3 PREPARING TECHNOLOGIES

Fossil preparators see all objects as potential tools. They are proud tinkerers, bricoleurs, recyclers, and sometimes dumpster divers. Most of the labs I visited happily accept donated tools, such as dentists' cast-off drills and scrapers. Preparators scour their institution's storage closets for unloved hardware. They surf the internet for deals on air scribes and drill bits as well as supplies for specimen storage and fieldwork. They also value the tools they have by taking meticulous care of them and avoiding throwing things away. For example, during my visit to the Southern Museum, someone invited the preparators to adopt supplies from the office of a recently deceased colleague. Despite this macabre context, Jay and Kevin were thrilled to find a well-stocked tool chest that included telescoping screwdrivers, piles of pin vises, and antique engraving tools. Lab manager Amber did not share their enthusiasm and teased them for saving junk. As they combed through the office, Amber opened a dusty cigar box to reveal a single razor blade. She asked where the sharps disposal was, and Kevin replied, deadpan, "What's wrong with it? Give it here." Amber rolled her eyes at the idea of keeping a rusty, broken razor. Poking fun at Kevin's hoarding tendency, she asked wryly, "Is it OK if I throw out this twist tie I found?" Jay chimed in with fake eagerness. "Has it been twisted?" Kevin followed up with, "Does it have any twist left?"

These preparators' self-deprecating embrace of their reputation as "obsessive-compulsive pack rats," in Jay's words, reflects the object-centered mission of museums as well as preparators' need for a variety of tools. As a result, many fossil labs look like cluttered workshops, with assorted surprising objects including power tools, delicate artists' brushes, former yogurt containers filled with freshly mixed plaster or liquid adhesive, unidentifiable metal pieces carefully bent into precise but mysterious shapes, and fossils cradled on sandbags hand-sewn from old jeans. These collections are partly inspired by small supply budgets, though the pleasure that preparators take from creating, using, and adapting tools extends beyond thrift. Rather, their ability to imagine and use a tool to achieve each of the myriad tasks and priorities of preparing specimens encapsulates their skill. As discussed in chapter 2, the crucial autonomy to exercise this skill of preparing technologies belongs to staff preparators, not volunteers. It is this autonomy over techniques and tools, as opposed to the particular techniques and tools themselves, that shapes preparators' identity and the specimens they prepare.

We've seen that preparing evidence (chapter 1) and communities (chapter 2) are crucial components of preparing knowledge; how then do community members work with evidence? This chapter shows how practitioners prepare technologies—that is, how they create, adopt, adapt, maintain, and/or reject techniques and tools. By choosing how to work with fossils, preparators make momentous, though rarely documented, decisions about the physical and epistemic characteristics of the evidence they prepare.

Social studies of technology provide valuable insights into how and why people create and use techniques and tools. These studies typically investigate a sociotechnical system made up of components including designers, users, social values, environments, institutions, and objects (see classic studies in the social construction of technology, such as those collected in Bijker, Hughes, and Pinch 2012). This approach has inspired important analyses of the typically invisible infrastructure of science, such as material culture, representation techniques, and built environments. Yet somehow technicians tend to be lost or undervalued in these analyses. Hardware and its operation seem to attract STS scholars' interest more than the difficult-to-categorize humans who work with both.

This chapter demonstrates the fundamental role of technicians in sociotechnical systems by arguing that the history of fossil preparation technologies is better understood as a history of preparators. I trace the history of technologies used to remove rock from fossils from the centuries-old appropriation of stonemasons' hammers and chisels to the decades-old appropriation of doctors' computed tomography (CT) scanners.[1] These two technologies are enormously different in technical function and social meaning, however rock removal technologies have changed remarkably little in the time between these benchmarks. Instead of inventing or repurposing radically new technologies, preparators have invested in developing their own skill of modifying long-established ones for each particular specimen. The relative stability of rock removal technologies, in spite of significant changes in how fossils have been studied and displayed, indicates that preparing fossils relies on preparators' decisions and judgment more than on the tools. The importance of this expertise helps explain why fossil researchers and preparators are somewhat skeptical of CT scanning. They prefer physical fossils prepared by familiar people over digital fossils prepared by unfamiliar people and machines. Their skepticism of the newer technology is not Luddite, I argue, but rather a strategy for preserving their long-practiced skills and long-established trust in each other. Furthermore, by focusing on preparing technologies as a responsibility claimed by technicians, we can observe how skill, autonomy, and (lack of) technological change interact.

FROM HAMMER AND CHISEL TO PALEOTOOLS MICRO JACK #1

Nineteenth- and Twentieth-Century Preparation Practices

Examining the history of *who* prepared fossils alongside the history of *how* they did it reveals the rising status of preparators over the twentieth century, beginning with the widespread acceptance of pneumatic tools in the early 1900s. Paul Brinkman (2010, 71), a historian and former preparator, explains these new tools as well as a growing division of labor between researchers and preparators as inspired by "the race to obtain exhibit-quality

Jurassic dinosaurs." Museums such as the American Museum of Natural History in New York, the Field Columbian Museum (now called the Field Museum) in Chicago, and the Carnegie Museum in Pittsburgh wanted a giant mounted dinosaur to attract crowds and funders, and they each wanted to be the first to achieve such a display. But mounting a dinosaur required preparing a sauropod-size volume of fossils quickly and carefully (Brinkman 2010, 18–20). In contrast, Peter Whybrow (1985, 5), another preparator turned historian, argues that early twentieth-century inventions in preparation techniques were driven by research demand: "Techniques have evolved in parallel with and in response to requests for information about vertebrate fossils." Scientists today tend to agree with Whybrow. For example, researcher Randy described to me a "coevolution of preparators of some sort and paleontologists," thereby correlating researchers' interests and demands for fossil data with changes in preparators' techniques and skills. But this kind of instrumentalist explanation—that people selected better tools to produce better data—is always too simple to capture the reality of technological change.

Display and research are equally plausible causes for the development of more efficient preparation techniques at the turn of the twentieth century, and they are not mutually exclusive. But why has there been a relative lack of new mechanical tools ever since? The rest of the twentieth century saw only minor adaptations to the early twentieth-century pneumatic hammer and sandblast, despite major changes in fossil display styles and research interests.[2] I argue that the motivation for changing tools lies with preparators more than with museums or researchers. Overlooking technicians is a common practice in science and history, after all. In this case, the relatively static nature of preparation tools can be explained in part by preparators' development of skill in using and, crucially, modifying these tools in ways that they considered appropriate for each specimen.

In nineteenth-century Britain, the few geology handbooks and scientific articles that mention preparation describe it as a straightforward process of chipping off rock. Fossilists (i.e., naturalists who were interested in fossils) prepared specimens themselves or hired stonemasons for their rock-cutting skill. In 1842, George Fleming Richardson (1842, 493–494), an assistant in the department of minerals at the British Museum, wrote in a geology manual that fossil preparation was flexible and easy to learn, perhaps to encourage his readers to try it: “No particular rules can be given for the operation of breaking, trimming, and fashioning rock-specimens; but the skilful management of the hammer, though some patience and practice be required, is by no means of difficult acquisition.” His advice shows the preeminence of the hammer and chisel, traditionally stonemasons’ tools, and hints at the lack of “rules” for preparing specimens—an assertion that preparators still proclaim today. British naturalist Gideon Mantell agreed that preparation was simple enough to be done by any fossil collector. When he bought an unprepared iguanodon specimen in 1834, he wrote with excitement in his journal, “Now for three months’ hard work at night with my chisel, then a lecture!” (quoted in Dean 1999, 136). Mantell included instructions for matrix removal in his 1844 geology manual as well as a beautiful illustration of a fossil before, during, and after preparation (figure 3.1). He (1844, 57–58) also warned readers about the potential delicacy of preparation: “The bones of the large reptiles which occur in the Wealden and Oolite [geologic strata] . . . will often fly to pieces on the slightest blow of the hammer or chisel.” The hammer and chisel were the universal tools for removing matrix. Naturalists did not doubt that fossil preparation was skillful and hard work; nonetheless, they assumed that anyone could learn to do it.

