Intelligent Design and the Nature of Science: Philosophical and Pedagogical Points

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1 Introduction

In the United States, creationists and evangelical Christians have threatened high school instruction in evolutionary biology for decades, even in public schools (where religious views may not be taught due to the constitutional separation of state and church). Similar worrisome trends have more recently started in other Western countries, exacerbated by the promotion of the label 'intelligent design theory' (Numbers 2009). While this alleged theory has hardly any intellectual content and does not pose a scientific threat to evolutionary theory, intelligent design ideas and more generally alleged arguments against evolution are known to many students. For this reason it is important for teachers to develop their classroom instruction in evolutionary theory with the knowledge that some students may be hesitant to accept evolution due to religious reasons or because they are exposed to erroneous claims about evolutionary theory. At the very least, the teaching of evolutionary theory has to bring forward considerations that can serve as implicit responses to common objections to evolution.[1] It may also be fruitful to directly address intelligent design and why its 'arguments' fail, presented not as a rejection of intelligent design (or even religion) but as a critical thinking lesson for students. More generally, beyond teaching particular evolutionary facts it is worthwhile to make students reflect on, and teach them about,

[1]While traditional classroom instruction thoroughly covers different aspects of microevolution, using non-human animals as examples, it is essential to present more examples about macroevolutionary transformations, including the evolution of humans. This stems from the fact that young children can more easily conceive of microevolutionary changes than of macroevolutionary changes (Samarapungavan 2011) and a person can use multiple epistemologies, leaving room for the possibility that while using a scientific epistemology for microevolution, students may use a non-scientific epistemology when thinking about human origins (Evans et al. 2011).

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the *nature of science*. Understanding what the aim of scientific explanation is, how empirical methods function, and how science makes progress, gives students a much better appreciation of what science is and how it works—which in itself should be a goal of science education. It also has the side-effect of making plain to students what virtues evolutionary biology has over intelligent design.

This essay discusses intelligent design (ID) from the perspective of the philosophy of science, drawing several implications for science education.[2] I proceed from concrete biological issues to more general issues about the nature of science. Section 2 engages Michael Behe's irreducible complexity argument against evolution, highlighting why the ID portrayal of organisms as designed machines is not only at odds with contemporary biology but prevents an understanding of how organisms can evolve. A long-standing objection to evolution is that the formation of complex structures by means of processes involving chance is too improbable to be credible. This small probability argument has recently been developed and promoted by ID theorist William Dembski, and in Sect. 3 I show why it is easy to explain to students why such arguments are fallacious, connecting it to issues about the nature of scientific explanation. Science's commitment to explanations only in terms of natural causes—called 'methodological naturalism'—has been criticized by ID proponents on the grounds that it is presumed by scientists without valid justification and that it entails atheism. Section 4 lays out why neither is the case, and this discussion of why scientists have good reasons to use empirical methods has implications for the nature of science and how to demarcate science from pseudoscience. I broaden the scope yet again in Sect. 5 by highlighting the need for philosophers to construe scientific approaches as practices based on institutional factors and values, and to assess them in terms of the socially embedded activities of their practitioners. By implication, instructors should not just present science as a set of facts and theories, but convey that science is a practice, as this puts students in a position to see much clearer why evolutionary biology differs from intelligent design. The last section summarizes my overall discussion, emphasizing the various pedagogical points made about biology education. This is a long essay, but the four main sections can be read independently of each other.

2 Irreducible Complexity and Organisms as Machines

2.1 Behe's Irreducible Complexity Argument Against Evolution

A prominent intelligent design argument against evolution is based on the notion of irreducible complexity, explicitly introduced by ID proponent and biochemist Michael Behe in *Darwin's Black Box: The Biochemical Challenge to Evolution* (1996). He states his central idea as follows:

[2] ID proponents have only leveled arguments against evolutionary theory, and there is no intelligent design theory that makes predictions and explains phenomena. For this reason, 'ID proponent' has to henceforth refer to someone endorsing the 'intelligent design' label, and more concretely someone who is part of the intelligent design movement (Sect. 5).

> By *irreducibly complex* I mean a single system composed of several well-matched, interacting parts that contribute to the basic function, wherein the removal of any one of the parts causes the system to effectively cease functioning. An irreducibly complex system cannot be produced directly […] by slight, successive modifications of a precursor system, because any precursor to an irreducibly complex system that is missing a part is by definition nonfunctional. (Behe 1996, p. 39)

Behe often illustrates this idea with a simple example—the mousetrap. A mousetrap has the following parts: a base plate, a spring, a hammer (doing the killing), a bar that holds the hammer in place before the trap is activated, and the catch that holds the bait and releases the holding bar and hammer upon being touched. Given the way these parts are arranged, the mousetrap can be used to catch mice; but if any single part is missing, it is not functional any longer. Applied to the biological realm, the argument is that an evolutionary origin of an organismal system (without the influence of an intelligent designer) would require ancestral precursor systems that have been favored by natural selection, yet any precursor to an irreducibly complex system missing a part is non-functional.

This idea against the natural origin of complex organisms is not completely new, as it was already part of William Paley's (1802) watchmaker argument, which asserted that one may infer the presence of a designer from a watch found on a heath, given that the parts of the watch are arranged in a purposeful fashion and that it would not function if the parts were randomly assembled (see also Ayala, this volume; Avise, this volume; Lennox and Kampourakis, this volume).[3] However, the novelty of Behe's account is that he points to *molecular* systems within organisms. Systems that Behe claims to be irreducibly complex include the vertebrate immune system (suggesting a design influence during vertebrate evolution), the blood clotting cascade, and the cell's vesicular transport. To be sure, the icon of intelligent design has been the bacterial flagellum, the tail-like protrusion that by its motion propels the bacterial cell so as to permit motility. The central aspect for Behe is the flagellum's anchor point inside the cell wall, which consists of a few dozen proteins that are arranged in such a way that some of them rotate as in a motor, creating the flagellum's motion.

Behe's irreducible complexity argument has convincingly been criticized by many biologists and philosophers (Sarkar 2007; Shanks 2004; several of the contributions in Young and Edis 2004). I discuss this matter not because another argument against Behe is needed, but because seeing why he fails reveals how evolution works and how it is to be taught. Several have pointed out that even if upon removing a system's part it cannot fulfill its *current* function, it may well be able to perform a different, possibly simpler function—a function that may have been important for the ancestor, so that the system with fewer parts is a candidate for an ancestral precursor system. To illustrate this in the case of the bacterial flagellum as found in *Escherichia coli*, consider another bacterium, *Yersinia pestis*, which is the cause of the bubonic plague. Not dissimilar to a flagellum, *Y. pestis* also has a thin long

[3] One difference is that while Paley argued against a natural origin of organisms by mere chance, Behe argues (and has to argue) against an evolutionary origin by natural selection.

structure protruding from the cell wall; however, it does not move as a flagellum would. The reason is that the structure's anchor point in the cell wall consists of only a subset of the protein types present in the flagellum's base in *E. coli*, so that it cannot generate rotary motion. Still, though it has fewer components than a flagellum motor, the structure in *Y. pestis* does fulfill a function important for this microorganism. Being located in the cell wall it permits the transport of virulence factors from inside the cell into the long hollow structure attached to the cell, which functions as a syringe, injecting toxins into mammalian cells to suppress their immune response. Behe's irreducible complexity argument ignores that the primary functions of biological structures can change over the course of evolution, and a function essential for one species may not be relevant for another.

Y. pestis is an extant species, so that the structure in its cell wall is of course not the historical precursor of any other species. But a similar structure could have been the actual precursor of the flagellum motor in *E. coli*. More generally, comparing related structures in several extant species provides important clues to their evolution. Shared structures in extant species are often homologies, suggesting how ancestral conditions may have looked (Minelli and Fusco, this volume). While some ID proponents have claimed that among the 42 protein components of the flagellum, about 2/3 are unique to this system and not found in other systems, actually homologies to other proteins have been identified for all but 1/3 of the components. Moreover, since half of the components are missing in one or the other extant species, a functional flagellum is possible even with missing components. There are only two proteins (i.e., 5 % of components) that are indispensable and with no known homologies to other proteins (Pallen and Matzke 2006; for the immune system see Bottaro et al. 2006). Needless to say, this picture of the evolution of the bacterial flagellum is incomplete. But future comparative studies will add to the account, and most importantly, Behe and other ID proponents have not offered any explanation of how the flagellum evolved. Behe assumes that evolutionary descent with modification—albeit with the additional influence of an intelligent designer—has occurred, but he does not lay out at what time such interventions happened and what protein changes they yielded. Indeed, if his irreducible complexity argument was sound, given that there is not just 'the' bacterial flagellum, but that the protein composition of flagella differs across bacterial taxa, Behe would be forced to claim that many intelligent interventions have occurred during bacterial evolution. Yet he simply proclaims 'design', without attempting or intending to offer an explanation of the structural similarities and dissimilarities observed in extant species.

Of the points made so far, two are relevant to biology education. First that it is valuable to highlight to students the conceptual issue that the particular functions which enable an organism to survive and reproduce, and are favored by natural selection, are context-dependent and vary across species and evolutionary time. Second, rather than making inferences based on the study of one species, sound evolutionary biology uses the comparative method and the best evolutionary explanation is the one that yields an account of the features of many extant species.

