ARTICLE

'How Could the Dinosaurs Be So Close to the Future?': How Natural History Museum Educators Tackle Deep Time

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Abstract Natural history museums play an important role in engaging the public in critical conversations about science and society. However, understanding complex concepts such as the Anthropocene requires thinking at large spatial and temporal scales. This challenge is at the forefront of a research-practice partnership between the Carnegie Museum of Natural History (Museum) and the University of Pittsburgh Center for Learning in Out-of-School Environments (UPCLOSE). Together we designed a tool to help museum educators engage visitors in conceptualizing and connecting deep time with pressing environmental concerns. We observed educators using the tool in two settings: summer camp and on the Museum floor. We then interviewed educators to understand how they frame learning goals for understanding deep time and how their strategies support learner connections to the Anthropocene. While the tool was generally well received by educators, our observations and interviews also revealed two fundamental tensions. One tension was in pedagogical approaches – either inquiry or transmission – and the other was in learning goals – either wonder or relativity. Going forward, the Museum plans to use the tool both for exploration of deep time and as a professional development tool for Museum educators to better balance their use of these different approaches.

INTRODUCTION

Natural history museums play an important role in engaging the public in critical conversations about science and society in the 21st century (Watson and Werb, 2013). Humanity's increasing influence on earth systems is evident in everything from ubiquitous plastics to increasing atmospheric carbon (Steffen, Broadgate, Deutsch, Gaffney, and Ludwig, 2015). These influences are expected to make a lasting mark in the earth's geology, marking the beginning of what many are calling the Anthropocene (Waters et al., 2016). Natural history museums can build the public's knowledge about humanity's impact on these changing earth systems. Their unique combination of historic and ongoing scientific collections, paired with robust public education programs, position natural history museums as critical leaders for engaging the public in tough Anthropocene issues such as climate change (Dorfman, 2018).

However, understanding complex concepts such as the Anthropocene requires thinking at large spatial and temporal scales. Implementing educational activities that support scalar

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thinking for visitors is a persistent problem of practice for museum educators (Wormald, 2017). Teaching the public about dinosaurs, typically the most popular attraction for many natural history museums, immediately surfaces the challenge that educators have of presenting concepts related to geologic time scale, or deep time. The need to impact public thinking about issues at large scale becomes even more pronounced when museums work to illuminate the Anthropocene. This paper, which is the product of ongoing research-practice partnership work between the University of Pittsburgh Center for Learning in Out-of-School Environments (UPCLOSE) and the Carnegie Museum of Natural History (Museum), describes how we worked in partnership to tackle this problem of practice by codesigning a simple tool for educators to use when discussing deep time with museum visitors. We focus here on researcher observation of, and practitioner self-reflection on, pedagogical practices in two settings: on the museum floor and in a summer camp.

The Museum has adopted a strong focus on bringing concepts of the Anthropocene to its visitors. In 2018, the Museum hired an ecologist and climate scientist to become the Curator of the Anthropocene, the first position of this kind internationally. That same year, they featured a 10-month exhibit entitled, 'We Are Nature: Living in the Anthropocene' (Carnegie Museum of Natural History, 2018). The exhibit exemplifies the significance of deep time for understanding the Anthropocene. For example, the exhibit relied on museum visitors' ability to conceptualize large temporal and spatial scalar shifts. When visitors first entered the exhibit, they were greeted with signage that read:

> 'What the heck is the Anthropocene? The Anthropocene is a newly proposed epoch, or geological time period, defined by humans' effect on the environment.'

This immediate reference to a 'geologic time period' was intended to position visitors to think about the vast temporal scale of deep time as a core environmental concept.

Visitors were also expected to make spatial scalar jumps to consider environmental systems at the scale of the entire planet. As they rounded the corner, visitors were confronted with a graph covering a large wall of the exhibit. The graph depicted the twin phenomena of sharply rising population and atmospheric carbon dioxide beginning in the middle of the 20th century (See Figure 1). These deceptively simple but engaging visuals demanded that visitors think at both the spatial scale of the entire earth and the temporal scale of geologic time. While both are difficult, spatial scalar shifts can be supported through the use of modern tools and technologies, such as satellite images that allow us to visualize the entirety of the planet. But the concept of deep time is much more difficult to illustrate and notoriously hard to learn (Truscott, Boyle, Burkill, Libarkin, and Lonsdale, 2013).

