Figure 1. The Walcott quarry in the Burgess Shale, Yoho National Park, Canada. Photo by Ellen M. Nelson.

Walcott Quarry, British Columbia, Canada: Spatial Thinking

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Geological logline: *Interpretation of the Burgess Shale biota required three-dimensional reconstruction of unusual organisms that developed in the Cambrian period; many of these organisms have no modern descendants.*

Cognitive logline: *Theory-driven (top-down) and observation-driven (bottom-up) approaches mutually support each other but require different cognitive processes: top-down processes—such as reasoning from past experiences—reflect memory and social inputs; bottom-up processes—such as three-dimensional spatial reasoning—reflect the predictability of objects and events.*

> *"Organisms are not billiard balls, propelled by simple and measurable external forces to predictable new positions on life's pool table. Sufficiently complex systems have greater richness. Organisms have a history that constrains their future in myriad, subtle ways."*
>
> ***—S.J. Gould (1980, p. 16)***

On a hillslope in British Columbia, Canada, in 1909, Charles D. Walcott noticed some very unusual fossils in the Burgess Shale. As a prominent paleontologist, he immediately recognized their extraordinary preservation. From 1910 until 1913, he quarried the deposit for a month every summer; he also returned for 50 days to excavate in 1917 (Figs. 1 and 2). The specimens—and there were a lot of

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them—were packed up and shipped back to the Smithsonian Institution, where Walcott was the Secretary. And there these fossils—what became known as the Burgess Shale biota—sat for a long time. Harry Whittington, a professor from the University of Cambridge, finally revisited the Walcott quarry site in 1966 and 1967, in excavations led by the Geological Survey of Canada. It took over five years for Whittington to understand their significance, which was that these fossilized organisms are dissimilar to anything that is currently living. In 1972, Whittington recruited two graduate students, Derek Briggs and Simon Conway Morris, to start "mining" the Walcott collection at the Smithsonian Institution. There is a well-known anecdote in which Conway Morris opens a drawer in the fossil collection, looks inside, and says, "Oh f*%$, another new phylum" (Gould, 1989, p. 143). Somehow, this alliterative phrase captures both the drudgery and excitement of research science, and the challenges encountered in doing science when one starts to question past interpretations and guiding theory.

The Burgess Shale biota is fascinating for many reasons, both scientific and cultural. Harry Whittington and others deserve credit for the scientific understanding, but Stephen J. Gould deserves credit for popularizing it. Gould's *Wonderful Life* is one of the best books about science we have read. We are not sure how he makes the pygidium—the north end of a southbound trilobite—so interesting, but he somehow manages. He provides a narrative of the discovery of the Burgess Shale biota—how understanding of these organisms unfolded over the years, the significance of the fossils, and the new view it gave of life on the planet. The new view was simply this: If you ran the "experiment" of life on Earth another time, you would not get the same outcome. "The race is not to the swift or the battle to the strong... but time and chance happen to them all" (Ecclesiastes 9:11) seems to also play out on phylum, genus, and species levels. It is the forms of Cambrian critters found in a quarry near Burgess Pass, in British Columbia, that revealed that insight.

Part of what makes Gould's book so, well, wonderful are the asides about how science works: the role of advisors and graduate students, how natural history is treated as a second-class citizen to the hypothetico-deductive sciences (e.g., physics, chemistry), why Walcott never engaged in a full characterization of the Burgess Shale fauna, and how the observations of the Burgess fauna motivated Whittington to treat some species as unrelated to any documented or living animal. At this point in the essay series, the reader's ear may be tuned to the joining of social and natural science in a narrative of geological discovery. In this essay, we will pick up on the different approaches of Walcott and Whittington. Walcott's approach will be used as an exemplar of theory-driven science, where one uses familiar examples to classify unfamiliar ones. In cognitive science, this approach—using the known to help assimilate an object or event—is known as "top-down" processing. Whittington's approach, in contrast, is the exemplar of observation-driven science, where one accepts that one is dealing with an unknown

Figure 2. A fossil trilobite from the Walcott quarry. Photo by Ellen M. Nelson.

and proceeding from that point; this approach is a "bottom-up" process in cognitive science. We acknowledge that this division and our assignment of human archetypes is a simplification, but it is a useful one for our purposes. In this essay, we employ spatial thinking to illustrate the value and limitations of bottom-up cognitive processes.

