1 Introduction

The term "dinosaur" was coined in the mid-19th century (Owen, 1842). Soon thereafter, dinosaurs and other extinct reptiles began to capture the attention of not only naturalists and collectors like William Buckland, Gideon Mantell, Mary Anning, and Charles Darwin, but also of a captivated public. Dinosaurs took the British Isles by storm, from the first print reconstructions of dinosaurs in *The Primitive World* (Unger, 1851), to the Crystal Palace dinosaur statuary in south London unveiled in 1854, to the public opening of the British Museum of Natural History in 1881. Since then, society has been enthralled by these animals, and has marveled at their size and diversity.

Taking advantage of this interest, many universities offer courses on dinosaurs. While some are restricted to majors, many serve as recruitment tools for biology and geology departments. This value of dinosaurs as a captivating ingress to science cannot be understated, and many geologists and biologists have come to natural sciences via the dinosaur pathway. Renewed interest in dinosaurs in response to popular cinema, television, and video games has resulted in filled lecture halls in dinosaur courses, especially with interested nonscience majors.

The South Dakota School of Mines and Technology (SDSMT) specializes in science and engineering degrees. At SDSMT, GEOL 372: Dinosaurs, is offered every spring semester. The course has no prerequisites, so despite the 300 course level, it is regularly attended by underclassmen and nonmajors. I have instructed this course since 2010. This three-credit, lecture-only course is primarily taken by geology majors, many of whom aspire to careers in vertebrate paleontology, but because course registration is not restricted, participation includes students from other science and engineering disciplines, as well as nonscience majors in the Interdisciplinary Studies degree program. The course has evolved to include a significant component of critical thought exercises, using dinosaurs as a catalyst for the development of thought processes that, ideally, benefit the students far beyond the single semester they devote to their nascent interest in terrestrial Mesozoic reptiles. This Element is presented based on experiences instructing GEOL 372, and on methods built to enhance critical thinking skills while developing and adjusting course content.

2 Critical Thought

2.1 Defining Critical Thought

The term "critical thought" (CT) is disseminated liberally from educational literature to legislative session. Facione (1990) outlined a comprehensive interpretation, including six cognitive skills (interpretation, analysis, evaluation, inference, explanation, and self-regulation) and multiple subskills (e.g., examining ideas and identifying arguments under the "analysis" skill). Numerous additional definitions of CT appear throughout the literature (McPeck, 1981; Paul, 1981; Ennis, 1987; Lipman, 1988; Siegel, 1988). All are disposed toward concepts of information processing, self-reflection, distinguishing "good" information from "bad," and generally employing a level of disciplined thought beyond the automatic thinking that occurs minute by minute, day by day.

While paleontology typically necessitates understanding facts about the history of life, these facts can be effectively used to develop a much broader set of intellectual skills than that of recognition of extinct taxa and evolutionary trends. Our goals as postsecondary educators are to motivate, spark enthusiasm, and impart the skills that make students better at interpreting not only academic information but also the additional deluge of material they face via television, the Internet, and social media. In GEOL 372, students learn a set of intellectual tools to evaluate claims and arguments. The art of baloney detection has provided an applicable model to realize this goal (Sagan, 1995; Schmaltz et al., 2017).

In *The Demon-Haunted World*, Carl Sagan (1995) promoted a comprehensive, yet user-friendly thought process for identifying poorly constructed arguments, logical fallacies, and spurious claims. Sagan (p. 197) advocated the ability to "understand a reasoned argument" and to "recognize a fallacious or fraudulent argument." This set of principles is ideal for classroom application, and the appropriate exercises can be implemented to foster these skills.

3 Dinosaurs As Critical Thought Catalysts

Because of their popularity, dinosaurs can be effective in developing critical thinking skills (Salmi et al., 2016). Students can be motivated to engage in discussion, activities, or thought exercises they would normally avoid by capitalizing on their innate interest in dinosaurs. Here I describe three methods, employing dinosaurs, by which these skills can be nurtured in undergraduates. The first is the use of dinosaur examples to exemplify logical fallacies. The second is a straightforward method to engage in evaluation of primary dinosaur literature that is friendly for even nonscience majors. Finally, I consider the evaluation of popular dinosaur documentaries and their portrayal of dinosaurs.

