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ARTICLE

Why the Difference Between Explanation and Argument Matters to Science Education

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Abstract Contributing to the recent debate on whether or not explanations ought to be differentiated from arguments, this article argues that the distinction matters to science education. I articulate the distinction in terms of explanations and arguments having to meet different standards of adequacy. Standards of explanatory adequacy are important because they correspond to what counts as a good explanation in a science classroom, whereas a focus on evidence-based argumentation can obscure such standards of what makes an explanation explanatory. I provide further reasons for the relevance of not conflating explanations with arguments (and having standards of explanatory adequacy in view). First, what guides the adoption of the particular standards of explanatory adequacy that are relevant in a scientific case is the explanatory aim pursued in this context. Apart from explanatory aims being an important aspect of the nature of science, including explanatory aims in classroom instruction also promotes students seeing explanations as more than facts, and engages them in developing explanations as responses to interesting explanatory problems. Second, it is of relevance to science curricula that science aims at intervening in natural processes, not only for technological applications, but also as part of experimental discovery. Not any argument enables intervention in nature, as successful intervention specifically presupposes causal explanations. Students can fruitfully explore in the classroom how an explanatory account suggests different options for intervention.

1 Introduction

Putting forward explanations of various phenomena is a core aspect of scientific theorizing, and the nature of explanation has been extensively discussed by philosophers during the last few decades (W. C. Salmon 1989; Woodward 2014). Scientific explanation is likewise

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an important issue for science education. To adduce examples from different countries, curriculum development has to reflect that “science is a human endeavour that uses processes … to propose explanations about the natural world” (Council of Ministers of Education, Canada 2013, p. 3) and that the “Scientific method is about developing and evaluating explanations” (Department for Education, England 2004, p. 70). In addition to conveying explanations from the body of scientific knowledge to the class, classroom instruction must put students in a position to themselves construct “reasoned explanations” (Department for Education, England 2014, p. 59), a typical achievement objective being that: “Students can … investigate and offer explanations for commonly experienced physical phenomena and compare their ideas with scientific ideas, e.g., sound notes and tones, light and lenses, colors, electric current, condensation, force, speed; …” (Ministry of Education, New Zealand 1993, p. 78). But the most compelling reason for addressing explanation is that classroom instruction ought to enhance science literacy and critical thinking about alleged scientific claims encountered in daily life, so that students need to be put in a position to distinguish good scientific explanations from pseudo-explanations (Yang and Wang 2014), based on an understanding of “how inquiries are conducted in science to provide evidence-based explanations of natural phenomena” (Council of Ministers of Education, Canada 2013, p. 11).

Despite the prominent role of scientific explanation in science education, Jonathan Osborne and Alexis Patterson (2011, 2012) allege that a fundamental flaw of science education scholarship is that the notions of *explanation* and *argument* tend to be conflated, so that science educators fail to convey the distinctive features of scientific explanations. (A similar position is taken by Melissa Braaten and Mark Windschitl 2011.) In response, while not claiming that explanation and argument are exactly the same, Leema Berland and Katherine McNeill (2012) maintain that explanation and argumentation are so strongly entwined in classroom discussion that using a distinction between explanation and argument may even disrupt students’ practice at constructing explanations (see also Berland and Reiser 2009).

The present article contributes to this recent science education debate on the distinction between explanations and arguments. After briefly reviewing how explanation and argument are viewed in science education, Sect. 3 points to known considerations from the philosophy of science literature that scientific explanation and argument are not the same, which I articulate in terms of explanations and arguments having to meet different standards of adequacy. Standards of explanatory adequacy are important as they correspond to what counts as a good explanation in the science classroom. In contrast, science education approaches to explanation that emphasize evidence-based argumentation obscure the standards of what makes an explanation explanatory (which are largely orthogonal to considerations about evidence).

Then I develop additional considerations for why science educators should not conflate explanations with arguments, and take the notion of standards of explanatory adequacy into account. First, an important aspect of science is that explanations are developed to solve explanatory problems. Explanatory problems and aims are not captured by a framework that merely assumes that science gathers evidence and makes arguments based on evidence. But explanatory aims matter because they guide the adoption of particular standards of explanatory adequacy (i.e., what counts as a good explanation in a specific context), and because student engagement is enhanced by viewing explanations as responses to explanatory problems (Sect. 4). Second, in Sect. 5 I address the fact that science sometimes aims at controlling and intervening in nature, an issue of relevance to classroom instruction as well. While successful intervention in natural phenomena (e.g., as part of experimental discovery) requires explanatory knowledge, not every argument provides the knowledge about causes that is needed for intervention.

2 Explanation and Argument in Science Education

In science education, the term 'explanation' is used in two different ways (see also Braaten and Windschitl 2011). First, there is explanation as the *explication* of a concept or of one's reasoning. In a science classroom, the teacher will explain a scientific idea (including a theory as a complex idea), for instance, what the notions of 'inertia' or 'natural selection' mean, or what the theory of Mendelian genetics asserts. She may also ask a student to explain a concept, such as explaining to others what the student meant when saying that an object will 'accelerate.' Likewise, a teacher may explain some steps of scientific reasoning to students, for example, how to set up and solve an equation describing an instance of projectile motion. It is important that students are prompted to explain their own reasoning, so as to convey to their classmates and their teacher how they actually arrived at an answer, and to reflect themselves on their reasoning process.

But the topic of my discussion in this article is 'explanation' in its second meaning, which is *scientific explanation*. A scientific explanation is to account for a phenomenon of nature—obviously a very different issue from explanation as explication, which pertains to some mental content (a concept or one's reasoning). An explication conveys and clarifies an idea, while a scientific explanation has to explain *why* something happened or why an object has certain properties. In addition to the explanations from a certain domain of science provided by a teacher, students are expected to construct explanations in the classroom (Zangori et al. 2013). For example, students are asked to explain why the temperature of water increases when put above a heat source, why salt dissolves when put in water, or why certain species have the same anatomical structures. On both senses of 'explanation,' the term can refer to the practice of putting forward an explanation—i.e., explaining an idea to others or collaboratively developing an explanation of a natural phenomenon—as well as the *product* of this practice, i.e., an explanatory account as for example published in a scientific journal or textbook. In the context of scientific explanation as a product, for the science teacher it is important to notice when (and to understand why) there is a mismatch between the explanation offered by the student and what science deems to be the correct explanation (Kampourakis and Nehm 2014).

Besides explanation, another essential aspect of classroom instructional practice is justification and argumentation. Students are called to offer *arguments* in support of the tentative answers they provide and claims they make in the classroom. Science itself has to justify various claims based on observational data and theoretical background knowledge, which also holds for constructing and defending scientific explanations. An explanatory account includes various factual claims (e.g., about causes that are unobservable entities or events of the evolutionary past), which have to be supported by arguments. Moreover, given that rival scientific explanations for the same phenomenon are routinely entertained (e.g., gastric ulcers being due to stomach acid or being caused by bacteria), evidence-based arguments are needed to adjudicate the merits of a proposed explanation and to establish which explanation is the correct one.

