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Teaching Ichthyology Online with a Virtual Specimen Collection
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Abstract:	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.

Symposium Contribution:

Teaching Ichthyology Online with a Virtual Specimen Collection

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Suggested Running Head: Virtual Specimen Collection

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3

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22 inference, and affords substantial instructional resiliency when unexpected challenges
23 arise.

24

25 Key words: active learning; comparative method; digitization; discovery learning; natural
26 history collection, pedagogy; undergraduate education

27

28 *"I shall never forget the sense of power in dealing with things which I felt in beginning the*
29 *more extended work on a group of animals. I had learned the art of comparing objects, which*
30 *is the basis of the naturalist's work."* — Nathaniel Southgate Shaler, 1909

31

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

41 In the instruction that he provided to Shaler, Agassiz continued a tradition of
42 teaching anatomy and natural history through the comparative method that began with the
43 ancient Greeks, resurged in the late Renaissance and still continues (reviewed in Sanford et
44 al., 2002). Present day classes in organismal biology worldwide use the comparative
45 method to teach students inferential tasks, such as how to extrapolate an organism’s
46 ecology from its morphology, separate homology from analogy, infer degrees of relatedness

47 among a set of specimens, or identify the shared derived characteristics uniting a group of
48 organisms (Mayer, 1988; Singer et al., 2001; Petto and Mead, 2009). Most readers of this
49 article will have taken such a class at some point in their careers, and indeed, the
50 laboratory practical in a systematics or comparative anatomy class provides one of the
51 foundational experiences on the way to becoming a professional ichthyologist or
52 herpetologist. Who can forget the “thirty seconds of panic every three minutes” (pers.
53 comm by a former student), each time one confronts a new set of creatures laid out upon
54 trays in a room perfumed with alcohol vapor, followed by the realization that one has
55 learned something enduring and real from all the hours of study in the teaching laboratory?

56 Ever since Belon (1955) laid out his formal comparisons of the bones of a human
57 and a bird or Tyson (1699) advocated the use of primates as substitute for human cadavers
58 in the training of medical students, instructors have relied upon physical specimens when
59 teaching the comparative method. The need to provide access to such specimens to
60 students fueled much of the history of collection building, particularly among university-
61 based collections (Pietsch and Anderson Jr., 1997) and many institutions that value
62 organismal biology maintain and teach with such collections in the present day. For
63 example, specimen-based active-learning exercises fill the canonical lab manual used in
64 ichthyology classes over last several decades (Cailliet et al., 1986). These exercises
65 challenge students to dissect, measure, observe and compare whole specimens and various
66 portions of their anatomy, such as gonads, muscles, bones and otoliths.

67 Yet, modern universities are changing rapidly, and the increasing proportion of
68 students pursuing degrees online (Palvia et al., 2018) challenges instructors to find virtual
69 alternatives to traditional laboratories. Prior to the SARS-CoV-2 pandemic, the electronic

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

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

90 This new academic landscape poses substantial challenges to the instruction of any
91 laboratory course, and particular difficulty to those classes that employ a comparative
92 approach. Without specimens to compare, how is one to teach the comparative method? It

93 would be simplest to conclude that this can't be done online, and to focus on instructing
94 face-to-face students. Yet, such a decision leaves many students without access to
95 instruction and creates an unequal situation in which only those individuals able to
96 physically relocate to a campus hosting a teaching collection can benefit from a course in
97 comparative biology. Even among students enrolled at such a campus, not all have the
98 capacity to return to the laboratory for extra practice, since many work part-time jobs, and
99 some bear responsibilities for childcare or eldercare. Such unequal access to a critical
100 study resource can translate into unequal student success.

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

111 To open online access to credit-bearing classes in Ichthyology and Systematics of
112 Fishes, and to augment after-hours specimen access for students enrolled in face-to-face
113 versions of the same, we developed a virtual version of the teaching collection of fishes at
114 Oregon State University and deployed it in 2016. Our decision to digitize builds upon
115 successes in constructing virtual laboratories in other disciplines, most notably in

116 introductory classes in chemistry (Hawkins and Phelps, 2013; Zeynep and Alipasa, 2013),
117 engineering (Candelas-Herías et al., 2003) and biology (Breakey et al., 2008; Lewis, 2014).
118 We also follow examples of the successful use of 3D specimen digitation to educate medical
119 students about pathologies (Kalinski et al., 2009) or to allow the public to interact with rare
120 fossils (Rahman et al., 2012). As became abundantly clear in 2020, the virtualization also
121 afforded substantial flexibility in the modality of course delivery and allowed us to quickly
122 adapt face-to-face classes to remote delivery when the novel coronavirus reconfigured the
123 academic landscape.

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

131

132 **MATERIAL AND METHODS**

133

134 **Specimen selection and origin.**— Most of the virtualized specimens originated within the
135 Oregon State Ichthyology Collection (online at <http://ichthyology.oregonstate.edu>).
136 Because virtual specimens do not degrade with repeated use, we were able to select the
137 best individuals for imaging. These often originated in the research collection, but
138 occasionally in the teaching collection, such a South American Lungfish (*Lepidosiren*

139 *paradoxa*) that was apparently once a pet of Carl and Lenora Bond and their family (pers.
140 Comm., Nancy Bond Hemming on July 1, 2019). To incorporate important and rare species
141 not represented in our collection, such as the Coelacanth (*Latimeria chalumnae*) or the
142 Australian Lungfish (*Neoceratodus forsteri*) we requested express permission to use images
143 of specimens held elsewhere from their respective curators. Because of the need to
144 document copyright clearance for the use of each external image, we limited such requests
145 to species from major branches of the fish phylogeny that otherwise lacked representation
146 in the database.

147

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

158 Students and instructors access the images and data in the virtual specimen
159 collection by logging into a custom website using their academic credentials. Once logged
160 in, students can navigate to a page serving information on any taxon by clicking on its name
161 in lists sorted by taxonomic hierarchy or by the week of the class. Students can also search

162 for any taxon to head directly to its page. Each such page, such as the example in Figure 2,
163 offers at least one image of the fish or fishes in question, plus information on habitat,
164 trophic ecology, geographic range, reproduction, diversity, and key characteristics for
165 identification. The database draws much of its ecological, geographic and morphological
166 information at the familial and ordinal level from the 5th edition of Fishes of World (Nelson
167 et al., 2016), thanks to gracious permission of those authors to paraphrase extensively from
168 their work. The underlying phylogeny mostly reflects Betancur-R et al. (2013), which was
169 current at the time that we began database development.

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

182
183 **Database construction.**— From the student perspective, the easy user interface (UI)
184 described above is probably the most important feature of the database design, and much

185 initial development focused on creating simple ways for students to locate and navigate to
186 information. However, the underlying architecture of the database holds even greater
187 importance in ensuring the longevity and efficient expandability of the resource. A flexible
188 relational database and programming configuration facilitates ongoing improvements as
189 does an architecture that uses well established information technology (IT) systems and
190 common skillsets. If the designers construct such a database with technologies known to
191 be reliably performant, simple to install and maintain, and widespread in use, it becomes
192 much more likely that future developers will be able to pick up and continue the original
193 work, particularly if the original designer has moved on to a new position. And indeed, our
194 original designer (MK of the author list) has a new job and no longer holds direct
195 responsibility for upgrades to the database.

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

205 Some of a website's efficiency comes from the design of the links between the data
206 that power it. To architect flexibility into the data model, we abstracted each piece of
207 content as it was saved to the database and assigned identifying data points that slot the

208 information into the proper spots in the website. For example, data from all levels of the
209 taxonomic hierarchy are saved to the same table, and an index column identifies whether
210 the data correspond to a family, genus, species, or any other taxonomic level. Each
211 biological descriptor (size range, reproductive mode, geographic range, diagnostic
212 characteristics, etc.) received its own indexed table.

213 Ichthyologists discover new information about the biology and relationships of
214 fishes regularly, and classification changes frequently. Thus, the virtual collection's long-
215 term success relies on the ability of the instructors to update information easily. To aid in
216 content management, the developer produced a content inventory interface that allows the
217 instructors to review uploaded data, view images for any taxon and verify that fundamental
218 details were saved. The interface can filter and sort the inventory quickly. Clicking the icon
219 for "edit" brings up the content management screen for any taxon, whereupon the
220 instructor can enter new data or update the existing information. Shifts in classification
221 can be easily accommodated by changing the "parent" of any given taxon, such as by
222 shifting a family from one order to another. New taxa can also be added to the database
223 with a simple click, which brings up a blank data form for the instructor to populate.
224 Instructors can upload and link photos to any taxon in the course database through a
225 simple web interface, along with information about the photographer, the view, the
226 specimen's catalog number, and the image's copyright information.

