Gamifying virtual exploration of the past 350 million years of vertebrate evolution

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Abstract

Surviving Extinction is an interactive, adaptive, digital learning experience through which students learn about the history of vertebrate evolution over the last 350 million years. This experience is self-contained, providing students with immediate feedback. It is designed to be used in a wide range of educational settings from junior high school (~12 years old) to university level. *Surviving Extinction*'s design draws on effective aspects of existing virtual field trip-based learning experiences. Most important among these is the capacity for students to learn through self-directed virtual explorations of simulated historical ecosystems and significant modern-day geologic field sites. *Surviving Extinction* also makes significant innovations beyond what has previously been done in this area, including extensive use of gamified elements such as collectibles and hidden locations. Additionally, it blends scientifically accurate animations with captured media via a user interface that presents an attractive, engaging, and immersive experience. *Surviving Extinction* has been field-tested with students at the undergraduate, high school, and pre-high school levels to assess how well it achieves the intended learning outcomes. In all settings we found significant gains pre- to post-activity on a knowledge survey with medium to large effect sizes. This evidence of learning is further supported with data from the gamified elements such as the number of locations discovered and total points earned. *Surviving Extinction* is freely available for use and detailed resources for educators are provided. It is appropriate for a range of undergraduate courses that cover the history of life on Earth, including ones from a biology, ecology, or geology perspective and courses for either majors or non-majors. Additionally, at the high school level, *Surviving Extinction* is directly appropriate to teaching adaptation, one of the disciplinary core ideas in the next generation science standards. Beyond providing this resource to the educational community, we hope that the design ideas demonstrated in *Surviving Extinction* will influence future development of interactive digital learning experiences.

1 Introduction

Virtual field trips (VFTs), in various forms, have more than 20 years of history of use in geoscience education (e.g., Hurst, 1998). VFTs help to address a growing problem in geoscience education (and in other field-based subjects), which is that while learning in the field is an essential part of education it is also expensive, logistically complicated, and difficult to provide in a manner that is equitably accessible to all students (Baker, 2006; Garner and Gallo, 2005; Boyle et al., 2007; Atchison and Libarkin, 2013; Gilley et al., 2015). VFTs in science education are designed to bring students—virtually—to important field locations. This can be done through either web browser-based interfaces or through virtual reality (VR) systems (e.g., Mead et al., 2019; Klippel et al., 2020). Having the option to engage in field learning from their own computer substantially addresses the issues of access related to field learning. Comparative research has shown both browser-based and VR-based VFTs lead to equal or better learning as in-person field trips (Klippel et al., 2019; Ruberto 2018). Moreover, the option of high-quality VFTs encourages instructors to add field learning to courses without any prior field components.

Effective teaching and learning about paleosciences—such as paleontology, historical geology, and the study of evolution—relies on good examples from the historical record (Kastens et al., 2009; De Paor and Whitmeyer, 2009; Petcovic et al., 2014; O'Connell et al., 2021). Whereas in-person field trips are limited to sites within a certain distance from school or home, VFTs have no such limitation. They can also allow students to learn from scientists who conducted research at a particularly significant site. Field learning is valuable in part because of the opportunity to not only learn scientific concepts, but to learn about the scientific process that led to our current scientific understanding. The unique affordances of VFTs make them an important part of the instructional toolkit across all field-based sciences.

In the present study, we describe a new VFT called *Surviving Extinction*. *Surviving Extinction* teaches scientific concepts related to vertebrate evolution, ecology, adaptation, and mass extinction. It also builds on our previous VFT work through a novel combination of both simulated environments and actual captured imagery and through the use of gamified elements.

2 Pedagogical framework

The design of *Surviving Extinction* builds on the foundation of previous VFTs developed by our group (Mead et al., 2019; 2020; https://vft.asu.edu). In that prior work, we made a distinction between a VFT and what we termed an iVFT (immersive, interactive virtual field trip), with the latter being distinguished by greater interactivity and the use of adaptivity to allow the iVFT to respond intelligently to student actions. In short, iVFTs work to encourage active learning within interactive and graphically rich 360° environments where the students are guided by adaptive feedback. This strategy is well-supported by previous research into effective pedagogy, which we will briefly summarize.

Underlying all of the pedagogical ideas that follow is the fundamental importance of field learning to field-based sciences. There is a strong consensus among practitioners that field learning is distinctly valuable (e.g., Petcovic et al., 2014). Prior research on in-person field learning has also shown it to provide substantial benefits to content learning (Easton & Gilburn, 2012) and understanding of the process of science (Patrick, 2010); to positively influence persistence in STEM degrees (Kortz et al., 2020); and to result in positive affective domain outcomes (Boyle et al., 2007; van der Hoeven Kraft et al., 2011).

Most importantly, it is now well-documented that active learning leads to better outcomes than passive learning (e.g., Freeman et al., 2014; Chi & Wylie, 2014; Hake, 1998). The interactive design of *Surviving Extinction* means that students are nearly always active in their learning. As we will describe in detail in the next section, this active learning takes the form of students seeking out information about new animals in each scene and using what they have learned about their various traits to make decisions about which evolutionary lineages to follow when moving between scenes.

The advantages of active learning notwithstanding, it can be challenging to effectively implement in asynchronous learning environments when the human instructor cannot provide real-time feedback. Thus, *Surviving Extinction* is also designed to respond automatically and adaptively to the student's actions. Although it is not as complex as most intelligent tutoring systems, the adaptivity used in *Surviving Extinction* should still provide some of the benefits observed in those systems (e.g., VanLehn, 2011).

