FEATURE ARTICLE

Adventures in Evolution: The Narrative of Tardigrada, Trundlers in Time

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Abstract

A lesson plan on the phylum Tardigrada is presented in a storytelling workbook that introduces the evolutionary concepts of adaptive radiation, speciation, divergence, and "tree-thinking" through narrative, transitional art, contemplative coloring, and data searches, which can be enhanced with microscopy wet labs. Students gain insight into the invertebrate world of the highly adaptable, ubiquitous microorganisms known colloquially as "water bears," generating a microevolutionary and macroevolutionary perspective through a narrative that includes an introduction to the TimeTree database.

Key Words: *Tardigrada; storytelling; TimeTree; speciation; divergence; tree-thinking; adaptive radiation; evolution; art; scientific drawing.*

○ Introduction

Evolution is the unifying principle of biology, and understanding the core concepts of evolutionary process is critical to understanding all biological systems (Mayr, 1970). Common student misconceptions in regard to evolutionary process include interpretations that rely on hierarchal values such as "inferior" and "superior," and the cultural construct of "older" being inferior and "newer" being superior (Cooper, 2005), rather than a continuum of branching and diversifications with no attached value judgment. Examining the cultural perspectives that undermine an acceptance of evolutionary process and the unity of life is critical to resolving such disconnects (Suzuki & Knudtson, 1992). Constructs of better/worse based on perceived obsolescence may be a result of consumer culture, which perpetuates the notion that anything not "new" must be less "advanced" or less valuable (Hsu, 1964). Students' reasoning patterns are embedded in linear, consumerist economic thinking (Maser, 1992), which may influence their conceptualization of the natural processes that renew and repurpose biological chemistries and systems.

> *Tardigrades are the "organism of the moment," their Pokémon-like features having seized the attention of non-biologists.*

Another factor that may contribute to students' difficulty with evolutionary thinking involves the hemispheres of the human brain. Right-hemispheric skill sets are useful for understanding broad, macroevolutionary timescales, whereas left-hemispheric skill sets help elucidate small-scale changes within individuals and populations. Our educational system appears to overemphasize left-hemispheric skills and downplay right-hemispheric aptitudes such as synthesis and connectivity (Fagan et al., 1979). Roger Sperry's work with hemispheric qualities has provided insight into brain function, including the way we process language and images differently in each hemisphere (Sperry, 1961). This ability of the brain to take the small and sequential and merge it with the expansive may permit an understanding of the complex issue of defining multidimensional phenomena in complex biological processes and systems.

Terminology and imagery have strong implications for the way we see the world (Fauconnier & Turner, 2003), including the evolving planetary world. Consumer patterns create linear economy-thinking models and, perhaps, an oversimplification of processes. This type of thinking, along with other factors (e.g., religious concepts), may undermine the conceptualizations central to the idea of evolving systems in nature (Roszak et al., 1995; Wilson, 1999). Grasping "big-picture" processes like macroevolution and geological time essentially requires a "right-brain" thinking mode, which may benefit from the use of narrative in our consumer-minded culture. How can biology educators alter a strongly, culturally established view about life on a geological timescale within a fast-paced, throwaway environment? How can students see ecosystems, teeming with the complex interactions of organisms and their nucleotide sequences in spatiotemporal stages, as interdependent and networked, rather than envisioning these systems as isolated, rigidly constructed

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objects? Is there a simple way to present complex evolutionary processes and the geological timescale without perplexing students further? Is there a way to express evolution's key concepts that is relevant and appealing to students?

It has been suggested that experience with real scientific data and professional research will help students master computational reasoning and tree-thinking (Kong et al., 2017). While that is certainly true, we present a complementary perspective here, using "right-brain" storytelling and images to engage students in evolutionary thinking, phylogenies, and computational biology concepts. We combine these elements with smaller molecular ideas, leading to phylogenies and simplified but organism-based tree-thinking. Tree-thinking, which is a large part of current biological research, is also (understandably) a difficult concept for students to visualize and grasp (Meir et al., 2007). To ease into the molecular-evolutionary diagrams of sequence comparisons and phylogenetic trees, this article will focus on establishing, through storytelling, a narrative on the evolution of a particular phylum. Storytelling is a process of context and connecting the dots; it provides both a wide lens and ordered, detailed focus (Agosto, 1999). These two perspectives rework and parallel macroevolutionary and microevolutionary processes within a narrative form that utilizes real species as protagonists. The organisms of choice for this work are tardigrades, members of the phylum Tardigrada (known colloquially as "water bears"). Their story is told in the style of an illustrated children's book, similar to Maurice Sendak's *Where the Wild Things Are*, Kenneth Grahame's *The Wind in the Willows*, and A. A. Milne's *Winnie the Pooh*.

