

1 VirtualPal: a remote undergraduate invertebrate paleontology practical course using 3D fossils

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3 VirtualPal : un cours en ligne de travaux pratiques en paléontologie des invertébrés base sur  
4 des fossils en 3D

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14 Keywords: Invertebrate paleontology; photogrammetry; 3D fossils; remote teaching;  
15 pedagogical design; moodle

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17 Mots-clés : Paléontologie des invertébrés ; photogrammètrie ; fossiles en 3D ; enseignement  
18 à distance ; modèle pédagogique ; moodle

19  
20 Abstract

21 Paleontology is a natural science discipline based on the observation of fossils. Therefore,  
22 paleontology education requires extensive training, and thus significant time, dedicated to  
23 observing and describing fossils. In the classroom, teachers often lack sufficient time to  
24 showcase the vast majority of key and basic fossil diversity typically encountered in the field.  
25 Moreover, students cannot spend enough time in class to properly study each sample. This  
26 challenge becomes even more critical in remote learning settings where access to fossils is  
27 limited. To address these limitations, we present a remote class dedicated to invertebrate  
28 paleontology bachelor students, based on a collection of 3D fossils. These models are  
29 reconstructed using photogrammetry and hosted online on Sketchfab web platform. We  
30 present a comprehensive Moodle remote course so-called VirtualPal that seamlessly  
31 integrates instructional videos, interactive 3D fossil models, specific lessons, formative and  
32 summative quizzes. The VirtualPal model can be easily adapted to other observational  
33 disciplines such as micropaleontology or petrology but still requires a proper evaluation of its  
34 effectiveness using educational science methodologies.

35  
36 Résumé

37 La paléontologie est une discipline des sciences naturelles fondée sur l'observation des  
38 fossiles. Son enseignement exige donc une formation approfondie, et par conséquent un  
39 temps significatif, consacré à l'observation et à la description des fossiles. En salle de classe,  
40 les enseignants manquent souvent de temps pour présenter la majorité des fossiles clés et  
41 fondamentaux, généralement rencontrés sur le terrain. De plus, les étudiants ne peuvent pas  
42 consacrer suffisamment de temps en cours pour étudier chaque échantillon de manière  
43 adéquate. Ce défi devient encore plus crucial dans le cadre de l'enseignement à distance, où  
44 l'accès aux fossiles est limité. Pour répondre à ces contraintes, nous avons créé un cours à  
45 distance de paléontologie des invertébrés dédié aux étudiants en licence, basé sur une  
46 collection de fossiles en 3D. Ces modèles sont reconstruits par photogrammètrie et hébergés  
47 en ligne sur la plateforme Sketchfab. Dans le détail, le cours complet designé sur Moodle,  
48 nommé VirtualPal, intègre de manière fluide des vidéos pédagogiques, des modèles interactifs  
49 de fossiles en 3D, des leçons spécifiques, ainsi que des quiz formatifs et sommatifs. Le modèle  
50 VirtualPal peut être facilement adapté à d'autres disciplines observationnelles, telles que la  
51 micropaléontologie ou la pétrologie, mais nécessite encore une évaluation rigoureuse de son  
52 efficacité à l'aide de méthodologies issues des sciences de l'éducation.

53  
54 1. Introduction

55 Paleontology is an observation-based science, similar to many other fields within geoscience.  
56 Education in paleontology, specifically invertebrate paleontology, is centered on the  
57 observation of fossils. Students are required to observe and identify the various morphological  
58 features of fossils and determine their taxonomic affiliation. As a result, undergraduate  
59 invertebrate paleontology courses dedicate a significant portion of class time to practical work.  
60 However, most students do not have enough time to thoroughly study each fossil presented  
61 during class, as the number of specimens is often too large. In other words, the time allocated  
62 to practical work is too limited for students to practice on a sample set representative of the  
63 vast diversity of fossils found in nature. In many cases, a student may observe a given fossil  
64 only once, weeks before the exam. Conversely, the teaching of paleontology could be  
65 hampered in some emerging countries due to a lack of materials (i.e., fossils) or insufficient  
66 university buildings to accommodate the explosion in student numbers.