227

228 **2D imaging.**— To generate the large series of two dimensional photographs that populate
229 the virtual collection, we followed Sabaj Perez's (2009) image tank protocol, with
230 postprocessing in Adobe Photoshop to place each specimen on a solid black background

231 and add a scale bar. Since specimens vary widely in size, we contracted with a local glass
232 company to construct immersion tanks in various sizes. Each of these tanks includes a
233 pane of Starphire glass, a low-iron material typical used for storefronts and display cases,
234 but which also provides high optical clarity for photography. Lighting involved ambient
235 light and two freestanding LED arrays that could be positioned at will (Fig. 3). We
236 employed a Nikon D90 DSLR camera with a 60mm macro lens on a tripod, though any
237 modern camera with a lens capable of close focus would likely serve. Most images were
238 captured at low ISO (e.g., 200) to reduce “grain” size in each image, with a relatively high F-
239 stop (typically 16 or 18) to allow for adequate depth of field. These camera settings reduce
240 the sensitivity of the image detector and the amount of light that passes onto the detector
241 (respectively) and thus typically necessitate long exposure times (up to several seconds),
242 even with supplemental lighting.

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

250

251 **3D surface scanning.**— While two dimensional images can convey a great deal of
252 information, they can obscure the true shape of specimens and reduce the visibility of key
253 diagnostic characteristics like mouth position, and the presence of spines, barbels and

254 scutes. To improve the virtual representation of such anatomical features and to better
255 illustrate the shape diversity of fishes generally, we began trials with structured light
256 scanners. We eventually chose an Artec Spider over the major alternative (DAVID) because
257 it was substantially faster, more accurate and did not require careful calibration. Scanning
258 with the DAVID scanner regularly took several hours per specimen, while the Artec Spider
259 could scan a simple specimen like a cyprinid or chaetodontid in just a few minutes. The
260 specifications for the computer used in post-production approximate those typical of
261 gaming machines, with a high-end graphics card (NVIDIA GeForce GTX 1080 with 8GB
262 dedicated RAM at 10 gbs), fast CPU (Intel i7-6800K @3.4 GHz, 6 processing cores), 64 GB of
263 RAM and a 500GB solid-state hard drive. As with most computing tasks, a faster processor
264 (higher GHz) and more RAM will translate to better performance. Output file sizes are very
265 large, and thus we moved files regularly to remote storage via Box. We hosted finished
266 models on SketchFab (<https://sketchfab.com/osuecampus/models>) because of that
267 platform's relatively low cost for academic institutions, and because the site automatically
268 generates html code that allows easy insertion of each model into other applications.
269 Figure 5 illustrates the workflow that guides a specimen through scanning, postproduction
270 and final upload.

271

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

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

292 By drawing and labelling their observations (Fig. 6), students also produce study
293 guides to which they have access during the practical exams and earn points towards their
294 final grade by scanning or photographing their worksheets and uploading them weekly.
295 The instructor grades these on the basis of overall clarity, thoroughness, and accuracy of
296 observation, but not on artistic merit or on the correctness of inferential questions. For
297 example, some stations ask students to infer the function of the morphologies that they
298 observe, such as the rostrum of *Pristis*, the nozzles on the anal fins of some breeding
299 embiotocid males, or the mental barbels of stomiids. Answers to such questions can earn

300 full credit even if biologically incorrect, provided that they result from clear and consistent
301 reasoning. The instructor also provides general feedback on elements that the students
302 should re-examine with the help of a key released after each laboratory exercise comes
303 due. Thus, the worksheets provide a low stakes assessment opportunity where the
304 instructor can catch general problems with comprehension and provide individual
305 feedback before the students need to demonstrate their mastery during practical exams.
306 The success of enhanced discovery instruction depends on such feedback (Alfieri et al.,
307 2011).

308

309 **Discussion boards.**— In face-to-face versions of the class, students complete lab
310 worksheets in pairs or trios and thereby enjoy opportunities to learn from each other. That
311 interaction is often key to student success by creating an informal peer support group, but
312 it is harder to replicate in an online setting because the courses are asynchronous, often
313 with students participating from different time zones. To help facilitate peer instruction
314 through student-student interaction online, we implemented a “think-pair-share” (Lyman,
315 1987) technique through weekly discussion boards that require students to think
316 individually about a topic and share ideas with classmates. Many of these boards draw on
317 specimens from the virtual collection. For example, each week we use a photograph or
318 model of an unfamiliar fish in a newly introduced order to seed a discussion about
319 diagnostic morphologies. Students guess about its correct identification and justify their
320 guess by citing the morphologies that they observe and tying those morphologies to
321 diagnostic features listed in the virtual specimen collection. Other students comment on the
322 identification and discuss additional diagnostic characters. Then, the student with the

323 correct identification posts an image of another fish for the next student in line to identify.
324 These discussions are mostly led by the students, with minimal interruption by the
325 instructor, allowing each student to freely explore their knowledge of diagnostic characters
326 in a low stress, peer driven environment. Though these boards cannot fully substitute for
327 the experience of working with a lab partner, they do make the class feel a little less
328 isolating, and for the most engaged students, they provide a way to collaborate with other
329 students to achieve a deeper contextualization and understanding of the course material.

330

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

340 We tackled this endeavor with the understanding that some elements of the field
341 collection experience were impossible to replicate online. In particular, there was no
342 reasonable way for online students to capture and euthanize live fishes as part of the
343 course. There are a host of ethical and legal impediments barring IACUC approval of such
344 an activity online because there is no way for the class instructors to supervise the students
345 directly. Instead we provide the students with instructions on how to perform these steps,

346 videos of people capturing fishes, photographs of the location of capture, and immediately
347 post-euthanization photographs of fishes captured in various habitats.

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

363

364 **Lectures.**— Though much of online learning works best when students can interact
365 directly with the material in labs, discussions, and field trips, lectures can still assist
366 comprehension. Lecture convey information concisely, provide students with context for
367 the lab exercises and discussions and let them verify their understanding of the take-home
368 lessons from course interactives. Lectures also help to convey the designer’s personality

369 and excitement about the course. When paired with messages of welcome and
370 encouragement and personal engagement in discussions, lectures can help online learners
371 feel less disconnected from their instructors (Dolan et al., 2017). For these reasons, we do
372 use lectures in both online courses.

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

386 When constructing online lectures, we eventually realized that PowerPoint slides
387 sometimes fail to convey information in ways that students comprehend easily.
388 Information density can become too great for students to know where to focus, and in
389 general information retention seems low when PowerPoints are the primary method of
390 delivery. Recently, we have been finding much greater success by replicating the more
391 traditional chalk-and-board style of teaching with a tool called a lightboard (Birdwell and

392 Peshkin, 2015; Skibinski et al., 2015). This device achieves remarkable results with very
393 simple construction. The lecturer stands behind a large pane of the same high clarity (low-
394 iron) glass that we use in our photo tanks, and in front of a black curtain while facing a
395 digital video camera. They write and sketch on the glass using colored markers while
396 narrating. During post-processing, the image is reversed left to right, meaning that the
397 students will see the finished image in the correct orientation. Colors can also be enhanced,
398 and elements of the drawing process accelerated in post-production.

