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Published in:
NorDiNa: Nordic Studies in Science Education

Publication date:
2019

Citation for published version (APA):
Estrup, E. J., & Achiam, M. (2019). The potential of palaeontology for science education. *NorDiNa: Nordic Studies in Science Education*.

Download date: 20. sep.. 2019

The potential of palaeontology for science education

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Abstract. Science education frequently portrays science as a monolithic and experimental endeavour. Here, we argue that to counteract this simplistic conception of science, a reintroduction of the historically oriented sciences is in order. To this end, we analyse the discipline of palaeontology and its educational relevance. Using Kuhn's disciplinary matrix, we deconstruct palaeontology into elements for educational purposes, and subsequently examine how these elements can be utilised to enrich contemporary science curricula. We conclude by discussing how including palaeontology in science education encourages diversity, pluralism, and ultimately, public interest in science.

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Present-day science education does not reflect the richness and pluralism of the scientific endeavour. Many primary and secondary school students encounter a version of science that is monolithic and mainly experimental. This simplistic view of science may discourage or even exclude children and youth from considering a science education trajectory; ultimately, it may even contribute to undermining public confidence in science. In the following, we describe and substantiate this problem in further detail with particular attention to the Nordic context. We then develop our proposal, namely that science curricula at the primary and secondary levels can be enriched through a renewed consideration of the so-called historical sciences, exemplified here by palaeontology. Our proposal is based on a deconstruction and reconstruction of palaeontology, and leads to concrete suggestions for activities in schools, teacher professional development, and in out-of-school environments. We conclude by discussing the implications of a reintroduction of palaeontology for increased inclusion in science education. The intended readership of this text includes not just science teachers, whom we hope will be inspired by the richness of palaeontology and the historical sciences, but also out-of-school science educators, teacher trainers and curriculum developers at the national level.

The Science in Science Education

The natural sciences aim to understand the world through the accumulation of empirical evidence, acquired through observation and experimentation. Across the sciences, knowledge production is based on these two ways of gathering evidence; however, the relation(s) between observing and experimenting on one hand, and creating abstract, theoretical knowledge on the other, differ significantly both between and within the disciplines. This relation, the scientific method, can be divided into two general families: *Inductivism* and *hypothetico-deductivism* (Andersen & Hepburn, 2015). Inductivism reflects the view that observations and experiments precipitate the construction of hypotheses and theory; hypothetico-deductivism reflects the view that the theoretical hypothesis goes before the experiment or observation. Although neither family of methods can alone explain knowledge production in any scientific discipline (Forber & Griffith, 2011), many disciplines identify strongly with one account or the other. For instance, geology and palaeobiology make extensive use of the inductive method, because they deal with past events and/or events that cannot be replicated; thus, they are often termed *historical sciences*. Molecular biology and chemistry, for example, make extensive use of the hypothetico-deductive method because they deal with the controlled replication of events in laboratory settings; accordingly, these disciplines are often called *experimental sciences* (Cleland, 2002; Jeffares, 2008). However, the two approaches do not map directly onto the scientific disciplines; most disciplines use both experimental and historical methodologies (Forber & Griffith, 2011).

Yet, there is a tendency within science education to portray science as a step-by-step process of hypothesis testing that is fundamentally experimental (Bauer, 1992). For example, Blachowicz (2009) and Woodcock (2014) demonstrate how, in Anglo-American education resources, scientific method is often reduced to a sequence of steps that reflect the hypothetico-deductive method, e.g. forming hypotheses and testing them through experiments. Similar results have been found in education resources from Turkey (Irez, 2016), Brazil (Pagliarini & Silva, 2007), and China and Hong Kong (Cheng & Wong, 2014). Although some simplification is required for pedagogical purposes, representing scientific method in education as a universally applicable, mainly experimental, stepwise procedure seems both inadequate and misleading (Ault & Dodick, 2010; Woodcock, 2014).

