Are There Both Causal and Non-Causal Explanations of a Rocket's Acceleration?

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A typical textbook explanation of a rocket's motion when its engine is fired appeals to momentum conservation: the rocket accelerates forward because its exhaust accelerates rearward and the system's momentum must be conserved. This paper examines how this explanation works, considering three challenges it faces. First, the explanation does not proceed by describing the forces causing the rocket's motion. Second, the rocket's motion has a causal-mechanical explanation involving those forces. Third, if momentum conservation and the rearward motion of the rocket's exhaust explain why the rocket accelerates forward, then presumably momentum conservation and the rocket's forward motion likewise explain why the rocket emits exhaust rearward. Explanatory circularity threatens to follow from this pair of explanations. This paper examines how the conservation-law explanation works and how it is compatible with the causal-mechanical explanation. The paper argues that these two explanations do not explain precisely the same fact relative to the same contrast class. The paper interprets the two conservation-law explanations as non-causal and argues that they yield no explanatory circularity.

1. Introduction

Consider a rocket (feeling negligible gravitational influences) consisting primarily of a chamber filled with gas that can serve as fuel, a mechanism for igniting the gas (suddenly increasing its temperature and pressure), and a valve on the left side of the chamber (that is, a wall that can be removed by some means requiring negligible force and making negligible contribution to the system's momentum). Suppose that the rocket is initially at rest and then the gas is ignited. The rocket remains at rest with the high-pressure gas inside until the valve is opened. When that happens, gas escapes to the left as exhaust while the rocket accelerates to the right.

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A typical textbook explanation of the rocket's beginning to move rightward appeals to the law of the conservation of linear momentum: if a closed system is uninfluenced by external forces, then its total linear momentum is constant. The rocket system's total initial momentum is zero, since it is initially at rest, and it is a closed system uninfluenced by external forces. When the valve is opened, the exhaust has a leftward velocity, and so the rocket must move rightward in order for the system's total momentum to remain zero. This explanation of the rocket's motion is familiar from many textbooks. For instance:

> The propulsion of a rocket through space can be explained in terms of momentum conservation. Hot gases produced by the combustion of the fuel are expelled at high speed from the rear of the rocket. Although the total mass of these hot gases may not be large, the gases move with such a high velocity that the total momentum associated with them is appreciable. The momentum of the gases is directed backward. For momentum to be conserved, the rocket must acquire an equal momentum in the forward direction. (Schmidt 2002, p. 642; Schmidt 2014)

Textbooks commonly say that the rocket's motion can thereby "be explained on the basis of the conservation of momentum" (Giancoli 2008, p. 219). One aim of this paper is to understand whether this textbook account is indeed a scientific explanation of the rocket's motion and, if so, how this explanation works.[1]

If momentum conservation does explain the rocket's motion, then this explanation must coexist with another explanation that appeals not to momentum conservation, but rather to gas pressure. According to this explanation, when the fuel is ignited and the valve remains closed, the pressure of the ignited fuel pushes the rocket chamber's right wall to the right and its left wall to the left. The two forces balance so the rocket remains stationary. When the valve is opened, there is a hole in the left wall, and so there is no longer enough leftward force generated by the gas pressure to balance the rightward force it exerts. The gas escapes to the left and the unbalanced rightward force pushes the rocket to the right. Accordingly, textbooks frequently say that an "explanation" of the rocket's motion is "that the burning fuel explodes both toward the front of the rocket and toward the rear, with the fuel that explodes toward the front pushing

1. Of course, I am throughout giving arguments that explain according to classical physics. We can learn about how scientific explanations work by studying these "explanations" even if we also believe that these arguments are not actually explanations because classical physics is not true.

the rocket forward, while the fuel that explodes toward the rear simply escapes out the open end of the rocket" (Spivak 2010, p. 32).

This is clearly a "causal" (or "mechanical") explanation of the rocket's motion. By terming it "causal," I mean (following Lange 2013, 2017) that it derives its explanatory power by virtue of supplying information (of the sort demanded in the given context) about the causal antecedents of the rocket's motion or, more broadly, about the world's causal structure. What makes an explanation causal, on this understanding, is how the explanation works, i.e., what gives it explanatory power. A causal explanation of the rocket's motion derives its explanatory power from providing information about causal connections (where context may influence what specific information about the causes of the rocket's motion is required to explain the rocket's motion).[2]

We must consider whether the existence of the above causal explanation of the rocket's motion undermines the explanatory credentials of the momentum-conservation account. If the momentum-conservation account also explains the rocket's motion, then we must consider whether or not it too is a causal explanation. If the momentum-conservation account is an explanation (whether causal or non-causal), then apparently it explains the same fact as the causal explanation appealing to gas pressure. We then have two different explanations of the same fact, which is exactly the way that some textbooks present the two accounts. For instance:

