Preparing Dinosaurs

The Work behind the Scenes

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1 PREPARING EVIDENCE

Early in my visit to the Northern Museum, near the end of a workday, Carla invited me to watch as she removed matrix from a flattened, fossilized fish skeleton. As I leaned over her shoulder, she precisely pressed the slim vibrating tip of the smallest-available air scribe (a pen-size pneumatic jackhammer, also called a micro jack) against the thin layer of rock covering the delicate bones. The slightly jumbled skeleton bulged beneath the matrix like that of a freshly dead fish lying just below wave-lapped sand (figure 1.1). Carla read my mind about the fish's lifelike appearance, saying loudly over the air scribe's buzz, "What I like about this fish aesthetically is you can see the bones under the scales. So I'm trying to keep as much [of the scales] on as possible, because to me it's artistic." She admired the fish's morphology and preservation, which shaped her vision of how the prepared fossil should look. Achieving this "artistic" vision would do justice to the fish's beautiful natural shape. She was worried, however, that the scales were only loosely attached to the bones, and thus "it takes time to keep them on." She planned to be extra careful while removing matrix, and she considered gluing the scales in place if necessary: "You can always prep the glue off, but I want to make sure that the scales stay on." Glue-coated scales are better than no scales for Carla since "if they come off, it'd be hard to re-create them because of that texture." A sculpted scale can't capture a real scale's subtle parallel ridges. She pointed her air scribe tip at a round, grooved scale: "They're like little records. . . . If you paint them on, it wouldn't look really convincing" without the three-dimensional surface.

Figure 1.1
A preparator removes matrix from a "beautiful" fish skeleton covered in tiny fossilized scales.

So Carla strove to laboriously preserve the scales in place rather than drill through them and replace them later with painted reconstructions. Carla was not just cleaning this fish; she was deciding what it should look like.

Carla watched the pulverized rock fly off the end of her air scribe for only a few seconds before she stopped, narrating her thoughts for my sake: "I don't want to get too cocky with my micro jack here, so I'm going to switch tools." She delicately slid the plate-size rock slab containing the fish into a clear plastic box with tubes and armholes cut through the sides. She adjusted the air abrader, a modified sandblaster, to blow fine abrasive powder through a handheld nozzle at low air pressure and low flow rate, a gentle setting to protect the fossil's fragile scales. Carla sat beside the box, put her hands through the holes, and turned on the nozzle's flow to hit an area of matrix away from the fish, testing the potency of the pressurized particles. She was unsatisfied with the test and adjusted the machine to further weaken the flow, then aimed the nozzle at the ranks of scales on the fish's flank. Despite swapping an air scribe for the gentler air abrader and her careful calibration of the machine, the particles immediately pulverized a hole through the matrix and loosened one of the underlying scales. Carla stopped the flow, swore calmly, and reached for the little bottle of glue she'd already set inside the glass box in expectation of such unfortunate outcomes. She balanced a single drop of cyanoacrylate (also called by the brand names Super Glue or Krazy Glue) on the tip of a metal dental scraper and touched it to the edge of the loose scale, where it was absorbed into the bone through capillary action and instantly bonded the scale in place. With a deep breath, Carla shook off the stress of the repair and aimed the nozzle at the next scale, moving it around the fossil a little faster than before to prevent boring another hole. She explained that air abrasion can blow matrix off gently, "but if you're not really diligent, you can do a lot of damage in a short amount of time." She meant that you have to watch carefully to see what effect the abrader is having on the fossil, and adjust the machine and your technique accordingly. The other option is "you can have [the air abrader] on such low pressure that you never get anything done. You gotta find a balance" between damage and progress. Carla considers finding and maintaining this balance an art that requires careful attention and experimentation.

With its precisely adjusted pressure and flow rate along with Carla's skillful way of moving it quickly and smoothly around the specimen, the nozzle looked like a magic wand that turned rock into fish. As the skeleton emerged under Carla's hands, she described preparation as individualized work: "Everybody's different; they all have their own style. Me, I like a crisp, clean line" of fossil, such as by exposing each individual fish tooth in their tight rows. "I look at other people's and they just do the outline, just half prepared. But it's somebody else's standard." She didn't sound critical of people who only outline teeth; rather, she presented this diversity of expectations of a prepared fossil as normal and unproblematic. Carla sighed happily: "I love these guys." When I asked her why she loves fish, she said as if it were obvious, "What's not to love? They're beautiful."

One of the key processes of preparing knowledge is preparing evidence. We know from studies of scientific practice that the work of distinguishing evidence from not evidence, such as "noise" or "background," is complex, situated, and not obvious (e.g., Latour and Woolgar 1986; Galison 1987, 1997; Latour 1999; Collins 2004; Kohler 2006; Leonelli 2009; Chapman and Wylie 2016). Preparing evidence, then, involves deciding what materials and/or observations are relevant, what form they should take (e.g., physical appearance and organization), and how to achieve that form. These decisions often fall to individual practitioners, who make in-the-moment judgments based on their expert observations and then apply skillful actions to pursue their expectations of the evidence. Diversity in individuals' preferences, skills, and priorities, including judgments of what is beautiful, results in a variety of possible forms that a single piece of evidence can take (Wylie 2019a). It is therefore crucial to study the factors that influence how those possible forms take shape.

Evidence comes from physical objects that require preservation and/or ephemeral observations that require documentation. All forms of evidence must be organized and stored. For example, philosopher Sabina Leonelli (2008, 2016) argues that biological data sets are "packaged" (i.e., categorized, formatted, and labeled) for inclusion in an online, open-access database in ways that obscure how they were made. Omitting data sets' origins allows them to seem more universal and thus useful for a wider variety of research questions. Yet "the reliability of facts cannot be assessed except by reference to the way in which facts are produced" (Leonelli 2008, 12). Given this, the database also includes information about how each data set was made, which is stored at a separate link from the data set itself. The conflicting need to both obscure and access data preparation is evident in most scientific publications, which either omit preparation work altogether or offer a simplified description without mentioning the embodied knowledge and tacit rules of thumb involved (e.g., Collins 1975; Latour and Woolgar 1986; Latour 1987; Cambrosio and Keating 1988; Jordan and Lynch 1992, 1998; Barley and Bechky 1994; Lynch 2002). Ethnography, then, is the most informative—and perhaps sole—way to study how practitioners define, preserve, and categorize evidence.

This chapter explores specimens as one of the many possible kinds of evidence. Fossil preparation is a powerful example of the epistemic significance of how people prepare specimens because prepared fossils are more visible and tangible than many scientific objects, such as cells, stars, or readouts from laboratory instruments. Also, unlike technicians who follow published, widely used protocols (even with their own tacit, skillful strategies), fossil preparators choose and design methods to prepare a fossil that matches scientists' priorities as well as their own. The expectation, freedom, and perhaps necessity to tinker, adapt, and invent techniques characterize the iterative craftwork of preparing fossils. This chapter asks how preparators and scientists define good fossils physically and epistemically as an example of how research workers define good specimens more generally.

As we'll see, good specimens are the product of good preparation, not purely of lucky preservation. Because all specimens are different and these variations often require flexible, tailored methods, preparing specimens involves skillful craft and expert judgment. For instance, a "good" vertebrate fossil in the field is scientifically interesting, such as a representative of a new or rare species, or an unusual animal for that locality. Once it's collected, preparators are responsible for making that fossil researchable, with arguably any method they deem appropriate. To identify the characteristics of good evidence and preparation, first I follow preparator Jay through a typical set of tasks. Like Carla's detailed work with the fish, Jay's experiences preparing, repairing, and replicating fossils offer insights into preparators' usually tacit priorities for specimens as well as their methodological flexibility. Next, a fierce controversy about a crucial element of preparation work—glue—sheds light on preparators' beliefs about good fossils, good practices, and whether their decision-making power should belong to individuals or the collective community of preparators. Finally, preparators claim autonomy over their techniques and tools by likening preparing fossils to making art, based on a shared reliance on creative problem solving. Methodological flexibility, I argue, empowers practitioners of constitutive cleaning. How preparators prepare fossils, then, reveals the unwritten epistemic and social foundations of paleontological practice and knowledge, and raises questions about why this work is largely undocumented and nonstandard.

