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ARTICLE

A Justification of Legitimate Teleological Explanations in Physics Education

An Argument from Necessary Constraints

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Abstract
Scientific teleological explanations cite end states as causes to account for physical phenomena. Researchers in science education have noted that students can use teleological explanations in ways that are illegitimate, for example, by implying that inanimate objects are acting intentionally. Despite such cases, several examples of legitimate teleological explanation have been described, and the use of the explanatory form in several contexts in biological education has been encouraged. We argue that, in addition to those biological cases, teleological accounts that meet two criteria can be a legitimate and valuable tool in physics education. We propose that teleological accounts are legitimate when, first, the account reflects the cause-and-effect relationships that exist in reality and, second, when the end state has a degree of necessity. Our account is based on Lange's model of constraint-based causality, in which he argues that phenomena can be explained by reference to constraints, necessary restrictions, for example, physical laws, that limit the behaviour of phenomena. We introduce seven examples of constraint-based teleology in the context of physics education and consider to what extent the two criteria are met in each case and hence their legitimacy. Five potential criticisms of the approach are introduced, discussed, and dismissed. Strategies for using legitimate teleological explanations in the physics classroom are proposed.

Keywords Epistemology · Philosophy of physics · Philosophy of science · Physics education · Secondary science education

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1 Introduction

The development of good explanations of natural phenomena is central to many (though not all) scientific research programmes (Grimm et al., 2017; Skow, 2016; Strevens, 2008). Whilst there remains some controversy over the features that demarcate better and worse explanations, researchers in science education have suggested teachers avoid explanations that cite a purpose or an end as a cause, teleological explanations, in most classroom contexts (Kampourakis & Zogza, 2008; Bartov, 1978; Tamir & Zohar, 1991). Scientific explanations often account for the behaviour of inanimate entities, and therefore explanations which refer to purposes or ends, which require the intervention of an intentional being, are illegitimate in many contexts. The prohibition is not, however, absolute—there are a number of cases of legitimate teleological explanations in biology (Jungwirth, 1975; Lennox, 1993; Lennox & Kampourakis, 2013; Kampourakis, 2020; Trommler & Hammann, 2020; Zohar & Ginossar, 1998).

Legitimate cases go beyond those which cite the agency of organisms as a cause, an obvious example of legitimate teleological explanation in biology, and include explanations of functions in the context of natural selection and homeostasis. For example, the claim that a species of finches evolved long beaks in order to puncture holes in the fruit of cacti is an instance of a legitimate application of teleological explanation to a biological context. In such cases, teleological explanations are legitimate because the end state cited points to the relevant causes that underlie the phenomena being explained (in this case, the processes of natural selection) and the explanations apply across contexts and over time. Because of the advantage it conveys to its bearers, a feature is therefore favoured by natural selection. In other words, a feature exists because of what it does, and in this sense for doing it, hence, the explanation is teleological.

We build on these allowable biological cases to develop two criteria for legitimate teleological explanations in science education, based on a constraint model of causality (Lange, 2017). Despite their use in expert discourse, reservations over the use of legitimate physical teleological explanations in classrooms (Ruse, 2020; Trommler & Hammann, 2020) have led to the neglect of a valuable explanatory tool. In this article, by defining criteria for legitimate teleological explanations, we aim to remedy that omission.

2 Models of Teleology

Writers in epistemology of science and science education have produced several accounts of scientific explanation (Braaten & Windschitl, 2011; McCain, 2022; Weber et al., 2013). The dominant model of explanation assumed that scientific explanations were successful to the degree to which they identified the causes of phenomena (Lewis, 1986; Salmon, 1998). Whilst causes are doubtless an important aspect of some forms of explanation, a recent movement has acknowledged that non-causal explanations, that do not explicitly cite the causes of a phenomenon, are also an aspect of scientific practice (Lange, 2017; Reutlinger & Saatsi, 2018). Explanations connect, in a deterministic or probabilistic form, a phenomenon with the constraints that lead to its occurrence (Lange, 2017). Some explanations describe the conditions that give rise to a phenomenon, so-called causal explanations (Woodward, 2003). Causal explanations have been categorised into two approaches—difference-making accounts and those which describe causal processes (Woodward, 2007).

The difference-making model associates the potency of a cause with the disparity between an event and a counterfactual case in which the cause is absent. For example, in describing the causes of a fire, a lit match may be cited as the cause because, had the match not been present, combustion would not have occurred. By contrast, the causal process model rejects the need to compare actual cases with imagined scenarios and instead accounts for phenomena through descriptions of connections between cause and effect. In the case above, a causal process account would focus on heat transfer from the match as a necessary process condition to initiate a fire. The model of legitimate teleological explanation we propose is an example of the process model of causality, in particular, a constraint-based approach which explains by pointing to features that make an event a necessary outcome (Lange, 2017). In a constraint-based account of the cause of the fire, a combination of conditions that include the presence of fuel, oxygen, and a source of heat constrained the possible phenomena that might have occurred and made combustion inevitable.