> …the law of *conservation of momentum* … can help us understand how rockets propel themselves. Rockets carry their own fuel. They burn it at a controlled rate and expel the exhaust gases out the back. This accelerates the rocket forward. How does this happen: how does having a hole at the back help the rocket move forward? The gases that come out of the rocket nozzle … carry a lot of momentum. There are no forces acting on the rocket from outside (let's forget the small effect of gravity for the purposes of this discussion), so the total momentum of the rocket plus gases is constant. Therefore, the momentum carried away by the gases is lost by the rocket. But this momentum is directed backwards, so it is negative: the velocity of the exhaust gases is a negative number. The rocket loses this negative number from its momentum, and this means it actually *increases* its

2. An explanans might happen to rule out some hypothetical causal histories of the explanandum E without deriving its explanatory power from doing so. For this reason, I reject Bradford Skow's (2014) understanding of a causal explanation as any explanation that contains facts about what causes (if any) E had. On my view, if the explanation is causal, then that the facts it contains concern E's causes must not be incidental to the explanation's explanatory power, but must be part of what gives it explanatory power.

> momentum. … we should equally well be able to explain the acceleration of the rocket by the fact that the exhaust gases exert a force on it, propelling it forwards…. (Schutz 2003, pp. 52–3)

It is not impossible in principle for the two accounts to explain the same fact. Indeed, the literature on scientific explanation includes canonical examples of ways in which the same fact purportedly receives several explanations. These examples include: Wesley Salmon's (1989, pp. 180–82) "friendly physicist" case where the same fact purportedly receives both a "bottom-up," "causal-mechanical" explanation and a "top-down," "unificationist" explanation; Frank Jackson's and Philip Pettit's (1992) examples in which different explanations of the same fact differ in how "close-grained" or "small-grained" they are; and Norwood Russell Hanson's (1958, p. 34) famous example where a death in an automobile accident is explained differently by the physician, the barrister, and the traffic engineer, because of their different interests.

Purported cases of explanatory pluralism deserve philosophical investigation for the light they can shed on the nature of scientific explanation. One aim of this paper is to understand whether the momentum-conservation account is indeed another explanation of the same fact that is explained causally by appealing to gas pressure. (If so, the next step would be to identify how explanatory pluralism arises in this example: whether it arises in the same way as it does in one of the above canonical examples, or by some other means.)[3]

In section 2, I will pose a challenge to the explanatory power of the momentum-conservation account arising from the "explanatory symmetry" between the rocket's and gas's motions. In view of this explanatory symmetry, I will conclude that the rocket's motion cannot be explained by momentum conservation. Nevertheless, I will argue in section 3 that there is a fact in the neighborhood that the momentum-conservation account explains, thereby accounting for the account's role in scientific practice. In section 4, I will argue that this explanation does not work by describing the world's network of causal relations and so is not a causal explanation in the sense I have specified. The conservation law does not derive its explanatory relevance from its supplying information about the causes of the rocket's motion. Rather, its explanatory relevance comes from its possessing

3. Of course, the case of the rocket is just one example; many others pose the very same questions. Another textbook favorite is a cannon (free to move) firing a cannon ball horizontally and recoiling. Textbooks explain the cannon's recoil either by appealing to momentum conservation or by saying that the expanding gases in the barrel push the cannon backward as much as they push the shell forward.

an especially strong variety of necessity and so rendering the explanandum more inevitable than any causal considerations could. In section 5, I will conclude that the causal explanation (from gas pressure) and momentum-conservation explanation are not two explanations of the same fact relative to the same contrast class. What the conservation-law explanation explains has no causal explanation. Furthermore, the conservation-law explanation has an explanatory virtue that the causal explanation lacks.

2. The Challenge from Explanatory Symmetry

Let's study the putative explanation of the rocket's rightward motion that appeals to momentum conservation. This explanation purports to use the conservation law and various initial and boundary conditions to explain the rocket's motion. The purported explanation proceeds in two steps. First, it uses the fact that the rocket system is closed and under no external influence, the law of momentum conservation, and the fact that the system's initial momentum is zero to explain why its final momentum is zero. This fact is then used in the second step, along with the fact that the final system consists of the gas and the rocket (i.e., that the rocket does not break apart) and the fact that the gas in the final system is moving leftward. They explain why the rocket in the final system is moving rightward.

This putative explanation thus uses the fact that the gas moves leftward to help explain why the rocket moves rightward; the rocket must move rightward in order for the total momentum to be conserved. This is precisely the way that the putative explanation is given in the textbook passages quoted in the previous section. However, this feature of the putative explanation prompts a serious challenge to its explanatory power: what gives the exhaust's leftward motion explanatory priority over the rocket's rightward motion? For this putative explanation of the rocket's rightward motion to succeed, the rocket's rightward motion must owe partly to the gas's leftward motion. But there is no apparent reason for any explanatory asymmetry between the gas's motion and the rocket's motion. (The two motions must be simultaneous in order for momentum to be conserved).