THE EVERYDAY WORK OF PREPARING SPECIMENS

Defining Fossils

On a Thursday at 9:30 a.m., Jay, a longtime staff preparator at the Southern Museum, had a list of things to do. He wanted to search a bag of matrix for microscopic fossil mammal teeth and start gluing them in place on their tiny jaw, deliver light bulbs to the museum's glass-walled preparation lab, replace a microscope light bulb in the specimen research space, check the lab's air filtration system, buy a more powerful microscope lens (to facilitate his work on the mammal jaw), make a storage jacket for a fossil horse skull, mold a fossil squirrel skull to produce a replica, "and I have to finish my coffee." This diversity of tasks, workplaces, and even ranges of vision—from searching for teeth under a microscope to inspecting the lab's huge air filtration apparatus—indicate the many kinds of knowledge, skills, and priorities involved in producing and maintaining specimens. This section follows Jay through the three fossil-focused tasks on his to-do list. I analyze these particular tasks because they represent commonplace activities and because Jay worked on them all on the same day (and then finished them over several days); thus they portray the everyday realities of preparing fossils to serve as scientific evidence.

In each of these tasks, Jay invented or tinkered with techniques. Critics could label this work a "kludge," a colloquial term that distinguishes "rational" and "elegant" techniques from lucky, sometimes mysterious actions that simply "work" (O'Malley 2011, 409). Kludging and preparing specimens both rely on methodological adaptation and the ongoing assessment of techniques' results. Also, both approaches value the finished product and its effectiveness for its purpose more than the process of achieving that product. But that process is also a critical component of scientific work, even if seemingly irrational or inelegant. It reveals the tacit values that inform practitioners' judgments of whether a technique "works" and thereby how they conceptualize good evidence. Furthermore, adaptable techniques, including kludges, crucially enable the study of diverse and unpredictable pieces of evidence.

Reconstructing fragmented fossils, like Jay's mammal jaw, is technically difficult, epistemically loaded, and strikingly quotidian. Fossils almost always arrive in the lab in pieces, but without all their pieces. So which fragments preparators reattach—and where they reattach them—is rarely obvious and requires judgment calls. Even defining what is a fragment relies on expertise. Jay began work on the mammal jaw by searching a small box of sand-grain-size matrix under a microscope, hoping to find more slivers of teeth to match the jaw that he and colleagues had discovered during a collection trip a few months earlier. As I watched, Jay triumphantly lifted a barely visible "frag" (fragment) of fossilized tooth enamel out of the matrix with tweezers. He inspected it and guessed that the frag might "bridge the gap" between two other pieces he'd found, thereby making it possible to assemble all three pieces into one reconstructed tooth. Removing matrix from fossils is a process of defining them in their current state, while repairing and reconstructing fossils involves, as the prefix "re-" implies, returning a specimen to its appearance in life. That achievement is, of course, impossible, but making a tooth look complete instead of shattered is considered a step closer to seeing that tooth as it looked when it was part of an animal. Soon after finding the frag, Jay decided to stop searching because the loose matrix contained only "tooth dust"—pieces of enamel that he judged too small to reconstruct or be scientifically useful.

Jay planned ahead, thinking through his decisions about how to best reunite the two pieces of the jawbone and, later, the teeth. First, he purposefully left finger-size hunks of matrix attached to the half-centimeter-long jaw pieces, as "handholds" to help him manipulate the tiny fossils while gluing them together. He would prepare away the handholds after he finished the repair. Next, he evaluated the options for adhesives. He decided on cyanoacrylate for its faster and stronger bond than other glues, which are important benefits when working with microfossils. The downside is that "you only get one shot," he said, because cyanoacrylate bonds instantly and it would be nearly impossible to undo the join on such small bones. Positioning the pieces by their handholds and holding his breath, Jay delicately placed cyanoacrylate on the nearly invisible gap between them, adhering the two pieces. This task required steady hands, knowledge of adhesives' properties, and judgment of which pieces had once formed the same bone and how they fit together.

With the jaw pieces reunited, next Jay "built" each microscopic tooth, placing its frags in a base of soft clay to hold them while he aligned their broken edges. He put a drop of cyanoacrylate on a single paintbrush hair and allowed capillary action to suck the glue into the crack between two frags, where it bonded them together. He repeated these actions for each frag in each tooth. Finally, based on his knowledge of anatomy and assessment of which broken edges corresponded, Jay lined up the rebuilt teeth in a small box in the order he thought they belonged on the jaw. He spent a long time getting ready to glue the teeth to the jaw, even though—or perhaps because—the task would only take an instant. But then he paused, and decided that he needed a few quiet days to best set up this final, stressful, "one-shot" reconstruction. He put the task "on standby" and eventually completed it a few weeks later.

Jay's decisions about the mammal jaw aimed at enabling research by making the specimen as complete as possible. By reconstructing the jaw, Jay also protected its fragments from becoming separated or lost. He chose his methods in response to the fossil's physical and epistemic statuses. For example, because it was tiny and in multiple pieces, he carved matrix handholds and applied cyanoacrylate with a paintbrush hair. The rarity of Cretaceous mammal fossils makes this jaw scientifically significant, so Jay planned ahead, relied on the broken edges to guide his decisions, and took his time. These approaches drew from his embodied knowledge of handling fragile microfossils and his understanding of scientists' interest in the specimen. Crucially, Jay assessed his own state of mind as a factor in how well he could prepare the fossil. Because he felt rushed by his busy day and worried about the difficult final task, he postponed it. He therefore acknowledged his own role in the system of tools, techniques, priorities, and objects, and altered his preparation work accordingly. His in-the-moment assessments and reactions to the situation resemble the "reflection in action" (Schön 1983) that craft workers and other experts practice. These judgment calls, based on expertise, experience, goals, and values, shaped how Jay conducted the common tasks of defining and reconstructing fossils, and thus how that mammal jaw and its teeth look. Furthermore, teeth are scientists' primary diagnostic feature for mammals. By saving the tooth frags (and not the tooth dust) and by reconstructing the gross morphology of the teeth and jaw, Jay turned barely-visible chunks of preserved bone into a researchable specimen of a long-dead mammal that lived alongside dinosaurs.

Later that day, Jay repaired another fossil, but not one fresh from the field: a holotype specimen of a small proto-horse species that had been first prepared in the 1950s. (A holotype or "type" specimen is the individual that scientists designate as the permanent defining example of its species.) A visiting scientist had found the narrow, palm-length skull lying in pieces in its storage box, so he brought it to Jay. Glue from many previous repairs coated the pieces' broken edges, hiding their shape. Jay told me, "I don't see any obvious joins. But that doesn't mean there aren't any." Preparators' power over a specimen's appearance includes their ability to *not* apply techniques, such as by not identifying or attaching broken pieces. When I suggested that one frag belonged to the skull's eye socket, Jay disagreed, saying wryly, "Put it there if you want it to be a *new* type," meaning a new—and invented—species. Then he suggested gluing an unattached canine tooth on the end of the skull's nose like a horn. These jokes highlight preparators' power to decide how a specimen looks, such as by their judgments of if and how broken bones fit together (chapter 4).

After many failed attempts to match the loose pieces with the skull's broken edges, Jay decided to consult the specimen's published description and photographs from the 1950s. I have seen preparators check scientific papers only a few times; this unusual step reflects how stumped Jay felt about how to reassemble this skull. Based on the paper's text and images, Jay identified and adhered several pieces. He also found traces of glue on a canine tooth fragment and a matching glue-lined edge on the skull, indicating a former join. So he adhered the tooth there, even though it was absent in the published photos. There is a kind of circularity in this story in that a preparator prepared this specimen, then a researcher described it in a publication, and then a later preparator (Jay) repaired the specimen to match the publication. Preparation thus seems to strive for continuity to preserve how a specimen looks over time. Jay, however, added an unpublished feature, the canine tooth, based on another preparator's undocumented repair work. He consulted the specimen's published description as a reconstruction guide, but when he disagreed with it about the canine tooth, he acted on his own assessment. It is a power play of sorts between a publication (which in this case is particularly significant because it defines a species based on this type specimen) and Jay's visual judgment of potential joins as well as trust in the unknown preparator who had glued that tooth.