We don't have any technological tools to help our senses make a temporal scalar jump. Temporal scalar understanding is inherently difficult because it requires abstract, conceptual thinking (Jones and Taylor, 2009; Resnick, Davatzes, Newcombe, and Shipley, 2017). Given the complex and abstract nature of deep time, it is possible that an educator could introduce the concept of deep time to a museum visitor, but the visitor might not bring this information to bear as a resource when confronted with the concept of the Anthropocene. For example, we might imagine a visitor being presented with a piece of shale rock from the Pennsylvanian period by a docent and being told

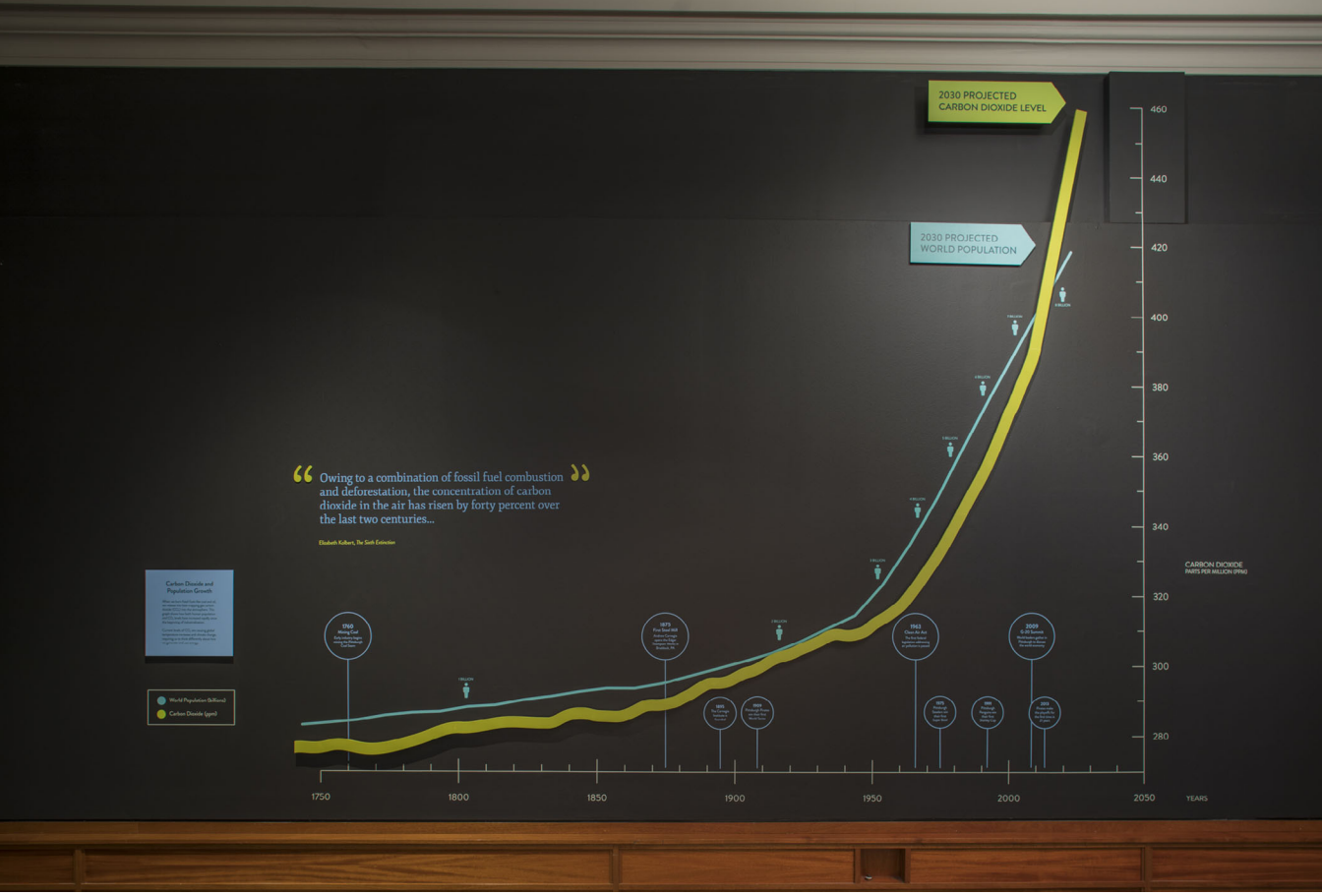

Figure 1. Image of the We are Nature exhibit graph depicting rising population and atmospheric carbon dioxide. (Photo credit: Joshua Franzos/CMNH). [Color figure can be viewed at wileyonlinelibrary.com]

that it is 300 million years old. The visitor may note this information with a nod, but they may still not understand how mind-bogglingly big 300 million years is, nor be able to connect this fact with the idea that plastiglomerate (an artifact of the Anthropocene) may be present 300 million years into the future.