In other words, if the gas's leftward motion (together with the fact that the system's only other component is the rocket) can help to explain why the rocket moves rightward, then apparently by the same token the rocket's rightward motion (together with the fact that the system's only other component is the gas) can help to explain why the gas moves leftward: the gas must move leftward in order for total momentum to be conserved. But the latter "explanation" is never found in textbooks, and for good reason: it cannot be that the rocket's rightward motion helps to explain the gas's leftward motion and vice versa! (Even if time travel produces causal and hence explanatory circles (as Lewis (1986, p. 74) appears to countenance), the rocket example surely involves no such exotic phenomenon.) To avoid an explanatory circle, it seems that we must conclude that the gas's leftward motion cannot help to explain the rocket's rightward motion (or vice versa). This is a serious challenge to the putative momentum-conservation explanation of the rocket's rightward motion.

This objection to the momentum-conservation explanation invokes an explanatory symmetry between the gas's moving leftward and the rocket's moving rightward, so I will refer to this objection as "the challenge from explanatory symmetry." Of course, even if this challenge succeeds and so momentum conservation and the exhaust's moving leftward cannot be used to explain the rocket's moving rightward, they could still be used to predict the rocket's moving rightward. In other words, we could use the momentum-conservation argument to conclude that we can propel the rocket to the right by finding a means for it to shoot gas to the left. However, simply to deny the explanatory power of the momentum-conservation argument seems contrary to scientific practice. As we have seen, textbooks routinely present this argument (and analogous arguments concerning other examples)[4] as explanatory.

We might try to resist the challenge from explanatory symmetry by responding that it fails to challenge our using the fact that the rocket system is closed and under no external influence, the law of momentum conservation, and the fact that the system's initial momentum is zero to explain why its final momentum is zero. But this response, though correct, does not do enough to account for scientific practice. The response permits us to explain the system's final total momentum, whereas the textbook explanation goes a step further: its explanandum is the rocket's rightward motion. To use momentum conservation to explain that fact, we must appeal to the gas's leftward motion and thus accord it explanatory priority over the rocket's rightward motion. The challenge is that these two facts are explanatorily symmetric.

Another possible response to the challenge is to reply that the momentum-conservation explanation is not a causal explanation. In other words (unpacking "non-causal explanation" in terms of the notion of "causal explanation" given in section 1), this response proposes that the conservation-law explanation derives its explanatory power by some means other than from supplying information (of a certain sought-after kind) about the causal chain leading to the rocket's motion. Perhaps it works instead by subsuming the explanandum under a broad law (momentum conservation) and so works in the same kind of top-down, unificationist fashion as Salmon (1989) regards one explanation in his "friendly physicist" example as

4. See note 3.

doing. This response to the challenge from explanatory symmetry might go on to suggest that the momentum-conservation argument derives its explanatory power by virtue of instantiating an argument scheme in the best set of argument schemes—what Philip Kitcher (1989) calls "the explanatory store." (This is not the picture of non-causal explanation that I will endorse later when I discuss non-causal explanation in more detail.) In any case, without (for now) depending upon any particular account of how such a non-causal explanation would work, this response to the challenge from explanatory symmetry is that unlike causal explanations (in non-exotic cases), non-causal explanations can run in circles. Hence, there is nothing problematic about the gas's leftward motion helping to explain why the rocket moves rightward and the rocket's rightward motion helping to explain why the gas moves leftward.

However, I do not believe that non-causal explanations are any more able to run in circles than causal explanations are. Non-causal explanations also respect an order of explanatory priority, though it is not the order of causal priority. For instance, symmetry principles help to explain conservation laws non-causally, but although Noether's theorem likewise allows conservation laws (within a Hamiltonian framework) to entail symmetry principles, this direction of entailment is never considered explanatory. As another example, a particular topological feature of the Königsberg bridges (that they constitute a "non-Eulerian graph") is often thought (e.g., Pincock 2007; Lange 2013) to explain non-causally why those bridges cannot all be crossed exactly once in a continuous landlocked path. But the fact that they cannot all be so crossed does not help to explain why (despite entailing that) the bridge network exhibits this topological feature. Similarly, Craig Callender (2005, pp. 128–30) suggests that the dimensionality of space is widely recognized as taking priority in a non-causal explanation over a feature of space's inhabitants; perhaps the three-dimensionality of space helps to explain non-causally why there exist stable orbits. But the existence of stable orbits does not also help to non-causally explain the three-dimensionality of space. Scientific practice seems to avoid embracing circularity in non-causal explanations.

Another possible response to the challenge from explanatory symmetry is for the gas's leftward motion to help explain the rocket's rightward motion in one context, but for the rocket's rightward motion to help explain the gas's leftward motion in another context. No explanatory circularity results because there is no context where the two explanations both hold. Bas van Fraassen gives such an account: the tower's height explains the shadow's length in a context where we are interested in optics, whereas (in his gothic tale) the shadow's length explains the tower's height in a context where we are interested in an intentional explanation of the

Chevalier's actions in ordering the tower's construction (van Fraassen 1980, pp. 132–4).