To protect the skull and his reconstruction work, Jay decided to build a custom storage container for it. This seemingly simple decision illustrates the priorities and constraints that influence how preparators choose techniques. Jay suspected that the skull's damage had resulted from rolling around inside its box, so he considered several ways to immobilize the skull. First he planned to make a "cradle," a plaster platform molded to fit one side of the skull. Then preparator Kevin suggested making a "housing," a box lined with foam cut to fit a fossil's shape. Jay and Kevin had recently learned how to make housings at a conference workshop led by another preparator. But Jay worried that there was no safe place to put "finger holds" in the foam lining to show people where to safely pick up the skull without grabbing its many fragile areas. As a result, Jay rejected building a housing and realized that a cradle would also lack a safe way to pick up the skull. Jay then decided not to be "lazy" and instead make a "clamshell jacket," in which two cradles fully encase a specimen. He half buried the skull upside down in a sandbox, where it was fully supported and protected while he laid plastic wrap and then wet plaster-soaked strips of cloth over it. Overnight, the plaster dried into a rigid, perfectly matched mold of the bottom of the skull. Then Jay laid more plaster-soaked strips across the half jacket's unmolded side and set it on a table to dry, thereby creating a flat bottom surface. Finally, Jay lined the top of the half jacket with a thin layer of archival foam, which cushions the fossil and resists chemical degradation.

When Jay set the skull in its finished half jacket, he realized that adding a top half would make the specimen too tall to fit in its storage drawer. Jay wanted to keep the skull in that drawer because its skeleton was in there too and he didn't want them to become disassociated. It was also important to him (like all museum staff) to minimize the space each specimen takes in the museum's overcrowded collection. So Jay declared the half jacket to be a finished cradle. The skull "is already more protected now than it was," he said with a shrug. Jay's lengthy experience as a preparator as well as consultation with a coworker informed his evaluation of which design would best achieve his goals for this fragile and important specimen. The constraints and many possible forms of storage support alone point to the many embedded values and contingencies for a specimen. The cradle, after all, becomes part of the fossil's history and future.

No one had told Jay what to repair about the skull or to change the specimen's storage. He followed best practices he'd learned from experience, not from published instructions. He decided to reattach as many frags to the fossil as possible, including ones not pictured in its published description. Jay chose to invest time in making a cradle in hopes of preventing damage and reducing future preparators' time spent repairing this specimen. This example shows preparators' independence in choosing their methods and sometimes their tasks as well as how their priorities of preparing researchable specimens extend to protecting specimens from potential harm. Alongside these values-based decisions, the embodied expertise of finding, matching, and gluing fossil pieces into a stable, trustworthy representation of an extinct animal is a physical and epistemic triumph.

Making Fossils Mobile

In addition to being prepared and repaired, specimens must be transported. Scientifically valuable objects often circulate in the form of high-quality replicas. These replicas can be studied or put on display as replaceable but ostensibly exact copies of the original. Making representations of nature that are mobile and reliable (Latour 1986) requires trust in representation methods and makers, such as illustrators, photographers, and modelers. Preparators are responsible for molding and casting fossils to make researchable replicas. This process is long established and well trusted, even though preparators use a variety of materials and techniques.

When a scientist at another museum asked to borrow the skull of the type specimen of a fossil squirrel species, researcher Henry wanted to avoid mailing the important specimen. So he asked Jay if he could mold and cast the finger-length skull. This was not an order or even a request but rather a sincere question. Henry knew the small skull with its fragile eye sockets would be complicated to mold and an especially perilous endeavor because type specimens are irreplaceable. Molding is always risky because removing the mold puts pressure and torque on the fossil. Preparators often recount stories about bad technique or "luck" that resulted in specimens breaking disastrously during molding. Still, Henry hoped that molding would be safer than mailing. According to Jay, Henry asked about molding "with a tone of 'tell me what I want to hear!'" Jay examined the skull, noting the paper-thin bone of the eye sockets, and said that he could mold it. Henry happily left the skull with Jay, relieved to loan a copy and spare the specimen a dangerous journey.

Jay's problems, on the other hand, were just beginning. He was not sure that he could deliver a research-worthy cast as well as an undamaged specimen. First, he was concerned that the liquid silicone molding material might penetrate the thin cracks lacing the fossil and then widen them or even pull the skull apart when Jay peeled off the dried silicone. So he painted thin water-soluble wax over the cracks, temporarily sealing them. The wax didn't dry smoothly, so Jay scraped off the excess with a delicate metal scraper that sculptors use to carve minute details into clay. Jay was trying "to get rid of the lumps" so they wouldn't be recorded in the mold and then appear as lumps on the cast. A researcher might interpret those lumps as natural bone features, as there would be no documentation of these unintended artifacts of molding. Jay knew he had the power to alter the cast's appearance and therefore the knowledge claims it might inspire. He was responsible for the skull's safety too. He balanced these roles by trying to maximize the cast's accuracy even as he minimized harm to the skull.

Molding is generally a dynamic compromise between protecting the specimen, making an accurate copy, and not wasting the expensive materials. These judgments rely on a practitioner's ongoing reflection in action to identify problems and adapt ways to respond (Schön 1983). For one side of the skull, Jay decided to use the "block mold" technique, which creates a thick, firm mold to provide support for the specimen. For the other side, which had a well-preserved and fragile eye socket, he planned an unusually thin—and hence flexible—mold that could be peeled off the eye socket with more control than the inflexible block mold. “It may still break anyway but maybe I can minimize the damage” with this combination design, Jay said, planning for contingencies. To make the block mold, he first embedded one side of the skull in clay so that half the specimen rose above the clay’s surface. Then he built a “wall” of clay a few centimeters away from the skull as a container for the liquid silicone that would form the mold. On the “floor” of the clay container, between the walls and specimen, he used the circular end of a dental tool to push shallow, round depressions into the clay, which would make “registration keys” in the mold to allow the mold’s two halves to lock together. Then he prepared the liquid silicone, which involved careful measuring, mixing, and time in a vacuum chamber followed by slow pouring into the clay container around the fossil. These steps aimed to extract air bubbles, which leave holes in the mold and misleading lumps on the cast.

After several days, Jay hoped that the silicone had “cured” enough to make the second, flexible half of the mold. He gently removed the clay floor from the block mold, revealing the side of the skull that had been embedded in the clay. He built clay walls around the newly revealed skull side, with the floor now the skull surrounded by the block mold’s surface with the registration keys. He made the silicone as before, but without bothering to put it in the vacuum chamber because he would “paint it on” instead of pouring it. Jay gave the painted-on silicone an hour or so to cure and thicken, then he brushed more on to create layers to improve the mold’s flexibility. He repeated this procedure four times in one day, then pronounced the thin, layered mold finished and ready to fully cure. Jay made these decisions based on his ongoing assessments of the fossil and molding material.

Jay managed to delicately peel the cured, thin half of the mold off the eye socket with no damage. Relieved, he held the block mold as stretched open as he could and told me to remove the skull. I gently worked the skull back and forth until it pulled free. Jay was satisfied: the “specimen didn’t break” and the “seam line looks good” between the two mold halves, meaning that they would close together tightly when making casts. Finally, Jay dissolved the wax from the skull by applying water with a paintbrush and then put the specimen safely back in its storage box. The mold was finished and a success, according to Jay. The next step was to produce two research-quality casts, one to lend and one to keep.