Given that the ability to think across systems and scale is an essential element for understanding contemporary environmental issues (Tewksbury et al., 2014), and that Museum educators struggle with this topic, we brought this challenge to the forefront of our research-practice partnership (RPP), which brings learning science research to bear on Museum practices (Steiner and Crowley, 2013). Some of our previous RPP work has focused on the role of reflective practice for docent professional development (Allen and Crowley, 2014) as well as the need for the Museum to have flexible, low cost, educational tools that can be rapidly tested and improved (Knutson et al., 2016; Hecht et al., 2019). The current project is an extension of these prior efforts and brings together a team made up of Museum educators, Museum scientists, and university-based learning researchers.

Based on conversations within the team about the significance of systems and scale for understanding the Anthropocene, we endeavored to develop a concrete tool to help educators support the conceptualization of temporal scales that extend beyond human senses. Our tool was designed for educators to better engage visitors in this difficult conceptual idea and help to connect deep time with pressing environmental concerns. The Museum's

educators have previously used various interactive tools to explain deep time. For this project, we wanted to extend the ways in which Museum educators approach deep time and see if we could create some new, low-tech tools that they could use in various program settings. We hoped to evoke both wonder in the expanse of deep time and context for building knowledge about deep time.

Museum educators indicated that they have previously used several approaches to exploring deep time, including presenting all of the earth's history as a clock, where modern humans do not appear until 11:59, as well as asking learners to consider the length of their arm as the entirety of the planet's history. These types of analogous models are commonly used in both formal and informal settings. In addition to two-dimensional visual depictions of deep time (e.g., the Geological Society of America's geologic time scale), there have been a number of other hands-on educational efforts to explore deep time including field experiences that examine rock strata (Zen, 1995), geologic-themed puzzles used to explore student understanding (Dodick and Orion, 2003), and linear models which include both large scale walkable exhibits, e.g. at the Grand Canyon (Karlstrom et al., 2008; Semken et al., 2009) and smaller scale depictions, e.g. using ropes (Richardson, 2005) or toilet paper (Wenner, 2018).

The tool we developed – a rope wrapped on a reel – was a linear depiction of deep time which was labeled to indicate calibrated geological time intervals. The Rope included markers with significant events in the earth's history and was based on other educational examples of linear depictions of deep time. We sought to develop a tangible object that combined visualization and interaction in order to afford learners the opportunity to engage with this complex and conceptual material (Block, Horn, and Phillips, 2012; Horn, 2018). Although the term *tangible objects* is sometimes equated with computational objects (Hornecker, 2011), here we focus on non-digital objects that present unique affordances for museum educators working to support museum visitors as they grapple with complex ideas of natural history, such as evolution (Horn, 2013) and deep time.

Our approach, which is similar to other linear depictions (Richardson, 2005; Wenner, 2018) had several affordances and it could be simple, both in construction and interpretation. This built off previous research-practice partnership work between the Museum and UPCLOSE that surfaced the value of concrete and simple objects for public audiences to engage with abstractions such as climate change (Steiner, 2016). It was also physically appropriate for the Museum setting and could easily be used in both classroom and Museum floor settings. The tool was also designed so that it would be useful for educators working with Museum visitors of a variety of ages.

After co-designing the Rope with Museum educators, we observed educators using the tool in two settings – summer camp and on the Museum floor. We then interviewed educators to understand how they conceptualized the challenges of conveying temporal ideas to the public and if they were able to explicitly address some of the challenges of scale in relation to the Anthropocene.

Our research questions were:

1. How do Museum educators, when considering the tangible object, frame their learning goals for understanding deep time?

2. What strategies do Museum educators use to engage learners in thinking about

deep time in the presence of the tangible object?

3. How do educator strategies and goals with respect to the tangible object support learner connections to the Anthropocene?

IMPLEMENTATION

Developing The Rope

To meet Museum educators' needs, we created a rope that was portable, simple and cheap to construct, and flexible enough to be interpreted differently for different ages. It could be unwound to reveal important events in geological time that occurred between the formation of Earth (4.6 billion years ago) and the present. Our hope was to create a tool that models the vastness of the history of the Earth and gives visitors a sense of awe for the relatively small amount of time that humans have been on the planet. Ideally, the Rope would help learners conceptualize humanity's position in deep time and also give some context for how significant it is for humans to be making a permanent shift in the stratigraphy with the rise of the Anthropocene.

First, we built several prototypes and iteratively refined these with educators. We initially used a 50-foot rope, an electrical cord storage reel (for winding and storing), and markers made out of felt indicating major events in geologic time (see appendix for list of events). We chose to divide the major events into three conceptual categories: geologic events (e.g. eras, epochs), abiotic events (e.g. oxygenation of the Earth's atmosphere) and biotic events (e.g. the rise of dinosaurs). We marked the Rope at 100 million year increments every 1-foot (indicated by red tape) and billion year increments every 10-foot (indicated by black tape).

