. During one interaction with the exhibit, Chloe and Braden come across a picture of DNA when they are using the *relate* feature. Chloe says, "I guess that's like the stuff we saw in the glass," and Braden replies, "It's DNA." Chloe then points to the picture of DNA and says, "Cool, that's the molecules I think." Braden restates, "Yeah, that's the DNA." Chloe ends the conversation by saying, "So DNA was what they were studying in the thing." In this example Chloe seems to recognize the picture of DNA as something she also saw in the other exhibit. Chloe and Braden converge on a (simplified) understanding of DNA molecules through increasingly more specific talk that draws on the greater museum context to make meaning of the information on the table.

Serendipitous discovery and making connections are patterns seen on a moment-to-moment basis and at any time during interaction with the exhibit. The third pattern we identified, *goal-oriented discovery*, is a result of a dyad's broader goal negotiation. As discussed earlier, we found that Max and Gabrielle frequently negotiate contemplated goals for the exhibit. This in turn allowed them to jointly develop a big picture goal that drove their interactions with the visualization. While in pursuit of their higher-level goal, Max and Gabrielle took advantage of specific opportunities to make meaning about smaller components of the big picture. For example, during their second trial using the *relate* function, Max and Gabrielle relate modern humans to clown fish. This is part of their contemplated goal to compare opposite kinds of species. A simplified tree appears on the screen showing the traits that humans and clown fish have in common. Max reads aloud the text on one of the branches of the tree, "Jaws perfected to chew food." Gabrielle says, "Okay. Yeah we can chew." Then she asks, "So apparently they can too, right?" In this example, Max and Gabrielle are reasoning about how to read this new diagram. They know that the diagram mentions jaws for chewing and they also know that humans can chew. In order to converge on the conclusion that fish can chew—as Gabrielle does when she says, "Apparently they can too"—the pair needs to understand that the graphic shows shared traits between the two species. In fact, later in the session they use this understanding about the graphic again when they are comparing humans with bacteria. Max expresses surprise when the modified tree appears and shows that humans and bacteria have only one trait in common—that they are both made of cells. Max says, "So basically they're the exact opposites." Looking down at the graphic, Gabrielle adds, "Yeah, but they're living cells. That's pretty much it." Here again their interpretation of the graphic allows them to make meaning about the relatedness of different species. Furthermore, this example of meaning making is nested into the pursuit of their larger goal. In this case, Max and Gabrielle's convergence on more surface level meaning (Fish have jaws), allows them to also converge on an understanding of a higher order evolutionary concepts (common descent).

Design Supports for Exploration and Meaning Making

Our third research question relates to the role of design in shaping children's collaborative interaction around the tabletop. Specifically, given the diverse types of exploration and meaning-making activities that we observed, how does the *DeepTree* design function to make visitor experiences more worthwhile?

Suchman (2007) uses an analogy of a person confronting river rapids in a canoe to help illustrate the concepts of *planning* and *situated action*. We extend this analogy to consider dyads interacting with the *DeepTree* exhibit. Imagine two inexperienced paddlers in a tandem kayak floating in the middle of a large body of water. Each person has a paddle that can be used with immediate effect—move the paddle in the water and the boat moves in response, if not necessarily in a predictable way. Because both kayakers are inexperienced, they are still learning how to most effectively steer the boat in a desired and consistent direction. And, since both paddlers are interacting at the same time, coordination is required. This is complicated by the fact that it can be difficult to figure out how each person is causing the boat to move if both partners are paddling at the same time. So, the kayakers must simultaneously figure out how to use the paddles (the interface), decide on a mutually agreeable direction (a goal), and figure out how to coordinate actions (negotiation and reciprocal learning). Inevitably, novice paddlers spend a period of time splashing around and not making much progress in any observable direction. We hope that the relationship between the tandem kayak and dyadic interaction with tabletop exhibits is clear. The body of water corresponds to the information space that visitors can explore with the *DeepTree* exhibit. The paddlers are the youth themselves, and the paddles are their fingers, hands, and arms (the input devices).

With this analogy in mind, we see two critical roles for design. The first relates to the body of water. Effective design shapes this open expanse into a river with a gentle but persistent current. Along this river are landmarks or points of interest. This relates to the second goal of design, which is to include a collection of appealing and strategically placed features that invite attention. Earlier we mentioned that Diego and Anna seem to be reactive in their goal negotiation—they are like two rowers each paddling in their own direction, at their own speed, and with their own intentions. This could result in a great deal of effort with no discernible outcome. However, because opposing movements on the table cancel each other out, the table forces their goals into conflict, requiring them to negotiate and coordinate their efforts. In fact, Diego and Anna's independent movements result in the table zooming. While this was not either of their intentions, the result causes them to both hold the zoom to fly through the tree and have the same "wow" experience we saw earlier with Chloe and Braden. In this instance, the exhibit design guided their exploration and in so doing allowed them to spontaneously find and make meaning out of a "landmark"—the fly-through that portrays massive biodiversity. So, for learners in a reactive form of goal setting, the table guides the exploration in a persistent direction toward interesting information—just as the river's current pulls rowers past interesting viewpoints downstream. In other words, even if reactive dyads, like Diego and Anna, still tend to explore surface features of the exhibit; nonetheless, the exhibit design elicits apparently spontaneous meaning making and leads them to some level of understanding of evolutionary concepts.

What about dyads who already articulate or contemplate goals that are also supported by the exhibit design? As previously discussed, Gabrielle and Max explicitly articulate higher-level goals that drive their moment-by-moment interaction with the exhibit. This dyad can be viewed as tandem rowers who are in harmony in terms of the direction they wish to follow (even if they are still learning how to paddle more effectively). They work together to explore and experiment with the exhibit and to discover meaning, directed by their articulated goals. But, just as with the discordant rowers, the exhibit is not merely an inert tool for synchronized rowers. Though Gabrielle and Max control the direction of their kayak, the current of the river brings them to their goal more rapidly than they could have achieved on their own. Contemplated dyads, such as Gabrielle and Max, quickly move past the surface level, and the exhibit guides them to a feature, such as the *relate* function, which allows them to surge more deeply into the content and construct richer understandings.

The design of the *DeepTree* exhibit affords many strategies for goal negotiation, and both spontaneous and contemplated meaning making. Some meaning making, such as making connections to outside knowledge, is not directly supported, but by driving collaboration in the service of convergence, *DeepTree* encourages learners to find meaning through whatever interactive strategy they happen upon.

Conclusion and Future Work

Despite its centrality to modern biology, evolution remains a challenging subject for learners and its understanding persists to be an elusive goal of science education—particularly in informal educational environments. In this paper, we have examined a design for a novel museum exhibit that conveys the rich complexities of dynamic evolutionary processes through an interactive visualization. In a study, we find that children negotiate their exploration of the exhibit in a variety of ways including *reactive*, *articulated*, and *contemplated* exploration, and that these negotiations impact the ways children make meaning from the exhibit content and their interactions with one another. We argue that particular aspects of the design guide visitors in their interaction and collaboration. For example, the "fly-through" motion supports the *serendipitous discovery* of biodiversity, while the *relate* function encourages experimentation and the *goal-oriented discovery* of common descent. By encouraging a flow through the exhibit and providing specific landmarks for discovery, the *DeepTree* exhibit allows learners to make sense of evolution through their own free choice interactive techniques. In future work we plan to operationalize the framework proposed in this paper and systematically apply it to all of the video data collected in our study in order to help build and strengthen theories on collaborative learning in science museums.

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