399

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

407

408 **Exams.**— Each practical exam presents students with twenty virtual stations displaying
409 one or more fishes, and asks a series of questions about their identification, natural history,
410 relationships, biogeography, or conservation. The exams emphasize fish identification (a
411 key skill for fisheries professionals), and many stations closely parallel questions asked in
412 the weekly worksheets. Many stations also ask a question emphasizing comparisons and
413 connections among the specimens outside of those drawn during the weekly labs. For
414 example, a station might display *Pomoxis annularis* (White Crappie), *Acipenser*

415 *transmontanus* (White Sturgeon) and *Prosopium williamsoni* (Mountain Whitefish) and ask
416 the students to identify the thread linking the English common names of the all the species,
417 and to name another species that follows the pattern (e.g., White Shark). Other questions
418 might ask the students to select the specimen on display with the most dissimilar diet from
419 the others, to pick out all that were encountered during the field trip, to list all that possess
420 cycloid scales, to identify the order to which an unfamiliar fish belongs, or to name a
421 synapomorphy of the least inclusive group containing all the specimens on display. These
422 kinds of questions challenge the students to demonstrate their ability to apply the
423 comparative method, and to respond to questions that require information synthesis,
424 rather than simple repetition of answers already in their notes. To allow students to focus
425 on understanding the relationships between pieces of information, rather than on rote
426 memorization of diagnoses and names, the exams are completely open note, but timed
427 tightly enough that students still need to study and organize their notes *a priori*.

428

429 **RESULTS**

430

431 **Specimen selection, 2D scanning and database population.** — At the time of this
432 writing, the virtual collection contains more than 1,000 flat images spanning about 300
433 species in over 200 genera, of which figure 7 shows a representative sample. We add
434 more images periodically, prioritizing specimens of taxa that students have found
435 challenging to identify or visualize. Since not all undergraduate assistants have had prior
436 experience with ichthyology or photography, we found that course instructors were best
437 suited to selecting the specimens in the best condition, or in which the diagnostic features

438 were most clearly visible. Even with optimal specimens, variance in student proficiency in
439 photography led to variance in image quality. The biggest problems occurred with
440 photographs that were out of focus, underexposed, with the specimen filling a tiny portion
441 of the field of view, or with the fins folded against the body. Images of small diagnostic
442 morphologies were most prone to being out of focus, likely due to variance in student
443 familiarity with the key structures. The most common problem in postproduction involved
444 deletion of entire fins or parts of fins during the process of placing each specimen on a
445 uniform black background, or omission of the scale bar. Explicit workflows with
446 photographic examples, pins in diagnostic features, and screenshots of each step reduce
447 such error, but even with such resources mistakes still happen. See for example, the
448 diversity of scale bars (Fig. 7), which result from an ambiguous step in the workflow.
449 Instructor review provides an important quality control step to filter out more serious
450 errors prior to database upload, and to send specimens back to the assistants for another
451 try when necessary.

452

453 **3D scanning.** — At the time of this writing, we have completed scans of about 50
454 specimens of nearly as many species. Many of the final scans from the Artec Spider
455 beautifully represent the original specimens and provide students with access to 3D
456 models that can be freely rotated and zoomed (Fig. 8, see also supplementary videos).
457 Unfortunately, the equipment needed to produce and process such scans is not cheap.
458 After the dust settled with discounts and auxiliary gear, we spent around \$23,000 on the
459 Artec Spider, and another \$3,000 on a workstation to run the postprocessing software.
460 Unless one already has a powerful computer on hand, the workstation is a non-negotiable

461 cost. Model production requires substantial post-processing to clean, align, and fuse
462 multiple scans of a specimen, no matter which scanner one chooses. Prospective users
463 should also keep in mind that the massive project files turned out to require hundreds of
464 gigabytes of storage. We ultimately ended up using Oregon State University's Box
465 subscription to store and share these large files but went through several protocols before
466 settling on that workflow.

467 For rigid specimens, post-processing was fairly straightforward, as the software can
468 easily detect and align physical landmarks. Soft, or non-rigid specimens presented many
469 more challenges because they often shifted position slightly during scanning, and thus
470 forced the software to shift the resulting data to align the scans. This comes at a price in
471 time, and non-rigid specimens took substantially more time to process. Once we practiced
472 and refined the technique, we found that many fish specimens can be scanned and
473 processed in about an hour, with about 80% of that time spent waiting for the software
474 during post-processing. More difficult specimens such as large individuals (acipenserids,
475 selachians), floppy specimens (pleuronectiforms, batoids) or specimens with thin fins or
476 filamentous projections (siluriforms, *Pterois*), can take as long as 3 hours.

477 Filiform fishes and most anguilliform and depressiform species have proven elusive
478 because their shape changes too greatly when the specimen is flipped over to allow the
479 ventral surface to be scanned. The current generation of the scanning software has been
480 unable to align and fuse the dorsal and ventral views of such elongate and flexible
481 specimens. That said, initial trials with another Artec Scanner (the Leo) and new versions
482 of the scanning software suggest that this scanner might be able to handle those species.

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

492

493 **Lectures.** — Perhaps because the technique forces instructors to slow down, or perhaps
494 because it prompts students to create their own drawings while following the video, the
495 lightboard presentations seem to enhance comprehension of the most challenging material
496 in the courses. For example, conveying the structure of the teleost skull has proven to be a
497 consistent challenge, despite the construction of what we thought was a clear PowerPoint
498 animation that built up a diagrammatic version of the skull gradually, and paired it with an
499 exercise in which students colored in matching elements of a salmon cranium. We recently
500 converted that lecture to the lightboard format (available at <https://perma.cc/MQ47-EGUH>
501 and received some positive student feedback and subjectively fewer requests for extra
502 help. Given that encouraging result, we also constructed a lightboard video updating our
503 presentation of jaw origins (still shot in Fig. 9, full video available at
504 <https://perma.cc/BY3R-Y7UC>) to reflect recent advances from comparative development
505 (Kuratani, 2012; Oisi et al., 2013).

506 When constructing online lectures using either a lightboard or screencasting
507 solution, instructors should strive to keep lectures as short as possible, with the optimum
508 length possibly as brief as five minutes for lectures that might be watched on mobile
509 devices (Thomson et al., 2014). While lectures as brief as Youtube clips may not be feasible
510 in most classroom settings, there is substantial value in keeping each video to under 15
511 minutes in length, and ideally under 10. It is difficult to sustain one's focus on a non-
512 interactive video for longer than this, as information fatigue sets in quickly. These
513 durations seem brief, but because the lectures are recorded without a live audience, the
514 natural pauses in which students may ask questions, or in which the instructor consults
515 their notes are absent. We have found that prerecorded lectures cover the same amount of
516 material as a live lecture in about half the time, particularly if the instructor scripts the
517 lecture. Scripting makes the lectures seem more polished, and greatly facilitates closed-
518 captioning or translation to other languages. Breaking lectures into smaller, easily
519 digestible chunks also makes it easy for students to locate information later, and to review
520 the most challenging sections during their preparation for exams.

521

522 **Exams.**— Translating practical exams to the online format proved straightforward but
523 time consuming. The biggest challenge lay in producing enough images that the exams
524 could display specimens other than the ones visible to the students during the weekly labs
525 and in the student-facing portions of the virtual specimen collection. Truth be told, we
526 ended up reusing some images and are still building up the set of specimens designated
527 exclusively for exams. This challenge has been most acute with the 3D scans, since each

528 scan represents several hours of work. Even so, we have begun integrating those scans
529 into exams.

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

542 Interestingly, our greatest success in testing with the 3D specimens to date has
543 occurred in the biology-focused Ichthyology class, rather than the taxonomy-focused
544 Systematics of Fishes class. The 3D scans have greatly enhanced the unit dealing with
545 locomotion and functional morphology, which emphasizes how different body plans adapt
546 fishes to different swimming and predation styles. The exam on this unit includes a multi-
547 part short answer question juxtaposing two fishes with very different swimming modes,
548 such as a carangid and a cottid, or *Esox* versus *Chaetodon*. The question asks the student to
549 compare and contrast the probable locomotion of the two species, to explain how their
550 body morphology adapts each to that locomotory mode, and to hypothesize about the likely

551 diet of each species. In comparison to flat images, the 3D models greatly improve the
552 ability of the students to visualize the aspects of morphology needed to answer the
553 question fully, such as the body's surface area and cross-sectional area, and the size, shape
554 and placement of the fins. The beauty of this question lies in that it challenges students to
555 apply their knowledge to examples other than the ones discussed in the lecture and that
556 the instructor can refresh it regularly by swapping one of the models for another. Such
557 updates have become necessary with the rise of websites like Course Hero, Kloofers, and
558 Quizlet. While these sites ostensibly provide a place for students to share lecture notes and
559 study guides, in practice they are rife with copies of old exams, often complete with answer
560 keys. While we regularly scan these sites for such material and request removal when we
561 find it, we are always at least one step behind the students in that race.

