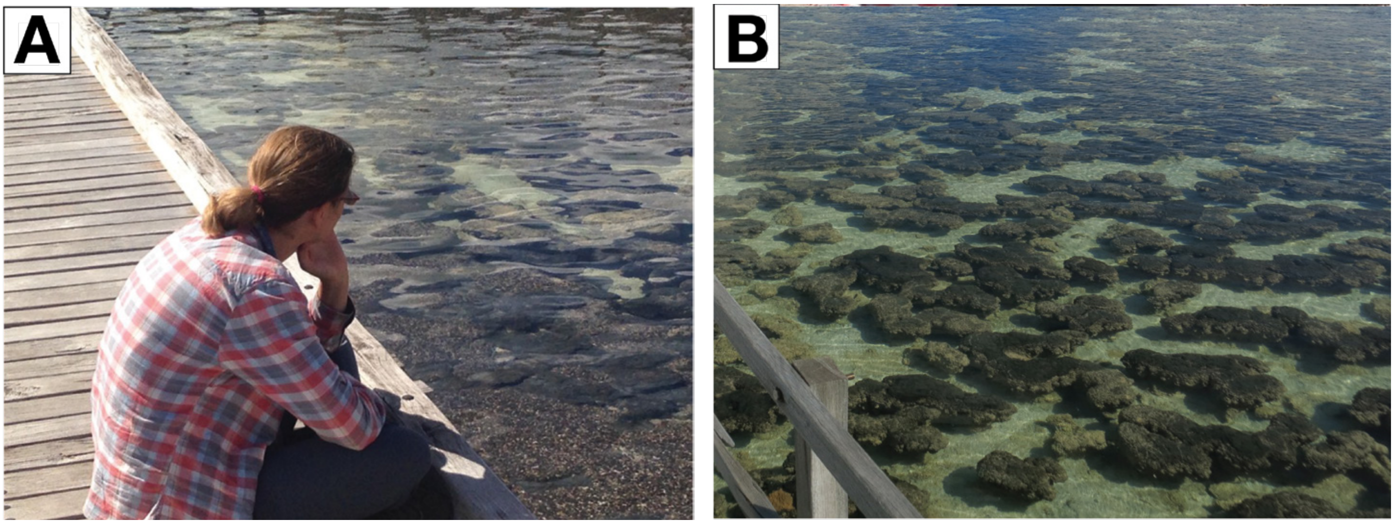

Figure 1. (A) A geologist contemplates living stromatolites at Shark Bay, Australia. Photo by T. Shipley. (B) A close-up of living stromatolites in Shark Bay, Australia.

Shark Bay, Australia, and the Centrality of Analogical Thinking

Basil Tikoff *,[1] and Thomas F. Shipley[2]

Geology logline: *The stromatolites preserved in the ca. 3.4 Ga rocks of the Pilbara craton of Western Australia are understood, in part, by analogy to living microbial mats in Shark Bay, Australia.*

Cognitive logline: *Analogies are the foundation of reasoning about the past where alignment of two related concepts allows inferences about less-well-understood concepts from well-understood concepts.*

> *out on the islands … you can watch the time of the world go by, from minute to minute, hour to hour, from day to day, season to season.*
>
> —Robert McCloskey, *Time of Wonder* (1957)

Shark Bay, Australia, is the home of some of the best-known present-day stromatolites (Fig. 1). Stromatolites are accretionary structures made by microbial mats, which are biofilms containing symbiotic colonies of bacteria and algae that occur in shallow marine settings. They are common in the fossil record from the Archean until the middle of the Paleozoic. Their relative scarcity since the Devonian is a result of being eaten by a variety of marine animals. The stromatolites of Shark Bay are thought to flourish because of the extreme salinity of the water in the bay, which limits the presence of predators.

Shark Bay is on many geologists' bucket lists. Tim visited in 2015 with a group of geologists. These geologists took time away from fieldwork—their only break—to make the 2600+ km roundtrip visit to Shark Bay. What brings scientists to see these unassuming black lumps? Geologists traveling great distances to visit a place is hardly notable; for psychologists, however, this is far outside the realm of familiar practice. Tim observed that geologists visiting those stromatolites in Shark Bay, Australia, registered the sense of wonder parents see in their young children, as captured by Robert McCloskey in *Time of Wonder* (Fig. 1A). What the geologists saw was more than irregular dark lumps. It was like seeing a relative's name on a passenger arrival list at Ellis Island: A place to go where one might viscerally experience the travels of a relative at a different time. What they saw embodied their profession in the way that no historical artifact does.

Historical artifacts are valuable, as they mean something to those who know the temporal and spatial connections, but the connections have no physical necessity, and their meaning comes from community knowledge. For example,

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Freud lived at Berggasse 19 in Vienna's 9th district, but it could have been a different address and his ideas still would have been important. Nothing intrinsically links Freud to that space. In contrast, the meaning of stromatolites is intrinsic. For a geologist, time is not an abstract unidimensional construct that occurs in isolation. Geologic time is revealed by events that leave their traces on the objects that participate in them. The stromatolites of Shark Bay have the ability to embody a different time on Earth. This essay explores how that occurs.

