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Teaching Ichthyology Online with a Virtual Specimen Collection

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For generations, organismal biologists have learned their craft in hands-on laboratories that teach anatomy, evolution, natural history, systematics, and functional morphology through specimen collection, observation, comparison, and manipulation. Though these activities teach the comparative method that lies at the heart of our discipline, students without access to specimen collections have been excluded from this foundational experience. To fill that gap, we developed a virtual collection of photographs and 3D specimen models and designed entirely online versions of courses in ichthyology and systematics of fishes. The virtualization allows students to illustrate and compare specimens in online labs, identify species from different habitats using dichotomous keys, contextualize the relationships of species, recognize synapomorphies using a phylogeny, take online specimen-based practical exams, and help each other recognize adaptations and diagnostic features on threaded discussion boards. The classes built around the collection educate and provide university credit to students lacking access to similar courses, and their infrastructure allowed face-to-face instruction to shift online rapidly after 2020's novel coronavirus shut down our brick-and-mortar campus. While we may never be able to replicate the aroma of oil-laden alcohol online, specimen virtualization opens access to experiential learning to an underserved and widespread audience; allows new generations of students to develop crucial skills in observation, comparison, and inference; and affords substantial instructional resiliency when unexpected challenges arise.

I shall never forget the sense of power in dealing with things which I felt in beginning the more extended work on a group of animals. I had learned the art of comparing objects, which is the basis of the naturalist's work.

—Nathaniel Southgate Shaler, 1909

A famous anecdote about university education in centuries past recounts how the ichthyologist Louis Agassiz taught "the art of comparing objects" by setting objects from natural history collections before students with little instruction other than to "find out what you can, without damaging the specimen" (Shaler and Shaler, 1909: 97–100). Though Agassiz's student found the approach maddening at first, he complied and painstakingly described the morphology he observed, reassembled disassociated skeletons, and compared the anatomical structures of different species. In so doing, he participated actively in his own learning and as the quote above attests, he acquired the ability to discover new knowledge on his own.

In the instruction that he provided to Shaler, Agassiz continued a tradition of teaching anatomy and natural history through the comparative method that began with the ancient Greeks, resurged in the late Renaissance, and still continues (reviewed in Sanford et al., 2002). Present day classes in organismal biology worldwide use the comparative method to teach students inferential tasks, such as how to extrapolate an organism's ecology from its morphology, separate homology from analogy, infer degrees of relatedness among a set of specimens, or identify the shared derived characteristics uniting a group of organisms (Mayer, 1988; Singer et al., 2001; Petto and Mead, 2009). Most readers of this article will have taken such a class at some point in their careers, and indeed, the laboratory practical in a systematics or comparative anatomy class provides one of the foundational experiences on the way to becoming a professional ichthyologist or herpetologist. Who can forget the "thirty seconds of panic every three minutes" (pers. comm. by a former student), each time one confronts a new set of creatures laid out upon trays in a room perfumed with alcohol vapor, followed by the realization that one has learned something enduring and real from all the hours of study in the teaching laboratory?

Ever since Belon (1555) laid out his formal comparisons of the bones of a human and a bird or Tyson (1699) advocated the use of primates as substitute for human cadavers in the training of medical students, instructors have relied upon physical specimens when teaching the comparative method. The need to provide access to such specimens to students fueled much of the history of collection building, particularly among university-based collections (Pietsch and Anderson, 1997), and many institutions that value organismal biology maintain and teach with such collections in the present day. For example, specimen-based active-learning exercises fill the canonical lab manual used in ichthyology classes over last several decades (Cailliet et al., 1986). These exercises challenge students to dissect, measure, observe, and compare whole specimens and various portions of their anatomy, such as gonads, muscles, bones, and otoliths.

Yet, modern universities are changing rapidly, and the increasing proportion of students pursuing degrees online (Palvia et al., 2018) challenges instructors to find virtual alternatives to traditional laboratories. Prior to the SARS-CoV-

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2 pandemic, the electronic campus (Ecampus) at our own institution (Oregon State University) offered instruction annually to more than 24,000 students in more than 1,300 classes distributed among seventy degree programs, with more than 7,000 students completing their degrees entirely online (https://ecampus.oregonstate.edu, accessed 9 January 2020). During the pandemic, all 33,000 students at Oregon State pursued their education through remote or online delivery, with the date of a return to face-to-face instruction still months away more than a year after the initial closure. Clearly, the need to provide effective online training in organismal biology, natural history, and every other discipline has never been so acute.

Even before the pandemic, in Oregon State University's Department of Fisheries and Wildlife, more than half of degree-seeking students enrolled entirely online. Familial obligations bind many of these students to rural areas and require them to travel digitally to access higher education. Others are training for future careers while working outside of the commuting radius of a university. Students in the latter category include active-duty military personnel on deployment, high-school teachers looking to change careers, or people working seasonal jobs in remote areas. Many of these students will complete their programs without setting foot into a physical laboratory, and some will never visit the brick-and-mortar campus that will become their alma mater. Even face-to-face students in the modern university often take several courses online to circumvent scheduling conflicts, permit travel for extracurricular activities, allow them more time with their dependents during daylight hours, or take a class not offered at their home institution.

This new academic landscape poses substantial challenges to the instruction of any laboratory course, and particular difficulty to those classes that employ a comparative approach. Without specimens to compare, how is one to teach the comparative method? It would be simplest to conclude that this can't be done online and to focus on instructing face-to-face students. Yet, such a decision leaves many students without access to instruction and creates an unequal situation in which only those individuals able to physically relocate to a campus hosting a teaching collection can benefit from a course in comparative biology. Even among students enrolled at such a campus, not all have the capacity to return to the laboratory for extra practice, since many work part-time jobs and some bear responsibilities for childcare or eldercare. Such unequal access to a critical study resource can translate into unequal student success.

The development of online versions of successful educational programs can reduce such access barriers by globalizing educational opportunities and has the potential to help diversify student bodies (Moreira, 2016). That said, many other dimensions of access and privilege affect student recruitment, retention, and success (Yorke and Longden, 2004; Maher and Tetreault, 2013), with the online environment presenting particularly acute obstacles such as the difficulty in fostering a sense of belonging and engagement among geographically dispersed and disconnected students (Yorke, 2004). Improved access to courses and learning materials represents a necessary, but hardly sufficient, component of any overall strategy aimed at enhancing the representation of underserved populations in the academy and supporting their success.

To open online access to Oregon State University's (OSU) credit-bearing classes in Ichthyology and Systematics of Fishes, and to augment after-hours specimen access for students enrolled in face-to-face versions of the same, we developed a virtual version of the teaching collection of fishes at OSU and deployed it in 2016. Our decision to digitize builds upon successes in constructing virtual laboratories in other disciplines, most notably in introductory classes in chemistry (Hawkins and Phelps, 2013; Tatli and Ayas), engineering (Candelas-Herías et al., 2003), and biology (Breakey et al., 2008; Lewis, 2014). We also follow examples of the successful use of 3D specimen digitization to educate medical students about pathologies (Kalinski et al., 2009) or to allow the public to interact with rare fossils (Rahman et al., 2012). As became abundantly clear in 2020, the virtualization also afforded substantial flexibility in the modality of course delivery and allowed us to quickly adapt face-to-face classes to remote delivery when the novel coronavirus reconfigured the academic landscape.

Herein, we describe our approach to virtualizing the collection and deploying digital specimens to make online learning via the comparative method possible. We cover the construction of an original database, its population with two-dimensional photographs, subsequent enhancement via 3D surface scanning, and various ways that we have employed the resultant images and models in virtual lectures, labs, discussions, exams, and even a field trip. We conclude with some discussion of success and challenges and a look ahead to the future.