2.2 *Why Organisms Should Not Be Portrayed as Machines*

Apart from the fact that the removal of a system's parts may lead to a system that can perform a different function, there is another problem with Behe's irreducible complexity argument. For in the above quote he tacitly presupposes that any ancestral precursor system has *fewer* parts than the descendant. But it may well have more parts, and exhibit *redundancy*, i.e., some of its parts can be eliminated or some activities can be deactivated without any loss in function (so that systems with redundancy are not irreducibly complex). Despite Behe's claim that an irreducibly complex system cannot evolve, such a system can be obtained if one starts out with a system exhibiting redundancy, and then removes all redundant parts and activities. One common evolutionary way to generate novel structures and functions on the molecular level is gene duplication. Upon duplication of a gene, there are two identical copies G and G′. They still have the same function A (e.g., coding for a certain protein or activating the expression of certain genes), so that the system exhibits redundancy. For this reason, it often happens that one of the copies is destroyed by mutation. If mutations do not destroy, but increasingly modify one of the copies, say G′, the gene may eventually acquire a new function B, which could have some beneficial role for the organism (while G still has function A). Then a new gene G′ with a new function B has evolved. Should both functions A and B eventually become essential for the survival of later descendants, the evolutionary outcome is an irreducibly complex system.

Behe and other ID proponents are fond of likening cells to artifacts and its components to machines, by terming cellular structures as 'highways', 'factories', and 'assembly lines'. DNA is conceived as a blueprint, where gene expression is like the reading of a computer punched card (Pigliucci and Boudry 2011). Behe uses the mousetrap to illustrate his notion of irreducible complexity. Needless to say, all these machine metaphors are used to create the impression that biological systems are designed, similar to artifacts. Apart from this being rhetorical rather than logical support for intelligent design, Behe's irreducible complexity argument—that organisms are machines that break down if one of their parts is removed—is empirically false. For the molecular systems he points to are not irreducibly complex, and organismal systems often exhibit redundancy (Shanks and Joplin 1999). In the case of *robustness* in gene regulatory networks and developmental processes, a gene may well be involved in an important function, yet a deactivation of this gene (e.g., in a knockout study) hardly leads to any phenotypic difference, as the organism compensates for this situation by activating other genes (Brigandt in press-a; Edelman and Gally 2001; Mitchell 2009; Wagner 2005). Organisms can flexibly react to potentially harmful disturbances, even genetic modifications. This has important evolutionary consequences.

Evolvability is a biological system's ability to evolve (see also Love, this volume). More specifically, evolutionary developmental biologists use this term to refer to an organism's capacity to generate viable, heritable variation

(Hendrikse et al. 2007; Kirschner and Gerhart 1998; Wagner 2005).[4] Morphological change can take place only when there is heritable phenotypic variation, on which natural selection acts. Genetic mutations occur in a random fashion, but due to an organism's mode of development, this random genetic variation translates to a structured *phenotypic* variation, where the heritable phenotypic variation generated tends to be more viable and functional than if it was generated in a random fashion. An account of evolvability aims at explaining how this is possible, as this is vital for understanding how sufficiently rapid morphological change is possible. A mere appeal to long periods of time being available is unconvincing as an explanation of how complex structures could have evolved if not supplemented with an explanation of why sufficiently large amounts of phenotypic variation tend to be functional.

Upon modification of an artifact like Paley's watch, either no significant change results or the artifact breaks down. If organisms were artifacts as Behe contends, they would not be able to evolve. Marc Kirschner and John Gerhart address this issue in *The Plausibility of Life: Resolving Darwin's Dilemma* (2005), which lays out their account of evolvability (which they dub a theory of facilitated phenotypic variation) in a manner accessible to a general audience. They point to different features enabling evolvability, such as weak regulatory linkage, compartmentation, and exploratory behavior. A cellular or developmental process exhibits exploratory behavior if it is able to generate many, if not an unlimited number, of outcome states, any of which can be physiologically stabilized if it is adaptive to the organism. One example is how microtubules generate the shape of eukaryotic cells, by each of the many microtubules growing and shrinking (exploring), until the length of some of them is stabilized by a signal from outside the cell. In this fashion, many cell shapes can be produced in an individual organism, with remodeling of a cell being possible. Another instructive example is the development of the limb of land-living vertebrates. Apart from several skeletal elements and muscles, the limb needs blood vessels and nerves. The positions of the latter are not represented in some organismal blueprint; instead, their anatomy emerges by means of exploratory developmental processes, with new nerves (and blood vessels) growing from the body core toward the developing limb, guided by chemical signals and their current surrounding milieu, with those nerves that do not find a target degenerating by cell death (Kirschner and Gerhart 2005, Ch.5).

One advantage of this mode of development is that it creates the regular functional outcome even if the developmental process is temporarily disturbed. It also facilitates evolutionary modification. The size and placement of limbs differs significantly in different vertebrates. If the placement of a limb changes in evolutionary time, it is not necessary to respecify the new positions of the developed bones, muscles, blood vessels, and nerves—all of which have to be at the right place for the limb to function—on an alleged organismal blueprint. Instead, these structures

[4] For a historical discussion of the concept of evolvability and its relation to the concept of developmental constraint see Brigandt (in press-b), and for a connection to the phenomenon of homology see Brigandt (2007).

adjust to the new situation accordingly by means of exploratory developmental processes. This shows that it is possible that a *simple* genetic change (e.g., changing the position where the limb starts to develop) can lead to a coordinated, complex phenotypic modification, involving *many simultaneous* phenotypic changes. In general, Kirschner and Gerhart (2005) point to mechanisms that permit physiological adaptation and developmental robustness, where a functional developmental outcome is created even in the face of an environmental change or a developmental disturbance. Such developmental aspects of organisms have evolutionary implications. For they not only ensure that a functional phenotype is produced upon an environmental change, but they also make it likely that a *functional* phenotype results from a *genetic* change, so that evolutionary modification is enabled (see also Wagner 2005).

In the eighteenth and early nineteenth century, debates about reductionism in physiology and embryology were typically phrased in terms of 'mechanism' versus 'organicism' (Brigandt and Love 2008). Mechanists assumed that developmental and physiological processes could potentially be explained by a framework relying primarily on the physical contact of bodily particles, broadly in line with Newtonian mechanics. Mechanists were favorable toward viewing organisms as complicated machines governed by the laws of physics and chemistry. Organicists, in contrast, were unconvinced that a mechanical framework sufficed for the explanation of life processes. As evidence, they pointed to development and regeneration. The freshwater hydra, for example, can regenerate into several full organisms even if cut into pieces. In sea urchins, splitting the blastomere or taking some of its cells away can in some cases still lead to a normally developed embryo. This was seen as a clear disanalogy between organisms and machines.

Within a twentieth century framework, organisms can be conceived as machine-like if one uses the human artifact metaphors of genetic 'information' and organisms developing from a genetic 'blueprint'. Among other things, this image has been promoted in the widely influential popular science book *The Selfish Gene*, with Richard Dawkins asserting that the "argument of this book is that we, and all other animals, are machines created by our genes" (Dawkins 1989, p. 2). Dawkins conflates the legitimate *evolutionary* idea that genes have a past involving natural selection that makes them evolutionary adaptations for certain functions with the problematic *developmental* idea that every organism is a "machine built by […] genes" (p. 44)—suggesting genetic determinism (on this issue see Moore, this volume; Jamieson and Radick, this volume; Burian and Kampourakis, this volume).[5] The notions of genetic information, blueprints and programs have been rightly criticized on the grounds that they are empty metaphors that do not provide a mechanistic explanation of development while creating the illusion of explanatory

[5]Dawkins's (1989) presentation also construes organisms as largely passive machines (controlled by genes), while portraying genes as active agents that have desires (selfish aims) and carry out actions (building organisms). However, while it may make the material more attractive, the anthropomorphizing of nature in classrooms can have negative effects on students' epistemological development (Evans et al. 2011).

understanding (Robert 2004). The information metaphor erroneously suggests that the function of molecular genes is context-independent ('if the information for making a phenotype is in the gene, the gene will produce it in any context'). To the extent that there is biological information underlying development, it does not reside in genes alone. The activation of genes and the production of their products in different cells emerges from the interaction of molecular genes, various non-DNA molecules inside the cell, and the neighboring cells, so that rather than development being controlled by an organism's DNA as a *central* agent (every cell has a separate set of DNA anyway), the generation and modification of biological information in development is a temporally dynamic and spatially *distributed* process (Brigandt in press-a; Stotz 2006; Wagner 2005; see also Marcos and Arp, this volume).

Talk about molecular machines can be repeatedly found in contemporary molecular and cellular biology (Alberts 1998). While this may get at some features of cellular systems, such metaphors at the same time obscure many features that reveal cellular and organismal systems to be unlike machines (Kirschner et al. 2000). In the context of explanations of development, already eighteenth century organicists pointed to regeneration and robust development as being at variance with an organism-as-machine picture. But it has more recently become clear that this is essential for an understanding of *evolution*. My above discussion of evolvability explained why physiological adaptability and robustness in development are the reasons why organisms can generate heritable phenotypic variation that tends to be functional, so as to permit evolutionary change by natural selection. Thereby viewing organisms as flexible developmental systems rather than machines is the key to understanding morphological evolvability, so that machine metaphors are not just biologically inadequate, but also harmful for science education (Brigandt 2013; Pigliucci and Boudry 2011; but see Bechtel, this volume).

