Different Types of Explanation across Biological Fields

Ingo Brigandt

Department of Philosophy, University of Alberta, Edmonton, Canada
Email: brigandt@ualberta.ca

Abstract

Even within biology, different types of explanation can be found: causal explanations, mechanistic explanations, reductive explanations, mathematical model-based explanations, actual-sequence explanations, and robust-process explanations. On top of this, different types of explanation can be sought for the same phenomenon, entailing different conditions of what counts as a satisfactory explanation of this phenomenon. I make sense of this complexity by using the notions of explanatory aims and standards of explanatory adequacy. Pertaining to scientific practice rather than the empirical content of science, these ideas likewise matter to science education and classroom practice. Standards of explanatory adequacy permit adjudicating the goodness of different explanations suggested by students, and they underlie the explanatory sense-making one obtains upon having constructed an explanation. Explanatory aims guide the type of explanation sought after, so as to foster student engagement and motivate explanation construction.

1 Introduction

Explaining phenomena is a hallmark of science, and scientific explanations contribute to our efforts to make sense of the natural world. This is also reflected in science education curriculum and assessment standards: “A high-quality science education provides the foundations for understanding the world … pupils should be encouraged to recognise the power of rational explanation and develop a sense of excitement and curiosity about natural phenomena" (Department for Education, England 2013b, 3). Explanation is often mentioned as a major aspect of the nature of science: "A key aspect of scientific literacy is an understanding of the nature of science as a human endeavour. Some important characteristics of science include … the use of logical, evidence-based arguments and explanations" (Council of Ministers of Education, Canada 2024, 13).

Paradoxically, not always throughout history was explanation seen as characteristic of science (Brigandt 2013a). As forerunners of the modern discipline of philosophy, the early logical positivists in the first half of the 20th century envisioned an empirical foundation of science and knowledge in general, where they opposed what they deemed to be metaphysics. While they took for granted that science establishes laws of nature and uses them to make predictions, 'explanations' over and above this, such as asking for why the laws of physics hold, appeared to invoke some cosmological or teleological order that the anti-metaphysical positivists eschewed. Even when not anthropomorphically assigning purposes to nature, any explanatory sense-making was also too psychological a topic for the purely logical-empirical study of science pursued by the logical positivist agenda. This situation has drastically changed with the advent of modern philosophy of science, which not only views explanation as a cornerstone of science but has developed and compared various models of what characterizes a scientific explanation (Salmon 1989; see also Braaten and Windschitl 2011). While that preeminent status of explanation is uncontested in current philosophy of science and science education, there are open issues. One is the relation between explanation and argument (Brigandt 2016). The science educators Berland and McNeill (2012) argue for an intimate connection between explanation and argument. And a standard document may even define an explanation as a reasoned justification of a claim by evidence, i.e., 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, 6). In contrast, Braaten and Windschitl (2011) and Osborne and Patterson (2011) maintain that explanation and argument are to be distinguished. Interestingly, predictions based on laws—which the logical positivists took as an uncontroversial aspect of science—are arguments, so the positivists likewise were wary of conflating argument and explanation, albeit for very different reasons than some current science educators and philosophers of science (who endorse scientific explanation).

Although the idea that science puts forward explanations sounds straightforward, another question arises from the fact that there are quite different kinds of scientific explanation. There are many different scientific fields. Biology education is structured by scientific domains, as are textbooks, for instance, a general biology textbook will cover different biological fields (Nehm 2019). Even restricting the scope to biology hardly reduces the complexity. As we will see, within biology alone, there is a diversity of types of explanation, each of which has different standards of what an adequate explanation should include. This is of particular importance given that there can be different kinds of explanation of one and the same phenomenon. As a result, the phenomenon to be explained and the scientific facts underdetermine how the explanation ought to proceed. Instead, the underlying explanatory aims not only yield the type of explanation sought after, but also guide the explanatory project in the first place. This matters to science education as explanatory aims motivate student interest in seeking explanations and engender the sense-making provided by having explained a phenomenon.

This chapter takes as its starting point the diversity of explanations found across biology (see also Peck and Potochnik, Chapter 2). Despite the variety of types of explanation, I can then extract some core features of scientific explanation and discuss their relevance to biology education. In this context, we revisit how explanations have interesting features that go beyond making arguments. I finally engage with the sense-making aspect of scientific explanations by addressing how this intellectual aim sometimes also connects up with practical aims such as experimental intervention and technological application.

2 A variety of types of explanation in biology

To illustrate the diversity of types of explanation (even within biology) and make the point for biology education that explanation is not a monolithic category, I cover causal explanations, mechanistic explanations, reductive explanations, mathematical model-based explanations, actual-sequence explanations, and robust-process explanations. Two things should be highlighted from the outset. First, although one type of explanation may be particularly prominent in and even characteristic of a certain biological field (e.g., mechanistic explanations in molecular and cellular biology), any type of explanation can be found across many biological fields, so one should not identify a type of explanation with a scientific field. Second, while different types of explanation use different considerations of what makes a scientific account explanatory, different types do not rule each other out, so there can be different explanations of the same phenomenon—an issue to be discussed in Section 3.

In many scientific contexts, an explanation is simply understood to be a *causal explanation*, which explains a phenomenon by adducing one or several of its causes. One individual cause alone need not guarantee that an event to be explained happened. Instead, the presence of the cause contributes to the event's occurrence in that the event is at least more likely to happen compared to the situation where the cause was absent (Woodward 2003). For example, having regularly smoked tobacco is a cause of a person's contracting lung cancer, even though smoking does not always lead to cancer. Pointing to the (merely) heightened risk of getting a disease is relevant for the explanation, which also illustrates that while some causes have a deterministic effect, others can have a probabilistic impact on the outcome to be explained. Causal explanations abound in biology. In ecology, we explain the extinction of a species in terms of the significant reduction of its habitat, and in developmental biology, we explain vertebrate neurulation (a tissue folding process creating the neural tube) in terms of induction by means of growth factors and other signalling proteins. There are often several causes of a phenomenon, e.g., a lactose-intolerant person's belly pain is caused by genetic factors (underlying her lactose intolerance) as well as by her having consumed milk containing lactose. An explanation may focus on one such cause (or one type of cause) depending on what guides the explanatory project (Gannett 1999). Preventive efforts in public health (or political efforts attempting to combat environmental racism) will explain a heightened cancer incidence in a certain community in terms of industrial pollution as an environmental situation rather than the genetics of the individuals in this community—even when there is some genetic contribution (Tabery 2023).