We introduced the prototype at a workshop for educators in the Museum's network. The workshop included 24 educators, including K-12 art and science teachers and out-of-school educators. We asked educators to play with the Rope and consider what might make it more functional for their use. Based on this feedback we made two major changes to the Rope. (1) We shortened the Rope length to 25-feet to better meet the physical constraints of many indoor educational spaces (1 billion years = 5 feet; 100 million years = 6 inches), and (2) we reversed the order of the event markers so that the first thing learners will see is the Earth's formation 4.6 billion years ago; the Rope then has to be unfurled to reveal the present day. Later, when several educators expressed a desire to have learners try to make guesses about where the events belonged on the timeline before seeing the known information, we made a third prototype of the Rope which had fewer events attached to the Rope. The remaining events, which did not include the dates, were written on loose pieces of felt that could be manipulated by learners. We also made this version of the Rope 30 feet long so that it could extend approximately 1 billion years into the future in order to provide a platform for future thinking, a topic that docents wanted to explore in a summer camp program.

After the design of the Rope we wanted to better understand educator practices in two of the Museum's educational settings: (1) summer camps led by camp counselors and (2) on the Museum floor at activity stations staffed by docents. We chose these two settings because they are focal program areas for the Museum's education team that offered an opportunity to engage visitors in issues of the Anthropocene.

We conducted observations of educators' practices using the Rope in both camp and on the Museum floor. Ultimately, the educators chose to use two of the ropes for their activities: the second prototype, which we call the 'key rope' because it had the correct locations for all event markers, and the third prototype, which we call the 'simple rope'. We followed the observations with educator interviews. After completing observations and interviews, our research team did thematic analysis of the data. For this, we identified patterns in educator practices and then examined those patterns through data visualization that allowed us to see how different approaches and learning goals may have related to one another (Miles, Huberman, and Saldaña, 2014).

Educator Practices on The Museum Floor

The Museum floor observation was part of what the docents call a 'spotlight' activity. During a spotlight activity, docents are at fixed locations on the Museum floor where they engage Museum visitors by encouraging them to look more closely at objects from the Museum's collection. For this activity, docents had the simple and key deep time ropes and some small Museum objects, which they call 'touchables', that related to the event markers. The docents hung one of the deep time ropes from a set of stanchions placed adjacent to the largest and most prominent of the dinosaur displays.

We observed two pairs of docents: one for one and a half hours on a weekday; the other for two and a half hours on a weekend when spotlight activities are scheduled to run longer. During these observations, educators engaged with 52 visitor groups that included families with children, mixed aged groups, and adult groups. The docents spent varied amounts of time with visitors, ranging from 1 to 19 minutes with an average amount of time being approximately 6 minutes. Immediately following activity observations, we interviewed the docent pairs about their experience.

Each of the two docent pairs elected to use slightly different configurations for the activity. One docent pair displayed the simple Rope (with fewer event markers) on the stanchions. They used the detailed key Rope (with more event markers) as an engagement tool for visitors as they passed, asking them if they would like to unfurl the Rope themselves. The other docent pair chose a different configuration: they displayed the more detailed key Rope and after some experimentation with asking visitors to unfurl the simple Rope, this team found that people were resistant to this, and they abandoned using the this Rope.

The hall also had a large wooden bench that both teams used to display touchable objects from the Museum's collection. This gave Museum visitors a chance to engage directly with Museum objects and consider how they related to the Rope and to deep time. Because the Museum allows for significant docent autonomy, each docent pair used a slightly different set of touchable objects. One pair's set included a stromatolite, a trilobite, a hunk of bituminous coal, a cast of a dinosaur claw, and a cast of an ancient Egyptian scarab. The other pair also used the trilobite, the coal, the dinosaur claw and scarab casts, as well as a cast of a fish fossil from the Museum's collection. They supplemented these with additional objects that one of the docents brought in from their personal collection, which included a piece of banded iron, a different stromatolite, an ammonite, and a megalodon tooth.

Educator Practices in A Summer Camp

The Rope was also used in a weeklong summer camp designed for 8–10-year olds, which had 17 attendees. We chose to work with this particular camp and counselor because the camp had explicit Anthropocene connections. The camp was called "Escape the Extinction" and it included activities for children to explore the causes of previous extinctions and consider implications for the future. The camp was designed as an immersive role-playing game, where campers took on the role of detectives building a time machine and moving through time to solve the mystery of a missing scientist.