MATERIALS AND METHODS

Specimen selection and origin.—Most of the virtualized specimens originated within the Oregon State Ichthyology Collection (online at http://ichthyology.oregonstate.edu). Because virtual specimens do not degrade with repeated use, we were able to select the best individuals for imaging. These often originated in the research collection, but occasionally in the teaching collection, such a South American Lungfish (*Lepidosiren paradoxa*) that was apparently once a pet of Carl and Lenora Bond and their family (Nancy Bond Hemming, pers. comm., 1 July 2019). To incorporate important and rare species not represented in our collection, such as the Coelacanth (*Latimeria chalumnae*) or the Australian Lungfish (*Neoceratodus forsteri*), we requested express permission to use images of specimens held elsewhere from their respective curators. Because of the need to document copyright clearance for the use of each external image, we limited such requests to species from major branches of the fish phylogeny that otherwise lacked representation in the database.

Database interface.—Successful websites or web apps should allow users to access important information with low effort. For example, they should provide efficient link navigation and ensure that tools and elements of the site can adapt to user input, such as by making all content searchable or allowing advanced users (e.g., course instructors) to update the underlying data tables easily. Figure 1 illustrates how a database's multi-tier architecture can allow for a dynamic user experience that is also adaptable. In effect, the middleware translates user queries into requests for specific data and images stored in the cloud and then renders a webpage using

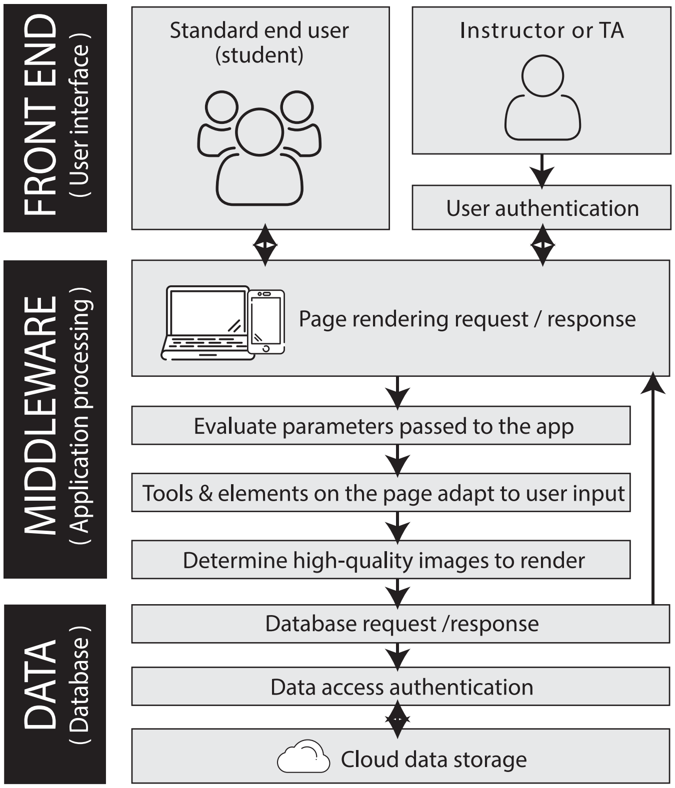

Fig. 1. Tiered application architecture diagram outlining the design of the virtual specimen collection. The collection's middleware processes user queries to retrieve relevant data and images from cloud storage, and then constructs a dynamic webpage displaying those data or allowing the user to modify the desired section of the database. (Credit: M. Kindred).

those data that responds to the user's needs. We designed the underlying architecture of our virtual specimen collection with these principles in mind.

Students and instructors access the images and data in the virtual specimen collection by logging into a custom website using their academic credentials. Once logged in, students can navigate to a page serving information on any taxon by clicking on its name in lists sorted by taxonomic hierarchy or by the week of the class. Students can also search for any taxon to head directly to its page. Each such page, such as the example in Figure 2, offers at least one image of the fish or fishes in question, plus information on habitat, trophic ecology, geographic range, reproduction, diversity, and key characteristics for identification. The database draws much of its ecological, geographic, and morphological information at the familial and ordinal level from the fifth edition of *Fishes of World* (Nelson et al., 2016), thanks to gracious permission of those authors to paraphrase extensively from their work. The underlying phylogeny mostly reflects Betancur-R et al. (2013), which was current at the time that we began database development.

Pages are organized hierarchically, and those for taxonomic levels above species automatically aggregate images from their daughter pages, such that the page for Salmonidae (a taxon of particular interest in Oregon) draws photographs from a dozen species. Each image also has its own unique URL that can be easily linked to an external webpage or embedded within any component of a course management system like Canvas or Blackboard. This link does not reference the specimen's identification directly, meaning that students cannot determine which species is depicted simply by right-clicking on the image. Because the images are not accessible via webcrawler, a reverse image search will also fail to reveal the correct identification. The database also includes a set of hidden images visible only to the course designers and instructors. These are intended for the online practical exams, where they can test the ability of students to identify unfamiliar specimens of species or higher taxa that they have studied.

Database construction.—From the student perspective, the easy user interface (UI) described above is probably the most important feature of the database design, and much initial development focused on creating simple ways for students to locate and navigate to information. However, the underlying architecture of the database holds even greater importance in ensuring the longevity and efficient expandability of the resource. A flexible relational database and programming configuration facilitates ongoing improvements as does an architecture that uses well-established information technology (IT) systems and common skill sets. If the designers construct such a database with technologies known to be reliably performant, simple to install and maintain, and widespread in use, it becomes much more likely that future developers will be able to pick up and continue the original work, particularly if the original designer has moved on to a new position. And indeed, our original designer (MK of the author list) has a new job and no longer holds direct responsibility for upgrades to the database.

In today's technological landscape, several powerful consumer-grade relational databases, such as PostreSQL, MariaDB, and MySQL meet the requirements described above. In combination with general-purpose scripting language (e.g., Perl or PHP), any of these would have yielded a software product able to be hosted on virtually any server and maintained by any developer with standard website development skills. For this virtual specimen collection, we chose a MySQL database paired with the PHP scripting language because several members of the programming team had experience in those platforms, and because some preexisting source code from a similar effort was available. Those portions of the code made it easy to commence review and testing of an initial version.

Some of a website's efficiency comes from the design of the links between the data that power it. To architect flexibility into the data model, we abstracted each piece of content as it was saved to the database and assigned identifying data points that slot the information into the proper spots in the website. For example, data from all levels of the taxonomic hierarchy are saved to the same table, and an index column identifies whether the data correspond to a family, genus, species, or any other taxonomic level. Each biological descriptor (size range, reproductive mode, geographic range, diagnostic characteristics, etc.) received its own indexed table.

Ichthyologists discover new information about the biology and relationships of fishes regularly, and classification changes frequently. Thus, the virtual collection's long-term success relies on the ability of the instructors to update information easily. To aid in content management, the developer produced a content inventory interface that allows