A *mechanistic explanation* puts forward a mechanism for a phenomenon. A mechanism consists of entities and activities that are organized in such a fashion that the interactions among the component entities produce the phenomenon to be explained (Bechtel and Abrahamsen 2005; Craver and Darden 2013). An iconic example is protein synthesis, consisting of the transcription of a DNA segment to RNA and the subsequent translation of RNA to a polypeptide, which forms a protein. There is more detail to this mechanism, e.g., transcription starts with double-stranded DNA, the enzyme helicase locally separates the two strands so that an RNA polymerase can bind to the sense strand of the DNA and generate a single-stranded (primary) mRNA transcript, which is further processed to form the mature mRNA. Instead of such a complicated description in one or more sentences, it is very common to depict a mechanism in a diagram, as in Figure 1, which permits scientists and science students alike to understand the mechanism and its operation. Indeed, it is an interesting question of how the explanatory understanding provided by a diagram differs from the explanatory understanding in terms of deducing from a law of nature (Sheredos et al. 2013). Although in a mechanism there are causal interactions among the mechanism components, a mechanistic explanation is not the same as a causal explanation. In the latter, the cause temporally precedes the effect (and may explain without detailing the intermediate steps), while all of a mechanism's components taken together and the mechanism's organization and operation explain the phenomenon of interest. In a nutshell, a mechanistic explanation explains a property or activity of a whole in terms of its parts (and their interactions). Protein synthesis (explained in terms of its underlying mechanism) is ultimately identical to the component entities and activities doing the explaining, whereas a cause explaining some effect is distinct from the effect. While mechanistic explanations are common in molecular, cellular, and developmental biology, they can be found in other biological domains as well, including ecology (Pâslaru 2018). One example is how the mechanism of enemy release accounts for some cases of a species spreading within a new range so as to become an invasive species (Heger 2022).[1]

[1] Natural selection is often called an evolutionary 'mechanism,' but it is controversial whether natural selection explanations are mechanistic explanations (Skipper and Millstein 2005). Barros (2008) defends the mechanistic vision by arguing that an individual's interaction with its environment and organisms from other species (e.g., predators) yields its survival, reproduction, or death (with a certain likelihood), which is an outcome of a mechanism—once stochastic mechanisms are taken into account. However, one aspect of natural selection explanations is that they abstract from a good deal of the physical interactions within a population. Such an explanation may simply note that organisms with a certain phenotype spread within the population because this phenotype increases their chances of survival, compared to organisms with other phenotypes. This abstraction from most details is at odds with a mechanistic explanation in terms of all the components and their interactions producing some phenomenon (see also my below discussion of robust-process explanations). And what is in my view most crucial about natural selection explanations is that they are *contrastive*: they appeal to fitness *differences* between phenotypes. Such an explanation in terms of differences is dissimilar to how mechanistic explanations proceed.

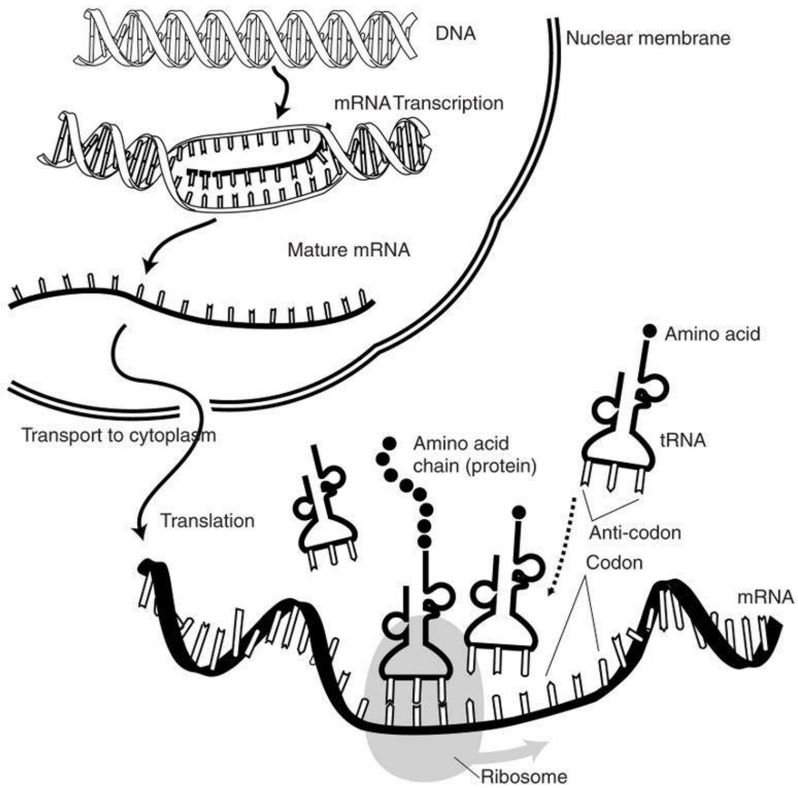

Figure 1. The mechanism of protein synthesis in a eukaryotic cell, consisting of transcription (inside the nucleus) and translation (in the cytoplasm).

Mechanistic explanations are often perceived to be reductive in nature, given that a whole is explained in terms of its parts, which are on a lower level. However, as proponents of mechanistic explanations in biology and neuroscience, Carl Craver and Lindley Darden (2013, Ch. 10) argue that mechanistic explanations need not be *reductive explanations*. Instead, they point to examples of multilevel (or interlevel) explanations in mechanistic research on the neurophysiological basis of learning and memory. While such neuronal processes as long-term potentiation have a molecular underpinning, long-term potentiation is just one ingredient in the overall mechanisms of learning and memory, where the explanation has to integrate features from several levels, from the molecular to the cellular, neuronal circuit, and brain region level—where several fields contribute to the explanation, in contrast to the classical vision that reduction is a reduction to the theory of one more fundamental field. Based on their mechanistic perspective, they also view the relation between classical and molecular genetics as integrative rather than reductive.

Marie Kaiser (2015) has developed a more thorough account of what a reductive explanation is, and how it differs from a mechanistic explanation (and from what she calls part-whole explanations). A reductive explanation explains exclusively in terms of lower-level parts, while the parts can be treated in isolation (from their original context). One way in which such a reductive explanation is not possible is when the interactions among a biological system's components exhibit feedback loops, where the system's dynamical operation changes the properties of some of its parts (so that such a part cannot be considered in isolation). A case in point is explanations of circadian rhythms, which are rhythmic oscillations of gene activities and gene product levels with a daily period. Not only has it to be accounted for why the oscillations in a single cell are sustained rather than damped and fading out—which hinges on the feedback organization and the strength of the interactions. But apart from the central oscillator in the hypothalamus region of the mammalian brain, there are also peripheral oscillators that interact with the central oscillator in a bidirectional fashion, all of which are also impacted by external inputs such as daylight (Bechtel 2010).