67 To encourage careful observation during practical sessions, students are typically asked to  
68 draw and annotate the fossils. The advent of low-cost digital cameras and smartphones has  
69 helped extend observation time and improve recognition by allowing students to take reference  
70 photos alongside their drawings. However, many of these photos are of insufficient quality to  
71 serve as reliable aids for further observation or sketching. Additionally, many students struggle  
72 to mentally reconstruct a 3D object from a series of 2D photographs. The benefits of 3D  
73 visualization in learning processes have been demonstrated across various scientific  
74 disciplines (e.g., Güven and Kosa, 2008; Silén et al., 2008; Abdinejab et al., 2021; Yamakami  
75 et al., 2021). Similarly, the ability to translate 2D information into a 3D understanding is a crucial  
76 skill in geosciences, one that requires more than a single undergraduate course to fully  
77 develop. What are so called spatial thinking skills remain fundamentally important in the  
78 geosciences (Kastens and Ishikawa, 2006). Among the multiple dimensions of spatial thinking  
79 skills, this pedagogical project is mainly orientated toward developing (i) mental rotation, which  
80 is the ability to rapidly and accurately rotate a two- or three-dimensional figure in one's mind  
81 (Kadam et al., 2021) and (ii) perspective taking which is the cognitive ability to imagine how an  
82 object or scene would appear from a viewpoint different from one's own current physical  
83 position and to a lesser extent. To a lesser extent, the spatial thinking of disembedding (the  
84 ability to separate a figure from its background, that is, to identify a shape hidden within a  
85 larger, visually complex configuration; Bodner and Guay, 1997) and penetrative thinking (which  
86 is the capacity for imaging the interior of an object; He et al., 2022) are addressed although  
87 not specifically trained. These issues are also prevalent in fully remote paleontology courses.  
88 The materials typically provided consist of generalized morphological diagrams and series of  
89 fossil photographs. Students must then mentally translate these generic diagrams to specific  
90 specimens and infer their 3D structure from 2D images. Moreover, the learning process is often  
91 unsupervised, reducing its overall effectiveness (Clark and James, 2005; Day, 2022).

92 In this manuscript, we describe a fully remote invertebrate paleontology course based on 3D  
93 invertebrate fossils (hereafter called VirtualPal), supplemented by instructional videos, Moodle-  
94 based lessons, and both formative and summative quizzes. Most of the fossils are  
95 reconstructed in 3D using photogrammetry, providing a realistic representation of their color,  
96 texture, and morphology. VirtualPal is hosted by Unisciel (*Université des Sciences en ligne –*  
97 *Online Science University*) and is freely accessible with open registration.

98

## 99 2. The VirtualPal learning objects

100 This study adopts the widely accepted definition of a Learning Object (LO) as “any digital  
101 resource that can be reused to support learning” (Wiley, 2002). Within the project, four  
102 categories of LOs are employed: interactive 3D fossil models, instructional videos, interactive  
103 lessons and quizzes. The LOs are utilized and reused across multiple tiers of the VirtualPal  
104 pedagogical framework (see Section 3 below). All these LO are structured in a moodle (see  
105 Section 3). Moodle is a free and open-source learning management system written in PHP,  
106 widely used worldwide by universities to host the digital parts (documents, images, etc) of a  
107 course, for blended learning or even for distance learning.

108

### 109 2.1. 3D fossils

110 The vast majority of the 3D models in the fossil collection are generated using photogrammetry.  
111 Most of the models are produced by the team SIGeo from CEREGE using the protocol described  
112 below. A few other contributions come from colleagues from Université Paul Sabatier, Toulouse  
113 namely Marc de Rafélis and Océane Nicolas using a similar procedure. The complete  
114 methodology, including parameters, setup procedure, and relevant literature, is provided in the  
115 supplementary material (Supplementary Material 1).