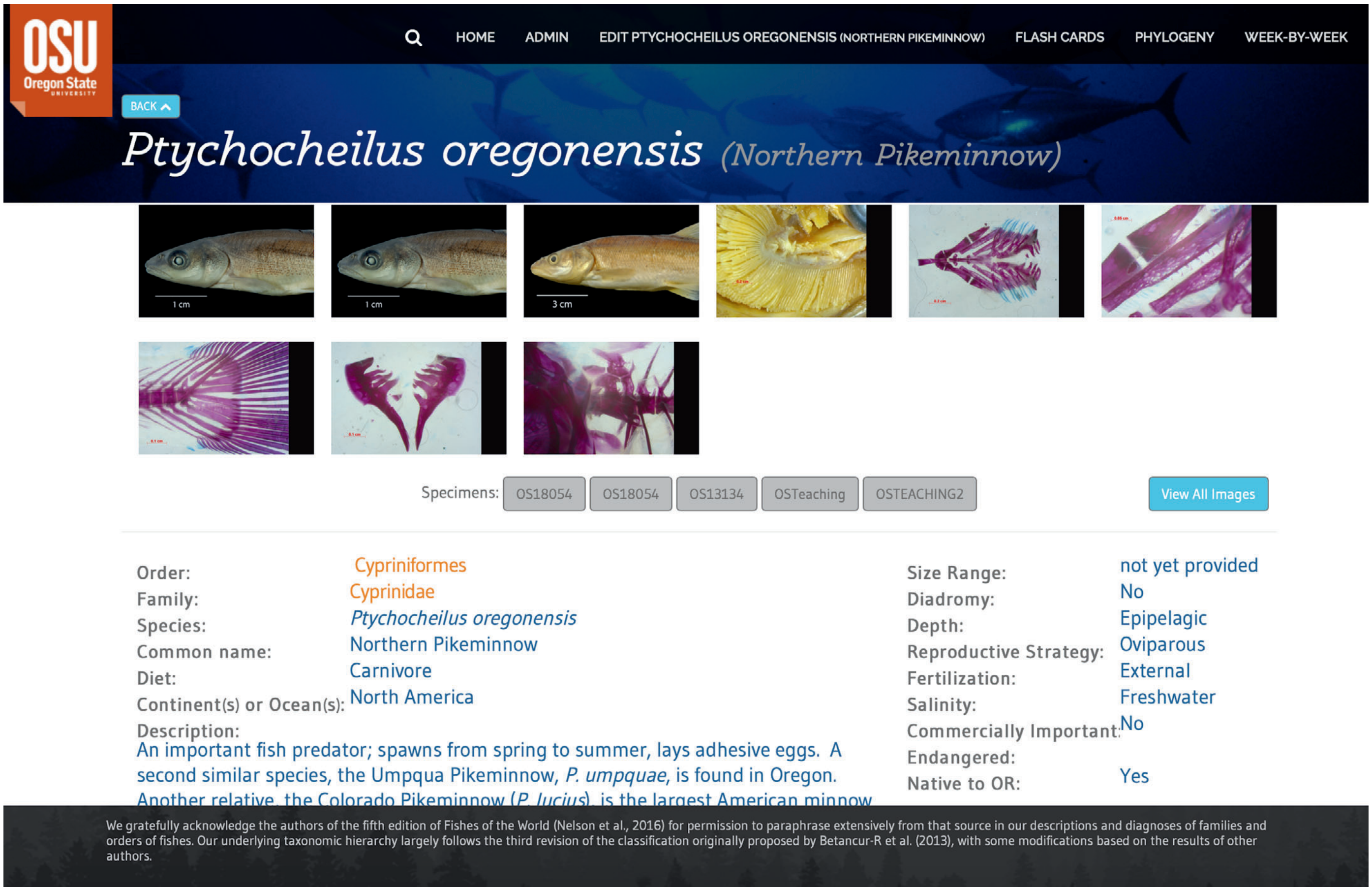

Fig. 2. The species page for *Ptychocheilus oregonensis* from the virtual specimen collection, including links to lateral views of alcohol-preserved specimens, a closeup of the gill rakers, and cleared and stained material. Clicking on any image pulls up a full-size version and some accompanying metadata, such as the species identification and the specimen's catalog number. Scrolling down reveals more textual information. (Credit: B. Sidlauskas).

the instructors to review uploaded data, view images for any taxon, and verify that fundamental details were saved. The interface can filter and sort the inventory quickly. Clicking the icon for "edit" brings up the content management screen for any taxon, whereupon the instructor can enter new data or update the existing information. Shifts in classification can be easily accommodated by changing the "parent" of any given taxon, such as by shifting a family from one order to another. New taxa can also be added to the database with a simple click, which brings up a blank data form for the instructor to populate. Instructors can upload and link photos to any taxon in the course database through a simple web interface, along with information about the photographer, the view, the specimen's catalog number, and the image's copyright information.

2D imaging.—To generate the large series of two-dimensional photographs that populate the virtual collection, we followed Sabaj Perez's (2009) image tank protocol, with postprocessing in Adobe Photoshop to place each specimen on a solid black background and add a scale bar. Since specimens vary widely in size, we contracted with a local glass company to construct immersion tanks in various sizes. Each of these tanks includes a pane of Starphire glass, a low-iron material typical used for storefronts and display cases, but which also provides high optical clarity for photography. Lighting involved ambient light and two freestanding LED arrays that could be positioned at will (Fig. 3). We employed a Nikon D90 DSLR camera with a 60mm macro lens on a tripod, though any modern camera with a lens capable of close focus would likely serve. Most images were captured at low ISO (e.g., 200) to reduce "grain" size in each image, with a relatively high F-stop (typically 16 or 18) to allow for adequate depth of field. These camera settings reduce the sensitivity of the image detector and the amount of light that passes onto the detector (respectively) and thus typically necessitate long exposure times (up to several seconds), even with supplemental lighting.

The database emphasizes lateral views, but it also includes close-ups or additional views in cases where these are critical for proper identification. Thus, catostomid specimens include views of the mouth and lips, and members of Gobiidae, Cyclopteridae, and some similar families such as Blenniidae include ventral views showing the presence or absence of the characteristic fused pelvic fins (Fig. 4). To produce many images in a relatively short time, we enlisted the help of nearly a dozen undergraduate photographers and developed written workflows to guide their efforts.

3D surface scanning.—While two-dimensional images can convey a great deal of information, they can obscure the true shape of specimens and reduce the visibility of key diagnostic

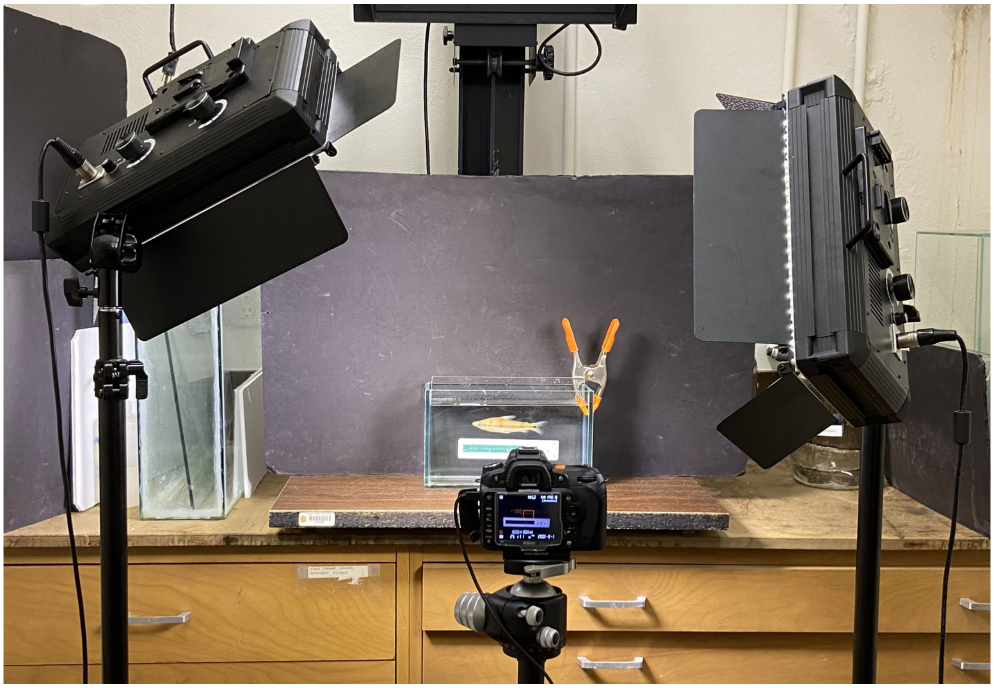

Fig. 3. The photography room at the Oregon State Ichthyology Collection, including photo tanks, LED arrays, camera, and tripod. (Credit: B. Sidlauskas).

Fig. 4. Paired lateral and ventral views of a Pacific Spiny Lumpsucker specimen (*Eumicrotremus orbis*, OS6725). (Credit: K. Knight).