562

563 **DISCUSSION**

564

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

572 The virtualization has opened access to specimen-based learning to the underserved
573 online segment of the student population. Thanks to this virtualization, students raising

574 families in rural Oregon, stationed overseas, employed as fisheries observers in Alaska, or
575 enrolled at universities that have jettisoned their programs in organismal biology can still
576 learn ichthyology, fish identification, phylogenetics, morphology and the comparative
577 method. The included fieldwork simulation reduces barriers to participation for students
578 otherwise unable to engage in such activities, such as those with a mobility impairment
579 (Giles et al., 2020). Even students enrolled at the Corvallis campus who normally enjoy
580 access to the physical specimens during scheduled laboratory sessions benefit, because the
581 virtual collection is available at any hour, even during a global pandemic.

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

590 Despite these successes, it is also important to acknowledge the limitations of the
591 online experience, particularly those that stem from incomplete virtualization. Despite the
592 thousands of hours of work underlying the class database, the total number of specimens
593 available to the online students is still much smaller than that available to the face-to-face
594 students. Students with access to the physical specimens can also physically manipulate
595 specimens during labs and exams, such as to open the mouth to check the teeth of a
596 characiform, or to feel along the ventrum of a clupeid for the telltale scutes. The 3D scans

597 do a better job than still images at replicating some of those experiences but have not
598 completely bridged the gap. For example, we introduced the concept of a “Mystery Box” as
599 a whimsical bonus question, taking inspiration from a similar approach used by Adam
600 Summers at the University of Washington. Students reach inside the box (a giant paper-
601 maché ceratoid) and attempt to identify the specimen therein using only their sense of
602 touch. At least until virtual reality technology makes another massive leap forward, that
603 memorable experience will remain out of the reach of online students.

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

614

615 ***Future directions.***— In the years to come, we envision several expansions to the course
616 and its database that should improve student success or allow additional courses to use the
617 resource. One of the most important will involve greater integration with the wealth of CT
618 scanned specimens that have recently become available on Morphosource (Boyer et al.,
619 2016); <https://perma.cc/K4SY-7T2U>). That resource houses open-access CT scan data for

620 thousands of specimens, including ~3,000 specimens of fishes, ~2,000 of reptiles, and
621 ~1,000 of amphibians at the time of this writing. Several of the current laboratories in the
622 Systematics of Fishes class teach skeletal anatomy using images of cleared and stained
623 specimens. Instructing these sections has proven challenging without being able to
624 manipulate the skeletal specimens. For example, it is hard to demonstrate the position and
625 function of the cypriniform kinethmoid without rotating the fish or pulling open the jaw.

626 One potential solution to this problem is to construct virtual anatomical models for
627 students to dissect, manipulate, and explore online (see Manzano et al., 2015). For
628 distance-learning students who might not otherwise have a means to engage in specimen
629 dissection, the opportunity to dissect or manipulate a specimen virtually would provide an
630 opportunity for the kind of exploratory learning that many of us take for granted but is
631 difficult to replicate online. While virtual experiences of this kind cannot fully replace real
632 world experiences, they do offer the benefit of repeatability (digital specimens are never
633 damaged as a result of dissection), low cost, and the potential for great taxonomic breadth
634 of specimens. Labelled models can be paired with XROMM videos to give students a look
635 into how the anatomy functions in a living organism (Brainerd et al., 2010; Gidmark et al.,
636 2012)

637 The future direct addition of 3D specimen models (whether surface scans or CT-
638 based) to the virtual collection exemplifies a website expansion that will be made possible
639 by the flexibility in the database's architecture. The model is already poised to store the
640 actual metadata for the digital model. Following the insertion of a new identifier to signify
641 "3D model" content type, the records could be indexed as info related to the model (such
642 as the URL linking to an embedded viewer). Alternatively, if we decide to store each digital 3D

643 model itself in the same infrastructure as the website, it would be possible to devise a
644 suitable storage architecture to accommodate the voluminous datafiles. Addition of a
645 simple “View 3D Specimen” link would integrate 3D viewing into the extant user interface.
646 We look forward to the functionality that the integrated 3D viewer will bring and anticipate
647 improved active learning opportunities for the students once those new elements of the
648 database are in place. For example, we will be able to juxtapose models side by side,
649 display 2D and 3D versions of the same species simultaneously, or allow annotations
650 (labels) to be toggled between different versions. That latter functionality would allow an
651 instructor to use the same model to teach and test comprehension of terms simply by
652 swapping the informative set of labels with a numbered list. Tighter integration with the
653 course database would also help automate the creation of online flash cards and study
654 guides for each week of a course, or to easily sort the models into taxonomic bins.

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

665 3D printing of accurate models can also enhance instruction in anatomy and
666 evolution. Structures printed at enlarged scales give students a macroscopic assist to
667 studying minute structures and supplement exercises that would otherwise rely entirely on
668 microscopy. For example, a team in our department used printed models to train
669 undergraduates to identify salamander limb bones within owl pellets. Online students who
670 have access to 3D printers (on their own or through a public library) can print anatomical
671 models for themselves, but even without creating a physical representation, digital models
672 can be used in much the same ways as physical specimens for teaching. David Blackburn's
673 lab at the University of Florida, for example, maintains a Sketchfab site with a virtual
674 collection for Herpetology (curated by Rachel Keeffe, <https://skfb.ly/6FXvV>), as well as
675 reconstructions of soft and hard tissues in several species of burrowing frogs (e.g., *Hemisus*
676 *guineensis*, <https://skfb.ly/6yJAM>).

677 Any interested course designer could create their own digital teaching collection
678 using the CT data that is already publicly available on Morphosource, including rare taxa
679 that would be extremely difficult to acquire in the real world (Gidmark, 2019; Staab, 2019).
680 Many datasets are available as pre-made 3D models (<http://bit.ly/MeshSource>), and many
681 more are available as CT image stacks. Constructing a 3D model from image stacks can be
682 accomplished with any reasonably up to date computer and at no monetary cost using one
683 of the myriad open-source software packages capable of processing and analyzing CT data.
684 Buser et al. (2020) describe a step-by-step workflow for processing CT data using only
685 open source, cross-platform programs to create 3D models and visualizations such as that
686 shown in Figure 10, which we use to help students learn to identify the bones of the
687 opercular series (see also supplementary video). Using such a workflow, educators can

688 model whole skeletons or individual bones from any species for which such CT data is
689 available and even instruct students in how to make models for themselves.

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

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

707 Finally, the most important needed update to the database involves creation of an
708 open access edition. Currently the database requires login credentials that demonstrate
709 that the user is part of Oregon State University. In the sense that the university uses
710 course tuition to help pay for the development of resources like these, the existence of the

711 enrollment wall made sense initially. Now that the database is functional, we are exploring
712 options for opening access to instructors and students outside of our institution. In so
713 doing, we anticipate being able to greatly increase the number of students and instructors
714 who can benefit, while enlisting the aid of other scholars and teachers to expand the
715 taxonomic coverage and the number of images available in the database.

716

717 **Advice on rapid virtualization.**— The coronavirus pandemic broke during the review and
718 revision of this paper and prompted several inquiries about how to virtualize an
719 organismal biology class quickly. Had we been in that situation, we likely would have
720 relied upon images already digitized and available on the internet to flesh out weekly labs.
721 To prevent the use of reverse image searching during tests, we would have focused our
722 initial digitization efforts on images destined for inclusion in exams and would have
723 refrained from posting these publicly outside of the online course. We would have
724 assigned the next highest priority to range-restricted taxa common in our region. For
725 example, cypriniform species tend to have relatively narrow ranges, and the species
726 common in the Pacific Northwest differ substantially from those in the Southwest, Midwest
727 or points further east. Instructors elsewhere would have been unlikely to image or scan
728 our locally endemic species (*Oregonichthys crameri*, *Catostomus bondi*, etc.) and students
729 in our geographic region need to learn to identify those taxa in order to secure jobs with
730 state agencies. The collection of 3D surface scans digitized during the pandemic by Jessica
731 Arbour to support her ichthyology course at Middle Tennessee State University
732 (<https://perma.cc/NQ6U-ZBWU>) represents an excellent example of a locally-focused
733 virtualization effort designed to meet the immediate needs of a specific course. It also

734 provides a resource that other instructors can draw upon to diversify their own courses
735 and indeed, we have incorporated a few of her scans in our most recent offering. By
736 working together and sharing resources, we can improve everyone's instruction and avoid
737 needing to scramble so frantically the next time that disaster strikes.