We observed the counselors' introduction of the Rope during a 1-hour activity on the morning of the first day of camp and interviewed the lead counselor immediately following the camp that afternoon. During the initial activity, the counselor unfurled the simple Rope and laid it across the floor of the Museum classroom. After some initial probing questions, she gave pairs of children 2–3 of the loose felt event markers and had them work together for about 10 minutes to make guesses about where the events belonged along the Rope. She then brought the whole group together near the more recent end of the timeline, where they gathered closely on the floor. She encouraged the campers to explain and debate where the event markers were placed. After this discussion, she unfurled the key Rope next to the simple Rope and asked the children to see how their ideas compared with scientific evidence. This led to a longer large group discussion about deep time.

At the conclusion of the activity, the camp counselor hung the key Rope up in the classroom and left it there throughout the week as a reference for campers as they imaginatively moved through time using their time machine. Later in the week the campers were also given blank pieces of felt on which to add their own ideas about the deep future. We conducted a second interview with the camp counselor after the last day of camp to learn about her impressions of the use of the Rope and deep time throughout the week.

Educator Reflections on Learner Reactions

Overall, educators both in the camp and on the Museum floor described learners as being more engaged in the Rope activity than in other deep time activities, such as the clock analogy that they had previously used. Docents reflected on how much longer people participated in this activity compared both with other deep time and other spotlight activities they had used in the past. Amy, the camp counselor, also remarked on her surprise at how long the campers were engaged (all names are pseudonyms).

> I had planned I think like 30–45 minutes for that lesson and it went over an hour on time, so that was really exciting because they were just engaged and why stop a good thing when it is happening?

Educators also reflected on the value of having a tangible object to represent deep time. One of the docents, Kelly, said, "I use the arm a lot. And the arm works, but I like the timeline better. . .the Rope is longer, which I like.' Here, we heard Kelly referring to the physical properties of the Rope as a key aspect of what helped make it valuable for thinking about deep time. The length of the Rope was able to provide a physical depiction of time that was much greater than either an arm or a clock.

The Rope was long enough that learners could not see the entirety of the Rope from one position and were forced to walk along the Rope in order to move 'forward' or 'backward' in time.

This generated a lot of interest for the young campers, but also for many of the Museum visitors who made regular comments on the tangible object itself, saying things such as, 'You know it, but it doesn't really process until you see it like that.' Or as in this interpretation that a father gave to his 5-year-old daughter as they walked along the Rope during a spotlight activity:

> This whole thing is the whole earth. Keep walking way further – come all the way down here to where the dinosaurs are. Dinosaurs didn't even come around til down here. That's pretty crazy. We're like a little blip on the map.

When we asked the educators to consider how visitors connected the Rope to the Anthropocene, expression of fear and negative ideas were common. Robert, a docent, noted:

> I think, part of it is they get afraid. Because they see these extinctions occurring and they're thinking 'How much time are humans going to be around?' It's kind of like knowing your mortality – you know you're going to die, it just a matter of when it is going to occur. They think of humanity in that respect. They know humanity is going to end, but when is it going to end.

This suggests that not only did the Rope provide a tangible object through which to ponder deep time, it also evoked an emotional response in the learners that included deep fear of the future.

Our observations revealed that in both settings many learners expressed a visceral sense of fear about the future. The campers, all between the ages of 8 and 10, made 16 future event markers that they added to the Rope during the week of camp. Of these, half reflected very negative predictions about the near and deep future, including such events as the sun exploding, the moon exploding, mass extinction, and a coming world war.

This negative sense of humans' role in the earth and our future was also evident during some of the Spotlight activities. For example, after being asked about his thoughts on the activity, one Museum visitor responded, 'It's mind blowing how long this is on the scale of things and how short a time it takes for humans to destroy everything.'

TWO FUNDAMENTAL TENSIONS

While the Rope was generally well received by the educators, our observations and interviews also revealed two fundamental tensions for their practice. One tension was in their pedagogical approaches – either inquiry or transmission – and the other was in their learning goals for teaching deep time – either wonder or relativity. The educators tended to favor one or the other of these two elements, though we found that the alignment between approaches and goals was varied and that some educators' practices varied their approaches in response to the group of learners.

Pedagogical Approaches: Transmission vs. Inquiry

The tension between an *inquiry* and a *transmission* approach to learner engagement is illustrated through a comparison of the educators we observed. This tension in educator practice has been observed before in this Museum (Allen and Crowley, 2014) and is explored further here in order to consider how each approach may be used to its full advantage. Amy, the camp counselor, used a strong inquiry approach, characterized by learner autonomy, conversation and reflection. This approach stands in contrast with

the transmission-oriented approaches that we observed from several docents. The transmission approach assumes that knowledge is a property that gets transmitted from a more knowledgeable person, the docent, to a less knowledgeable person, the Museum visitor.