In addition to these more general pedagogical concepts, the design of *Surviving Extinction* was informed by the educational and motivational value of immersive and interactive media. The educational value of sophisticated VFTs is fairly well established at this point (Ruberto, 2018; Mead et al., 2019; Zhao et al., 2020; Klippel et al., 2019). It may be surprising that, in a study comparing an in-person field trip to a very closely parallel VFT, Zhao et al. (2020) found that the VFT led to higher student enjoyment and satisfaction in the field trip as compared to students in the in-person field trip. Place-based education is also an important part of VFT designs and one that follows from the interactive, 360° imagery.

Another way that iVFTs and *Surviving Extinction* raise engagement and motivation is by building and leveraging sense of place. In this context, "place" refers to a socially constructed combination of landscape, culture, and personal attachments (Brandenburg and Carroll, 1995; Cresswell, 2015; Semken et al., 2017). The combination of high-resolution imagery and interactivity helps students to understand the physical spaces captured by the iVFTs, while the scientific content and the human perspectives provided by the researchers who are featured help students to see these locations as *places*.

The first of two substantial advances made in *Surviving Extinction* is its use of simulated environments, by which we mean digital reconstructions of ancient environments. Whereas previous iVFTs designed by our group have primarily used imagery collected from real world geologic field sites, *Surviving Extinction* is made up primarily of simulated (reconstructed) environments that depict ecosystems as they might have been millions or hundreds of millions of years in the past, including scientifically informed landscapes, plants, animals, and even sounds. *Surviving Extinction* includes real world sites as well, but each one must be discovered through a simulated environment. This linkage between the simulated environments and modern day sites helps emphasize the connection between the fossil evidence we see today and the historical time period during which the animals that left those fossils lived. This also provides additional depth to each student's sense of place for these sites.

The second major advance is *Surviving Extinction*'s use of gamification, which, in the case of education, means to employ features commonly found in games to improve learning outcomes (Deterding et al., 2011; Landers et al., 2018). Such features can include an interactive narrative or explicit progression systems (e.g., points, new abilities/options, or new locations to discover). The value of gamification is often framed as following from self-determination theory (Ryan and Deci, 2000), i.e., the gamified elements allow students to feel a sense of autonomy and accomplishment through their actions in the learning experience. A recent meta-analysis of gamification in learning found it to have a small effect on both cognitive (Hedge's g = 0.49) and motivational (g = 0.36) outcomes (Sailer and Homner, 2018). For *Surviving Extinction*, gamification provides multiple distinct benefits. Through these features, students receive immediate and engaging feedback on their conceptual understanding of competition within ecosystems. On the narrative level, by taking on the role of a particular animal at each point in history, they may even see these scenes through that animal's eyes, thus adding an additional dimension to their sense of these historical scenes as places.

3 Learning objectives and learning design

3.1 Learning objectives

The key learning outcomes for *Surviving Extinction* are for learners to be able to:

1. Recall, describe, and order key events (such as dominant animals and mass extinctions) in history from 350 Ma to present.
2. Recognize and categorize key mammalian and reptilian adaptive traits.
3. Explain the benefits of specific adaptive traits for species survival.

At the undergraduate level, the topics covered in *Surviving Extinction* are relevant to the material typically included in a historical geology course in undergraduate geology programs. It is similarly relevant to introductory paleontology or to geology courses for non-geology majors and it would be appropriate as a supplementary activity in biology courses talking about evolution. At the high school level, *Surviving Extinction* is directly appropriate to teaching adaptation, a key topic in biology and one of the disciplinary core ideas in the NGSS (Next Generation Science Standards), a set of K–12 science teaching standards widely used in the United States (NGSS Lead States, 2013). In addition to these content learning outcomes, Surviving Extinction embeds independent decision making by rewarding students for making sound decisions based on the information presented throughout the experience.

3.2 Learning design

3.2.1 Design innovations

Like other iVFTs produced by our group, *Surviving Extinction* is built around spherical images in which the learner is free to rotate their viewpoint in 360°, to zoom in/out, and to click on a variety of interactive elements that vary from scene to scene or even within the same scene in response to student actions (Figure 1). The majority of scenes in *Surviving Extinction* are built with realistic-looking and scientifically accurate recreations of what environments might have looked like (and even sounded like) at points from 350 million years ago (Ma) to the more recent past. The learning design within these scenes emphasizes the traits of each animal and each animal's place within the ecosystem. In addition to these simulated environments, *Surviving Extinction* includes 360° spherical imagery and other media assets from 10 real world sites where paleontological research has been conducted. The learning design within these scenes calls back to the lessons learned in the simulated environments, but also emphasizes the scientific process of discovery. These real world sites are also directly analogous to our prior work (e.g., Mead et al., 2019).

The design of *Surviving Extinction* includes several examples of gamification (Deterding et al., 2011). These include the use of coins (i.e., points) as rewards for correct answers, the progressive discovery of new animals and time periods, the discovery of hidden elements such as the real world iVFT locations and the summative challenge activities, and the tracking of progress between multiple "play throughs". These elements are reinforced with visual feedback and a tracking screen where students can view their progress (Figure 2). Related to gamification, *Surviving Extinction* also has a stronger narrative component than our previous iVFTs, with students taking on the role of a particular animal at each location and tracking an animal lineage through time.

Beyond the expected motivational benefits of gamification, the way it has been employed in *Surviving Extinction* also makes it easy for instructors to craft flexible, but meaningful assignments around this iVFT. Because the real world sites and the challenge keys are hidden, instructors can require a certain threshold for credit while still giving students substantial agency in exploring *Surviving Extinction* in ways that are interesting to them. Similarly, because coins and the student's scores on certain challenge activities are tracked, it is straightforward for an instructor to require a certain minimum score in order to receive credit for the activity.