3.1 Logical Fallacies

An important step in understanding argumentation and logic is recognition of logical fallacies. Logical fallacies are so commonplace in modern discourse that their very definition has become broad beyond reasonable application. A general definition used here is a flawed argument resulting from faulty logic (Sagan, 1995; Hansen, 2002). More specific definitions include the formal fallacy, or those that relate directly to an argument's improper syntax, or the more common informal fallacy, which relates to the argument's content and reasoning. Although ostensibly aware of logical fallacies through their scientific training, as many as 50% of physical scientists may not employ sound logic in their arguments (Jungwirth, 1987). This percentage is likely much higher among those never introduced to the concept of flawed argumentation. Thus, recognition of logical fallacies can aid students in recognizing bad information, allowing them to be better informed and to make sounder judgments.

One of the most common informal fallacies is "slippery slope" (Floyd, 2011). In this instance the arguer falsely assumes that one event *must* lead to another. A timely slippery slope argument is that of gun control resulting in government seizure of personal firearms. The reality is that reasonable gun control measures can be effectively employed without resorting to public surrender of firearms. Table 1 lists several examples of informal fallacies in a dinosaur context.

For example, the slippery slope argument is adapted in an appeal to sensible fossil resource management. Students assess the statement that "if we allow monitored amateur collection of dinosaur fossils on public lands, then valuable dinosaur fossils will be lost to science." Students then argue the veracity of this statement, developing pro and con statements such as "yes, amateur collectors cannot be trusted to report valuable specimens even if monitored," or "no, proper safety nets can be effective for the recognition and salvage of scientifically valuable specimens." When students typically conclude that allowing monitored amateur collection on public lands does not inevitably lead to loss of valuable specimens, they are introduced to the underlying slippery slope concept. Once they understand the fallacy in a dinosaur-oriented context, they are then encouraged to provide additional, everyday examples, such as that of reasonable gun control. Students learn, recognize, and apply their knowledge of logical fallacies to current issues.

Dinosaur paleontology is rife with applicable examples of logical fallacies (Table 1). The correlative nature of the late Cretaceous bolide impact and the K-Pg extinction event, an example of the *post hoc ergo prompter hoc* fallacy, effectively illustrates the pitfalls of falsely assuming causation from correlation, even if we as paleontologists are somewhat forced to assume that correlation equals causality in a historical science. Real-world application can be found with the erroneous link between vaccination and autism. Examples of

Cambridge University Press
978-1-108-71792-2 — Dinosaurs
Darrin Pagnac
Excerpt
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Table 1 List of common informal logical fallacies from dinosaur pal

Fallacy	Definition	Example
Slippery slope	If we allow A to happen, then inevitably, B will follow.	If we allow amateur collecting on public lands, all valuable fossil resources will be lost.
Post hoc ergo prompter hoc	If event B occurred following event A, A must have caused B.	After a bolide hit Earth, dinosaurs went extinct.
Appeal to emotion	An emotional response replaces a valid argument.	I grew up with the idea that pachycephalosaurs butted heads. I refuse to accept the idea that they didn't.
False dichotomy	Two alternative states are presented as the only alternatives.	Dinosaurs were either ectothermic or endothermic.
Ad hominin	Attacking character rather than argument	Dr. Joe Velociraptor treated me disrespectfully at GSA so I don't accept his results.
Circular reasoning	Reasoning that begins with what it is concluding	This is a late Jurassic fauna because it contains late Jurassic taxa.
Anecdotal reasoning	Using personal experience in place of actual data	Every *Torosaurus* and *Triceratops* specimen looks the same, so *Torosaurus* is invalid.