A pedagogically significant form of causal explanation, which has received considerable attention in science education research, is teleological explanation. In general, teleological explanations cite an end (the telos) as the explanation of a phenomenon (Kampourakis, 2020). There is some variation in accounts of teleology, but common to all models is a reversal of the temporal order of causality, a state or event that occurs after the explained phenomenon is categorised as its cause (Lennox & Kampourakis, 2013; Hernik, 2020; Talanquer, 2007), for example: 'In the case of a conducting wire, the free electrons move so as to reduce the electrical potential energy, just as a rock falls to the earth to reduce the gravitational potential energy' (West & Griffin, 2004, p. 209). We will discuss, below, Bunge's (2010) qualification that states should not be categorised as causes, but events, changes between states, may be legitimate causes. In addition to linking a phenomenon and a future state (in the examples above, a state of minimum potential energy), some accounts of teleological explanations include additional criteria. A subset of models imply that the caused phenomenon is somehow valuable or advantageous (Zohar & Ginossar, 1998). Other definitions of teleology require an element of design or intentionality (Gresch & Martens, 2019; Poling & Evans, 2002). However, we assume that teleological explanations need not have anthropomorphic (Beckner, 1959) or purposive elements:

> Purposes and deliberate goals admittedly play important roles in human activities, but there is no basis whatever for assuming them in the study of physicochemical and most biological phenomena. However, as has already been noted, a great many explanations counted as teleological do not postulate any purposes or ends-in-view; for explanations are often said to be "teleological" only in the sense that they specify the functions which things or processes possess. (Nagel, 1961, p. 402)

Teleological explanations may be divided into two categories: first, explanations that imply the intervention of a conscious agent to achieve a final state (for example, a photon is released because the electron *wants* to reduce its potential energy), which we refer to as *intentional teleology*, and, second, those which cite an end state as a cause and invoke non-agential constraints (for example, a photon is emitted to conserve total momentum), which we label *constraint teleology*. This categorisation expands on Kampourakis, (2020) distinction, in the context of biological education, between design (the occurrence of a feature in organism to achieve some goal, an intentional process) and selection teleology (the occurrence of a feature in organism due to it being favoured by natural selection, a non-agential process). The intentional and constraint teleology categories are seen as applicable across scientific domains. As we will argue below, constraints refer to facts about the world which possess some form of necessity, for example, the requirement to conserve the total quantity of matter (Lange, 2017). Given that some teleological explanations refer to constraints which occur in the absence of conscious agents, definitions of teleology by reference only to purpose or design (Gresch & Martens, 2019; Poling & Evans, 2002) are too narrow, and we prefer a broader understanding of teleology as explanations that deploy end states as causes. This conceptualisation allows a reanalysis of the legitimacy of some types of teleological explanations in physics education.

3 The Legitimacy of Teleological Explanations in Science

Almost as long as teleology has been discussed in science education, researchers have acknowledged that the form of explanation may be used in legitimate and illegitimate ways.

The categorisation of teleological explanations as legitimate or illegitimate, in general, depends on whether the implied causality reflects the reality of underlying cause and effect relationships (Kampourakis, 2020). For example, a category of illegitimate teleological explanations are those in which causal power is ascribed to a conscious agent when the cause lies elsewhere, as in the claim that the development of a trait, for example, the colour of insect, was consciously chosen: ‘Since birds could easily see the green beetles and eat them, something had to be done so that they [the green beetles] could survive’ (Kampourakis & Zogza, 2008, p. 35). The explanation in this case is illegitimate because beetles do not have direct control over their colouring—the proposed causal mechanism is erroneous. Empirical research suggests that students studying science can develop models of causality that differ from accepted scientific models (Chi et al., 2012; Grotzer, 2012; Kelemen, 2019). In particular, researchers have noted instances of students’ illegitimate teleological explanations, for example, those in which agency is attributed to non-conscious entities, such as sodium reacts with water because its atoms *want* to get a complete outer electron shell (for various examples, see Bartov, 1978; Author 2 et al., 2008; Tamir & Zohar, 1991).

Whilst such illegitimate intentional teleology explanations should be challenged in classrooms, teleological explanations can, in some cases, be legitimate (Kampourakis, 2020; Lange, 2017). A case has been made for the legitimacy of teleology explanations in at least three biological contexts (Jungwirth, 1975; Kampourakis, 2020; Lennox, 1993; Lennox and Kampourakis, 2013; Trommler & Hammann, 2020; Zohar & Ginossar, 1998). The first is when intentional explanations reflect the reality of organisms’ agency in achieving goals (such as reproducing) (Hempel, 1965), for example, ‘…peacocks are showing off their tails—signaling—in order to attract mates’ (Sanderson, 2018, p. 597). Second, some teleological explanations, for example, those based on biological functions (for instance, humans have a heart in order to pump blood), have been argued to be legitimate because they invoke a selection history and hence imply a set of causal relationships that are the outcome of historical natural processes, such as natural selection (Author 2, 2020). Third, biological systems which are goal-directed, for example, homeostatic processes in the human body (Nagel, 1979, 1977), may be legitimately described by teleological accounts. Feedback mechanisms are systems in which the outcome of some process or processes are simultaneously inputs, leading in some cases to the maintenance of a state (Thomas & D’Ari, 1990). For example, a feedback mechanism in the body is blood glucose regulation—the level of blood glucose is both an input to and outcome of a negative feedback loop. A feedback loop can be considered a constraint because it set limits on the phenomena that can occur. Hence, explanations that cite the final states resulting from feedback mechanisms can be considered legitimate forms of teleological explanation. For example, in the context of glucose regulation, a legitimate teleological explanation argues that insulin is secreted in order to reduce blood glucose to within normal limits.

Whilst students' illegitimate teleological explanations have been noted in empirical research, Jungwirth (1975) lamented that the productive use of legitimate teleological explanations was not emphasised in guidance for teachers. Two decades later, Zohar and Ginossar (1998) called for a lifting of the 'taboo' on the use of legitimate teleological explanations in biology, a call which has been recently renewed (Kampourakis, 2020; Trommler & Hammann, 2020). Where the legitimate use of teleological explanations has been accepted, the endorsement has been limited to a few contexts in biological explanations (Mainx, 1955; Nagel, 1961; Ruse, 2020; Trommler & Hammann, 2020). Physics and physics education, by contrast, are claimed to be domains in which teleological reasoning is illegitimate: 'Whereas physicists and chemists investigate cause–effect relationships without considering the effects as ends, biologists consider biological functions not merely as effects but as ends caused by some means' (Trommler & Hammann, 2020, p. 3). In the next section, we make a case for a broadened conceptualisation of teleology that permits constraint-based explanations. This understanding of teleology allows for the proposal of some cases of legitimate teleological explanations in the context of physics education.