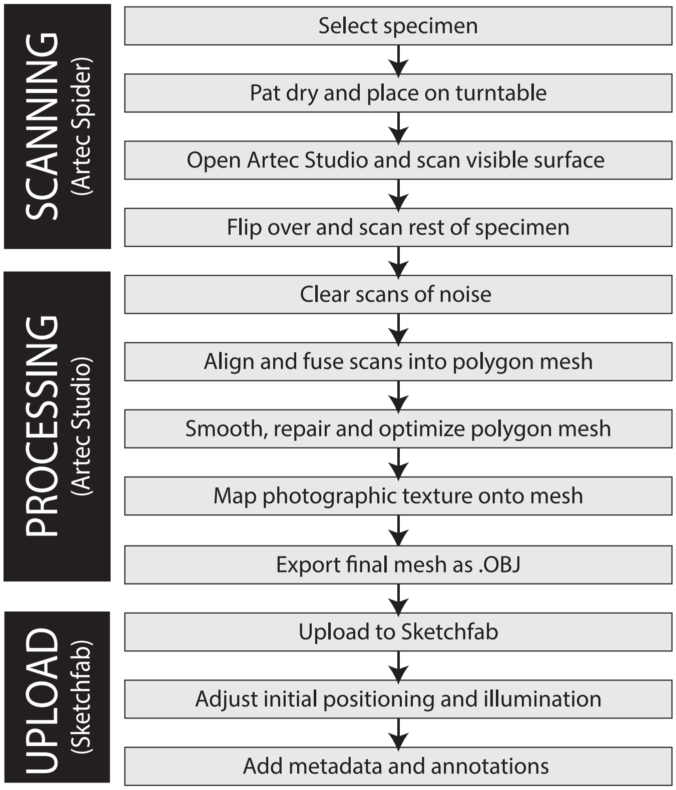

Fig. 5. Three-dimensional surface-scanning workflow. (Credit. N. Harper).

characteristics like mouth position and the presence of spines, barbels, and scutes. To improve the virtual representation of such anatomical features and to better illustrate the shape diversity of fishes generally, we began trials with structured light scanners. We eventually chose an Artec Spider over the major alternative (DAVID) because it was substantially faster, more accurate, and did not require careful calibration. Scanning with the DAVID scanner regularly took several hours per specimen, while the Artec Spider could scan a simple specimen like a cyprinid or chaetodontid in just a few minutes. The specifications for the computer used in post-production approximate those typical of gaming machines, with a high-end graphics card (NVIDIA GeForce GTX 1080 with 8GB dedicated RAM at 10 gbs), fast CPU (Intel i7-6800K @3.4 GHz, 6 processing cores), and 64 GB of RAM. As with most computing tasks, a faster processor (higher GHz) and more RAM will translate to better performance. Output file sizes were very large, and thus we moved files regularly to remote storage via Box. We hosted finished models on SketchFab (https://sketchfab.com/osuecampus/models) because of that platform's relatively low cost for academic institutions, and because the site automatically generates html code that allows easy insertion of each model into other applications. Figure 5 illustrates the workflow that guides a specimen through scanning, post-production, and final upload.

Overview of class deployment.—Students interact with images and 3D models of the virtualized specimens throughout the online courses, and indeed, most activities and assessments draw on the virtual collection in one form or another. The specimens feature most prominently in virtual labs and practical exams, but they also support discussion boards, recorded lectures, flashcards, and a virtual field trip.

Virtual laboratories.—Of all the course elements, the virtual specimen collection integrates most thoroughly with the weekly laboratories. Each of these presents the students with a series of a virtual lab stations requiring them to observe, compare, describe, draw, or hypothesize about the morphology of the pictured species and specimens. For example, the lab introducing embiotocid surfperches (a diverse and common family off the Oregon coast) asks the students to sketch and label the dorsal fin morphologies of four different species as an aid in learning their diagnoses. A similar station directs students to compare caudal peduncle shape, fin position, mouth size, and mouth orientation to separate four frequently confused cyprinid species. Importantly, the question prompts provide scaffolding that allows student discovery by telling the students what to compare, but not what the differences are. A meta-analysis (Alfieri et al., 2011) demonstrated that this "enhanced discovery" mode of instruction better assists student learning than either explicit instruction (lecturing) or the unassisted discovery approach exemplified by Agassiz's challenge to Shaler.

By drawing and labeling their observations (Fig. 6), students also produce study guides to which they have access during the practical exams and earn points toward their final grade by scanning or photographing their worksheets and uploading them weekly. The instructor grades these on the basis of overall clarity, thoroughness, and accuracy of observation, but not on artistic merit or on the correctness of inferential questions. For example, some stations ask students to infer the function of the morphologies that they observe, such as the rostrum of *Pristis*, the nozzles on the anal fins of some breeding embiotocid males, or the mental barbels of stomiids. Answers to such questions can earn full credit even if biologically incorrect, provided that they result from clear and consistent reasoning. The instructor also provides general feedback on elements that the students should re-examine with the help of a key released after each laboratory exercise comes due. Thus, the worksheets provide a low stakes assessment opportunity where the instructor can catch general problems with comprehension and provide individual feedback before the students need to demonstrate their mastery during practical exams. The success of enhanced discovery instruction depends on such feedback (Alfieri et al., 2011).

Discussion boards.—In face-to-face versions of the class, students complete lab worksheets in pairs or trios and thereby enjoy opportunities to learn from each other. That interaction is often key to student success by creating an informal peer support group, but it is harder to replicate in an online setting because the courses are asynchronous, often with students participating from different time zones. To help facilitate peer instruction through student–student interaction online, we implemented a "think-pair-share" (Lyman, 1987) technique through weekly discussion boards that require students to think individually about a topic and share ideas with classmates. Many of these boards draw on specimens from the virtual collection. For example, each week we use a photograph or model of an unfamiliar fish in a newly introduced order to seed a discussion about diagnostic morphologies. Students guess about its correct identification