116 The basic principle of the structure-from-motion (SfM) photogrammetry method hereby applied  
117 (e.g., Granshaw, 2016) involves taking images from multiple angles, ranging from planar to  
118 apical views, by rotating the specimen on a turntable. The specimen is then repositioned to  
119 repeat the process for all its faces. Photographs are taken using four Canon™ EOS 77D  
120 cameras, each equipped with a 24.2-megapixel CMOS sensor (22.3 × 14.9 mm) and a  
121 resolution of 6000 × 4000 pixels. Macro lenses are selected as a function of the subject's  
122 dimensions, either a 60 mm  $f/2.8$  for large objects (up to 40 cm) or a 100 mm  $f/2.8$  for small  
123 objects (down to 2 cm). The number of photos taken per sample ranges from 192 to 576,  
124 depending on the specimen's surface complexity. To ensure high-quality images, lighting  
125 conditions are controlled using a Foldio© Studio 360 lightbox and four LED panels (Dörr©  
126 3040BC).

127 The typical image processing workflow includes: i) loading and cleaning the images; ii) aligning  
128 and orienting the images through tie-point detection and bundle block adjustment; iii)  
129 generating a dense point cloud via dense image correlation; and iv) meshing the dense cloud  
130 and texturing the model using the original images.

131 This process is carried out using Agisoft © Metashape Professional version 1.8. Once a 3D  
132 reconstruction meets sufficient quality standards, it is exported in .obj format and uploaded  
133 online. Although Sketchfab generously provides free Pro accounts to academic institutions  
134 through its support program, the maximum file size per model is limited to 200 MB. Therefore,  
135 the resolution of some models has to be reduced, though this never compromises key  
136 morphological features.

137 The fossils reconstructed using photogrammetry are hosted online on Sketchfab. Sketchfab is  
138 the largest online platform for hosting, viewing, manipulating, and sharing 3D models. This  
139 platform was selected because of its HTML integration capabilities. The collection is titled  
140 *Secteur Sciences et Technologies – AMU* ([https://sketchfab.com/Secteur\\_Sci\\_Techno-AMU](https://sketchfab.com/Secteur_Sci_Techno-AMU))  
141 and corresponds to a Pro account provided by Sketchfab through its education support  
142 program. All teaching samples, except those used for evaluation, are openly accessible and  
143 downloadable directly from Sketchfab under the CC-BY-NC-SA 4.0 license. Out of the 104  
144 samples used for teaching, 72 are annotated using Sketchfab's built-in annotation tool (Fig. 1),  
145 while the 78 specimens used for formative and summative evaluation purposes are not  
146 annotated. The annotations are based on the Paleontology class taught at Aix-Marseille  
147 University by Bertrand Martin-Garin and Baptiste Suchéras-Marx and controlled using a  
148 textbook, *Paléontologie et évolution des invertébrés* (Dera et al., 2025).

149 The manipulation of 3D fossils actively engages students in exercising multiple critical spatial  
150 thinking skills. First, mental rotation skill is trained by moving the fossils in any direction, which  
151 facilitates apprehending the various shapes of the fossils. Second, disembedding skill is  
152 exercised by focusing on specific features across the entire fossils, extracting the critical piece  
153 of information. Third, perspective taking skill is trained by moving the fossils to the different key  
154 views where morphological features are visible. Fourth, in rare cases, the penetrative thinking  
155 skill is exercised by observing internal features from external views, forcing to imagine the  
156 internal organization.

157  
158 Please insert Figure 1 here

## 159 160 2.2. Videos

161 A series of videos (Table 1) were previously recorded to demonstrate how to use Sketchfab (1  
162 video) and to present the morphological features of each fossil group or subgroup (12 videos).  
163 The videos are captured using OBS Studio, showing both (i) the instructor via the webcam of  
164 a Dell Precision 3571 laptop (32 GB RAM, 64-bit, 12th Gen Intel® Core™ i7-12700H 2.30

165 GHz) running Windows 10 Professional, and (ii) the 3D fossil model on Sketchfab, accessed  
166 through the Firefox browser. Audio is simultaneously recorded using an external Røde NT-USB  
167 microphone. No video editing is used. Videos are hosted on AMUpod ([https://amupod.univ-  
169 amu.fr/playlist/207-tp-de-paleontologie-des-invertebres/](https://amupod.univ-<br/>168 amu.fr/playlist/207-tp-de-paleontologie-des-invertebres/)) and accessible without registration  
170 although those were designed to be used in the remote class and not without it.