These authors may have presented preparation as learnable as an invitation to amateurs to try it. In nineteenth-century Britain, amateurs regularly contributed to research in natural history, such as by collecting and disseminating specimens, forming naturalist clubs, and corresponding with “gentlemen of science” to share their findings (Secord 1994; Kohler 2006; Gibson 2017). Identifying and mapping geologic features, and collecting and displaying fossils, were popular hobbies across social classes. Paleontological knowledge at the time relied on specimens provided by amateur collectors and prepared by working-class stonemasons, who rarely received scientific recognition and whose names typically went unrecorded. Their tools and techniques, though, were not forgotten.

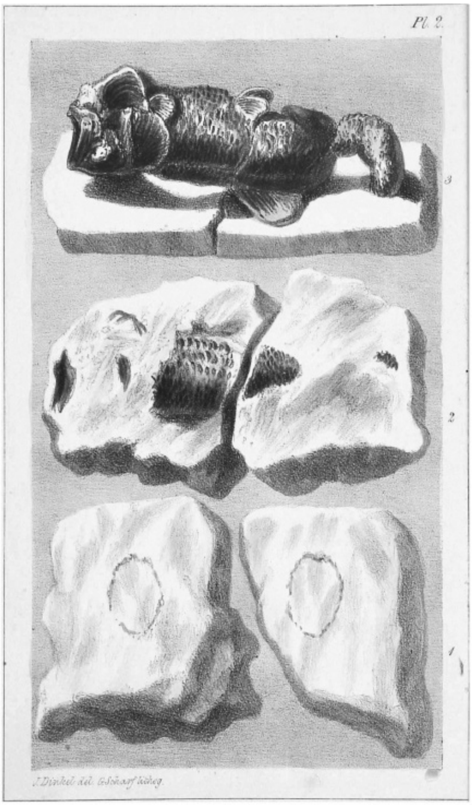

Figure 3.1
A rare nineteenth-century image of fossil preparation work, showing (bottom) “two corresponding surfaces of a block of Chalk split asunder,” (middle) the halves “cemented together” to match up the ovals of broken bone and “the chalk has been chiseled away . . . [and] a fish has been thus brought to light,” and (top) “the specimen completely developed” (Mantell 1844, vol. 2, frontispiece).

By the early twentieth century, the conception of easily learnable hammer-and-chisel preparation was shaken by two inventions that would become preparators’ tools of choice for at least a century: a sandblast and a pneumatic hammer. In 1894, invertebrate paleontologist H. M. Bernard (1894, 553) complained, “Picking at the fossil with a steel point taught me, what every worker soon finds out for himself, that the [trilobite] limbs . . . could not be differentiated from the matrix by any such method." Bernard wondered whether washing the specimens in grit-filled water might help. Thus inspired, he visited the "London Sandblast Works," four miles from his job at Imperial College, where "the proprietor was kind enough to express interest in the idea, and showed me blocks of granite which had been treated with the sand-blast, and in which the harder elements stood out in good relief" (Bernard 1894, 554). Continuing fossilists' tradition of adopting tools built by tradespeople with rock-cutting expertise, Bernard designed an air-pressure-driven apparatus that blew sand down a rubber hose and against a specimen, eroding away the matrix. He found that the "sand-blast" only worked if the matrix was of less dense mineral content than the specimen; otherwise the sand ground away the fossil too. Yet "when the matrix is soft as compared with the fossil . . . the sand-blast cleans the objects very beautifully" (Bernard 1894, 557).

The quick adoption of Bernard's idea in the United States and Britain suggests that museums' workers were watching each other closely due to their intense competition for spectacular fossils. By 1904, the sandblast had crossed the Atlantic and been adopted at the American Museum of Natural History. Henry Fairfield Osborn (1904, 256), a curator of vertebrate paleontology, reported in a conference abstract that he had "recently been experimenting with a sand-blast, driven by a compressed air engine, with admirable results . . . both in cleaning surfaces and in removing the matrix in the cavities of small skulls."[3] By 1908, however, the sandblast was still not widely available in Britain. Francis Bather (1908, 81), an assistant keeper (i.e., assistant curator) of geology at the British Museum, wrote regretfully, "While every museum probably has access to a supply of electricity, it is not likely to be able to obtain compressed air. I will therefore merely recall the fact that attempts have been made to utilise the differentiating action of the sand-blast for the development of fossils." Adam Hermann (1909, 292–293), a preparator at the American Museum of Natural History, praised the sandblast in 1909 despite the scarcity of air compressors: "Wherever compressed air is installed, the sand blast may be of great help in freeing the bones from their matrix." This problem was alleviated with the rise in the availability of electric air compressors. The sandblast, now called an air abrasive machine or air abrader, still retains the fundamentals of Bernard's design.

Like Bernard, Elmer Riggs (1903, 747), a paleontologist and preparator at the Field Museum in Chicago, was frustrated with hand tools: "The tedious work of removing fossils from their matrix by means of the hammer, chisel and awl has led to various experimentation with machine tools in the hope of devising some more rapid method." First he tried electric dental tools, which he deemed weak and therefore useful for "light work" only. Next Riggs (1903, 747–748) tried the handheld compressed-air-driven jackhammer used for masonry and metal engraving:

> The hammer in use consists of a cylindrical chamber in which a five-eighth-inch steel plunger having a five-eighth-inch stroke is caused to play upon the head of the chisel at the rate of 3,000 to 3,500 strokes per minute. This rapid succession of light blows sets up a vibration in the chisel, which, with even a slight pressure against the work, gives it a remarkable cutting capacity.

This tool is not so different from, and clearly inspired by, the hammer and chisel, as it replaces a few powerful human blows of the hammer with many gentle mechanical hammer blows. The pneumatic hammer was so effective at cutting rock that Riggs (1903, 748) feared it was a danger to fossils. As a result, he weakened the tool's power by attaching a small, light chisel to the smallest, lightest pneumatic hammer available, lamenting that "a still smaller size would often be convenient." Riggs (1903, 747–748) recommended that preparators alter the tool as appropriate for each specimen: "By adapting the size of the chisel to the work at hand and gauging the amount of air admitted to the tool by means of a push-button throttle valve, the stroke can be reduced so that [even] a scale may be removed from the most delicate surface." Clearly, even as preparators built mechanized tools, they assumed that other preparators would continue to adapt the tools for each specimen.

Preparators and researchers lauded the efficiency of Riggs's modified pneumatic hammer, reflecting the competition for fossil exhibits at the time. Osborn (1904, 256), as a thrifty museum administrator, noted the financial advantages of the two inventions: "Combined with the compressed air chisel [the sandblast] will probably reduce the cost of preparing fossils to one third of that involved by the use of hand tools." As an adaptable tool that removed rock quickly and delicately, the pneumatic hammer—known today as an air scribe—was widely adopted by preparators.