3.2.2 Detailed description

From the student perspective, the goal of *Surviving Extinction* is to traverse a phylogenetic tree starting from a common ancestor of all modern amniotes (mammals, birds, and reptiles) 350 million years ago and moving forward in time to reach a modern animal of their choosing (Figure 3). This journey begins with the student selecting a target animal from the 12 available. *Surviving Extinction*, much like the fossil record, has more examples of certain lineages, such as birds and mammals, and fewer about others, such as turtles and snakes. Consequently, students are free to choose an easier or harder path through their journey. Since progress is saved, students are allowed and encouraged to begin a new journey after they complete their first one in order to work towards a different animal. As a reminder, the experience is freely available, so we encourage interested readers to explore it for themselves at https://vft.asu.edu/survive as a supplement to this description.

Surviving Extinction was designed to be as self-contained as possible. Therefore, it features an introductory video, a short set of text and graphical instructions at the outset, plus instructions and reminders of important features that appear during the early part of the activity. These tutorials are always accessible through an icon at the corner of each screen.

Although the details differ, students will go through the following steps at most locations within *Surviving Extinction*:

First, while viewing the tree of life, they will select the next animal and time period to learn about. Typically, they have a choice of two or more organisms to follow, each of which will be evolutionary descendants from the animal they learned about previously. They will be able to read about each animal, see their traits, and consider which group moves them closer to their ultimate goal (their modern day animal). Based on this choice, a new location and time period will be introduced, and the simulated environment of that location will load. The first step in a new location is always for the student to locate their animal in the environment. They are also free to look around the scene and learn about the other animals living at this time period.

Next, they will answer a few questions designed to encourage them to think about how specific traits allow animals to survive in a particular ecosystem. These questions are accessed, and often answered, by clicking on icons or animals directly in the scene. In addition, hidden challenges may appear depending on which locations the student has already visited.

Finally, the student can progress to the "versus battles". Presented in a faux fighting arena, students must identify their animal's ecological relationship to five other animals from the same era. Like other questions, students earn coins for correct answers. Additionally, these battle wins are saved, allowing students to see their total wins and losses throughout their playthrough. With the battles completed, students restart the cycle with a new set of descendants to choose from on the tree of life.

The main exceptions to this standard cycle are the extinction events. Indicated with red X's on Figure 2, students will find many of these evolutionary "dead ends" as they progress through *Surviving Extinction*. These locations do not offer the kind of interactivity of the non-extinction locations, but they do provide a short description of the circumstances that led to the animal's extinction, and they include one knowledge check. After revealing multiple extinctions, students should begin to appreciate the scope of the three mass extinction events that occurred during the period covered by *Surviving Extinction*. To underscore these higher-level themes, challenge questions will also appear from time to time on the tree of life screen. These questions focus on large scale trends that cut across the different time periods and locations.

As mentioned, certain hidden activities are accessible to students only after visiting a particular location or a combination of multiple locations. These include the 10 real world iVFT locations as well as the three challenge "keys" (Figure 3). The real world sites are presented as spherical images, just like the other locations, but each one presents images and video captured at a site where important paleontology research was (and is) conducted. These range from Ireland to South Africa to Argentina to the Western United States and at each site the student is guided by a scientist who has worked at the location. As in the simulated environments, students answer questions to progress through the real world sites, but whenever possible the questions are answered by observing and interacting with the rocks and fossils visible in these scenes.

Lastly, the challenge keys serve as embedded summative assessments to test students' knowledge of the three primary learning objectives of *Surviving Extinction*. First is the bronze key, which covers the geologic timeline, what vertebrate groups were dominant during each period, and when the three major mass extinctions occurred. The bronze key is unlocked once the student has explored enough locations in time to learn about each of the major time periods. Second is the silver key, which covers the distinctive traits that characterize mammals and modern reptiles. This key is unlocked once the student has explored part of both the mammalian and reptilian/avian lineages. Lastly is the gold key, which covers the survival benefits of some of the traits discussed in *Surviving Extinction*. This key is unlocked after a large number of the total lineages have been visited. Note how the silver and gold keys both require students to take multiple journeys through the activity to unlock.

4 Assessment of learning outcomes

4.1 Overview of evaluation

To test the broad applicability of *Surviving Extinction*, our assessment spanned multiple age groups and educational settings (Table 1). We first performed a formative testing phase, which was an opportunity to study the usability of *Surviving Extinction* with students and to test and refine our assessment instrument. Following formative testing, we made a number of small changes to the activity in response to the feedback and we revised the assessment to gather more fine-grained information. This was followed by the summative testing, which was intended to directly answer the question of whether *Surviving Extinction* was effective in leading to its intended learning outcomes. In addition to this controlled testing, we also collected website analytics which speak to the popularity of this resource. The formative and summative testing was done using web-based survey tools and thus occurred outside of the *Surviving Extinction* experience itself.

For the formative testing, we collected data from both middle school students and undergraduate geology majors. The middle school students were participating in a week-long, online summer program held at a large public research university in Summer 2020. *Surviving Extinction* was one of several options for the students to choose. Their total time on task with the activity was about three hours. The undergraduate data collection occurred in Spring 2020. Students were enrolled in "History of Earth and the Solar System", the second course in the geology major curriculum at the same large public research university. They used *Surviving Extinction* as one of their weekly virtual lab exercises, which were completed individually. The activity was required, and students earned points based on reaching certain milestones within the experience.