171 Except for the first video, there is a basic organization used for all of them with the presentation  
172 of typical morphological features on several specimens and a quick but not exhaustive tour of  
173 the diversity of shapes of the shells within a given group. The videos help students to bridge  
174 the gap between simple passive observation and active use of the 3D fossils. The manipulation  
175 within the videos, although primarily used to guide for observation and identification of  
176 morphological features, also shows the process that would ultimately result in training in mental  
177 rotation, disembedding, and perspective taking processes.

### 178 2.3. Lessons

179 A lesson is a specific activity in Moodle, basically a series of pages with branching and learning  
180 paths based on student choice or correctness in formative evaluation. Several lessons have  
181 been designed in VirtualPal to address specific topics often challenging for students. Within  
182 each page of a lesson, a text is supplemented with a 3D fossil. The text guides the student  
183 toward the specific features that should be observed. Step by step, morphological features are  
184 shown. At the end of the lesson, a formative evaluation is given. In case of success, the lesson  
185 is completed and rewarded with a badge. In case of failure, the student is sent back to the  
186 page showing the morphological features that were not identified. Lessons may focus on  
187 specific spatial skills, namely disembedding and penetrative thinking. But in many cases, these  
188 are also designed to teach the correct taxonomic or morphological nomenclature used for  
189 descriptions.

190  
191 Please insert Table 1 here

### 192 2.4. Quizzes

193 A quiz is a specific activity in Moodle. It is one or several questions that could be specifically  
194 organized or sampled randomly in a question bank. The design of every question in VirtualPal  
195 follows these principles: (i) multiple choice question with only one correct answer out of four  
196 possibilities (sometimes three or five); (ii) a question is always composed of a question and a  
197 3D fossil (e.g. Which morphological feature is labeled by annotation 1?) (iii) a specific feedback  
198 is associated with every answer, correct or incorrect; (iv) the order of the possible answers is  
199 randomized. The quiz itself has a minimum of 10 questions and up to 21 questions depending  
200 on the quiz type. In VirtualPal, two types of quizzes are designed, formative evaluation for  
201 training and summative evaluation for validation of the course. Quizzes are not designed to  
202 train to specific spatial skills, but students will need to sufficiently master these skills to  
203 succeed.  
204

## 205 3. Pedagogical organization of VirtualPal

206 The VirtualPal platform integrates the three aforementioned LO types within a systematically  
207 structured Moodle learning environment. It is hosted on Socles3, the Unisciel platform running  
208 Moodle version 4.0. Unisciel is the French online university for science, offering free and open-  
209 access courses and educational resources  
210 (<https://socles3.unisciel.fr/course/view.php?id=229>).

211 First, the main objective of using 3D fossils is to provide students with unrestricted access to  
212 fossil specimens, accompanied by detailed annotations directly on the fossil itself and,  
213 importantly, a realistic 3D representation with natural color and texture. Second, 3D fossils can  
214 easily be integrated into videos, lessons, and quizzes, thereby expanding the range of  
215 pedagogical activities and enhancing learning effectiveness. VirtualPal is designed to help  
216 students learn to recognize common invertebrate fossils without any lectures or fieldwork. It is  
217 structured as a fully self-contained remote learning experience. VirtualPal is divided into  
218 sections, each of which contains several chapters. The structure is composed of an  
219

220 Introduction section, Collection section, Taxonomical chapters sections, and Summative  
221 section (Fig. 2).

222

### 223 3.1. Introduction section

224 The first section is called *Introduction*. It explains the objectives of the course, its organization,  
225 and the recommended working methodology through a short text. This section also includes a  
226 video that demonstrates how to use Sketchfab. In the video, the narrator shows how to  
227 manipulate a fossil in 3D using Sketchfab and how to navigate from one annotation to another.  
228 This section is essential for students to understand the course's purpose and how to engage  
229 with the content effectively.

230

### 231 3.2. Collection section

232 The second section is called *Collection*. It contains a Moodle book resource with all the 3D  
233 fossils. This resource is organized according to taxonomy, with chapters (e.g., Mollusca,  
234 Echinodermata) and, when necessary, subchapters (e.g., Mollusca – Bivalvia, Cephalopoda,  
235 etc.). The objective of this section is to centralize access to the complete set of 3D fossils;  
236 learners are able to explore and consult any of the models independently and at their  
237 convenience.