Today PaleoTools, an influential preparation tool manufacturer, sells five varieties of air scribe ranging from the Micro Jack to the Mighty Jack, which vary in power by size and air pressure. The Micro Jacks are intended for more precise work and have six types, each costing about $450 (PaleoTools 2020). The newest and smallest Micro Jack, the #1, has achieved celebrity status among preparators. When Bill Murray, the owner of PaleoTools and inventor of its air scribe varieties, first sold the #1 at the 2010 SVP meeting, the Northern Museum preparators tried it and were so impressed that they bought Murray's entire conference supply of #1s, including the demonstration set. Murray explained the tool's appeal to me as a lack of lateral movement from the "fixed" pin, and that the #1's small size and lower air pressure makes matrix "chip off" rather than "turns it to dust" as other air scribes do. His website also offers to tailor the #1 for buyers by adding an on/off switch or lengthening the handle or pin (PaleoTools 2020). Murray told me that his business began when he found a fossil and brought it to a local university for identification. He offered to donate it to the university if the preparators would teach him how to prepare. They agreed, and he has been a volunteer preparator ever since. But he was soon frustrated with the destructiveness and limited control of the air scribes that the lab was using. Murray drew on his training as an engineer to modify the tool, and other lab members quickly bought the versions he built. He started PaleoTools in 1998. Air scribes, such as PaleoTools' Micro Jacks #1–6, exemplify preparators' preference for making minor adaptations to a design instead of inventing a new one.

Preparation as Skillful

Concurrent with the adoption of pneumatic tools, technical articles and manuals began to mention that preparation required skill, in contrast to the earlier view of preparation as a straightforward process that anyone could learn. Bather (1908, 90) wrote that "each case presents its own difficulties and there is plenty of room for the exercise of ingenuity on the part of a practical palaeontologist." Similarly, Hermann (1909, 290) recommended, "The selection of tools, as to strength of the blow, etc., must be left to the judgment of the preparator." The variety of tools available by the early twentieth century, including electric, pneumatic, and hand tools, required specialized "judgment" or even "ingenuity" to select the best tools for each specimen. Also, because pneumatic tools could destroy rock—and fossil—faster than the hammer and chisel could, institutions discouraged their use by unskilled preparators. But preparators remained uncredentialed, unlike other emerging professions in science at the time (Bowler and Morus 2005, chap. 14).

Nonetheless, preparators' specialization and skill development are evident in two dicynodont skulls in one museum's collection. These mammal-like reptiles, who lived alongside the dinosaurs, belong to the same species yet look very different (figure 3.2). Researcher Kyle explained that they were prepared about fifty years apart:

> Not very much of this specimen's details are exposed, and you can see the damage the bone surface suffered from that issue where sediment and bone don't separate very well. . . . So that's an example of 1920s', 1930s' preparation techniques. Here is another specimen of [this species] that was collected at the same time in basically the same place that's been prepared with more modern preparation techniques [in the 1980s], and you can see you can get much better results, including much better separation of the matrix and the bone.

Kyle pointed out bone sutures visible on the 1980s' skull, but not on the 1930s' one, suggesting the sutures were destroyed during preparation. Similarly, there are ridges and grooves on the 1980s' prepared snout, but these are not discernible on the 1930s' snout. Kyle credits improved techniques for the better quality of the 1980s' skull, although the *techniques* probably differed little. Instead, I surmise that the most significant difference in these specimens' preparation was the preparators' skill. In the 1930s, preparators could be "people off the street" with no experience with fossils, as one preparator told me. But by the 1980s, preparators were expected to

Figure 3.2
These dicynodont skulls were prepared in the 1980s (left) and 1930s (right).

have specific skills and knowledge gained from experience preparing fossils (though they still lacked formal preparation training or credentials).

Experienced preparators have long been considered valuable employees.[4] Brinkman (2009, 25–26) describes the "luring" of preparators from one museum to another in the early twentieth century as sometimes "hostile." This was because "a staff of skilled and experienced technicians was the most vital ingredient for operating an efficient fossil preparation lab" (Brinkman 2009, 25–26). Current preparators report that their predecessors had all sorts of backgrounds, and rarely scientific ones. Most came from jobs that required manual skill and attention to detail. Drawing on institutional memory, one museum's staff members told me that a preparator hired in the 1950s had previously worked as an undertaker, while two hired as late as the 1970s were a shoemaker and pipe fitter, respectively. The rarity of experienced preparators at the time meant that museums sought out people whose previous jobs required skills applicable to preparation. By the early twenty-first century, preparators were hired primarily for their experience specifically in fossil preparation, as shown by its requirement in most of today's preparator job listings (chapter 2).

In the early twenty-first century, preparation is no longer considered a straightforward task that anyone can do, as it was perceived in the nineteenth century. New tools are no longer thought to be the answer to efficiently producing quality fossils, as early twentieth-century researchers and preparators believed. Instead, the vertebrate paleontology community values preparators with specific knowledge and skills, acquired through and evidenced by preparation experience. A century of relatively stable technology has been both a cause and effect of the development of preparators' expertise in choosing, adapting, and applying techniques. For example, preparator Brown (2013) published an article tracing the continuity of preparation tools between 1900 and 2013, including a striking image of Hermann's (1909) hand tools alongside matching tools that Brown found in his own laboratory at the University of Texas at Austin. The expertise of preparing these technologies, including not replacing them with significantly different approaches, came to define preparators as a community over the twentieth century.

PREPARING DIGITAL FOSSILS

How to See through Rock in Old and New Ways

It may seem obvious that using rather basic tools like sandblasts, hammers, and chisels—even those driven by compressed air—requires skill to successfully remove matrix from fragile fossils. Investing in the slow, painstaking development of that skill can explain why preparators would be disinclined to invent new tools that don't require that particular skill. But what about digital, mechanized technologies? One might think that they would operate more or less on their own, regardless of the operator's skill. This is, of course, a misconception, as shown by studies of the skill involved in successfully using such high-tech machines as electron microscopes (Rasmussen 1997), synchrotrons (Doing 2009), and DNA sequencers (Stevens 2013). Likewise, a recent challenge to preparators' technological stability offers insights into how scientists view technicians as a foundation for trustworthy evidence. Technologies alone, even impressively complex ones, are not sufficient to prepare good evidence. As historian Nicolas

Rasmussen (1997, 254) argued based on the electron microscope's adoption in twentieth-century biology, "New techniques must be assimilable to both paradigm and habitus, or both cognitively and culturally," such that they align with existing components of a discipline's identity, including its epistemology, social norms, and aesthetics. The same context dependence is true for technologies that are *not* adopted or adapted over time, and we can learn much about a community based on the techniques it chooses to use and not use. Like the long stability of rock removal tools, the skepticism surrounding a new and entirely different rock removal technology demonstrates that technicians are more important than technologies to the process of preparing knowledge from fossils.

At the end of the twentieth century, the medical imaging technology of CT scanning offered an intriguing potential: seeing *through rock* to the fossil bone encased in it (Chapman 1997; Kevles 1997, 159; Wylie 2018b). This still-developing approach can negate the need to remove that rock, which would seem to make preparators—and their time-consuming, potentially destructive work—obsolete. While scientists praise the "magic" of CT scans for their pristine views of unprepared fossils, they also express skepticism about this unfamiliar, suspiciously magical technique. They worry that it reduces their interactions with specimens and preparators, which they consider unwelcome changes to their well-established research practices. I argue that these seemingly contradictory assessments coexist because the crucial factor of any technological system is the people doing the work. Thus scientists' and preparators' responses to this revolutionary way of viewing fossils shed light on how they understand their own symbiosis as complementary communities as well as how they define good evidence and good technologies.