In the classroom, student explanations can likewise be put in opposition to each other, creating the need to convince the peers of one's proposal (Berland and Reiser 2009). It is this involvement of argumentation in the process of constructing and evaluating explanations that has led to the conflation of the notions of explanation and argument, to which Braaten and Windschitl (2011) critically point and Osborne and Patterson (2011) explicitly object. Indeed, even though explanation and argument are occasionally distinguished (Castro e Freire and Motokane 2013; Yang and Wang 2014; Zangori et al. 2013), the science education literature often treats them on a par. For example, in the USA the science standard document of The College Board even *defines* an explanation as a justification of a claim based on evidence and reasoning, in other words, as an argument:

> In this standards document, the term ‘explanation’ means a statement that is composed of the following: at least one claim, the evidence that is related to the claim, and the reasoning that makes clear the nature of the relationship between them. (College Board, USA 2009, p. 6)

Likewise, a classroom study on explanation by science education researchers states that

> The scientific explanation framework includes three components: a claim (a conclusion about a problem); evidence (data that supports the claim); and reasoning (a justification, built from scientific principles, for why the evidence supports the claim). (McNeill and Krajcik 2008, p. 55)

Even when the distinction is made, it is often emphasized how argumentation is involved in explanation (Adúriz-Bravo 2014; Berland and Reiser 2009; Dauer et al. 2014; McNeill 2009, 2011; McNeill et al. 2006; National Research Council, USA 2012; Sandoval and Reiser 2004), e.g., an argument for the best explanation (Falk and Brodsky 2013), whereas the features that set an explanation apart from an argument are not explored.

In contrast, although acknowledging that argumentation is needed when justifying an explanation put forward, Osborne and Patterson (2011) point out that explanation and argument are still different, and maintain that science education must be mindful of this distinction if it is to promote the concept of explanation among teachers and to successfully explore scientific explanations as part of classroom practice:

> Thus, the essential difference between the two linguistic acts—argument and explanation—lies in their epistemic function. One, explanation, seeks to make plain, to generate that sense of increased understanding, whereas the other, argument, seeks to justify a claim to knowledge or to persuade. (Osborne and Patterson 2011, p. 633)

Their primary reason for why explanation and argument should not be conflated is the idea that a crucial difference is that in an argument, the conclusion is *less* certain than the premises, while in an explanation the explanandum (the feature being explained) is *more* certain than the explanans (the explanatory account provided):

> The nature of that asymmetry is that in argument we reason from what we believe are secure premises to a *tentative conclusion*. … In contrast, in constructing an explanation, what is to be explained is not in doubt and we reason from a *tentative premise* to a definitive conclusion. (Osborne and Patterson 2011, p. 634, see also p. 631)

Although Osborne and Patterson present legitimate examples of arguments that are not explanations, their above characterization of the explanation–argument difference is problematic. Sometimes one is more secure about the claim one is trying to defend by an argument than about the premises one comes up in support. For instance, one may justify one’s assertion that gold conducts electricity by the premise that *all* metals conduct electricity (although one is not sure about this). Conversely, the facts adduced as part of some explanatory accounts are very certain, whereas scientists occasionally disagree about the phenomenon to be explained, e.g., whether something is in fact a mental disorder distinct from other disorders.

Most importantly for our purposes, Osborne and Patterson (2011) do not lay out why this alleged difference between explanation and argument matters *to science education*, and it is doubtful that it does. In fact, their focus on the certainty of an explanation’s explanandum directs attention away from the explanans—the actual explanatory account—in particular the question of whether the explanans put forward is in fact explanatory. What makes a scientific account a *good explanation* is the issue that matters most to science education, as one has to be able to adjudicate what makes one explanation offered by a student in the classroom a better explanation than another one. So in what follows my task is to offer a clearer account of the distinction between explanation and argument, which addresses the issue of why the considerations that make something a good explanation (in the science classroom) differ from what makes for a good argument.

3 Standards of Explanatory Adequacy as the Crucial Difference to Argument

3.1 Standards of Adequacy: Explanations Must Be Explanatory

The philosophy of science literature offers a more decisive reason for differentiating between explanations and arguments than the considerations of Osborne and Patterson (2011) I have critically discussed in the previous section. In a nutshell, the conditions that make something a good explanation differ from the conditions for being a valid argument. I will articulate this in terms of explanations and arguments having to meet distinct *standards of adequacy*, which stem from their different epistemic functions. Whereas the aim of an explanation is to provide *understanding of why* a phenomenon occurs (or why an object has certain properties), the aim of an argument is to *convince someone that* a claim is true. Formally, an argument consists of premises that are adduced to support the conclusion. A deductive argument is an argument where the conclusion is true whenever the premises are true, in other words, the conclusion necessarily follows from the premises, as in a mathematical proof or a quantitative derivation in physics. An inductive argument, in contrast, obtains when the truth of the premises (merely) makes it likely that the conclusion is true, so that still some support for the conclusion claim is being offered.[1] Thus arguments have distinctive standards of adequacy: For some account to be a valid argument, it has to adduce premises from which the conclusion (likely) follows.

Turning to explanation, a core issue in historical debates about different philosophical models of explanation has actually been to criticize the earlier assumption that explanations were arguments (Brigandt 2013a; Woodward 2014; for a particularly detailed review see W. C. Salmon 1989). The deductive-nomological (D-N) account of explanation proposed by Hempel and Oppenheim (1948) took explanations to be deductive arguments of a special type, where the explanandum (a description of the phenomenon to be explained) deductively follows from several premises, at least one of which must be a law of nature. An example would be to explain a pressure increase in a solid gas container by deducing this pressure increase (the explanandum) from a quantitative temperature increase together with the ideal gas law (two premises making up the explanans, i.e., the explanatory account). Given that not every explanation (e.g., in the medical or social sciences) conclusively accounts for the explanandum phenomenon, soon after Hempel (1965) introduced the inductive-statistical (I-S) model as an additional option. The only difference to the D-N model was that this explanation was an inductive argument, where the explanandum is shown to be *likely* given the premises constituting the explanans, including

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[1] Inductive inference is a quite generic category (including even abductive inference), so that often different types of inductive arguments are distinguished (M. H. Salmon 2002).

laws or quantitative regularities. An equivalent way of putting this overall philosophical approach to explanation was to endorse an explanation–prediction symmetry. A prediction is an argument, either a deductive argument that an event will definitely occur, or an inductive argument that an event is likely to occur. Explanations, once taken by Hempel to be arguments, could be seen as logically equivalent to predictions, the only difference being pragmatic, in that a prediction typically pertains to a future event, while an explanation is usually of a phenomenon that is known to have already occurred.

Several counterexamples to the D-N and I-S models were raised that pointed to particular scientific explanations that are not arguments and conversely to some D-N or I-S arguments that cannot qualify as explanations. At the same time, general considerations against explanations being arguments were put forward—most prominently by Wesley Salmon—considerations which also motivated alternative philosophical models of explanation. In the birth-control example, from the premise that a man has taken birth-control pills and the law-like generalization that every man who takes birth-control pills will not get pregnant, one can indeed deductively infer (and justify the claim) that the man is not pregnant. But surely appeal to him having taken birth-control pills is not *explanatory* of him not being pregnant. Apart from being a technical counterexample—an argument fully conforming to the D-N model without being an explanation—it clearly illustrates that what is wrong with this pseudo-explanation is its citing facts that are irrelevant to this man not being pregnant.

Thus, an explanation must adduce factors that are *relevant* to the explanandum. Richard Jeffrey and Wesley Salmon pointed out that these factors need not make the explanandum claim certain and not even likely—as an argument would, given its defining characteristic (W. C. Salmon et al. 1971). An example showing why the I-S model also fails renders this point particularly vivid. Genetic mutations may predispose one to a disease, such as colorectal cancer, but some alleles do so only with a very low probability. A particular person's having such a mutation does *not* make it *likely* that she will get colorectal cancer; so this does not yield an inductive argument, including an argument of the type required by the I-S model of explanation. But her having this mutation is still explanatory (should she get cancer), in that the mutation made getting colorectal cancer *more likely than* her not undergoing treatment would have. Not only does this show that very unlikely events can be explained (which is impossible according to the I-S model), but it also suggests that even likely events are not explained in line with the I-S model, but in the same fashion as unlikely events. The crucial lesson is that explanation is not about showing that the explanandum is certain (as in a deductive argument) or likely (as in an inductive argument), but about adducing some of the factors that are explanatorily relevant by *making a difference* to the explanandum phenomenon.