In the summative testing phase, we collected data from high school students and a second group of undergraduate geology majors, distinct from the group in the formative phase. This data collection took place in Spring 2021. We conducted the summative testing in a high school (secondary school) setting and at the undergraduate level. The high school setting was a 9th grade (~15 years old) Earth Science course offered at a private high school in the Southwestern United States. At the time this study was conducted, the students had not yet covered mass extinctions or vertebrate evolution. The instructor gave students three class periods to work through the activity. Students were not given a specific requirement for progress within *Surviving Extinction*. The undergraduate setting was the Spring 2021 "History of Earth and the Solar System" course. At the time of the study, students had just completed a unit on mass extinctions. To earn full points, the undergraduates were expected to unlock and complete the bronze and silver challenge keys and do one of the following: complete the gold key, discover eight real world locations, or accumulate at least 7000 coins.

4.2 Measures and statistical analysis

Data collection in the formative phase included Likert-scale questions about students' experience with *Surviving Extinction* and, in the case of the middle school group, a short knowledge survey administered before and after using *Surviving Extinction*. We also collected qualitative data about ease-of-use from either observing students directly, in the case of the middle school setting, or talking with the teaching assistant, in the case of the undergraduate setting. In the summative testing phase, we administered the revised knowledge survey before and after the activity and, in the undergraduate setting, we collected scores from the assessments that are embedded in *Surviving Extinction*.

Both knowledge surveys were based on the overall learning outcomes of *Surviving Extinction*. They were written and refined collaboratively among the co-authors to ensure that they were appropriate for our learning goals and were scientifically accurate. The survey used in formative testing had three multiple-choice questions and two short answer questions. Although it proved to be useful for the middle school setting, the difficulty and depth of the assessment would not have been suitable for the summative testing. The final survey had five questions, each with multiple parts. Question 1 was closed-ended, employing an answer-bank format, while the other questions were open-ended. Students were given partial credit where appropriate. The survey was worth 18 points in total. CM wrote a scoring rubric and scored a subset of student surveys. SB independently scored the same set. After discussion, the small number of scoring discrepancies were resolved and all surveys were scored by either CM or SB. The final survey and scoring rubric are provided in the supplementary materials. Referring to the learning objectives listed in section 3.1, Questions 1, 2, and 3 provide evidence of Learning Outcome 1 and Questions 4 and 5 each provide evidence of Learning Outcomes 2/3.

In accordance with common reporting standards (APA, 2020) we report effect sizes (Cohen's d) alongside the results of tests of statistical significance (t-test). Unlike the t-test, which is highly sensitive to sample size and provides no indication of whether the observed difference is meaningful, measures of effect size speak to the magnitude of a change and are useful for comparing across studies. The magnitude of this type of standardized mean difference measure of effect size is commonly compared against the "small" (> 0.2), "medium" (> 0.5), and "large" (> 0.8) categories proposed by Cohen (1988). Such rules of thumb are convenient, but it is useful to also compare results against studies from the subfield in question (Schäfer and Schwarz, 2019). Two recent studies of iVFTs compared outcomes against in-person field trips. Klippel et al. (2019) found the iVFT condition earned higher lab grades with an effect size of 0.7, while Ruberto (2018) found the iVFT condition showed greater pre- to post-trip learning gains with an effect size of 0.59. Although our design does not compare outcomes against an in-person field trip, these numbers along with Cohen's categories can be used to evaluate our results.

4.3 Formative testing results

We received 30 valid responses from the middle school students and eight for the undergraduates. On seven-point Likert scales, nearly all students in both groups reported that *Surviving Extinction* was interesting ($M_{m\text{-}s} = 6.3$; $M_{u\text{-}grad} = 6.7$) and an effective learning experience ($M_{m\text{-}s} = 6.3$; $M_{u\text{-}grad} = 6.2$). A majority also reported that it was easy to use ($M_{m\text{-}s} = 5.9$; $M_{u\text{-}grad} = 4.3$), but the students clearly found some issues with usability. Additionally, the undergraduates were asked if they would like to see more activities like this in their courses, to which all students either responded positively or neutrally (M = 5.8). The middle school students (n = 28) showed significant improvement on their knowledge survey scores pre- to post-activity ($M_{pre} = 2.9$ [6 points maximum], $SD_{pre} = 1.4$, $M_{post} = 4.1$, $SD_{post} = 1.1$, $p < .001$). This represented a "large" effect (d = 0.94). From comments on the survey and our own observations, we identified several ways that the usability of the activity could be improved. These included changing some instructions, particularly near the start of the activity, and changing parts of the user interface to make it more obvious how to move forward in each exercise.

4.4 Summative testing results

Results from both the high school and undergraduate testing showed significant and substantial learning gains pre- to post-activity. Individual pre- and post-activity scores are plotted by group in Figure 4 and shown also in Table 2. Across the two groups, roughly 80% of students showed a score increase. In the high school sample (n = 50) scores increased by 2.4 points on average ($M_{pre} = 4.8$, $SD_{pre} = 2.4$; $M_{post} = 7.3$, $SD_{post} = 2.8$). This shift is statistically significant based on a paired t-test ($t = 6.66$, $p < .001$) and represents a "large" effect size (d = 0.94). In the undergraduate sample (n = 20) scores increased by 2.1 points on average, but from a higher pre-activity baseline than the high school group ($M_{pre} = 10.4$, $SD_{pre} = 3.1$; $M_{post} = 12.4$, $SD_{post} = 3.6$). This was also statistically significant ($t = 3.94$, $p < .001$) and represents a "medium" effect size (d = 0.62). Because the undergraduate students had received previous instruction on mass extinctions, these gains represent learning above and beyond typical instruction in this course. These effects are also comparable to or larger than other recently published results (Klippel et al., 2019; Ruberto, 2018). We present the results by learning objectives in Table 2. The gains were slightly stronger for the first learning objective, but were nonetheless significant across the objectives.