In basic terms, a CT scanner sends X-rays through an object and then recaptures them, thereby producing a cross section—a "slice"—of density readings. It rotates around an object to capture slices of its external and internal structure in three dimensions. Because of this mechanism, CT doesn't work on all fossils. Specifically, X-rays cannot penetrate some types of rock, and CT data only distinguish between matrix and fossil if the two have different densities. Also, some vertebrate fossils are larger than typical

CT scanners. The strength of the X-rays and sensitivity of the sensors vary with the kind and size of CT scanner and with the parameters set before each scan by the machine's operator, who is typically an imaging technologist, physicist, or materials scientist. One of these imaging experts or a fossil researcher then uses software to compute the quantitative density measurements into images, including views of each slice and a compilation of the slices into a three-dimensional, on-screen model of the specimen (figure 3.3). The images are then processed to depict areas of different densities in different colors or levels of opaqueness, depending on what the fossil researchers want to see. For example, certain densities can be removed from the on-screen model altogether, such as by making matrix transparent so as to display only fossil. The bones can also be manipulated to allow on-screen comparisons and measurements. Researchers access CT scanners at their own institution, or pay for scanner time at other universities, museums, or medical or industrial imaging centers. Scanner time is tough to access because museums' scanners are in high demand, and using

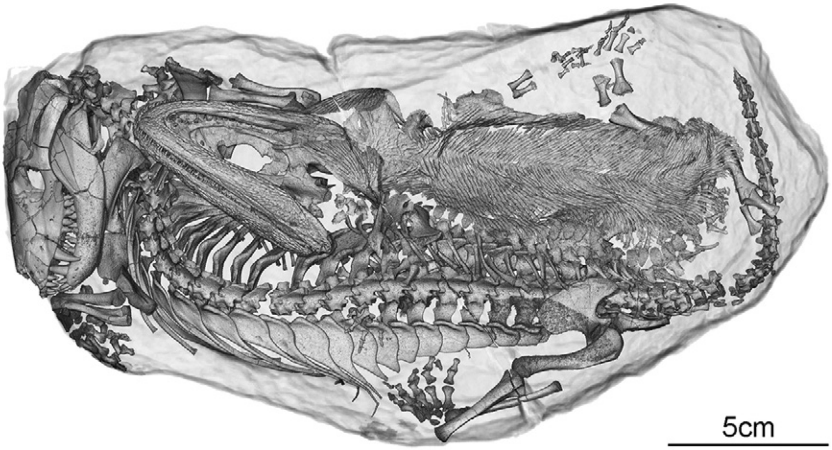

Figure 3.3

This image was made from data collected by synchrotron imaging (i.e., a high-resolution form of CT). It shows two fossil skeletons encased in an intact, three-dimensional burrow. The animals' bones are displayed as distinct from the surrounding matrix based on their different densities, with the edges of the burrow visible around them (Fernandez et al. 2013, 2). Reproduced with a Creative Commons license.

other institutions' scanners is expensive and/or logistically challenging (e.g., transporting the fossil).

A fossil appearing on a computer screen may seem futuristic, yet scientists and their fossilist predecessors have long practiced methods of representing fossils and what they may have looked like in life, such as drawing and model making (e.g., Rudwick 2000; Davidson 2008; Sommer 2010). Patty, a scientific illustrator at the Southern Museum, explained that she never draws specimens as they are, as was done in the nineteenth century, because photographs capture that information in more detail than she can (see Daston and Galison 2007). Instead, Patty draws reconstructions of damaged or incomplete specimens to produce views of how they may have looked without the effects of fossilization. For a fossil seal preserved in its natural death pose, for example, researchers decided to prepare it only from one side and leave it in its rock slab "because it had more information" that way, Patty said, such as about taphonomy (i.e., how it became fossilized). As an alternative to disassembling the skeleton, researchers asked Patty to draw it in a neutral pose, as if in life. She labeled every bone and its typical position in the skeleton with guidance from the researchers, and then drew each bone in its place. Her drawing served as a reconstruction of the skeleton without damaging its rare in situ preservation. It was based primarily on plausible guesses about body and bone position, as is typical for reconstructions of extinct organisms (e.g., Davidson 2008; Hochadel 2013). Researcher Sam believes artists' informed-speculation reconstruction work is irreplaceable because CT can't reconstruct crushed specimens, for instance, or imagine the missing pieces of a specimen.

Paleoartists also contribute to research by building 3D physical reconstructions of fossils and even flesh models of extinct organisms based on the available anatomical data. While most of paleoartists' work is for display (Hochadel 2013, chap. 7), their models are also used for experiments on physiology and locomotion as well as to inform researchers which bones might fit where. Digital models made from CT data are becoming increasingly common for such experiments. For example, one study asks whether a velociraptor's enormous claws could support its body weight and thus enable the animal to climb (Manning et al. 2009). Testing the mechanical strength of a physical velociraptor claw would risk breaking a fossil, but on-screen bones can't be damaged. Digital models are difficult to build and require potentially questionable assumptions and parameters. As a result, many researchers prefer physical models, including cast replicas or sculpted reconstructions, which they consider easier to control than digital ones. Also, they believe that human model makers, unlike CT, can reconstruct any fossil, regardless of rock composition and density distinctions, even if the specimen is distorted, crushed, or incomplete. The preference for human skill and informed imagination over a machine's measurements and computations is not typical of today's science, and highlights the value of an individual's skill of preparing evidence over the value of technologies alone.

To inform drawings, models, and research, fossilists have historically relied on slicing through fossils (and rock) to view them in physical, fragile, crumbly cross-section. For example, paleontologist Jenny Clack's (1994, 7) descriptions of the skull of the tetrapod *Acanthostega gunnari* were based on anatomical data from specimens that had been "sectioned into approximately 1.5 mm slices using a Well diamond-wire saw." One preparator described such sawn slices to me as "an early form of CT, in a way." Physical slices show internal bone structures that are critical to anatomical description like Clack's, and otherwise invisible inside a skull and/or rock. As a result, though, these sectioned skulls now exist only as slices. Other methods of revealing internal structures such as serial grinding leave no specimen behind at all. Researcher Wayne described these methods as commonplace in the recent past: "For many years . . . they just took a specimen, embedded it in some kind of a plaster or plastic, and then just ground it away, maybe a millimeter at a time. Take photographs, and then they transferred the photographs to celluloid sheets, just drew it out like that, and then they just stacked the sheets up." By grinding away thin layers of a fossil and recording each layer as a photograph, researchers could "see" inside the fossil. Transferring the photos to sheets of plastic or wax and stacking the sheets—a technique also used to preserve organs and other anatomical specimens (e.g., Hopwood 2002)—created a 3D model made of cross-section views, which can serve similar purposes as a CT model.

Yet those images and model replaced the specimen, which was destroyed to create them. The noninvasiveness of CT scanning is more appealing to research workers than these destructive forms of analysis. In Wayne's opinion, thin sectioning and serial grinding are mercifully outdated: "Nobody does that sort of thing anymore. They don't need to. They can do it with [CT]." Some fossils no longer have to be ground away to reveal their insides. As one researcher told me, "Before modern times with CT scanning and things like that, you couldn't do anything with a vertebrate fossil until it's out of the rock." This observation highlights the fundamental importance of fossil preparation to vertebrate paleontology before CT as well as the significant potential of CT to upend that connection.

CT in Research: Visualizing the Invisible

How research workers talk about CT differentiates them by field, namely researchers, preparators, and conservators, but there are two shared themes: amazement at CT's images and skepticism about its widespread utility for fossil research. Everyone talks about CT scanning in fossil research in tones of awe and excitement, much like doctors' and patients' views of the "magic" of CT and MRI (Joyce 2008, 149–150; Saunders 2008, 175). Researcher Wayne's explanation of CT demonstrates this sense of wonder at the technique's capabilities: "Now we've got this tomography business that allows us to reconstruct a skeleton without ever taking it out of the rock. . . . They can turn it in any direction. They can make a model of any of the elements out of plastic. They can enlarge it, they can reduce it to any size you want. They can duplicate one side to the other, and it's just incredible." Wayne, whose career in paleontology spanned over sixty years when he spoke with me in 2010, was an expert preparator and mount maker in addition to researcher. His admiring description of CT reflects its ability to do what researchers dream of: accessing the maximum possible data from specimens by exposing, manipulating, and reconstructing them. CT can achieve these actions without fossil preparation, and also performs actions that can't be done to specimens such as changes in size. This concept of a magical and incredible technology captures CT's unique and rich data as well as the mystery of "this tomography business" to its users, in both paleontology and medicine. Radiologists, patients, fossil researchers, and preparators rarely know the details of how CT works. They assume that the information is the realm of physicists, materials scientists, and imaging technologists—people whom Wayne refers to above only as an unnamed "they"—and as a result, they are generally uninterested beyond getting useful images.