In his irreducible complexity arguments, Behe focuses on molecular or biochemical pathways—a reductionist vision ignoring the larger context. Even if it is the case that the removal of some parts leads to a breakdown of this specific pathway, due to redundancy or robustness, the larger system may compensate for it so as to avoid detrimental effects to the organism. The irony is that whereas ID proponents often charge biologists with endorsing a materialist and reductionist view of living creatures, in fact their metaphor-based representations of organisms as designed machines (that would break down if modified by random mutation) are guilty of an empirically false reductionism. While neo-Darwinists, like Dawkins, who focus on population genetics have sympathies for viewing organisms as designed machines (a commonality with ID proponents even if they assume that natural selection was the designer), many evolutionary biologists who attempt to understand organismal evolvability and the evolutionary origin of morphological novelty have moved away from a machine vision of organisms. They see evolutionary developmental biology (evo-devo) as allowing for an interdisciplinary approach that offers integrative explanations appealing not just to the molecular level but to the interaction of entities on several levels of organization (on the non-reductionist epistemology of evo-devo see Brigandt 2010, 2013, in press-a; Love 2008, 2013, this volume).

The main lesson for biology education to be derived from this section's critique of Behe's irreducible complexity claims is that teachers should, wherever possible, avoid describing organismal features using machine and information metaphors, as they prime the false inference that organisms were designed by an intelligent agent, and prevent a proper understanding of how organismal development works and why flexibility and robustness in development make morphological evolution possible.

3 Small Probability Arguments and the Nature of Explanation

A very common idea brought forward against evolution and in favor of intelligent design is that organisms are so complex and consist of so many individual traits that their origination by an unguided process involving chance (such as naturalistic evolution) is *extremely improbable*, so improbable that intelligent design must have occurred. Such small probability arguments against the possibility of evolution have been raised by creationists for decades, but they have also more recently been employed by intelligent design proponents (Berlinski 2008; Gauger and Axe 2011; Sewell 2000, 2001). In his more recent book *The Edge of Evolution* (2007), Michael Behe points, among other examples, to the structural fit among different interacting proteins, arguing that several mutations in different proteins must have occurred to generate such a function-enabling fit, but the probability of this happening decreases exponentially with the number of mutations required.[6] One of the most prominent intelligent design proponents, the mathematically trained theologian William Dembski, has developed the most sophisticated version of this probabilistic argument against naturalistic evolution. In *The Design Inference: Eliminating Chance through Small Probabilities* (1998a), Dembski develops his 'explanatory filter', that first seeks to eliminate the possibility that an event has occurred as a matter of natural regularity, and then to rule out that it was due to chance, so as to conclude that the event came about by design. Dembski presents a universal probability bound of 1 in 10^{150}, where an event more improbable than this can be assumed to not have arisen by chance. He obtains this number by multiplying the number of particles in the known universe, the maximal rate of change in physical states, and the age of the universe, multiplying again with one billion. In later work, Dembski (2002b) invokes mathematical information theory and introduces the notion of complex specified information, where in line with his earlier account, 'complex' refers to an extremely improbable event. Dembski's account is more complicated than this,[7] but the details of his mathematical account do not concern us here and have been

[6]Section 2.2 pointed out that exploratory behavior and other aspects of developmental processes permit several coordinated and instantaneous phenotypic changes to result from a simple genetic change.

[7]For instance, Dembski does not infer design simply from an event being extremely improbable, but from it being improbable and specified (exhibiting a pattern), although he has not offered a consistent account of specificity.

rigorously criticized by others (Elsberry and Shallit 2011; Felsentein 2007; Fitelson et al. 1999; Häggström 2007; Olofsson 2008; Sarkar 2007), with some critics pointing to Dembski's extensive use of irrelevant mathematical formalism, which may impress his intended audience while concealing the actual incoherence of his account (Perakh 2004; Sarkar 2011).

Luckily, small probability arguments for design can be shown to be problematic without much mathematical sophistication, as they all are based on a basic fallacy. In contrast to Behe's notion of irreducible complexity, small probability arguments are less tied to concrete biology, but I discuss them here as the small probability fallacy is so common that it must be addressed by science and mathematics teachers. Beyond direct attacks against evolution, similar arguments occur in the context of the idea of a fine-tuned universe and the strong anthropic principle, i.e., the argument that since conscious life can occur only when the basic physical constants are within a very narrow range, the universe and its constants must have been designed. Small probability arguments are so common and even educated people are prone to fallacious reasoning involving probabilities, that this is something to pay attention to when teaching students about probability.

3.1 Why Small Probability Arguments Are Fallacious

The basic argument from small probabilities can be reconstructed as follows:

(1) The evolution of complex biological features (be it anatomical structures, be it genetic information) solely by means of Darwinian processes is extremely improbable.
(2) Therefore, Darwinian evolutionary theory is probably false (given that there are complex biological features).
(3) Therefore, intelligent design is probably true.

There are several obvious issues with this argument. First, premise (1) can be challenged. Often a small probability is just asserted, but not calculated. If a probability is derived, the calculation may misrepresent the process of evolution by assuming that it is a purely random process. This is the case with the common argument that the naturalistic evolution of organisms is as absurd as a Boeing 747 being assembled by a tornado going through a junkyard. Such probability calculations ignore that mutations occur, not just in a single genome, but in thousands of organisms within a species at the same time, and that most importantly, natural selection retains the best variants, so that evolution does not have to randomly start in every generation from scratch.[8] However, while many probability assertions can be shown

[8]The discussion on evolvability in Sect. 2.2 mentioned further relevant aspects of the evolutionary process.

to be faulty, some version of (1) is the case, as a specific outcome of the evolutionary process is unlikely. Second, statement (2) does not entail statement (3). Even if the current version of evolutionary theory is false, another theory based on purely natural processes may be true, so that the probable truth of intelligent design does not follow. Still, if (2) was the case, i.e., if current evolutionary theory was probably false, this alone would be very damaging for evolutionary biology. Statement (2) is a claim that no evolutionist is willing to accept.

For this reason, my discussion focuses on the fact that *(1) does not entail (2)*. The small probability argument starts out with the legitimate statement that the evolution of complex biological structures, given only Darwinian processes, is very unlikely. In mathematical terms:

(1) $P(\text{complex structures}|\text{Darwinian evolution}) \approx 0$

However, what intelligent design proponents want to conclude, and must argue, is that the truth of evolutionary theory is very unlikely given that we have evidence about the presence of complex biological structures. That is:

(2) $P(\text{Darwinian evolution}|\text{complex structures}) \approx 0$

Yet the conditional probabilities $P(O|H)$ and $P(H|O)$ are very different probabilities. Moreover, they can have completely different values. According to Bayes's formula, $P(H|O) = P(O|H) \cdot P(H)/P(O)$. Thus, even if, as asserted by premise (1), $P(O|H)$ is extremely small and close to 0, $P(H|O)$ can be close to 1, depending on $P(H)$ and $P(O)$. As a result, (1) does not entail (2), and the small probability argument is fallacious based on the confusion of two conditional probabilities.[9]

This fallacy has been further analyzed by Elliott Sober (2008), who explains why it appears to be such a compelling line of reasoning, as it is a probabilistic analogue of falsification (Brigandt 2011). Strict falsification is a valid deductive inference, based on the logical principle of modus tollens. If hypothesis H deductively predicts that observable event O will *not* happen but it is observed that O is the case, then hypothesis H is shown to be false. That is, from $H \rightarrow \text{not-}O$ and O one may infer that not-H. The small probability argument is a probabilistic analogue of this, starting not with premise $H \rightarrow \text{not-}O$ (if hypothesis H is true, then O is false), but with the weaker claim that $P(O|H) \approx 0$ (assuming hypothesis H to be true, O is very unlikely). Combined with observation O, the intended conclusion is not that hypothesis H is false, but H is *probably* false. However, while deductive falsification is a valid inference, Sober is at pains to argue that there is *no probabilistic analogue of falsification*. Not even an inductive or probabilistic inference is possible. From the fact that

[9] A similar conflation of two distinct conditional probabilities can occur not only in small probability arguments against evolution, but also in more direct 'arguments' for intelligent design. Inferring that an irreducibly complex or machine-like object is likely to have been designed on the grounds that (human) designers frequently produce irreducibly complex and machine-like objects is a fallacy. For while the premise is that P(machine-like object|designed) is high, the conclusion states that P(designed|machine-like object) is high.

an observation O is extremely unlikely according to hypothesis H (though O turns out to be the case), *nothing* can be said about the probability or improbability of hypothesis H.

Here is the reason why any small probability argument inferring (2) from (1) is fallacious. This can fortunately be made plain to students without mentioning the above philosophical analysis that the argument is a probabilistic analogue of falsification. Very small probabilities mean little, as such events can be easily generated. Assume that a given coin is fair, and that our hypothesis H is that the coin is fair, so that it asserts that the probability of heads and tails is each ½, i.e., P(h) = ½ and P(t) = ½. Consider five tosses of this coin and a particular outcome (a certain sequence of heads and tails): P(h,t,t,h,t) = ½ · ½ · ½ · ½ · ½, which is equal to 1 in 2^5. For 70 tosses the probability of a particular outcome P(t,h,t,…) is 1 in 2^{70}, and for 500 tosses the probability P(t,t,h,…) is 1 in 2^{500}, which is smaller than 1 in 10^{150} and thus smaller than Dembski's universal probability bound.[10] Inferring the falsity of the hypothesis 'coin is fair' because of this extremely small probability would be fallacious; we cannot even infer that the hypothesis is *probably* false, as by assumption it is true. In fact, this hypothesis assigns a high probability to some events (one coin toss = ½) and an extremely low probability to other events (500 tosses of the coin)—but we cannot infer that the hypothesis is at the same time probably true and probably false. Both a *true* hypothesis (coin is fair) and a *false* hypothesis (coin is biased with P(h) = ¾) can assign a very small probability to *one and the same* event (500 tosses of the coin), which makes plain that nothing can be inferred about the probable truth or probable falsity of the hypothesis asserting the small probability. The problem with Dembski's universal probability bound is not that the number he provides is still too large, but that there cannot be any such bound!