CHARLES WALCOTT AND THEORY-DRIVEN SCIENCE: RECOGNITION OF A PREEXISTING FORM

Like most spatial problems, there are numerous ways to reason out the shape of a plausible organism from a fossil. The various ways differ in their reliability and spatial thinking demands. Walcott approached the problem of what these organisms looked like as akin to a projection problem. He searched for samples where the projection was easy to understand with the dorsal surface up. Here, human visual sensitivity to bilateral symmetry could assist in the search for a recognizable preexisting form (e.g., a known fossil type). A challenge was that the soft-bodied organisms had collapsed. To estimate depth, one could use what one knows about other fossilized organisms. Walcott, for example, recognized and illustrated "dorsal" and "side" views of the Burgess Shale organisms in his papers (Walcott, 1912). Walcott most likely employed this strategy, consciously or unconsciously, as he placed these organisms within existing biological categories.

To the point, as Gould (1989) highlights, Walcott concluded the *Opabinia* must be like modern annelids and arthropods and then reasoned from there. When expected appendages and mouth parts were not visible in the head, he concluded they must have been removed by the fossilization processes. We note that, in this example, theory is riding roughshod over data to infer both missing object and a process that removed it. Thus, a potential source of the delay in recognizing that these fossils were not like anything currently living was using familiar forms for three-dimensional reconstruction. This strategy of recognition of a preexisting form is open to the problem of false positives of familiar objects. This approach makes seeing something novel difficult, if not impossible.

The cognitive processes that Walcott employed may be recognizable to the reader. He is essentially arguing from analogy (Tikoff and Shipley, 2024b). Because the form will never be an exact match between a sample and a reference sample (or an exemplar that is aggregated from many samples), one needs to evaluate whether the fit is close enough. Effectively, as discussed in Tikoff and Shipley (2024c), Walcott was evaluating this fossil shape against his mental library of shapes of fossils and living branchiopod crustaceans. This is a case of pattern matching, which is a type of analogical thinking. And the working hypothesis that these organisms are members of a known taxonomy was sufficiently biasing to miss discrepancies in the data that signaled poor analogical alignment.

HARRY WHITTINGTON AND OBSERVATION-DRIVEN SCIENCE

Harry Whittington's realization that the Burgess Shale fauna were distinct from other described fossil groups is a moment of great insight in science. Gould, in *Wonderful Life*, describes how Whittington came to this conclusion, in a way that could only be done by someone with intimate knowledge of the field. Recent research argues that the Burgess Shale fauna do indeed integrate into the phylogeny of other Cambrian forms, which contradicts the polyphyletic interpretation of Gould (e.g., Briggs, 2015). The importance of Whittington's insight, however, does not rest on a specific interpretation. Moreover, Whittington's investigation of the Burgess Shale fauna provides an example of what happens when one is forced to work without a theory: observation-driven (or bottom-up) science.

Whittington was able to transform the fossil by mentally unsquashing and undistorting back to the original form. How could the depth apparently lost in the fossilization process be recovered from data? One possibility is that the fine sediment of this Cambrian environment meant that mud adhering to any substructures served to define layers. Careful dissection of the layers could reveal soft tissue shapes and a type of depth information—ordinal information about what parts were above or below which others. Ordinal information is categorical, not interval or ratio (e.g., conventional measures of distance), and additional information must be added to visualize the original three-dimensional form. One source of information is the geometry of the flattened parts from multiple fossils. These, as a collection that could be fit together, might provide sufficient constraints to specify a robust three-dimensional solution.