In support of the knowledge survey data, we also examined the progress data generated directly from *Surviving Extinction*. As described previously, the iVFT tracks student progress and success in several ways and presents this information to the student as shown in Figure 3. In the undergraduate testing, the course instructor asked students to submit a screenshot of this screen as part of their assignment. We were able to analyze screenshots for 16 of the 20 students. If use of *Surviving Extinction* leads to learning gains (hence high post-activity scores), then we would expect scores on the embedded assessments to be correlated with post-activity scores. To test this, we calculated Pearson correlation coefficients between the post-activity score and each of: the number of real world sites visited ($r = .72$, $p = .001$); the number of challenge keys unlocked and completed ($r = .66$, $p = .005$); and the number of total coins earned ($r = .68$, $p = .004$). In other words, students who completed more of *Surviving Extinction* (higher numbers of sites and keys) and students who were careful and attentive during these explorations (higher numbers of coins) were likely to earn high post-activity scores. This finding provides strong evidence that it was the *Surviving Extinction* activity itself that led to the learning demonstrated on the knowledge survey.

These results provide a strong indication that the *Surviving Extinction* iVFT is an effective tool for teaching students about the history of vertebrate evolution on land, the history and causes of mass extinction, how competition and adaptation explain key mammalian and reptilian traits. It is also important to note that we found significant learning in two groups with substantially different levels of prior knowledge. On our 18-point knowledge survey, the high school students averaged only 4.8 points pre-activity while the undergraduates averaged 10.4 points. This finding supports our claim of *Surviving Extinction*'s broad applicability.

4.5 Usage statistics

Using website analytics, we are able to report on the number and geographic region of people who have accessed *Surviving Extinction*. Since its public release May 2020, the activity has been launched more than 12,000 times by users in 95 countries.

5 Discussion of practical implications

Surviving Extinction, along with many other iVFTs, are free to use at the URLs provided: https://vft.asu.edu/survive/ and https://vft.asu.edu/. Our design was intended to accommodate undergraduate students, such as introductory level Earth science majors and general education non-science majors, as well as high school science students. However, because of the wide appeal of vertebrate paleontology (and dinosaurs), we expect it will also be engaging for pre-high school students (such as those in our formative testing phase) and the general public.

Surviving Extinction is amenable to a variety of classroom uses. These include synchronous use in a computer-enabled classroom or as an independent activity for students. Because each student can take a distinct path through the activity, there are also opportunities for discussion or knowledge sharing between students after spending some time with *Surviving Extinction*. For reference, in our summative testing, the undergraduate students worked independently outside of class time, while the high school students also worked independently but did so during dedicated class time.

The time required to complete *Surviving Extinction* varies. A short exploration could be done in 30 minutes, but 2–3 hours would be recommended to really understand the contrast between the mammalian and reptilian/avian lineages. In a class, this could be spread out over a week to allow for class discussions. The student choice provided makes this a good fit to a "jigsaw" discussion (Aronson, 1978) whereby students share their own explorations and learn from each other. The embedded assessments also give instructors flexibility when assigning *Surviving Extinction*, because students can be given the freedom to choose their own path while still being accountable. For example, the assignment might require them to discover a minimum number of the 10 real world locations, find and complete a certain number of the three keys, or even earn a minimum number of coins. Mastery can additionally be judged based on students' scores on the challenge key questions. Ultimately, all of these objectives require students to explore a substantial portion of the tree of life, but this approach still offers both perceived and genuine autonomy to students.

To make *Surviving Extinction* easily adoptable, particularly at the high school level, we have written two teacher guides: one focused on mass extinctions and the other on natural selection and adaptation. These can also be found on our website at: https://vft.asu.edu/survive/teachers/index.html. Each guide follows the 5E structure (i.e., Engage, Explore, Explain, Elaborate, and Evaluate; Bybee et al., 2006). The guides include detailed student instructions and activities to support the work within the iVFT and each is accompanied by a grading key.

From a technical standpoint, *Surviving Extinction* experience runs in standard web browsers and does not require any additional downloads or installation. Because no software is installed on student computers, saving of progress is done using browser cookies. This does require that students use the same computer and browser and avoid deleting cookies between sessions if they wish to stop work and continue later.

6 Limitations

Beyond access to a computer and an internet connection, there are no specialized requirements for using *Surviving Extinction*. Nor does classroom use demand extensive preparation on the part of the instructor, although it is advisable to complete the activity in advance in order to be prepared to answer student questions.

Regarding our effectiveness data, it should be reiterated that we tested the learning experience in only two schools and with fewer than 100 students in total. Given the generally large effect sizes observed, it is very unlikely that our results were due to a measurement error, however, the limited number of testing sites does leave open the possibility that results would be less favourable at other schools or universities.

7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8 Author Contributions

ADA secured the funding for this project. All authors contributed to defining the learning objectives for *Surviving Extinction*. GB was the lead designer. WT served as a science content expert and also contributed to design. CM and SB wrote and revised the assessments, coordinated the data collection, scored, and analyzed the surveys. CM wrote the initial manuscript draft. All authors contributed to the writing of the final manuscript.