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The Nordic situation

A similar issue may be at stake in the Nordic countries. At the upper secondary school level, national frame curricula in Finland, Norway, and Sweden reflect a view of chemistry as an experimental science that follows a series of steps including formulating a hypothesis and conducting an experiment (Vesterinen, Aksela, & Sundberg, 2009). Similarly, upper secondary school textbooks in Finland and Sweden portray chemistry as an exclusively experimental science, even though scientific claims in chemistry are also produced through other methods (Vesterinen, Aksela, & Lavonen, 2013). In Denmark, no systematic studies have been carried out at the upper secondary level, but a quick glance in the influential textbook *Fundamentals of natural science - an introduction to scientific methodology* for upper secondary school shows the scientific method described as the formulation of a hypothesis and the subsequent experimental testing of it (Marker, Andersen, Pedersen, & Samsøe, 2012, p. 8). Other Danish textbooks have more nuanced formulations, i.e. *there is no one scientific method for the development of new theories; nor do scientists use only one method when they carry out scientific work* (Lund et al., 2010, authors' translation).

At the primary/lower secondary level, Johansson and Wickman (2012) demonstrate how the Swedish science curriculum has a more open view of scientific method, describing it as *the formulation of (simple) questions as well as plans for the systematic investigation of them* (p. 204; our translation). In contrast to this, the focus on problem-based education at the Danish primary/lower secondary level has led to increased use of Inquiry-Based Science Education (IBSE). In a position piece, Østergaard, Sillasen, Hagelskjær, and Bavnhøj (2010) argue the merits of the IBSE approach, sketching it in terms of the following four steps: definition of problem, construction of hypothesis; investigation; conclusion, validation, and contextualisation (p. 28, our translation). While the positive results reported by these authors are laudable, the stepwise account of scientific method embodied by the IBSE method remains potentially problematic. Finally, Knain (2001) describes how Norwegian textbooks for the lower secondary level represent scientific method as *a three or four step procedure, which mimics hypothetical-deductive method* (p. 324).

Although this review gives a brief and somewhat sporadic overview of the situation, it does show that the scientific method is described as a stepwise, experimental, hypothesis-testing procedure in science education curricula and resources in the Nordic countries. Because

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curricula and textbooks strongly influence teachers' practices (Binns, 2013), we assume that taught science in many cases has a similar, oversimplified representation of scientific method. This is problematic for several reasons. Learners may come to equate the practice of formulating and testing hypotheses in controlled laboratory settings with science as certain, precise, and predictive (Gray, 2014; Sharma & Anderson, 2009). This simplistic conception of science makes the uncertainties of scientific claims made by for example climatologists easy targets for those who wish to undermine them, ultimately weakening public confidence in science at large (Frodeman, 1995; Rudolph, 2007). Furthermore, the simplistic view of science as a dispassionate and depersonalised sequence of steps, rather than an authentic human adventure, may dehumanise science among learners and ultimately, in the public eye (McComas, 2008). But why does this skewed account of science exist?

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Historical/Experimental Divergence

As mentioned in the preceding sections, the natural science disciplines exist on a spectrum from experimental to historical based on their different methodologies and epistemologies, which reflect different views of the world, of nature, and of science. In the following, we explore the reasons behind the divergence between the historical and experimental approaches.

Cultural-historical reasons for the historical/experimental divergence

Historically, the natural sciences have fluctuated between more theoretical approaches beginning with Aristotle in ancient Greece, and more empirical approaches, founded in the 17th century by Francis Bacon as a consequence of the many collected exotica appearing from the new world. Since then, the two approaches have alternated. Kant's and Newton's views on science and nature as purely objective unities in the 18th century were gradually subsumed by the perspectives of the 19th century natural philosophers Dilthey and Windelband, who viewed science as having more subjective elements, represented by the knowledge, values and even emotions of the executive scientist (Baron, 2004). The pendulum swung back towards logical positivism in the 20th century when Karl Popper introduced the philosophical tool of empirical falsification, ultimately supporting the view of science as having only one universal method. And in the mid 20th century, science philosopher Thomas Kuhn (1922-1996) established the term paradigm as a concept to explain the shared views and values of a given scientific environment, ubiquitously influencing the work of the researchers, and allowing only rare scientific revolutions – paradigm shifts – to mentally open up the world of science to new ways of thinking. On the backdrop of these fluctuating currents, we can see the present-day focus on nanotechnology and the industrial use of scientific results as a return to the more theoretical analytic philosophy of what today is widely considered as the one and only scientific method: The experimental approach (Baron, 2004; Cleland, 2002).