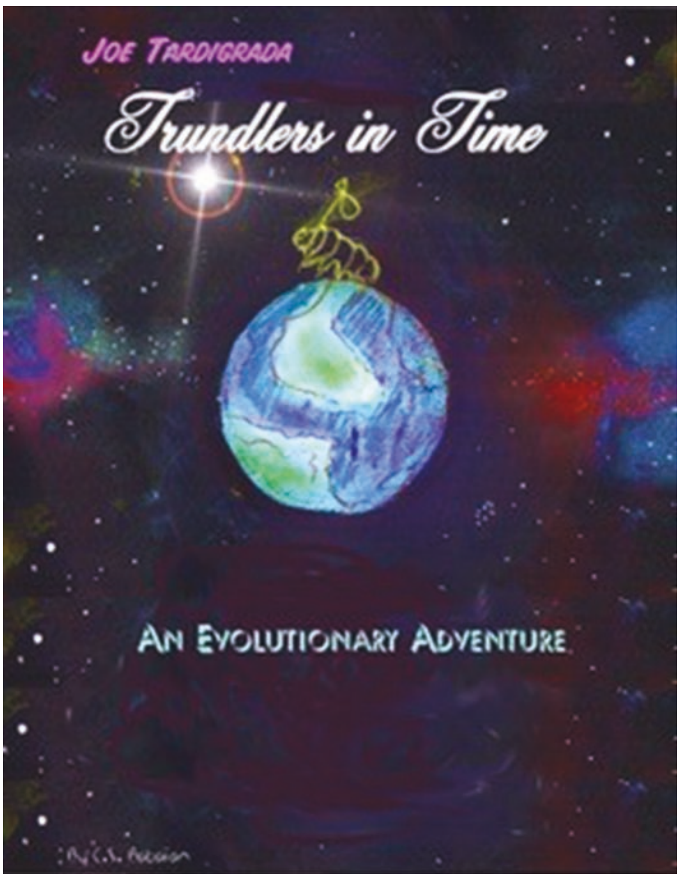

Figure 1. Tardigrada workbook cover.

The illustrations translate the abstract concepts of genomes, niches, microevolution, macroevolution, and phylogenetic trees within a narrative workbook (see Figure 1 and Table 1; the workbook is available for download at http://www.timetree.org/public/data/pdf/JoeTardigrada.pdf). This workbook was produced by the authors in a computational evolutionary science lab to explore the potential of storytelling, artistic process, and evolutionary and biological processes.

In exploring tardigrades' unique, evolving destinies in geological time, we create an equality between the reader, the organism, and the concept of evolutionary process that circumvents inferior/superior roles. Stories cross cultural boundaries and tell universal tales of creation, metamorphosis, and change (McKeough et al., 2008). Like many children's stories, this work relies on anthropomorphic views that are typically frowned upon in science (Davies, 2010), but it is through these views that we become conceptually aligned with other forms of life at an early age. Through the use of narrative, drawing-to-learn exercises, contemplative coloring activities, and database searches, students may become reacquainted with, innately drawn to, and connected to other life forms and their evolutionary journeys.

○ Tardigrade Background

Much has been written about tardigrades. They have – like sloths, panda bears, and a host of other animals – become embedded in pop culture, with little regard to their humble beginnings (Kinchin, 2000). Tardigrades are the "organism of the moment," their Pokémon-like features having seized the attention of non-biologists – a difficult task indeed for any protostome, but human moments of fame don't mean much in geological time, as students may soon find out. Tardigrades were "discovered" under the observant eye of microscope aficionados like the clergyman Joseph Goeze (Wełnicz et al., 2011). Another clergyman, Lazzaro Spallanzani, experimented with the little invertebrates to reveal some of their desiccating properties and their bear-like gait, which earned them the name "slow steppers" (Withers & Cooper, 2010).

Throughout the 1700s and scattered through time, observations of microscopic organisms becoming reanimated from desiccated states were recorded (Jönsson & Bertolani, 2001). The ability to desiccate or enter cryptobiotic states was documented in a number of aquatic organisms, including rotifers, nematodes, crustaceans, and protozoans. But it was the tardigrades' "cuteness" factor that reanimated them in the minds of the general public. Tardigrades are bilateral micro-metazoans with four pairs of lobopod legs that terminate into claws or sucking disks (Nelson, 2002). Their mouthparts are also variable; most siphon sap, but there is one known parasitic species (Pohlad & Bernard, 1978). Tardigrades have been trundling through time since their segmentation, more than 550 million years ago in the Cambrian era, and will likely be moss mingling long after we're gone. What makes these organisms so attractive to humans is their staying power and their extremophile physiology. They occupy a diverse set of niches, are often only 1 mm long, exhibit a variety of colors as well as being transparent, and are global travelers, existing even in Antarctica. While they prefer wet environments, their unique ability to desiccate and to reproduce parthenogenetically has contributed to their worldwide ubiquity. Tardigrades typically exhibit low population density but immense diversity, with 1000–12,000

Table 1. Tardigrada workbook features.