Small probabilities have a strange psychological effect on us and can even mislead educated persons into fallacious inferences.[11] For this reason, this issue ought to be clarified when teaching probability theory to high school students. Arbitrarily small probabilities result if one considers the conjunction of different events, and the particular outcome of a sequence of many evolutionary events (such as all mutations in a lineage leading from a remote ancestor to an extant descendant) is no exception. Since complex events (involving many individual events) with small probabilities happen all the time in nature, a small probability suggests neither that the hypothesis postulating this probability is probably false, nor that some intelligent intervention must have taken place.

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[10] If one does not want to toss a coin 500 times, using two decks of cards likewise yields an outcome whose probability is smaller than the universal probability bound.

[11] In addition to persons being poor at reasoning with probability and detecting patterns where there are none, Elsberry and Shallit (2011) point to cognitive science studies according to which humans have agency attribution systems, which may be biased toward overdetection of agency.

3.2 Comparative Testing and the Nature of Explanation

Likelihoods of the form P(observations|hypothesis) as occurring in premise (1) can matter, but only if *several* rival hypotheses are compared. If $P(O|H_1) > P(O|H_2)$, observations O favor hypothesis H_1 over hypothesis H_2. Thus, even if $P(O|H_1)$ is an extremely small probability, it may still be higher than the probability assigned by an alternative hypothesis, and possibly higher than the various likelihoods $P(O|H_i)$ assigned by all other relevant hypotheses. It is well-known that in science, alternative hypotheses often happen to be in competition, but the point here is that a scientific hypothesis often cannot be tested in isolation but *must* be tested *relative to* other hypotheses (Sober 1999, 2007). The fact that P(complex structures|Darwinian evolution) is extremely small does not tell us anything about Darwinian evolutionary theory. It does not make evolutionary theory implausible—as creationists and ID proponents falsely claim—nor does it make ID theory plausible. What intelligent design proponents would have to show is that P(observations|intelligent design) > P(observations|Darwinian evolution).

Now the question is how to assess P(observation|intelligent design) for some given observation. At this point intelligent design proponents face a dilemma. To portray ID as a non-religious theory and to avoid having to confess that God is the assumed designer, ID theory is often described as the hypothesis that at *some* point in the remote past *some* intelligent agent influenced the history of life in *some* way. But this version of ID does not predict any observation, and does not even assign a probability to observations. Intelligent design proponents routinely claim that ID does make testable predictions, for instance the presence of complex specified information in living systems, the occurrence of irreducible complexity, the increase of biological complexity across time, and that DNA, even that considered to be junk DNA, is functional (Meyer 2009; Wells 2011). However, while all these observational claims are *consistent* with intelligent design theory, they do not follow from intelligent design theory as construed here, whereas an actual prediction has to *follow* from the theory predicting it. If its proponents construe ID in a vacuous fashion like the one above, no concrete prediction can be made from it, in fact, not even a probability P(observation|intelligent design) can be assigned. Thus, by trying to portray ID as a scientific (in the sense of non-religious) theory, its proponents have rendered intelligent design untestable!

Predictions are made and probabilities can be assigned only if ID is made more concrete by a specification of the intentions and abilities of the designer, but this is not an option for those who want to create the illusion that ID is not a religious approach.[12] Intelligent design proponents routinely claim that their design inference

[12] If ID is made more concrete so that predictions result, there is still the question of whether it fits the known evidence to a higher degree than evolutionary theory. Young Earth creationism of course makes concrete, testable claims (e.g., about the age of the Earth and the occurrence of a worldwide flood), which have been shown to be false.

is analogous to how human agency is inferred in forensic science, archaeology, and physical anthropology, suggesting that since the latter are scientific inferences, so is the ID inference. However, in forensics it is possible to distinguish between a non-human cause of a fire and arson because for each cause its mode of operations and its specific effects are well known, so that the plausibility of each possible scenario (hypothesis), given the evidence, can be assessed. The same applies for paleoarchaeologists determining whether the marks on stones are due to non-human natural causes or due to the agency of ancestral humans—such an inference gets off the ground only because scientists know what marks are left by natural processes such as erosion, and why and how humans modify certain stones. In sum, its proponents portray ID as a modest approach, which merely attempts to infer the existence of some kind of design from natural phenomena. However, no such inference to design can be made without (a) providing a specification of the nature of this design and the operation of the designer (Sarkar 2011; Sober 2008), and (b) showing that intelligent design fits the evidence better than other relevant theories, in particular evolutionary theory (Elsberry and Shallit 2011; Sober 2008).

So far I have phrased the point that science can work only by comparing different hypotheses (two contemporary rivals, or an earlier and later version of a theory) in terms of prediction: one has to determine whether H_1 predicts observation O to a higher degree than H_2 does, i.e., $P(O|H_1) > P(O|H_2)$. But the same point can also be cast in terms of explanation: the question is always whether one approach offers a better explanation of a phenomenon than another approach. In this context, ID proponents have been criticized for putting nothing forward but illicit 'God of the gaps' arguments, i.e., pointing to phenomena for which science does not have a satisfactory explanation and using this as evidence for a supernatural influence (Scott 2004). Creationists and ID proponents are fond of making 'arguments' against evolutionary theory and pointing to aspects of extant species for which no detailed evolutionary explanation is available. But this is irrelevant as long as no intelligent design explanation of this phenomenon is put forward. ID proponents do not bother to offer explanations; in Sect. 2.1 we have seen that Behe and others do not attempt to offer an explanation of how the biological features they allege to be irreducibly complex have originated in time. They could not offer an explanation, as the vacuous hypothesis that somehow some kind of intelligent influence was involved does not explain at all. Similar to the above mentioned erroneous claim that ID makes predictions, creationists may feel that something having been designed offers an explanation (or a better explanation) of complex biological features. But this is an illusion, as an explanation has to lay out why an entity exists at a certain time *rather than* failing to exist, and why it has the properties it has *rather than* having different properties. The mere appeal to that entity being designed does not shed any light on this.

This is a lesson about the *nature of scientific explanation* that can and should be conveyed to students. While ID proponents suggest that making inferences from evidence is the essence of science, the central aim of science is to put forward explanations. An explanation of a phenomenon has to shed light on why it is the way it is rather than otherwise. Explanations are typically incomplete, where for some phenomena no explanation is currently available. But science strives to make explanations more complete and revise and improve upon past explanations. The adequacy of a proposed explanation for a phenomenon must always be assessed in terms of how it *compares* to other attempts to explain the phenomenon, including past explanations. Science in general, and evolutionary biology in particular, develops explanations in ever increasing detail, whereas ID proponents do not undertake anything like this.

This section implies that science education needs to explain to students why an event being extremely improbable, given the mechanisms postulated by a scientific theory, does not undermine this theory in any way. While ID proponents phrase their approach in terms of making inferences from observations, the real issue in biology is explaining observable phenomena, where rival explanations of a phenomenon are to be compared. Evolutionary explanations are often incomplete, but improve over time, whereas intelligent design does not have a positive explanatory agenda. While ID proponents pick on a few observations and claim that one can infer design from it, evolutionary theory offers explanations of a vast array of phenomena.

4 Methodological Naturalism and the Nature of Science

An important characteristic of science is its commitment to methodological naturalism, which is broadly speaking the scientific approach. *Methodological naturalism* asserts that science ought to make claims about natural (in the sense of material) phenomena only, as its claims have to be backed up by empirically accessible evidence. Science explains by appeal to natural causes, as opposed to invoking supernatural causes. This is a commitment pertaining to the methods of science, but also embodies a limitation of the scope of scientific claims, and thus the basic aims of science. Methodological naturalism does *not* claim that no supernatural phenomena exist, it merely claims that science cannot study the supernatural. *Metaphysical naturalism*, in contrast, claims that only natural, i.e., material, phenomena exist. The latter is a not a tenet about the methods or aims of science, but a metaphysical tenet referring to what does and does not exist (Sarkar 2007; Shanks 2004). (In popular evolution vs. intelligent design debates metaphysical naturalism is often called 'philosophical naturalism', which is a bad term as in philosophy many different varieties of naturalism are distinguished.) The reason this distinction is so important is that while metaphysical naturalism entails atheism, methodological naturalism does not have any religious implications—though intelligent design proponents have tried to muddy the waters by claiming that methodological naturalism slides into inherently atheist metaphysical naturalism (Forrest 2011). The fact that many scientists, including evolutionary biologists, are religious believers shows that science and its commitment to methodological naturalism do not amount to atheism.

Methodological naturalism provides a clear way to distinguish between theistic evolutionism and intelligent design. Theistic evolutionists believe that the cosmos and the laws of nature were created by God, but that subsequently all material processes have unfolded due to natural laws without any divine intervention, so that material, worldly phenomena (including the history of life) are to be explained using the standard resources of science—i.e., a commitment to methodological naturalism (Lamoureux 2008). Intelligent design proponents, in contrast, assume that there had to be some direct influence by a supernatural agent *during* the history of the world, and definitely during the history of organismal life. William Dembski states that "theistic evolution is no different from atheistic evolution, treating only undirected natural processes in the origin and development of life" (Dembski 1998b, p. 20). Even though ID proponents attempt to portray intelligent design as a good scientific approach that uses empirical evidence, through its insistence that the history of life is partially to be explained by the influence of a supernatural intelligence, ID rejects methodological naturalism, and thus is actually opposed to the scientific approach. In fact, ID proponents have heavily criticized theistic evolutionists (Johnson and Lamoureux 1999), with Dembski asserting that "theistic evolution remains intelligent design's most implacable foe" (Dembski 2002a).