Epistemological reasons for the historical/experimental divergence

In addition to the cultural-historical explanation described in the preceding section, the divergence between historical and experimental approaches to science is caused by their two distinct ways of constructing hypotheses and validating evidence (Cleland, 2011; Gray, 2014). The experimental method sets up controlled laboratory settings and predicts the outcome. Consequently the experiment can be repeated a number of times in an attempt to avoid false positives or false negatives, which gives the results an appearance of falsification. However, this appearance is deceptive, since true falsification, or proof of validation, can never be obtained for certain. No matter how many times one repeats the experiment, it will always be subject to effects from the environment or chance (Cleland, 2002).

In contrast, the historical method takes a point of departure in several hypotheses, of which one is potentially more likely than the others. The quest for this one hypothesis in the traces of the past events can be compared to a criminal investigation, with the advantage of what Cleland (2001, 2011) calls *the time asymmetry of causation.* This is the phenomena of an event leaving a multitude of traces of its existence after the event, but none before the event. This gives the historical scientist an explanatory advantage (depending on the state of preservation and the number of traces left and found), compared to the experimental scientist trying to predict the future – which is of course impossible. It is obviously not possible, either, to gain certain knowledge of what happened in the past. One can only know what is most likely to have happened in the past, in terms of parsimony. This comparison at least leaves both the historically and the experimentally oriented sciences without definite ways to prove their results, but with very different methods to attempt to do so (Cleland, 2001, 2002, 2011).

In summary, the exploration of the divergence of historically and experimentally oriented sciences points to the following conclusion: Although the historically oriented sciences seem to be at a disadvantage in contemporary society in terms of perceived relevance and validity,

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there is no reason to exclude the historical approach from our discussions of science. On the contrary, the historical sciences have an important role to play in creating a more realistic and complete version of science and scientific method among learners (King & Achiam, 2017). In the following, we substantiate this argument employing the discipline of palaeontology, but we believe our thesis could be supported by any of the historically oriented sciences. Furthermore, we discuss the implications of a stronger presence of palaeontology in science education, both inside and outside school. Throughout this text, we address science education at the primary and secondary school level, but we believe this problem goes beyond the school system and into the larger public.

The Discipline of Palaeontology

Palaeontology is the scientific study of prehistoric life through investigations of its fossilized traces, located between the study of life (biology) and the study of the sedimentary rocks wherein the fossils are embedded (geology). It originated in ancient times and emerged in Europe in the 1600s as a part of natural philosophy. An important milestone was Steno's thought that Earth is not an unchangeable unit, but contains geological layers representing different time eras, with the oldest layers at the bottom and potentially containing fossilized life from the represented era. The consciousness of geological deep time and life following a succession of layers, along with Cuvier's foundation of comparative anatomy in the late 1700s, paved the way for Darwin's controversial publication *On the Origin of Species* in 1859. Palaeontology subsequently became an independent discipline in the late 1800s. In the following, we analyse the discipline of palaeontology to elucidate its educational significance.

Educational significance

The term educational significance is part of the Model of Educational Reconstruction (MER) designed to scrutinise areas of science to gauge the merit of including them in teaching and dissemination (Duit, Gropengiesser, & Kattmann, 2005). It has been used in a number of different disciplines, e.g. nanoscience, where Laherto (2010) used MER to evaluate the utility of incorporating nanoscience and technology into curricula, or cell biology, where Riemeier and Gropengießer (2008) used it to clarify the subject of cell division for the design of teaching/learning sequences. It has three main components: 1) Clarification and analysis of science content, 2) Research on teaching and learning, and 3) Design and evaluation of

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teaching and learning sequences. Here, we employ the first component, clarifying paleontological content in order to elucidate its educational significance.