There are different ways of articulating *explanatory relevance*. Originally, Salmon focused on statistical relevance, i.e., making a difference to statistical frequencies—in my example a mutation increasing the frequency of colorectal cancer (W. C. Salmon 1970). Later he appealed to causal relevance by introducing a causal account of explanation, according to which an explanation situates the explanandum phenomenon in the causal structure of the world (W. C. Salmon 1984). This approach can handle the flagpole example that was a problem for the D-N model. Given a particular position of the sun, from the height of a flagpole one can deduce the length of the shadow cast by the flagpole, and from the length of the shadow one can equally well deductively infer the height of the flagpole, so that the D-N model has to count both accounts as explanations. But the latter is not an explanation, as it is not the length of the shadow that causes the height of the flagpole—Salmon's considerations about causal relevance gets right which of the two accounts is explanatory. More generally, any correlation can be used to make predictions and inductive arguments, but need not yield a causal explanation. Explanatory relevance in terms of causal difference-making figures not only in contemporary accounts of causal explanation (Woodward 2003), but also in the related account of mechanistic explanation (Bechtel and Abrahamsen 2005; Craver 2006).[2]

I do not assume that explanatory relevance is always causal relevance, or that every explanation is causal-mechanistic. In fact, different types of explanations are recognized by philosophers (Braaten and Windschitl 2011; Brigandt 2013a). But the considerations about explanatory relevance from the philosophy of science tradition clearly demonstrate that unlike an argument *that* something is the case, an explanation of *why* something is the case must adduce features that are explanatory. The criteria that a scientific representation has to meet to be explanatory I call *standards of explanatory adequacy*. Some scientific explanations are in fact D-N style derivations from laws, e.g., my above example from physics, which explains a pressure increase with reference to the ideal gas law. But note that even if this explanation can formally be represented as an argument, what makes it explanatory is not its being an argument, but its meeting additional standards, in this case invoking physical laws and other factors that are relevant to the particular explanandum, and leaving out considerations that are not explanatorily relevant. Thus, standards of explanatory adequacy differ from the standards of adequacy for a valid argument—which, as laid out at the beginning of the section, require the adducing of premises from which the conclusion follows or at least is likely to follow (so as to serve the epistemic function of justification).

Returning to the context of science education, apart from challenging Osborne and Patterson's (2011) specific characterization of the explanation–argument difference (in terms of the explanandum being certain but the explanans being tentative), in Sect. 2 I also pointed out that they do not lay out why this difference matters to science education. In contrast, the discussion by Braaten and Windschitl (2011) offers a better point of entry. For while they are likewise skeptical of the tendency of some science education researchers "to prioritize argumentation at the expense of explanation" (p. 656), Braaten and Windschitl directly address the features that make something an explanation, aiming toward "guidance for science educators, curriculum developers, or other stakeholders regarding what gives a scientific explanation its explanatory power" (p. 658). To this end, three questions have to be addressed:

> (1) What constitutes a "good" scientific explanation in a science classroom?, (2) What makes an explanation explanatory rather than descriptive?, and (3) How might we evaluate the merits of alternate explanations offered by students in classrooms? (Braaten and Windschitl 2011, p. 651)

This is indeed a core issue that ought to guide classroom instruction and discussion about individual explanations, e.g., one needs to be able to tell what is problematic about the suggested explanation that an animal species occupies a certain climatic region because they prefer to live there. From my perspective, such considerations of what constitutes a good scientific explanation or makes something explanatory (rather than merely describing a phenomenon) are standards of explanatory adequacy.

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[2] Even though Osborne and Patterson's (2011) characterization of the explanation-argument difference does not rely on the idea of causation, their discussion of the nature of explanation explicitly invokes causation: "the particular view adopted here is that the bread and butter explanations of school science are causal, for example, why do things fall, why is matter conserved, or how does photosynthesis happen … explanations consist of a subset of descriptions where new entities or properties are brought into being or invented to provide a causal account." (pp. 628–629).

What makes it additionally important to be clear about the standards used to adjudicate what counts as a good explanation is the fact that such standards can differ across explanations. While some accounts have to point to laws of nature in order to be explanatory, others can do without reference to laws, and instead explain why something happens in terms of describing how it is brought about by a mechanism. This suggests that different standards of explanatory adequacy correspond to different types of explanations, as used in different fields of science, for example, law-based explanations in physics as opposed to mechanistic explanations in molecular biology. To a first approximation this is correct and provides a broad guideline that also works for the purposes of science education (although Sect. 4 will explore that in general an individual research context determines the more precise standards of explanatory adequacy that are operative).

3.2 How a Focus on Evidence Obscures Standards of Explanatory Adequacy

In opposition to Osborne and Patterson's (2011) call to clearly distinguish explanations and arguments, Berland and McNeill (2012) emphasize the "synergistic relationship between argumentation and explanation" (p. 809) for the purpose of classroom instruction:

> we fear that the subtle message communicated by an emphasis on these distinctions is that the practices stand-alone, that individuals can construct explanations without argumentation. We worry that this implication could result in teachers asking students to construct an explanation first, and engage in an argument about their explanations second … (Berland and McNeill 2012, p. 810)

But this misconstrues the position of those who explicitly want to distinguish explanation and argument, given that Osborne and Patterson (and Braaten and Windschitl) do not assume that in the classroom one could put forward and evaluate explanations without argumentation. Instead, the issue is that it is vital to be clear about the standards that make a scientific account a good explanation—an explanation in the first place, given that not every argument or scientific inference from evidence is an explanation. And in classroom discussion, a student may well be asked to suggest an explanation for a phenomenon, and only in a second step be prompted to verbally defend this suggestion by means of argumentation (e.g., over other students' proposals).

I am inclined to think that the main reason for conflating explanation and argumentation in science education is a general focus on *evidence* and thus evidence-based argumentation. Standard documents may appeal to evidence (and arguments) even when characterizing what an explanation is: "Scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories." (National Research Council, USA 1996, p. 148). Science educators such as Berland and Reiser (2009), who view argumentation as the core of explanation, also appeal to evidence when endorsing a strategy that "uses the structure of a scientific argument—claims defended with evidence—to support students' explanation construction." (Berland and Reiser 2009, p. 28). Not only do such approaches fail to include considerations of what would make an account put forward by scientists or by a student explanatory, but a focus on evidence can even obscure such standards of explanatory adequacy. The reason is that considerations about explanatory relevance are orthogonal to truth and evidence, as shown by the prevalence of *how-possibly explanations* in science.

Before the correct explanation is discovered, scientists often entertain one or more potential explanations, i.e., how-possibly explanations. A molecular mechanism, postulating certain entities, their organization, and interactions, may be suggested to account for a phenomenon. Several aspects of this how-possibly mechanism are still hypothetical, and experimentally based evidence is needed to show that this is the actual mechanism (Craver 2007, ch. 4). But note that even before the evidence is in, and even when several rival how-possibly mechanisms are still debated, the hypothetical mechanism is still *explanatory*, in that it would be a mechanism generating the phenomenon to be explained. Thus, in explanation there are two issues at stake: (1) whether the individual claims made by a scientific account (e.g., about the existence of certain entities and their properties) are actually true, and (2) whether this scientific account (assuming that it was true) would be explanatory of the phenomenon at hand—which is a question about whether the particular standards of explanatory adequacy are met.[3] Evidence-based arguments for the truth of some account (issue 1) are insufficient for the purpose of scientific explanation, because the account also needs to be explanatory rather than merely describing a phenomenon (issue 2).