238

### 239 3.3. Taxonomical chapters sections

240 The following sections are taxonomical chapters, with seven chapters:

- 241 - Mollusca – Gastropoda (1 video, 9 3D fossils, 1 lesson)
- 242 - Mollusca – Bivalvia (2 videos, 12 3D fossils, 2 lessons)
- 243 - Mollusca – Cephalopoda (5 videos, 22 3D fossils, 2 lessons)
- 244 - Brachiopoda (1 video, 7 3D fossils, 1 lesson)
- 245 - Echinodermata (2 videos, 9 3D fossils)
- 246 - Cnidaria (1 video, 10 3D fossils, 2 lessons)
- 247 - Trilobita (1 video, 3 3D fossils)

248

249 Within each chapter, there is a list of taxa hosted in this section, including their full taxonomy  
250 down to the genus level. Students are expected to recognize and name these specimens down  
251 to the genus level. One or more videos highlight (using 3D fossil manipulation) the main  
252 morphological characteristics that must be observed and identified. The narrator uses  
253 Sketchfab directly to simulate student interactions and to explain the key observations. The  
254 fossils shown in the videos are typical examples; not all 3D fossils are displayed.

255 Then, a subsection called *Observe* hosts the annotated 3D fossils. The last subsection labeled  
256 *Learn*, which is not always present, contains one or two Moodle lesson activities. Each lesson  
257 has a specific purpose and includes an evaluation at the end. The lessons are:

- 258 – recognize growth lines from ornamentation in gastropods (disembedding skill);
- 259 – recognize the different hinges in bivalves;
- 260 – recognize suture lines in cephalopods (disembedding and penetrative thinking skills);
- 261 – distinguish the difference between nautilus, goniatites, ceratites, and ammonites;
- 262 – distinguish the difference between brachiopods and bivalves;
- 263 – recognize the different morphologies of colonies in scleractinian corals;
- 264 – recognize the organization of corallites in scleractinian corals.

265

266 Please insert Table 2 here

267

268 At the end of each chapter, there is a quiz activity used as formative evaluation focusing  
269 exclusively on the specimens from that chapter. This quiz consists of ten questions covering  
270 three themes:

- 271 – two questions on group identification;
- 272 – two questions on genus identification within a group;
- 273 – six questions on morphological characteristic identification within a group.

274

275 In each quiz, questions are randomly sampled from different question banks (Table 2).  
276 Students have unlimited attempts for these quizzes and can use them to practice recognizing  
277 fossils or identifying morphological characteristics. As a formative evaluation, feedback is  
278 provided to the students. In this way, students identify which concepts they actually master and  
279 where they need additional practice, fostering self-regulated learning.

280

### 281 3.5. Summative evaluation section

282 The final section, called *Evaluation*, consists of three quiz activities using the same question  
283 database as the quizzes at the end of the chapters.

284 The first quiz assesses the student's ability to identify a fossil at the group level. It is accessible  
285 only if the student has attempted each chapter quiz at least once. This quiz contains 14  
286 questions—2 per group—randomly sampled from a set of 67 questions. To pass, the student  
287 must correctly answer at least 9 questions within 21 minutes. There is no limit to the number  
288 of attempts. The second quiz evaluates the student's ability to identify a fossil at the genus  
289 level. It is available only if the student has passed the first *Evaluation* quiz. This quiz also  
290 contains 14 questions—2 per group—randomly sampled from a set of 61 questions. To pass,  
291 the student must correctly answer at least 9 questions within 21 minutes. There is no limit to  
292 the number of attempts. The third and final *Evaluation* quiz tests the student's ability to  
293 recognize morphological characteristics for each group. It includes 21 questions—3 per  
294 group—randomly sampled from a set of 174 questions. To pass, the student must correctly  
295 answer at least 14 questions within 32 minutes. There is no limit to the number of attempts.  
296 Passing the last quiz is considered validation of the remote course.