We approach the discipline of palaeontology using Kuhn's notion of a disciplinary matrix, consisting of the *symbolic generalisations*, *metaphysical presumptions*, *values*, and *exemplars* shared by its community of practitioners (Kuhn, 1962). A discipline's symbolic generalisations are those formalisations that are not usually questioned by scientists within the discipline (Kuhn, 1962); they correspond to its central theories or laws. A discipline's metaphysical presumptions are the epistemic and ontological beliefs held by its practitioners. A discipline's values refer to the criteria used to judge the explanatory sufficiency of evidence, whereas its exemplars are the characteristic problems and objects that give the discipline empirical substance (Kuhn, 1962). These four elements structure our analysis and subsequent suggestions about educationally important aspects of palaeontology.

Theory in palaeontology

The most important symbolic generalisation of palaeontology is the theory of evolution by natural selection. The theory of evolution is not an empirically testable generalisation in the sense of the universal laws of physics or chemistry. The theory leads to how-possibly questions rather than why-necessarily questions because it involves directional, asymmetric, and temporal relations between species (Cat, 2014). For example, the theory can retrodictively explain how birds and crocodiles can most possibly be the descendants of an extinct animal called an archosaur, but it cannot explain why birds and crocodiles are necessarily the descendants of archosaurs, because it cannot predict the exact course of evolution. This characteristic causes the theory of evolution to conflict with a widespread perception of what a scientific theory is, namely something that can make predictions (Dagher & Boujaoude, 2005). This perception is a misunderstanding: In fact, both concepts of prediction and retrodiction are equally important across a range of sciences (Gray, 2014).

Educational significance of theory in palaeontology

From an educational point of view, a more sophisticated understanding of the theory of evolution among learners may precipitate more nuanced and realistic views of the nature of scientific theory across the disciplines. Studies suggest that the most efficacious way of disseminating the theory of evolution is to engage learners in inductive reasoning patterns that

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mirror those of palaeontologists, rather than taking the theory as a starting point and attempting to infuse it into content (cf. Dagher, Brickhouse, Shipman, & Letts, 2004; Passmore & Stewart, 2002). This way of grounding science education in specific cases would help learners grasp what science is about in each particular instance (Rudolph, 2000), allowing them to understand that different lines of scientific inquiry are associated with different theory structures (Dagher & Boujaoude, 2005).

Epistemic and ontological beliefs in palaeontology

Coherence is a central belief in palaeontology, i.e. the dependency between contemporary forms and past events, but also between past events (Currie, 2017). Palaeontologists draw on this belief when dealing with the challenge of interpreting long-past events. One example is the technique of comparative anatomy which involves comparing the anatomy of different species, both extinct and extant, to postulate a common cause for them (von Bonin, 1946). Similarities may indicate shared ancestry (e.g. the shared bone structure of whale and human front appendages), or they may indicate convergent evolution (e.g. wings in bats and birds). In either case, palaeontologists exploit the dependency relationship between past entities and events: A shared ancestor and the constraints of this ancestry on the genotype and phenotype of descendants, and similar (past) selection pressure, respectively.

Educational significance of epistemic and ontological beliefs in palaeontology

Studies show that engaging learners in the intellectual problems of palaeontology can help them develop its techniques of inquiry for themselves; developing these techniques, in turn, allows the discipline's epistemic and ontological assumptions to emerge. For example, Thomson and Beall (2008) show how learners used comparisons of skulls to make inferences about diet and locomotion among hominids, which in turn led them to construct possible phylogenetic pathways for hominid evolution. Elsewhere, Achiam, Simony and Lindow (2016) show how groups of learners engaged in comparing the anatomical features of modern birds and a fossil *Archaeopteryx* (a small feathered dinosaur) identified a number of similarities and correctly identified them as being due to shared ancestry or convergent evolution, respectively.