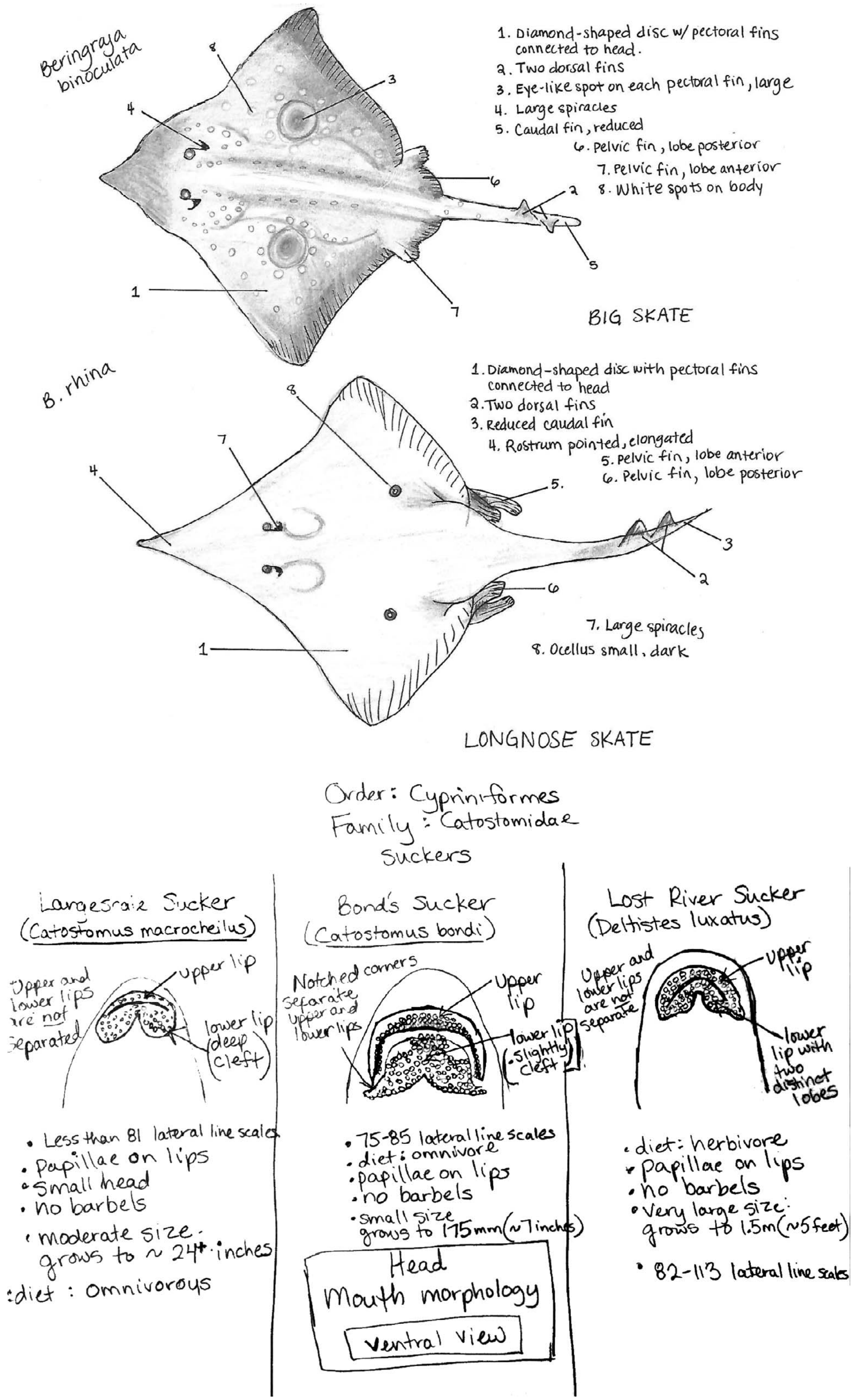

Fig. 6. Examples of worksheet pages completed by students in the online version of FW316, Systematics of Fishes. Drawings © 2020 K. Webber (upper panel) and © 2020 T. Chapman (lower panel), used with permission of their creators.

and justify their guess by citing the morphologies that they observe and tying those morphologies to diagnostic features listed in the virtual specimen collection. Other students comment on the identification and discuss additional diagnostic characters. Then, the student with the correct identification posts an image of another fish for the next student in line to identify. These discussions are mostly led by the students, with minimal interruption by the instructor, allowing each student to freely explore their knowledge of diagnostic characters in a low stress, peer-driven environment. Though these boards cannot fully substitute for the experience of working with a lab partner, they do make the class feel a little less isolating, and for the most engaged students, they provide a way to collaborate with other students to achieve a deeper contextualization and understanding of the course material.

Virtual field trips.—Students in the face-to-face version of the Systematics of Fishes class often cite the two class field trips as among their favorite and most effective elements of the course. One of these (a taxonomic scavenger hunt at the Oregon Coast Aquarium) was easy to translate to remote delivery: students simply visit an aquarium in their part of the world, or that failing, a pet shop or fish market. With the onset of the coronavirus and closure of such facilities, webcams at the Monterey Bay Aquarium, Georgia Aquarium, and elsewhere have allowed this activity to migrate entirely online. The fish collection trip to various aquatic habitats near Oregon State University provided a much greater challenge during online course development.

We tackled this endeavor with the understanding that some elements of the field collection experience were impossible to replicate online. In particular, there was no reasonable way for online students to capture and euthanize live fishes as part of the course. There are a host of ethical and legal impediments barring IACUC approval of such an activity online because there is no way for the class instructors to supervise the students directly. Instead, we provided the students with instructions on how to perform these steps, videos of people capturing fishes, photographs of the location of capture, and immediately post-euthanization photographs of fishes captured in various habitats.

With these tools at their disposal, the online students can still do a lot. For example, they practice filling out field notes based on their view of the habitat in the photos and the video, and they practice keying out the fishes from the photographs using the same resources that the face-to-face students do. A group project challenges students to work together to compile lists of the species encountered in different habitats and to compare and contrast which species seem suited to fast flowing versus slow or stagnant water. The online students even practice taking tissue samples, though unfortunately not on real fishes. Rather, we ask them to practice on multicolored fishy candy, under the pretense that these are specimens of genus "Suecichthys," recently introduced to the US from their native range in Sweden. The students prepare tissue tags, cut samples from the right side of their specimen, photograph the vouchers and place the finished tissue samples and vouchers in appropriately labeled vessels. This is not quite as good as actually learning to cut samples off of tiny fishes with even tinier scissors, but it gets the students most of the way there, and it definitely teaches the importance of correct labeling, which we posit is a far more important skill.

Lectures.—Though much of online learning works best when students can interact directly with the material in labs, discussions, and field trips, lectures can still assist comprehension. Lectures convey information concisely, provide students with context for the lab exercises and discussions, and let them verify their understanding of the take-home lessons from course interactives. Lectures also help to convey the designer's personality and excitement about the course. When paired with messages of welcome and encouragement and personal engagement in discussions, lectures can help online learners feel less disconnected from their instructors (Dolan et al., 2017). For these reasons, we do use lectures in both online courses.

Several different pieces of technology help us to deliver lectures to students as far away from Oregon as Japan, Guam, and Afghanistan. Most frequently, we use Adobe Presenter or Camtasia to narrate a series of PowerPoint slides. Adobe Presenter is a slightly older piece of software that functions as a PowerPoint plugin. It has some nice features such as the ability to set up clicker-style student response questions within a presentation, or to re-record just a single slide's worth of narration if a presentation needs editing. Camtasia can as also serve as a PowerPoint plugin, but functions more efficiently as a screencasting solution and proves particularly useful when the presenter wants to switch between PowerPoint and another program during a recording. Camtasia also has a powerful suite of features for drawing on screen during the lecture, which can really help to call attention to particular elements of the presentation, given that one cannot simply point at the screen. Though most of our lectures were recorded originally in Presenter, we are moving towards Camtasia for newer creations.

When constructing online lectures, we eventually realized that PowerPoint slides sometimes fail to convey information in ways that students comprehend easily. Information density can become too great for students to know where to focus, and in general information retention seems low when slideshows are the primary method of delivery. Recently, we have been finding much greater success by replicating the more traditional chalk-and-board style of teaching with a tool called a lightboard (Birdwell and Peshkin, 2015; Skibinski et al., 2015). This device achieves remarkable results with very simple construction. The lecturer stands behind a large pane of the same high clarity (low-iron) glass that we use in our photo tanks, and in front of a black curtain while facing a digital video camera. They write and sketch on the glass using colored markers while narrating. During post-processing, the image is reversed left to right, meaning that the students will see the finished image in the correct orientation. Colors can also be enhanced, and elements of the drawing process accelerated in post-production.

Flashcards.—Though the mere existence of the virtual specimen collection goes a long way towards equalizing access, students still benefit from instruction in how to use the resource effectively. To provide some scaffolding for online study, we created a flashcard module that pulls random images from the class database and automatically generates multiple choice questions about their proper identification. The goal of the online flashcard module was to mimic the informal peer study techniques employed by students in the face-to-face campus course who quiz each other on species identification.

Exams.—Each practical exam presents students with twenty virtual stations displaying one or more fishes and asks a series of questions about their identification, natural history, relationships, biogeography, or conservation. The exams emphasize fish identification (a key skill for fisheries professionals), and many stations closely parallel questions asked in the weekly worksheets. Many stations also ask a question emphasizing comparisons and connections among the specimens outside of those drawn during the weekly labs. For example, a station might display *Pomoxis annularis* (White Crappie), *Acipenser transmontanus* (White Sturgeon), and *Prosopium williamsoni* (Mountain Whitefish) and ask the students to identify the thread linking the English common names of the all the species, and to name another species that follows the pattern (e.g., White Shark). Other questions might ask the students to select the specimen on display with the most dissimilar diet from the others, to pick out all that were encountered during the field trip, to list all that possess cycloid scales, to identify the order to which an unfamiliar fish belongs, or to name a synapomorphy of the least inclusive group containing all the specimens on display. These kinds of questions challenge the students to demonstrate their ability to apply the comparative method, and to respond to questions that require information synthesis, rather than simple repetition of answers already in their notes. To allow students to focus on understanding the relationships between pieces of information, rather than on rote memorization of diagnoses and names, the exams are completely open note, but timed tightly enough that students still need to study and organize their notes *a priori*.