Evolutionary Concept	Activities	Outcome
Characters	Using morphological characters to draw a tardigrade	Students familiarize themselves with species' anatomy through drawing to understand visible phenotypic changes and the metabolisms of Tardigrada as part of phenotypic expression (cryptobiosis, oxybiosis).
Divergence	Text, cartoons, and story line	Students connect concepts of divergence and speciation through cartoon metaphors.
Adaptive radiation	Exploring a variety of ecosystems with tardigrades and morphing a "prototype" tardigrade through drawing	Students learn the importance of variation, natural selection, and the concept of transitional processes as they make their drawings "morph" in new environments.
Phylogenetic tree	Exploring unresolved relationships in invertebrate metazoans through drawing	Students understand morphological physical traits as being coded by genes. They see variations in forms and explore how DNA, which codes for the proteins expressed, produces this variation. Size, shape, colors, patterns, and presence or absence of characteristics are highlighted by the workbook activities.
TimeTree database exercise	Comparing a wide range of species with Tardigrada, including vertebrate mammals	Students play with the database and familiarize themselves with the potential of TimeTree, with more structured and specific applications to follow.

species currently identified (Nelson, 2002). Their occupation of many diverse niches, attributed to their ability to adapt to radically changing ecological conditions, sets the platform for their evolutionary story. Tardigrades are readily available in moss and lichens and can be cultured for students to observe and take care of in terrariums (Nelson, 2002).

○ Workbook Background

The workbook "Tardigrada: Trundlers in Time" was created to engage students in a slightly fanciful narrative that highlights tardigrade evolution, along with amusing activities and relaxing lessons with coloring-book elements. The workbook has not been published but is available for download on the TimeTree website (http://www.timetree.org/public/data/pdf/JoeTardigrada.pdf). A few of the images are presented in this article, but the full effect of the workbook is intended to move students through many of the common terms of evolutionary thinking. We propose evolutionary thinking as the "master narrative" to help students casually synthesize a dynamic, comprehensive, panoramic view of evolutionary process. We also present tardigrade evolution within a broad ecological framework. "One innovative notion," writes Catley (2006), "is that classification is best understood in an ecological context, such that the sets of interrelationships are presented as manifestations of natural selection over very long periods of time." We achieve this geological timescale in our narrative through the character "Joe Tardigrada" and his travels around the globe.

Thus, the workbook takes an evolutionary/ecological view in story format, encourages naturalist-style observation, and includes classical drawing exercises, while promoting phylogenetic thinking. It should be printed and used to color in, draw in, and make notes in. It can be given as homework or structured as an in-class assignment. We suggest that the workbook be used in conjunction with a wet lab or as part of a larger lesson plan on evolution, at the discretion of the instructor. It takes about one hour to finish but is intended as a contemplative prelude to more rigorous study, so students can take up to a week to complete it. Many comprehensive, visually well-presented articles have been published on tardigrade metabolism, anatomy, ecology, and evolution, and labs are available online for culturing or maintaining living specimens (see Further Resources below). Our purpose is not to rewrite this already accessible knowledge, but rather to provide a "point of entry," an alternative to the standard PowerPoint presentation on tardigrades. The workbook introduces evolution, phylogeny, and computer databases to start building an evolutionary mental construct and more intuitive thinking in interpreting phylogenetic trees.

Visual metaphor is used in the workbook as a powerful way to imagine processes we cannot see (Pramling, 2009) and enhance comprehension of ideas. An example of this can be seen in Figure 2, which depicts Joe Tardigrada carrying his genome with him as he travels through time and around the earth – a simple cartoon conveying the concept of a genome, represented as a vagabond's belongings. When we speak of genomes, students typically conceive of them only as abstracted sequence data and may forget that genomes are a nested network of complementary, replicating molecules in the cells of an organism. The takeaway message from Figure 2 is that where an organism travels, so does its genome.

The workbook uses the phylum Tardigrada to channel the complexities students may encounter in evolutionary theory in a way that can be applied to any organism. The entertaining, artistic narrative is designed to help students retain useful genetic and evolutionary

Figure 2. "Joe Tardigrada" and his genome. This image offers students an analogy for the ubiquitous nature of the tardigrade genome. It also suggests to students that organisms, including humans, take their genome with them as they enter new environments. Selective pressures change with the movement of the genome as it encounters new organisms and new environments.

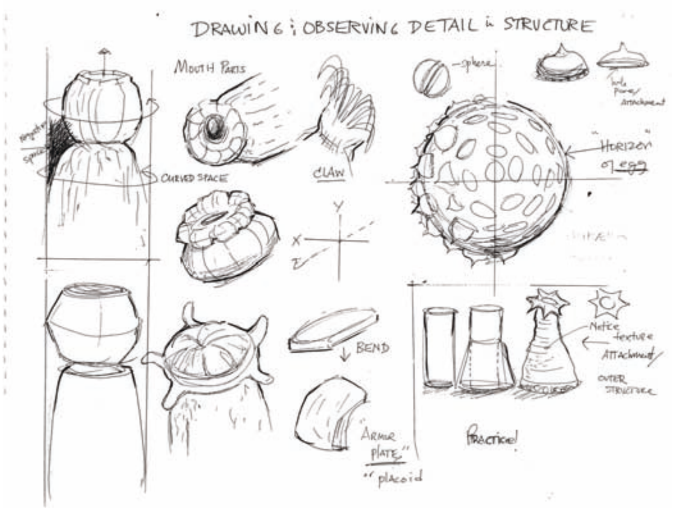

Figure 3. Drawing the specialized mouthparts of Tardigrada and the ornamental characters of eggs. Up close, students can see the morphological complexity that can help distinguish and establish species. Even "cutely" illustrated tardigrades are far more complex than they appear.