Table 2 Cognitive and affective aspects of literature review

Facet to Consider	Questions to Ask
Information (Cognitive)	What is the goal of the publication?
	What is the hypothesis?
	Are the methods appropriate?
	Do the data support the conclusions?
	Was the literature cited appropriate and timely?
	Where does investigation go from here?
Delivery (Affective)	Was the paper organized clearly?
	Were the sections and headings appropriate?
	Was there enough background information?
	Was the writing style readable and informative?
	Did the figures add in a meaningful way?
	Did the author(s) appear biased in any way?

the anecdotal reasoning fallacy can be used to reinforce the axiom that the plural of anecdote is not data. The notion of personal experience as a reasonable substitute for quantifiable data is a common public misconception. Many examples within dinosaur paleontology, such as the debate over the validity of *Triceratops* and *Torosaurus* (Scanella and Horner, 2010), can be used to illustrate this concept effectively (Table 1). Using accumulated data, the authors drew scientifically valid, if unpopular, conclusions about the taxonomic validity of two ceratopsian genera. They based their results on quantitative measurements, not anecdotal observation of trends.

Further examination of anecdotal evidence also serves to introduce the concept of authoritarianism. Just because an author is a world-renowned expert on a topic does not make their publications inherently true or accurate. It is necessary, and imperative, to examine the data, methods, and conclusions behind the work. Studying the data, not the author, is an important first step in helping students understand the nature of science.

The first logical fallacy I applied to dinosaur paleontology in GEOL 372 was the appeal to emotion. While the debate over the feasibility of head-butting in pachycephalosaurs (e.g., *Stygimoloch, Stegoceras*) still ensues (Snively and Cox, 2008; Snively and Theodore, 2011), examination of this issue in GEOL 372 led students to the conclusion that this behavior was not likely in these dome-skulled ornithischians. Mechanical engineering students easily discerned the fatal shortcomings of one organic sphere impacting another. Students subsequently became agitated during this lecture. When queried why, they stated that they grew up with, and loved, the image of these dinosaurs butting heads. Despite evidence to the contrary, their sense of awe and nostalgia made it difficult for them to abandon this image. Examination of hypothetical pachycephalosaur behavior exposes one of the most prevalent logical fallacies in society, that of emotion overriding logic and data. While false dichotomies, *ad hominin* attacks, and circular reasoning apply to specific situations, appeals to emotion underlie nearly every controversial debate in contemporary culture. Using this example to illustrate this common human failing demonstrates that, 66 million years later, pachycephalosaurs, and dinosaurs overall, can still have a meaningful impact.

3.2 Evaluation of Primary Literature by Students

Upon understanding the nature of properly executed arguments, students can more effectively evaluate primary literature. Primary literature in the undergraduate classroom has come into common usage in recent decades, as it has been shown to have cognitive benefits, despite the complexity of the material (Herman, 1999; Hoskins et al., 2007; Krontiris-Litowitz, 2013). Numerous methods of evaluation are employed, such as the "jigsaw" format (Aronson, 1978; Choe and Drennan, 2001), the CREATE method (Hoskins et al., 2007), the use of companion assignments (Shannon and Winterman, 2012), or simply library resources to compare primary literature with popular science content (Chisman, 1998). The goals of using primary literature center on teaching a fundamental skill set of information retrieval, developing comfort with data and method evaluation, becoming familiar with specialized terminology and parlance, and improving the construction of argumentation on scientific topics (Hoskins et al., 2007; Gehring and Eastman, 2008; Snow, 2010).

Although these methods maximize the benefit of primary literature for majors, they commonly do not appeal to a more general audience (Gehring and Eastman, 2008; Krontiris-Litowitz, 2013). These approaches are problematic in a low-level dinosaurs course for several reasons: 1) there are rarely "paleontology majors" as no such undergraduate programs exist (students with an interest pursue a degree in biology, geology, or other related field); 2) the dinosaur literature contains a combination of biology and geology content that is often not completely accessible to students focused on only one of these disciplines; 3) many dinosaur courses are populated by students with an avocational interest in the topic, especially nonscience majors. The specialized content of dinosaur literature, including anatomy, physiology, ecology, stratigraphy, taphonomy, and geologic time, must often be presented to undergraduate majors who have yet to encounter much of this specialized information. Nonscience majors have none of this background, and considering current popular portrayal of dinosaurs, have likely been exposed to erroneous information.