The significance of letting learners develop disciplinary techniques and concepts for themselves, in content-rich contexts, is that it counteracts the notion of science as a

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depersonalised, monolithic practice, devoid of personal or social features. It emphasises the point that science involves the use of the imagination to engineer methods of inquiry that are suitable within specific contexts (Ault & Dodick, 2010).

Values in palaeontology

What is considered appropriate evidence in palaeontology differs from what is considered appropriate in the experimentally oriented sciences (Passmore & Stewart, 2002). These different patterns of evidential reasoning utilise different sides of the time asymmetry of causation mentioned previously. Palaeontologists are typically not able to directly test their hypotheses by means of controlled experiments (Cleland, 2002). Instead, palaeontology often deals with indirect and circumstantial evidence such as fossil traces or homological structures in different species, and the quality of effective palaeontological research is often based on how well the hypothesis explains a variety of such evidence. For example, the hypothesis of an asteroid hitting Earth 65 million years ago can explain a variety of historical evidence such as the thin layer of iridium-containing sediment that can be found throughout the world, the presence of a large crater in the Gulf of Mexico, and the mass extinction of animal and plant species evidenced by the fossil record. In other words, effective *explanation* is valued in palaeontology (Cleland, 2011).

Educational significance of values in palaeontology

Explanatory reasoning of the kind used in palaeontology requires combining many items and types of evidence, both for and against the hypothesis in question; this again necessitates understanding scientific concepts in addition to those familiar to the experimentally oriented sciences (e.g. predictions, controls, and variables). Multiple working hypotheses, retrodiction, abductive reasoning, and reasoning from analogy are some such concepts (Dodick, Argamon, & Chase, 2009); in fact, it is argued that not only are these concepts important resources for understanding palaeontology, they are also important resources for creating a more nuanced understanding of the experimentally oriented sciences as well (Gray, 2014).

Exemplars in palaeontology

Exemplars are what give theory empirical content (Kuhn, 1962), and serve as a kind of practical approach to the discipline. In science education, exemplars may be thought of as the textbook or laboratory examples that learners engage with, and that are used as introduction to

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the discipline's tacit knowledge. In palaeontology, these exemplars are fossils. Fossils are rare, and have unique fossilisation histories, which affect what can reliably be predicted from them (Ault & Dodick, 2010), unlike the natural kinds of chemistry or physics, i.e. compounds or particles (Frodeman, 1995).

Of special note are transitional fossils, so called because they display anatomical features that are shared by several groups of species, thereby indicating a genealogical relationship between those groups. Perhaps the most well known transitional fossil of them all is the aforementioned *Archaeopteryx*, which represents a transitional form between reptiles and birds. It thus represents a classic exemplar of a hypothesis (speciation as the basis of evolution) embodied by a concrete object. *Archaeopteryx* has a long bony tail and teeth (as do reptiles), but also asymmetrical feathers suited for flight (as do only birds). When the first specimen was discovered in the 19th century, transitional forms were unknown, but this concept has since proved crucial in the understanding of evolutionary mechanisms and speciation processes.

Educational significance of exemplars in palaeontology

Transitional fossils may have an important role to play in education. Transitional fossils are often termed *missing links*, which is a concept that can easily be misleading (Miller, 2012). A transitional fossil does not represent a link in a chain that proceeds directly from simple to complex, because evolution does not take place in a linear sequence (Mead, 2009). Rather, evolution should be conceptualised as a branching structure, where transitional fossils represent descendants of shared ancestors. For example, the transitional fossil *Archaeopteryx* is descended from the same ancestor as modern birds and reptiles; thus, *Archaeopteryx* shares features with both of those groups but cannot be said to be an intermediate between them (cf. Mead, 2009). If used carefully in education, transitional fossils may thus enhance learners' understanding of the process of speciation, giving rise to a more sophisticated understanding of the evolutionary process.