metaphors while becoming comfortable with the skill set of drawing (and toggling between using technology and functioning without it), thus inspiring their own process of descriptive discovery. Students are given several pages of drawing lessons specific to live, potentially moving organisms viewed under a microscope (Figure 3). We have condensed adaptive radiation into a few pages of "evolving" your own tardigrade through drawing. Since adaptive radiation, speciation, and divergence require another set of perspectives, we provide separate activities. The adaptive radiation cartoons provide a concept whereby students can infer hypothetical morphological changes into the future, which may help students appreciate the spatiotemporal components of adaptive radiation (Figure 4). Evolutionary thinking requires mentally "weaving" in and out of large timescales; small genetic changes; large, visible organisms like dinosaurs; and microscopic organisms like invertebrates, protozoa, and microbes. It links these "parts" with the greater whole of ecology (Dodick & Orion, 2003). A flexibility in temporal thinking is encouraged, along with an ability to imagine continual animation amid "worlds within worlds," a concept that is considerably complex but accessible through a storybook. To improve students' chances of grasping these difficult concepts (Aigner, 2007), we chose a relatable, distinctive, and fascinating organism that both represents the microscopic realm and also contains the expansive dynamic of macroevolution.

Visualizing the expression of genes into phenotypes requires what may be called a "phantom" perspective, imagining the form a genotype might take when it is translated into a phenotype. Genes and genomes can be compared to notes in music, which exist on the page but are not communicated into sound unless they are played. The genotype is "played" and phenotypic expressions occur with the progressive colonization of a new environment and a host of complex cues that occur at the molecular level (Pigliucci, 2003). Students may ask how genomes arrange and prepare themselves for transformations and ecological uncertainties. Tardigrada's revolutionary extremophile genetics might lead students to think about pressures continually exerted on populations, as well as about the salient features of the tardigrades themselves and how stressful conditions shape their interesting appearance and physiology (Figure 5).

Biologists have long been fascinated by the exceptionally high diversity displayed by some evolutionary groups. According to the naturalists of the first half of the twentieth century, adaptive radiation is the outcome of three ecological processes: (1) phenotypic differentiation of populations by resource-based divergent natural selection,

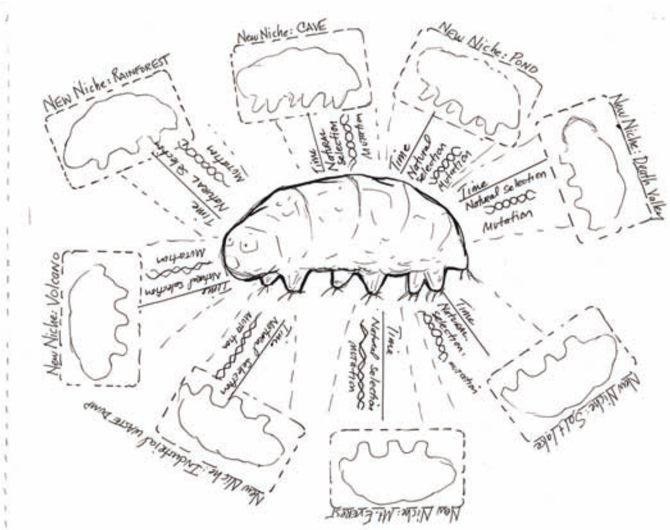

Figure 4. Drawing imaginary future tardigrades as they undergo adaptive radiation. This workbook feature encourages students to think in an evolutionary way through morphing the blank outlines into new species.