738

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

756 be able to fully replace the real thing, or at least not in the lifetime of anyone alive at the
757 time that we write this paper.

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

770

771 **DATA ACCESSIBILITY**

772 Supplementary material is available at <https://wwwCOPEIAjournal.org/XXX>.

773

- 774 1. Screencast of a surface-scanned model of OS17247 *Leptagonus frenatus*
- 775 2. Screencast of a surface-scanned model of OS5698 *Chaetodon fremblii*
- 776 3. Screencast of a surface-scanned model of OS18514 *Hypostomus taphorni*
- 777 4. Screencast of a CT-scanned and annotated model of OS6720 *Artedius lateralis*

778 (credit: T. Buser and A. Summers).

779

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901

902 **FIGURE CAPTIONS**

903

904 Fig. 1. Tiered application architecture diagram outlining the design of the virtual specimen

905 collection. The collection's middleware processes user queries to retrieve relevant data and

906 images from cloud storage, and then constructs a dynamic webpage displaying those data

907 or allowing the user to modify the desired section of the database.

908

909 Fig. 2. The species page for *Ptychocheilus oregonensis* from the virtual specimen collection,

910 including links to lateral views of alcohol preserved specimens, a closeup of the gill rakers,

911 and cleared and stained material. Clicking on any image pulls up a full-size version and

912 some accompanying metadata, such as the species identification and the specimen's catalog

913 number. Scrolling down reveals more textual information.

914

915 Fig. 3. The photography room at the Oregon State Ichthyology Collection, including photo
916 tanks, LED arrays, camera and tripod.

917

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

920

921 Fig. 5. Three-dimensional surface-scanning workflow.

922

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

926

927 Fig. 7. Two dimensional images from the virtual specimen collection. Species and
928 specimens pictured: *Cymatogaster aggregata* (OS5910), *Dendrochirus* sp. (OS teaching
929 collection), *Lepomis macrochirus* (OS18438), *Oncorhyncus tshawytscha* (OS16943),
930 *Parophrys vetulus* (OS898) *Hydrolagus colliei* (OS1942), *Percopsis transmontana* (OS17965),
931 *Catostomus bondi* (OS16985) and *Lepisosteus oculatus* (OS teaching collection). Image
932 credits: K. Knight and M. Vazquez.

933

934 Fig. 8. Still images of 3D models for *Leptagonus frenatus* (OS17247) and *Chaetodon fremblii*
935 (OS5698). See the supplementary videos for examples of these and other models being
936 manipulated in three dimensions.

937

938 Fig. 9. Image capture from a lightboard presentation in the online version of FW315:

939 Ichthyology.

940

941 Fig. 10. Annotated skull model of *Artedius lateralis* (OS6720) from CT scan data collected

942 by T. Buser and A. Summers at the Karel F. Liem Imaging Facility at Friday Harbor,

943 Washington. See the supplementary videos to view this model in motion.

AUTHOR CONTRIBUTIONS

BLS designed and developed these courses, directed the development of the virtual specimen collection, prepared most figures and wrote most sections of the manuscript. MB helped to design, implement and populate the virtual specimen collection with 2D images, and supervised the students working on that project. TB wrote the section on the use of CT scanned data in online pedagogy. TB and MB helped to design and instruct both courses and contributed text related to best practices in online teaching. NH developed the protocol for 3D surface scanning, led the model post-processing, helped to supervise undergraduate assistants, and wrote the sections of the manuscript dealing with 3D surface models. MK was the primary database developer for the virtual collection, contributed text to those sections of the manuscript, and created Figure 1. All authors approved submission of the work for publication.

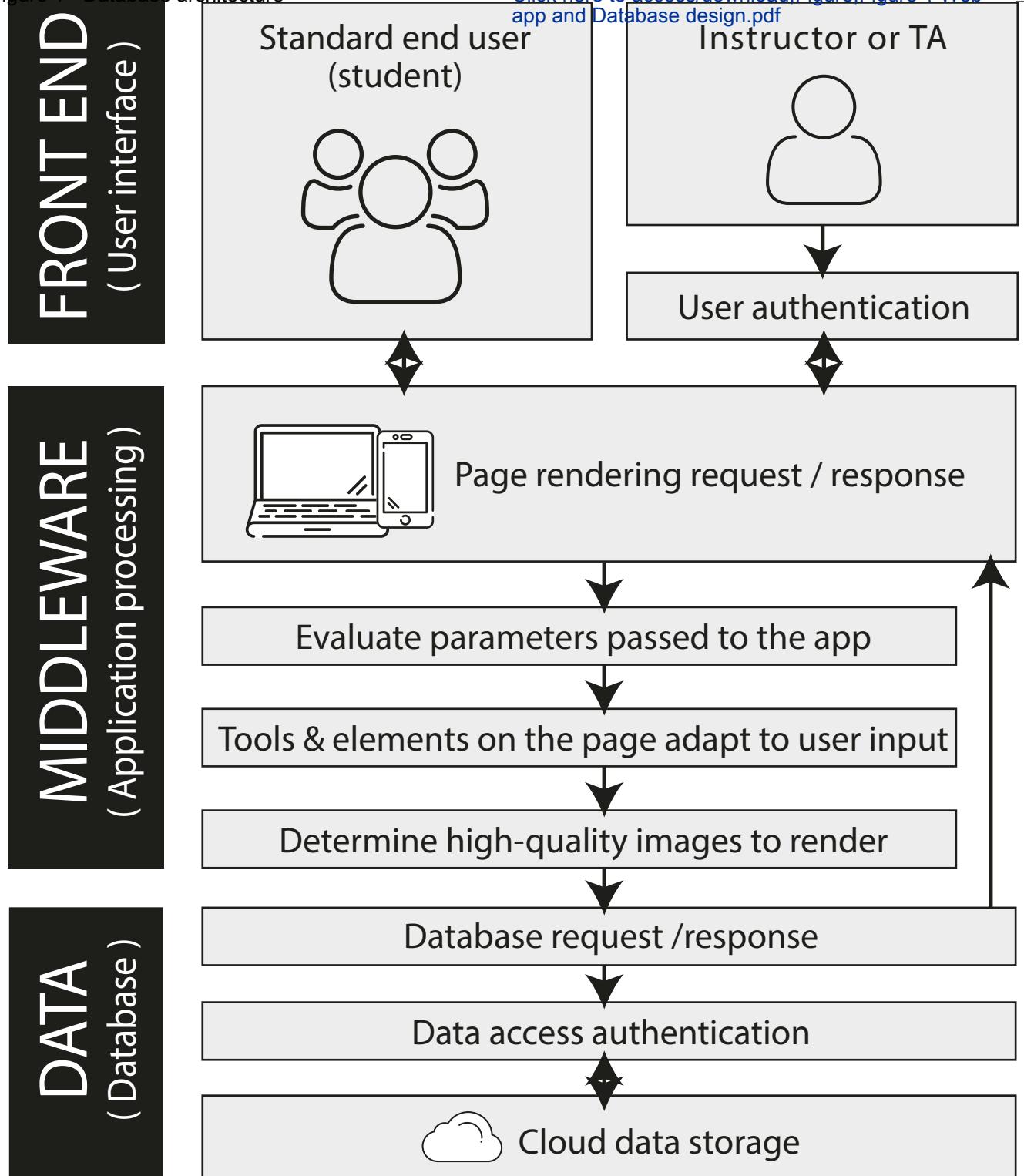
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most of the 3D surface scans. Philip Krzeminski expertly photo-edited some of the most recent database additions and helped to develop post-processing workflows. Online students Kimberlie Webber and Tammy Chapman graciously permitted reproduction of their worksheet pages. In developing these courses BLS drew upon his own experience as a student in outstanding courses in ichthyology, systematics or comparative biology taught by Barry Chernoff, Bruce Collette, Amy McCune, Doug Markle, Mark Westneat and Michael LaBarbera. We thank Álvaro Cortés for substantial feedback, discussions, and suggestions as an undergraduate student and assistant in these courses, and later as a course instructor in his own right. Whit Bronaugh, Marcus Chatfield, Kendra Hoekzema and Peter Konstantinidis also served as online instructors for these courses and proposed various improvements. Alison Rabosky suggested adding the section on adapting courses to remote delivery during the COVID-19 pandemic. Funding for course and database development was provided by Oregon State University's Ecampus and Department of Fisheries and Wildlife, a Learning Innovation Grant from OSU's Office of Information and Technology, and by NSF grant DBI-1057452 to BLS. We thank Eric Hilton, Sarah Huber and Leo Smith for the invitation to participate in the 2019 symposium on innovative uses of natural history specimens, the opportunity to submit this work for publication, and their patience while waiting for its completion. Comments from two anonymous reviewers improved this paper substantially. Finally, BLS thanks Rae Sidlauskas deeply for taking more than her shares of shifts caring for their infant daughter Fiona while he worked to finish this paper.