Making an accurate cast relies on removing air bubbles from the liquid casting material (plaster in this case), among many other factors. If allowed to remain, bubbles would form holes and therefore inaccuracies in the cast. Jay planned to carve off any bumps on the cast caused by bubble holes in the mold, but there is no way to fix bubble holes in the *cast*. After mixing plaster powder with water, he poured it slowly into the block mold, pausing to tap the mold on the table, push and pull its sides, and run a metal scraper along the bottom, all to chase out air bubbles. He did the same with the thin mold half, then quickly flipped it on top of the block mold so that the registration keys would seal before the plaster leaked out. Filling the mold felt less tense than making the mold because the safety of the fossil was not at stake, but it nonetheless required Jay's full attention for several minutes.

After the plaster dried, Jay peeled off the mold to reveal the cast inside, which he described to Kevin as "99 percent good except for the bubbles on the teeth. They're not important." This was a joke because, as they both knew, teeth are the most important part of a mammal skull for researchers, as diagnostic indicators of species. Holes on the cast's teeth, made by air bubbles in the plaster, made it useless for research. Jay pointed out the importance of preparators knowing how artifacts of casting might affect research: "That's why it's good to go to [research] talks to see what they're looking at," meaning which anatomical features researchers consider significant. The rest of the cast, besides the bubble-obscured teeth, was "good," Jay said, because of the "faint seam line" around the skull where the two mold halves met. He used a metal scraper to carve off the raised seam, saying, "Have to be careful not to remove the sagittal crest," a raised bone suture on top of mammal skulls that lies just beneath this cast's seam. I wondered how he knew how much of the delicate ridge represented bone and how much was created by the mold. I asked if a researcher could distinguish between a seam and an anatomical feature, and Jay said, "Probably."

Researchers can easily distinguish casts from bones based on their weight and color, but deciding what about the cast to trust as evidence about an animal is more obvious if researchers understand the processes of molding and casting. Yet these processes, like other forms of preparing evidence, are rarely described in publications.

To prevent air bubbles in his second attempt at a cast, Jay planned and then followed a different procedure: mix plaster that is thicker in consistency (i.e., less likely to form bubbles), paint it into the mold instead of pouring it, then "top it off and vibrate it" to remove bubbles before fitting the two mold halves together. The next day, Jay removed the second cast from the mold and decided that it had fewer bubbles but looked different. I found small plaster pieces stuck in the mold, where they had broken off the cast's eye sockets. Disappointed, Jay decided he'd "pulled it [out of the mold] too early," when "the plaster was set but not hardened," as indicated by the eye socket edges that "shouldn't have broken." In the interactive triangle of technician, technique, and tools, Jay deemed the tools/materials to be appropriate and didn't fire himself as the task's technician. Rather, he saw a problem in the technique.

For the third cast, Jay copied his second procedure but with a longer cure time. When he pulled out the cast, Jay dubbed it "a keeper": the teeth were visible, and the eye sockets were intact. Jay assigned me to make a fourth cast by following his third procedure. I imitated his steps carefully, but the fourth cast had bubble holes on its teeth. Jay was dissatisfied yet friendly about my failure, setting a new plan for the next cast by saying to me, "Want to do the side without the teeth?" He judged my mold-filling skill as inadequate for the most important and trickiest area of the mold. In this case, the technician (i.e., me) was the weak link, not the techniques or tools. To improve on the technician variable, Jay decided to paint plaster into the fifth cast's teeth himself. But then a coworker started talking to him. Jay did not appreciate the interruption as he was filling the mold, saying quietly to me, "I forgot where I was" and "I have no idea what's going on with this." When his coworker left, Jay kept brushing plaster into the mold's tiny teeth-shaped crevices and tapping the mold to shake bubbles loose, trying to repair the effects of his lost concentration. I asked him if he ever felt frustrated with his work. He said yes. I asked what he did to calm down, and he said, "Swear." I said that in my experience, he didn't swear, and Jay said that things don't usually bother him. His job includes many potential sources of stress that he can do little about, such as failed techniques, difficult tasks, unpredictable fossils, and rude people. So when the fifth cast's eye sockets broke inside the mold, Jay was frustrated but resigned. He settled for the one successful cast.

To achieve his task of making a reliable, useful cast, Jay set requirements such as visible teeth, intact eye sockets, and a minimal seam line. His adaptations of his methods relied on trial and error to identify a set of techniques that produced results from this particular fossil that matched his requirements. Different variations of technique, skill (his versus mine), and luck, however, produced bubble-obscured teeth and broken eye sockets. Thus these methods were difficult to replicate, even on the same mold. As craft workers respond to unexpected variations in ways that preserve their overall priorities and technicians tinker to preserve or restore the functionality of machines and techniques, evidence preparers evaluate materials' reactions to their work and then adapt their work in response. Specimens, then, are prepared based on ongoing, expert assessments of the materials of the physical world and the priorities of the social one.

CONTROVERSIAL TECHNIQUES: "PALEONTOLOGY DEPENDS ON ADHESIVES"

Instantaneity versus Reversibility

Preparators' methodological flexibility is widespread and well established, but occasionally it inspires fierce debates about which techniques are best and, therefore, the meaning of good fossil evidence. These debates shed light on the community's priorities for what specimens should be like. For example, the "cyanoacrylate controversy" (as one preparator called it) of the early 2000s blew up around preparators' divergent beliefs about whether cyanoacrylate is an effective and ethical adhesive to use on fossils. According to preparators, the conflict centers on whether specimens should be prepared primarily for immediate research or unknown future research.

But the underlying issue, I argue, is preparators' defense of their power to choose and invent techniques versus their desire for everyone to use certain "good" techniques and shun "bad" ones. Crucially, preparators disagree about whether certain techniques are always good or bad, or whether that judgment must depend on context.

The cyanoacrylate controversy reveals a plurality of priorities among preparators. Many preparators appreciate cyanoacrylate as a strong, instant adhesive, while other preparators as well as conservators and most collection managers oppose cyanoacrylate for its permanence and risk of degrading over the centuries-long shelf life of prepared fossils. Cyanoacrylate is a reaction adhesive, meaning that it undergoes an instantaneous chemical reaction to adhere to surrounding material. In fossils, it wicks into cracks and creates a strong network of bonds below the bone surface, which means it is impossible to fully remove. In comparison, solution adhesives create bonds when the solvent in them evaporates. These bonds can be dissolved by applying more solvent, such as acetone, which is why solution adhesives are considered "reversible." Common reversible adhesives in fossil preparation are a confusing list of synonyms and brand names that preparators use interchangeably and not always accurately. These include Vinac (aka McGean B-15 or polyvinyl acetate), Paraloid B-72 (aka Acryloid), and Butvar B-76 and B-98 (aka polyvinyl butyral) (Elder et al. 1997; Davidson and Alderson 2009). These adhesives are also archival materials, meaning they are relatively chemically stable and thus resistant to deterioration over time.

Reversible techniques and archival materials are key components of conservation, which is a field of research and methods to preserve objects in as close to their original state as possible, including artwork, paper, textiles, and specimens. Conservators assess the state of objects over time, and regulate storage environments to prevent destructive temperature changes, humidity, and pests (e.g., mice and insects). They perform chemical treatments, such as adding adhesives, as rarely as possible because they fear that any materials, even apparently archival ones, might damage the object over time. Conservators' work sometimes overlaps with that of preparators, such as Jay's storage cradle for the horse skull. Conservators, though, have a master's degree in conservation, thereby defining their field through shared training and techniques. Their promotion of reversible adhesives and other archival materials, like the foam Jay used to line the cradle, has been gaining support among preparators. Traditionally, preparators have tended to prioritize researchers' rush to publish about specimens over the specimens' long-term well-being. But preparators often work with historic specimens that have been damaged by crude rock removal tools (e.g., hammers and chisels) and adhesives that degrade (e.g., crumbled plaster, rusty nails, and pest-nibbled glues made from flour or animal fat). As a result, many preparators want to avoid future damage by preparing today's fossils in more conservation-minded ways. Conflict between these seemingly irreconcilable priorities of the present and future underlies the cyanoacrylate controversy.