4 Constraint Teleology—a Legitimate Form of Teleology in Physics

In addition to cases of legitimate intentional teleology in the physics classroom (for example, in the case of explaining the design of devices by agents: 'Kettles made of metal have shiny surfaces to reduce heat loss by radiation' (Punter et al., 2006, p. 47)), there is a significant, underdiscussed category of legitimate teleological explanations in physics that cite the constraints expressed in physical laws as causes. A category of scientific explanation accounts for the occurrence of phenomena by reference to "great general principles" (Feynman, 1994, p. 53), for example, the law of conservation of energy or quantum number conservation. Such principles are constraints that make some outcomes inevitable and others impossible (Lange, 2017). Constraints refer to facts that entail necessity and are statements of the requirement of the occurrence of some phenomena and not others, as in, for example, conservation laws. Phenomena may be explained by reference to necessary restrictions on entities' behaviour, and if such explanations reference a final state, they can be labelled constraint teleology. For example, the constraint that a quantum number is conserved has been used to explain pair production: '… leptons are created in pairs of a lepton and an antilepton in order to conserve the lepton number' (Prakash, 2012, p. 248). In *Because without Cause*, Marc Lange (2017) has set out a detailed account of constraint teleology. He argues that constraints transcend the particulars of contexts and must be invariant across a range of counterfactual situations. Indeed, Lange proposes a strong criterion on constraints suggesting that they must have a necessary quality, similar to mathematical axioms, that is, they are 'maximally resilient' (Lange, 2017, p. 80). As Hertz, who Lange quotes, commented, constraints cannot be broken, their violation '…is by the nature of things excluded' (Hertz, 2018, p. 334). In a later section, we examine how the stability (i.e. their applicability across contexts) of constraints determines their value in teleological explanations.

Legitimate constraint teleological explanations occur in the work of several natural philosophers and physicists. Boyle (1688) wrote a treatise, *A Disquisition about the Final Causes of Natural Things*, praising the value of teleological explanations. Boyle identified four forms of final cause. Human and animal ends refer to intentional teleology, whereas cosmic and universal ends, whilst theologically inspired, hint at natural constraints that necessitate the behaviour of objects. Though Boyle was sensitive to illegitimate applications of final causes, he argued that, in some cases, teleological explanations are complementary to mechanical causal explanations and a legitimate aspect of scientific work. Moreover, he suggested that in explanatory contexts where it is challenging to explicate all the relevant causal factors, teleological accounts have greater explanatory power (the property of being able to effectively account for the occurrence of a phenomenon (Ylikoski & Kuorikoski, 2010), see below) than mechanical causal explanations. Boyle (1688, p. 72) argued that an excessive focus on the minutiae of causal networks can limit explanatory power, 'they, that, to solve the phenomena of nature, have recourse to agents… though they may in certain cases tell us some things, yet they tell us nothing'. He argued that effective explanation, including teleological accounts, confers a holistic appreciation of agency that does not arise through an exhaustive analysis of causal networks.

Like Boyle, Leibniz's championing of teleological explanations had a theological basis. Leibniz argued that final-cause explanations have value because they are 'useful not only for admiring the ingenuity of the great workman, but also for discovering something useful in physics and medicine' (Leibniz, 1988, p. 65). Leibniz used constraint teleology explanations in his work, notably in his Most Determined Path Principle, the claim that light will travel along the path that minimises distance travelled and 'resistance' from the medium it passes through (McDonough, 2009). By contrast with a non-teleological explanation that describes causal mechanisms (for example, in the case of determining the path of a ray of light, by reference to the velocities of light in different media), Leibniz (1998) suggested that invoking final states as causes can be an efficient form of explanation (he argued that the approach enabled Snell to develop his explanation of refraction) and that both causal and teleological explanations are useful approaches. The expediency of legitimate constraint teleological arguments supports the case for their use in scientific explanations and the science classroom.

Fermat, like Leibniz, applied teleological argument to explain the travel of light rays in his Principle of Least Time (Schoemaker, 1991). In Fermat's Principle, the end state of a minimum of travel time is cited as a cause, rather than invoking mechanisms such as the refractive properties of the media. In a 1664 letter, Fermat argued for an expansive application of teleological explanation in physics: 'Our demonstration rests on a single postulate: that nature operates by the easiest and most expedite ways and means' (Descartes quoted in Osler, 2001, p. 157). This claim highlights the value of constraint-based explanations and, in particular, those based on variational principles. Another endorsement of explanation via variational principles is found in Faraday's writing who has been noted for his use of teleological reasoning (Gooding, 1982). For example, Faraday reflected on the 'final purpose' of the magnetic permeability of the atmosphere (Faraday, 1850/2012, p. 268) and explained the movement of magnetic materials by reference to the minimisation of the forces acting.