Amy, the counselor, began the activity with a few framing questions to the whole group, and quickly transitioned to a hands-on activity. She distributed the loose and undated felt event markers to pairs of students, asked them to place them along the simple Rope, and then stepped back to allow the children free reign of the activity. She encouraged the students to discuss their ideas with their partners, but did not guide them to place the markers anywhere in particular. During this time, there was a lot of debate both within and between groups about absolute and relative position of the event markers. Amy encouraged the debate, explained that they would have a chance to review and adjust all markers as a group and did not weigh in on the 'correct' placement.

After a full 10 minutes of having campers walk up and down the Rope, loudly debating with one another, Amy asked them to sit together in a close jumble on the floor near the more recent end of the Rope. The children immediately began to ask questions about the relative position of events, as seen in this exchange about dinosaurs.

Amy: Let's work on this dinosaur end

Boy (looking at the position of the dinosaur extinction event marker 65 million years ago): How could the dinosaurs be so close to the future?

Amy: Is it possible that dinosaurs are a recent thing? [making air quotes around 'recent thing']

Many children (shouting): Yes!

The children, who were emboldened by the authority Amy gave them, began to loudly discuss how something that feels very old, like dinosaurs, could actually be recent in geologic time. Several campers also vociferously questioned the placement of other event markers. For example, one child asked, 'What are humans doing back there?' pointing to markers relating to human existence which were placed at about 500 million years ago near the first shelled marine animals (see Figure 2). Amy used this question, along with others like it, to encourage the children to articulate arguments for or against the placement of event markers. These loosely organized debates led to Amy and the campers moving several event markers to new locations.

Amy then told the campers that they were going to compare their guesses to what scientists know about these events, at which point she unfurled the key Rope, lining it up next to the simple Rope so that event markers on each Rope could be compared. The children immediately erupted into noisy exclamations, noting where their guesses were correct and where they still needed to be adjusted. Amy asked, 'What did we discover?' and one child said, 'All the things that we're familiar with are piled up.' This led to several minutes of discussion about the relative scale of events on the Rope.

Throughout the activity, Amy allowed the children to construct their own knowledge about events in deep time. She pushed them to move beyond random guessing and towards defensible ideas based on prior knowledge. Even when the children's guesses did not align with existing scientific understanding, Amy did not make immediate corrections and instead continued to press the children to articulate their reasoning. When she did finally reveal the accurate scientific information, she continued

Figure 2. Campers gathering around the Rope to discuss their placement of event markers for human habitation alongside a marker for the Paleozoic Era. (Photo credit: Marijke Hecht/LRDC). [Color figure can be viewed at wileyonlinelibrary.com]

to use a discovery method by letting the children walk around comparing the two ropes. Amy's inquiry approach is reflected in this comment where she emphasizes the role of play and talk for knowledge building for the campers.

> We compared the answer key Rope to our Rope that we had played with. . .and the talk that came out of that

We also observed a strong transmission approach in other educators' practices. For example, after some experimentation with both ropes, both Denise and her partner, Faith, developed a transmission dominated approach to the deep time activity. They would begin by introducing the concept of the Rope and then introduced each of the touchable objects. Although they asked visitors to try to sequence the touchable objects, this was often heavily managed by the docents with frequent correction and guidance, which was followed by the docents facilitating the object's placement at the correct point along the Rope without allowing for substantive opportunity for the visitors to articulate their ideas for sequencing. We observed this emphasis on transmission in the following interaction between Denise and a family group consisting of a mother and a

father, their middle-school-aged son and high-school-aged daughter.

Denise began by introducing the concept of deep time and explaining how the Rope is scaled to reflect the entire history of the earth. She then invited the group to look at the touchable objects, where she introduced the stromatolite, explaining how it is formed and how old they can be, which elicited some visible interest from the family and an audible 'hmmh' from the daughter. Denise then began to explain what each of the touchable objects were before asking the family to try to place the objects in the correct sequence on the wooden bench. The daughter took up this challenge, thinking out loud about whether the trilobite should come before the dinosaur claw. Denise did not use questions or prompts to encourage the daughter to expand or explain her thinking. Instead, she transitioned to transmitting information about the objects to the group. She then worked closely with the two children (the mother and father had receded by this point) by directing the sequence of each of the objects on the bench and walking with them to place the now-ordered objects in the correct position along the Rope.