297

### 298 3.6. Evolution of the pedagogical model and caveats

299 VirtualPal was originally based on a blended class that used 3D fossils for students' revision  
300 prior to the final practical exam. In this blended class, the first versions of the project consisted  
301 only of a collection of 3D fossils. This model was updated following students' recommendations  
302 requesting more organization, guidance, and help in recognizing fossils' morphological  
303 characteristics. Hence, the series of videos and lessons were added. Although lesson activities  
304 are used less frequently than videos, they were also incorporated. Moreover, skill validation  
305 was not introduced until the design of the final evaluation quizzes. Thus, the class presented  
306 here now guides students through the learning process between and within taxonomic  
307 chapters. This new pedagogical model from the blended class version at Aix-Marseille  
308 universit  was then adapted to construct the remote class on Socles3.

309 Despite significant improvements over the years, some limitations remain. The main limitation  
310 of the remote class is its total disconnection from any lecture-based paleontology or evolution  
311 courses and from fieldwork. The objectives are not anchored in a broader context, which may  
312 reduce students' interest in the class. Additionally, students cannot physically handle the  
313 samples, losing access to tactile information that could aid identification, such as weight or  
314 texture. Finally, because this class is fully remote, there is no evaluation of students' abilities  
315 to draw fossils or identify fossils in rock matrices, where characteristics may be less visible.

316

## 317 4. Conclusions

318 Remote classes in natural science disciplines are challenging because they require designing  
319 the course around the main targeted competencies, namely observation and description. The  
320 3D fossils and associated resources presented here succeed in that aspect. The design of this  
321 type of class is also easily transferable to other disciplines in Earth Science, such as  
322 micropaleontology, vertebrate paleontology, or petrology.

323 Currently, according to the literature, the Earth Science community is more focused on the  
324 development of virtual fieldwork (e.g., Mead et al., 2019; M tois et al., 2021; Guillaume et al.,  
325 2023), although several developments in virtual microscopes have also been seen (e.g., Engel  
326 et al., 2023) and several projects using 3D objects in Earth Science teaching are developed in  
327 numerous universities worldwide (e.g., Universit  Franche-Comt , Universit  de Li ge,  
328 University of Newcastle). Open-access remote classes represent an interesting opportunity for  
329 students in emerging countries where pedagogical materials are often lacking. They also offer

330 an opportunity for teachers, who can use the activities or 3D materials to design blended  
331 classes at their own universities. However, the remaining caveat of the pedagogical model  
332 presented here is the lack of evaluation of learning efficiency following educational science  
333 protocols.

334  
335 Acknowledgement

336 Sophie Jequier is warmly thanked for her comments on the pedagogical model developed on  
337 Socles3. The original project called *VirtualPal* was funded by the FIP (i.e., Pedagogical  
338 Intervention Fund) program by Aix-Marseille université in 2018. This manuscript is a  
339 contribution to the team *Climate* at CEREGE, OSU Pythéas, Aix-Marseille université. We also  
340 thanks the reviewers – Valentin Fischer and Nicolas Rudolph Thibault – as well as the  
341 associate editor Borja Cascales-Minana and the editor-in-chief Olivier Vanderhaeghe for their  
342 constructive comments on the submitted version.

343  
344 CRediT

345 **Baptiste Suchéras-Marx**: conceptualization, funding acquisition, project administration,  
346 resource, visualization, writing – original draft preparation, writing – review & editing. **Yann**  
347 **Ternois**: investigation, validation, writing – original draft preparation, writing – review & editing.  
348 **Jules Fleury**: data curation, investigation, methodology, supervision, validation, writing –  
349 review & editing. **Paul Ré**: investigation. **Bertrand Martin-Garin**: investigation. **Jérémy**  
350 **Castera**: validation, writing – original draft preparation.

351  
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403

#### 404 Supplementary Material

405 Exhaustive description of the photogrammetry set-up and methodology applied with a picture  
406 of our structure for photo capture and a table describing the camera and set-up parameters  
407 used.

408

#### 409 Figures and Tables list

410 Figure 1: On the left panel, an ammonite in side view with the annotation n°1 open. On the  
411 right, the same ammonite in frontal view moved 90° on the left.

412 Sur le panneau de gauche, une ammonite en vue latérale avec l'annotation n°1 ouverte. À  
413 droite, la même ammonite en vue frontale, tournée de 90° vers la gauche.