While a how-possibly explanation puts forward a hypothetical explanans to account for a *factual* explanandum phenomenon, there is also some role in science for showing that a *hypothetical* phenomenon that may not actually exist *could* be explained. This occurs in the context of exploring the overall explanatory capacity of a theory. Darwin, for instance, contended based on reflections similar to thought experiments that his theory, unlike previous theories, had the ability to explain different kinds of potential biological phenomena (Lennox 1991). This was reasoning in favour of Darwin's theory, at least its explanatory power, where it mattered less whether these phenomena that he could explain were concrete phenomena already observed in some species.[4] The science educators Berland and Reiser assert in general that

> evidence is at the core of scientific [explanatory] sensemaking. (Berland and Reiser 2009, p. 29)

However, adducing evidence for the truth of an account does not address whether this account is explanatory (which is actually the core of explanatory sensemaking). Moreover, in science there are instances of explanations of purely hypothetical phenomena, in which case truth and evidence are not even an issue.

I have argued that the use of evidence in science by no means exhausts the considerations of explanatory adequacy that matter to scientists when developing explanations. Students also profit from explicitly discussing not only whether there is evidence for their claims, but also what makes their accounts explanatory. For example, when wondering why a smoldering wood fire inside a partially closed glass container lights up when the ventilation of the container increases, the response that this is because oxygen is added can be scrutinized further. The account becomes explanatory once someone points out that combustion is a reaction with oxygen. By making explicit that oxygen is a necessary causal ingredient, a causal and thus explanatory connection between the addition of oxygen and the fire lighting up has been established. When accounting for why an unsupported object falls down to the ground, while saying that the object and the Earth move toward each

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[3] This matters also in inference to the best explanation. Given that here one wants to infer the truth of one explanatory account (e.g., that the butler committed the murder using poison), Lipton (2004) recognizes that circular reasoning would result if 'explanation' always meant a true account. As a result, he disambiguates by using the term 'potential explanation'—which has all characteristics of a valid explanation except possibly for truth—and clarifies that the inference is more precisely an inference to the best potential explanation (i.e., inferring that this potential explanation is true).

[4] In Sect. 2 I already challenged Osborne and Patterson's (2011) characterization of the explanation-argument difference, who rely on the idea that an explanation's explanandum is known to be true (while the explanans is tentative). Explanations of hypothetical phenomena provide an additional reason against this idea.

other merely restates the phenomenon to be explained, student suggestions become explanatory when the idea of an attractive force is added. A deeper explanation would indicate that it is a law of nature that (not only the Earth and this object but) any two bodies exert an attractive force on each other.

4 Explanatory Aims Motivate Explanatory Efforts and Guide the Adoption of Particular Standards of Adequacy

So far the discussion has emphasized standards of explanatory adequacy. Not every inference or argument is an explanation; instead, a scientific representation has to conform to additional standards (such as connecting features by means of causal relations or laws) in order to be explanatory. While explanatory *standards* have been mentioned in the philosophical literature on explanation and are implicit in Braaten and Windschitl's (2011) focus on what qualifies as a 'good' explanation in the science classroom, now I introduce an idea that has not been addressed in the science education debate on the relation between explanation and argument: explanatory *aims*.[5] In addition to pointing to general benefits for science education of viewing explanations together with explanatory aims, I follow up on standards of adequacy as marking the distinction between explanation and argument by discussing how the adoption of particular standards of explanatory adequacy is motivated by explanatory aims. By guiding scientific theory development and practice, explanatory aims also go beyond the content of science and relations among empirical ideas, including arguments.

The *first* reason for taking explanatory aims into account is that they motivate and guide the use of *particular standards* of explanatory adequacy. Instead of addressing a generic aim of science as a whole, by 'explanatory aim' I refer to a particular aim, which is pursued by some scientists only, and in a certain historical period, such as attempting to explain programmed cell death, or to explain radioactive decay. Philip Kitcher (2001, ch. 6) has already argued that we should not think in terms of overarching aims of 'science,' such as identifying laws, providing explanations, or discovering the fundamental features of nature, but better in terms of local aims that obtain scientific significance in a contextual fashion. As an example he uses the question of how the cloning of mammals works (i.e., Dolly the sheep), illustrating how this specific question is connected to other concrete issues in the larger disciplinary context of developmental biology. The phenomenon of cloning could be conceptualized only once relevant scientific background knowledge was in place, and the cloning of mammals became an important explanatory issue in a specific historical context. Let us take a closer look at different standards of explanatory adequacy, and how they are guided by explanatory aims.

In many situations, individual causal claims are each deemed to be explanatory, but some scientific contexts involve more demanding standards, where only an explanation that unifies diverse instances will be adequate. Often a phenomenon can be explained by citing a temporally prior cause, but sometimes, the explanation sought after is synchronic-reductive, in which case standards of adequacy stipulate that the explanation must break down the complex phenomenon into component parts (e.g., lower-level entities and activities). Different standards of explanatory adequacy can even hold for one and the same

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[5] Osborne and Patterson (2011) mention the goal of explanation, contrasting it with the goal of argumentation, however, as we will see, what matters in my context is the aim of an individual explanation (which differs from the aim of another explanation).

feature to be explained. For instance, in some contexts, a relatively remote cause–effect relation may be deemed to be fully explanatory, such as knowing that allergy symptoms were caused by a pharmaceutical drug taken (rather than other possible causes). In other contexts, however, only an account of the intermediate causal steps by which the drug leads to this allergic side effect will be adequate. To provide a further example, for a given anatomical trait, biologists may seek an explanation in terms of how the trait develops during an organism's ontogeny. But biologists may also want to explain how the same trait arose in evolutionary history, implying different explanatory ingredients that in this context would make an account adequate, unlike a developmental account. Even in the case of the evolutionary explanation of a trait, one can distinguish between actual-sequence explanations and robust-process explanations (Sterelny 1996). The former's standards demand that a sequence of steps—as they actually happened—leading up to the outcome trait be laid out, e.g., a phylogenetic sequence of character transformations. In contrast, the actual historical trajectory taken does not matter for a robust-process explanation. Instead, in order to be adequate, it has to show why the particular outcome was bound to result even if the trajectory would have been disturbed, e.g., the trait being adaptively optimal and under the operation of stabilizing selection.

These examples suggest that what guides the use of standards of explanatory adequacy are concrete *explanatory aims*. This is possible because an explanatory aim is richer than wanting some explanation of a certain natural phenomenon or physical feature. In the case of the presence of lungs in certain organisms, arriving at a developmental explanation of this feature and arriving at an evolutionary explanation of it are two distinct explanatory aims. Thus, an explanatory aim includes not only the phenomenon to be accounted for, but also what *kind* of explanation is intended in this context, which *implies* certain standards of explanatory adequacy. The aim of offering an evolutionary explanation of the origin of lungs entails that an adequate explanation has to make recourse to phylogenetic history or natural selection—standards which differ if the aim is instead to put forward a developmental explanation of the formation of lungs. In a similar vein, in one context the aim may be to offer an actual-sequence explanation of a certain outcome, while in another situation a robust-process explanation of it is intended. Correspondingly, although both are causal explanations, different (more specific) standards of adequacy are to be met by an actual-sequence explanation and a robust-process explanation.