"Cognition" and "affection" comprise two of the primary components of Bloom's hierarchical taxonomy of educational objectives (Anderson and Kraftwohl, 2001). In GEOL 372, literature evaluation is broken into two parts, cognitive and affective facets of the paper in question (Table 2). To address the cognitive side, students consider only the information contained within the paper, asking the question "what did this paper tell me?" Evaluating cognitive content is typical of evaluation conducted in any required major course. In group discussion students assess the goal of the publication, the hypothesis, methods, etc. (Table 2). Thus, they directly evaluate the credibility of the research, the applicability of the methodology, and whether the conclusions are supported by the data. Consideration of the cognitive facets of the publication allows students to engage in typical evaluation based on conventional scientific methods, a procedure that appeals to science majors and familiarizes the nonscience majors with the process.

Based on my observations, engineering or nonscience undergraduates in GEOL 372 generally appeared laconic in group literature discussion. Direct inquiry and course evaluations revealed that these students were uncomfortable with the content of the publications and believed themselves unable to meaningfully contribute to discussion. Subsequently, review of my own course evaluations revealed that, even if unfamiliar and uncomfortable with course content, any student could critique the *delivery* of the material. I then began to encourage students to evaluate the affective portion of primary literature.

When considering the affective side of literature review, students pose the question "how did I react to the paper?" They are asked to gauge their internal reactions to the publication presentation and to consider these factors independently of the technical content (Table 2). When evaluating the affective side of a publication, students consider organization, background information, writing style, figure presentation, and logical flaws or biases. Even if students are unable to assess the scientific content of the paper, they can estimate the author(s) attempts to communicate clearly and effectively.

This cognitive and affective approach is typically employed by devoting class time to one "good" article and one "bad." "Good" articles are based on sound hypotheses, methods, and appropriately conservative conclusions supported by the data. "Bad" articles characteristically contain incomplete or inappropriate methods, poorly formulated hypotheses, or extrapolated conclusions that stretch the data beyond relevancy. By comparing publications, students can directly contrast effective versus flawed examples. Individuals with a science background can communicate the value of logical conclusions based on robust data to nonscience majors. Conversely, those with more experience in nonscience fields are often more willing to critique the stylistic choices of figures, the organization, or the approachability of the writing style.

A popular publication for in-class consideration involves an examination of a proposed mechanism for the origin of flight in birds. The purpose herein is not to critique the work, so the publication is not referenced. The author suggests that flight evolved when eumaniraptors (e.g., *Deinonychus*) leapt on the backs of large herbivorous dinosaurs. The predators inflicted wounds with their pedal claws or teeth and leapt to safety. Examination of the content of the paper reveals several flaws apparent to science majors, most notably that the geologic timing is off (eumaniraptors existed long after flight evolved in birds), and that modern analogs (*Gulo gulo*, the wolverine) are not effective surrogates for eumaniraptors. The nonscience majors can point out flaws based on delivery of the material, such as the inapplicability of the figures to the text, or that the author is “cherry-picking” information to support his/her hypothesis rather than using sound arguments (e.g., Because *Gulo gulo* is known to jump on the backs of elk, *Deinonychus* likely did as well). This twofold approach to literature evaluation not only facilitates full participation regardless of educational background but also allows for an effective exchange of viewpoints maximizing the critique of the paper and emphasizing the critical thought approach employed in baloney detection. Students are then encouraged to employ this approach whenever faced with new information on a day-to-day basis.

3.3 Dinosaur Documentaries

The current state of science documentary has been described as the “rotting carcass of science TV” (Campbell, 2016, p. 1). Paleontology documentaries, particularly those about dinosaurs, are generally regarded among scientists as exceptionally guilty of poor quality. *Walking with Dinosaurs* (2000), which received lukewarm reception from paleontologists, ushered the dinosaur documentary into the 21st century. Since then, science networks have been inundated with a variety of documentary forms, from more well received entries like *Prehistoric Monsters Revealed* (2008), to the fantastically outlandish *Jurassic Fight Club* (2008) series. Paleontologists criticize several aspects of dinosaur documentaries, including out-of-context quotations, rampant speculation, and outright dishonest editing (Wedel, 2009a, 2009b). Theropod paleontologist Thomas Holtz has written of the 2009 documentary *Clash of Dinosaurs*: "The documentarians often [took] anything that any of the talking heads [interviewed paleontologists] speculated about and transformed these into declarative statements of fact. In some cases, this [was] particularly egregious" (Wedel, 2009a).