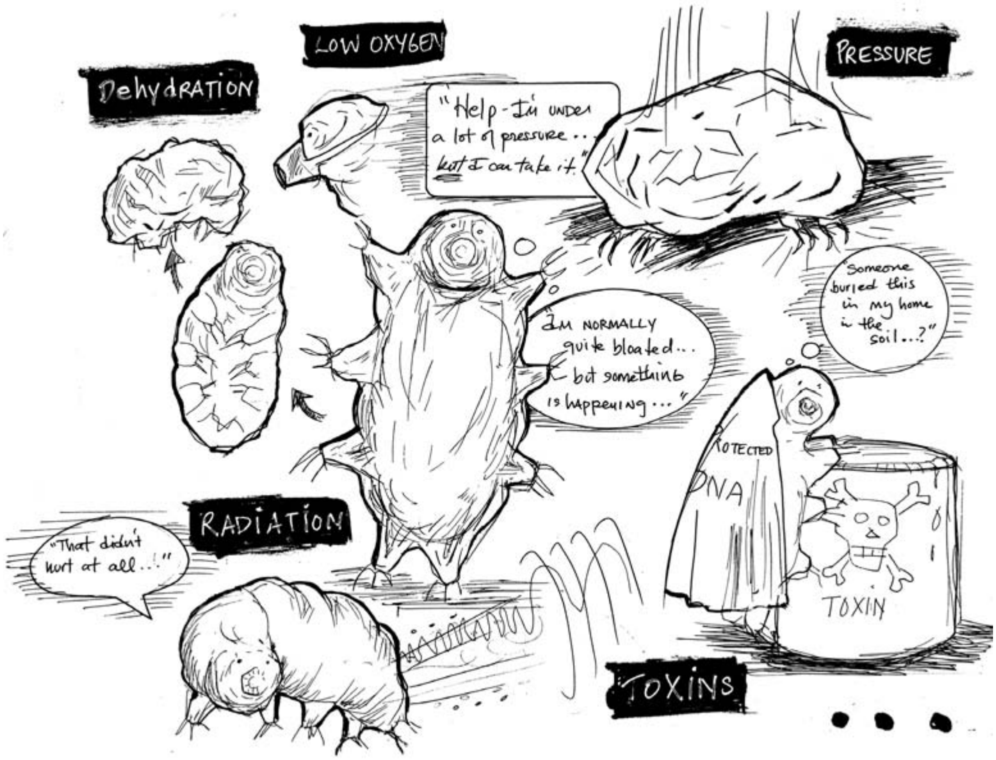

Figure 5. The many extremophile adaptations of the phylum Tardigrada in response to stressful conditions, depicted in cartoon style. In one drawing, readers get an overview of Tardigrada's extremophile phenotype. This encourages questions about how these adaptations came into existence and what type of environmental pressures may have culminated in a constellation of extreme survival skills.

(2) phenotypic differentiation through resource competition (ecological opportunity and divergent character displacement), and (3) ecological speciation (Schutler, 1996). This kind of conceptualization requires a multilayered story and timeline. Tardigrades show an unusually high degree of phenotypic diversity; for example, within an aquatic ecosystem, a micro-sized animal has many possible niches, from leaf litter to salinity changes to parasitic modes (Nelson, 2002). Adaptive radiation in such clades is not only spectacular, but is also an extremely complex process influenced by a variety of ecological, genetic, and developmental factors and strongly dependent on historical contingencies (Gavrilets & Losos, 2009).

○ Tardigrades & Trees

Phylum Tardigrada and "Trundlers in Time" offer some unique perspectives on tree-thinking. Unresolved questions regarding nematodes, oychenophorans, and annelids provide examples of ongoing issues with phylogenetic relationships and molecular data. The metaphorical illustrations in the workbook depict a "family tree" of just Tardigrada to introduce names and appearances (Figure 6). This presents another interesting conflict in tardigrade genomes: horizontal gene transfer (Figure 7), which is not easily depicted or visualized in the tree format (Makarenkov et al., 2006). Figure 6 provides the reader with the idea that other genes from other organisms, mostly prokaryotes, are being "acquired" and incorporated continuously in the branching tree of life. Discussing how this might be represented poses an interesting problem for researchers and one that students can attempt to think about creatively, perhaps inventing their own tree depiction. Finally, the workbook presents the TimeTree database (see http://www.timetree.org/about) as a children's book might; the windows encountered in the software are modified so that students can read, "unplugged," the applications they will be encountering later on the actual website (Figure 8).

○ Tardigrades & Speciation

The branching-within-branching patterns of trees provide biologists a convincing metaphor with which to organize their knowledge of continually evolving life forms and their relationships. However, abstracted from the experience of nature's patterns, the tree metaphor, rather than being enlightening, can be ominous and confusing. In *The Book of Trees*, author Manuel Lima (2014) explains how the vertical and horizontal form of a tree – with roots, growing tips, nodes, and leaves – became a powerful tool for understanding biological relationships. Lima (2014) also makes this revealing statement as to why the tree metaphor may present a problem for the average student:

> In a time when more than half the world's population live in cities, surrounded on a daily basis by asphalt, cement, iron, and glass, it's hard to conceive a time when trees were of immense and tangible significance to our existence.