Since many high school students tend to view evolution and religion as being in conflict, it is important to convey to them that science does not take a stance on religious matters (no matter whether the label 'methodological naturalism' is used or whether this is more simply phrased as a lesson about the methods, nature, and limits of science). Students can fruitfully be taught how there is a common ground in science which permits scientifically minded persons to either be religious or atheist, whereas only ID proponents and creationists view science and religion in conflict (for the relation between evolutionary biology and religion see Ayala, this volume; Alexander, this volume). Once it is clarified that science and religion not only use different epistemologies, but also concern different domains regarding the human condition, students will have a conceptual framework through which they can reconcile their religious beliefs with the evolutionary biology taught to them (Sinatra and Nadelson 2011).

4.1 Why Methodological Naturalism Is Not an a Priori Commitment

In addition to claiming that it slides into metaphysical naturalism, creationists have directly objected to methodological naturalism on the alleged grounds that scientists simply presuppose it without justification. Science has to presuppose its methods before being able to use them to conduct research. But if methodological naturalism is just presupposed, then the supernatural is by sheer assumption excluded from the realm of science. The creationist objection continues that just as naturalistic scientists can avail themselves of a 'philosophy' (epistemology) as a starting point, so creation scientists may use their epistemological point of departure—the fact that the bible is the inerrant word of God—and proceed from there in their interpretation and formation of beliefs about the biological world. This criticism of methodological naturalism has been put in a more sophisticated fashion by some intelligent design proponents, who have claimed that methodological naturalism is an *a priori* philosophical commitment (Beckwith 2003a, b; Johnson 1991). Whereas a posteriori knowledge is knowledge obtained based on experience and the empirical investigation of the world, a priori knowledge is obtained without the involvement of any experience or investigation of the observable world. Logical and mathematical principles have typically been considered by philosophers to be knowable a priori, and metaphysical and theological principles have been other traditional candidates for a priori knowledge (if they are knowledge at all). If scientists endorsed methodological naturalism a priori, they would use it to test hypotheses, but they could not *empirically* test the methodological naturalism presupposed or empirically support it. In what follows, I discuss why scientists' endorsement of methodological naturalism is not a priori, as apart from showing the claims by ID proponents to be wrong, it prepares subsequent lessons for how to demarcate science and non-science.

That scientists do not endorse methodological naturalism *a priori* is shown by the fact that their understanding of what methodological naturalism involves and what counts as a 'natural' phenomenon has *changed* substantially over the course of history. Several centuries ago it was assumed that natural philosophy (as science was called back then) could, in its study of the natural world, appeal to the divine realm. The astronomer Johannes Kepler, a proponent of the new heliocentric system, wondered why the solar system had six planets, rather than more or less (only six planets where known at this point). His *Mysterium Cosmographicum* (1596) proposed a mathematical explanation based on the fact that there are only five perfect solids, motivated by the conviction that the heavenly bodies were arranged by an elegant plan of God the mathematician. Even if not combined with theological considerations, nowadays such a purely mathematical or metaphysical explanation is deemed unscientific, and the number of bodies in the solar system or in the universe is not even deemed to be a central astronomical *question*.

Views about what scientific *methods* are reliable, what can be observed, and what can be empirically tested have changed over the history of science. When the telescope was developed, its use for the purpose of astronomy was initially challenged based on the idea that naked eye observation was the way to obtain valid knowledge. Due to the simple lenses available, early telescopes made the observer see some stars double or even suggested heavenly bodies where there were none. It took astronomers decades to learn which visual observations with a telescope actually represented features of the cosmos (the same holds for the introduction of the microscope; Hacking 1983), but the method of telescopic observation eventually became universally accepted. Likewise, while the scientific consensus once held that the study of a person's facial features permits inferences about her intellectual abilities, personality features, and criminal tendencies, this method has been soundly rejected, resulting in phrenology—once a reputable scientific approach—being nowadays considered pseudoscience. Likewise, views about what counts as a 'natural' phenomenon, and what is *physically possible* and impossible have changed in history based on new views about what the laws of nature are and what kinds of entities exist. Is it possible to penetrate a massive body like a ghost? In the past this may have seemed absurd, but nowadays it is clear that this is possible as there are elementary particles that penetrate massive bodies all the time. Spontaneous generation was the idea of a simple living organism (e.g., a little worm) emerging from inanimate matter in a short period of time. This biological view was generally held for centuries, until 200 years ago, and it was assumed that the spontaneous generation of new simple organisms was an everyday occurrence. Why spontaneous generation is virtually impossible has become clear with the advent of the cell theory of organisms in the nineteenth century. Such a change in views about what natural phenomena there are and what is physically possible is important in the context of methodological naturalism as it entails a change of which phenomena and causes a scientific explanation may or may not appeal to.

Methodological naturalism includes a number of concrete commitments about what counts as a scientific question, what methods are valid, what natural causes there are, and what qualifies as a scientific explanation. Methodological naturalism is endorsed by science, but it is not an a priori 'philosophical' commitment, as past construals of methodological naturalism came to be rejected and replaced by revised construals of what methods are empirically reliable, what causes exist, and what explanations are valid. Indeed, science will continue to revise and improve its understanding of methodological naturalism. These various past revisions were done for good empirical reasons, as hinted at in the above examples.[13] As a result, current scientists endorse methodological naturalism because of its historical track record; it is accepted *a posteriori* based on past experience. This shows that scientists are justified in endorsing methodological naturalism, including its current construal that excludes appeal to supernatural features. Far from being an arbitrary 'philosophical' commitment, the current construal and use of methodological naturalism is *justified* by the historical reasons for changing past construals of methodological naturalism. These considerations about methodological naturalism also have implications for how to possibly demarcate science from pseudoscience.

4.2 Demarcation and the Nature of Science

One strategy for pointing to the inadequacy of creationism and intelligent design is to argue that it is not a scientific approach, based on a *demarcation* account that distinguishes science and pseudoscience (or sound science and junk science).

[13] In the case of the use of the telescope for astronomical observations, even though this method was controversial upon its introduction, some reasons for its increased acceptance were that repeated observations gave consistent orbits and that telescope-based predictions on the future positions of planetary bodies were borne out. Moreover, it was demonstrated that the telescope reliably represented distant objects on Earth, whose properties could be verified by naked eye observation. Using lamps, Galileo showed that, unlike telescopic observations, naked eye observations overestimated the size of distant bright lights against a dark background, so that he was in a position to explain the inconsistency of the apparent size of the planets and stars viewed by naked eye vs. telescope. Thus, a previously accepted scientific method (naked eye observation) can be used to show the reliability and even superiority of a new method (telescopic observation), yielding an empirical justification for a change in method.

The 1982 ruling in *McLean v. Arkansas Board of Education*, which found the teaching of creationism in public schools of the US state of Arkansas to be unconstitutional, was, among other things, based on such a demarcation account. However, it has turned out to be difficult to put forward valid demarcation criteria. An idea that enjoys wide popularity among scientists is that the essential feature of a scientific theory is that it is falsifiable. Below in this section and in Sect. 5, I make plain why falsifiability should not be the primary demarcation criterion as it is insensitive to the empirical context and focuses on theories rather than scientific practices. However, there are also other initial problems with it. Any hypothesis that has been falsified—including Nazi race theory or a pseudoscientific claim—is a falsifi*able* hypothesis, which shows that it is moot to use falsifiability as a demarcation criterion, given that one does not want to give credence to long discarded hypotheses by still calling them 'scientific'. Furthermore, statistical and probabilistic theories are widespread in science, occurring even in physics, and, due to the involvement of population genetics, evolutionary theory is a statistical theory. Yet any probabilistic theory is unfalsifiable (and would thus count as 'unscientific'), because, while assigning probabilities to various events, such a theory does not predict that certain events must happen, events which could then be shown to be failed predictions.[14]

The 1982 *McLean v. Arkansas* judgment relied on the testimony of philosopher of science Michael Ruse, who in addition to using falsifiability, employed other considerations to determine whether a theory is scientific, such as being testable against the empirical world and explaining by reference to laws of nature (Ruse's testimony, his defenses of his demarcation account, and criticisms of it by others are reprinted in Ruse 1988). Ruse's demarcation account has been found wanting by some philosophers, most prominently Larry Laudan, who apart from criticizing particular demarcation criteria by counterexamples from the history of science, concluded that in general "the problem of demarcation between science and non-science is a pseudo-problem (at least as far as philosophy is concerned)" (Laudan 1983, p. 124). While the idea of demarcating science from pseudoscience suggests the existence of a *one-dimensional* scale from 'scientific' to 'unscientific', my view is

[14] Another drawback is that the notion of falsifiability stems from Karl Popper's (1959) falsificationism. This general doctrine of confirmation assumes that while it is possible to conclusively *dis*confirm (falsify) a theory, there is no incremental confirmation of theories by evidence. Falsificationism maintains that it is not rationally possible to inductively increase one's degree of belief in a theory as evidence accumulates. In fact, one cannot have any degree of confidence in its truth—one may only believe that a particular theory has shown to be false. However, even if a theory is incompatible with some observations, scientists may very well continue using the theory if it is supported by other lines of evidence and if there is no better alternative available, as opposed to rejecting it as 'falsified'. More importantly, the only way to rationally justify one's actions is with reference to factual beliefs for which one has some support, so there has to be some degree of positive belief in theoretical claims. Since scientists do have rational support for their (limited) endorsement of a theory (e.g., mechanics) and since scientists and policy makers use this theory for further action (e.g., building space rockets), philosophers of science have generally rejected falsificationism (Godfrey-Smith 2003).

that approaches claiming to be science have to be judged and compared based on a variety of important considerations that are better kept separate than merged into the single feature of 'being scientific' (Hoyningen-Huene 2008). In this sense, offering an account of demarcation, or providing a definition of science, is not a central *aim* of philosophy of science. Still, there are important questions about the nature of science and the credentials of particular approaches claiming to be sound science in the philosophical vicinity.[15] And even if many considerations can be used to assess theoretical approaches, intelligent design falls short of all of them, unlike evolutionary theory (Thagard 2011).