The above historical examples indicate that important figures in the history of physics have considered teleological explanations legitimate forms of explanation. By considering seven examples of constraint teleology from physics textbooks, we will develop an account of the legitimacy of this form of explanation in physics classrooms. The examples are not intended to form a representative sample of instances of legitimate teleological explanation in physics texts. Rather, they are instances drawn from our reading to illustrate our argument and are not intended to reflect general patterns of usage.

a) '… the compact star will shrink to minimize the total energy, eventually collapsing to a black hole' (Schaffner-Bielich, 2020, pp. 86–87).
b) 'In order for momentum to be conserved, the products of the reaction must be moving and, therefore, they must have some kinetic energy' (Christodoulides, 2016, p. 233).
c) '… a force called radiation-reaction force, must be present in order to avoid violating the conservation law of energy' (Cornille, 2003, p. 388).
d) '…an antibaryon must appear simultaneously to keep the baryon number the same' (Motz & Weaver, 2013, p. 339).
e) 'When asked why a balloon is round, we might say it chooses this form over others to equalize interior pressure' (Schoemaker, 1991, p. 210).
f) '…a gas expands with increasing T[emperature] in order to keep P[ressure] constant. (Jespersen & Hyslop, 2022, p. 520).
g) [In the context of a rotating object]: '…for there to be a resultant force towards the centre …, the frictional force must increase' (OCR, 2019, p. 28).

The examples will be used to discuss Lange's constraint teleology as a basis for legitimate teleological explanations in physics. The first requirement we place on legitimate teleological explanations is that they should reflect the reality of cause-and-effect relationships. Note, in explanation (e), the illegitimate use of intentional teleology, 'a balloon… *chooses* this form…'. Whilst 'chooses' is illegitimately applied to a material entity, the explanation need not invoke an agent and can be rewritten in a constraint-based form to give a legitimate account: a balloon takes on a spherical shape in order to minimise surface energy. The phrase 'in order to' in teleological constraint explanations (as in examples (b) and (c) above) indicates an end state that is cited as a cause and need not imply intention.

Second, Lange (2017, p. 80) proposes that constraints ought to be 'maximally resilient', that is, to hold across different context and conditions. The seven examples above invoke constraints of varying degrees of universality. Laws can be imagined as existing on a continuum of stability, the extent to which they hold under a range of different counterfactual situations (Lange, 2005). At one end of the spectrum of stability, physical laws are universal constraints that guide the behaviour of all physical phenomena (Lange, 2017; Van Gulick, 1993). In the explanations above, examples (a) to (d) cite physical laws that are assumed to apply across all contexts (Wheeler, 2018). One type of legitimate constraint teleological explanation in physics are those which invoke conservation laws (Wright, 1976), for example, Lenz's law (Louie, 2010) and the second law of thermodynamics (Short, 1983). Alternatively, variational principles, constraints that describe a systems tendency for a quantity to tend towards a maximum or minimum (Schoemaker, 1991), have been cited as causes. The Principle of Least Action (Terekhovich, 2018) and Fermat's Principle of Optics (Schoemaker, 1991) have been described as legitimate explanatory causes. Explanation (a) above is an example of the invocation of a variational principle to indicate an end state, a system with minimum energy, as a cause. By contrast to explanations based on universal constraints, local conditions that lack the generality of laws have been used in some teleological explanations. Example (e) refers to an end state in which the pressures inside and outside a balloon are equalised that applies in some contexts but not others and therefore does not meet Lange's necessity condition on constraints. Constraints can have differing degrees of applicability across contexts and over time. How determinations of sufficient necessity of constraints can be made to establish the legitimacy of constraint teleological explanations is an open question.

Kampourakis (2020) has argued that teleological explanations, in the context of biology, are legitimate when they reflect underlying causal processes and the constraining system has a degree of inevitability. For example, the hydrodynamic shapes of fish can be explained by invoking an end state, the ability to move rapidly, that supports the organism's survival, because the explanation invokes (albeit tacitly) the causal processes of natural selection which underlie the occurrence of the body shape and can be conceptualised as having some necessity (Reznick, 2020). In general, in a constraint model of teleology, legitimate explanations arise because the end state stands in for a body of causal relationships enshrined in the constraint, without necessarily explicating any individual mechanism (Jackson & Pettit, 1990; Lange, 2017). We propose two criteria for legitimate constraint-based teleological explanations in science education:

a) The causal relationships implied by reference to an end state must reflect the cause-and-effect relationships that underly the phenomenon being explained.
b) The constraint or constraints implied must have an aspect of necessity, that is, it or they must make the explained phenomenon inevitable across a suitably wide range of contexts and be relatively stable over time.

To illustrate the two criteria, we examine three examples (one legitimate and two illegitimate cases) which give a sense of how the criteria can indicate the legitimacy of explanations, first, example (a) above which explains the behaviour of a star by reference to a minimum energy end state. The collapse of a star, which could be accounted for through mechanistic causality, for example, by describing the forces which act, can be legitimately explained by reference to a universal constraint, conservation of energy, and an end state, an energetic minimum. In this case, energetic considerations are causally valid, and the law of conservation of energy is a universal constraint, legitimising the explanation. The necessity condition prohibits constraint-based explanations that invoke conditions which lack sufficient inevitability, as illustrated in the next example.

Second, consider an explanation that cites a gas 'law' as a cause. In a textbook discussion of Charles' Law, it is argued that '…a gas expands with increasing T[emperature] in order to keep P[ressure] constant' (Jespersen & Hyslop, 2022, p. 520). This is a teleological explanation, in which an end state, the state of constant pressure, is invoked as a cause of the expansion of a gas. However, by contrast with the universal necessity of conservation of energy, the condition of constant pressure is not universally true. Charles' law is an example of a ceteris paribus law, one that only holds in systems where pressure remains constant (Ruthenberg & Harré, 2012). The conditional nature of Charles' Law is, we argue, insufficiently necessary to meet the second criterion, and we do not consider this an instance of legitimate constraint teleological explanation.