Later, when Denise and Faith were asked about how the activity went, Denise reflected her sense that there was a lot of information for them to impart to the visitors, 'we were giving them so much, we were giving them the timeline, we were giving them the touchables…' Faith, added that they were, 'helping them place their items that were touchables.' Here, we can see how these two docents viewed the activity as one in which there was a lot of information which they worked to transmit to Museum visitors.

Learning Goals: Wonder vs. Relativity

The second tension was between two different learning goals: some educators worked to promote a feeling of *wonder* about deep time, while others aimed to increase learners understanding by exploring the *relativity* of deep time. This relativity includes both the relative sequence of events on the geologic timeline, as well as the relative duration of the events (Resnick et al., 2017). Robert and Kelly, one of the docent pairs, individually tended towards each of these two approaches; they also demonstrated how they could be brought together for greater effectiveness.

Kelly's playful interaction with Museum visitors suggested that she had an inquiry approach, which she used to encourage wonder about deep time in the visitors. As groups approached the spotlight activity, Kelly would hold up the coiled key Rope and ask them things such as 'Do you ever think about how old the earth is?' or 'Would you like to pull out the line of life?' She encouraged them to take the end of the Rope which represented the formation of the earth 4.6 billion years ago, and to walk across the Museum floor with it until the Rope was completely unfurled. During this walk, she would point out a few of the events on the Rope and frequently encouraged people to place the touchable objects along the Rope. Although visitors, both children and adults alike, often resisted, Kelly stressed that it was alright for them to make guesses, and use what she called their 'inner child'. Her approach led almost all of the Museum visitors that she engaged with to participate in the activity in a relaxed fashion. When we asked Kelly in her interview to reflect on her approach, her emphasis on wonder came through:

> And then, when we made it a game it took the pressure off. Who cares if you get it right? It was a fun activity. It wasn't like 'I have to learn this blah blah blah science. I'm just having fun at the Museum today.'

Her partner docent, Robert, specifically emphasized content and the relativity of deep time, both in terms of sequence and duration. Robert is the docent who brought touchable objects from his personal collection and he was eager to give visitors a chance to examine the objects. For example, after providing an overview of the scale of the Rope to a family group with adult children Robert asked them to estimate several of the objects' locations. He then sequentially considered each of the touchable objects with the group, using a transmission approach to give explanations for each object's formation. In some cases, as with the stromatolite and the piece of banded iron, he provided fairly detailed explanations of their formation, but in all cases, we observed his emphasis on the relative nature of the objects. When asked to describe his approach, Robert reflected,

> It's more trying to put it in relative dating, relative time. As opposed to specific times. Did this occur before this? What do you think occurred first?

We can see from this that Robert valued the visitors learning specific content about geological processes and deep time over wonder.

DISCUSSION

It is important to consider how these two educational activities – a brief one-time interaction on the Museum floor and a week-long interaction during a summer camp – present very different constraints and affordances for the educators and learners. How do these different Museum settings support the application of a transmission or an inquiry approach to teaching deep time? How might both wonder and relativity be explored with learners?

In the summer camp, educators were able to build conceptual knowledge over an extended 1-hour lesson and to continue this thinking with campers over the course of the week. This setting provided a platform for the inquiry-based approach that Amy used in her presentation of deep time. She was able to let the campers construct their understanding of how deep time works through a series of scaffolded activities that moved from independent work in pairs, to large group discussion, to large group comparison with scientific consensus. She used the physical timeline and made it into an object of surprise. Amy did not waver from this inquiry approach, and we observed her using it to support both wonder and understanding of relativity of deep time.

This longer camp program contrasts sharply with the spotlight activity on the Museum floor, where docents have to draw Museum visitors in and then have only a short time for engagement. This setting requires docents to read the visitors quickly and adapt approaches almost instantaneously or risk losing an educational opportunity. Denise, one of the most experienced docents at the Museum, noted in her interview that Museum visitors have very different interests and expectations.

> For some it was really the start of 'OK, we're thinking beyond this' and for some it was just, 'Oh!'. We got the aha moment and that was pretty much as far as they were going to go with it.

However, we observed that not all the educators calibrated their pedagogical approaches

to respond to these different learner expectations. Denise and Faith relied almost exclusively on transmission to ensure that they could convey important ideas about deep time. We noticed that during their spotlight activity, visitors may have received specific pieces of relevant information, but did not ask as many questions or make as many excited comments as we saw with Robert and Kelly.