Sahotra Sarkar (2011) favors showing intelligent design to be intellectually problematic independently of an account of demarcation, as demarcation criteria that are context-independent and assume scientific approaches to be historically static are bound to fail. The latter is well taken, but it leaves the option of using 'demarcation' considerations that are *context-dependent and historically dynamic*. Robert Pennock (2011) emphasizes that a commitment to methodological naturalism was used as one demarcation criterion in the 2005 *Kitzmiller v. Dover Area School District* trial (which ruled intelligent design to not be science), as ID proponents admit that they reject methodological naturalism. Combine this with my above point that scientists' understanding of what methodological naturalism involves has changed over the course of history. For the purposes of Pennock's trial testimony, it sufficed to show that intelligent design proponents want to explain biological phenomena by appeal to *divine* influences, but my notion of methodological naturalism laid out in the previous subsection is richer by including a variety of considerations about what phenomena currently count as natural, what kinds of explanations are currently permitted, and what methods are currently deemed to be valid. For instance, I have pointed out that while appeal to spontaneous generation was once scientifically legitimate, it is not any longer. Thus, a contemporary approach that explains by invoking spontaneous generation is scientifically flawed, even if it does not appeal to divine causes. Rather than offering a universal philosophical account of science, any account of what science involves, what is scientifically legitimate, and what makes an approach scientifically dubious—at a certain point in history—has to be based on a variety of considerations that are taken from the concrete scientific traditions in the relevant historical period.

In addition to changing across *historical* time, an account of what science consists in has to be context-dependent in a second fashion—it may differ across different *domains* of science. Ruse's testimony in the 1982 court case included the idea that science explains by reference to laws of nature. This may hold true for physics,

[15] Here is an analogy: While biological attempts to define 'life' exist, such definitions are fraught with difficulties (see Cleland and Zerella, this volume). This is not a problem, as biology offers many insights into the features of living organisms independently of a definition of life. The biology of viruses offers empirical understanding even if it is not settled whether or not a virus is a living entity. Biologists pursue various aims and address concrete questions about particular organism groups, but defining life is not an aim of biology. In the same vein, philosophy can address various normative issues about scientific approaches without aiming at a definition of 'science'.

but quantitative generalities that could be called laws of nature can hardly be found in molecular, cellular, and developmental biology (see also Lange, this volume). In these domains, explanations in terms of molecular mechanisms are used, so that how scientific explanations look and whether they involve laws can differ from domain to domain (Bechtel, this volume; Bechtel and Abrahamsen 2005; Brigandt 2013; Potochnik, this volume). In fundamental physics, relativity theory and quantum mechanics have not been reconciled yet, and applications in physics use many models that may make mutually incompatible idealizations. In contrast, a database of telephone numbers may be free of any inconsistencies and its data may have a degree of precision clearly exceeding measurements in experimental physics. Of course, this does not entail that this database is more scientific than physics, as it concerns a different domain of knowledge. Thus, considerations about the features characterizing 'science' have to be relative to historical periods and scientific domains or disciplines.

Finally, there is another way in which history matters in judging the credentials of a scientific approach (apart from criteria of legitimate science changing across time), namely, the past track record of the approach (Hoyningen-Huene 2008). While some scientific approaches may have started in a promising fashion (e.g., phrenology), they later failed to generate new insights, degenerated, and became abandoned. Such a consideration of the advance of a scientific approach gains traction when two rival approaches are compared. A striking difference between evolutionary biology and creationism/intelligent design is that only the former has steadily improved its explanations and closed gaps in our knowledge. In fact, creationists and ID proponents are not interested in advancing our knowledge of the origin and change of organisms, as they primarily aim to put forward 'arguments' against evolution without developing rival explanations (as pointed out in Sects. 2.1 and 3.2).

In summary, there is no universal and unchanging philosophical account of the nature of science. Rather than treating science as a monolithic whole, there are many different scientific fields with differing standards of evidence and explanation. Any adjudication of an approach claiming to be sound science (e.g., intelligent design or alternative medicine) has to be based on a variety of factors that are specific to the particular empirical domain. Falsifiability is a poor demarcation criterion because, apart from erroneously suggesting that a single consideration (promising a yes-or-no answer) will suffice, falsifiability, as a universal criterion, cannot capture considerations that differ across fields or history. Furthermore, falsifiability focuses on a particular theory and thus an approach at a single point in time, rather than evaluating the past development and future promise of the approach.

The pedagogical lesson of this section is that one should make plain to students that science addresses a restricted domain and does not speak on religious matters, but that it has a solid method to gain knowledge about the empirical realm. Teachers have to avoid conveying to students a monolithic picture of science that is exclusively modeled on current science or even an area of current science. Ideally, the diversity of scientific disciplines and their different scientific characteristics are to be addressed (Brigandt 2013; Love 2013; Pigliucci, this volume). It is important to point out to students that methodological and explanatory standards and the criteria for a scientific approach have changed through time. They have not done so in an arbitrary fashion, as scientific standards have improved and past developments offer a *justification* for the current standards and conception of science. As a result, even though past scientists appealed to religious considerations, there are good reasons why this is not legitimate for any contemporary approach, including intelligent design.

5 Practices and Values: Epistemic and Social

5.1 Construing Science as Epistemic and Social Practices

Growing out of logical positivism, several decades ago philosophy of science tended to construe science in terms of various factual claims, in particular observation statements and theoretical claims. Confirmation was construed as a logical relation between observation statements and theories. While this justification of theories by evidence was seen as an objective procedure, it was assumed that scientific discovery need not always be a rational procedure, so that discovery was not a matter for philosophy, but rather for psychology and history of science. This situation has changed, leading to a broader picture of what science involves and what philosophers of science must take into account. Apart from various factual claims about the natural world, the aims pursued by scientists (e.g., which phenomena are currently deemed in need of explanation) are an important part of science, as the recognition of an explanatory problem prompts various scientific efforts devoted toward it, and a change in what are deemed to be the relevant scientific problems accounts for the historical dynamics of a field and different trends among disciplines (Brigandt 2012, 2013). Nowadays, scientific discovery and the employment and refinement of various experimental methods are of concern to philosophers. More generally, the study and assessment of *scientific practice*—in fact, various scientific practices—is a central topic for philosophy, in particular naturalistic philosophy of science.[16] Modern science generates and validates knowledge in a collaborative fashion, involving various institutional factors, such as funded projects and the peer-review system, making it necessary for philosophers to take into account the social dimensions of science (Downes 1993; Solomon 2001; see also Gannett, this volume). Against the traditional rational–social dichotomy that views social factors as subverting objective science, Helen Longino (2002) argues that

[16]Footnote 15 argued that just like developing a definition of life is not a genuine aim of biology, so philosophy of science need not aim at a definition of science. The biology–philosophy analogy can be extended further. Similar to biology making progress by understanding various life *processes*, philosophers should not ask what science is, but analyze how science *works* and judge the credentials of intellectual traditions based on their epistemic and social practices.

certain social factors are constitutive of scientific rationality, such as mechanisms of establishing intellectual authority, publically recognized standards, diversity of perspectives, and venues for criticism.

Apart from the fact that it offers a more faithful portrayal of science, conveying science as an investigative practice has benefits for science education (Brigandt 2013; Love 2013). Especially in secondary education, the traditional focus is on presenting scientific facts and theories, and, given the rapid progress of science, it turns out to be impossible to teach even those recent scientific ideas that are well-supported. Rather than exclusively teaching the *content* of science, it is fruitful to give students an idea of the *practice* of science, which would provide an understanding of how scientific knowledge is generated, validated, and subsequently revised—a lesson that has validity even if some of the content taught in classrooms is already outdated. By conceiving of scientific activity directed at scientific questions and problems, it becomes plain to students that scientific explanations are initially incomplete but improved over time, and that assessing an explanation involves comparing it with other explanations targeting the same question—entailing that intelligent design's arguments against incomplete evolutionary explanations would be cogent only if ID offered better explanations. Given the collaborative nature of modern science, there can be substantial support for a scientific theory such as anthropogenic climate change even if no individual scientist—lest a science teacher in the classroom—can present it. Students should also be aware of the collaborative practice and what counts as consensus in science, and who qualifies as having expertise in a certain topic.