The fact that standards need not be the same across contexts reinforces my point from the previous section that science educators need to be aware of standards of explanatory adequacy, when adjudicating what counts as a good explanation in a science classroom. The United States National Research Council's (2012) K-12 education framework states that "Deciding on the best explanation is a matter of argument that is resolved by how well any given explanation fits with all available data, how much it simplifies what would seem to be complex, and whether it produces a sense of understanding" (p. 68). However, apart from the fact that only some explanatory aims call for simplification or unification (and even then one would also have to indicate what kind of simplification would be explanatory), what counts as 'producing understanding' has to be fleshed out depending on what particular standards of explanatory adequacy are operative in the given classroom context. In addition to the domain of evolutionary biology mentioned above, actual-sequence explanations are also put forward in physics (e.g., two objects colliding after each having moved with a particular trajectory), but so are robust-process explanations (e.g., a ball rolling around in a glass bowl until eventually coming to rest at the bottom of the bowl). It may well happen that students suggest an actual-sequence explanation as well as a robust-process explanation for the same case. In this situation, one can acknowledge that both explanations are generally legitimate, while clarifying that only one type of explanation was *sought after* in the present context and discussing why only one explanation is adequate *given this explanatory aim*. Or one can explore the understanding that each type of explanation affords (and that the other does not), so as to reveal the rationale behind adopting certain explanatory aims and standards.

A *second* line of support for the idea of explanatory aims stems from the fact that the *nature of science* is of relevance to science education. While the learning of facts is the basis of all science instruction, students should also acquire an understanding of the nature of science, so as to make them critical science consumers (Brigandt 2013b; Flick and Lederman 2004; McComas 1998; Sandoval and Reiser 2004). A clear aspect of the nature of science is that science not only possesses explanations, but that scientists deliberately aim at developing explanations, as acknowledged by curriculum frameworks:

> The goal of science is the construction of theories that can provide explanatory accounts of features of the world. (National Research Council, USA 2012, p. 52)

One approach in science education is to start out with general aspects of the nature of science (a ‘consensus view’ held across disciplines), including that scientific knowledge is based on evidence, that it involves inference in addition to observation, and that scientific knowledge is tentative (Lederman 2007; Lederman et al. 2002; McComas et al. 1998; Osborne et al. 2003; Schwartz and Lederman 2008). Others caution against such a consensus view on the grounds that it fails to do justice to the heterogeneity of science (Allchin 2011, 2013; Irzik and Nola 2011). Combining both kinds of consideration my view is that while general notions relevant to the nature of science (e.g., ‘explanation’ and ‘explanatory aim’) can be used across physics, biology, and other classrooms, such notions have to be illustrated by actual cases (e.g., a particular explanatory aim arising in specific disciplinary context), so that students obtain an understanding of the nature of science based on concrete instances of scientific theorizing (see also Kampourakis 2016; Rudolph 2000; Tala and Vesterinen 2015; van Dijk 2011, 2014).

Explanatory aims have a distinctive status, in that they are not part of the empirical content of science. The latter consists of various representations of nature, be it individual observations, or more complex relations among empirical ideas, including arguments, explanatory models, and theories. In contrast, explanatory aims are not claims about the *natural* world; instead, they are values pertaining to what *scientists* want to achieve. Thereby explanatory aims provide *additional structure* to science; in fact, they guide scientific theorizing and theory development (an activity broader than the content of current theories) as well as scientific inquiry and practice in a certain direction. The various explanatory aims pursued by scientists enhance the diversity of science. An explanatory aim arises in a certain historical context, but may be replaced by other aims later deemed to be the most important challenges yet to be solved. As a result, explanatory aims are to be taken into account if one is to understand science as diverse and historically changing (Brigandt 2013a, b).

This also matters to science education (regardless of whether the nature of science is the explicit topic of a lesson plan), given that students have to “…understand that scientific methods and theories develop as earlier explanations are modified to take account of new evidence and ideas” (Department for Education, England 2013, p. 3). The sustained pursuit of an explanatory aim provides the target that motivates the modification of earlier explanations.[6] For this reason, the discussion of concrete explanatory aims in classroom

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[6] Brigandt (2010b, 2012) illustrates how even the historical change of an individual scientific concept can be understood with reference to scientific aims, including explanatory aims.

instruction would allow students to view some individual explanations not just as isolated scientific facts, but as an improvement of an earlier explanation toward an enhanced explanatory account, for example, from simple explanations in mechanics appealing to forces to Newton's laws of motion, or from explanations using the classical gene concept (the simple idea that genes are beads on a chromosomal string) to explanations in molecular genetics.

More generally, beyond what Richard Duschl (1990) critically calls 'final form science,' science educators have argued that student should obtain an appreciation of the process of science. In addition to learning about the content of science, students need to acquire process skills and engage in the practice of science, including the activity of constructing explanations (Berland and Reiser 2009; Lehrer and Schauble 2006). One benefit of also teaching the practice of science is that nowadays scientific content is very expansive and constantly being revised. While some content from current science conveyed to a student may soon be outdated, a classroom lesson about how scientists methodologically went about in addressing an explanatory problem may continue to have pedagogical validity (Love 2013a). This is a reason for considering explanations together with the explanatory aims that motivate the establishment and revision of explanations; and aims as scientific values go beyond relations among empirical ideas, including arguments.

My discussion of the fact that the adoption and pursuit of explanatory aims is a crucial aspect of the nature of science has already hinted at a *third* reason for why the notion of explanatory aims matters to science education: an explanatory aim motivates explanatory efforts and *makes a particular explanation interesting to a person* in the first place. Once an explanatory aim has arisen in a certain historical and disciplinary context, it becomes important for scientists to develop the explanatory account now sought after. In some cases an explanatory aim may even call for a very complex explanatory account that integrates contributions from several scientific fields, so that explanatory aims can motivate interdisciplinary research (Brigandt 2013a; Darden and Maull 1977; Szostak 2002). In line with my focus on local explanatory aims, the formation of integrative theories is also guided more by specific aims than by a global unification agenda (Brigandt 2010a; O'Malley et al. 2014). While many explanatory aims can be met using the resources of a single discipline, there are some that require an interdisciplinary approach. Love (2008) uses the term 'problem agenda' for such complex explanatory problem that consists of many interrelated questions. A case in point is explanations of the evolutionary origin of novelties, such as the evolution of fins in fish and thus the very origin of vertebrate appendages. This aim motivates serious scientific efforts and requires explanatory contributions from paleontology, phylogenetics, developmental biology, functional anatomy, and evolutionary genetics (Love 2013a; see also Brigandt 2010a).[7]

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[7] Given that curricula and classroom instruction are structured along the boundaries of traditional disciplines, only little place can be given to interdisciplinarity. But there are examples from the science classroom. For instance, an explanation of the evolution of horses, e.g., the change of the leg and foot bones, involves fossil data about these skeletal features (from the discipline of paleontology), an evolutionary tree leading up to modern horses (provided by systematics), and considerations about what makes a particular leg length and foot structure adapted to a particular habitat, such as permitting faster locomotion to outrun predators upon the shift from forest to steppe (involving the fields of functional anatomy and ecology). To be sure, for the purpose of classroom instruction, what matters less than discussing whether the explanatory ingredients are from distinct disciplines is to explore how some explanations involve *several* ingredients. Many explanations suggested by students are not false, but incomplete, so that it is relevant to understand how the suggestions from other students add to one's explanation, and why given the explanatory aim or question at hand, an adequate explanation combines a number of considerations.