Their heavy use of transmission rests on the assumption that knowledge is object to be conveyed from teacher to learner (Allen and Crowley, 2014). However, understanding of deep time requires conceptual change in which learning is a process, rather than the possession of knowing a thing (Resnick et al., 2017). This suggests that the learner is not forming a specific cognitive object in their mind, but is instead in a cognitive state that supports the process of knowing (Hammer, Elby, Scherr, and Redish, 2005). Based on this, deep time is not a cognitive object to be grasped correctly or incorrectly – it cannot be transmitted. Instead, understanding of deep time builds as part of a process of learning that draws on existing learner resources. A learner may know about something, but they may not be able to engage and participate with the knowledge; in other words, they may not yet understand it (Greeno et al., 1996).

Ideally educators are facilitating the learner's movement from factoid-based knowledge of deep time to conceptual understanding of deep time. Educators may feel that the looseness of an inquiry approach, what Kelly called 'chaos', presents too many challenges in a short time period and in the unpredictability of the Museum floor. In fact, we observed Denise and Faith begin to attempt some inquiry approaches but then abandon them in favor of transmission. During our later interview, Denise wondered if she was giving the visitors too much information, indicating her own sense of the tension between transmission and inquiry.

We do not wish to imply that transmission is a wrong approach. To the contrary, in certain situations, it may be the most effective strategy. Instead, our observations suggest that the flexible use of both transmission and inquiry may be the most effective strategy for reaching visitors that enter the Museum with a range of interests and expectations. We observed this responsive and flexible approach from Robert and Kelly. While they each tended towards either transmission or inquiry to meet their respective learning goals, they also adjusted strategies as needed. Kelly, who was strongly oriented towards a learning goal of wonder, tried leading with inquiry approaches on many occasions. However, she adapted to use transmission as an approach when visitors did not engage quickly in the activity. In these instances, she would talk visitors through key aspects of the Rope, pointing out the density of events at the more recent end of the Rope, where she said 'life just explodes'. Her use of transmission still placed an emphasis on the vastness of deep time and aligned with her learning goal of wonder. Robert, who tended to use transmission to convey relativity as a core concept of deep time, still infused several of his interactions with inquiry approaches. For example, he would sometimes encourage visitors to formulate their own arguments for why to place objects in different locations along the Rope. Our observation of this pair suggests that the tension between transmission and inquiry, and wonder and relativity, can be used to good effect when educators are comfortable employing both strategies in response to learners' apparent engagement and interest.

CONCLUSION

Natural history Museums, rich in collections and exhibits related to the Earth's history, are uniquely positioned to tackle critical issues of the Anthropocene, such as deep time, with the public. However, the scalar leap needed to conceptualize deep time has proven a challenging and persistent problem of practice. The Rope was meant to be a tangible object that would act as a resource to help educators lead learners in exploration of the deep geological timescale in order to make connections to the present and future. This approach was intended to support the Museum's on-going goal to engage visitors in considering the Anthropocene and humanity's role in Earth systems. The Rope leveraged the work of a research-practice partnership to integrate understanding of learning and tangible objects (Horn, 2018) into the construction of a simple and inexpensive tool that the Museum could easily modify and use in multiple learning settings (Hecht et al., 2019).

An unexpected side benefit of using the Rope in different Museum settings was the opportunity it afforded for Museum educators to reflect on their practice. After noticing how educators both identified their own default approaches and questioned whether that was always the right fit for different audiences and settings, the Museum is now exploring ways the Rope might be used for professional development as a tool both for reflection and practicing new techniques. This is an opportunity to explore the relative strengths of the different approaches and to consider how they may be used in different combinations depending on the circumstance. This additional application of the Rope, in addition to further developing it as a tool for exploring deep time with Museum visitors, extends its value as a tool for educator training. The Museum education department has begun to use this as part of their on-ramping process for new docents and will continue to refine the tool.

We found that the Rope generated awe and understanding in many learners, but also evoked fear about our present and future. In her recent book, geologist Marcia Bjornerud (2018) argues that thinking like a geologist is essential for people to understand our human relationship with the natural world. Here we saw a tool used to explore deep time being used to help learners connect to the Anthropocene, our present and our future. This connection appeared to be strongest where educators used a pedagogical balance between wonder and content, such as the relativity of deep time, whether through a transmission or an inquiry-based approach. It is this balance, and these connections, that can foster and encourage 21st century naturalists. However, we need additional tools to support educators as they work with learners to face, and even transform their fear of the future. END

ACKNOWLEDGMENTS

Many thanks to the educators at the Carnegie Museum of Natural History for their contributions to this work. Thanks also to the anonymous reviewers for their helpful comments, which greatly improved this manuscript. The research reported in this article was made possible by a grant from the Spencer Foundation (#201600114). The views expressed are those of the authors and do not necessarily reflect the views of the Spencer Foundation.

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SUPPORTING INFORMATION

Additional supporting information can be found in the online version of this article:

Appendix S1. Rope of Deep Time markers included on the prototypes.