The typical cause of practitioners' wonder at CT is its portrayal of views that are otherwise impossible, such as the interiors of fossil eggshells and skulls (e.g., Conroy, Vannier, and Tobias 1990; Balanoff et al. 2008, 2013). Then the image *is* the specimen. There is no physically visible object with which a researcher can compare the image. Historian Martin Rudwick (2000) describes Georges Cuvier's solution to the problem of rare and geographically dispersed fossils in the eighteenth and nineteenth centuries as the accumulation of a "paper museum" of "paper fossils"—specimen drawings—to complement Cuvier's collection of physical fossils at the Muséum d'Histoire Naturelle in Paris. By treating images as equally informative as specimens, Cuvier was able to improve his data access and therefore his research career. Cuvier's situation of inaccessible specimens is comparable to that of particle physicists, astronomers, molecular biologists, and many other researchers who rely on imaging technologies to provide the only visual access to their subatomic, telescopic, or microscopic research objects. Here I explore how CT images function as "digital fossils" that serve as specimen proxies and on-screen versions of Cuvier's paper fossils, and then I discuss scientists' preference for physical fossils.

In cases of invisible, unpreparable fossils, researchers trust CT images as digital fossils. Preparator and model maker Tim described how CT scans showed parts of an extinct crocodile's skull that preparation could not reach:

> You couldn't see any teeth on the lower jaw . . . because of how the skull was overhanging it. . . . I looked at the slices of CT data . . . and I could see that there were little teeth along the back of the jaw. . . . We never saw those. We still don't really know what they look like, but at least from the data we have this concept that they're there and that they're sharp, they're small, they're evenly spaced. So that was really neat.

Tim emphasizes the absence of direct views of the lower teeth, which is clearly striking to him in comparison with his vision-centric work of preparation and model making. He included the teeth in his sculpted reconstruction model, even though evidence for them exists only in CT images that create "this concept that they're there." His amazement is evident in his words, as he distinguishes ideas of vision based on teeth "I could see" on a scan from what "we never saw" in reality. For Tim, the CT data are *data*, meaning information about the skull's characteristics, but those data are also somehow different from data about teeth that are visible to his own eyes.

If the densities of matrix and bone are different enough, then software programs can differentiate ("segmentate") these substances based on CT data. Crucially, then the software can remove or reveal each density level from an image, such as "digitally preparing" a specimen by showing it without matrix. Wayne, for example, referred to the CT scanner as "the truth machine . . . because you can see everything. It's like looking at something in a glass box." He meant that looking at scans is like looking at a prepared fossil, with the only difference being that the fossil is inside a glass box—a computer screen. He thus suggests that a digital image can be treated like a specimen. Likewise, evolutionary biologist Vincent Fernandez and colleagues (2013) used only synchrotron scans (a technique similar to CT) to describe an amphibian and a mammal-like reptile that were fossilized together inside a burrow in the early Triassic. The burrow is a solid, three-dimensional rock nodule roughly the size of a bread loaf, with the eroded tip of one animal's skull peeking through the rock as the only indicator that anything is inside. Soon after the burrow was found in 1975, researchers broke it open to find out whether it contained more bone. The broken halves showed a cross section of two articulated skeletons, which inspired Fernandez and coauthors' recent analysis. Today the skeletons remain inside the rock, though their bones, positions, and even injuries are visible to researchers via image reconstructions from the scan data (figure 3.3). Thus the scans *are* the specimen; they are the only access to the fossils. If a preparator were to remove the rock around the fossils, they would have to dismantle the skeletons. This approach would destroy the unique information preserved in the animals' remarkable 3D preservation, such as about posture, taphonomy, and why on earth a mammal-like reptile might have shared its burrow with an amphibian.[5]

Research workers consider CT most useful for accessing information that would otherwise require destroying the specimen, as in the case of the burrow. Preparator Mary explained that one role of CT is to do what preparators cannot: "The things you see in the scan are the things you can't really get to with preparation. I mean, you're limited to where the needle can get to and it's a straight line. You can't really do ninety degree bends back in space." Preparation tools, such as a "needle" of steel or tungsten carbide clamped in a handheld pin vise or air scribe, cannot reach certain spaces. Wayne's fossil-in-a-glass-box specimen thus seems ideal for studying these unreachable spaces. After all, a digital fossil is easily maneuvered and offers complete views of all its pieces, while a physical fossil is most likely fragile, heavy, not fully visible, and potentially damaged by preparation.

Another valued purpose for digital fossils, especially according to collection managers and conservators, is protecting physical fossils from transport and handling. Bob, a collection manager at the Southern Museum, finds the dangers of making specimens accessible to researchers particularly acute for unwieldy and scientifically important fossils:

> The type specimen of [an extinct species] is a whale skull six feet long. Maybe two of us could get it flipped [to study the underside]. . . . Every time I do that, [there's] a terror that "please please God, I hope I didn't bust it this time." . . . Gee, wouldn't it be easier on the specimen if we took that sucker and did an external scan, probably with lasers? And we could probably do a CT scan, though it's pretty big, if you wanted internal structure. Have it out there someplace on the web. You wouldn't throw away the original specimen, I'm not suggesting that. But I wonder how many people could save the trip in the airplane coming here [to study this skull], save my poor aching back and my nerves from flipping the thing, and the potential damage from handling this specimen.

Studying digital views of a fossil instead of the fossil itself would reduce stress on both the specimen and its caretaker. A fossil's digital scans can also act as an archive or backup of the specimen's data. Oliver, a collection manager, extolled the benefits of digital specimen documentation: "By having a CT scan data set, you have a permanent visual record of the object. 3D, the whole thing. So that if it disappears for any reason, if it's in a cloud of dust, if it's gone, if it gets hit by a meteorite or something, you still have a record of it that you can go to and measure and compare with other things." No one suggested "throw[ing] away the original specimen," as Bob put it, but many scientists, collection managers, and conservators believe that digital data can and should substitute for specimens for some research purposes. As an extra bonus, digital specimens can make at least some information about specimens disaster proof.

Preparators appreciate CT as a way to protect fossils too, though from *preparation* damage rather than damage from handling or disaster. Like doctors who order CT scans to inform diagnosis and treatment, preparators see CT as a potential aid to choosing and applying preparation techniques. For example, preparator Marc explained, "Opening [field] jackets is always a terrifying experience" because preparators have to cut through a jacket's rigid plaster-and-burlap shell with a power saw and without knowing where the fossils are inside the jacket. It is easy to inadvertently grind through both the plaster and the fossil beneath it. As a solution, Marc said wistfully, it "would be great to CT-scan jackets before they're opened" to provide the saw-wielding preparator with a bone map of the jacket. His institution doesn't have access to a CT scanner, but he wishes they did. Several labs CT-scan or x-ray unopened field jackets. Researcher Luke at the Northern Museum noted, "We'll often x-ray rocks that we know have fossils in them to see, is this a high-priority prep job or a low-priority one?" These exploratory images of unprepared fossils rarely have research-quality resolutions, but they can inform preparation decisions. A few times I saw preparators consult CT images of specimens as they prepared them to see where bones were. CT scanning is too expensive and unreliable to use primarily as a preparation guide, especially because preparators have other ways of avoiding hidden bones (such as adding layers of dirt or packaging material around fossils before jacketing them in the field, labeling new jackets with maps to show the fossils' location, removing only small amounts of matrix at a time once the jacket is open, “following the fossil” once they have found it, etc.). But if a specimen has already been scanned for research purposes, then those scans can serve double duty by helping the fossil’s preparator see through—and selectively remove—rock.