If students are distanced and distracted from observing the patterns of nature, then evolutionary trees may lose their power to

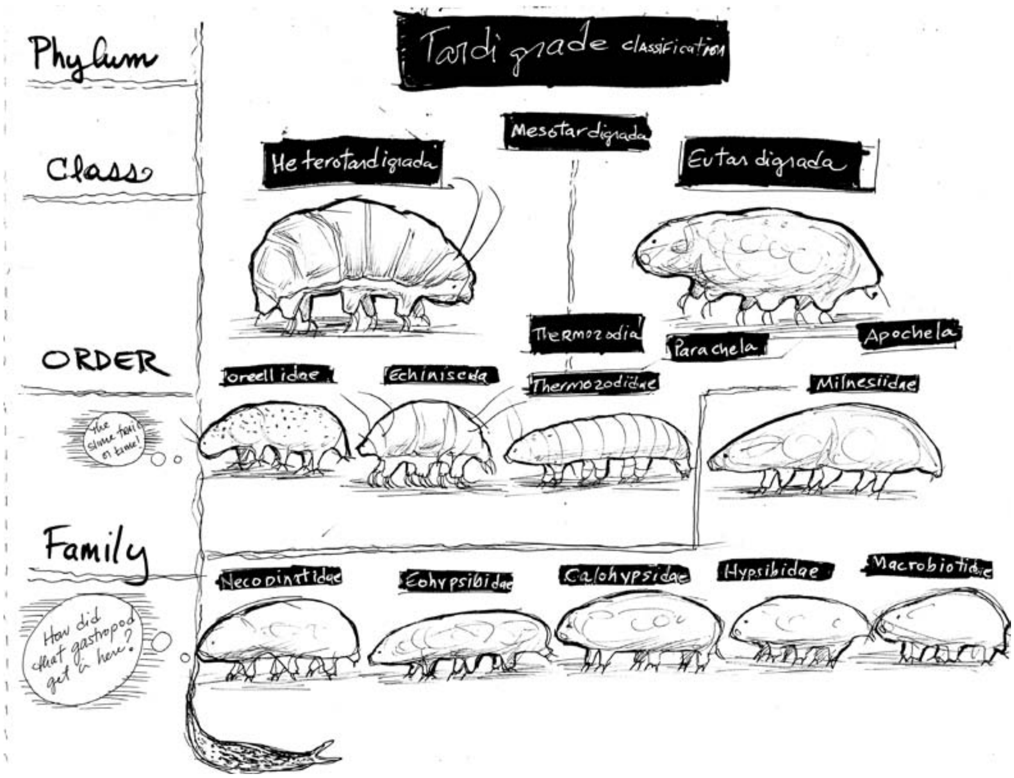

Figure 6. Tardigrada family tree, showing physical appearance and hierarchical classification. This reminds students that behind the branch of a phylogenetic tree is an actual living organism. Sometimes the simplicity of diagrams can be too abstract for students and a more visually based image is needed.

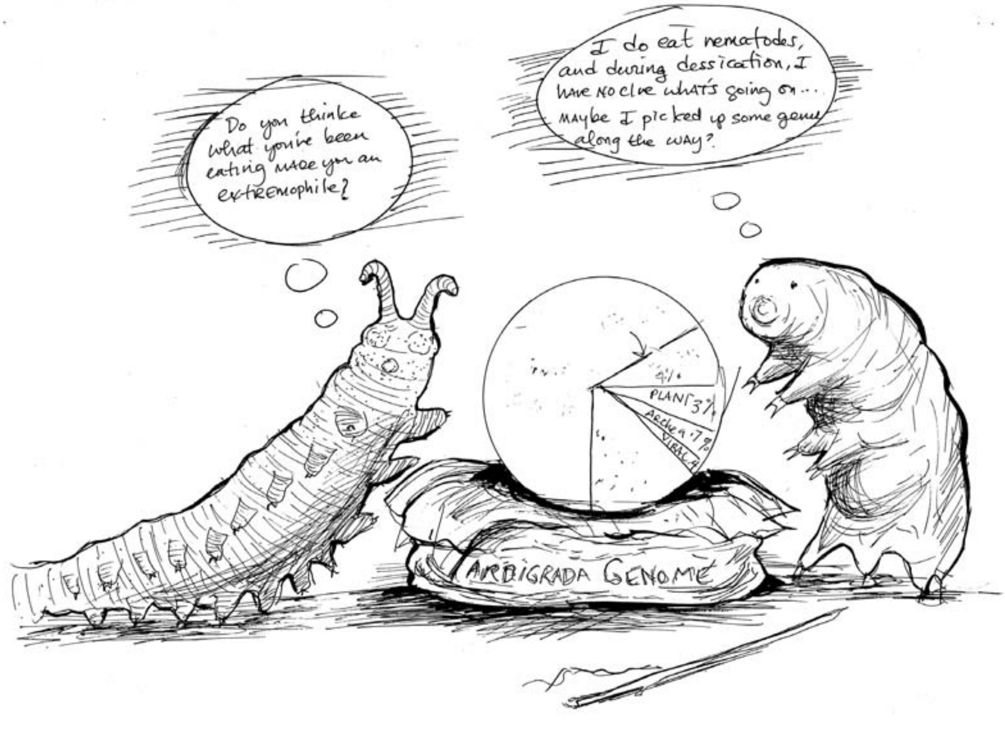

Figure 7. Did tardigrades undergo horizontal gene transfer? A cartoon depicts the conflicting hypotheses. Teachers can use this drawing by itself to focus on research papers that allude to horizontal gene transfer. Cartoons make for an easy entry point into a research paper, as suggested in the dialogue between the velvet worm and the water bear.