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12 Figures

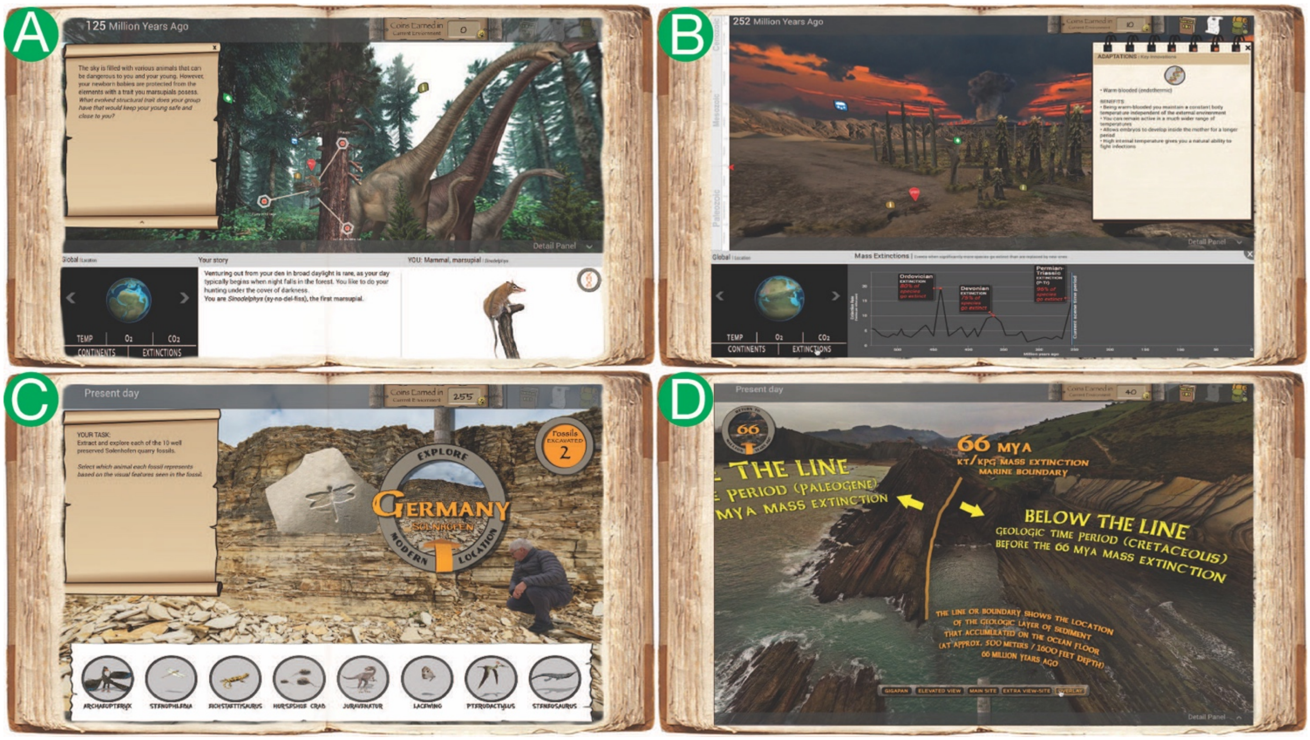

Figure 1. Representative screenshots from *Surviving Extinction*. Panels (**A**) and (**B**) show some of the simulated environments while Panels (**C**) and (**D**) show two of the real world sites.

Figure 2. A screen showing a student's progress through *Surviving Extinction*. This is shown just after starting, so none of the three challenge keys have been unlocked nor have any of the 10 real world locations been discovered.