CT as “Not a Panacea”

Despite enthusiasm about digital fossils as specimen proxies, research workers almost universally dismiss CT as not sufficiently detailed, reliable, or “real” to fully replace prepared specimens. This skepticism makes sense for a relatively new technology, and especially for one that was designed to image living humans and has been co-opted to visualize rock-embedded fossils. In researcher Preston’s words, CT “is not a panacea for what we do. . . . It gives you a lot of power to do things, but it’s not a complete answer.” Workers give practical reasons (e.g., technical limitations) and epistemic reasons (e.g., trust in their own sensory interaction with a fossil) for their reservations about CT (Wylie 2018b). One common complaint is the size of micro-CT scanners, which offer the best scanning resolution but only for small specimens.

Crucially, whether a specimen can be successfully scanned is unpredictable. Northern Museum researcher Kyle described this frustration in his “two unsuccessful forays into CT scanning,” caused by the geologic composition of the fossils and matrix. One attempt was several skulls of mammal-like reptiles found in the same locality: “The specimens had been altered by a mineral, presumably a fairly dense, metal-bearing mineral that caused a lot of artifacts in the scan, so it was very difficult to get a good clear image.” Certain minerals deflect X-rays and thus create measurement “artifacts” that obscure the fossil. For Kyle’s other CT attempt, an unprepared skull, “the problem is that the specimen and the sediment had very similar compositions . . . so when you’re looking at the image of CT slices, it’s very hard to say, all right, this is where the bone ends and this is where the sediment begins.” Because CT works by sending X-rays through a specimen, it can only distinguish between areas of different densities. Kyle points out that he could manually draw this boundary onto CT images with software programs, but he rejects that option as too imprecise.

This issue of defining specimen versus not specimen appears in arguably all data processing methods and is one way in which practitioners skillfully prepare evidence. Galison writes of this definition task as a crucial application of workers' "laboratory judgment" in particle physics. He argues that editing out unwanted information is inseparable from denoting the desired information: "The task of removing the background is not ancillary to identifying the foreground—*the two tasks are one and the same*" (Galison 1987, 256, original emphasis). Deciding how to differentiate the foreground from the background can be controversial, especially when accessing nature indirectly via technology.

As in Kyle's experience, processing CT data into images is complicated. For example, a student in Wayne's department used CT images to reconstruct a digital fossil but "didn't do a very good job of Photoshopping. These [images of individual bones] are kind of ragged around the edges," Wayne complained. Using software like Photoshop is a difficult skill that has implications for the reliability of evidence. Image making as expertise is similarly discussed among astronomers (Lynch and Edgerton 1988) and cell biologists (Rasmussen 1997; Cambrosio and Keating 2000). Likewise, anthropologist Natasha Myers (2015, 144) found that protein crystallographers distrust and reject software that claims to automate the process of building models of protein structures. Instead, crystallographers consider models to be crafted, bespoke products of skillful human work and expertise. These scientific communities use images to judge the quality of *workers* as well as evidence and knowledge claims, much like fossil lab communities use prepared specimens as indicators of preparators' skills.

Subjective Images, Objective Specimens

Researchers in many fields worry about their own control over what images look like as a potential threat to the objectivity of their claims. Astronomers told sociologist Michael Lynch and art historian Samuel Edgerton (1988, 192–196, 202) that they process their digital telescope readouts into "pretty pictures" only for public viewers, not for researchers. However, Lynch and Edgerton witnessed such processing for both public and research images. In the mid-twentieth century, particle physicists advised against physics training for the supposedly unskilled "scanners" who searched cloud chamber images for tracks of subatomic particles. They feared that the scanners would then "see" imaginary evidence that they thought would please the physicists (Galison 1997, 199–200; Traweek 1988, 28–29). These scanners were mostly women with little education but significant control over physicists' data. Likewise, leaders of the Manhattan Project found to their surprise that women with high school diplomas (or less) were more effective workers in uranium enrichment factories than PhD-holding scientists (Kiernan 2013, 109–110). They believed that the women, who were not told what the factory was producing or why, followed instructions better than the scientists, who knew the end goals and deviated from instructions to try to improve the process. Outsourcing evidence preparation to nonscientists can thus be a way of preventing scientists' assumptions from affecting the data. Another approach is to standardize protocols. For nanotechnology, which relies on indirect images, sociologist Martin Ruivenkamp and philosopher Arie Rip note that published descriptions of ways of processing the images produced by scanning tunneling microscopy became rarer as the methods became more standardized. They worry that as this trend continues, "the distinction between artist's impression and pictures linked to data may become invisible, and the image of nanotechnology becomes like a work of art" (Ruivenkamp and Rip 2010, 30). If research workers don't document how they make scientific images, then other workers may struggle to understand or interpret those images accurately because they can't know which aspects of the images were based on data.

This fear of inadvertently creating the phenomena they want to study drives practitioners either to set standards and attempt to police them, or to reject digital images altogether, as Kyle did. Scientific communities and journals try to impose standards for image making for publications, although they struggle to define or enforce characteristics of acceptable images (Frow 2012). In response to this fear, fossil researchers emphasize visible, tangible fossils as reliable evidence for scientific knowledge. Researcher Nathan believes CT images will never replace specimens because "specimens are the truth, in the end." Regardless of whether data processing is digital or physical, researchers hold physical fossils as the bearers of "truth."

Researchers often list examples of information that CT cannot provide, thereby criticizing the technique and implicitly promoting direct observation of fossils. Even if a fossil is scannable in size, mineral composition, and density differentiation, critical questions remain. For instance, the CT images published by Fernandez and coauthors (2013) of the fossilized burrow are "sensational," researcher Tobias (who was not involved in the study) said with admiration. Tobias "thought [the CT image] was a line drawing" because it was so clear and detailed. Despite these high-quality images that impress colleagues, the paper's authors admit that these digital fossils don't explain everything, such as the cause of two holes on the amphibian's skull. The holes' size does not match the mammal-like reptile's teeth, so it is not a sign of predation. They are in a thin-boned part of the skull, suggesting they may have been caused by disease or chemical changes during fossilization. "Unfortunately, the resolution of the scan does not allow further investigation," conclude Fernandez and colleagues (2013, 5). Researchers express frustration that CT cannot always yield the information they want to study, from Kyle's completely failed attempts to missing details like the origins of the amphibian's skull holes.

Today's CT data and images also cannot show bone surface details, histology, or cellular structures. Kirk, who studies the ear anatomy of fossil mammals, finds CT evidence unsatisfactory: "I can spend hours staring down a microscope at the thing, trying to figure out if . . . this shallow depression on the surface of the bone that I'm seeing is actually where a nerve or a blood vessel used to run. . . . I can only do that because I've done it before lots of times and because I am looking at the real thing in extraordinary detail." Perhaps CT cannot record the subtle anatomical details that Kirk studies; it is also possible that because Kirk has long done research by looking at real specimens, he is accustomed to that method and considers it the basis for his professional expertise. This is a version of "trained judgment," which historians Lorraine Daston and Peter Galison (2007, 355) define as the way twentieth-century scientists represented the natural world through "pictorial representation by (and for) the trained eye." Trained judgment relies on "skilled vision," which belongs to—and defines—a community of practitioners, such as cattle breeders and judges who must interpret what makes a cow "beautiful" (Grasseni 2004, 2005). Both trained judgment and skilled vision are in some ways tacit, and therefore must be learned through direct experience as well as instructions and feedback. Studying CT data or images doesn't draw on fossil researchers' long-practiced skills of observing real specimens; perhaps as a result, they find CT alone inadequate for research. I suggest then that even if the resolution of future CT images could reveal the data that researchers seek, they would still be skeptical of how those data were prepared as evidence, such as accessed, processed, and analyzed. This skepticism, I argue, derives more from satisfaction with the social status quo than dissatisfaction with CT as a technology.