RESULTS

Specimen selection, 2D scanning, and database population.—At the time of this writing, the virtual collection contains more than 1,000 flat images spanning about 300 species in over 200 genera, of which Figure 7 shows a representative sample. We add more images periodically, prioritizing specimens of taxa that students have found challenging to identify or visualize. Since not all undergraduate assistants have had prior experience with ichthyology or photography, we found that course instructors were best suited to selecting the specimens in the best condition, or in which the diagnostic features were most clearly visible. Even with optimal specimens, variance in student proficiency in photography led to variance in image quality. The biggest problems occurred with photographs that were out of focus, underexposed, with the specimen filling a tiny portion of the field of view, or with the fins folded against the body. Images of small diagnostic morphologies were most prone to being out of focus, likely due to variance in student familiarity with the key structures. The most common problem in postproduction involved deletion of entire fins or parts of fins during the process of placing each specimen on a uniform black background, or omission of the scale bar. Explicit workflows with photographic examples, pins in diagnostic features, and screenshots of each step reduce such error, but even with such resources, mistakes still happen. See, for example, the diversity of scale bars (Fig. 7), which resulted from an ambiguous step in the workflow. Instructor review provides an important quality control step to filter out more serious errors prior to database upload and to send specimens back to the assistants for another try when necessary.

3D scanning.—At the time of this writing, we have completed scans of about 50 specimens of nearly as many species. Many of the final scans from the Artec Spider beautifully represent the original specimens and provide students with access to 3D models that can be freely rotated and zoomed (Fig. 8, see also supplementary videos; see Data Accessibility). Unfortunately, the equipment needed to produce and process such scans is not cheap. After the dust settled with discounts and auxiliary gear, we spent around $23,000 on the Artec Spider, and another $3,000 on a workstation to run the postprocessing software. Unless one already has a powerful computer on hand, the workstation is a non-negotiable cost. Model production requires substantial post-processing to clean, align, and fuse multiple scans of a specimen, no matter which scanner one chooses. Prospective users should also keep in mind that the massive project files turned out to require hundreds of gigabytes of storage. We ultimately ended up using Oregon State University's Box subscription to store and share these large files but went through several protocols before settling on that workflow.

For rigid specimens, post-processing was fairly straightforward, as the software can easily detect and align physical landmarks. Soft or non-rigid specimens presented many more challenges because they often shifted position slightly during scanning, and thus forced the software to shift the resulting data to align the scans. This comes at a price in time, and non-rigid specimens took substantially more time to process. Once we practiced and refined the technique, we found that many fish specimens can be scanned and processed in about an hour, with about 80% of that time spent waiting for the software during post-processing. More difficult specimens such as large individuals (acipenserids, selachiians), floppy specimens (pleuronectiforms, batoids), or specimens with thin fins or filamentous projections (siluriforms, *Pterois*), can take as long as three hours. Filiform fishes and most anguilliform and depressiform species have proven elusive because their shape changes too greatly when the specimen is flipped over to allow the ventral surface to be scanned. The current generation of the scanning software has been unable to align and fuse the dorsal and ventral views of such elongate and flexible specimens. That said, initial trials with another Artec Scanner (the Leo) and new versions of the scanning software suggest that this scanner might be able to handle those species.

Some specimens turned out to possess optical properties that interfere with the reflected light that the scanner needs to construct its model. For example, high transparency specimens (*Centriscus*, some gymnotiforms such as *Gymnorhamphichthys*) let most of the light pass through, and black specimens (many ceratioid anglerfishes) absorb all the light. Highly reflective specimens (marine hatchetfishes such as *Argyropelecus*) bounce back too much light and confuse the scanner as soon as its perspective changes. Coating specimens with an opaque, neutrally colored powder such as chalk dust (Mathys et al., 2015), or the alternate digitization technique of photogrammetry (Mathys et al., 2019), may offer feasible paths forward for digitization of these challenging specimens.

Lectures.—Perhaps because the technique forces instructors to slow down, or perhaps because it prompts students to create their own drawings while following the video, the lightboard presentations seem to enhance comprehension of the most challenging material in the courses. For example, conveying the structure of the teleost skull has proven to be a consistent challenge, despite the construction of what we thought was a clear PowerPoint animation that built up a diagrammatic version of the skull gradually, and paired it

Fig. 7. Two-dimensional images from the virtual specimen collection. Species and specimens pictured: *Cymatogaster aggregata* (OS5910), *Dendrochirus* sp. (OS teaching collection), *Lepomis macrochirus* (OS18438), *Oncorhynchus tshawytscha* (OS16943), *Parophrys vetulus* (OS898), *Hydrolagus colliei* (OS1942), *Percopsis transmontana* (OS17965), *Catostomus bondi* (OS16985), and *Lepisosteus oculatus* (OS teaching collection). (Credit: M. Burns, K. Knight, and M. Vazquez).

Fig. 8. Still images of 3D models for *Leptagonus frenatus* (OS17247) and *Chaetodon fremblii* (OS5698). See the supplementary videos for examples of these and other models being manipulated in three dimensions (see Data Accessibility). (Credit: L. Carr, N. Harper, and M. Leppin).

with an exercise in which students colored in matching elements of a salmon cranium. We recently converted that lecture to the lightboard format (available at https://perma.cc/MQ47-EGUH) and received some positive student feedback and subjectively fewer requests for extra help. Given that encouraging result, we also constructed a lightboard video updating our presentation of jaw origins (still shot in Fig. 9, full video available at https://perma.cc/BY3R-Y7UC) to reflect recent advances from comparative development (Kuratani, 2012; Oisi et al., 2013).

When constructing online lectures using either a lightboard or screencasting solution, instructors should strive to keep lectures as short as possible, with the optimum length possibly as brief as five minutes for lectures that might be watched on mobile devices (Thomson et al., 2014). While lectures as brief as YouTube clips may not be feasible in most classroom settings, there is substantial value in keeping each

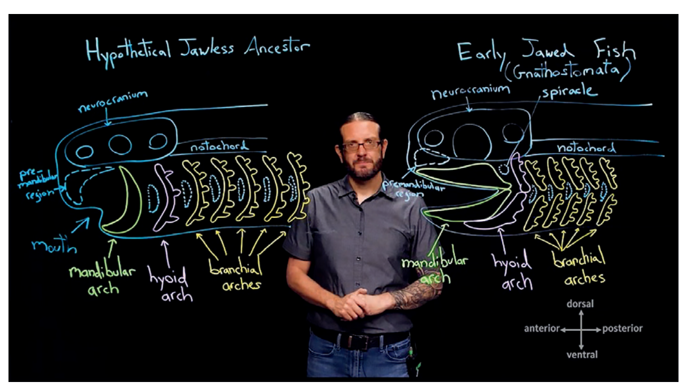

Fig. 9. Image capture from a lightboard presentation in the online version of FW315, Ichthyology. (Credit: B. Sidlauskas).

video to under 15 minutes in length, and ideally under 10. It is difficult to sustain one's focus on a non-interactive video for longer than this, as information fatigue sets in quickly. These durations seem brief, but because the lectures are recorded without a live audience, the natural pauses in which students may ask questions, or in which the instructor consults their notes are absent. We have found that prerecorded lectures cover the same amount of material as a live lecture in about half the time, particularly if the instructor scripts the lecture. Scripting makes the lectures seem more polished, and greatly facilitates closed-captioning or translation to other languages. Breaking lectures into smaller, easily digestible chunks also makes it easy for students to locate information later and to review the most challenging sections during their preparation for exams.

Exams.—Translating practical exams to the online format proved straightforward but time consuming. The biggest challenge lay in producing enough images that the exams could display specimens other than the ones visible to the students during the weekly labs and in the student-facing portions of the virtual specimen collection. Truth be told, we ended up reusing some images and are still building up the set of specimens designated exclusively for exams. This challenge has been most acute with the 3D scans, since each scan represents several hours of work. Even so, we have begun integrating those scans into exams.