Additionally, research points to the educational efficacy of scientific objects. Tangible scientific objects have been shown to increase learners' motivation (Cook et al. 2014), suggest lines of inquiry (Kreuzer & Dreesmann, 2016), and make scientific processes visible

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(Roehl, 2012). Accordingly, the macroscopic fossils of palaeontology with their often strong visual cues seem especially well suited for educational purposes.

Palaeontology in Education

On the basis of the analysis of its educational relevance, palaeontology has a number of features that make it germane to richer and more inclusive approaches to science education. Not only can an increased attention to palaeontology provide learners with a more complete picture of the natural sciences, but it can also improve and nuance their understanding of the experimentally oriented sciences. Accordingly, in the following we offer concrete suggestions for systematically enriching learners' experiences with science in their education processes, both in schools and outside them.

Science classrooms

As discussed in the opening sections of this text, the perspective on science in many Nordic education contexts may lead learners to equate scientific practice with the production of facts through the linear formulation and testing of hypotheses. Based on our analysis, we suggest that palaeontology offers the means to go beyond what Sharma and Anderson (2009) critique as the rule-bound science experiments that consistently provide predetermined answers. We suggest that the introduction of palaeontological inquiry activities, with their tangible objects and prompting of contextually relevant techniques, can provide learners with complex science milieus. In such milieus, learners have opportunities to engineer their own lines of inquiry on the basis of the macroscopic and often compelling fossil objects; this, we argue, prompts the learners to use their empirical constructs as rhetorical tools to convince themselves and others of their claims (Achiam, Lindow, & Simony, forthcoming). When learners create and justify knowledge claims using retrodiction, abduction, reasoning from analogy and multiple working hypotheses, not only do they gain domain-specific insights into palaeontological methodology, they may also gain an improved understanding of inquiry in the experimentally oriented sciences (Gray, 2014).

Although the tangible and macroscopic nature of many palaeontological objects means that there are many ways to conduct authentic, hands-on activities without expensive equipment or laboratory apparatus (King & Achiam, 2017), a potential obstacle to implementing palaeontological inquiry in the classroom is that schools do not always have access to

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specimens and objects. Even though casts and models can be relatively cheaply obtained, we acknowledge that school budgets are restrictive. However, with careful planning, the educational affordances of palaeontological objects may be made available through other types of media, i.e. digital representations such as *The Human Animal* (The Natural History Museum of Denmark, 2013), images, or even simple hand-outs (e.g. Achiam, Sølberg, & Evans, 2013). These representations can arguably embody the salient features that prompt authentic palaeontological inquiry.

Teacher professional development

Incorporating palaeontology in science education would be impossible without the science teachers. Research shows that science teaching practices are strongly affected by textbooks (Binns, 2013); given the emphasis in science textbooks on the experimental approach, we might assume that science teachers as a general rule do not teach historical approaches in their science classes. Furthermore, studies show that pre-service teachers rarely encounter the distinctions between experimental and historical approaches in their training (Dodick et al., 2009; Gray, 2014). Although we acknowledge that the studies cited here describe the conditions in the USA, we assume that science teachers in other countries face similar situations: Implementing palaeontological activities in science education represents a challenge to many science teachers.

One study analysed science teachers' construction of scientific arguments in the classroom for topics that involved experimental and historical approaches, respectively (Gray & Kang, 2014). These authors found that the arguments made by teachers did indeed reflect differences between the approaches. While in the experimental teaching units, the teachers portrayed the epistemic process of science as a linear progression from data to knowledge claim; in the historical science units, the process of science was portrayed as the accumulation of multiple pieces of data, leading towards a generalised claim (Gray & Kang, 2014). This means that even without specific training in the diversity of scientific methods, teachers may to some extent be capable of giving pluralistic accounts of the natural sciences.