Complementary Technologies

As a solution for insufficient detail, scientists argue for digital fossils as a complement to physical fossils rather than a replacement. Preston explained, "When you work with CT scans, it's quite important to actually have the 3D object too, to be able to relate some of the structures." In this view, the specimen should serve as a check on the images. In a rare mention of preparators in a publication, researcher Christopher Brochu (2003, 36) hailed them as the solution to CT's technical limitations:

> Upon receipt of the CT data [of a T. rex skull], this author assumed the stapes was not preserved on either side; he was proved wrong when the preparators asked him to identify a slender rod of bone projecting from the braincase. He then returned to the [CT] data set and was able to pinpoint the stapes—an example of reciprocal illumination in comparative anatomy. The stapes is approximately as thick as the original slice thickness and nearly in the same plane; it was very easy to miss. This demonstrates that however powerful modern CT technology may be, it still cannot replace a well-trained preparator.

The unlucky coincidence of a scientifically valuable bone (a T. rex's stapes, which is an inner-ear bone) being roughly the same thickness and orientation as the CT scanner's "slice" parameters meant that Brochu would have overlooked the bone's existence if he had studied only the CT data or if the preparators had missed the tiny unexpected bone. Brochu concludes in a well-cited paper that CT "cannot replace a well-trained preparator."

The need to balance the limitations of digital and physical techniques as well as the variety of specimen conditions emphasizes the importance of adaptability and skill in preparing fossils as evidence.

When I asked preparator Mary whether CT could replace preparation, she laughed at the very idea. Then she answered dismissively, "No, because there's always things you can't see in the scan, or it's not clear in the scan, or some things don't scan well, so I end up preparing them anyway." Preparators are researchers' answer when CT is not good enough, just as researchers believe that their own trained judgment equips them to analyze bones better than CT can. I interpret researchers' complaints about CT's data detail and clarity as a perhaps unconscious way to promote their own and preparators' sensory judgment.

Researchers sometimes state directly that it's good to "evaluate with your own eyes," in Frank's words. They mention the scientific importance of fossil elements that are missing in CT scans, such as texture, color, or subtle impressions of skin or feathers. For researcher Maurice, CT is a poor substitute for his own experience with a specimen: "I have never seen a CT scan that didn't make me feel like I wanted to see it prepared. . . . It's just not the same as seeing the thing for real." In contrast to substituting for prepared specimens, CT images *heighten* Maurice's interest in seeing them directly. Researchers struggle to articulate the power of seeing the thing for real and why digital images cannot match that experience. By not explaining this mysterious quality of direct experience, researchers make it even more mysterious and thus in some ways preserve it as tacit knowledge. Collins (2010) categorizes different types of tacit knowledge based on whether or not they can be articulated, however he does not explore reasons *why* certain knowledge might be preserved as tacit instead of made explicit. Perhaps fossil researchers are not consciously aware of what they do with a fossil that cannot be done with a digital image, and therefore they cannot put words to it. Or this knowledge could be a kind of trade secret, whose secrecy defines a community while also claiming a domain of control for that community. Historian Myles Jackson (2003) contrasts eighteenth-century scientific instrument makers' closely guarded trade secrets—which are tacit in the sense of unarticulated by the knowers' *choice*—with the purported openness and transparency claimed by the scientific community. By not defining how they study objects as compared to images, fossil researchers promote their own mastery of this process and thus their control over it. They stand to benefit from *not* explaining why fossils are better sources of evidence than images.

The Symbiosis of Researchers and Preparators

Researchers do not reject CT outright; most interviewees told me that CT should be used alongside specimens in a mixed-methods approach. According to Sam, the most "fruitful" research method is a combination of "CT and the human eye, an expert eye," on a physical fossil. By highlighting the limitations of CT, researchers show their preference for the flexibility and reliability of "expert" eyes.

So whose eyes are expert? Research workers recognize and appreciate each other's trained judgment, not just researchers'. For example, like Brochu, Maurice doubts that CT can replace the information a preparator learns about specimens while preparing them: "I know lots of examples of preparators discovering things in fossils, just by virtue of the fact that they're so intimately involved with the specimen. And they might say, 'Do you want this cleaned out?' And it's like, 'What is that? I never saw that before' [*laughs*]. And that kind of thing happens a lot, so it's hard to imagine not having that anymore." Maurice's appreciation for preparators' input reflects the symbiosis of the many kinds of fossil work and workers. Researchers depend on preparators' work, which depends on researchers' funding, all of which rely on the care and organization of specimens by conservators and collection managers (Wylie 2019b).

Perhaps because of this interdependence, preparator Bill framed his answer to whether CT can replace preparation in terms of people: "You do need to see the fossil and have a CT scan at the same time. I don't think we'll ever really be able to get rid of preparators. Might be able to cut back on the number you need, but I think there always will be a need for them as long as there's paleontology—paleontologists." Based on his own interests—preserving his job—as well as researchers' need to see the fossil, Bill justifies why preparators and researchers are inseparable. When he changed his response from paleontology to paleontologists, Bill indicated an underlying connection specifically between these kinds of workers rather than between preparators and fossil *research*. Workers define their work and roles relative to each other, as opposed to relative to a process of research or specimen care. If CT were to replace preparation and thus preparators, this network of social roles and divided labor in labs would collapse. As merely an additional tool, however, CT does not threaten the status quo.

By rejecting CT as a panacea for fossil research, research workers reinforce the technology's perceived role as exterior to the fossil lab community. They worry about adding another field to the work of preparing and studying fossils, perhaps in the interest of preserving their current community. CT, after all, requires different skills, training, and tools than a prep lab can provide. Preparator Steve views this as a significant disadvantage of CT: "You've got to have someone to understand all the information you're getting out. You don't just get a lovely three-dimensional image, you have to take all that information and then merge it all together and decide on the resolution, how much you're going to have a contrast between the bone and the rock." Steve portrays CT as complex and reliant on parameters that few preparators or researchers know how to manage. He implies that having a preparator determine the physical boundary between fossil and rock is preferable to hiring someone to understand CT data and make decisions about how to turn it into images. Steve seemed wary of this someone, such as a CT operator or physicist, because they are not part of the lab or even necessarily the broader fossil community.

Likewise, many preparators consider CT irrelevant to their work. Max explained with a shrug, "Some of the things I've worked on have been scanned later by researchers. I had nothing to do with that process, though. . . . You pay somebody else to do that." Research workers' disinterest in the process of CT may implicitly serve to bar it from changing their skill sets or the social structure of their community. Researchers already trust preparators for their skill and judgment, and preparators' absence from publications protects them somewhat from researchers' scrutiny of their methods (chapter 1). In comparison, if researchers don't know CT operators or understand their work, they may perceive them as suspiciously subjective or untrustworthy.

Even when fossil researchers process CT data into images themselves, sometimes with CT experts' assistance, they portray the scanning process as black boxed and somewhat uninteresting, as preparators do. Paleontologists consider CT's mechanism and operation to belong to the domain of imaging experts. When I asked researcher Tobias how the different kinds of digital scanning techniques work, he told me that he doesn't know: "I'm not a physicist," implying that it's not his responsibility to know. Sara, a CT facility manager and biophysicist, does not expect researchers to understand her work or CT: "Most paleontologists have no idea about the physics of a CT scanner." In her experience, because "they just want a picture," researchers typically aren't interested in how the picture is made. As a result, they need their "hands held" in the form of help from CT specialists to process and interpret scan images. Researchers often acknowledge this contribution by making Sara an author on papers about her scans. Tobias also lists the physicists and materials scientists who do his CT scans as coauthors because "they didn't do only the technical stuff but also the [image] construction, so it's justified." These imaging experts operate the scanner, which for Tobias is the technical stuff, and also discuss with him how to process the data into the views he wants. This latter contribution deserves authorship, according to Tobias.