In van Fraassen's example, the key difference between the two contexts is supposed to be a difference in what van Fraassen calls the "relevance relation": the relation to the explanandum that the why questioner requires of an explanans. Different relations (through different laws) connect the explanans and explanandum in the two contexts.[5] (The same is true in Hanson's example: the physician, the barrister, and the traffic engineer are interested in events standing in different sorts of causal relations to the motorist's death.) By contrast, in the rocket case, the same relation (through the same law: momentum conservation) connects the putative explanans and explanandum whether the gas's motion is explaining the rocket's or vice versa. So different relevance relations are not obviously making for different contexts in this example and thereby averting explanatory circularity.

Ultimately, I will propose that there are indeed different contexts here—but not with different relevance relations. Rather, the why questions answered by the causal-mechanical and conservation-law explanations do not concern the same explanandum relative to the same contrast class. I will develop this response in section 3.

Another possible response to the challenge from explanatory symmetry is to construe the momentum-conservation explanation as a causal explanation and to regard the gas's leftward motion as causally prior to the rocket's rightward motion. After all, what is being manipulated in this example is the valve on the rocket's left side, so some events on the left are causally prior to the rocket's rightward motion. It might be thought, then, that the valve's being opened causes the exhaust to escape leftward, which causes the rocket to begin to move rightward. That is why the motion of the exhaust on the left is causally and hence explanatorily prior to the rocket's rightward motion.

This response mischaracterizes the causal roles of two distinct events on the left: the valve's opening and the gas's moving to the left and thereby escaping as exhaust. The gas escaping does not cause the rocket's rightward motion. Rather, the gas's moving to the left as exhaust and the rocket's moving rightward are two effects of a common cause: the valve's opening. In particular, the valve's opening removes some of the chamber's left wall

5. Perhaps van Fraassen's example fails to be a case where the explanatory direction is reversed under change in context. Perhaps it is the Chevalier's beliefs about what the shadow's length would be, not the shadow's actual length, that helps to explain the tower's height. My concern is with what van Fraassen was aiming to illustrate, even if his particular example fails to illustrate it.

and thereby prevents many collisions that would otherwise have occurred between that wall and the enclosed gas molecules. The valve's opening thereby allows gas molecules to escape to the left and also causes the leftward force exerted by the gas on the chamber's left wall to decrease—but the gas molecules' escaping does not cause the leftward force to decrease. Both are effects of the left wall's removal. So, the exhaust's leftward motion as it escapes from the rocket is not causally (and thereby explanatorily) prior to the rocket's rightward motion.

We can, of course, give a causal explanation of the rocket's rightward motion that appeals to the valve's opening as causing a decrease in the leftward force on the rocket and hence as helping to cause an unbalanced rightward force that propels the rocket. But this explanation does not appeal to momentum conservation. By contrast, a momentum-conservation explanation appeals to the escaping gas's leftward velocity.

Since the gas's motion is not a cause of the rocket's motion, it remains mysterious what makes the gas's motion able to help explain the rocket's motion. The gas's and rocket's motions have a common cause in the valve's opening. But then to cite the gas's motion in explaining the rocket's would be as incorrect as citing the barometer reading's falling in explaining the storm (in the famous counterexample to the D-N model [Salmon 1989, p. 47]).

Of course, there is an event on the left that is causally prior to the rocket's rightward motion—namely, the valve's opening. But that the valve is on the left and its opening is a cause of the gas escaping does not make the gas's escaping causally (and hence explanatorily) prior to the rocket's moving rightward. After all, if the momentum-conservation explanation applies to the original rocket, then it applies also to a rocket where the manipulation occurs on the right rather than the left. Suppose that the rocket begins with identical open valves on both the left and right. Suppose the gas is then ignited and begins shooting out both leftward and rightward as the rocket remains stationary. Suppose the right valve is then closed as the rocket accelerates to the right. That the valve manipulation now occurs on the right rather than the left does not make the gas's escaping leftward an effect of the rocket's rightward motion. Having the manipulation occur on the right rather than the left makes no difference to the momentum-conservation argument; that argument is just as successful (or not) in explaining this rocket's motion as it was in explaining the original rocket's motion.

3. Clarifying the Explanandum

In view of the explanatory symmetry between the gas's leftward motion and the rocket's rightward motion, I conclude that momentum conservation and the gas's leftward motion cannot explain why the rocket moves rightward. However, we can avoid doing too much violence to scientific practice by finding a different way to construe the conservation-law argument so that it does possess explanatory power. Rather than construing it as answering the question "Why does the rocket start moving rightward?," I suggest that it answers a question more like "Given that the gas starts moving leftward (as exhaust), why does the rocket start moving rightward?" In other words, I will now argue that with a slight change to the explanandum, we can find something that the conservation law helps to explain. Given that the gas moves leftward, the rocket has got to move rightward in order for the system's total momentum to be conserved. That is why the rocket moves rightward, given that the exhaust moves leftward. But what does "Given A, why B?" mean and what role does A play in replying to this question? How does the gas's leftward motion (as A) help to answer this question about the rocket's rightward motion (as B) while respecting the explanatory symmetry between them?