The final example, drawn from an exam board examiner commentary in England, provides a second example of insufficient necessity of conditions. In discussing a problem related to the rotation of an object, the examiners argue that '…for there to be a resultant force towards the centre …, the frictional force must increase' (OCR, 2019, p. 28). Rotational motion of the object is cited as an end state to explain an increase in centripetal force. As with the Charles' law case, the condition in this context lacks the necessity required of constraints (the force is only experienced by rotating objects), and this constraint teleological explanation can be categorised as illegitimate. A summary of our analysis of the seven example explanations is presented in Table 1.

Table 1 A summary of the application of teleological explanation in the context of physics

Example	Legitimate (L) or illegitimate (I)	Reason
a) '… the compact star will shrink to minimize the total energy, eventually collapsing to a black hole' (Schaffner-Bielich, 2020, pp. 86–87).	L	The causal networks invoked are appropriate, and the principle of minimisation of total energy is sufficiently necessary to meet the two criteria.
b) 'In order for momentum to be conserved, the products of the reaction must be moving and, therefore, they must have some kinetic energy' (Christodoulides, 2016, p. 233).	L	Appropriate cause and effect are implied, and conservation principles have a high degree of necessity.
c) '… a force called radiation-reaction force, must be present in order to avoid violating the conservation law of energy' (Cornille, 2003, p. 388).	L	The prevailing causal relationships are reflected, and a universal principle is cited.
d) '…an antibaryon must appear simultaneously to keep the baryon number the same' (Motz & Weaver, 2013, p. 339).	L	The existing causal structure is invoked, and conservation laws have appropriate necessity.
e) 'When asked why a balloon is round, we might say it chooses this form over others to equalize interior pressure' (Schoemaker, 1991, p. 210).	I	This account is illegitimate due to the anthropomorphic implication and the insufficiently necessary constraint (equalisation of pressure).
f) '…a gas expands with increasing T[emperature] in order to keep P[ressure] constant' (Jespersen & Hyslop, 2022, p. 520).	I	Whilst the cause-and-effect relationships are appropriately reflected, the constraint draws on a ceteris paribus law and is hence is insufficiently necessary.
g) [In the context of a rotating object]: '…for there to be a resultant force towards the centre …, the frictional force must increase' (OCR, 2019, p. 28).	I	A legitimate causal relationship is referred to, but, because the presence of a resultant force is not a requirement across contexts, the necessity of the constraint is too limited.

Rather than being entirely distinct from mechanistic explanations, constraint-based teleology can be considered a form of shorthand in which an end state points towards a network of causes and effects (Lange, 2017). Explanations of this kind cite a relevant constraining system without explicating causal agents directly—laws represent regularities in the universe which indicate the action of causal agents (Heathcote & Armstrong, 1991). Jackson and Petit (1990) have proposed the notion of a programme explanation in which the cause referred to is not itself causally active but ensures the causal action of some other entity. For example, the explanation of why a soap film takes on a particular shape via the argument that 'the molecules in the soap film arrange themselves in a way that minimizes the potential energy between them' (Lyon, 2012, p. 563) does not describe the causal agents (the forces acting between particles) but a general principle (that of the reduction of potential energy).

Another example of a constraint account in which causal agents are not referred to directly is Sober's (1983) equilibrium explanation. Equilibrium explanations do not describe causal mechanisms, but they indicate the inevitability of a phenomenon in the face of several causes that may act to move the system away from equilibrium. For example, Sober presents a biological example—he describes how the ratio of male to female organisms in a population tends to a 1:1 ratio, regardless of the initial conditions in the population (more male or female individuals). In the context of physics, an equilibrium explanation can be used to account, for example, for the motion of a ball released from the side of a concave bowl (Strevens, 2008). An equilibrium explanation of the context would reference the insensitivity of the end state (the ball, at rest, in the centre of the bowl) to initial conditions (initial location, net force on release, etc.). Whilst Sober (2014) categorises end states as causally inefficacious, he argues that equilibrium explanations have explanatory power. Below, we follow this line of thinking, drawing on Jackson and Petit's (1990) programme explanations, to argue that end states need not be causally active for legitimate teleological explanations to be useful tools in physics education. Accounts which cite feedback mechanisms (as in the case of blood glucose, discussed above) might be considered instances of equilibrium explanations. The feedback mechanism can be conceptualised as a constraint, and the accounts are legitimate if the systems have sufficient necessity. In physics, consider the case of a binary star system in which one star draws in matter from the other. Such systems can display sudden drops in brightness (a period gap) which have been explained as follows: 'The period gap occurs when the companion [star] becomes completely covered by starspots, so that the mass transfer is inhibited long enough for the companion to shrink inside its Roche surface shutting off the feedback loop' (Jokipii et al., 1997, p. 124). Here, a state, the proliferation of starspots, that is an element of a feedback loop, is cited as a cause which allows the authors to omit details of the causal network.

Finally, we assume that all legitimate teleological explanations can be expressed in a non-teleological form (Johnson, 1985). For example, the description of the collapse of a star by reference to conservation of energy may also be expressed in a mechanistic form, by reference to the forces that act on it. As Boyle and Leibniz argued, the value of constraint-based teleological explanations arises from their explanatory parsimony, especially in contexts where causal networks are extensive and complex (for example, the causal network underlying the evolution of a particular feature of an organism). We see constraint accounts as alternatives to mechanical explanations, rather than replacements, due to the educational affordances they present.