Figure 1 - Database architecture

[Click here to access/download:Figure:Figure 1 Web app and Database design.pdf](#)



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Oregon State University

Q HOME ADMIN EDIT PTYCHOCHEILUS OREGONENSIS (NORTHERN PIKEMINNOW) FLASH CARDS PHYLOGENY WEEK-BY-WEEK

Ptychocheilus oregonensis (Northern Pikeminnow)



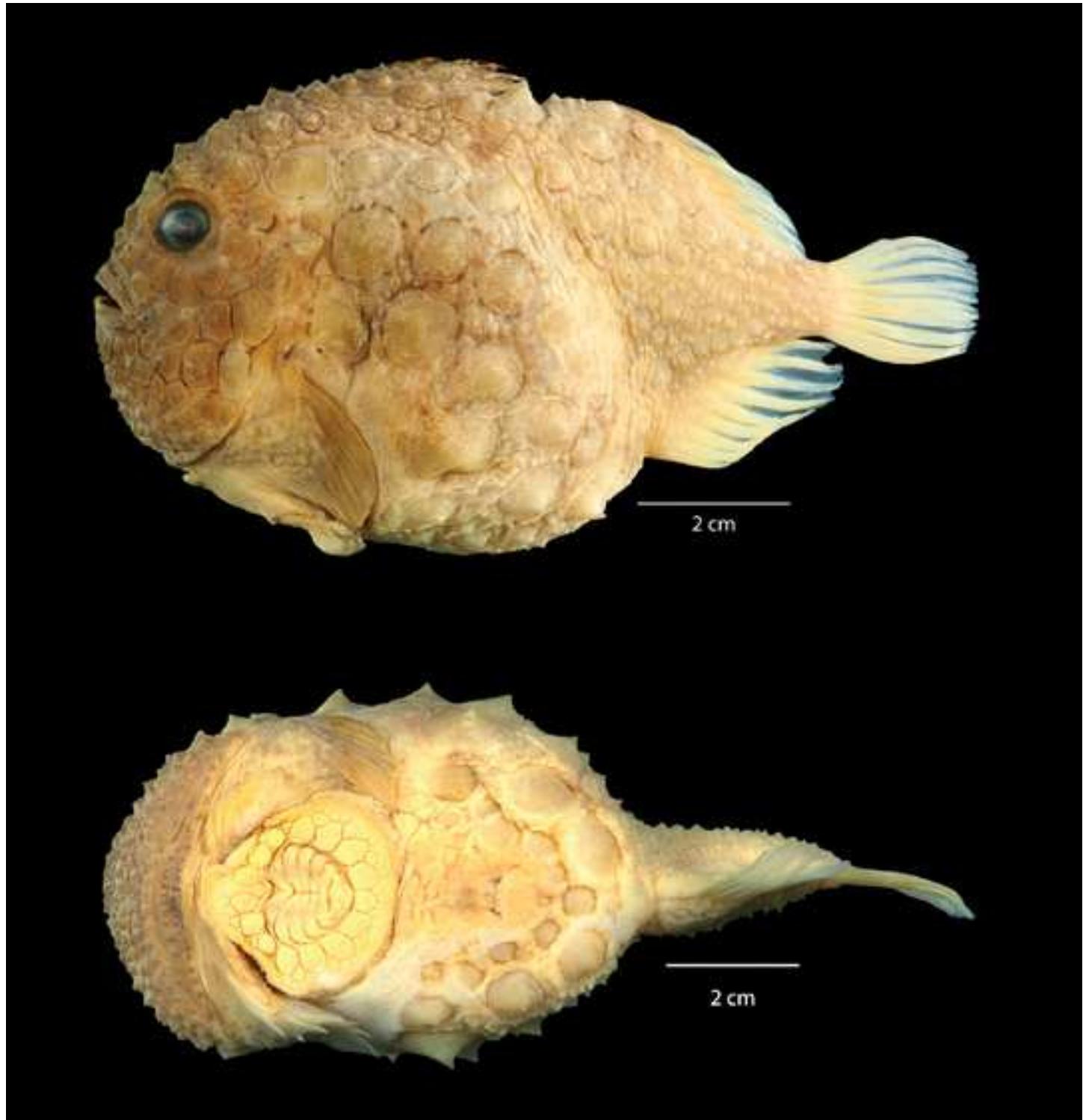

Specimens: [OS18054](#) [OS18054](#) [OS12136](#) [OSTeaching](#) [OSTeaching7](#) [View All Images](#)

Order:	Cypriniformes	Size Range:	not yet provided
Family:	Cyprinidae	Diadromy:	No
Species:	Ptychocheilus oregonensis	Depth:	Epipelagic
Common name:	Northern Pikeminnow	Reproductive Strategy:	Oviparous
Diet:	Carnivore	Fertilization:	External
Continent(s) or Ocean(s):	North America	Salinity:	Freshwater
Description:	An important fish predator; spawns from spring to summer, lays adhesive eggs. A second similar species, the Umpqua Pikeminnow, <i>P. umpquae</i> , is found in Oregon. Another relative, the Colorado Pikeminnow (<i>P. lucius</i>), is the largest American minnow.		
	Commercially Important:	No	
	Endangered:	Yes	
	Native to OR:	Yes	

We gratefully acknowledge the authors of the fifth edition of *Fishes of the World* (Nelson et al., 2008) for permission to paraphrase extensively from that source in our descriptions and diagnoses of families and orders of fishes. Our underlying taxonomic hierarchy largely follows the third revision of the classification originally proposed by Betancur-R et al. (2013), with some modifications based on the results of other authors.

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SCANNING

(Artec Spider)