Within biology, *explanations based on mathematical models* are well-known from ecology and evolutionary biology (including population genetics and quantitative genetics). Teaching about modelling may start with fairly simple models, such as the Lotka-Volterra model of the ecological interaction and population size of one predator and one prey species, but these can be used to develop more complex and realistic models accounting for the dynamics of ecological communities. In population genetics, the Hardy-Weinberg model is basic in that it makes many idealizing assumptions, such as infinite population size and random mating, while many other models of gene frequency changes in populations have been set up. Mathematical models can also be found in molecular and cellular biology, more precisely in the field of systems biology, which models complex molecular and cellular systems using various mathematical tools (Klipp et al. 2010). While for a causal explanation it can suffice to cite one cause impacting an effect to be explained, a model-based explanation captures the relations and interactions among various features, including their change across a significant period of time.

A mathematical model-based explanation can at the same time be a mechanistic explanation, if it details all the relevant components and interactions within a mechanism that produce a phenomenon (Bechtel 2012). However, even when mathematically modelling a molecular system, a model-based explanation need not be mechanistic. A model-based explanation may be fruitful by making abstractions and idealizations that obscure the real mechanism, whereas a mechanistic explanation is committed to an account as realistic as possible (MacLeod and Nersessian 2015). A model-based explanation may be successful by capturing how the change in one system property affects some other system property, without detailing intermediate steps and mechanistic interactions. Indeed, explanations in systems biology can be exclusively in terms of the concentrations of types of entity (e.g., the concentration of a protein or a neurotransmitter), not in terms of several concrete entities, e.g., how one specific signalling molecule binds to one concrete protein—as a mechanistic explanation envisions (Brigandt 2015a).

Finally, actual-sequence explanations can be distinguished from robust-process explanations (Sterelny 1996). An *actual-sequence explanation* details the temporal sequence of events leading up to the feature to be explained. A straightforward example is the evolution of a morphological trait, such as the forelimb in chickens. An actual sequence explanation maps out ancestral traits, their transformation into modified traits or the origin of new traits, including at which junctures in the phylogenetic tree these steps took place. Such an explanation of the history of the chicken forelimb could start with pectoral fins in fish, detail their substantial transformation into tetrapod limbs, which includes the loss of fin rays and the eventual evolution of digits, and capture other steps in the sequence, including a reduction of the originally five digits of amphibians to three in chicken as well as the replacement of reptilian scales by feathers.

In contrast, even when the same outcome is to be explained, a *robust-process explanation* (if it is possible) shows why the particular outcome would (likely) have arisen even if the path toward it had changed, e.g., due to disturbances along the way.[2] Such an explanation indicates why the outcome is the result of a process that robustly leads to it. And although the outcome resulted from a particular sequence of steps, this sequence is of no interest to this mode of explaining, given that the whole point is that other trajectories (or sequences of steps) would still have resulted in the same outcome. In evolutionary contexts, explanations in terms of natural selection are a paradigmatic case of robust-process explanations. In the case of stabilizing selection, since one particular trait yields optimal fitness, it will eventually evolve and become dominant in the population even when random effects due to genetic drift temporarily lead to a move away from the optimal trait. There are robust-process explanations in other biological fields. In developmental biology, robustness is the ability of an organism to developmentally generate or physiologically maintain a certain feature even in the case of internal developmental noise or environmental disturbances. How developmental processes exhibit robustness is an important explanatory question (Brigandt 2015a). Even in crocodiles, where an organism’s sex is not chromosomally but environmentally determined and the temperature influences the ratio of male versus female crocodiles that develop, an organism reliably adopts either a male or a female developmental trajectory (Kirschner and Gerhart 2005), where molecular signalling with negative feedback loops explains how either trajectory is robustly maintained.

While there can be overlap between the types of explanation surveyed so far, my discussion illustrates that, even within biology, there is a variety of kinds of explanation (and I do not claim to have exhausted the types of explanation that one could distinguish). It is now time to highlight

---

[2] McCain, Chapter 1, discusses this type of explanation under the label ‘equilibrium explanations.’

some core features of explanation—despite the diversity of explanations—and discuss their relevance to science education.

3 Core characteristics of explanations and their import for biology education

One crucial implication stemming from the diverse types of explanation is that there can be different types of explanation of the same phenomenon, where a scientist's interests determine which kind of explanation is sought after in the given context. Recalling an example given in the previous section, for a morphological trait in an extant species, such as the digits of the chicken forelimb, some may seek an actual-sequence explanation that involves laying out a historical sequence of ancestral traits and their transformation up to the trait as seen in the extant species. At the same time, we can also request a robust-process explanation of this trait, more precisely, an explanation in terms of natural selection that accounts for why only three particular digits remain in the chicken forelimb, which would have to provide the functional anatomical adaptive benefits of reducing the number of digits to these three (regardless of which of the initially five digits was lost first, as would be detailed in an actual-sequence explanation). Even if it pertains to the same phenomenon to be explained, offering one such explanation does not yield the other kind of explanation.

To give another example from biology, we may seek an explanation of an action potential along a neuron's axon, which is a change in cell membrane voltage travelling along the axon toward the axon terminal (which then signals another neuron). Some may advance a causal explanation in terms of an increase in the cell membrane's potential (the electrical charge differential between the interior and the exterior of the cell) above a threshold value, as this triggers a cascade of changes in the membrane's electrical potential along the axon toward the axon terminal. But we may also be interested in a mechanistic explanation of the action potential along the axon. This would have to attend to the relevant components and intermediate activities of the mechanism, especially the presence of sodium-gated and potassium-gated ion channels within the membrane, which (depending on the magnitude of the membrane's electric potential) open to permit sodium and potassium ions, respectively, to flow inside the axon. In the case at hand, it is legitimate to request either type of explanation, where pointing to the causal explanation is insufficient if we are interested in a mechanistic explanation.[3]

What is behind any explanatory sense-making in general and different types of explanations in particular are explanatory aims (Brigandt 2013a) and standards of explanatory adequacy (Brigandt 2016). Both are features of a person seeking an explanation, be it a scientist or a student in a science classroom. Beyond merely noticing several natural phenomena (and even beyond acknowledging natural phenomena as in need of scientific explanation in an abstract fashion), *explanatory aims* make a particular natural phenomenon something a person is actively interested in understanding scientifically. For an individual person, including a science student, having an explanatory aim (e.g., accounting for why lung cancer forms) motivates engagement and work toward the explanation. An explanatory aim that is shared by many persons furthermore motivates collaborative efforts, some of which are classroom interactions or even enduring investigations in science. Indeed, some explanatory aims pertain to scientific problems that can only be solved in an interdisciplinary fashion, for example, the problem of the