But apart from motivating scientists, explanatory aims have a direct impact on classroom instruction. For beyond conveying scientific facts and expecting students to learn them, classroom instruction must promote students' engagement with these matters. Yet an excellent way of triggering interest is to present a scientific account as solving a *problem* (Love 2013b), where the question to be scientifically answered is raised before giving the answer—which without the problem would be a mere fact. Education research has generally emphasized the impact of problem-based learning (Hmelo-Silver 2004; Hmelo-Silver and DeSimone 2013; Strobel and van Barneveld 2009), and in the more specific context of science education advocated the use of 'driving questions' (Krajcik and Blumenfeld 2014; Krajcik and Mamlok-Naaman 2006) or a science teacher's 'goal system' that indicates why teaching materials used are relevant and motivate her students (Janssen and Berkel 2015). Many scientific problems are explanatory aims in that they are issues in need of an explanation. To give three examples, why does water expand when it freezes (even though water generally contracts whenever the temperature drops)? Why do animals from some species live in groups (while other animals are solitary)? Why do centipedes always have an odd number of leg-bearing segments (even though the number of segments varies from 19 to over 301 across species)? In the science classroom, once such an explanatory problem is raised, students' interest and engagement can be fostered by having them attempt to provide an explanation and discussing such answers, before eventually covering the scientific explanation and what makes it the correct one.

In contrast, some science educators emphasizing the explanation-argument connection have viewed argumentation as the feature that makes students value explanations:

> argumentation creates a context in which robust explanations—those with which the community (the students) can agree—are valued. (Berland and Reiser 2009, p. 28)

However, the triggering of student engagement by argumentation is a pedagogical tool that is not specific to explanation (unless one takes into account standards of explanatory adequacy that would provide guidelines for when argumentation gets at robust explanations). More importantly, from my perspective, what makes someone—be it a scientist or a high school student—value a valid explanation is that it answers a problem deemed to be of interest and relevance. While the three examples I have given are serious questions for scientists (requiring sophisticated explanations) and at the same time puzzling issues to high school students, not every explanatory aim in science will be automatically of interest to a student if it can only be seen as a problem once the relevant scientific background knowledge is in place. Conversely, some explanatory questions have by now commonly known answers, so that they are not explanatory problems any longer. But even when such cases figure in classroom instruction, it is important to convey that scientific explanations are not just facts, but that they have been developed in response to what—at least in the past—was an explanatory problem or an important explanatory aim.[8]

In summary, I have laid out how an explanatory aim (given the scientific context in which it is pursued) implies particular standards of explanatory adequacy. In addition to reinforcing the distinction between explanations and arguments that Sect. 3 made in terms of standards of adequacy, the present section has highlighted the relevance for science educators to bear in mind that standards of explanatory adequacy (and thus what makes

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[8] The United States National Research Council's (2012) K-12 science education framework portrays science in this fashion, when breaking it into eight practices (pp. 49–53). As the first practice, the framework lists that "Science begins with a question about a phenomenon … and seeks to develop theories that can provide explanatory answers to such questions" (p. 50), while practices 6 and 7 are the construction of explanations and engaging in argument from evidence so as to find the best explanation for a phenomenon.

something a good explanation) can differ across explanations. I have also pointed to further benefits of taking explanatory aims into consideration by portraying a particular explanation as having been developed in response to an explanatory aim. In addition to making classroom instruction more engaging by motivating students to see some scientific facts as addressing an interesting explanatory problem, the pursuit of various explanatory aims is a central aspect of the nature of science. Pertaining to what a *person* wants to achieve or how she evaluates achievement, aims and standards go beyond representations of natural phenomena (including arguments as relations among empirical facts). This dimension of knowledge formation cannot be captured by a framework that merely conceives of science as the gathering of evidence and the making of arguments based on evidence. Yet such a narrow framework is used by some argumentation-focused science education approaches, even when they are specifically devoted to explanation:

> Our explanation framework includes three components: a claim (similar to Toulmin's claim), evidence (similar to Toulmin's data), and reasoning (a combination of Toulmin's warrants and backing). (McNeill and Krajcik 2007, p. 234)

> Together with students, teachers and researchers have constructed, tested, and refined criteria for producing scientific explanations that include 1. Making a claim. 2. Providing multiple pieces of evidence drawn from experimentation or from others' research. 3. Reasoning how it is that the evidence links back to the claim. … We use these criteria in the classroom teaching and in our analysis of classroom data. (Moje et al. 2004, p. 232)

In contrast to an exclusive focus on relations among empirical ideas (including arguments), explanatory aims and standards go beyond the empirical content of science and are important precisely because they motivate a person's explanatory efforts and guide her theorizing and practice.

5 Successful Intervention in Nature Requires Explanatory Knowledge

While Sect. 3 pointed to standards of adequacy as a decisive difference between explanations and arguments, the previous section broadened the perspective by introducing explanatory aims. I have already discussed the connection between standards and aims, but now I bring them together in a special context—the standard of capturing causal relations and the aim of intervening in nature—a context with clear relevance to science education.

Not only does science attempt to intellectually understand nature, but it also aims at providing the means of *intervening in and controlling nature* (Lacey 1999). This is obviously the case for applied research in engineering and medical science geared toward the development of specific technologies or other products. But it likewise holds for many instances of basic research, which—without aiming at an immediate application—yields enhanced scientific knowledge that is intended to also provide the basis for various applications. In the case of molecular biology, the potential applications in view are typically medical or agricultural. Scientists may justify the importance of a particular research project on regeneration in animals with reference to possible medical therapies in humans. In addition to human pathogens, microbiologists study how different types of microbes (bacteria, fungi, and others) create diseases in plants, which is often relevant for agricultural and forestry purposes. The previous section mentioned Kitcher's argument that scientific aims are local, illustrated by the specific aim of cloning. Kitcher actually emphasizes how intellectual aims (e.g., explanatory understanding about cellular and developmental processes) are enmeshed with practical aims (e.g., the cloning of certain mammals for animal breeding purposes); and he critically scrutinizes the idea that pure and applied science can be separated (Kitcher 2001, ch. 6–7).

The applied aspect of research is also acknowledged in science education, for example, by curriculum frameworks that include engineering (National Research Council, USA 2012). Specific achievement objectives may pertain to how technological items of everyday life function, for example that

> Students can … investigate and offer explanations of how selected items of technology function and enhance everyday activities of people, e.g., telephone, switch, spectacles, devices which open supermarket doors, bicycle tyres, bicycle helmets (Ministry of Education, New Zealand 1993, p. 78),

which is motivated by the general idea that

> it is important for students to learn … that science offers frameworks for explanations and control … which have thus become accepted by the scientific community and by society as a whole. (Council of Ministers of Education, Canada 1997, ch. 4)

While the aim of science to intervene in nature (including creating novel objects and processes) is often acknowledged, what is rarely discussed in philosophy of science and science education scholarship is the connection to scientific explanation. The simple point is that the ability to successfully intervene in nature is enhanced by and in fact presupposes *explanatory* knowledge. This is most obvious in the context of causal-mechanistic explanations, whose *standards* of adequacy demand that the explanation capture some of the various causal factors that produce the phenomenon to be explained. Intervening so as to modify this phenomenon is only possible if some of its causes are changed, so that explanatory knowledge as to what some of the relevant causes are informs us about possible points of successful intervention.

Used by philosophical accounts of causal explanation, an interventionist (also called manipulationist) construal of causation defines the notion of a cause in terms of what effect an intervention on a physical feature would have. James Woodward (2002, 2003) appeals to ‘ideal interventions,’ each of which targets only one factor.[9] The idea is that if A is a cause of B, an ideal intervention that sets A to a particular value leads to a change in the value of B, because of the causal connection from A to B, which is not removed by this intervention on A only. In contrast, if A and B are merely correlated (say C is a common cause of A and B), the value of B could not be changed by an intervention on A. This shows how causal explanation goes beyond some instances of prediction (and argument). In the case of knowing that A and B are correlated but being unaware of the causal connections, while one can predict the value of B from the (non-manipulated) value of A, one cannot predict the value of B from the value of A that would result from an intervention on A. Thus, causal explanatory knowledge permits *prediction upon intervention* in nature.