Select specimen

Pat dry and place on turntable

Open Artec Studio and scan visible surface

Flip over and scan rest of specimen

Clear scans of noise

Align and fuse scans into polygon mesh

Smooth, repair and optimize polygon mesh

Map photographic texture onto mesh

Export final mesh as .OBJ

Upload to Sketchfab

Adjust initial positioning and illumination

Add metadata and annotations

PROCESSING

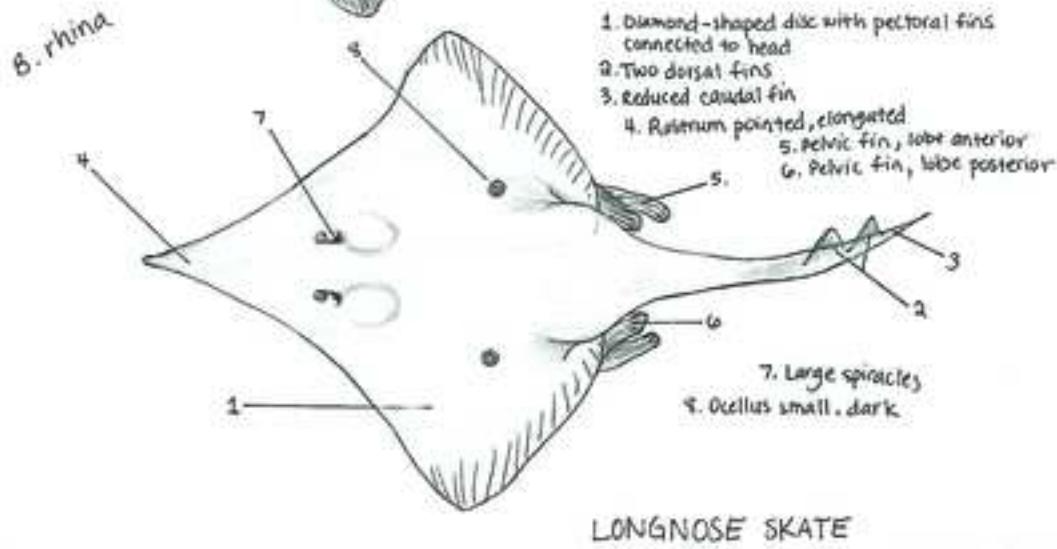
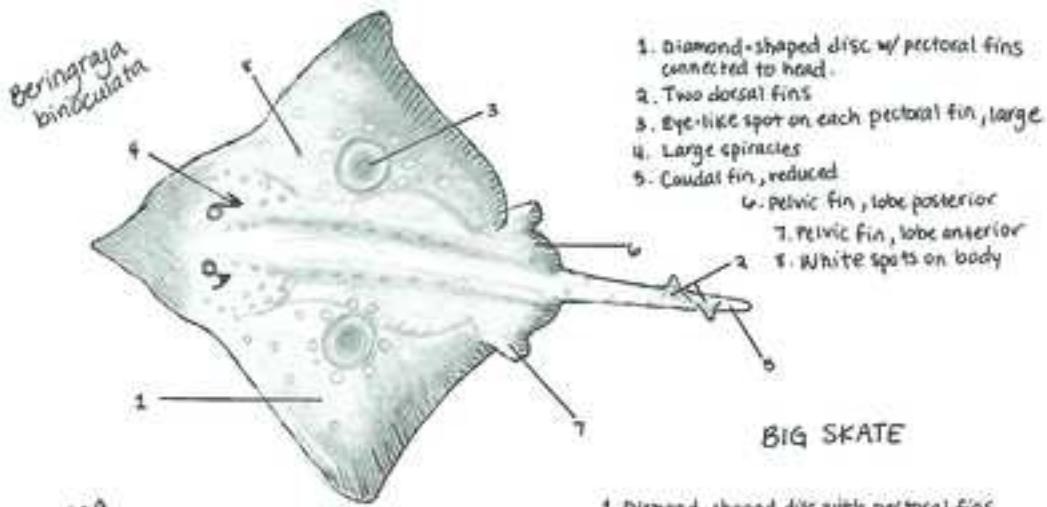
(Artec Studio)

UPLOAD

(Sketchfab)

Figure 6 - example student work

Click here to access/download; Figure; Figure 6
ExampleWorkWebberChapman.tif



Order: Cypriniformes
Family: Catostomidae
Suckers

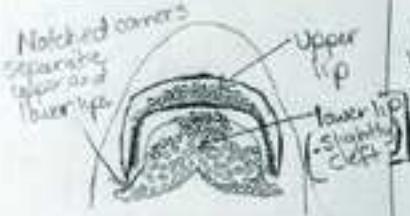
Largemouth Sucker
(*Catostomus macrocheilus*)



- Less than 81 lateral line scales
- Papillae on lips
- Small head
- No barbels
- Moderate size: grows to ~24 inches

diet: omnivorous

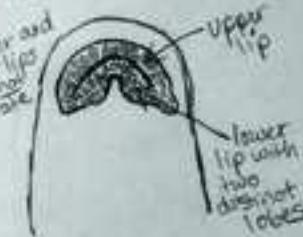
Bone's Sucker
(*Catostomus bonei*)



- 75-85 lateral line scales
- diet: omnivore
- papillae on lips
- no barbels
- small size: grows to 175 mm (~7 inches)

Head
Mouth morphology
Ventral view

Lost River Sucker
(*Diplostomus luxatus*)

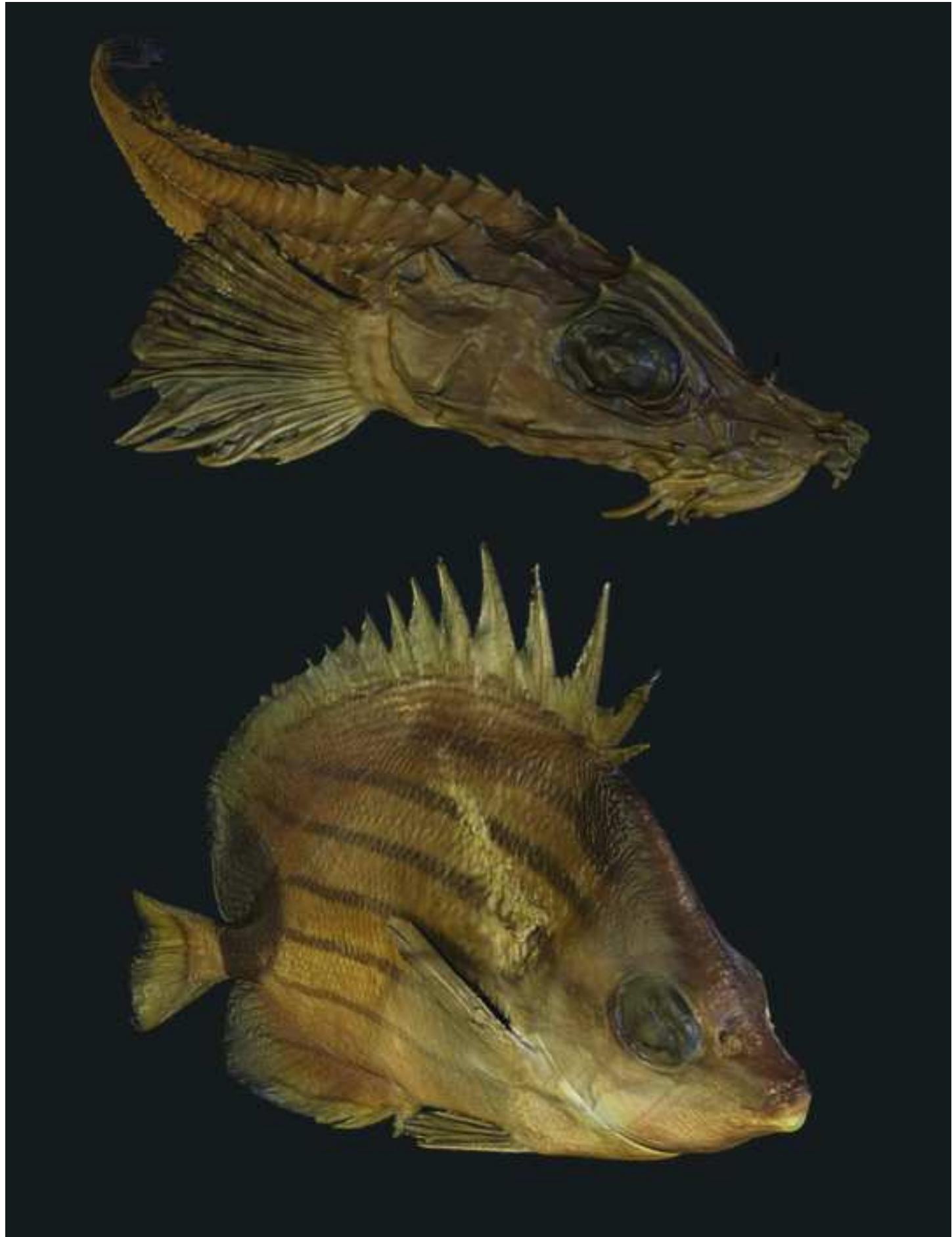


- diet: herbivore
- papillae on lips
- no barbels
- very large size: grows to 1.5m (~5 feet)
- 82-113 lateral line scales

Figure 7 - 2D specimen plate

[Click here to access/download;Figure;Figure 7 Specimens_final.tif](#)