5 Constraint-Based Teleological Explanation in Biology and Chemistry

The two criteria for constraint-based teleology arose from consideration of a particular context, physics, in which teleological explanations had been argued to be illegitimate. The criteria are, however, also applicable to the assessment of cases of constraint teleology in biology and chemistry. In biology, at least two contexts lend themselves to constraint-based teleological explanations, because they meet the two criteria, appropriate causal efficacy and necessity, introduced above. First, explanations of natural selection that cite functions (for example, brown beetles are brown, in order to be well concealed) are legitimate teleological explanations. Explanations of this form meet the two conditions. First, the functions of organisms cited are a cause of some phenotypes being favoured by natural selection; hence, the description of cause is valid. Second, if variation that makes a different to survival and reproduction exists, natural selection will inevitably occur, meeting the necessity condition (Avise & Ayala, 2007; Kampourakis, 2020). A second context, where biological teleology is legitimate, is explanations of the self-regulating behaviour of biological systems, for example, the claim that when exercising, the heart beats faster in order to supply more blood to the organs (Ayala, 1998). Explanation via reference to a final state (an increase in blood flow) is a legitimate form of teleology as the explanation points to an appropriate causal network (the action of the sympathetic nervous system) that, given the existence of the biological system, has sufficient necessity. This categorisation might be seen as contradictory given our rejection of a conditional relationship, Charles' Law, as a legitimate constraint above. The necessity of explanations of goal-directed systems arises because the form of explanation only makes sense if it is assumed that the self-regulating system being explained exists, hence its inevitable quality. By contrast, in the case of the Charles' law explanation, isothermal conditions are not a necessary aspect when considering the relationship between pressure and volume. Contexts in which temperature both is and is not constant are possible. Whilst the constraints in the two biological contexts (explaining functions in natural selection and self-regulating systems) do not have the universal necessity of some constraint teleology explanations in physics, the necessity of the constraints are sufficiently high to legitimise the explanations.

In chemistry, Harré (2012) has observed that, whilst the disciplinary discourse includes many general statements about natural phenomena (for example, those represented in chemical equations), few chemical laws are asserted. Examples of chemical laws include the law of conservation of mass, the law of partial pressures, and the laws of thermodynamics. The legitimacy of constraint-based teleological explanations in chemistry education has been championed by Talanquer (2007) who has emphasised their educational value. Several examples of constraint teleology explanations can be found in chemistry textbooks. In the context of chemical engineering, conservation of mass is used as a legitimate constraint to account for changes to fluid flow: 'Because of conservation of mass and charge, the velocity of an analyte in the channel decreases as the channel cross-section increases' (Ross et al., 2004, p. 3694). By contrast to explanation based on laws, some explanations draw on principles, for example, Le Chatelier's principle:

> … because of Le Chatelier's principle, the hydrogen ions from the strong acid are consumed by combination with the acetate ions present. (Kenkel, 1994, p. 72)
> When H^+ concentration increases, the solution becomes acidic, its pH decreases and its OH^- concentration decreases because of Le Chatelier's principle. (Saunders et al., 2020)

Examination guides (Beavon, 2008; Facer & Beavon, 2015) counsel students against answering equilibrium problems with a response ‘due to Le Chatelier’s principle’ because, it is argued, stating the name of a principle does no explanatory work. In the context of an examination, reference to a constraint is a partial response because, though a causal network is indicated, the student does not display an appreciation of the relevant mechanisms. We concur with the concern here and also emphasise that Le Chatelier’s principle does not have sufficient necessity to be considered a legitimate constraint.

Talanquer (2007) has categorised the octet rule, the tendency of atoms to form bonds with eight electrons in the valence shell, as a constraint that has a lower degree of generality than chemical laws. Nonetheless, the octet rule, Talanquer argues, has sufficient stability to allow teleological explanations of the form:

> To form bonds, main group elements gain, lose, or share electrons to achieve a stable electron configuration characterized by eight valence electrons. (Moore et al., 2005, p. 332)

The legitimacy of constraint-based teleological explanations rests on the necessity of the conditions proposed as potential constraints. Given that a number of exceptions to the octet rule exist (Weeks & Winter, 2014), such explanations fail to meet the necessity criterion. An examination of teleological constraint explanations in biology and chemistry highlights why they may be particularly appropriate in the context of physics education. Explanations based on laws and principles, which have the form of necessary constraints, are more common in explanations in physics, than in biology and chemistry (Dhar & Giuliani, 2010). Hence, in contrast to the reported prohibition on teleological accounts in physics (Trommler & Hammann, 2020), the form of explanation may be particularly appropriate to that context. In order to strengthen the case for the legitimacy of constraint-based teleology, in the next section, we examine and dismiss five potential objections to the explanatory approach.

6 Five Criticisms of Constraint-Based Teleological Explanations

We anticipate five potential objections to the expansion of legitimate teleological explanations to include constraint teleology, four epistemological and one pedagogical. First, the causal power of a significant category of constraints, physical laws, has been disputed (Lewis, 1973b; Russell, 1912). The line of argument questions the legitimacy of constraints as causes. Laws are empirical descriptions of physical regularities and hence, the critique suggests, do not have the ability to act on events (Russell, 1912). That is, it is illegitimate to explain a phenomenon as being due to, for example, the second law of thermodynamics, as the law lacks causal potency. This claim, we argue, is not relevant to the argument asserted here in favour of constraint teleology, which considers the explanatory appropriateness of constraint teleology and does not assert a claim about the causal powers of laws. A law can be considered a legitimate explanatory tool whilst remaining agnostic about or even rejecting its causal power. In constraint teleological explanations, we consider laws as a potential element of the explanans, the propositions that account for the phenomenon (Hempel & Oppenheim, 1948). Constraint teleology can be thought of as an instance of Jackson and Petit’s (1990) programme explanations in which the cause referred to (for example, a law) is conceptualised as causally inactive but indicates the causal action of some other entity or entities, for example, the explanation that a glass breaks because it is fragile. The fragility of the glass indicates an efficacious cause in this context, the forces in the molecular structure of the glass.