Preparators explain the properties of adhesives with reference to specimens' characteristics, suggesting that they organize their knowledge of materials by potential applications. Max, for example, prefers cyanoacrylate to Acryloid (a reversible adhesive) for his work with microfossils:

> Putting together a fossil that's in three pieces and altogether may be a millimeter wide, I want a glue with certain properties. And one of the beauties of cyanoacrylate is its ability to wick into cracks and practically disappear. . . . How are you going to get a drop of Acryloid in there? Acryloid does its work by the evaporation of the solvent . . . and that takes a certain amount of time and a certain amount of volume. What I need is something that I can apply what I call a microdot.

Max's justification demonstrates his knowledge of how the two kinds of adhesives work and how they align—or don't—with his goals for a fossil. His reasoning matches Jay's while assembling the mammal jaw. Bill, like many preparators, justified the use of cyanoacrylate based on confidence in his own skill and judgment: "If I get a joint cleaned and prepared so well that when it goes back together I would never want to take it apart again . . . or anyone else would ever want to take it apart, I don't see why I can't use a Krazy Glue on it." For Bill, the permanence of cyanoacrylate is appropriate for the timeless quality of his work. Furthermore, he explained, "Whether people in the future, a hundred years, two hundred years from now, will have problems with it, I don't know, but I feel my job right now is to prepare the fossil the best I can to get as much information out of it now as I can. What's going to happen in the future is anybody's guess." The question of current versus future utility is a foundation of preparators' decision making and this debate.

Conceptions of time for specimens are contentious (Wylie 2019b). Conservators and conservation-minded preparators argue that investing time in conservation techniques now ensures longer-lived specimens, and hence more future research for scientists. For example, preparator Charles justifies using reversible adhesives to enable flexible research methods:

> If in the future there's some kind of technology coming along that you want to study some aspect of the specimen and the glue gets in your way of doing that, if you use a glue that's reversible . . . you'll be able to get that glue out of there and undertake that study.

All adhesives change the results of geochemical analyses, such as carbon dating for more recent bones; they therefore inherently limit research possibilities. Charles, like many conservation-minded preparators, dismissed cyanoacrylate as "just a quick fix" and not an ethical or justifiable practice. Most scientists agree, because conserving fossils maximizes future research opportunities. But the pressures of career advancement and time-limited funding can push scientists to need researchable fossils *now*. In the cyanoacrylate controversy, preparators debated whether and how to compromise between these temporal priorities for specimens.

Universality versus Preparators' Right to Choose

For preparators, their choices of materials and methods are indicators of their expertise and control over their work. The passionate, surprisingly confrontational cyanoacrylate controversy challenged this value. Several preparators told me that the worst of the conflict revolved around Walter, the inventor of a cyanoacrylate product that I call Geo Glue. Walter told me that he is a longtime fossil collector and preparator, as a hobbyist and museum volunteer. While working in the adhesive industry, he patented several cyanoacrylate formulas, tested them on fossils at home, and founded a company to produce and sell them as Geo Glue.

When Walter started advertising Geo Glue at conferences in the 1980s, such as the Society for Vertebrate Paleontology (SVP), he did not sense a warm reception: "It upset several people within the paleontology prep business because their professors had said, 'We use polyvinyl acetate, we use polyvinyl butyral, we use plaster of paris, we use'—oh god, there was so many different chemistries used." Interestingly, not all preparators attend college, and they learn to prepare from preparators, not professors. These inaccuracies suggest Walter's lack of familiarity with preparators' training and values. His point was to portray the opponents of his product as resistant to change and thus obstructors of progress. For example, he wrote in an email to me, "The politics in the 'SVP' NIH [not invented here] mentality cripple our beautiful quest to find answers within our passion to know." Walter's dramatic phrasing captures his indignation at his product's rejection by some preparators. But he identifies a problem that many preparators agree with: the plurality of adhesives, which can complicate research and repair work because their use is not documented.

Preparators told me their skepticism about Geo Glue was a response to Walter's assertion of its universal utility. Jay mimicked Walter as saying Geo Glue was "all you need" in a prep lab so you should "throw away all your other stuff." Max explained Walter's single-option presentation as that of a businessperson, not a preparator: "[Walter] can be a very abrasive person and very opinionated. And he's a vendor, you know, he's selling a product." Max implied that Walter had a different motivation than preparators: making a profit, not necessarily preparing the best fossils. Another preparator told me that preparators suspect any mention of tools' or materials' brand names in presentations to be product placements, which they find offensive. This disapproval of marketing perhaps stems from preparators' suspicion of Walter's motivations for promoting Geo Glue as a capitalist rather than as an evidence-based advocate. Furthermore, most preparators are eager to exchange tips about materials. Profit seeking could pose a serious barrier to preparators' culture of information sharing.

Walter did not seem aware of preparators' disapproval of his advertising in the guise of information sharing. Instead, he understood his opponents' main criticism of Geo Glue, besides its novelty, to be its permanence—a concern he dismissed to me as irrelevant: "How many times, when you glue something together, are you going to take it apart? If you happen to know you're going to analyze something technically [i.e., geochemically], don't use this stuff. . . . But for day-to-day, everyday assembly, you're not going to analyze all that stuff." Walter argued for his product's universality not by denying its limitations on research methods but rather through appeals to efficiency. Many cyanoacrylate users share this view about the rarity of geochemical analyses relative to the overall number of prepared fossils.

Cyanoacrylate use may seem like a primarily technical debate, but the controversy is also inspired by social interactions. Preparator Anne explained why she is an ardent opponent of cyanoacrylate:

> It was talking with conservators and . . . there's a lot of back and forth with [Walter], who's marketing [Geo Glue] very aggressively with the Society [of Vertebrate Paleontology]. I know from personal experience that cyanoacrylates are not appropriate. They just simply don't work on certain things, and it's detrimental to our profession to promote this one adhesive that can actually be harmful to specimens.

In addition to conservators' and her own doubts about cyanoacrylate's functionality, Anne blamed Walter's forceful sales pitch for spurring her from mere disagreement to outspoken opposition. She fears for "our profession" as a potential victim of promoting cyanoacrylate, highlighting the importance of practices—and choosing them—to preparators' identity and reputation. "I always say, paleontology depends on adhesives. . . . And we're the ones making those decisions," Anne told me, emphasizing the scientific implications of preparators' judgment of tools and techniques. For Anne, using reversible adhesives helps preparators prepare good specimens, which is crucial for enabling good research and respect for the community of preparators.

Preparators blame individual personalities for escalating disagreements about cyanoacrylate. Jay described Walter and Anne as "like oil and water.

Or more like oil and fire." Their zealous opinions made them clash explosively, in Jay's terms. Max used the same metaphor to explain the conflict: "[Walter] mixed like oil and water with some of the folks here [in SVP], and they got just as crazy as he did. [*laughs*] So bring on the mediators!" Max was referring to an official attempt to calmly discuss the debate at the 2002 SVP meeting: "We actually had a special afternoon symposium regarding cyanoacrylates, and . . . they hired a professional mediator to oversee this meeting, trying to make sure everybody behaved themselves [*laughs*] and stayed in order and didn't get too crazy." Walter echoed Max's view of the symposium as a potentially unrestrained fight: "You have a monitor who keeps peace between divergent opinions. . . . Unfortunately [Anne]—you'd say the word 'cyanoacrylate' and it was like throwing a bomb. [*laughs*] She was just totally out of hand, I mean, just completely went crazy." Walter blamed his opponents for behaving badly, telling me that "it was an emotional diatribe . . . on their part." In contrast, Max said that "everybody behaved very well" at the symposium and the mediator was not needed. Regardless of how the symposium actually went, the controversy is widely perceived as a vicious dispute, and one that remains unresolved.