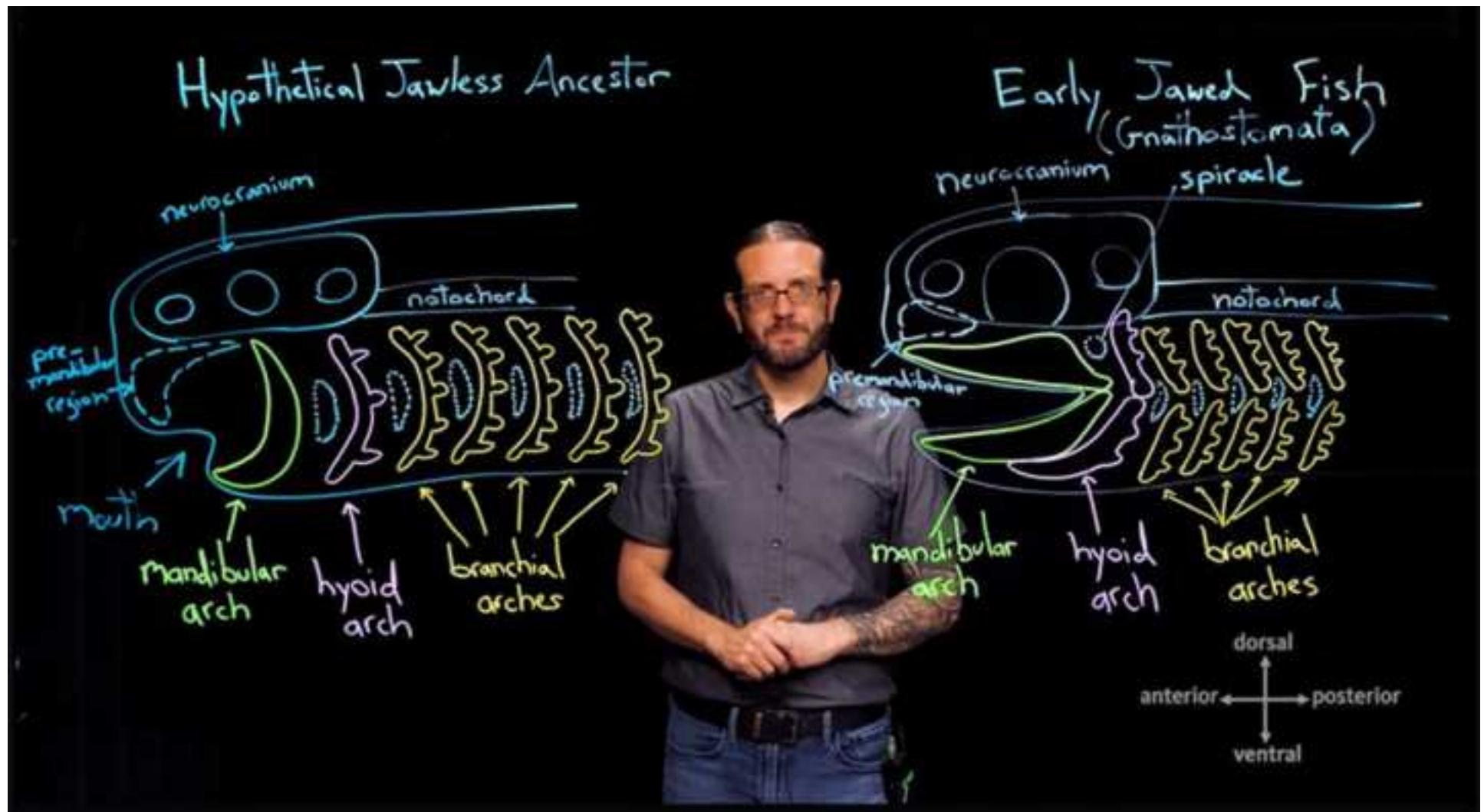
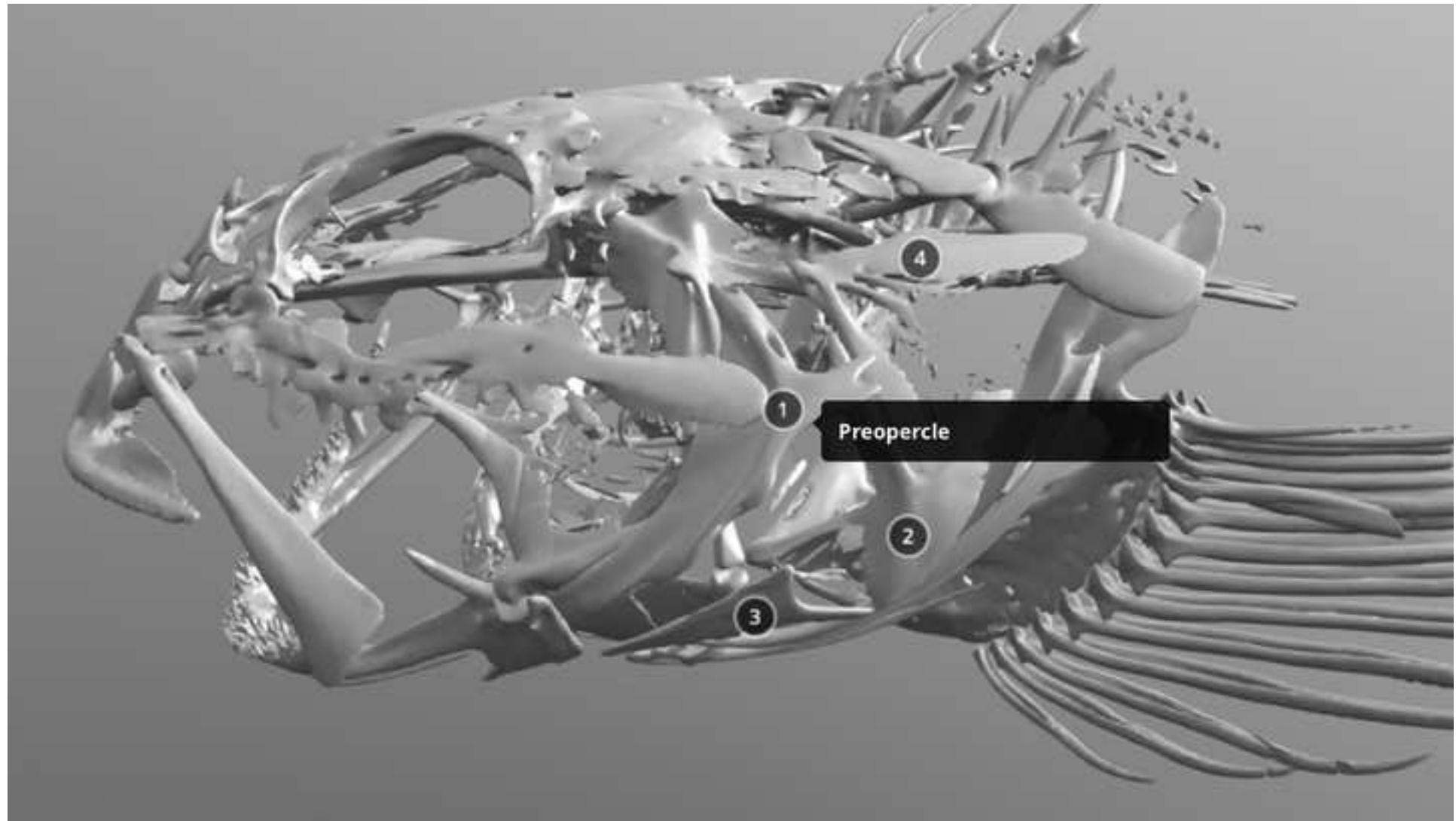


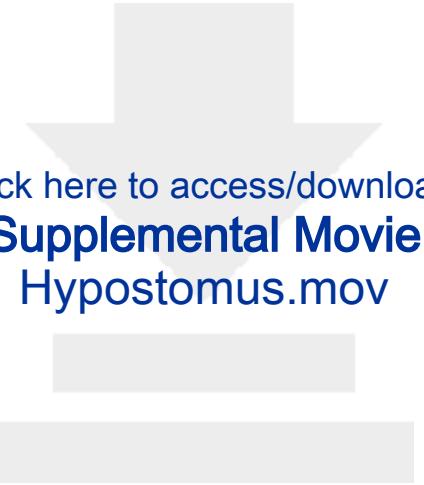
Figure 10 - Sculpin skull model

[Click here to access/download;Figure;Figure 10 sculpin annotation screenshot grayscale.tiff](#)

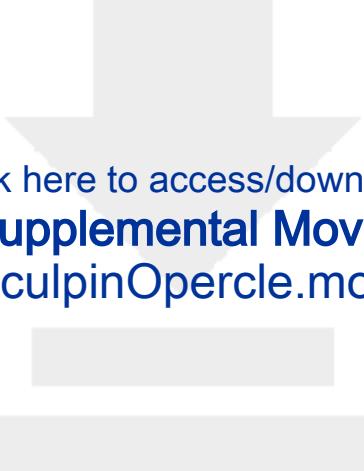




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