In a related criticism, Bunge (1959) has argued that a state cannot be considered a causal agent, whereas an event, a change between two states, can be. In this categorisation, whilst a minimum energy end state, for example, might be considered an illegitimate cause, the transition from a higher to lower potential energy state is, Bunge (2010) argues, an acceptable causal mechanism. As with Russell's argument, Bunge's critique focuses on demarcating legitimate ontologies for the entities cited as causes. Whilst a final state alone may not have an appropriate causal status, reference to a single event can be seen as a form of shorthand. We conceptualise arguments that cite a final state as a cause, as being potentially legitimate as a compressed form of an explanation that cites a process (a transition between states) as the cause by assuming an initial state. For example, the explanation of stellar collapse (example (a), in Table 1) by reference to an end state of minimum energy is referring to a change between states (between a higher and lower potential energy state during which energy is transferred from the star to its surroundings) as a cause. Constraint teleological explanations can legitimately refer only to a final state where there is an implication of a transition between two states, for example, 'When the spin glass is embedded into such an external potential field, the spin orientations rotate in order to reach a minimum of energy' (Cointepas et al., 2002, p. 478).

A second, potentially more damaging, criticism argues that constraint teleology lacks a necessary feature of legitimate explanations, a distinction between cause and effect. This objection is illustrated by Salmon's (1989) criticism of Hempel and Oppenheim's deductive-nomological model of explanation through a thought experiment related to a flagpole. An explanation of a flagpole's height is proposed based on a mathematical relationship—the height of the pole must be a certain value because its shadow is a particular length. The explanation is constraint based, drawing on the rules of geometric optics and Pythagoras' theorem to explain the pole's height. Explanations of this form, Salmon argued, are illegitimate because explanations have asymmetric properties. Causes and effects belong to different categories, and law-based explanations are incomplete if they fail to explicitly differentiate cause from effect. Explanations arise from a cause that precedes an effect. For example, in Newton's first law, the relationship between net force and acceleration is not symmetric, as net forces cause acceleration and not vice versa. A good explanation, in Salmon's model, involves a statement of a physical law and an additional feature that breaks any temporal symmetry between cause and effect. In this understanding of causality, reference to a constraint that is invariant over time, for example, conservation of energy, is an illegitimate form of explanation. This objection to a perceived temporal symmetry in constraint-based teleological explanations arises because the accounts are a form of shorthand in which causes and effects are not referred to directly. However, the critique is dismissed because of the criterion on legitimate teleological accounts to reflect relevant causal structures. As argued above, whilst referring to conservation of momentum (as in example b, above) as a cause might appear to be the type of symmetric explanation Salmon prohibits, the explanation functions by pointing to an initial and final state which differ (components of the system have different values of total momentum before and after some event). Legitimate teleological accounts are required to maintain the underlying causal structure of the processes referred to and hence, by definition, will reflect a causal asymmetry even if it is not explicitly stated.

A third objection to constraint based teleological explanations arises from counterfactual models of causality which assume that causes give rise to differences (Lewis, 1973a). Within counterfactual causal models, causes are identified by reference to an imagined scenario in which the potential cause is absent. For example, the causal efficacy of aspirin on the pain of a headache is inferred from a comparison of a situation in which a patient has taken the medication against an imaginary scenario in which no treatment is given. We have argued that constraint-based explanations can cite laws, which are universal and invariant over time, as causes. The necessary character of such constraints means, by definition, counterfactual cases are physically impossible. For example, the explanation of the collapse of a star (example (a) above) references conservation of energy as a cause. A difference-making model requires that causes are understood by comparison to a counterfactual scenario, in this case a universe in which energy is not conserved, a physically impossible case. Lange (2017) has argued that, given the physical impossibility of counterfactual cases within some difference-making models of causality, law-based constraints might be considered causally impotent. He goes on to claim that the requirement to refer to how an event might have been otherwise suggests that the counterfactual model is too narrow an account of causality (Lange, 2017). By contrast, we do not feel a rejection of difference-making models follows from our proposal of legitimate teleological accounts. Woodward (2003) has argued that explanations which refer to physically impossible cases, because they do not cite a possible intervention that causes a difference, should not be considered causal explanations. For example, there is no intervention that could make the law of conservation of energy be otherwise. Woodward categorises such cases as non-causal explanations. This classification, we argue, is too narrow a conceptualisation of causal accounts for two reasons. First, citing a law as a constraint need not invoke physically impossible counterfactuals. Rather, as Skow (2020) has argued, it is an indication that, in some context, there are no possible alternative cases, and hence the event is inevitable. Second, physically impossible cases can be metaphysically possible (a universe where energy is not conserved can be imagined and discussed) and are useful reasoning tools for scientists (Nolan, 1997; Wilson, 2021). Hence, the attack does not threaten the overall validity of the case for legitimate teleological accounts.

Fourth, Bennett (2001) introduces a slippery slope argument—if some forms of teleological explanation are accepted, the doors are opened to legitimising all types of teleology. Once an explanation based on an end state as a cause is accepted, all instances of such accounts become permissible. For example, Bennett describes the case of an explanation of the movement of water in a pool by reference to a variational principle, the reduction in the pool's surface energy. Bennett suggests that, whilst the explanation based on the variational principle may seem legitimate, if teleological accounts in general are accepted, any explanation of the water's motion by reference to some final state become legitimate. For example, an alternative teleological explanation could claim that the water flows to develop a smooth surface, an argument, Bennett proposes, which would be illegitimate. This attack is addressed by the condition we place on legitimate explanations that requires they maintain appropriate causal relationships. The smooth surface of a pool is not causally efficacious and would be rejected in our model as legitimate constraint. With the two conditions we propose, reflection of relevant causal relationships and sufficient necessity of constraint, criticisms of legitimate constraint-based teleological accounts can be dismissed.