Alan Garfinkel has proposed that "Given A, why B?" should often be understood as a why question where A figures in every member of the contrast class: "Roughly speaking, the question '*Given* A, why B?' is equivalent to the contrast 'Why B *rather than* any of the other alternatives to B in which A is true?'" (Garfinkel 1990, p. 29). As I understand Garfinkel's suggestion, the question "Given that someone from our Department is picking up the visiting speaker from the airport, why is Jones picking up the visiting speaker from the airport?" can (in a realistic context) be understood as "Why is Jones rather than someone else from our Department picking up the visiting speaker from the airport?"

Garfinkel's suggestion seems plausible to me—at least regarding many ordinary cases. However, that the "Why B?" question includes "Given A," ensuring that A figures in every member of the contrast class, does not render superfluous an additional "rather than…" clause in the question. That is because "Given A" may not suffice to fix the intended contrast class since that class may not include every alternative to B in which A is true. For example, I was recently dining with my son at a restaurant. He was ordering steak and a Caesar salad. Concerned that he was ordering too much, I asked him, "Given that you are ordering steak, why are you ordering a Caesar salad?" He answered, "Because I like Caesar salad." My question had been unclear. I clarified it by asking, "Given that you are ordering steak, why are you ordering a Caesar salad rather than nothing else?" He answered, "Because I am very hungry and so I don't think that a steak will be enough." In my question, "Given that you are ordering steak" signaled that every member of the intended contrast class includes his ordering steak. Despite including "Given that you are ordering steak," my question still needed "rather than nothing else" to establish that I was not asking why he was ordering steak and Caesar salad rather than steak and shrimp, for instance.[6]

In the rocket example, then, the question "Given that the gas starts moving leftward (as exhaust), why does the rocket start moving rightward?" unpacks as "Why does the gas start moving leftward and the rocket start moving rightward rather than the gas starting to move leftward and the rocket not starting to move rightward (e.g., remaining stationary, starting to move leftward, etc.)?" (Moreover, since the fact that the gas starts to move leftward implies that it was not doing so previously, perhaps the "given" in the why question also implicitly includes that the gas and rocket begin at rest.) The explanans (the momentum conservation law; that the system's total initial momentum was zero; and that the system is closed, is constituted by the rocket—which remains whole—and the gas, and is uninfluenced by external forces) is logically inconsistent with one member of the contrast class (that the gas starts moving leftward and the rocket does not start moving rightward) but is logically consistent with the contrast class's other member (that the gas starts to move leftward and the rocket starts to move rightward). Of course, the explanans is also logically consistent with the rocket and the gas remaining stationary—but the why question's "given" precludes this option; it is not in the contrast class.

For this explanation to succeed, the gas's starting to move leftward does not have to be explanatorily prior to the rocket's starting to move rightward. The explanatory symmetry between the rocket's and the gas's motions does not block this explanation. The gas's moving leftward is able to play its role in this explanation not because the gas's moving leftward is causally (or otherwise explanatorily) prior to the rocket's moving rightward, but simply because it is "given." It is not in the explanans.

Let's consider an objection to this approach. On this reading of "Given A, why B?," the question amounts to "Why A&B rather than A&(some alternative to B)?"[7] The explanandum is thus a conjunction. For instance,

6. Garfinkel holds that for me to ask "Given A, why B?" requires that I already have a satisfactory explanation of why A holds (Garfinkel 1990, p. 29). But Garfinkel is mistaken. I can ask my son "Given that you ordered steak, why did you order a Caesar salad rather than nothing else?" without knowing why he ordered steak (rather than shrimp, or even rather than nothing).

7. I have just interpreted "Given A, why B?" as "Why A&B rather than A&(some alternative to B)?" But perhaps the initial question could also be interpreted simply as "Why B rather than A&(some alternative to B)?" For my main purpose, it makes no difference which of these interpretations is adopted, since I can conclude in either case that the causal and conservation-law explanations are not explaining the same fact relative to

the explanandum for the conservation–law explanation in the rocket example is that the gas starts moving leftward and the rocket starts moving rightward. But an explanation of a conjunction must explain both conjuncts. John Carroll, for example, says that in most ordinary contexts, for C to explain why A&B is for C to explain why A and for C to explain why B (Carroll 1999, p. 72). Clearly, this "conjunctive view" (as Carroll calls it) is often correct. For instance, ordinarily to explain why Jones and Smith were in Chicago on a given day, we would have to explain why both of them were there; it would not suffice to explain why Jones was in Chicago. But in the rocket example, I have suggested that to explain why the gas starts moving leftward and the rocket starts moving rightward, we do not have to explain why the gas starts moving leftward.