Mechanistic explanations likewise provide guidelines for successful intervention in natural processes. A mechanism for a phenomenon of interest includes those entities, activities, and their organization that produce this phenomenon (Bechtel and Abrahamsen 2005; Craver 2007), so that from a concrete mechanistic explanation one can infer which entities, activities, or organizational features of a larger system would have to be modified

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[9] Carrying out an ideal intervention on an individual cause A is in many practical situations not possible given that an experimental intervention often affects many features adjacent to A (e.g., in the case of brain surgery), or a cause cannot be practically influenced at all (e.g., the earth mantle convection currents that cause the movement of the continents). Yet an interventionist account is merely meant as a metaphysical account of what a cause is; and a scientific explanation that cites some such causes still reveals at least in principle possible avenues for intervention.

or removed to obtain a different phenomenon. A concrete example is possible options of treating cystic fibrosis, a disease characterized by thickened mucus in the lungs, among other affected organs (Craver and Darden 2013, ch. 11). An *explanation* of the disease proceeds from the fact that it is due to mutations in both copies of the CFTR gene, which mechanistically results in a modified mRNA and then in a modified, non-functional protein, which otherwise regulates chloride transport across the membrane of epithelial cells. One *therapeutic* target that this mechanistic explanation immediately suggests is the genome, and more precisely gene therapy by adding a functional copy of the CFTR gene into an affected person's DNA. This may be hard to practically achieve, so another strategy is to address the next step in the mechanism, the mRNA produced by the mutated CFTR gene. An option that has shown preliminary promise in mouse models is to insert a short DNA segment, whose mRNA is spliced together with the mRNA produced by the mutated CFTR gene so as to result in a functional mRNA. A third approach concerns the protein created as yet a further step in the explanatory mechanism. In the majority of cystic fibrosis cases, a protein is produced (from the mutated CFTR gene) but its amino acid chain does not fold into the regular three-dimensional shape, so that the use of appropriate chaperones may provide a therapeutic option of generating the correctly folded, functional protein.

Beyond informing us about which features are points of possible intervention, some scientific explanations can be used to predict what actual effect an intervention would have, including the likelihood and degree with which the effect would result. For instance, even if it is not mechanistically known why a pharmaceutical drug has its effect, it still qualifies as explanatory knowledge that a randomized controlled trial shows that the drug has this particular causal effect—to a certain degree and for a specific proportion of those taking the drug. If the precise quantitative impact of a cause on another feature is known, probabilities can be assigned. Then, one option of modeling causal networks are Bayesian networks, which use the above interventionist understanding of causation, and entail what an intervention's *quantitative* response on several variables would be (Glymour 2003; Pearl 2000). Given the complexity of molecular and cellular processes, the field of systems biology models them using a variety of mathematical tools (Klipp et al. 2010). The ideal is to arrive at explanatory models that quantitatively predict the effects of manipulations to the molecular-cellular system, given that systems biology also aims at tools for therapeutic treatments (Brigandt 2013c).

As mentioned at the beginning of the section, science education scholarship and classroom instruction may point out that science also aims at intervening in and controlling nature. However, only seldom is the connection to *scientific explanation* explicitly discussed, even though one does not need sophisticated explanations to discuss why explanatory knowledge is indispensable for successful intervention.[10] In fact, explanations routinely covered in science classrooms can be used to illustrate how explanatory accounts enhance intervention. Take, for example, the mechanism of gene expression and protein synthesis. This explanation is the basis for the possible options of treating cystic fibrosis discussed above. Science instruction is unlikely to cover the details of gene regulation (which is needed to fully understand the activation of a DNA segment inserted by gene therapy), of splicing (which is needed to grasp how therapeutically added mRNA can modify an otherwise defective mRNA), or of protein folding (which is needed to understand how pathological protein misfolding can be prevented). Yet even basic classroom coverage of gene expression is sufficient for illustrating how a different protein could be

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[10] Even Braaten and Windschitl's (2011) exemplary discussion of scientific explanation for the science education context fails to mention that science does and intends to intervene in nature.

generated if one intervened on a gene by changing one of its nucleotides. In the case of this and other biological mechanisms, fruitful classroom explorations can ask students where one could plausibly intervene in the mechanism and what the likely effect would be. Or one can start with an intended effect, and initiate discussion of what changes to the original mechanism would generate the effect, and whether there are several distinct ways of achieving the same intended outcome. The same holds for the technological artifacts from everyday life mentioned above (e.g., a telephone). Students can discuss which changes would not impact the device's functioning at all, which manipulations would modify its operation, and which interventions would lead to a breakdown of the functioning. In this fashion, explanatory knowledge of how a human artifact or natural mechanism works is not only used to explain its normal operation, but can also be utilized to understand the effects of interventions.

So far I have mentioned domains of science where explanations in terms of individual causes or larger mechanisms are sought after. But also in physics, where many explanations are adequate only when laws or equations are included, explanation provides the basis for intervention. An example from the science classroom is how a student sitting on a rotating chair can increase her rotational speed by means of drawing in her arms (similar to a spinning ice skater). Discussing this issue, some students may be able to construct an explanation of the effect of this arm position change using the principle of the conservation of angular momentum. This law asserts that (absent external influences) the product of the angular velocity and the moment of inertia is constant, so that a decrease of the latter due to drawing in one's arms yields an increase of the former (i.e., rotational speed). Quantitatively more difficult, but routinely covered in upper-level physics classrooms, is projectile motion. In the case of a projectile shot from a plain surface at a certain angle with a certain initial velocity, an equation combining the horizontal and vertical inertial movement (at the initial velocity) with the vertical accelerated movement (due to gravity) accounts for the particular trajectory of the projectile, including its range. Students can use this explanatory account to attempt to determine how an intervention on some of the features would quantitatively (or at least qualitatively) change the projectile trajectory, for instance, how (keeping the initial velocity unchanged) an intervention on the angle of projection would affect the range of the motion, and what angle would maximize the range.

While it is worth illustrating in classroom instruction how basic research can also have the control of nature by means of applications in view, intervention is crucial even when no technological and other applications are at stake. For *experimental discovery* in basic research routinely relies on interventions. Discovering new causal features of a material system involves its experimental manipulation, based on other causal aspects of the system being known. In this sense, *prior* explanatory knowledge is used to generate new explanations. Above I mentioned the insertion of DNA segments into a person's genome for the aim of gene therapy, but much more common and successful is the insertion of DNA segments into the genome of model organisms to create gene knockouts. This is done to experimentally uncover the function of a gene, e.g., its role in the organism's development. The creation and use of any such experimental intervention technique presupposes explanatory knowledge—not about this particular gene's function (which is to be discovered by this experiment), but about the general operation of gene regulation. To give another example, RNA interference is a class of processes in which small RNAs interfere with the functioning of (or destroy) mRNA molecules. It occurs naturally such that an organism upregulates or downregulates gene expression, or fends off viral RNA. Explanatory knowledge of how RNA interference works has led to its experimental use to study the functioning of genes and RNAs, including manipulating the operation of many genes at the same time.

Achieving *systematic and successful* intervention by means of prior explanatory knowledge is a matter of degree, and the same holds in a science classroom. Intervention-based discovery of students often employs a trial-and-error method, but even then basic explanatory knowledge about the causal effects of some interventions is being used. For example, when experimentally connecting different components to build an electrical circuit, even without the ability to predict (and explain) how a complicated circuit will function, there is a causal understanding of the functioning of individual components and the explanatory knowledge that only a connection with a complete path will yield some functioning.