Finally, Braaten and Windschitl (2011) report that explanations based on laws (which they refer to as 'covering law explanations') may be an aspect of students' initial attempts at explanation. They propose that covering law explanations should not, for pedagogic purposes, be considered full explanations, because they do not indicate the extent to which a student has grasped the relevant concepts. They cite the example of a student explaining why vapour rises from a beaker of water on a hot plate; the student replies: 'Because it's on the hot plate heating up, and that's what happens right before it boils' (Braaten

& Windschitl, 2011, p. 645). Concerns that reliance on laws in explanation may mask a lack of depth of understanding have been raised by other writers (Beavon, 2008; Driver, Leach, Scott, & Wood-Robinson, 1994; Facer & Beavon, 2015). However, the vapour case cited by Braaten and Windschitl does not have the necessity needed to meet our criteria for legitimacy, the constraint is not sufficiently applicable across contexts, and we would deny its status as a legitimate teleological explanation. By contrast, Driver and colleagues (1994) report the case of a parent who explains to a child that a frying pan has a plastic handle because plastic does not conduct heat. In this case, the account is a form of legitimate intentional teleological explanation because the intention of an agent, the designer of the pan, caused the pan to have the plastic handle. Whilst we acknowledge that there may be cases in which the compressed form of explanation found in teleological accounts may limit teachers' ability to judge students' understanding, the concern is a pedagogical consideration and need not, in general, undermine the legitimacy of some teleological accounts or their pedagogical affordances in some contexts.

7 Implications for Practice

Teleological explanations have, in general, been seen as illegitimate in science education because these are associated with intentionality and anthropomorphism. They carry the stigma of illegitimate supernatural explanations that attempt to explain by reference to non-existent or causally impotent factors, either external (e.g. God or Mother Nature), or internal (e.g. a need or wishful thinking) factors. We agree that such teleological explanations, based on design and intentions, are often illegitimate, expect in cases where there is reference to systems that reflect the intentional and conscious behaviour of organisms (e.g. mating behaviours aiming at reproduction, use of tools, or seasonal migration). However, there are cases where an outcome can be explained on the basis of what it confers. This is a legitimate form of teleological explanation. In physics, teleological explanations can legitimately cite end states that result from the existence of constraints, as causes, providing the two criteria we set out are met.

Legitimate constraint-based teleological explanations are a neglected pedagogical tool in science education in general and especially in physics teaching. Legitimate teleological explanations, it has been suggested, should be introduced with the intention of discarding or replacing them at a later stage in teaching, in a similar way to other pedagogic simplifications, such as the fluid model of electrical current (Zohar & Ginossar, 1998). By contrast, we argue that legitimate constraint teleology explanations reflect the discourse of expert scientists and are useful explanatory tools in their own right. Indeed, such explanations are already present in textbooks and should not be prohibited in a blanket exclusion of teleological explanations in classrooms. The explanatory power of an account arises from several dimensions: its application across contexts (its sensitivity), its precision, its accuracy, its coherence with knowledge structures of a domain, and the ease with which it can be followed (its cognitive salience) (Ylikoski & Kuorikoski, 2010). The qualities of precision, accuracy, and coherence apply to legitimate constraint teleology explanations as much as other forms of explanation. The dimensions of sensitivity and salience, however, suggest inherent virtues of legitimate teleological explanations. First, legitimate teleological explanations have low sensitivity to changing background conditions. Legitimate teleological explanations that reference constraints, such as laws, have the virtue of citing universal principles that have explanatory power across contexts and hence have significant epistemic value. Indeed, a goal of scientific explanation, explanatory unification, is to develop accounts of phenomena through a minimum of explanatory propositions (Kitcher, 1981). The second criterion we propose means that, by definition, legitimate teleological explanations will have wide application across contexts. Second, research into illegitimate teleological accounts in science education notes the intuitive appeal of this form of explanation (Scott, 2022; Trommler et al., 2018); hence, legitimate teleological explanations are likely to have a good degree of cognitive salience and hence explanatory power.

Where legitimate constraint teleology explanations are used, we suggest that teachers take the opportunity to discuss the assumptions underlying the approach. Such teaching could lead to productive class discussion about the value of different forms of explanation. For example, in the context of explaining Newton's cradle, a teacher could prompt debate as follows:

> One way to explain the motion of the balls in Newton's cradle is to argue that the motion occurs to conserve momentum and energy. Alternatively, you can explain the effect by describing the forces acting on the balls. What are the advantages and disadvantages of these explanations?

Whilst convergence to a 'best' explanation of a phenomenon is assumed to be an aim of scientific research programmes (Lipton, 2004), pedagogy might adopt a pluralistic approach, in which students are introduced to, or are encouraged to develop, multiple explanatory accounts which are compared and critiqued (Etkina & Planinšič, 2015; Trommler & Hammann, 2020). In a pluralistic model, legitimate teleological explanations offer an alternative to mechanistic accounts as they are often more compact, referring to a single constraint rather than multiple mechanisms (McDonough, 2009). Students might compare and contrast a legitimate teleological explanation with a non-teleological account and consider the advantages of each. A comparison of forms of explanations in the classroom should highlight the two conditions for legitimacy introduced above. The criteria additionally provide a guide for teachers when they are making decisions about the most appropriate explanatory approach for a lesson. With sufficient consideration of their underpinnings, appropriate constraint teleological can be a useful element of teachers' and students' explanatory toolkits in physics and other scientific disciplines.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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