Studying and evaluating a scientific approach in terms of its epistemic and social practice is particularly important in the case of intelligent design (Brigandt 2011, Sect.4). In the previous section I have argued that rather than using a universal demarcation criterion, the credentials of an approach claiming to be science have to be assessed based on various concrete considerations that are specific to a scientific domain in the respective historical period. I have also pointed to the need to pay attention to the approach's past track record and progress. A consideration of a theory (as a specific set of tenets) cannot achieve this—by implication the same holds for any alleged demarcation criterion that applies to theories only, such as falsifiability. To assess the *future* promise of a current theoretical approach (and how it compares to rival approaches), it is necessary to analyze the epistemic and social practice of its current practitioners. This reveals most strongly why intelligent design does not measure up with evolutionary biology.[17] Richard Duschl and Richard Grandy (2011) argue that in secondary school classrooms, science should not exclusively be construed as the inferring of predictions and testing of

[17] Arguing that the question is not whether theories are scientific, but whether epistemic practices are so, Chinn and Buckland (2011) compare the practices of evolutionary biologists, young Earth creationists, intelligent design proponents, and the nineteenth century scientist-creationists of Darwin's era. The latter's practice turns out to be more scientific than the practice of contemporary intelligent design proponents.

hypotheses (the hypothetico-deductive model of science), but in terms of their dialogic practice model of scientific method, which gives students a much better appreciation of why intelligent design proponents do not participate in crucial epistemic and social practices characteristic of science. I add that relying too much on the hypothetico-deductive model as a vision of science also plays into the intelligent design strategy of (falsely) claiming that ID makes predictions and is simply about making inferences from the evidence. The latter contributes to the misperception among students that intelligent design is scientific; and the hypothetico-deductive model obscures the necessity for ID to offer an alternative explanation of organismal diversity.

What follows are some aspects of the practice of ID proponents highlighting how they differ from most evolutionary biologists. Rather than developing explanations of biological phenomena, ID proponents promote alleged arguments against evolution, most of which were already developed by traditional creationists. Many academic ID proponents are lawyers or engineers, but only a few of them are biologists. A handful of the latter (such as Michael Behe) conducts bona fide scientific research and publishes in the peer-reviewed literature. However, none of these papers concern intelligent design. In fact, ID proponents do not even have enough scientific-looking material to keep alive the online journals founded and run by themselves.[18] Even though the ID arguments against evolution have been repeatedly debunked, ID advocates keep promoting them to their non-academic audience—so that failing to accommodate criticism is a feature of their practice. Not only is there currently no content-laden ID theory, but these practices of ID proponents show that no such theory is forthcoming.

There are reasons for this. The actual growth of scientific knowledge is not required given the primary aim of ID proponents, an aim which is to embed Christianity into all aspects of society.[19] This includes the ID proponents in academia, most of whom reject the idea of common ancestry for religious reasons. European scholars often underestimate the financial and political power of creationists and the religious right in the US, as well as the magnitude this organized threat poses to science education. The label 'intelligent design' was developed by American creationists in an attempt to have creationism taught in public schools, where religious views may not be promoted due to the separation of state and church

[18] See http://www.arn.org/odesign/odesign.htm (1996–2000) and http://www.iscid.org/pcid.php (2002–2005). The latter was abandoned just after *Kitzmiller v. Dover* ruled the teaching of intelligent design to be unconstitutional. In late 2009, largely the same group of editors set up a new journal http://bio-complexity.org, though in the last 3 years only 11 articles or reviews (all but one research article co-authored by the editors) have appeared.

[19] From an internal Discovery Institute memo leaked to the public: "Governing Goals: To defeat scientific materialism and its destructive moral, cultural and political legacies. To replace materialistic explanations with the theistic understanding that nature and human beings are created by God. […] Twenty Year Goals: […] To see design theory permeate our religious, cultural, moral and political life." (http://www.antievolution.org/features/wedge.pdf)

mandated by the US constitution (Forrest and Gross 2004). In December 2005, the teaching of intelligent design in public schools was ruled to be unconstitutional in *Kitzmiller v. Dover Area School District*. As a result, ID proponents have backed off from calls to teach ID (some now falsely claiming that they never advocated its teaching), and instead come to lobby for 'teaching the controversy', 'critical analysis of evolution', and 'academic freedom' in public schools—which does not make a difference given that there is no ID theory apart from alleged arguments against evolution—continuing the creationist strategy of undermining the teaching of evolution (Forrest 2010).

ID proponents are very active, but their activities are not so much devoted to scientific research, but to political and legal campaigns in the public arena. Financially supported by a conservative think tank called the Discovery Institute, ID supporters attempt to influence local school boards and state school boards (who are in charge of public school curricula), state politicians (to pass legislation that enables false critiques of evolution being taught), and the media. Given this, what matters is how ID is perceived by the general public. Creating the public impression of ID being a scientific approach and there being a scientific controversy about evolution—even if it is easy for academics to see that this is not the case—suffices to further the social goals of the ID movement. The inflation of credentials is one strategy. The Discovery Institute's 'Scientific Dissent from Darwinism' list features more than 700 persons claimed to be scientists, yet many of them obtained an academic degree in the past but are not active in research, and none of them are working in evolutionary biology, so that the list is populated with non-experts claimed to be otherwise.[20] Speaking to a scholarly audience or in the legal arena, ID proponents claim their approach is not tied to any religious assumptions; yet when speaking to their supporters they more frankly hail ID as part of a culture war about religion. ID advocates publicly misrepresent legitimate criticism of their views and actions, crying censorship, to the point of falsely claiming to have been removed from academic positions for criticizing evolutionary theory.[21] While the scientific publications of ID proponents do not support intelligent design, they are still advertised to intelligent design's non-academic followers as providing scientific support for ID.

In summary, any epistemological analysis of a scientific approach (or an approach claiming to be science) has to encompass considerations about its epistemic practice, including how the persons developing the approach interact with others individuals, and how their practices are institutionally and socially embedded. The fact that intelligent design, unlike evolutionary biology, will not improve in the future cannot be seen in terms of the current theories of each approach, but only in terms of the practices of the two communities and their epistemic and social aims.

[20] http://www.dissentfromdarwin.org

[21] Compare the statements made in the 'documentary' *Expelled: No Intelligence Allowed* with http://www.expelledexposed.com

5.2 How Epistemic and Social Values Matter

The thrust of this section's argument so far has been the necessity of construing and evaluating a theoretical approach in terms of its epistemic and social practice. But the discussion has also hinted at the relevance of *epistemic values*, such as intellectual honesty and the uptake of criticism. One of the particularly striking features of the intelligent design movement is the disingenuousness and underhanded tactics of several of its advocates. Epistemic values are not only relevant for studies in philosophy of science (Brigandt 2011, Sect.4), but they likewise ought to be addressed in science education. The many instances of research misconduct show that it does not suffice to train students in the use of scientific methods (narrowly construed), but that they have to be taught what ethical scientific conduct involves. More to the point of this chapter, making students aware of the relevance of epistemic values and standards of conduct in science may contribute to students approaching intelligent design (should they come across it) in these terms as well, as opposed to merely considering arguments for an alleged ID theory.

In addition to epistemic values, social values (including ethical and political values) may matter for discussions by contemporary philosophers of science, since research is to be assessed not only in terms of whether it is methodologically sound, but also in terms of whether this research is ethical and what consequences it will have for society (Douglas 2009; Fehr and Plaisance 2010; Kitcher 2001; Kourany 2010; Tuana 2010; Gannett, this volume).[22] Social values are likewise relevant to a portrayal of what science involves in the context of science education, to the extent that such values matter to practicing scientists. The reason that scientists publicly advocate the scientific consensus on anthropogenic climate change is not just due to this scientific view being well-supported by evidence, but primarily because scientists employ environmental and social values that entail that unchecked global warming has dire consequences. This has parallels to other cases, including intelligent design. A few decades ago the tobacco industry succeeded in preventing public recognition that smoking causes cancer, and averted state regulations against smoking for some while. Though the scientific opinion tended to go against the tobacco industry, it sufficed for the latter's purposes to merely spread doubts on this issue in the public mind by some industry-employed scientists. Nowadays many companies use this strategy to conceal the actual scientific evidence on the potential harmfulness of their products, and creating public doubt about the scientific consensus on anthropogenic climate change has been used by corporations opposed to regulations countering global warming (Michaels 2008; Oreskes and Conway 2010). Needless to say, even though the consensus among evolutionary biologists is solid, a primary

[22] I have argued in Sect. 4.2 that whereas a framing of philosophy of science in terms of a demarcation of science from pseudoscience erroneously suggests that approaches can be evaluated on a one-dimensional scale from scientific to unscientific, theoretical approaches differ in many respects. Considerations about ethical, social, and political consequences are yet other philosophical considerations that can be brought to bear in the assessment of epistemic traditions.

strategy of the ID movement is to create the public illusion that there is a debate about evolution and that evolutionary theory is poorly supported. Scientists react to such activities *outside* of science precisely because of their social-political consequences. This yields a dual task for science education: to teach sound science (against efforts to undermine science instruction) and to teach that scientists pay attention to the social implications of their research.

In Sect. 5.1 I have argued that an *epistemic* evaluation of intelligent design and its future (non-)promise benefits from knowledge of the ID movement's social aims—though this does not require judging these social aims. Of course, one can also engage in a *social* and political evaluation of the ID movement. The ID movement's ultimate aim is to re-Christianize largely secular Western societies and to more generally impose a socially conservative agenda upon them. In the US, this includes denial of equality and basic rights, particularly opposition to legal abortions and equal rights for homosexuals, as witnessed by the calls of several academic ID proponents that universities be permitted to hire only heterosexual professors. Barbara Forrest (2011) points to ideological affinities and institutional relations between several ID proponents (including William Dembski) and Christian Reconstructionism, which pursues a repressive social order by shaping public policy and legislation in terms of biblical principles (and hence is also called Theocratic Dominionism). At the very least, the ID movement's immediate social aim—a reprehensible aim at that—is to undermine the teaching of evolution in high schools. But this is part of a broader assault on school curricula, which includes the attempt to not include climate change (in line with the strong free-market and deregulation ideology of US conservatism) or embryonic stem cell research (in line with conservative objections to such research that are tied to its anti-abortion agenda). It would also involve the inclusion of a revisionist American history that downplays slavery and its impact on contemporary racism, and attempting to portray the US as a Christian nation by presenting its foundation and its constitution as a religious achievement, rather than a secular enterprise that set up a political and judicial system independently of religious commitments.