However, I reply, there is a good reason why we do not have to explain why the gas starts moving leftward: because the gas's doing so is entailed by every member of the contrast class (since the gas doing so is "given" in the question). Carroll's "conjunctive view" ordinarily applies when the why question is "Why A&B rather than not(A&B)?" This is the contrast class that we ordinarily intend when we ask "Why were Jones and Smith both in Chicago?" But we do not have to explain A when it belongs to every member of the contrast class. For instance, if I had asked my son "Why are you ordering steak and a Caesar salad rather than steak alone?," he would not have had to explain why he was ordering steak; he could have answered simply, "If I order steak, then I will still be hungry if I order nothing else." As another example, suppose we ask, "Why did Krakatoa erupt in 1883 rather than remain dormant?" This question is ordinarily answered by a causal explanation that begins with the volcano's state at some earlier moment and then describes the factors that produced changes in the magma's density and pressure, forcing it upward and eventually outward. But although Krakatoa could not have erupted in 1883 unless it had already come into existence, an answer to the above why question ordinarily does not have to explain why it existed in the first place (or, for that matter, why the Earth exists, or why there is something rather than nothing). That is because every member of the question's contrast class entails that the Krakatoa volcano (and Earth, and something) existed. The question grants that the contrast class exhausts the possibilities, and so an answer does not have to explain why the outcome is drawn from the contrast class.

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the same contrast class; they do not answer the same why question. However (as I am about to set out), under my interpretation it is more evident why an answer to "Given A, why B?" does not have to explain why A. I have no need to regard the various interpretations I give of "Given A, why B?" as exhausting all of the interpretations it receives in science. (See note 9.)

Let me now turn to another reasonable interpretation of "Given A, why B?" Instead of taking it as having the conjunction A&B as the explanandum, we might just as reasonably interpret it as "Why is it that if A, then B?" and so as having the conditional A → B as the explanandum. For instance, when I asked my son, "Given that you are ordering steak, why are you ordering a Caesar salad (rather than nothing else)?," my question could reasonably have been understood as "Why is it that if you order steak, then you are also ordering a Caesar salad (rather than its being that if you order steak, then you are ordering nothing else)?" My son's answer ("Because I am very hungry and so I don't think that a steak will be enough") would still be appropriate. He might just as well have answered with a conditional beginning with the same antecedent as the explanandum: "If I order steak, then I will still be hungry if I order nothing else." Notice that even with a conditional as the explanandum, a "rather than" clause is not superfluous; the question with "…rather than its being that if you order steak, then you are ordering nothing else" is different from the question with "…rather than its being that if you order steak, then you are also ordering shrimp."

In the rocket example, then, the question "Given that the gas starts moving leftward (as exhaust), why does the rocket start moving rightward?" unpacks as "Why is it that if the gas starts moving leftward, the rocket starts moving rightward (rather than its being that if the gas starts moving leftward, the rocket does not start moving rightward)?" The explanans (including the momentum-conservation law) entails the former conditional and entails the negation of the latter conditional. It must do both to answer the why question. Perhaps both conditionals are true if the gas does not start moving leftward. (If they are material conditionals, then they are both true if the gas does not start moving leftward—though I will not assume that the conditionals are material rather than indicative.)[8] But a claim entailing both conditionals cannot answer this why question because (as emphasized by van Fraassen 1980, p. 145) a why question presupposes that no more than one member of the contrast class is true. A response entailing both conditionals rejects the why question rather than answering it. This result fits with our intuitions about the meaning of "Given A, why B?"; to deny A would not be to answer the question.[9]

8. If the conditionals are material, then the rendering of "Given A, why B?" as "Why A → B rather than A → ~B?" collapses into the earlier rendering as "Why A&B rather than A&~B?" As material conditionals, both A → B and ~(A → ~B) hold iff A&B.

9. I am not claiming that "Given A, why B?" always means either "Why A&B (rather than ~(A&B))?" or "Why A → B (rather than A → ~B)?" (or with something stronger in place of B inside "rather than…"). For instance, "Given A, why B?" may demand an explanation of B (rather than ~B) by A (together, perhaps, with additional facts). This would

Let's return to the question "Why is it that if the gas starts moving leftward, the rocket starts moving rightward (rather than its being that if the gas starts moving leftward, the rocket does not start moving rightward)?" The gas's starting to move leftward does not have to be explanatorily prior to the rocket's starting to move rightward in order for this question to be answered by "Because if the gas starts moving leftward, the law of momentum-conservation requires that the rocket start moving rightward…." The gas's moving leftward is able to play its role in this explanation simply because it figures in the "given"—in particular, because it is entailed by the antecedent of every contrast-class member. (It is natural to answer with a conditional having the same antecedent.)

On either of these interpretations of the explanandum (that is, as a conjunction or a conditional), the gas's moving leftward is not being called upon to help explain why the rocket moves rightward. Rather, what is being explained is why the rocket moves rightward given that the gas moves leftward, and that the gas moves leftward does not help to explain that fact. Instead (on the interpretation of the explanandum as a conditional, for instance), that the gas moves leftward appears in the answer not as a statement of fact, but as the antecedent of a conditional—that is, as "If the gas starts moving leftward, then the law of momentum-conservation requires…." This conditional is used simply to show how the explanandum conditional is entailed by the explanans, which includes the momentum-conservation law but does not include the fact that the gas starts moving leftward.