There are many debates on preparation techniques, but this one inflames more discord and leaves more scars than any other I heard about from preparators. As a result, Max distances himself from the debate: "I never cease to be amazed by how passionate preparators can be about materials they use, particularly the cyanoacrylate controversy. . . . They totally get crazy about this and, well, it's just glue, man! And these are fossils! Nothing to get that upset about." Due to this passion, Paul keeps quiet about his preference for cyanoacrylate. He told me, "I like cyanoacrylate as a glue. Some of these people would hate me for it! [*laughs*]," meaning other preparators at the 2010 SVP meeting. I witnessed why Paul kept quiet when a group of preparators and I were at a bar later that day. One preparator suggested that I ask the group about adhesives and thus start a discussion. Marc said dismissively, "We're all on the same page," meaning that it wouldn't be interesting to talk about because he assumed that the group, all friends, were staunch opponents of cyanoacrylate use. But that was not true; Paul was there. He looked at me and said quietly to the group that he used cyanoacrylate, as if it were a confession. The others teased him in a friendly way, showing their awareness of the issue's potential hostility by making fun of the tension. Paul did not smile, though, and looked uncomfortable. Independently, Bill described techniques as the basis of sharp social divisions among preparators: "If you use Krazy Glue, you can't be in their clique." Jay suspects that all preparators use cyanoacrylate in certain situations, as he does, but that this choice has become stigmatized and is now something that "nobody wants to admit." Perhaps another bullied victim of the controversy is Walter himself. Max explained that Walter "got beat up so bad for so many years by some of the preparators in various discussions that he just decided he wasn't going to come [to SVP] anymore." Despite the opposition, Walter's company continues to profitably sell Geo Glue.

Tempers cooled after the 2002 SVP symposium, and both sides added nuance to their arguments. Most preparators have settled in a use-if-it's-the-best-option stretch of a spectrum of cyanoacrylate approval. Of seventy-three respondents to my 2010 survey, only 14 percent used cyanoacrylate most often, while 56 percent used reversible adhesives most often, and 30 percent used both equally often. In response to the statement "Cyanoacrylate should never be used on fossils," only 15 percent of the respondents agreed or strongly agreed, while 52 percent disagreed or strongly disagreed (and 33 percent neither agreed nor disagreed). Thus only a small number of the respondents opposed all cyanoacrylate use, while half considered it useful in at least some cases. Surprisingly, a third of the respondents did not have strong feelings either way. This group was perhaps shocked by the battle lines drawn between the two extremes and avoided joining in the fray.

These diverse responses suggest that preparators value choosing among many possible techniques, preferring to use "what works" for each particular fossil rather than a universal protocol. Many claim to be open to any technique, if there are good reasons for it. This is a kind of relativism in that preparators don't believe there can be a gold standard technique that works for all fossils. However, they do believe that techniques are not all equally good. "If for some reason you wanted to use Elmer's glue to glue something together, you have to be able to justify that reason," Alan explained. Preserving justifiable flexibility, even to include a material Alan considers inappropriate for fossils (Elmer's glue), allows the consideration of multiple factors before choosing (or refusing) a technique. Marc agreed, saying, "If you have logically thought about the reason you make a choice between two different glues, cyanoacrylates or otherwise, that's awesome. That's what I really want in my lab." Max framed his decision making as context dependent: "I probably have a reputation among some of the folks here as being sort of a cyanoacrylate advocate. Which I am to a certain extent. Sometimes it's the best tool for the job." Sociologists Adele Clarke and Joan Fujimura's (1992) influential edited volume shows how research workers construct the rightness of tools by defining the tasks along with the values and goals for achieving those tasks. Preparators value their power to judge "the best tool for the job," thereby constructing their own tasks and priorities as well as assessing a tool's properties. This expertise to evaluate situations and decide how to respond to them is shared by craft workers (Sennett 2008) and professionals (Abbott 1988). I suggest that the cyanoacrylate controversy inspired hostility in part because preparators felt they had to defend that autonomy and identity. A few "oil and fire" personalities created conflict that somewhat obscured this main issue of preparators' power to choose from a plurality of potentially good techniques.

Like other controversies in science, this case illustrates groups' usually implicit ways of defining their conceptions of good practices, social order, and knowledge claims. For example, preparators discuss adhesives formally and informally, such as in conference talks, at social events, in the lab, and on the PrepList email list host. Surprisingly, these conversations employ a relatively consistent discourse style. I did not witness preparators speaking in the separate styles that sociologists G. Nigel Gilbert and Michael Mulkay (1984, chap. 3) documented among scientists: an "empiricist repertoire" that presents evidence as objective and a "contingent repertoire" for informal discussions about the realities of lab work. Preparators' speech register is relatively uniform, regardless of audience and context, and resembles the contingent repertoire by taking the form of stories of personal experience.

This speech style—particularly the lack of an empiricist repertoire—may serve to distinguish preparators from scientists.

Also, the cyanoacrylate controversy itself was enacted almost entirely through discussion, not through publications like most scientific controversies (e.g., Latour and Woolgar 1986). Latour (1987, 43) describes the transition of controversies from discussion to text as typical: "We go from conversation between a few people to texts that soon fortify themselves, fending off opposition by enrolling many other allies" such as through citations. But the cyanoacrylate controversy did not move into print. The oral-based nature of this controversy and thus this community reflects historian Derek de Solla Price's (1965) conclusion that the principal difference between scientists and "technologists" is that the former values writing publications while the latter values making objects. Furthermore, unlike many controversies, this one has not produced a "fact" or widely accepted conclusion. Instead, the détente between the two sides seems to have been achieved by continuing to allow preparators to choose their own materials and methods, without establishing community-wide protocols or bans. This preservation of local decision making thus reflects and shapes preparators' practices and identity, and, consequently, the specimens they prepare.

SPECIMEN PREPARATION AS CREATIVE PROBLEM SOLVING

Beyond Standards

Preparators pride themselves on their skill at assessing each fossil's features and adapting their work accordingly to produce visible, stable, researchable fossils. Likewise, when faced with a unique object, craft workers approach it with goals in mind, such as carving a straight table leg from a twisted tree branch. They evaluate the object and devise ways to make it achieve their goals. Preparators refer to this process as creative problem solving (Wylie 2015). Viewing research work as creative, adaptive, context-dependent problem solving highlights its dependence on situated judgment as well as the autonomy to act on one's judgment. Philosopher Thomas Kuhn (1996, 38) defines "puzzle-solving" as a crucial component of science, such that a scientist's main motivation is "the conviction that, if he is skillful enough, he will succeed in solving a puzzle that no one before has solved or solved so well." Problem solving in ways acceptable to a field and its paradigm indicates a practitioner's socialization in that field.

But rarely do scientists attribute creativity to technicians. In physics, scientists and technicians are perceived as, respectively, "creative puzzle-solvers on the one hand, and those who are passive, uncreative, and unskilled on the other" (Law 1994, 123). As a result, scientists often "delete the work of subordinates: to assume that technical or low-status work gets done 'automatically,' as if people were programmable devices" (Law 1994, 131). Labeling technicians as "passive, uncreative, and unskilled" justifies "deleting" their work, as scientists delete fossil preparators' work in publications (Wylie 2016). Solving problems seems to serve as a high-status ability reserved for scientists. Preparator Alan defines technicians as those who fail to participate in knowledge making, observing that some preparators

> have no curiosity about what the animal is and they don't contribute any information to the research team when that specimen is being studied, except what they reveal physically. If you're just going to work on that level, kind of an automaton, then yeah, I guess you're just a technician, not part of the research process.

Alan disapproves of automaton-like preparators because they contribute to the perception of preparators as "just a technician," while other preparators—like Alan himself—actively participate in scientists' interpretations of prepared fossils. Claiming creativity helps preparators distinguish themselves from low-status technicians and liken themselves to high-status scientists (Wylie 2015).