---

[3] A developmental explanation and an evolutionary explanation of the origin of the same biological trait are likewise compatible with and complementary to each other (Brigandt 2016; Kampourakis and Niebert 2018). They clearly have different conditions of adequacy and thus can be considered different types of explanation. Section 2 didn't mention developmental as opposed to evolutionary explanations due to its focus on much more domain-general types of explanation. While in this chapter I emphasize cases where different types of explanation—and hence different explanations—of the same phenomenon are possible, there are of course many contexts where two explanations are in competition with each other. For instance, one can ask whether an evolutionary outcome is better explained in terms of natural selection or is largely the result of random genetic drift (Beggrow and Nehm 2012).

evolutionary origin of novelties (such as the origin of fins in fish). The pursuit of such a demanding explanatory aim then motivates interdisciplinary research involving several biological fields (Brigandt 2013a; Brigandt and Love 2012; Love 2013a).[4]

Having an explanatory aim can be more specific than seeking some explanation of a phenomenon (e.g., chicken forelimb evolution), but point to the type of explanation sought after. This can be more explicitly articulated in terms of *standards of explanatory adequacy* (Love 2008 introduced the label 'criteria' of explanatory adequacy). Standards of explanatory adequacy lay out what features count as being relevant for the explanation (irrelevant features should not be included in the explanation) and what explanatory ingredients all need to be included to make the account a satisfactory explanation. Even when being about the same phenomenon, an actual-sequence explanation and a robust-process explanation of it differ from each other precisely because these types of explanation have different kinds of standards of explanatory adequacy (calling for the respective features mentioned in the above chicken forelimb example to be included). While different types of explanations can be associated with different *kinds* of standards of adequacy, there can also be more specific standards of adequacy that hold for a particular explanation sought after. Likewise, scientists may happen to debate what the relevant standards of adequacy are, where some biologists deem a gene-centric explanation of a trait (in terms of gene regulatory networks) to be fully adequate while others insist on an explanation that captures the interaction of genetic and non-genetic factors or the involvement of traits above the genetic level (Love 2013b).

The (related) notions of explanatory aims and explanatory standards contribute to previous insights advanced by science educators. In their analysis of scientific explanation, Melissa

---

[4] Peck and Potochnik, Chapter 2, likewise emphasize the role of explanatory aims.

Braaten and Mark Windschitl (2011) lay out three overarching questions for the science education community to engage with:

> (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, 651)

In my terminology, what makes an account (2) *explanatory* in the first place rather than being merely descriptive is that it addresses a relevant explanatory aim (see also Peck and Potochnik, Chapter 2). And (1) what makes something a *good explanation* and (3) how *alternative attempts* at offering an explanation are to be evaluated hinges on the standards of explanatory adequacy at hand. One point I add to Braaten and Windschitl's framework is that the 'goodness' of explanations is not a uniform matter but can differ across investigative contexts.[5] It is obvious that what makes for an explanation based on laws of nature in physics diverges from the character of a mechanistic explanation in molecular biology. But even within biology, and even pertaining to the same phenomenon to be explained, there can be different standards of explanatory goodness, given that an actual-sequence and a robust-process explanation of the same phenomenon have distinct standards of explanatory adequacy to meet.

These core characteristics of explanation also shed light on *how explanation goes beyond argumentation*. Leema Berland and Katherine McNeill (2012) uphold an intimate connection between explanation and argument, among other things because the two are entwined given that evidence-based reasoning is important for both, where this emphasis on evidence is likewise seen

---

[5] Braaten and Windschitl (2011) acknowledge the relevance of context in their discussion of the pragmatics of scientific explanation. From my perspective, such 'pragmatic' aspects can be central to scientific explanations (including in the science classroom), at least when several types of explanation are an option.

in how many standard documents characterize explanations: "Scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories" (National Research Council, USA 1996, 148). In contrast, Jonathan Osborne and Alexis Patterson (2011) maintain that explanation and argument are to be distinguished. While I support this position and deem it important for approaching explanation in science education, I do not rely on the reason Osborne and Patterson adduce to distinguish explanation and argument:

> 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, 634)

Apart from the fact that this is not fully correct (we may be certain about a conclusion while being more tentative about the premises adduced when arguing for the conclusion), there is a more important way to distinguish argument and explanation, in terms of very different standards of adequacy (Brigandt 2016). For an argument, it suffices that the premises support the conclusion, but an explanation has to meet standards of *explanatory* adequacy that detail what makes an account explanatory at all (or "explanatory rather than descriptive," as Braaten and Windschitl stated above). For example, pointing to a high correlation between two features yields a good argument that one feature is present, given that the other is. But this *correlation* is woefully inadequate to offer a *causal* explanation of the former feature (see also McCain, Chapter 1). Moreover, adding premises that are irrelevant to the conclusion to an argument does not make it worse (the conclusion is still supported by the original premises), but adding explanatorily irrelevant features to an explanation (e.g., factors not causally impacting the phenomenon) reduces its quality, as an explanation should point to exactly those factors that are relevant to the explanation.

Of course, defending an explanation suggested and adjudicating between possible explanations does require argumentation. But an explanation of a phenomenon is not just an argument that we can be sure that the phenomenon obtains. The argumentation to defend an explanation not only needs to provide support that the different factors mentioned in the explanation obtain, but also that they are relevant to the phenomenon—in other words, meet the standards of explanatory adequacy.[6] For instance, explanatory relevance is achieved by showing that a factor is one cause of an effect to be explained in the case of a causal explanation, or that the entities and their interactions adduced by a mechanistic explanation actually produce the phenomenon to be explained (Bechtel and Abrahamsen 2005). Thereby, standards of explanatory adequacy also matter to biology education when it comes to adjudicating between different explanations suggested by students (Alameh and Abd-El-Khalick 2018; Alameh et al. 2023).