The geologists had been working in—and returned to—the Pilbara craton of Western Australia. The sedimentary rocks there and in the Barberton belt of South Africa contain some of the oldest stromatolites in the rock record. The stromatolites from the Dresser Formation of the Pilbara craton, which have an estimated age of 3.43 Ga, are one of the earliest visible signs of life in the fossil record (Fig. 2; Noffke et al., 2013). The living Shark Bay stromatolites are only a thousand kilometers from exposures of some of the oldest stromatolites in the Pilbara craton.

Consider how geologists think about stromatolites, past and present. Aligning the traces of past events to traces of present-day events permits reasoning about an event that can no longer be directly observed. As Charles Lyell (1830) succinctly put it, "The present is the key to the past." To understand the past from the present, geologists must reason by *analogy.* The black lumps in Shark Bay are *analogous* to lumps preserved in sedimentary rocks in the Pilbara craton that are 3.43 billion years old. The analogy is based on the mechanical properties of biofilms interacting with sediments, and the physics of such interactions would not have changed over the years. Thus, the similarities of three-dimensional structure between the Pilbara fossils and the Shark Bay stromatolites suggests an analogy.

Figure 2. Archean stromatolites from the Archean Dresser Formation, Pilbara craton, Australia. Photo by N.M. Roberts.

> TO UNDERSTAND THE PAST FROM THE PRESENT, GEOLOGISTS MUST REASON BY *ANALOGY.*

Formally, an analogy maps the relationships in one system onto the relationships in another system. In English, analogies are often marked by "is like," and can range from concrete perceptual similarity to more abstract relationships. Metaphors are also analogies where the mapped relationships have no perceptual similarity (Lakoff and Johnson, 1980). Analogies are not substituting one object for another, but rather aligning properties of one thing with properties of another. In this way analogies are not arbitrary but reflect relationships in the world. Gestures, which geologists use a lot, are often analogies. When a geologist communicates a subducting plate by sliding one hand under a horizontal palm, the spatial mapping to plate movement is direct. Many geological gestures are analogies where the meaning comes not from convention but through spatial mapping. The point is that if gestures are analogies, then it indicates that meaning of analogies comes directly from the world—via spatial mapping—rather than through language or social convention.

What we know about the properties of objects in the world is collected together, in our minds, as a set of relationships. These structured memories allow humans to employ analogical reasoning to use what they know to guide decisions when encountering something new (see suggested reading of Gentner et al., 2001). An analogy allows one to use known relationships to project aspects of a well-known category onto a lesser-understood category. We begin with a biological example where rich evolutionary knowledge allows strong analogies from taxonomic structures. To say that "a *Tasmanian devil* is like a *dog*" is to say that the various properties of dog, such as the relationship "dogs have fur," can be mapped onto those of the Tasmanian devil (each has fur, as well as teeth, eats meat, walks on four legs on the ground, weighs more than 2 kg and less than 30 kg, is taller than 10 cm and shorter than 1.5 m, etc.). Knowledge structured in this way allows humans to take what they know about dogs and use it to infer aspects of Tasmanian devils. Introductory geology textbooks are full of analogies so that students can learn about the unfamiliar from the familiar (e.g., the structure of the Earth is like a peach with concentric layers). We will return to analogies in future essays on mental models where we discuss experts' use of analogies.

Discovering a strong analogy requires identifying two categories of phenomena where the structure of relationships is similar. Comparison makes the common structure stand out more clearly. Once you notice the relationships that are shared by the dog and the Tasmanian devil, you are likely to consider possible inferences about unknown aspects of the Tasmanian devil. By mapping the relationships within a dog (dogs have canine teeth, dogs have live young) onto relationships of Tasmanian devils (devils have canine teeth, devils have live young) you may reason that other known relationships, such as dog suckles its young, are also applicable to a Tasmanian devil. Such inferences are hypotheses about the nature of the less familiar category. It is the relationship between relationships (e.g., the relationship between the relationships within the "dog" category and the relationships within the "Tasmanian devil" category) that is the key to this hypothesis generation. Without making the analogy/comparison between dogs and Tasmanian devils, it might never occur to you to think about how a female Tasmanian devil feeds her offspring. But the hypotheses about the nature of the less familiar category follow naturally once the analogy is made. Here is the main point: ***Analogies are a cognitive engine for hypothesis generation.***

THE ANALOGY CONTINUES TO SERVE SCIENCE AS A STIMULUS . . . TO MENTALLY TRAVEL BACK TO THE ARCHEAN TO ASK QUESTIONS FOR WHICH WE DO NOT YET HAVE SETTLED ANSWERS.