One way to see that this account respects the explanatory symmetry between the gas's and rocket's motions is to see that on this account, "If the rocket starts moving rightward, then the law of momentum-conservation requires…" answers the question "Why does the gas move leftward given that the rocket moves rightward?"[10] If we interpret this question as "Why is it that if the rocket starts moving rightward, the gas starts moving leftward (rather than its being that if the rocket starts moving rightward, the gas does not start moving leftward)?," then the explanans (including the

be a natural interpretation of "Given Newton's laws of motion and gravity, why do the planets move in ellipses with the sun at a focus (Kepler's first "law")?" This interpretation (unlike the interpretations of the explanandum as a conjunction or a conditional) requires that A be explanatorily prior to B.

10. There is one respect in which the gas's and rocket's motions differ explanatorily: textbooks typically do not make a point of asking "Why does the gas move left?," only "Why does the rocket move right?" I attribute this difference to pragmatics: the rocket's motion is more intriguing to us than the gas's. One reason for this may be that in typical examples, the rocket goes up into space, which is spectacular. Another reason may be that there is an obvious causal explanation of the gas's motion: the ignition of the gas forces it through the open valve. But the rocket's motion is more mysterious. Another reason is likely that we designed rockets to move in a certain way, not with the purpose of emitting gas as exhaust.

momentum conservation law) entails the former conditional and entails the negation of the latter conditional. This result yields no explanatory circularity since the "given" (that the rocket starts moving rightward) does not help to do any of this entailing and hence this explaining; it is not part of the explanans (as we saw in the previous paragraph). Thus, there is no danger that the rocket's motion helps to explain the gas's motion and vice versa. The explanandum in one case (a conditional) is not part of the explanans in the other case (momentum conservation, etc.), so there is no danger of explanatory circularity.[11]

4. What Makes the Conservation Law Explanatorily Relevant?

Although we have defused the threat of explanatory circularity by clarifying the explanandum, we have not fully understood how the conservation-law explanation works. What makes the conservation law explanatorily relevant to the explanadum? I agree with Garfinkel that in "Given A, why B?", "the 'given' clause tells us, at the very least, what the outer bound is on the variation in B: we are to consider only such alternatives to B as also satisfy A" (1990, p. 29). There are many ways that such an explanation could work. It could work by describing B's causal history without having to describe A's causal history, since A is "given." This is what happens in the answer to "Given that Krakatoa had been a quiescent volcano in previous years, why did it erupt in 1883 rather than remain dormant?" That is a causal explanation in the sense I introduced in section 1: this explanation derives its explanatory power by virtue of supplying contextually sought-after information about the causal antecedents of the volcano's eruption.

However, the conservation-law explanation that answers "Given that the gas starts moving leftward (as exhaust), why does the rocket start moving rightward?" does not work by describing the causal history of the rocket's motion. We saw in section 1 what that causal history involves (e.g., the pressure of the ignited fuel on the rocket chamber's walls). The conservation-law explanation does not describe any of that. What makes the conservation law explanatorily relevant to this explanandum has nothing to do with its supplying information about the causes of

11. Although the conservation law (and the initial zero momentum, etc.) explains why the conditional $A \rightarrow B$ (rather than $A \rightarrow \sim B$) holds, it does not follow that if A, then the conservation law (and the initial zero momentum, etc.) together with A explains why B (rather than ~B)—since A is not explanatorily prior to B. It is not the case that if the gas moves leftward, then the conservation law (etc.) and the gas's moving leftward explains why the rocket moves rightward. Of course, there are some cases where C explains why $A \rightarrow B$ (rather than $A \rightarrow \sim B$) and where if A, then A&C explains why B (rather than ~B). For instance, if C explains why it is that if I put the paper in the fire, then it ignites, then if I put the paper in the fire, C&(I put the paper in the fire) explains why it ignites.

the rocket's motion: the conservation law would still have been explanatory even if the motion's causes had been different. Under different force laws, momentum conservation would still have constrained what could possibly happen to this system: as long as it remains closed and isolated, its momentum must be conserved.

I argue (2011, 2017) that this constraint explains by virtue of possessing a variety of necessity stronger than any of the laws mediating causal connections: momentum-conservation would still have been a law even if there had been additional or different fundamental forces (since momentum-conservation arises from fundamental spacetime symmetries that would still have obtained even if the causal network connecting the events populating spacetime had been different). Because in this case the conservation law derives its power to explain from its status as a bound on any possible arrangement of events, transcending their causal connections, rather than from providing information specifically about the causal connections among events, this explanation is not a causal explanation (in the sense that I have been employing throughout).