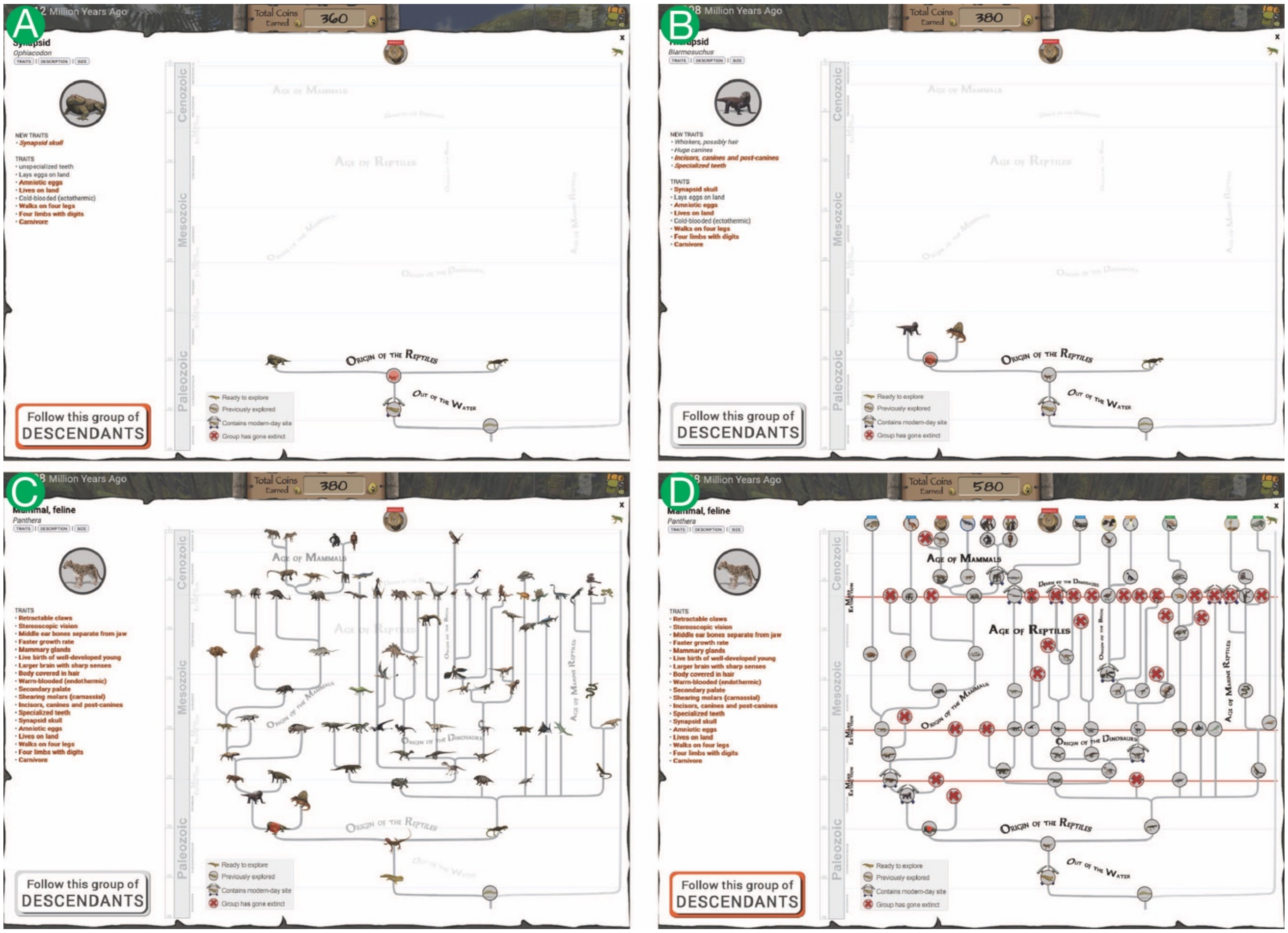

Figure 3. Images from the tree of life shown within *Surviving Extinction*. Each animal icon represents a time and location that students can visit. The tree is slowly revealed after each new location is visited (i.e., progression between panels (**A)** and (**B**)). All non-extinction event locations are shown in panel (**C**), while panel (**D**) additionally shows all extinction events (indicated by red X's) plus the locations where students can discover real world sites (indicated by crossed rock hammers). It is not expected that students would visit every location. Instead, the design goal was to include enough options to allow for genuine autonomy in the learning experience.

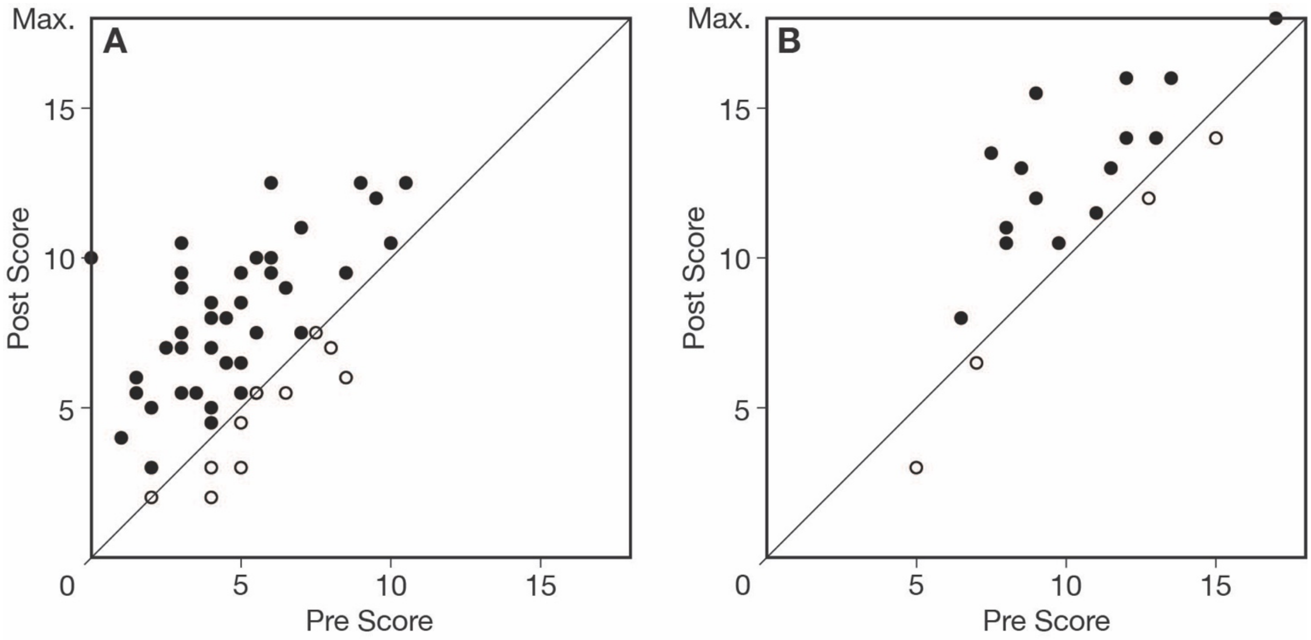

Figure 4. Pre- and post-activity scores for high school (**A**) and undergraduate (**B**) samples. A 1:1 line is plotted for reference. Students who improved pre- to post-activity are shown as filled circles. 78% of high school students and 80% of undergraduates improved pre- to post-activity. Although the undergraduates had high pre-activity scores, both groups showed similar improvements.

13 Tables

Table 1: Summary of Data Collection

Testing Phase	Student Population	Data Collection
Formative	Middle school	• Classroom observation • Pre- post-activity assessment • Attitude survey
Formative	Undergraduate geology majors	• Teacher interview • Pre- post-activity assessment • Attitude survey
Summative	High school	• Pre- post-activity assessment
Summative	Undergraduate geology majors	• Pre- post-activity assessment • Embedded assessments
Public usage	General public	• Website usage statistics

Table 2: Pre- and post-activity scores by learning objective

Population	Learning Objective	Pre-Activity Mean (SD)	Post-Activity Mean (SD)	Effect size (d)
High school	LO 1	4.0 (2.2)	6.0 (2.5) ***	0.9
High school	LO 2/3	0.8 (0.6)	1.2 (0.8) ***	0.6
High school	Overall	4.8 (2.4)	7.3 (2.8) ***	0.9
Undergraduate	LO 1	8.3 (2.4)	9.7 (2.5) **	0.6
Undergraduate	LO 2/3	2.0 (0.9)	2.7 (1.4) *	0.6
Undergraduate	Overall	10.4 (3.1)	12.4 (3.6) ***	0.6

'*' $p < .05$; '**' $p < .01$; '***' $p < .001$

14 Supplementary Materials

14.1 Summative Assessment

The assessment used in the main testing phase is shown below. Correct answers are shown in red text. The full scoring details are described in the next section.