With careful dissection, Whittington makes observations that dispose of the "*Opabinia* are annelids" hypothesis. He drops the assumption that he is dealing with fossils that are related to anything else on Earth. Where Walcott identified two *Opabinia* eyes, a familiar number, Whittington's reconstruction has five. Whittington's reconstruction process is data driven (at least in large measure if not in whole), compared to Walcott's use of prior knowledge (theory) to estimate form.

From a cognitive perspective, Whittington had to resort to a bottom-up approach, constructing the fossils from basic processes rather than using analogy to form the whole. Effectively, he had to determine shape from what he had in terms of fossils. However, he had to make assumptions based on the nature of the world, to come up with the fossil form. The first assumption is that some types of spatial information are retained (e.g., minimal lateral spreading during collapse) and some types are lost during the fossilization process. The second is that fossilized organisms had formed with the same physical limitations as other organisms. For instance, an eye must function as a photon detector, which places limitations on its form. If analogy was used at all, it was at the level below that of the entire organism (e.g., an appendage, although the form and function of some appendages were unclear).

An implication of the above analysis is that a strong analogy is often, but not always, an important scientific tool; G.K. Gilbert, in an 1896 essay, guides practitioners to look to analogy as they reach for hypotheses to explain observations (Gilbert, 1896). The mind will often default to analogy, as in the case of Walcott. It is generally cognitively easier to make an analogy to something better known than to treat an entity as something entirely new. New objects or theories require evaluation of individual parts, as well as figuring how to "lump" objects together (e.g., Tikoff and Shipley, 2025).

SPATIAL SKILLS: BUILDING SOMETHING NEW

A particular aside in Gould's account, which is central to the narrative of this essay, is the role of three-dimensional spatial thinking. Accurate reconstruction of fossils from distorted forms required a visual/spatial genius of "an uncommon and particular sort" (Gould, p. 100). Restoration relies on combining the evidence from multiple specimens preserved in different attitudes in bedding (see Briggs and Williams, 1981). This restoration was achieved without a guide for what it was supposed to resemble. This act undoubtedly required well-developed spatial thinking skills. Whittington had that gift; Gould admitted that he did not (and, by that admission, one can almost forgive him for being a Yankees fan). In a separate example, Gould recalls the time he spent with Richard Leakey working on early hominids, and the spatial genius displayed by Meave Leakey and Alan Walker in taking fragments of bone and reconstructing a three-dimensional skull. Leakey and Walker both exhibited these skills at an early age through independently developed passions for doing puzzles picture-side down using the shapes alone.

Embedded in this spatial thinking is the trust that we place in our visual system. We trust our eyes because the visual system does a good job using the statistical regularities of the world to make pretty good inferences. Moreover, it is self-correcting. People have trained themselves to see through prisms or ride bikes where the wheels turn in the opposite way from the handlebars.

Humans visually experience the world in three dimensions as naïve realists; we believe the world is as it appears to us. Perception of form occurs when the mind utilizes many clues as to the form in the world, although each one is imperfect. Even the products of human stereoscopic vision, in which differences between the images projected to each eye can be used to infer depth, are estimates and prone to errors when the information is faulty. To see why, consider how the visual system determines depth from stereovision. When the left and right eye are pointed directly at an object (e.g., the point of fixation), there is no difference between the images in the left and right eye. For a scene with multiple objects at different distances, the nearer and farther objects will have slightly different relative locations in the images of each eye; this difference is called stereoscopic disparity. The disparity provides information about ordinal (nearer, farther) information relative to the point of fixation. Determining absolute distances from stereovision requires distance information about how far the fixation point is, making the depth from stereovision estimates in the scene only as accurate as the estimate of fixation distance. The estimate of three-dimensional shape in stereo visualizations, therefore, is only as good as the distance information.

The ability to see objects as three-dimensional forms may be taken for granted by most geologists, yet it is a form of spatial thinking. It takes advantage of the optics of light, the locations of the eyes, and the structure of objects in our world to make reliable inferences. The collection of reasoning skills referred to as "spatial thinking" shares this property of going from observations and offering reliable inferences because they are built around the spatial regularities of the world.