It also proved challenging to generate 2D test images that highlighted key diagnostic features without providing students with a major clue to the correct species identification. Students enrolled in the face-to-face class must learn which diagnostic characters differentiate superficially similar taxa, such as by knowing (without instructor prompting) to examine the pelvic fins for fusion to identify whether a test specimen belongs to Gobiidae or Blenniidae. This type of question can be difficult to replicate using 2D images because the presence of an additional photo of the pelvic fins in ventral view provides a major clue about the correct identification. We tried to remedy this by photographing multiple angles and images of each specimen, regardless of whether the images highlighted diagnostic characters or not, but the endeavor proved to be too time consuming and we abandoned it. Inclusion of more 3D models has the potential to create a test taking experience that more closely replicates the face-to-face experience.

Interestingly, our greatest success in testing with the 3D specimens to date has occurred in the biology-focused Ichthyology class, rather than the taxonomy-focused Systematics of Fishes class. The 3D scans have greatly enhanced the unit dealing with locomotion and functional morphology, which emphasizes how different body plans adapt fishes to different swimming and predation styles. The exam on this unit includes a multi-part short answer question juxtaposing two fishes with very different swimming modes, such as a carangid and a cottid, or *Esox* versus *Chaetodon*. The question asks the student to compare and contrast the probable locomotion of the two species, to explain how their body morphology adapts each to that locomotory mode, and to hypothesize about the likely diet of each species. In comparison to flat images, the 3D models greatly improve the ability of the students to visualize the aspects of morphology needed to answer the question fully, such as the body's surface area and cross-sectional area, and the size, shape, and placement of the fins. The beauty of this question lies in that it challenges students to apply their knowledge to examples other than the ones discussed in the lecture and that the instructor can refresh it regularly by swapping one of the models for another. Such updates have become necessary with the rise of websites like Course Hero, Kloofers, and Quizlet. While these sites ostensibly provide a place for students to share lecture notes and study guides, in practice they are rife with copies of old exams, often complete with answer keys. While we regularly scan these sites for such material and request removal when we find it, we are always at least one step behind the students in that race.

DISCUSSION

Successes and challenges.—Face-to-face and online students at Oregon State University now enjoy access to a virtual specimen collection, with the students on the Corvallis campus using the virtual specimens primarily as an after-hours study aid, and the online students interacting exclusively with the virtual collection during labs, discussions, and practical exams. Though much room remains for expansion of the database and enhancement of the linked courses, the online courses fill an otherwise unoccupied niche in the educational landscape.

The virtualization has opened access to specimen-based learning to the underserved online segment of the student population. Thanks to this virtualization, students raising families in rural Oregon, stationed overseas, employed as fisheries observers in Alaska, or enrolled at universities that have jettisoned their programs in organismal biology can still learn ichthyology, fish identification, phylogenetics, morphology, and the comparative method. The included fieldwork simulation reduces barriers to participation for students otherwise unable to engage in such activities, such as those with a mobility impairment (Giles et al., 2020). Even students enrolled at the Corvallis campus who normally enjoy access to the physical specimens during scheduled laboratory sessions benefit, because the virtual collection is available at any hour, even during a global pandemic.

One might reasonably ask whether online and face-to-face versions of the classes produce similar student success. Alas, a statistical comparison here is impossible because of the strict restriction on using learning outcomes in human subjects without the express consent of those students. We can say only that online and face-to-face versions of both courses have enrolled students who submit impressive exams, respond cogently to discussion and essay prompts, submit detailed and accurate worksheets to the virtual lab assignments, and provide positive feedback about their experience. It is clearly possible to learn a great deal from both versions of these courses.

Despite these successes, it is also important to acknowledge the limitations of the online experience, particularly those that stem from incomplete virtualization. Despite the thousands of hours of work underlying the class database, the total number of specimens available to the online students is still much smaller than that available to the face-to-face students. Students with access to the physical specimens can also physically manipulate specimens during labs and exams, such as to open the mouth to check the teeth of a characiform, or to feel along the ventrum of a clupeid for the telltale scutes. The 3D scans do a better job than still images at replicating some of those experiences but have not completely bridged the gap. For example, we introduced the concept of a “Mystery Box” as a whimsical bonus question, taking inspiration from a similar approach used by Adam Summers at the University of Washington. Students reach inside the box (a giant paper-maché ceratioid) and attempt to identify the specimen therein using only their sense of touch. At least until virtual-reality technology makes another massive leap forward, that memorable experience will remain out of the reach of online students.

The course versions also differ in the ease of access to the instructor. In face-to-face lab sessions, the instructor and teaching assistants can easily circulate among the students and offer suggestions and friendly corrections in real time. They can also easily pull aside struggling students for pep talks and extra help, and our experience suggests that those informal interactions can substantially improve student morale and performance. The asynchronous nature of the online format impedes such interaction, even though we provide feedback to students through discussion board comments, email, and video messages. We are investigating several possible options to further guide student learning, such as gamifying a study strategy using a skill tree format or automating banks of practice questions.

Future directions.—In the years to come, we envision several expansions to the course and its database that should improve student success or allow additional courses to use the resource. One of the most important will involve greater integration with the wealth of CT-scanned specimens that have recently become available on Morphosource (Boyer et al., 2016; https://perma.cc/K4SY-7T2U). That resource houses open-access CT scan data for thousands of specimens, including ~3,000 specimens of fishes, ~2,000 of reptiles, and ~1,000 of amphibians at the time of this writing. Several of the current laboratories in the Systematics of Fishes class teach skeletal anatomy using images of cleared and stained specimens. Instructing these sections has proven challenging without being able to manipulate the skeletal specimens. For example, it is hard to demonstrate the position and function of the cypriniform kinethmoid without rotating the fish or pulling open the jaw.

One potential solution to this problem is to construct virtual anatomical models for students to dissect, manipulate, and explore online (see Manzano et al., 2015). For distance-learning students who might not otherwise have a means to engage in specimen dissection, the opportunity to dissect or manipulate a specimen virtually would provide an opportunity for the kind of exploratory learning that many of us take for granted but is difficult to replicate online. While virtual experiences of this kind cannot fully replace real world experiences, they do offer the benefit of repeatability (digital specimens are never damaged as a result of dissection), low cost, and the potential for great taxonomic breadth of specimens. Labeled models can be paired with XROMM videos to give students a look into how the anatomy functions in a living organism (Brainerd et al., 2010; Gidmark et al., 2012).

The future direct addition of 3D specimen models (whether surface scans or CT-based) to the virtual collection exemplifies a website expansion that will be made possible by the flexibility in the database’s architecture. The model is already poised to store the actual metadata for the digital model. Following the insertion of a new identifier to signify “3D model” content type, the records could be indexed as info related to the model (such the URL linking to an embedded viewer). Alternatively, if we decide to store each digital 3D model itself in the same infrastructure as the website, it would be possible to devise a suitable storage architecture to accommodate the voluminous datafiles. Addition of a simple “View 3D Specimen” link would integrate 3D viewing into the extant user interface. We look forward to the functionality that the integrated 3D viewer will bring and anticipate improved active learning opportunities for the students once those new elements of the database are in place. For example, we will be able to juxtapose models side by side, display 2D and 3D versions of the same species simultaneously, or allow annotations (labels) to be toggled between different versions. That latter functionality would allow an instructor to use the same model to teach and test comprehension of terms simply by swapping the informative set of labels with a numbered list. Tighter integration with the course database would also help automate the creation of online flash cards and study guides for each week of a course, or to easily sort the models into taxonomic bins.

Informal conversations with online and on-campus students suggest that many make heavy use of the automated flashcards. Though the current module helps students practice identification skills, it lacks the capacity to replicate test questions that require specimen comparisons. Thus, we are planning future development in this area, such as the creation of a module that will automatically create comparative questions. For example, such a module could pull three random fishes from the database and ask which two are most closely related, which inhabit marine environments, or which possess a Weberian apparatus. Such questions would closely approximate the kinds of questions likely to be asked on a practical exam, and help students practice that testing procedure before being tossed to the wolf-eels and lionfishes for the first time.