In geology, analogies are critical to discovering new understandings of the past. The known properties of present-day stromatolites are the key to the fossil stromatolites. What we know about modern stromatolites—how they function as systems with the intricate interrelations among species and the geometric forms they construct—allows scientists to construct hypotheses about what was occurring in the shallow pools that covered the Pilbara craton billions of years ago, and how those early environmental conditions controlled the development of life (Allwood et al., 2007). This scientific reasoning reveals the mind formally projecting the relationships from a well-understood system (modern stromatolites) onto an unfamiliar system (Archean stromatolites) to create an understanding of the relationships in the unfamiliar system. It took a while for consensus to develop. Scientists first constructed the analogy in the 1980s and offered it to others as a hypothesis (Walter et al., 1980). Further learning occurred as the various relationships in the analogy were considered (e.g., is the form a solid basis for function? Are there alternative, nonbiological, explanations for the structures?). For over 20 years debate ensued, in part due to structural, spatial, or diagenic uncertainty in key outcrops (Allwood et al., 2007). Discovery of unaltered outcrops allowed more certain observations. Eventually, consensus coalesced around a strong analogy, which became a theory. The analogy continues to serve science as a stimulus (a word that literally translates as "goad") to mentally travel back to the Archean to ask questions for which we do not yet have settled answers. For instance, where did the complex molecules come from to form these microbes that could organize into mats?

Analogies create knowledge. Learning through analogy can yield errors of omission and commission. A Tasmanian devil is not a dog; although both are mammals, the former is a marsupial and the latter is a placental mammal. Knowing that distinction explains a lot about the Tasmanian devil, including its biogeography as living in former parts of Gondwana. An analogy that is based on a sparse mapping may result in inferences that are akin to over-interpretations. One such example is to attribute features of placental mammals, such as long pregnancies where young are fed by a placenta, to marsupial mammals, such as a Tasmanian devil. For a more geological example of an analogy with drawbacks, consider the analogy sometimes made when teaching about convective overturn in the mantle: It is like the convection of cream in tea or convection cells in miso soup. Students typically assume that the mantle is liquid because the analogical object (convecting tea or soup) is liquid (Francek, 2013). The mantle, however, convects as a solid over very long times, a situation for which there is no strong analogy in typical human experience.

These challenges of analogical thinking have implications for both research and teaching. For research, it is possible that a "rigidity of thinking" may result from an assumption implicit in an analogy that may not be correct in reality. For teaching with analogy, there is benefit to providing guidance when initially mapping, which includes a clear statement of limits. For example, saying "an aquifer is like a sponge" helps students understand how water could be stored underground without it being a lake, but the pores' spaces and connectivity should not be inferred from kitchen sponge pores. Furthermore, having a community-vetted set of analogies to draw from when teaching would be a useful tool to avoid common student misconceptions.

Ilyse Resnick and colleagues (2017) have found that students encountering unfamiliar scales, such as billions of years, for the first time may have difficulty grasping analogies across the scales of geologic time (Cheek, 2012). Prior to a geology class, many students think of the entire range of geologic time as one big category of "a long time ago." Instructors make use of space-for-time analogies (e.g., Moore, 2014) in classrooms by mapping paper rolls and sports fields onto the 4.6 billion years of Earth history. Unfortunately, a single analogical mapping does little to differentiate within the too-large category of long ago. Multiple analogies that connect to familiar magnitudes can help. As scales of time move outside of the familiar scale of human recorded history, one encounters geological events far in the human past, such as the last ice age. The maximum ice extent of the last glacial stage (Wisconsin) was ~20,000 years ago. While 20,000 years is long ago in human time (~800 generations), from the broader perspective of geologic time, it is remarkably recent. Resnick and others suggest that students be given the opportunity to construct and align spatial analogies for time (e.g., where the events of human history are on a 1-m scale) for successive orders of magnitudes of geologic time (e.g., where the events of ice ages are on a 1-m scale), specifically including the entire previous scale (e.g., human history). Using this approach of nested scales, students begin to develop a sense of the time duration of stromatolites on Earth that goes beyond "well that's a big number ago," to understand the relative scale of geological events.

Just as the student learns by analogy in classroom and textbook, so too do experts learn new ideas by analogy. These analogies are shared at meetings, over meals, and on field trips. The learning may progress in fits and starts, but it is no less learning. Much of that learning is powered by analogies. Weaker analogies, where there is a flaw in the mapping, can derail learning and promote misconceptions for novice and expert alike. But strong analogies lead to new, testable hypotheses.

To finish, we return to Shark Bay, stromatolites, and the power of analogies. Stromatolites left a clear and lasting impression on Earth. They originally occurred on an Earth with little to no free oxygen in the atmosphere. By their mere existence, they helped transform Earth by oxygenating small pockets of their world. How do we know that stromatolites were oxygenating Earth? We are not certain, but one theory uses the present-day stromatolites, which produce oxygen, as an analog for past stromatolites. While the stromatolites are at least as old as ca. 3.4 Ga, they became widespread around 2.8 Ga. That timing is consistent with a fundamental change in our atmosphere—changing the relative balance of CO_2 and O_2 in Earth's atmosphere—known as the Great Oxygenation Event (see review by Ligrone, 2019). That event occurred over a prolonged period centered around ca. 2.5 billion years ago and made the way for almost all life on the planet; it was caused by both inorganic chemical reactions and stromatolites living (and dying). All that time understood by carefully aligning a lumpy bit of algae and bacteria with a rock!

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