In a similar vein, while evidence matters for scientific explanations, adducing evidence as such (which is widely done outside of explaining phenomena) fails at ensuring that the particular standards of explanatory adequacy are met, and thereby ensuring that the account is explanatory and a good explanation. Consequently, whereas Berland and Reiser (2009, 29) maintain that "evidence is at the core of scientific [explanatory] sensemaking," I maintain that *having realized that standards of explanatory adequacy are met is at the heart of explanatory sense-making*. This becomes particularly plain when different types of explanation of the same phenomenon are possible. Someone who is seeking a robust-process explanation of an outcome will not obtain the

---

[6] Berland and Reiser (2009, 28) describe some of science education as employing a strategy that "uses the structure of a scientific argument—claims defended with evidence—to support students' explanation construction." If this is to offer *some* of the support for explanation construction, then this is not objectionable, but the explanatory sense-making in terms of standards of explanatory adequacy is not in view in this particular science education strategy.

explanatory sense-making at stake from an actual-sequence explanation of the outcome—even when each step of the sequence is well supported by evidence.[7] This also points to gaps in past philosophy of science, which used to articulate science exclusively in terms of logical relations between theory and observation/evidence. Yet apart from science using various representations (evidence, models, and theories), philosophy of science nowadays recognizes that there are further aspects of science. These include scientific aims and standards (Potochnik 2017), which, unlike representations of nature, are our human aims and scientific agendas and our standards for what makes for successful scientific practice and theorizing, including our expectations for when an account offers explanatory sense-making (Brigandt 2013a, 2015b).

There are several additional reasons why the association of scientific explanation with explanatory aims and explanatory standards is important to biology education. First, in addition to teaching the content of science, one major aspect of science education is to critically convey the *nature of science* (Allchin 2013; Flick and Lederman 2004; McComas 1998; McDonald and Abd-El-Khalick 2017). This ranges from teaching about general aspects of science, such as a 'consensus view' held across scientific disciplines (Kampourakis 2016; Lederman 2007; Lederman et al. 2002; Osborne et al. 2003) to approaches that attempt to convey the

[7] Evidence and standards of explanatory adequacy are even independent components of an explanation. This can be seen in the case of how-possibly explanations in science (Brigandt 2016). When one is attempting to offer just one account that may explain how some puzzling phenomenon could possibly have occurred, this account must meet standards of explanatory relevance, while evidence for some parts of the account may be lacking—evidence that would make the account the correct (and not just a possible) explanation. While highlighting argumentation, the United States National Research Council's (2012, 68) K-12 education framework does treat evidence/data and explanatory sense-making as independent components: "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."

heterogeneity of science and its nature (Allchin 2011; Irzik and Nola 2011; Rudolph 2000; Tala and Vesterinen 2015; van Dijk 2014). One important aspect of the nature of science (NOS) is that science not only contains various explanations, but that scientists endeavour to develop novel explanatory accounts, as also reflected in 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, emphasis added)

Explanatory aims and standards are not about the phenomena studied by science, but about science (and its practice) itself. Consequently, conveying a NOS vision of science as a human endeavour and a social practice requires the inclusion of scientists' explanatory aims. And it obviously matters to science education to make students critical science consumers (Brigandt 2013b; Kampourakis 2022). This can be fostered by teaching that not all explanatory questions are legitimate questions for contemporary science and that answering an explanatory question properly involves standards of explanatory relevance and adequacy

Second, science students need to learn about *scientific discovery and practice* in general and how explanations in particular are generated, continuously revised, and improved. 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 2013a, 3). The connection to explanatory aims is important in this context, given that the sustained pursuit of an explanatory aim motivates the revision of earlier explanatory models. Beyond what Richard Duschl (1990) critically dubs 'final form science,' science educators have come to recognize that students need to obtain an appreciation of the process of science, including the skills and tools scientists use (see also Lehrer and Schauble 2006). In a similar vein, Alan Love (2013a) points out that given that scientific content as covered in a textbook will soon be outdated, a more lasting lesson is to teach about the practice of science, which generates new content and refines explanatory models. While traditional accounts of reductive explanation in philosophy of science have focused on finished reductions (arguing that they are *in principl*e possible), it has been rightly objected that this neglects how working toward explanations (including reductive ones) looks like in *actual* scientific practice (Brigandt 2013a). Indeed, contemporary philosophical accounts of mechanistic *explanation* emphasize the close connection to mechanistic *discovery*, among other things by investigating how mechanistic explanations, while typically incomplete, are constantly revised and refined (Craver and Darden 2013). This carries over to science education:

> If the goal of science education is to foster student participation in scientific practices then our understanding of explanation must expand to include the *process* of constructing these explanations. (Berland and Reiser 2009, 27, emphasis added)

Explanatory aims motivate this construction process, while standards of explanatory goodness and adequacy matter for adjudicating when there is a mismatch between an account suggested in the biology classroom and what science would deem as the correct explanation (see also Kampourakis and Nehm 2014).

Third, I argued that explanatory sense-making, provided by someone having pursued an explanatory aim and realized that one has met the underlying standards of explanatory adequacy, is at the core of explanation. This is important for biology education as sense-making generates a *student's interest* in a particular explanation, and the promise of sense-making *engages students* and motivates their search for potential explanations in the science classroom. Beyond expecting students to learn scientific facts, classroom instruction needs to foster such student engagement and initiative. This is in line with the emphasis on the merits of problem-based learning in general (Hmelo-Silver 2004; Hmelo-Silver and DeSimone 2013; Strobel and Van Barneveld 2009) and advocacy for the use of 'driving questions' in science education (Krajcik and

Blumenfeld 2005; Krajcik and Mamlok-Naaman 2005).[8] Many genuinely scientific questions are also of immediate interest to laypersons and students. To give two examples from biology, why do animals from certain species *live in groups*—while other species have animals with solitary lives? And why do centipedes—whose number of segments varies substantially across species from 19 to 301 segments—always have an *odd number* (and never an even number) of segments?

4 Sense-making and practical intervention

In the previous section, I emphasized the importance of sense-making for the activity of explaining and the success of an explanation, including in the science classroom. This view is widely shared among science educators, including those who distinguish explanation and argument (as I do) as well as those who strongly associate explanation with argumentation:

> Key to the distinction between explanation and argument is that an explanation should make sense of a phenomenon … (Osborne and Patterson 2011, 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, 809)

Sense-making suggests some purely intellectual understanding. However, there is more to it. I now want to display the connection between explaining as an *intellectual* endeavour and intervention into nature as a *practical* matter, also highlighting its relevance for explanation in

---

[8] The United States National Research Council's (2012, 50) K-12 science education framework depicts science in this fashion, where the starting point is that "Science begins with a question about a phenomenon … and seeks to develop theories that can provide explanatory answers to such questions," resulting in efforts to construct explanations and find the best explanation.

biology education. In contrast, many science education discussions of explanation do not mention that science happens and intends to intervene in nature (e.g., Braaten and Windschitl 2011). Some sort of connection between explanation and intervention/control is acknowledged by science education learning outcome frameworks:

> 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)

The question is what the particular relation between intellectual sense-making (explanation) and practical intervention is.