3D printing of accurate models can also enhance instruction in anatomy and evolution. Structures printed at enlarged scales give students a macroscopic assist to studying minute structures and supplement exercises that would otherwise rely entirely on microscopy. For example, a team in our department used printed models to train undergraduates to identify salamander limb bones within owl pellets. Online students who have access to 3D printers (on their own or through a public library) can print anatomical models for themselves, but even without creating a physical representation, digital models can be used in much the same ways as physical specimens for teaching. David Blackburn’s lab at the University of Florida, for example, maintains a Sketchfab site with a virtual collection for Herpetology (curated by Rachel Keeffe, https://skfb.ly/6FXvV), as well as reconstructions of soft and hard tissues in several species of burrowing frogs (e.g., *Hemisus guineensis*, https://skfb.ly/6yJAM).

Any interested course designer could create their own digital teaching collection using the CT data that are already publicly available on Morphosource, including rare taxa that would be extremely difficult to acquire in the real world (Gidmark, 2019; Staab, 2019). Many datasets are available as pre-made 3D models (http://bit.ly/MeshSource), and many more are available as CT image stacks. Constructing a 3D

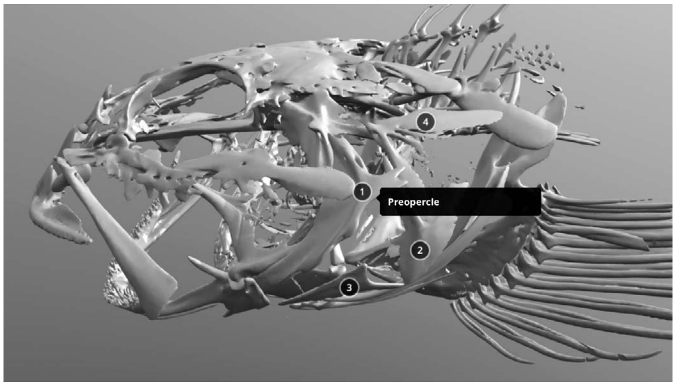

Fig. 10. Annotated skull model of *Artedius lateralis* (OS6720) from CT scan data collected at the Karel F. Liem Imaging Facility at Friday Harbor, Washington. See the supplementary videos to view this model in motion (see Data Accessibility). (Credit: T. Buser and A. Summers).

model from image stacks can be accomplished with any reasonably up-to-date computer and at no monetary cost using one of the myriad open-source software packages capable of processing and analyzing CT data. Buser et al. (2020) describe a step-by-step workflow for processing CT data using only open source, cross-platform programs to create 3D models and visualizations such as that shown in Figure 10, which we use to help students learn to identify the bones of the opercular series (see also supplementary video; see Data Accessibility). Using such a workflow, educators can model whole skeletons or individual bones from any species for which such CT data are available and even instruct students in how to make models for themselves.

Larval imaging represents another needed avenue of expansion, as almost all of the specimens currently pictured in the class database are adults or post-metamorphosis juveniles. Fish larvae can of course differ wildly from the adults, and the courses currently capture almost none of that diversity outside of discussions of leptocephali, the metamorphosis of flatfishes, and a general lecture on larval morphology and ecology. We anticipate adding larval images to the existing database structure, which should actualize another online course on larval identification without needing to create a new database from scratch.

The database structure itself could benefit from some revision, particularly with respect to improved integration of phylogenetic information. As currently constructed, the database accurately captures the hierarchy of taxonomic classification, but it does not integrate phylogenetic information natively. Changes to the course phylogeny therefore require manual editing of any taxa that have changed taxonomic rank or placement, and redesign of associated graphics. If we were designing this again from scratch, we probably would have integrated a phylogeny viewer directly into the database, ideally with functionality that would allow the instructor to drag nodes to new placements and automatically update graphics throughout the course.

Finally, the most important needed update to the database involves creation of an open-access edition. Currently the database requires login credentials that demonstrate that the user is part of Oregon State University. In the sense that the university uses course tuition to help pay for the development of resources like these, the existence of the enrollment wall made sense initially. Now that the database is functional, we are exploring options for opening access to instructors and students outside of our institution. In so doing, we anticipate being able to greatly increase the number of students and instructors who can benefit, while enlisting the aid of other scholars and teachers to expand the taxonomic coverage and the number of images available in the database.

***Advice on rapid virtualization.*—**The coronavirus pandemic broke during the review and revision of this paper and prompted several inquiries about how to virtualize an organismal biology class quickly. Had we been in that situation, we likely would have relied upon images already digitized and available on the internet to flesh out weekly labs. To prevent the use of reverse image searching during tests, we would have focused our initial digitization efforts on images destined for inclusion in exams and would have refrained from posting these publicly outside of the online course. We would have assigned the next highest priority to range-restricted taxa common in our region. For example, cypriniform species tend to have relatively narrow ranges, and the species common in the Pacific Northwest differ substantially from those in the Southwest, Midwest, or points further east. Instructors elsewhere would have been unlikely to image or scan our locally endemic species (*Oregonicththys crameri*, *Catostomus bondi*, etc.), and students in our geographic region need to learn to identify those taxa in order to secure jobs with state agencies. The collection of 3D surface scans digitized during the pandemic by Jessica Arbour to support her ichthyology course at Middle Tennessee State University (https://perma.cc/NQ6U-ZBWU) represents an excellent example of a locally focused virtualization effort designed to meet the immediate needs of a specific course. It also provides a resource that other instructors can draw upon to diversify their own courses and indeed, we have incorporated a few of her scans in our most recent offering. By working together and sharing resources, we can improve everyone's instruction and avoid needing to scramble so frantically the next time that disaster strikes.

***Is the future entirely virtual?*—**During the discussion that followed the symposium presentation in Snowbird, one noted professor suggested that our approach bore the danger of convincing universities to do away with teaching collections entirely. Why spend the money on storing and curating specimens if someone else will make them available for free? While we claim no ability to predict the actions of university administrators, we can certainly state that such a decision would represent a grave mistake. Despite the impressive technological advances that make virtualization possible, it is currently not possible to replicate fully the rich experience associated with access to a physical specimen collection. The tactile experience that helps students to understand differences in spine and scale types, the ability to dissect specimens or manipulate them freely under a microscope, and even the ability to fully understand the massive size differences among species have so far proven difficult or impossible to replicate online. Effective demonstrations of within-species variation have also proven elusive because of the great amount of effort needed to digitize each individual fish. In a physical lab, it is just as easy for the instructor to lay out a jar with fifty specimens as it is to lay out one, but no such economy exists online. Fifty virtual specimens imply fifty times the effort of one. This factor alone makes it clear that no online representation of a teaching collection will ever be able to fully replace the real thing, or at least not in the lifetime of anyone alive at the time that we write this paper.

Despite the limitations inherent in virtualization, we still argue that the effort has proven exceptionally worthwhile. Rather than replacing the physical collections, the virtual collections augment them, and provide even greater justification for the continued curation of the brown pickled fishes that have proven their ability to teach us so much. Not only can they tell us nearly infinite stories about how vertebrate life has thrived wherever water exists on our beautiful planet, they can teach us how to look more closely, compare more carefully, and think more deeply about the natural patterns all around us. That process of learning how to think was the greatest gift that Agassiz and his specimens gave to his student Shaler. The virtual collection offers the same bequest to students who have never before enjoyed such an opportunity. Rather than lamenting what might be missing from the experience, we should remember that a glass partially full can still quench the thirst of a student following their own journey of discovery.

DATA ACCESSIBILITY

Supplemental material is available at https://www.ichthyologyandherpetology.org/t2020031.

1. Screencast of a surface-scanned model of OS17247 *Leptagonus frenatus* (credit: L. Carr, N. Harper, and M. Leppin).
2. Screencast of a surface-scanned model of OS5698 *Chaetodon fremblii* (credit: L. Carr, N. Harper, and M. Leppin).
3. Screencast of a surface-scanned model of OS18514 *Hypostomus taphorni* (credit: L. Carr, N. Harper, and M. Leppin).
4. Screencast of a CT-scanned and annotated model of OS6720 *Artedius lateralis* (credit: T. Buser and A. Summers).

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