Documentary films can, however, serve useful purposes. Science television acts as a translator or middle man exposing a vast audience to some form of scientific fact, albeit fact that may be heavily adjusted to accommodate drama and ratings. Dissection of the gap between documentary claims and fact can serve as a useful tool for examining the public perception of science (Clemens, 1986; Suleski and Ibaraki, 2009; Miller, 2014), especially among nonscience students who may be less familiar with scientific methods. In GEOL 372, dinosaur documentaries are examined in this way, primarily through the examination of how dinosaur appearance reflects scientific knowledge, and through the distinction between storytelling and science.

3.3.1 Dinosaur Appearance and Scientific Knowledge

Public perception of dinosaurs is undoubtedly influenced by popular sources. Our mental images are set early in childhood by books, movies, and documentaries that lag cutting-edge science, sometimes by decades. Ross et al. (2013) showed that despite decades of scientific knowledge to the contrary, elementary, middle school, and college students still drew *Tyrannosaurus* with an outdated, upright posture. They concluded that outdated popular books only accounted for part of this perception and that cultural inertia led to outdated concepts that remained in public consciousness even though scientific advancement had abandoned these ideas. Television documentaries and movies may contribute to this phenomenon.

Close examination of these disparities in dinosaur appearance can reveal the subtle interplay between science and mass media. For example, when examining dinosaur posture and locomotion in documentaries, students are asked to assess their perceived validity of depictions of dinosaurs and the scientific basis for these depictions. They are encouraged to ask questions such as "how do we know *Tyrannosaurus* could pursue prey with a running gait?" or "what is the evidence for vertical neck posture in *Brachiosaurus*?" They then engage in exercises intended to supply supporting or contradictory evidence of these imagery assertions. For example, they will compare the superficial femoral anatomy of *Tyrannosaurus* with that of modern vertebrates, including horses, coyotes, and elephants. Close comparison of a tyrannosaur femur with those of cursorial horses and coyotes shows little similarity in appearance, but the lack of a femoral neck and columnar appearance mimic the graviportal condition seen in the elephant femur. Further examination of the speed and gait of elephants reveals a top speed of only 15 mph at a modified walk, not a run (Hutchinson et al., 2003). Students conclude that *Tyrannosaurus*, larger than an elephant, was not capable of rapid movement at all, a conclusion supported by experimental data (Hutchinson and Garcia, 2002).

A similar argument is undertaken with *Brachiosaurus* neck posture. Despite evidence refuting a nearly vertical orientation in sauropod necks (Stevens and Parish, 1999; Taylor et al., 2009), *Brachiosaurus* is regularly depicted with a vertical neck. Students are then asked to explore the disparity between dinosaur appearance and empirical data, and to entertain the possible motivation for continued depictions of vertical neck posture. Students have regularly suggested that dramatic aesthetic may have a greater influence on dinosaur imagery than actual science. This important concept of appealing to aesthetic or melodrama rather than presenting information based on data provides a lesson about the presentation of any information in a mass-disseminated format.

3.3.2 Storytelling in Dinosaur Documentaries

Like them or not, television documentaries are the medium through which much of the public is exposed to science. Paleontology is particularly prone to disproportionate public perception through television and social media because much of what paleontologists do can be difficult to bring to the public. While museums and traveling exhibits are popular, much of the everyday work in paleontology, remote dig sites, fragmentary samples, heavy and fragile skeletal elements, and esoteric statistic and modeling analyses is challenging, physically and conceptually, to present in an outreach setting. Thus, it benefits us as scientists and educators to critically examine the role documentaries play in the dissemination of science. Students, particularly nonscience majors, should be exposed to this examination themselves to observe firsthand the beneficial and detrimental facets of mass-circulated science education.

Much of the criticism surrounding dinosaur documentaries revolves around storytelling. Science education typically involves a paradigmatic, or logico-scientific approach (Bruner, 1986; Avraamidou and Osborne, 2009; Dahlstrom, 2014). Paradigmatic communication entails the exchange of abstract ideas,