One obvious scientific context where intervention in nature matters is the *application of scientific knowledge*. One example from the biological domain is conservation efforts directed at conserving species, ecological communities, or wetlands. Not all explanatory knowledge is equally effective for the purpose of practical intervention (e.g., many explanations in astronomy have a very limited potential for application). Indeed, my distinction between different types of explanations in Section 2 showed that scientific explanation, even within biology, is not a monolithic category. Yet there are types of explanation that create a direct connection to the possibility for practical intervention. One such type is *causal explanation*. While a correlation between two features alone is insufficient for telling whether one could be affected through intervening on the other, knowing about a causal connection reveals that the effect can be influenced by manipulating the cause. In fact, central to most philosophical theories of causation is the notion of difference-making, where causes make a difference to their effect. And the detailed theory of what causation is and what qualifies as a causal relation by James Woodward (2003) also appeals to the theoretical notion of an ‘ideal intervention’ (which is an intervention on one specific variable only). Thereby, causal explanatory knowledge permits prediction upon intervention in nature.

Mechanistic explanations likewise form the basis for practical intervention. From understanding the mechanism for some phenomenon, such as the mechanism of protein synthesis mentioned in Section 2 (see Figure 1), one can infer which entities, activities, or organization features would have to be modified to obtain a modified, desired phenomenon. A concrete example of using biological explanations for an application in the life sciences is potential treatment options for cystic fibrosis, which is a disease among other things involving thickened mucus in the lungs (Craver and Darden 2013). A mechanistic explanation of this disease starts with noting a mutation in both copies of the *CFTR* gene, which produces a modified mRNA and then a non-functional protein, where the functional CFTR protein regulates chloride transport through the membrane of epithelial cells. One obvious potential target for therapeutic intervention is the very mutated gene, by inserting a normal gene through gene therapy, although longstanding research on this has not resulted in a clinically viable treatment (Davies et al. 2019). Another intervention suggested by the mechanistic account is the next step in the mechanism, the modified mRNA produced from the mutated gene. One option that has been explored in mouse models is the insertion of a DNA segment, which produces an mRNA that splices together with the patient's modified mRNA so as to result in an mRNA that yields a functional protein. A further option which has clinical promise is to deliver the normal mRNA within lipid nanoparticles that the patients inhales (Rowe et al. 2023). Another strategy is suggested by the following step in the mechanism, the production of the CFRT protein, which, in the case of cystic fibrosis patients, is non-functional as it does not fold correctly. It is possible to administer proteins called CFTR modulators that achieve a sufficiently working protein in the patient. The protein to be administered depends on the patient's *CFTR* gene mutation and thus the kind of non-functional CFRT protein, where in some cases a chaperone is used that restores correct folding (Anwar et al. 2024). Overall, the road to therapeutic interventions that are safe and effective is often long, but a mechanistic explanation can direct the way.

Since many science curriculum documents include technological and other applications made possible by scientific knowledge, it matters to address the connection between intellectual explanation and practical intervention as part of biology education. And the previous example was based on the mechanism of protein synthesis as a topic widely covered in biology classrooms. But even when using a restrictive construal of science that does not include applied science, there is another reason for addressing the connection to practical intervention. For, as covered in the previous section, biology education should also teach about *scientific practice* and the *process of scientific discovery*. In this context, explanatory knowledge is relevant as it facilitates designing and improving experimental interventions in science labs. Experimentation is a major aspect of scientific practice, especially in biology, where experiments are designed to reveal new and hitherto unknown features as a means of scientific discovery. Explanatory knowledge about biological mechanisms, even if quite incomplete, permits the design of experimental interventions that are likely to reveal other aspects of the mechanism or features of different mechanisms in the larger system, e.g., a model organism (Craver and Darden 2013).

In the above context of applying scientific knowledge, I mentioned the possibility of inserting a DNA segment into a human patient (as an instance of gene therapy). But much more common is the insertion of DNA into a model organism for the purpose of discovery, to create a so-called gene knockout that results in an inactive version of the target gene. The resulting phenotype (including on the molecular, cellular, and developmental level) then provides clues about the causal effect of the target gene. While gene knockouts have been created in experimental practice for a few decades, during the last decade, the CRISPR-Cas9 system (popularly portrayed as ‘gene scissors’) has become an immensely prominent experimental tool for precise and effective genome editing.[9] While routinely used in molecular biology practice as

[9] Returning to the previous example of a life science application, the CRISPR-Cas9 tool has also been

a tool of discovery, the CRISPR-Cas9 system is also suitable for use in high school classrooms (Ziegler and Nellen 2020).

To sum up this section, biology education also addresses the application of scientific knowledge and the practice of biology, including the process of discovery. Although explanation and explanatory sense-making as such are intellectual matters, biology education should not neglect the connection to practical intervention in nature. The reason is that many instances of explanatory knowledge enable biologists and biology students to anticipate potential practical applications as well as experimental designs that promise the discovery of new biological features. Intervention-based discovery may sometimes employ a trial-and-error method, but even then, some explanatory knowledge can guide student strategies.

5 Conclusion

My discussion started with the diversity of types of explanation found even within biology. I distinguished causal explanations, mechanistic explanations, reductive explanations, mathematical model-based explanations, actual-sequence explanations, and robust-process explanations. To add to the complexity, the same phenomenon can be approached with different such explanation types, resulting in different explanations of said phenomenon. I made sense of this by deploying the notions of explanatory aims and standards of explanatory adequacy. An explanatory aim guides the project of seeking a particular explanation, which can go beyond pointing to the phenomenon of interest, and also include the type of explanation sought in the given context, e.g., aiming at a mechanistic (rather than a causal) explanation. And standards of explanatory adequacy indicate what makes for the goodness of an explanation in this context,

---

explored as a means to treat cystic fibrosis (Da Silva Sanchez et al. 2020).

where for instance a robust-process explanation has different adequacy standards than an actual sequence phenomenon. Apart from clarifying the variety of explanations in biology, these philosophical notions are also of relevance to science education. Standards of explanatory adequacy permit not only to adjudicate the goodness of different explanation attempts suggested by students in the classroom, but such expectations of explanatory relevance and adequacy also account for the very explanatory sense-making a student obtains from having constructed an explanation of a phenomenon of interest. Likewise, explanatory aims motivate an explanatory endeavour in the first place so as to engage and guide students in their effort at explanation seeking. Generally, explanatory aims and standards go beyond the empirical content of science and instead pertain to scientific practice and the process of science—an important aspect that likewise carries over to activities in the science classroom.