In our analysis of the educational significance of palaeontology, we pointed to the significance of explanatory reasoning. Palaeontology, like other historically oriented sciences, involves constructing and evaluating arguments for and against multiple hypotheses based on

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the evidence. Even though incorporating palaeontology inquiry activities in science lessons may be a daunting prospect for teachers with no training in the historically oriented sciences, we argue that to the extent that science teachers spontaneously invoke patterns of argumentation that are particular to the historical sciences in their teaching sequences (as demonstrated by Gray & Kang, 2014), they are already en route to offering their students a more pluralistic understanding of science. Starting small and gaining confidence could be the key for teachers, using the many resources freely available online, e.g. *Teaching Paleontology in the 21st Century* (Teach the Earth, n.d.).

Science education in out-of-school settings

More and more, the science education community focuses on the special contributions made to science education by museums, science centres, and other out-of-school learning institutions. Indeed, if teachers feel overwhelmed by the thought of introducing palaeontology in their classrooms, out-of-school science education institutions are well-positioned to engage learners in activities related to the historically oriented sciences and specifically, palaeontology. One familiar way to encounter palaeontology is in natural history museums, which frequently display authentic paleontological objects such as dinosaur skeletons and ichnofossils to the enthusiasm of their visitors. Other types of institutions may display other kinds of engaging palaeontological objects, i.e. animatronic dinosaurs, simulated fossil digs (physical or digital), or footage of real fossil excavations, and some may even offer programmes where participants can participate in real palaeontological excavations. Common to these representations of palaeontological objects and practices is that they offer glimpses into the real workings of palaeontology by providing compelling narratives about the often exotic expeditions that presaged them, the so-called Bone Wars, ancient worlds, and the intriguing process of palaeontological knowledge production (see e.g. Estrup, 2017).

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Research shows that disseminating science through such historical narratives has a positive effect on the understanding, retention and interest of learners (McComas, 2008). Specifically, the dissemination of difficult concepts such as the theory of evolution has been shown to be especially effective when it is embodied in its historical context. For example, Miller (2012) exemplifies how narratives of on-going fossil discoveries can be used to illustrate how different evolutionary hypotheses have been supported through time. Such narratives can help learners understand the interplay of retrodiction and prediction, not only in palaeontology, but across a range of sciences. Furthermore, disseminating palaeontology in its historical context provides learners with a more human and complete picture of the scientific enterprise (Miller, 2012), making it inclusive to a wider variety of learners.

Finally, excursions outside the classroom have been shown to enhance learners' motivation when used as a supplement to classroom-based teaching (Braund & Reiss, 2006). Accordingly, we encourage natural history museums, science centres and other out-of-school science institutions to develop their educational strategies towards clear distinctions between the historically and experimentally oriented sciences. Not only will this distinction benefit learners on school excursions, but also the members of the public who visit to conduct their own, voluntary science explorations.

Conclusion

Contemporary society is based on scientific knowledge, innovation and democracy; qualities that require comprehensive education in the natural sciences. Hence, it is alarming that science education portrays science as monolithic and univocal, recognising only the experimentally oriented sciences. In this text, we have argued how a reintroduction of the historically oriented sciences in the education system could reverse this tendency. In our analysis of the educational relevance of palaeontology - of one of the most classical of the historically oriented sciences - we have shown how palaeontology and its theory, values, epistemic and ontological assumptions, and exemplars have significant potential for a more complete, humanised, and pluralistic conception of the natural sciences. We suggest this will provide children and youth with more diverse pathways into science, thereby increasing the diversity of science learners and providing the basis not only for increased recruitment into scientific career pathways, but also for more well-informed democratic citizenship.

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Marianne Achiam is an associate professor at the Department of Science Education, University of Copenhagen. She has an MSc in Biology and a PhD in Science Education. Her research interests include science dissemination in out-of-school contexts, and the cultural, institutional, and didactical conditions that co-determine this science dissemination. She is the head of the Departmental research group on science education in out-of-school settings.

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