On the other hand, technicians outside science, such as those who repair refrigerators or copy machines, are often considered problem solvers (Henning 1998; Orr 1996). Many kinds of technicians report that the best training for their work is experience solving problems: "Since, almost by definition, problems involved unanticipated troubles, technicians found they had to piece together most of the information necessary for resolution from the situation itself" (Barley 1996, 425). Likewise, preparator Gary described the priorities that shape his problem-solving work: "What's the best way to solve this without compromising the integrity of the fossil or shortcutting conservation principles?" Understanding the many goals and constraints that shape a task, and acting accordingly, are key to expertise. To illustrate the importance of justifying problems and solutions, preparator Marc told a story to a group of preparators about a volunteer whose fossil was too large to fit under a microscope. To solve that problem, the volunteer picked up a hammer to break the fossil into smaller pieces. When Marc asked what he was doing, the volunteer was shocked at his own destructive plan. "We all get lost in our heads sometimes," Marc rationalized with a smile. Preparing specimens clearly requires solving problems, but not necessarily what scientists perceive as research problems.

Investigating the concept of "problem" reveals the situated work of defining and solving problems. "Puzzle-solving," according to anthropologist Tim Ingold (2000, 292–293), is not a standardized process but instead "is carried out within the context of involvement in a real world of persons, objects and relations." Fujimura (1996) likewise argues that scientists' success relies on their ability to construct "doable" problems and solutions, which are achievable as well as fit existing techniques, questions, and funding opportunities. This construction relies not just on knowledge or skill but also "articulation work: how to build and run laboratories, how to cultivate sponsors, how to manage and work with students and technicians, and how to negotiate with administrators" (Fujimura 1996, 185). Articulation work, also referred to as "housekeeping" (Garforth and Kerr 2010, 8) and "caretaking" (Knorr Cetina 1999, 38), is critical to the success of research communities. Yet it is considered low status and therefore made "invisible" (Fujimura 1996; Star and Strauss 1999). Despite its complexity and necessity, articulation work is not explicitly discussed, studied, or taught to science students (Star and Strauss 1999). If we recognize that "rational problem solving" is not objective or universal but instead specific to situation and culture (e.g., Lave 1988, 169), then problem solvers are expert judges of acceptable goals and practices. Presenting themselves as problem solvers as opposed to instruction followers can arguably promote preparators' expertise and elevate their status. It also allows them to adapt techniques, based on their skill and ingenuity, to prepare good specimens.

Intervention through Invention

Preparators take pride in their improvisational ability, a resourcefulness forced by unique objects and restrictive budgets. Walter criticized opponents of his Geo Glue for their narrow-mindedness, which he considered a serious insult: "I used to go crazy when I would have someone say, 'Well, we've never done it that way, consequently we're not going to do it.'" I imagine most preparators would dismiss such an accusation as untrue. As evidence of preparators' ongoing and open-minded search for good techniques, fossil labs often look like workshops, full of potentially useful objects (e.g., various containers or scraps of wood and metal) and purpose-built tools (chapter 3). Other repurposed materials include welders' magnifying goggles (which a few preparators wear) and sandblasters' garnet sand in specimen-holding sandboxes (because it is less dusty than common silica sand). The identification of factors as problems, such as inadequate vision and dusty sand, is just as variable and expertise dependent as the solutions.

Researchers tend to appreciate preparators' specimen-specific innovations. Researcher Frank described a beautifully preserved raptor skeleton that preparators in his lab completely dismantled bone by bone. They removed matrix from both the top and bottom of the thin rock slab containing the specimen, which lay curled on its side and flattened. Along the way, the preparators molded each side of the slab several times to create replicas that preserved data about the bones' location and articulation. "No other lab would have taken it so far," Frank said proudly, adding, "Taking it to the eleventh degree is what we like to do." Frank does not want preparators in his lab to do "boring," "routine" work; instead he thinks they should understand each specimen's scientific importance and create ways to tell "the most convincing scientific story," such as by accessing as much data as possible. As a researcher, Frank encourages preparators to develop techniques in order to gather more information than his competitor researchers. Bill, a preparator in Frank's lab, appreciates Frank's support for preparators' autonomy to generate new ideas: "[Frank] provides the money and the fossil and the equipment and the place to do it, and lets us figure out how to do it." As a result of this freedom, Bill has developed many techniques that he thinks might be novel, such as mailing a delicate fossil buried inside a box of sand to protect it.

Preparators consider most innovations to be welcome and uncontroversial. While preparing small, fragile fossils, Constance Van Beek (2011, 8) began to sharpen tool tips into specialized shapes to best remove matrix in particular situations, such as a "serrated blade," "hook," "cat claw," or "barb." The tips are thin needle-like cylinders of steel or tungsten carbide, and they fit into a pen-sized handle to create a ubiquitous preparation tool called a pin vise. Van Beek teaches other preparators to make these task-specific tool tips, and she published a rare paper to further disseminate the technique. Similarly, after volunteer Ken improved the design of plaster storage jackets, the Southern Museum hired him part time. Ken presented his technique at a conference and impressed Marc, who had previously made jackets at the Southern Museum: "He's done so many innovations. . . . His use of foam blocks for feet—you know, we were just taking gobs of fiberglass and balling them up [to become jacket feet], and it was all sort of slapdash and haphazard. . . . My jackets are not as pretty as the new guy's, for sure. His are just awesome." Marc praised Ken's jackets for being pretty, meaning carefully made. When comparing his own jacket design with Ken's, Marc sounded admiring rather than jealous or competitive. Preparators expect each other's practices to vary, and they're always on the lookout for good ideas. John explained, "There's no real, one right way to do anything in preparation, I don't think. And so that leaves a lot of room for people to come up creatively with their own solutions." Flexible practices allow—and perhaps require—innovation.

Outsiders to the preparator community seem unaware of the diversity of techniques and preparators' freedom to choose among them. For example, preparator Jay taught volunteer Derek how to make casts. One day when Jay was not at work, Derek asked staff preparator Kevin for help with a cast. Kevin said that he would have made the cast differently from the method that Jay had taught Derek, and Derek was surprised that two preparators would disagree. The next day, Derek told Jay that he had new ideas to try on the cast, thereby adopting Kevin's method. Jay and Kevin laughed at him dismissively, not because Derek had appropriated Kevin's technique, but because staff believe volunteers shouldn't propose techniques (chapter 2).

Preparators know that overlap is likely in a geographically distributed community of workers who are all designing techniques. Steve even thinks that there are no new inventions: "Everything comes around. Everything's been invented before." For instance, he occasionally uses the centuries-old method of hammer and chisel because in some cases he finds it more effective than modern tools, such as for removing extremely dense rock. Likewise, after Gary gave a conference talk describing how to repair bone surfaces by gluing thin veil cloth over them as an external support, Gary told me that ideas, like this technique, are rarely new:

> **Gary**: It's not a new technique. I didn't invent it, but I guarantee that 90 percent of people in that room had never even heard of it.
> **Caitlin**: Where did you hear about it?
> **Gary**: I invented it. But I wasn't the first to invent it.

To invent for Gary means creative problem solving, not necessarily novelty. But he finds creative problem solving inefficient: "We have enough creativity generally to invent things again, and again, and again. . . . But it's kind of a waste of time." Preparator Alan is also frustrated by reinvention: "So many people spend so much time reinventing the same wheel over and over again." He considers communication the solution to repetitive invention: "There were eight of us at [one museum] . . . so you'd problem solve and troubleshoot and just chat among one another. . . . We were able to do a lot of really neat innovating that way." Innovation can come from people working together, though rarely do many preparators work in one lab. The average number of people preparing fossils in sixty-nine survey respondents' labs was five (the median was three, the mode was one), which includes volunteers, who are not encouraged to innovate (chapter 2). So preparators' innovation typically comes from individuals' creative problem solving more often than from collaboration.