Given that I made specialized distinctions between different types of explanations and deployed the technical notions of explanatory aims and standards of adequacy, I conclude with a brief clarification. Who is supposed to learn about and use these concepts and distinctions? While I deem them to be valuable to science education researchers, I do not call for having them taught to students in the classroom.[10] The concepts and terminology used certainly depend on the audience, which can also include curriculum developers and classroom teachers. It is straightforward to convey that there are causal explanations that point to one among potentially several causes of an effect to be explained, or that there are mechanistic explanations that detail a larger mechanism producing a phenomenon to be understood. But rather than deploying the term ‘standards of explanatory adequacy’ in curriculum frameworks, it may well be sufficient to talk

---

[10] In a similar vein, while emphasizing the centrality of argumentation in the classroom (including when constructing and defending explanations), Berland and McNeill (2012, 811) do not deem it to be productive to explicitly teach science students what an argument is: “explicit instruction in how to argue might disrupt students’ authentic engagement in that practice.”

about the goodness of an explanation, while making plain that what makes for a good causal explanation can differ from a satisfactory mechanistic explanation.

Acknowledgments

I thank Ross Nehm and Kostas Kampourakis for the invitation to contribute to this edited volume and their comments on a draft of this chapter. Figure 1 is reproduced from an image in the public domain.

References

Alameh, S. and Abd-El-Khalick, F. (2018). Towards a philosophically guided schema for studying scientific explanation in science education. *Science & Education*, *27*(9): 831-861.

Alameh, S., Abd-El-Khalick, F., and Brown, D. (2023). The nature of scientific explanation: Examining the perceptions of the nature, quality, and "goodness" of explanation among college students, science teachers, and scientists. *Journal of Research in Science Teaching*, *60*(1): 100-135.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education*, *95*: 518-542.

——— (2013). *Teaching the nature of science: Perspectives & resources*. SHiPS Education Press.

Anwar, S., Peng, J.-L., Zahid, K. R., Zhou, Y.-M., Ali, Q., and Qiu, C.-R. (2024). Cystic fibrosis: Understanding cystic fibrosis transmembrane regulator mutation classification and modulator therapies. *Advances in Respiratory Medicine*, *92*(4): 263-277.

Barros, D. B. (2008). Natural selection as a mechanism. *Philosophy of Science*, *75*(3): 306-322.

Bechtel, W. (2010). The downs and ups of mechanistic research: Circadian rhythm research as an exemplar. *Erkenntnis*, *73*(3): 313-328.

——— (2012). Understanding endogenously active mechanisms: A scientific and philosophical challenge. *European Journal for Philosophy of Science*, *2*(2): 233-248.

Bechtel, W. and Abrahamsen, A. (2005). Explanation: A mechanist alternative. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *36*: 421-441.

Beggrow, E. P. and Nehm, R. H. (2012). Students' mental models of evolutionary causation: Natural selection and genetic drift. *Evolution: Education and Outreach*, *5*(3): 429-444.

Berland, L. K. and McNeill, K. L. (2012). For whom is argument and explanation a necessary distinction? A response to Osborne and Patterson. *Science Education*, *96*(5): 808-813.

Berland, L. K. and Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education*, *93*(1): 26-55.

Braaten, M. and Windschitl, M. (2011). Working toward a stronger conceptualization of scientific explanation for science education. *Science Education*, *95*(4): 639-669.
Brigandt, I. (2013a). Explanation in biology: Reduction, pluralism, and explanatory aims. *Science & Education*, *22*(1): 69-91.
——— (2013b). Intelligent design and the nature of science: Philosophical and pedagogical points. In K. Kampourakis (Ed.), *The philosophy of biology: A companion for educators* (pp. 205-238). Springer.
——— (2015a). Evolutionary developmental biology and the limits of philosophical accounts of mechanistic explanation. In P.-A. Braillard and C. Malaterre (Eds.), *Explanation in biology: An enquiry into the diversity of explanatory patterns in the life sciences* (pp. 135-173). Springer.
——— (2015b). Social values influence the adequacy conditions of scientific theories: Beyond inductive risk. *Canadian Journal of Philosophy*, *45*(3): 326-356.
——— (2016). Why the difference between explanation and argument matters to science education. *Science & Education*, *25*(3-4): 251-275.
Brigandt, I. and Love, A. C. (2012). Conceptualizing evolutionary novelty: Moving beyond definitional debates. *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*, *318*(6): 417-427.
College Board, USA (2009). *Science: College board standards for college success*. The College Board.
Council of Ministers of Education, Canada (1997). *The common framework of science learning outcomes, K to 12: Pan-canadian protocol for collaboration on school curriculum: For use by curriculum developers*. Council of Ministers of Education, Canada / Conseil des ministres de l'Éducation du Canada. http://science.cmec.ca/framework/Pages/english/CMEC%20Eng.html
——— (2024). *Pan-Canadian Assessment Program: PCAP 2023 assessment framework*. Council of Ministers of Education, Canada / Conseil des ministres de l'Éducation du Canada.
Craver, C. F. and Darden, L. (2013). *In search of mechanisms: Discoveries across the life sciences*. University of Chicago Press.
Da Silva Sanchez, A., Paunovska, K., Cristian, A., and Dahlman, J. E. (2020). Treating cystic fibrosis with mRNA and CRISPR. *Human Gene Therapy*, *31*(17-18): 940-955.
Davies, G., Griesenbach, U., Alton, E., and Davies, J. C. (2019). Molecular therapies for cystic fibrosis. In R. W. Wilmott, R. Deterding, A. Li, F. Ratjen, P. Sly, H. J. Zar, and A. Bush (Eds.), *Kendig's disorders of the respiratory tract in children*, *9th edition* (pp. 800-811.e3). Elsevier.
Department for Education, England (2013a). *Science programmes of study: Key stage 3: National curriculum in England*. Department for Education, United Kingdom.
——— (2013b). *Science programmes of study: Key stages 1 and 2: National curriculum in England*. Department for Education, United Kingdom.
Duschl, R. (1990). *Restructuring science education: The importance of theories and their developments*. Teachers College.
Flick, L. B. and Lederman, N. G. (Eds.). (2004). *Scientific inquiry and nature of science: Implications for teaching, learning, and teacher education*. Kluwer.
Gannett, L. (1999). What's in a cause?: The pragmatic dimensions of genetic explanations. *Biology and Philosophy*, *14*(3): 349-373.
Heger, T. (2022). What are ecological mechanisms? Suggestions for a fine-grained description of causal mechanisms in invasion ecology. *Biology & Philosophy*, *37*(2): 9.
Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn?