In the case of intelligent design and the ID movement, it may well be possible to give an assessment in terms of epistemic values without recourse to social values (the epistemic assessment demands knowledge of ID's social agenda, but does not require judgment of the agenda). However, there are cases in which epistemic and social considerations are entwined, so that it is impossible for a scientist or a philosopher of science to judge the epistemic credentials of some research *without* using ethical, social, or political values. Consider a hypothesis, the tentative endorsement of which by scientists will have policy implications, as will failure to endorse the hypothesis. Evidence never fully supports a hypothesis, so that, given uncertainty, scientists have to consider the social consequences of tentatively endorsing an actually false hypothesis, and the consequences of withholding endorsement of an actually true hypothesis, as has been prominently argued by Heather Douglas (2009). When there is evidence based on animal studies that a new pesticide which is to be approved by regulatory bodies is highly carcinogenic for humans, not asserting that the pesticide is dangerous (on the grounds that the evidence—as always—falls short of certainty) will have very harmful consequences to humans, should the substance be carcinogenic. In contrast, tentatively recommending that the pesticide be considered carcinogenic (so that this new pesticide is not approved) will have much more benign societal consequences, given that there are other pesticides available. In this scenario, it is sensible for scientists to recommend that the pesticide be deemed carcinogenic, and such scientific advice is partially influenced by social values—in fact, an epistemic decision of whether to endorse the hypothesis cannot responsibly be made independently of considerations about social consequences.

A stronger joint epistemic-social agenda for science and philosophy of science stems from Janet Kourany's (2010) call for a *socially responsible science*, motivated from the perspective of feminist philosophy of science. Studies that focus on male primates and men (no matter their veracity) can lead to such a biased and misleading picture of primate and human social organization and the role of females, that it has harmful effects on the condition of contemporary women. This shows that (selectively) obtaining well-confirmed items of knowledge is neither enough to achieve an adequate scientific account, nor socially responsible science (Anderson 1995). Women have traditionally been excluded from and still are underrepresented in many drug trials, because, among other things, their menstrual cycle has been seen as a confounding factor. But precisely due to their differing endocrinology, the results of the drug's efficacy, dosage, and side-effects do not carry over to women. As a result, doctors either have to withhold available drugs from women or prescribe them without knowing the involved risks or how to dose them properly (Goering 1994; Kim et al. 2010). Restricting scientific claims about such drugs to men—only to declare an 'epistemically' valid account—would still be research that excludes a relevant social group from the benefits of research. The better alternative is to acknowledge that *epistemic* considerations about how to design drug trials have to answer to *social* considerations. As an instance of exemplary socially responsible research, Kourany (2010) points to the studies by Carolyn West (2002) on domestic violence against African-American women, which aims at studying (and improving) the particular condition of these women but without promoting the stereotype that black men are inherently more violent. These social aims influence what counts as a proper epistemic approach in terms of choice of concepts, selection of study subject, data collection and analysis, and dissemination of results.

Let me conclude with a remark on education. I have indicated that, beyond the evidence for anthropogenic climate change, climate scientists publicly advocate the knowledge of their field because they employ social values according to which the consequences of global warming are socially harmful. The present point is that scientists may well have reasons (independently of their scientific expertise) for holding the social values prompting the public promotion of climate science. A primary motivation for religious belief is that it is deemed to give meaning and moral guidance, and the resistance to accepting the teaching of evolution among some high school students is often due to their perception that evolutionary biology, and more generally naturalistic science, promotes an amoral or moral relativist worldview. Of course, moral nihilism (or relativism) vs. religiously based moral dogma is a false dichotomy, and with Kantian ethics and utilitarianism, moral philosophy has created rigorous justifications of ethical principles that do not require recourse to the divine. Many high school teachers (especially in the US) will shy away from addressing ethics in the classroom, as it is easily deemed to be an encroachment on the personal views of students—but so can be the teaching of evolution. While it is not an issue for science classrooms, in those school systems where there are classes on ethics, it is useful to convey that ethics is not so much about particular moral principles, but about how to justify them. Just as students must learn about ambiguous evidence for scientific claims and that such claims can be revised based on increased evidential support, they must understand that there can be rational disagreement about ethical and social values, and that there are means to adjudicate such issues. We have good arguments for why past moral assumptions were wrong and why current ethical standards are superior.

Given that in many students' minds evolution is tied to a materialistic, amoral worldview, it is desirable that students be taught that not only are there adequate and inadequate ways to confirm factual and scientific claims, but there are also better and worse ways to justify ethical tenets.

6 Summary: Lessons for Science Education

Michael Behe's irreducible complexity argument against evolution fails because he ignores that precursor systems could have performed a different function. Structures in different extant species exhibit homologies and comparative studies show how structures have actually evolved, highlighting the need to teach students the comparative method as well as many examples of macroevolutionary transformations (beyond microevolutionary theories). Behe also focuses on isolated molecular systems, ignoring their context and, more generally, the redundancy and robustness of organismal systems. Systems need not break down or lead to detrimental effects for the organism when they are modified or some of their parts are removed. The notion of a genetic blueprint is a metaphor that fails to actually explain the process of development and obscures its flexibility. Robust development and physiological adaptability—which are the opposite of irreducible complexity and organisms being like Paley's watch—have come to be seen as the key to understanding morphological evolvability, so that biology instruction should avoid portraying organisms and organismal systems using information and machine metaphors.

Small probability arguments against evolution are common, and have recently been developed and promoted by William Dembski. Since they are fallacious and made even beyond the context of evolution, science and mathematics instructors should address them. The probability of the occurrence of complex structures assuming that naturalistic evolution occurred (which is indeed very low) must not be conflated with the probability of naturalistic evolution given the occurrence of complex structures: $P(\text{observation}|\text{hypothesis}) \neq P(\text{hypothesis}|\text{observation})$. In fact, from $P(\text{observation}|\text{hypothesis})$ being extremely small, nothing can be inferred about the probability of the hypothesis—it could be high or low. It is easy to see why, as both a true and a false hypothesis entail small probabilities for some observations if the conjunction of many random events is considered. Likelihoods of the form P(observation|hypothesis) can be relevant if several hypotheses are compared. So the real question is whether P(observations|Darwinian evolution) < P(observations|intelligent design), requiring intelligent design to put forward its positive account (the latter probability is undefined if intelligent design merely claims there has been some intelligent influence on some entities at some point in history) The lesson for science education is the need to highlight that hypothesis testing in science involves comparing several rival hypotheses, in which the one offering the best explanation is chosen. Both the irreducible complexity and the small probability arguments are merely arguments against evolution, but do not create any explanation of biological phenomena.

ID proponents have falsely claimed that methodological naturalism (science's study of natural phenomena and explanation by natural causes only) amounts to metaphysical naturalism, and thus atheism. They have also contended that methodological naturalism is an a priori philosophical commitment, and thus without scientific justification. However, that it is not endorsed *a priori* is shown by the fact that the construal of methodological naturalism (and thus what science actually endorses) has changed in the history of science. Over the past centuries there has been significant modification in views about what observational, experimental, and inferential methods are reliable, what can be empirically ascertained, what natural phenomena there are, what laws of nature obtain, what is empirically possible and impossible, and thus what qualifies as a scientific explanation or theory. The implication for science education is that there is not an unchanging, overarching scientific method or nature of science, and that the reasons for why the methods of science have been improved provides contemporary scientists with an *empirical* justification for why the current version of methodological naturalism is endorsed and used in scientific practice. My discussion has also shown that any assessment of the credentials of an approach (which often has problematically been phrased in terms of deciding whether it is science or pseudoscience) must be based on a variety of concrete considerations that may differ across scientific domains and fields.

Beyond the past philosophical focus of construing science in terms of theories, nowadays philosophers of science study the process of discovery and various concrete research practices, so as to assess intellectual approaches also in terms of their socially constituted epistemic practices. This is likewise relevant to biology education, as the difference between intelligent design and evolutionary biology is most marked in the practices of their respective proponents. Given their primarily social aims (undermining the teaching of evolution in high schools so as to make secular societies religious), ID proponents do not develop explanations of biological phenomena and properly react to scholarly criticism, but instead focus their efforts on the public and the political arena, promoting debunked arguments against evolution so as to create the public impression that there is scientific disagreement about evolutionary theory. Current philosophy of science assesses research, not only in terms of whether it is methodologically rigorous, but also in terms of what societal consequences it has and whether it is socially responsible. The intelligent design movement is not to be excluded from scrutiny in terms of social values.

This chapter's primary recommendation for science education is to not only teach the content of scientific theories, but also convey the aims and practice of science. Making students reflect on the nature of science in general attends them to what science actually involves. This pedagogy also has benefits in concrete scientific domains, as it endows students with a better appreciation of how evolutionary biology works, why it does not aim to compete with religious beliefs, what the merits of evolutionary explanations are, and why intelligent design falls short.

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