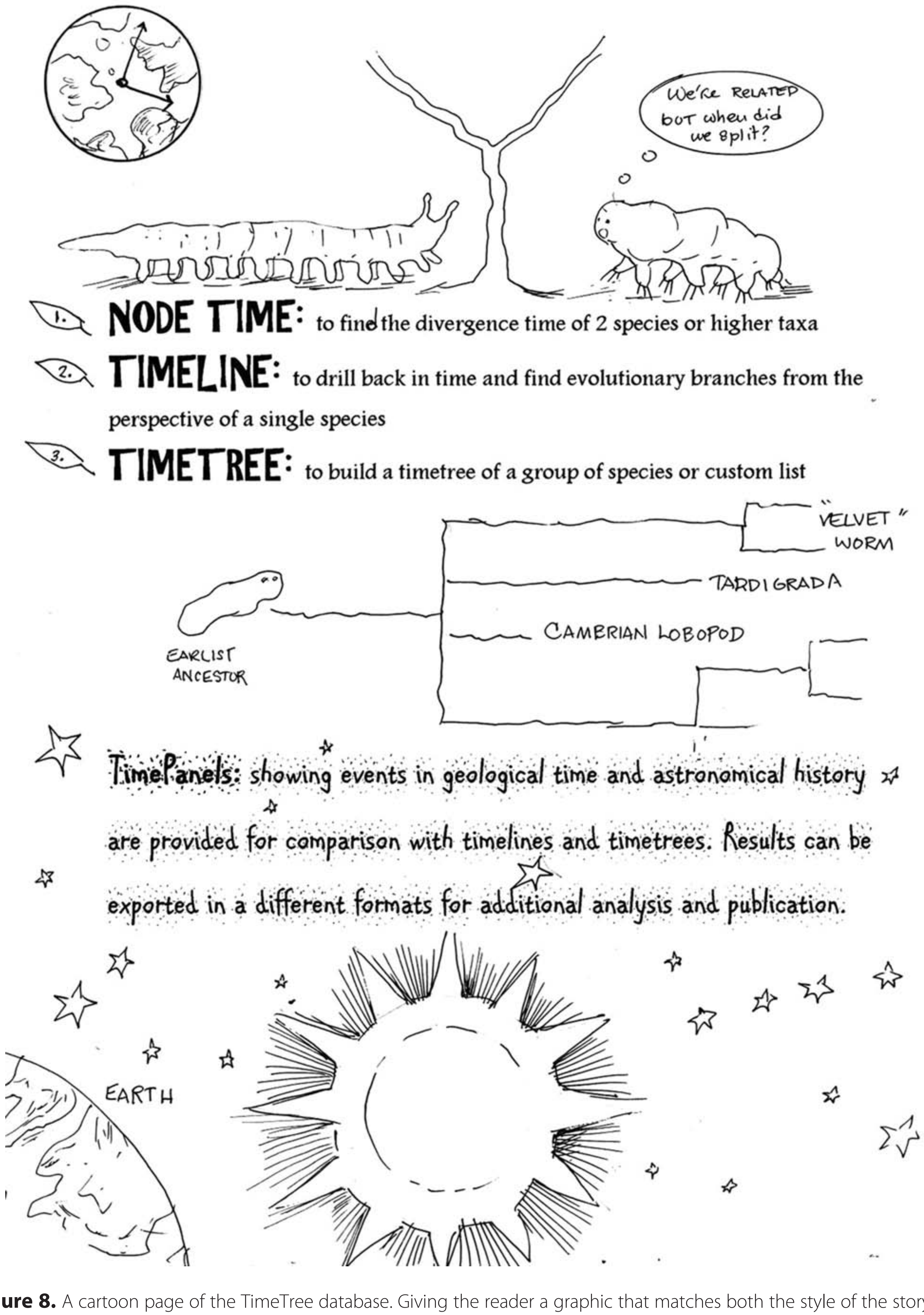

Figure 8. A cartoon page of the TimeTree database. Giving the reader a graphic that matches both the style of the story and the actual database links storytelling and characters in an intimate way to the use of the technology. TimeTree is then a continuation of the story in which the reader is a participant.

convey knowledge. If K–12 students demonstrate difficulties with this metaphor (Meisel, 2010) and with interpreting trees, it may be valuable to get back to the "root" of the problem with the pattern, the tree itself, and represent it with varying designs and versions. For this reason, phylogenetic trees are represented in the workbook as trees with leaves and branches and also as "implied" trees. Understanding how phylogenetic trees and data are used by scientists does not necessarily mean that students understand the relationship on a macroevolutionary scale or understand evolution itself. It may be beneficial to discuss how Darwin arrived at the tree metaphor from his immersion in the natural world, how the immense diversity of living things that occupied his days shaped his thinking. This reveals to students how culture, exposure to nature, and history shape the way we think. Broad perspectives on the past help reframe life processes that are typically viewed through increasingly narrow lenses. Even graduate students, biologists, and other professionals struggle to accurately interpret evolutionary relationships, so the cartooning and storytelling approach isn't just for schoolchildren but has potential uses at higher levels of knowledge.