In summary, both the proponents and the opponents of the explanation–argument distinction for the purpose of science education identify explanation with making sense of phenomena:

> Key to the distinction between explanation and argument is that an explanation should make sense of a phenomenon … (Osborne and Patterson 2011, p. 629)

> Sense making … focuses on developing an understanding of the phenomenon that is being investigated. This goal aligns with the practice of scientific explanation … (Berland and McNeill 2012, p. 809)

What this leaves out is that scientific explanations are not only about intellectually understanding nature, but also the basis for successfully intervening in and controlling nature. This connection holds even in contexts where scientists frame their aim in terms of control, without viewing explanation as their primary aim. The aim of control and intervention can only be systematically met by using knowledge about causes, mechanisms, or laws. Because such knowledge is at the same time explanatory knowledge, such explanations also serve the aim of successful intervention. In contrast, arguments merely have to show that something is likely to be the case, but need not appeal to causes, mechanisms, or laws (or any other features demanded by particular standards of explanatory adequacy). Any correlation can be used to predict that a phenomenon will result, as an instance of an argument, but (unlike a causal explanation) this is insufficient for predicting what would happen upon intervention. In addition to illustrating the difference between explanation and argument, I have also indicated how the aim of science to intervene in nature—if not in the context of technological application, then at least in the context of experimental discovery—provides a broader framework for classroom instruction involving explanations. Section 4 has emphasized how student engagement can be fostered by viewing explanations as answering problems; and in addition to being targeted at intellectual aims, a classroom context where explanations are also germane to practical aims will additionally enhance student interest.

6 Conclusion: The Target Audience of Conceptual Distinctions

Science educators Osborne and Patterson (2011) have pleaded for distinguishing between explanations and arguments, with Braaten and Windschitl (2011) arguing that what matters is what counts as a *good* explanation in the science classroom. I have articulated the latter issue in terms of explanations having to meet different standards of adequacy than arguments. An argument *that* something is the case has to adduce facts that entail or at least provide some degree of support for the truth of the conclusion being argued for, whereas an explanation of *why* something is the case has to adduce factors (and only those factors) that are explanatorily relevant for the phenomenon to be accounted for. A causal factor may well be explanatorily relevant, but an individual contributing causal factor often does not make the phenomenon likely and thus does not serve for the purpose of an argument. Conversely, some facts (e.g., correlations) entail or make it likely that a phenomenon is the case, but are not factors that would be explanatorily relevant (e.g., if the standards of explanatory adequacy call for causes). Thus, many explanations are not arguments, and many arguments are not explanations. Moreover, how-possibly explanations are known to include assumptions that may not be factual, but these assumed features still have to be explanatory of the phenomenon at hand, which illustrates how considerations about explanatory adequacy go considerably beyond the issues of evidence and truth that is at the core of arguments.

I have also offered additional considerations for why the explanation–argument distinction matters to science education, in particular by invoking explanatory aims as an idea that has not previously figured in the explanation–argument debate. Standards of explanatory adequacy can differ across scientific contexts (where there can be different kinds of explanation of the same phenomenon), and the concrete *explanatory aim* pursued guides the adoption of the particular standards of explanatory adequacy that specify the kind of explanation that is intended. Not only is the pursuit of explanatory aims an important aspect of the nature of science (and teaching about the nature of science), but it is also the explanatory aim—not the argumentation about a suggested explanation—that makes an explanation valuable. Including explanatory aims in classroom instruction promotes students seeing explanations not just as facts, and engages them in developing explanations as responses to explanatory problems. Furthermore, science curricula often include that science aims at intervening in natural processes, not only for technological applications, but also as part of experimental discovery. Not any argument or type of evidence enables intervention in nature, as successful intervention specifically presupposes explanations with standards of adequacy that stipulate the adducing of causes. Students can fruitfully explore in the classroom how an explanatory account suggests different options for intervention. Generally, aims and standards guide scientific theorizing and practice. And scientists' aims and standards are not representations of nature, so that they provide additional structure over and above science's empirical content—a dimension of scientific theorizing and practice not captured by a framework exclusively focusing on evidence and empirical arguments.

But there are still issues to be explored. What kind of people in the larger science education context are to be explicitly informed or taught about the difference between explanation and argument? There are science education researchers, standards and curriculum developers, classroom teachers, and students. Who is the legitimate target audience of such a conceptual distinction? Let us take a look at Osborne and Patterson's motivation of why the explanation–argument distinctions matters:

> For, if a field lacks clarity about the concept that it seeks to explore and promote as a feature of classroom practice, then it will fail to communicate its meaning and intent to the wider audience of curriculum developers, standards developers, and teachers. … if the author of a test item holds only a diffuse conception of the features of argument and/or explanation, it is more likely that its intent will be unclear both to the student who is required to respond *and* to teachers who read assessment items for insight into the true nature of the intended curriculum. (Osborne and Patterson 2011, p. 628)

While they clearly assert that the conceptual distinction should be employed by standards and curriculum developers (apart from science education researchers), and indicate that the distinction should also be conveyed to teachers, it is not fully clear whether they maintain that the terminological distinction and the nature of the difference is to be *explicitly taught to students*.

Yet there are clearly concepts relevant to science education that should not be taught to students. Take the five different models of scientific explanation that Braaten and Windschitl (2011) obtained from the philosophy of science literature: the covering-law model, the statistical-probabilistic model, the causal model, the pragmatic model, and the unification model. In addition to noting that all five models of explanation are legitimate, Braaten and Windschitl (2011) clearly address science education concerns by discussing the benefits and limitations of each model in the classroom. For instance, the causal model capitalizes on students' curiosity about unobservable causes for observable phenomena, though using it typically leads to reasoning in terms of linear cause–effect relationships rather than complex causal networks. A use of the unification model encourages students to address major scientific theories, but it is not helpful for exploring possible explanations of single events. At the same time, while distinguishing among these models of explanation provides tools for teachers, it is plausible that being told about this fivefold categorization would not be of any benefit to high school students. The same holds for my general notion of 'standards of explanatory adequacy,' which is relevant to science education researchers and may be fruitful for science teachers, whereas students in a classroom better discuss *in a concrete case* what makes a suggested explanation a 'good' explanation in this context.

In fact, Berland and McNeill's objection to the significance of the explanation–argument distinction for science education may stem from the assumption that those promoting the distinction want it to be taught to students as well:

> One educational response to the synergistic and overlapping relationship between argumentation and explanation is to use both terms and explicitly discuss the differences with teachers *and students*. … However, we fear that the subtle message communicated by an emphasis on these distinctions … (Berland and McNeill 2012, pp. 809–810, emphasis added)

They rightly worry that some instances of explicit conceptual instruction to students creates more distractions than it actually benefits students: "explicit instruction in how to argue might disrupt students' authentic engagement in that practice" (Berland and McNeill 2012, p. 811). Thus, even if the distinction between explanation and argument matters to science education—as I have argued—we need to obtain more knowledge about to whom this difference is to be conveyed. It may well be advantageous for classroom teachers to be aware of it (so that they can guide discussions of what the best scientific explanation of a phenomenon is), while this conceptual matter should not be part of lesson plans explicitly taught to students. But in what form the notions of explanation and argument are to be conveyed to science teachers, and what and curriculum development and teacher training strategies will result in the highest student learning outcome in the context of scientific explanations are questions yet to be settled by classroom studies.

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Compliance with ethical standards

Conflict of interest The author declares no conflict of interest.

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