This designation of CT experts as coauthors indicates the separateness of the primary author's disciplinary identity from imaging technology, and also recognizes imaging technology as a research field in itself, perhaps because many CT experts have PhDs. In comparison, preparators are rarely authors on fossil-based publications. Barley and colleagues (2016, 153–154) interpret this difference in contribution acknowledgment as based on status:

> When occupations are marked by well-understood differences in formal knowledge, respect for expertise is not usually a problem. For example, radiologists are unlikely to assume that they know what pathologists or orthopedic surgeons know. However, when collaboration involves occupations whose knowledge is contextual, practical, and situated and when those occupations

> are also embedded in a hierarchy of authority, then it is apparently more difficult for higher status occupations to acknowledge the expertise of lower status occupations.

CT researchers with PhDs and fossil researchers with PhDs see each other as status equals with different areas of expertise. In comparison, researchers do not recognize technicians—or other workers with "situated" knowledge and lower status—as coauthors, even if they are skillful experts.

Another result of this separateness is that CT experts are relatively uninterested in the objects they scan. For instance, some CT manufacturers donate scanners to museums, in part for public relations reasons (e.g., Kremer 2011) and in part because the designers want to know what the scanner is capable of. Museums' nonhuman objects (e.g., fossils, taxidermied animals, paintings, and Stradivarius violins) serve as experiments about the kinds of materials the scanner can detect. Sara, for example, is interested in the "technical stuff" of optimizing the scanner's parameters for different kinds of objects and developing new ways to analyze scan data, such as combining it with chemical composition data. Despite job offers from several CT companies, Sara chose to work in a museum's CT lab because of the variety of objects to scan, including a Martian meteorite, glass sculptures, and wet specimens. "I see everything!" she said proudly, unlike the limited test objects that CT researchers normally work with. Sara usually knows little about the specimens she scans; instead, she appreciates this diversity of materials as a test of the machine's capabilities and her own techniques for using the machine.

Although many CT facilities are run by imaging experts like Sara, some are run by researchers in other fields. Julian, an anthropologist, operates the CT scanner at the Southern Museum, which he learned to do by "trials and errors." Many of the specimens he scans are not human and thus are outside his research expertise, and he enjoys testing the machine's abilities like Sara and other CT experts do. He likes "to see what can be done," such as by scanning an extant animal specimen and then dissecting it to compare with the CT data. "It's all experimental," he said. Julian gets particular satisfaction from using scans of museum specimens to disprove the manufacturer's statements of what a scanner can do, such as successfully scanning metal-containing rocks. He then shares the results with the manufacturer to impress them and encourage them to donate scanners to museums. Preparator Jay describes this interaction between the museum and the CT company as "a symbiotic relationship" in that both sides benefit. Clearly most CT experts have different priorities from fossil researchers and preparators. Preparator Alan credits his institution's high-quality CT scanning work to its operators' expertise about CT *and* fossils. For example, Alan admired the software the operators built to filter "noise" from CT data of fossils based on their unusual interdisciplinary knowledge. He explained that CT requires skill, experience, and critical thinking to do well, "like preparation." Digital fossils are therefore not merely the automatic output of a machine.

Researchers believe that CT is a "great tool" (Sam) and "will become a standard method in paleontology" (Tobias), even if they believe CT is "not going to replace the preparator" (Sam). They are not Luddites; they are excited and optimistic about the use of CT on fossils, generally because they think it can provide otherwise impossible data access and a backup version of specimens. They just don't consider CT a panacea for all fossil research; it is a tool among many rather than a methodological revolution. This case illustrates the coexistence of technologies that take different approaches to the same goal: making fossils researchable. This complementarity matches the wide range of accepted methods for fossil preparation, such as preparators' fight to preserve their control over materials in the case of the cyanoacrylate controversy (chapter 1). Paleontologists share that flexibility in the form of an open-mindedness about research techniques that philosopher Adrian Currie (2015, 2018) calls "methodological omnivory." CT's technical disadvantages are not the only reasons research workers doubt that CT can fully replace prepared fossils or preparators. They value their own and each other's skills of seeing and interpreting fossil specimens, and resist the obsolescence of those skills by technology. Moreover, the underlying social and epistemic structures of scientific communities rely on divisions of labor between workers, which scientists do not want to lose by removing fossil preparators.

Preparing technologies, then, reveals research workers' priorities about their evidence and their communities.

CONCLUSION: TECHNICIANS AS TECHNOLOGY

Technologies—that is, techniques and tools—are a crucial part of science. In particular, they connect the preparation of communities with the preparation of evidence. By observing how communities prepare technologies in order to prepare evidence, and in turn how that evidence influences the design of technologies and how those technologies define communities' identities, we can see the intersections between preparation processes. Together, these processes prepare knowledge.

Preparing technologies can include developing and adapting tools and techniques as well as preserving and/or rejecting them. For example, rock removal tools have changed little in the history of fossil preparation. Even the primary tools today are only slightly modified from stonemasons' hammer and chisel (i.e., the air scribe) and sandblast (i.e., the air abrader). My explanation for this stability is that preparators have invested in their own skill development rather than in building radically new kinds of tools. This narrative aligns with the change in beliefs about whether fossil preparation was easy to learn, or dependent on extensive skill and experience. Thus in the sociotechnical system of tools, techniques, and technicians, preparators have developed the technician as the most valuable factor.

CT scanning offers a potential shake-up of fossil preparation technology by putting the need to remove rock into question. By converting a fossil into digital images, CT can help fossil researchers see through rock in some cases. Despite this apparent magic, researchers prefer to work with fossils over images. After all, they are accustomed to and skilled at interpreting objects; they consider images made by mysterious machines and unfamiliar operators questionable in comparison.

When fossil researchers talk about CT scanning, especially about its limitations, they articulate how preparators matter to epistemic work, specifically in terms of preparing evidence and implicitly in terms of preparing the community of people who work with fossils. This rare explanation for why skillful people are more important than machines emphasizes the role of trust in research work. Relationships matter in that scientists seem more comfortable working with preparators to prepare evidence than working with CT experts. Because researchers and preparators have worked side by side for over a century, their roles and interdependence are established as well as embedded in their practices and communities. The desire to preserve this apparently functional social status quo could be the deciding factor in scientists' skepticism toward CT.

As a way to reap the benefits of a new technology without it radically shifting their social order, scientists talk about CT and fossil preparation as serving different epistemic purposes. For instance, CT can access features that preparation can't without damaging the fossil, such as the insides of skulls, eggs, and burrows. The coexistence of digital and physical fossils is scientists' preferred reality, CT's technical limitations and cost notwithstanding. As a result, scientists happily CT-scan a fossil and then send it to the prep lab, or vice versa, without cognitive dissonance. Accordingly, preparators do not feel threatened by obsolescence. They regard CT with optimistic expectations for informing preparation work and creating backup versions of specimen data, or they dismiss CT as irrelevant. The fossil community is placing CT alongside long-standing technologies as a potential complementary option. Knowledge is a product of the ongoing processes of how people prepare technologies and communities of trust. This view suggests that workers' situated skill and experience plays such an integral role in science that scientists actively work to preserve it—and likely will continue to do so. This interdependence among research workers stems from a shared sense of science as their collective mission.

Preparing Dinosaurs

The Work behind the Scenes

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