The spatial skill that has received the overwhelming share of cognitive scientists' attention is mental rotation (Fig. 3). Longitudinal studies have found that mental rotation skill appears to peak in the late teens to early twenties (as does working memory) and then drops disconcertingly quickly

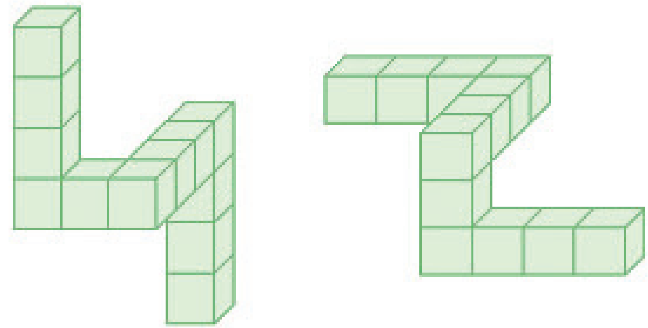

Figure 3. A mental rotation test item used in cognitive psychology. Public domain image from Wikipedia.

with age (Wilson et al., 1975). This finding needs to be interpreted carefully. First, this is a single spatial skills and the trajectory of age-related changes in other spatial skills is less well documented. Second, these are population-level data and we do not know how individuals with particular constellations of spatial thinking skill and experiences may change. At least some decline appears to be independent of experience (Salthouse et al., 1990). One point for optimism, however, is a study that finds that intensive navigation supports gains in hippocampal volume even in older people (Lövdén et al., 2012).

Figure 4. An item from the Resnick and Shipley (2013) faulted word test. Each item has a letter that repeats between the letters of the target word. Each letter string is cut and pieces displaced as if by a sequence of multiple low-angle faults. In the example the letter "z" repeats within the four-letter word, "area."

Our earliest research at the intersection of geology and cognitive science was on a related spatial reasoning skill—inferring fault sequences by mentally reversing faulting. Figure 4 shows an example of the stimuli used in that experiment. In a study of geologists and chemists, we found that both groups did well on an objective measure of mental rotation (relative to other academics). However, only the geologists excelled on reconstructing a whole from faulted fragments (Resnick and Shipley, 2013).

While geologists like this outcome, the result also highlights the skill-based nature of spatial thinking. People often conclude that spatial thinking is an ability, something innate that people have, to varying degrees. There is, however, little cognitive evidence to support such a conclusion. Here we use the term skill rather than ability to focus on the role of learning. There is a wide range of spatial thinking skills in the population, and we know that everyone can improve their spatial skills with training (Uttal et al., 2013). If so, why did Stephen Gould and Maeve

Leakey come to have such divergent skills? The answer is likely the existence of a positive feedback cycle where some spatial skill led to engaging in activities that further developed those skills. Having a particular facility to solve spatial problems early on likely sequentially led to spatial play (e.g., the upside-down jigsaw puzzles), academic fields, and eventually professional areas in which such skills were valued. Each step along such paths provided further training of the skills.

WHY DO SPATIAL SKILLS LEAD TO TRUST OF OBSERVATIONAL SCIENCE?

The history of the Burgess Shale biota reveals the spatial challenges of interpretation, as well as the struggle to select and apply appropriate mental strategies. The challenge of unsquashing animals from a small number of examples not only reveals sophisticated mental processes, but also is a key accomplishment of scientific and human thought: taking the few and making much.

Whittington and students were reasoning from a limited number of samples. For *Opabinia*, Whittington described ten specimens in detail, from a total of 28 specimens available to him (see Briggs, 2015). Geologists might not find that particularly unusual, perhaps even a luxury when often faced with having to work from a single critical example. Even a few examples, when coupled with the skill to accurately infer the past, can profoundly change minds. One may marvel at the power of the mind to reason about what appears to be an under-constrained problem and not be disastrously wrong all the time.