Educational Psychology Review, *16*: 235-266.
Hmelo-Silver, C. E. and DeSimone, C. (2013). Problem-based learning: An instructional model of collaborative learning *The international handbook of collaborative learning.* (pp. 370-385). Routledge.
Irzik, G. and Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education*, *20*(7-8): 591-607.
Kaiser, M. I. (2015). *Reductive explanation in the biological sciences*. Springer.
Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching*, *53*(5): 667-682.
——— (2022). Reconsidering the goals of evolution education: Defining evolution and evolutionary literacy. *Evolution: Education and Outreach*, *15*(1): 21.
Kampourakis, K. and Nehm, R. H. (2014). History and philosophy of science and the teaching of evolution: Students' conceptions and explanations. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 377-399). Springer.
Kampourakis, K. and Niebert, K. (2018). Explanation in biology education. In K. Kampourakis and M. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 236-248). Routledge.
Kirschner, M. W. and Gerhart, J. C. (2005). *The plausibility of life: Resolving Darwin's dilemma*. Yale University Press.
Klipp, E., Liebermeister, W., Wierling, C., Kowald, A., Lehrach, H., and Herwig, R. (2010). *Systems biology: A textbook*. Wiley-VCH.
Krajcik, J. S. and Blumenfeld, P. C. (2005). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317-334). Cambridge University Press.
Krajcik, J. S. and Mamlok-Naaman, R. (2005). Using driving questions to motivate and sustain student interest in learning science. In K. Tobin (Ed.), *Teaching and learning science: An encyclopedia* (pp. 317-327). Greenwood Publishing Group.
Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell and N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831-879). Lawrence Erlbaum Associates.
Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., and Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching*, *39*(6): 497-521.
Lehrer, R. and Schauble, L. (2006). Scientific thinking and science literacy. In K. A. Renninger, I. E. Sigel, W. Damon, and R. M. Lerner (Eds.), *Handbook of child psychology, Vol. 4: Child psychology in practice* (pp. 153-196). John Wiley & Sons.
Love, A. C. (2008). Explaining evolutionary innovations and novelties: Criteria of explanatory adequacy and epistemological prerequisites. *Philosophy of Science, 75*(5): 874-886.
——— (2013a). Interdisciplinary lessons for the teaching of biology from the practice of evo-devo. *Science & Education*, *22*(2): 255-278.
——— (2013b). Teaching evolutionary developmental biology: Concepts, problems, and controversies. In K. Kampourakis (Ed.), *The philosophy of biology: A companion for educators* (pp. 323-341). Springer.
MacLeod, M. and Nersessian, N. J. (2015). Modeling systems-level dynamics: Understanding without mechanistic explanation in integrative systems biology. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *49*: 1-11.
McCain, K. (in press). The nature and structure of scientific explanation. In R. H. Nehm and K. Kampourakis (Eds.), *Explanation in biology education: Theory and practice*. Springer.

McComas, W. F. (Ed.). (1998). *The nature of science in science education: Rationales and strategies*. Kluwer.

McDonald, C. and Abd-El-Khalick, F. (Eds.). (2017). *Representations of nature of science in school science textbooks: A global perspective*. Routledge.

National Research Council, USA (1996). *National science education standards*. The National Academies Press.

——— (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. The National Academies Press.

Nehm, R. H. (2019). Biology education research: Building integrative frameworks for teaching and learning about living systems. *Disciplinary and Interdisciplinary Science Education Research*, *1*(1): 15.

Osborne, J. F., Collins, S., Ratcliffe, M., Millar, R., and Duschl, R. (2003). What “ideas-about-science” should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching*, *40*(7): 692-720.

Osborne, J. F. and Patterson, A. (2011). Scientific argument and explanation: A necessary distinction? *Science Education*, *95*(4): 627-638.

Pâslaru, V. (2018). Mechanisms in ecology. In S. Glennan and P. Illari (Eds.), *The Routledge handbook of mechanisms and mechanical philosophy* (pp. 348-261). Routledge.

Peck, Z. and Potochnik, A. (in press). Varieties of explanation in biology. In R. H. Nehm and K. Kampourakis (Eds.), *Explanation in biology education: Theory and practice*. Springer.

Potochnik, A. (2017). *Idealization and the aims of science*. University of Chicago Press.

Rowe, S. M., Zuckerman, J. B., Dorgan, D., et al. (2023). Inhaled mRNA therapy for treatment of cystic fibrosis: Interim results of a randomized, double-blind, placebo-controlled phase 1/2 clinical study. *Journal of Cystic Fibrosis*, *22*(4): 656-664.

Rudolph, J. L. (2000). Reconsidering the ‘nature of science’ as a curriculum component. *Journal of Curriculum Studies*, *32*(3): 403-419.

Salmon, W. C. (1989). Four decades of scientific explanation. In P. Kitcher and W. C. Salmon (Eds.), *Scientific explanation* (pp. 3-219). University of Minnesota Press.

Sheredos, B., Burnston, D., Abrahamsen, A., and Bechtel, W. (2013). Why do biologists use so many diagrams? *Philosophy of Science*, *80*(5): 931-944.

Skipper, R. A., Jr. and Millstein, R. L. (2005). Thinking about evolutionary mechanisms: Natural selection. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *36*(2): 327-347.

Sterelny, K. (1996). Explanatory pluralism in evolutionary biology. *Biology and Philosophy*, *11*(2): 193-214.

Strobel, J. and Van Barneveld, A. (2009). When is PBL more effective? A meta-synthesis of meta-analyses comparing PBL to conventional classrooms. *Interdisciplinary Journal of Problem-Based Learning*, *3*(1): 4.

Tabery, J. (2023). *Tyranny of the gene: Personalized medicine and its threat to public health*. Knopf.

Tala, S. and Vesterinen, V.-M. (2015). Nature of science contextualized: Studying nature of science with scientists. *Science & Education*, *24*(4): 435-457.

van Dijk, E. M. (2014). Understanding the heterogeneous nature of science: A comprehensive notion of PCK for scientific literacy. *Science Education*, *98*(3): 397-411.

Woodward, J. (2003). *Making things happen: A theory of causal explanation*. Oxford University Press.

Ziegler, H. and Nellen, W. (2020). CRISPR-Cas experiments for schools and the public. *Methods*, *172*: 86-94.