414 Figure 2: VirtualPal organization. There are seven thematic chapters organized based on  
415 taxonomy. The different colors represent the four types of LOs: embedded videos, embedded  
416 Sketchfab 3D fossils, lessons and quizzes.

417 Organisation de *VirtualPal*. Le cours est structuré en sept chapitres thématiques organisés  
418 selon une approche taxinomique. Les différentes couleurs représentent les quatre types  
419 d'objets d'apprentissage (LO) : vidéos intégrées, fossiles 3D Sketchfab intégrés, leçons et  
420 quiz.

421 Table1: List of the embedded videos with durations and the pedagogical purposes.

422 Liste des vidéos intégrées avec leur durée et leurs objectifs pédagogiques.

423 Table 2: Number of questions per taxonomic group and per learning task (i.e., group  
424 identification, genus identification and morphological characteristics identification).

425 Nombre de questions par groupe taxinomique et par objectif d'apprentissage (c'est-à-dire :  
426 identification du groupe, identification du genre et identification des caractéristiques  
427 morphologiques).

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Ammonite - Perisphinctes  
 3D Model

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 3D Model

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Figure 1: On the left panel, an ammonite in side view with the annotation n°1 open. On the right, the same ammonite in frontal view moved 90° on the left.

Introduction	434
Aims of class	435
Online class design	436
Method	437
LO - Video	438
How to use sketchfab?	439
	440
	441

Figure 2: VirtualPal organization. There are seven thematic chapters organized based on taxonomy. The different colors represent the four types of LOs: embedded videos, embedded Sketchfab 3D fossils, lessons and quizzes.

Collection

All 3D samples using moodle *Book*

Chapter #
Taxonomy
LO - Video
Features to observe on fossils
LO - 3D fossil
Annotated fossil 1
LO - 3D fossil
Annotated fossil #
LO - Lesson
Specific topic
LO - Quiz
Formative evaluation
10 random questions on taxonomy and morphology using 3D fossils

Summative evaluation
LO - Quiz (#1)
14 random questions on group identification using 3D fossils
LO - Quiz (#2)
14 random questions on genus identification using 3D fossils
LO - Quiz (#3)
21 random questions on morphology using 3D fossils

Video title	Duration	Objectives
How using Sketchfab for 3D fossils observation?	03:12	Learning to correctly use the 3D visualization
Morphological features in gastropods	11:18	Learning to recognize the morphological features in gastropods Learning the different shapes of shells in gastropods
Morphological features in bivalves (except hippuritids)	10:22	Learning to recognize the morphological features in common bivalves Learning the different shapes of shells in common bivalves
Morphological features in hippuritids	04:28	Learning to recognize the morphological features in hippuritids Learning the different shapes of shells in hippuritids
Morphological features in cephalopods common between nautilus, goniatites, ceratites and ammonites	06:20	Learning to recognize the common morphological features between nautilus, goniatites, ceratites and ammonites
Morphological features in nautilus	07:24	Learning to recognize the morphological features in nautilus
Morphological features in goniatites	03:41	Learning to recognize the morphological features in goniatites
Morphological features in ceratites	03:20	Learning to recognize the morphological features in ceratites
Morphological features in ammonites	05:32	Learning to recognize the morphological features in ammonites
Morphological features in brachiopods	06:40	Learning to recognize the morphological features in brachiopods
Morphological features in regular echinoids	06:59	Learning to recognize the morphological features in regular echinoids
Morphological features in irregular echinoids	05:21	Learning to recognize the morphological features in irregular echinoids
Morphological features in tabulate and scleractinian hexacorals	05:01	Learning to recognize the morphological features in tabulate and scleractinian hexacorals
Morphological features in trilobites	06:09	Learning to recognize the morphological features in trilobites

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Table1: List of the embedded videos with durations and the pedagogical purposes.

Questions	Groups	Genera	Morphologies
Gastropoda	9	9	26
Bivalvia	12	12	45
Cephalopoda	15	15	25
Brachiopoda	7	7	21
Echinodermata	10	7	20
Cnidaria	9	6	22
Trilobita	5	5	15
Total	61	67	174

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Table 2: Number of questions per taxonomic group and per task (i.e., group identification, genus identification and morphological characteristics identification).