○ Whole-Brain Thinking & Evolutionary Process

It has been observed that the way we teach and our focus on cognitive function favor the left hemisphere. From a very early age, we are predominantly centered on verbal, symbolic, and sequential experiences (Sylwester, 1995). Even formulas like Hardy-Weinberg give the illusion that evolution is a step-by-step process, a sequenced formula. In the last decade, though, biologists have begun to recognize that despite knowledge being conveyed in a linear manner, actual living systems and biological processes are anything but simple linear progressions (Capra, 2005). Introducing a little fantasy can go a long way in teaching biology – and with tardigrades, nature has already produced something stranger than fiction. Fantasy literature can provide children the opportunity to engage the whole brain. As fantasy demands visualization, it immediately engages the right hemisphere (Aigner, 2007). The study of such literature can jar students out of linear thinking, help them synthesize ideas, and encourage them to think holistically (Moore, 2009). Such "right-brain" thinking can have tremendous benefits when applied to scales and complexities on Earth that are problematic to convey in texts. When comparing picture storybooks that employ interdependent storytelling, distinct categories emerge (Agosto, 1999). One of these categories is transformation. When knowledge is confusing – perceived as chaotic, disorganized, and lacking synthesis – stories provide a framework within which students can think transitionally while building a solid view of evolution and ecology, macro-processes, and micro-process concomitantly.

○ Conclusion

Tardigrades make intriguing characters to read about. They also make excellent characters for stories about evolutionary processes because they give students insights into qualities such as cryptobiosis, horizontal gene transfer, phylogenies, and adaptive radiation. Reading the story line; practicing the drawing of movement, shape, and detail; and coloring the workbook allows students to enter a cartoon world of an organism prior to labs, lectures, or database searches. These hands-on practices and perspectives allow students to incubate the complexities and work through activities at their own pace, employing their individual learning styles and becoming intimate with an organism that can prompt an immediate interest in evolution and phylogenetic tree-thinking.

○ Plan for "Trundlers in Time"

1. Lead students on a nature walk around any wooded area, finding mosses or lichens. With or without a lab, give an introductory talk on Tardigrada (30 minutes).
2. Present a short PowerPoint with various microscopic images of water bears (light field, dark field, scanning electron microscopy) for students to see what they really look like, including images of desiccated "tun" or cryptobiotic states (15 minutes).
3. Draw or show a phylogenetic tree of invertebrates, with the unresolved relationship of Tardigrada.
4. Download and print the workbook (http://www.timetree.org/public/data/pdf/JoeTardigrada.pdf). It can be printed on regular white paper for coloring purposes.
5. If this is a unit on evolution, pose the question "How did water bears become so specialized for extreme environments?"
6. Introduce the concepts of natural selection, divergence, extinction, speciation, niche, and phylogeny (45 minutes).
7. Hand out the workbook. Give students time to read and color. As a second assignment or continuation, ask them to look at the page with the tardigrade morphing into different niches. Ask them to choose a niche and draw what that new species might look like, and then finish coloring the workbook.
8. Ask students to explain their drawings ("Why does it look this way?").
9. If there is time for a lab, see "How to Find Tardigrades (Water Bears) in Your Own Backyard" at https://microcosmos.foldscope.com/?p=17901.
10. Have students perform the lab and observe organisms under the microscope, even if there are no tardigrades. Using the drawing exercises, ask them to draw any moving invertebrates they observe and describe their similarities to and differences from tardigrades.
11. Have students do an easy TimeTree database exercise to familiarize them with geological times and divergences.
12. Have students turn in their drawings and workbook. The workbook should be assessed on the level of completion. Rather than a rubric, it is easier to "eyeball" the work, to see if students applied the drawing/noticing instructions when looking over their work. You could also go through the drawing with them on the board by drawing the tardigrade, the onychophorans, and the annelids as well as the ornamental qualities of the eggs.
13. Give students a short quiz on terms studied, asking for short-essay explanations.

Further Resources

- Lab: https://microcosmos.foldscope.com/?p=17901
- Movie: *BBC Earth*, "Tardigrades Return from the Dead," http://www.bbc.com/earth/story/20150313-the-toughest-animals-on-earth
- Video of tardigrade life cycles: https://www.youtube.com/watch?v=xS3CZ_U8axU
- Tardigrades in time lapse: https://www.youtube.com/watch?v=v6JOeyTBkwI
- *Evolution News*: "Are Tardigrades 'a Head' of Arthropods?" https://evolutionnews.org/2016/01/are_tardigrades/
- TimeTree database: http://timetree.org

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