Perhaps because of their low numbers in most labs, preparators value collective brainstorming and methods sharing at conferences and on the PrepList. Tim, for example, supports communication among preparators and so does his researcher boss: "Over the years we've tried quite a few different things, and experimented and modified our techniques. And I've tried to share those at SVP meetings and the Preparators' Symposium.[1] So that's been nice. I think [Frank] really appreciates that too, that we're showing what we're doing here and getting the word out about interesting spins on ideas." Preparators tend to frame methods sharing as a service to each other and specimens rather than as a service to scientists. Most PrepList emails and conference talks are told as stories, narrating the speakers' personal encounters with problematic fossils and how they responded. Usually the approaches are widely applicable, such as Gary's "bone bandage" of glue and veil cloth. Preparators in peril email the PrepList, which "is devoted to the exchange [of] information, questions, opinions, etc. about preparation of vertebrate fossils. . . . Debate is encouraged for honing our knowledge and thinking skills, for truth-seeking, and for clarifying our perspectives" (Preparators' Resources 2020). On this informal forum, preparators describe their problems and then advice comes pouring in from other subscribers. The advice too comes in the form of storytelling about similar experiences and how the writers approached them. These stories almost always end well, with occasional mentions of failed techniques recounted as warnings to others. This generosity seems striking compared with scientists' tight-lipped world, where unpublished methods and results are typically closely guarded. Perhaps knowledge can be more freely shared in a community for which indicators of expertise do not involve publications or citation counts.

Only one preparator, as a unique exception, mentioned competition and proprietary methods:

> I would like to be known in the world of paleontology as one of the best preparators that has ever been. . . . [If] a preparator wants to come and visit, I would gladly show them how to do other things. But mainly I don't really spread out too much of my little secrets. I mean, there are many, many things

that we all know, [that] all the preparators know. But there's one or two things that *you* know.

Clearly preparators value the ability to design effective methods for the benefit of specimens and the preparator community as well as demonstrate individuals' skills. But they rarely guard these ideas as "little secrets."

The concept of innovation carries particularly positive connotations in the United States. For example, "framing agendas under the rubric of innovation and change is inevitably a strategic move, appropriating the positive value of the term for whatever the agenda to be pursued in its name might comprise" (Suchman and Bishop 2000, 331). The celebration of innovation has even inspired a countermovement among STS scholars to reframe technological work in terms of maintenance and care so as to emphasize the value of keeping technologies functioning over inventing new technologies (e.g., Puig de la Bellacasa 2011; Russell and Vinsel 2018, 2019). Innovation is valued as intellectual property and for keeping companies attuned to changing consumer demands, which are not concerns for preparators. Why then might innovation appeal to them? Sociologist Andrew Abbott (1988, 30) argues that professional groups' ability to assert control over certain tasks relies on "the power of the professions' knowledge systems, their abstracting ability to define old problems in new ways." Promoting their ability to adapt methods lends credence to preparators' control over their work. Furthermore, a professional group legitimizes the scope of its power in the workplace and society by claiming and enacting control, or "jurisdiction" (Abbott's term), over specific tasks. Preparators may describe their work as innovative and creative to highlight their expert decision making along with their jurisdiction over preparation work, thereby defining themselves as a professional and expert community.

The Limitations of Creativity

When preparators say that they admire creativity and that it is crucial to preparation work, they mean only certain kinds of creativity. In some cases, they consider creativity risky and therefore ill-advised. After all, if a new technique fails to solve a problem, the consequences can include damaged fossils, wasted time and materials, and lost credibility. At the 2010 SVP

Preparators' Committee meeting, attendees discussed their concern that sharing techniques through a proposed series of training workshops would threaten individuals' creativity. One preparator said he did not intend for workshops to "kill creativity" by standardizing methods but rather to point out pitfalls and help people avoid problematic techniques. Likewise, another noted that preparators sometimes "reinvent old bad things," which he suggested workshops could prevent. The concern expressed by many attendees was, as one put it, "creativity without rationale": inventing or choosing methods without justifying them. The proposed workshops have still not been established. Perhaps preparators' fears of limiting creativity by promoting training outweigh their desire to prevent "bad" practices.

But innovation is inherently risky. For instance, a scientist asked preparator Erica to mold and cast a delicate ceratopsian skull—a task she was not sure was possible without destroying the scientifically important specimen. She laboriously designed a network of small separate molds that would fit together to form a complete mold of the skull. As she applied this complex method, she was worried but optimistic: "Every day I was working with that thing, I was like, 'Please work.' Because you really don't know if it's ever going to." Not knowing the results of a time-consuming and potentially destructive task like molding, which also requires costly materials, means that Erica risked time and money as well as the fossil's safety in hopes of producing a mold and, from it, a cast. After four months of work, she succeeded, and was proud of her techniques and the resulting mold and cast. She later gave a conference talk about the project, complete with photos of her experimental mold and nerve-racking descriptions of carefully extracting the fossil from each of the mold's many parts. After listening to Erica's talk, volunteer Tom decided not to learn molding and casting. He exclaimed to me, "There were seventeen pieces to that mold!" Tom was impressed by Erica's skill and method—molds are typically two pieces and almost never as many as seventeen—but he was also so intimidated by the risks that he avoided molding altogether.

Most preparation tasks have less daunting uncertainty than Erica's mold. However, no preparators told me about ideas they tried that failed. Perhaps preparators forget such attempts because they don't document their methods, or perhaps they do not want to damage their pride or reputation by admitting to failed techniques. But for every successful innovation, there are surely many more that preparators reject. Preparing evidence, then, is a process of preparing practitioners' skills, priorities, and techniques as well as pieces of nature.

CONCLUSION: INVISIBILITY ALLOWS CREATIVITY

Fossils, as traces of past life, are rare and impressive objects. As specimens, fossils serve as enlightening evidence of the mechanisms of biology and geology. Learning about past life relies on the transformation of mysterious, incomplete, rock-encrusted objects in the field into specimens that can be seen, held, compared to other specimens, and trusted as a data source. To "clean" a specimen is to define it, because the boundary between a highly valued object and its inconvenient surroundings is not obvious and depends on its social and epistemic context. As anthropologist Mary Douglas (1966) argued, notions of clean and unclean, sacred and profane, or prepared and unprepared differ in different situations and communities. Preparing specimens involves defining those boundaries both epistemically and physically. These processes are requisite components of interpreting that object and its role in our knowledge about nature.

Everyday fossil preparation work reveals strikingly varied products—from cradles and casts to prepared fossils—which result from a diverse set of practices, such as searching, gluing, building, scraping, assessing, and discussing. Preparators' claims of creative problem solving further reflect the many ways in which they prepare nature into evidence. This case reinforces the view of evidence—and thus knowledge—as contingent and contextualized. It also sheds light on how workers' seemingly purely technical decisions about methods structure social roles as well as specimens that represent the physical world.

Preparators' autonomy over their practices may not be typical of science technicians, many of whom are expected to follow written protocols and document their work. Of course, craftwork is embedded in protocols too, such as knowing how to carry out incompletely described actions and applying skillful personal strategies that cause one technician's completion of a protocol to produce more desirable data than another's. But most technicians can't alter their techniques too much without threatening the reliability of the data they produce, which is supposed to be replicable by other people. In comparison, vertebrate fossils are usually rare, and are stored and restudied over centuries; they are not considered replicable. This view perhaps permits preparators the leeway to select and modify methods to match these diverse specimens, rather than try to standardize the methods or objects.

Also, crucially, preparators leave few written records. Lab notebooks and other written sources can be audited for fraud (e.g., historian Gerald Holton's [1978] reassessment of Robert Millikan's incompletely reported data in his famous 1909 oil-drop experiments to quantify the charge of an electron); the dearth of documentation about fossil preparation arguably prevents such accountability. Furthermore, because preparation methods are not part of researchers' papers, researchers don't get involved in it (despite the obvious influence of those methods on the physical appearance of the fossils described in the papers). This lack of record keeping and supervision grants preparators de facto power over their techniques. From this perspective, preparators' defense of their preferred glue becomes an indication of expertise and personal pride in their work as well as an assertion of their right to control how they prepare evidence. This invisibility thus enables preparators' autonomy in that scientists prioritize good specimens over standard or documented practices and practitioners. Preparators then use this autonomy as a defining characteristic of their community.