Question 1. In the table below, select the dominant group of vertebrates on land during each period. You may use the same answer more than once. If more than one answer applies, choose the most specific group name that applies.

Time period	Dominant land vertebrate group	Answer choices (shown in dropdown)
Neogene	mammals	amphibians, archosaurs, dinosaurs, euryapsids, mammals, synapsids, tetrapods marsupials
Paleogene	mammals	
Cretaceous	dinosaurs	
Jurassic	dinosaurs	
Triassic	archosaurs	
Permian	synapsids	

Question 2. Three large mass extinction events occurred from the Permian to the Neogene periods. When did each of these mass extinctions occur? Please be as specific as you can.

251 Ma, 201 Ma, 66 Ma

Question 3. (a) Name two causes for large mass extinction events? (b) Describe in a couple of sentences how these causes directly or indirectly led to mass extinctions of animals.

a. Impacts; large igneous provinces; some other reasonable answers

b. Igneous province eruptions massively increase atmospheric dust and aerosols, sulfur oxides, and CO_2. This in turn decimates the bases of ecosystems both on land and in the oceans and on a longer time scale leads to significant global warming. Impacts can have similar dust and aerosol-related consequences.

Question 4. Mammals, reptiles, and birds share a common ancestor. What trait distinguishes these three groups of vertebrates from the animals that came before them? Describe this trait and explain why it was beneficial.

The amniotic egg. It provides a protective structure to eggs and allows these animals to lay their eggs outside of water. This ultimately made it possible for amniotes to adapt to many new niches on land.

Question 5. Although they share a common ancestor, mammals have many specialized traits that distinguish them from reptiles. List three specific traits found in mammals but not generally found in reptiles. For each, provide a brief description of how and why the trait is beneficial.

Warm-blooded (generally) — Enables nocturnal lifestyle and survival in colder climates
Whiskers/hair — Insulation and a sensory function for nocturnal lifestyle
Specialized/differentiated teeth — Allows more varied diet, more effective digestion

14.2 Summative Assessment Scoring Rubric

Question 1 (6 pt) [Learning Outcome 1]

- a-f: mammals, mammals, dinosaurs, dinosaurs, archosaurs, synapsids
- 1 pt each; 6 total

Question 2 (3 pt) [Learning Outcome 1]

- +1 pt: ~66 Ma or after Cretaceous or before paleogene
- +1 pt: ~201 Ma or after Triassic or before Jurassic
- +1 pt: ~251 Ma or after Permian or before Triassic
- - partial credit at discretion if they show some understanding (e.g., correct name, wrong date, or very approximate dates)

Question 3a (2 pt) [Learning Outcome 1]

- +1 pt: impacts/meteor
- +1 pt: large igneous province
- +1 pt: rapid, global climate change
- +0 pt: drought without suggestion of global climate change
- +0.5 pt: volcanoes without suggestion of uncommon size and scope
- +0.5 pt: climate change
- +0 pt: "natural disasters"
- +0 pt: Infection

Question 3b (2 pt) [Learning Outcome 1]

- +2 pt: answer that describes a direct link between the cause and disruption of food chains, global change, etc.
- Igneous province eruptions massively increase atmospheric dust and aerosols, sulfur oxides, and CO2. This in turn decimates the bases of ecosystems both on land and in the oceans and on a longer time scale leads to significant global warming. Impacts can have similar dust and aerosol-related consequences.
- +1 pt: answer with a partially explained mechanism
- +0 pt: answer with no clearly explained mechanism for extinction

Question 4 (2 pt) [Learning Outcome 2/3]

- +1 pt: amniotic egg
- +1 pt: lay eggs on land
- +0.5 pt: Something about living on land, but not amniotic egg

Question 5 (3 pt) [Learning Outcome 2/3

- +0.5 pt: warm-blooded
- +0.5 pt: whiskers/hair
- +0.5 pt: specialized teeth-
- +0.5 pt each: explanation of benefit

14.3 Formative Assessment

1. Which of the following groups of animals first evolved the longest ago?
    - a) Mammals
    - b) Birds
    - **c) Reptiles**
    - d) Dinosaurs

2. About how far back in evolutionary history did mammals and reptiles share a common ancestor?
    - a) About 1 million years ago
    - b) About 65 million years ago
    - c) **About 320 million years ago**
    - d) About 540 million years ago
    - e) These groups have no common ancestor

3. The image below shows a skeleton of an extinct type of cynodont

In life, this animal had the following traits: It lived in a burrow; it was warm-blooded; it had specialized teeth; and it laid eggs on land. Based on those traits, which of the following modern animals are descended from animals like the cynodont shown here?
- **a) Mammals**
- b) Birds
- c) Reptiles
- d) Fish

4. Why might an animal evolve the ability to burrow? List two benefits that an animal might gain from being able to burrow.

    [free response]

5. You may know that at times in the history of life on Earth there have been "mass extinctions" in which many, many species of animals went extinct all at once. What kinds of things could have caused a mass extinction? List as many causes of mass extinctions as you can think of.

    [free response]