Why do we trust this process? One answer is pragmatic. Despite some detours, the field of geology has accumulated knowledge about Earth's past. For example, localities containing Burgess Shale fauna have been found in other places, including China (e.g., Chengjiang biota; Hou et al., 2017). A different type of answer is that mental constructive processes are effective in revealing unknowns, even with few cases, because they incorporate the constraints of the world. Spatial thinking effectively applies the regularities of objects and events on Earth to construct an understanding from partial information.

OBSERVATIONAL SCIENCE HAS LIMITS

The story of Harry Whittington shows the success of observational science. Geology is full of these stories, in large part because any field that requires natural history will always favor the observational and empirical. As noted in the quote by Gould at the beginning of this essay, history has subtle and multiple ways of influencing complex systems. History does not operate from first principles and go steadily marching forward.

Observational science, working in the absence of a theory, has limits. First, it is cognitively more challenging than working with a theory. Consider the comparison between Walcott, using a top-down approach, and Whittington, using a bottom-up approach. Walcott published seven major papers on Burgess Shale fossils in his five volumes on Cambrian Geology and Paleontology in the Smithsonian Miscellaneous Collections (e.g., Walcott, 1912). He did this while he was serving as the full-time Secretary of the Smithsonian Institution. Whittington, in contrast, had a decade-long pursuit of the unexpected forms using a bottom-up approach. Without the fallback to a known theory, significantly more mental energy was needed to make progress. This type of research can be exhilarating, but it is also exhausting. Second, human cognition indicates that people generally will start trying to make sense of the world almost immediately, by producing theories about how individual observations will be grouped. That tendency—and the need to counter it to avoid biasing one's data collection—is the value of multiple working hypotheses (discussed in Shipley and Tikoff, 2024a). Scientists may not be aware that they are using mental processes that have implicit (and sometimes explicit) limitations. With the benefits come the costs: Mental processes, like life itself, are a package deal.

The cycle of observation and theory in science is very similar to the cycle of perception advocated by Neisser (1976; e.g., Shipley and Tikoff, 2016). From the science perspective, it does not matter whether the breakthroughs happen because of new observation (e.g., Whittington) or new theory (e.g., Einstein). Whittington makes observations that dispose of the idea that the Burgess Shale fauna are something known, and this observation leaves a vacuum in its place. But the process of discovery that fills that vacuum must involve theory. Whittington had to speculate that the Burgess Shale fauna might contain uncharacterized organisms to move forward. Or, to put it more eloquently, the role of theory in observationally driven science might be summarized as "The mind must be prepared to comprehend what the eye sees" (to invert the quote attributed to Robertson Davies). And, in the case of Whittington, part of that preparation was well-developed spatial thinking skills and the ability to see the unexpected.

CONCLUDING THOUGHTS

"The ability to reconstruct three-dimensional form from flattened squashes, to integrate a score of specimens in differing orientations into a single entity, to marry disparate pieces on parts and counterparts into a functional whole—these are rare and precious skills. Why do we down-grade such integrative and qualitative ability, while we exalt analytical and quantitative achievement? Is one better, harder, more important than the other?" (Gould, 1989, p. 100)

This essay is about how observations at one place on Earth—the Walcott quarry, Yoho National Park, British Columbia—provided a new view of evolutionary processes and the variety of animals on Earth. This recognition required formidable spatial thinking, three-dimensional visualization, and explicit rejection of thinking by analogy to known organisms. The application of these skills is akin to visual perception (Neisser, 1976), in which an ongoing cycle of observations informs understanding of the world, which in turn leads to prediction of what will be observed next. This approach allows understanding on a topic (e.g., Burgess Shale fauna), in a place (Walcott quarry, Canada), to be carried to new places (e.g., Chengjiang biota, China). This type of spatial thinking—as an example of bottom-up cognitive processes—clearly demonstrates its value in the discovery of the Burgess Shale fauna, but it also has limitations. Scientists are always dealing with incomplete or partial information, even in cases of exceptional preservation such as in the Walcott quarry. Scientists can only experience some of the patterns (e.g., fossil types) left by Earth processes. These factors necessarily limit the inferences that are available to the mind. Yet, it is a wonderful mind that allows interpolation and extrapolation from such limited observations.

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