This proposal sheds further light on how the causal and conservation-law explanations of the rocket's motion manage to coexist. I have already argued that the two explanations do not have the same explanandum with the same contrast class. The conservation-law explanation explains why the rocket starts moving rightward (rather than not) if the gas starts moving leftward, whereas this is not the explanandum and contrast for the causal explanation. Now that we have seen that the conservation-law explanation works non-causally, I can argue that its particular explanandum (relative to its contrast class) has no causal explanation (rather than, say, having a causal explanation in certain contexts but not in others). My argument is that the conservation-law explanation reveals its explanandum to be more inevitable than facts about causal connections could make it; the explanandum results from a constraint that transcends the causal network. Therefore, any purported causal explanation of this explanandum mischaracterizes it as explanatorily dependent on the laws and mechanisms underwriting causal connections, whereas in fact, they are not responsible; the explanandum would still have obtained even if different forces had been operating. The non-causal explanation precludes this explanandum's having a causal explanation. The conservation-law explanation reveals that this explanandum (that the rocket accelerates rightward if the gas accelerates leftward) comes from somewhere deeper (ultimately, as it turns out, from the spacetime symmetries) than do facts having causal explanations (such as the fact that the rocket accelerates rightward).

In this respect, the momentum-conservation explanation is similar to what Lange (2013) terms "distinctively mathematical" scientific explanations.

Here is one example: Mother fails every time she tries to divide her 23 strawberries evenly among her 3 children without cutting any (strawberries!) because 3 does not go evenly into 23. This mathematical fact explains by limiting the range of the possible. This explanation precludes a causal explanation of Mother's failure because it reveals that the causal process by which Mother distributed her strawberries is not responsible for her failure. Her success was mathematically impossible. Likewise, the conservation-law explanation reveals that for the rocket not to accelerate rightward if the gas accelerates leftward (and the system remains closed, etc.) is impossible to a stronger degree than the causal processes at work could make it.

5. Conclusion

The account I have given not only respects the explanatory symmetry (set out in section 2) between the rocket's and gas's motions, but also illuminates the relationship between the conservation-law explanation and the causal explanation (given in section 1) appealing to the unbalanced pressure of the gas on the walls of the rocket chamber. These are both genuine explanations (as the textbooks say) but (contrary to the textbooks) they are not two explanations of the same fact relative to the same contrast class. The causal explanation explains why the rocket begins to move rightward rather than not beginning to move rightward (by either remaining stationary or beginning to move leftward or in some other direction). The conservation-law explanation explains something else—such as (under the conditional interpretation) why the rocket begins to move rightward if the gas begins to move leftward (rather than the rocket's not beginning to move rightward if the gas begins to move leftward). There is no causal explanation of this explanandum relative to this contrast class. Likewise, although there is a causal explanation of why the gas begins moving to the left (rather than not), there is no conservation-law explanation of it. That the causal and conservation-law explanations do not answer the same why questions runs contrary to common textbook remarks such as one quoted earlier: that although momentum-conservation explains the rocket's acceleration, "we should equally well be able to explain the acceleration of the rocket by the fact that the exhaust gases exert a force on it, propelling it forwards" (Schutz 2003, pp. 52–3).

Hence, the causal explanation does explanatory work that the conservation-law explanation cannot perform and vice versa. The conservation-law explanation also possesses an explanatory virtue that the causal explanation lacks. The conservation-law explanation can give the same treatment to (and so, in a sense, can "unify") rockets with various different propulsion mechanisms, whereas the causal explanation cannot since it is sensitive to the details of the rocket's propulsion system. For instance, we saw (in section 2) that the acceleration of a rocket with valves on the left and right, where the propulsion is caused by the closing of the right valve while the left valve remains open, will have a somewhat different causal explanation than the acceleration of a rocket with only a valve on the left. The details of the causal explanation will be even more different for a rocket with a more radically different propulsion mechanism, such as a cannon rigidly attached to the rocket that projects ballast out of the rocket leftward, the rocket recoiling to the right. However, the conservation-law explanation is the same in all of these cases.[12] Indeed, the conservation law explanation would still apply even if the rocket's internal mechanism were precluded by the fundamental microphysical laws—for example, even if the laws governing molecular collisions were radically different or, more exotically, even if the rocket and gas had been composed of continuous rigid substances rather than molecules. The conservation laws would presumably still have held, considering their origin in fundamental spacetime symmetries that would still have held even if spacetime's inhabitants had been different.

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12. Newton's third law is also commonly used to give causal explanations of the rocket's motion. For instance, as the cannon ejects the ballast from the rocket, the cannon's force on the ballast causes the ballast to exert an equal and opposite force on the cannon (by Newton's third law) and thereby on the rocket to which it is rigidly attached. Textbooks frequently give this explanation (e.g., Giancoli 2008, p. 90) and assert that the same fact that Newton's third law helps to explain is also explained by momentum conservation. For instance: "Consider rocket motion. The momentum of the rocket plus everything in it never changes. How then can the rocket accelerate forward? By ejecting debris through its rear with momentum in the backward direction, the rest of the rocket gets an increase in the forward momentum. Actually, everything that can be explained from Newton's third law can also be explained with the law of conservation of momentum" (Goswami 2000, p. 56). I disagree; as we have seen, conservation-law and causal explanations do not explain the same fact.

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