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Implicit and Formal Symmetries

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Abstract

In this paper, I distinguish between three different roles that symmetries play in physics practice that are not always distinguished in the philosophical literature and which seem to clash with each other. I then propose that the best way to make sense of these roles requires introducing a distinction between two different kinds of symmetries. One kind concerns invertible transformations that map solutions to solutions. The other is associated with the fact that one can use the same equation to model a system in many different frames.

1 Introduction

A philosophical project on what symmetries are in the context of physics must pay close attention to how physicists talk about them. After all, the word “symmetry" is not an ordinary one, at least not as used in physical contexts.[1] The problem is that different parts of scientific practice seem to pull in different directions. Although everybody agrees that at a minimum

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[1] I am discussing here “dynamical symmetries" (symmetries of the laws) but for brevity will drop the qualification.

a symmetry must preserve the laws (in a sense to be made precise later), some physicists speak as if they must also preserve observations or measurements, while others suggest that they often do not. Similarly, some treat symmetry-related solutions or models as different descriptions of the very same physical situation, while others treat them as representing physically distinct situations. This multitude of usages poses a serious challenge to any philosophical attempt trying to answer what symmetries are.

In this paper, I do two main things. First, in §2 and §3, I provide evidence illustrating that there are, at least, three roles symmetries play in physics that seem to clash with each other. Second, in §4, I develop a novel framework according to which this clash, or at least an important part of it, can be understood as a consequence of the fact that there are two different notions or concepts of symmetries at play in physics that are not properly distinguished. Both notions share in common the idea that symmetries preserve the laws of a theory but disagree on how to characterize such preservation.

2 Three Different Roles

This section identifies three different important roles that (dynamical) symmetries seem to play in physics practice.

2.1 Role 1: Symmetries Preserve Observations

Some symmetries are said to explain why certain observations or measurements performed on symmetry-related states yield identical outcomes (this kind of explanation is rather common in discussions of the relativity principle). For example, consider the following situation concerning different states of systems related by boosts:

> **Situation 1:** Systems inside a train cabin that is moving with constant velocity relative to the station behave in the exact same way regardless of what the velocity is. A direct consequence of this is that there is no experiment *confined* to the cabin that would allow us to determine the system's (or train's) velocity relative to the ground.[2]

Feynman, for instance, appeals to the fact that Galilean boosts are symmetries of Newton's laws to explain why experiments inside a uniformly moving ship yield the same outcomes as in one at rest (Feynman et al., 1963, Ch. 15). This kind of explanation is supposed to go beyond boosts: spatial translations being symmetries of Newtonian mechanics is similarly supposed to explain why identical experiments in distant laboratories yield the same outcomes.

The popularity of this "observational role" of symmetries in physics has been driving a significant part of the philosophical literature on symmetries in the last two decades.[3] For example, when some philosophers explain why two distinct but shift-related worlds in both Newtonian mechanics and

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[2] This is an instance of what Murgueitio Ramírez (2025) calls the "Internal Principle of Relativity"; Situation 3 (in §2.3) is an instance of the "External" version. Roughly, in the internal case the device and system are boosted together; in the external, only one of them is.

[3] See, for example, Ismael and van Fraassen (2003), Roberts (2008), Healey (2009), Baker (2010), Dewar (2015), Dasgupta (2016), Read and Møller-Nielsen (2020), and Wallace (2022).

General Relativity are empirically equivalent, they typically appeal to the fact that shifts are symmetries of the relevant laws.

2.2 Role 2: Symmetries Signal Representational Redundancy

Some symmetries are said to explain or ground why we can use different models or solutions of a theory to represent a given (single) physical state. For example, consider the following situation:

> **Situation 2:** Consider a metallic sphere of radius R with total electric charge Q, and suppose that we want to compute the electric field at a point P a distance d from the center of the sphere (say that $d > R$). Given the symmetries of Maxwell's equations, our results will be the same regardless of whether we use a model that sets the potential at a very far-away point (at "infinity" in the physics lingo) to 0, or a model that sets it to a positive value $C > 0$.

Here is Feynman expressing a similar point (emphasis added):

> If we have found [potential] ϕ for some problem, we can always find another potential ϕ' that is *equally good* by adding a constant:
>
> $$\phi' = \phi + C.$$
>
> The new potential ϕ' gives the same electric fields, since the gradient ∇C is zero; ϕ' and ϕ *represent the same physics* (Feynman et al., 1963, Ch. 14).

In summary, the fact that two solutions or models of Maxwell's equations that only differ in the values of the potential are symmetry-related (in this example, they are related by $\phi \mapsto \phi + C$) is supposed to imply that they represent the very *same* physical state of the target system.[4] It follows from this that we should not attribute direct physical significance to values of the potential, in a way analogous to how we should not attribute physical significance to the size of the font of a subway map of NYC.[5]

Like the observational role, this representational role that symmetries are often assumed to play has been central to philosophical discussions in recent years, especially in discussions of the hole argument, gauge transformations, and surplus structure.[6] For instance, it is common to find scholars saying that if there is a diffeomorphism between two models of general relativity, then they represent the very same relativistic world. Similarly, the fact that more than one model or solution of the laws of a theory can adequately represent a given physical state is taken by many as a sign that the theory has surplus structure (e.g., Baker (2022) has suggested that a fundamental and complete theory should not have symmetries precisely because if it has them, then it would have extra structure).

Notice that unlike the observational role, in the case of the representa-

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[4] The claim that symmetry-related models represent the very same situation or state of affairs is often called "Leibniz equivalence". For a recent critical overview of various formulations of the representational role of symmetries, see Hall and Murgueitio Ramírez (2024) and references therein.

[5] Whether it follows from this that the potential itself is not a genuine physical quantity is, however, a trickier question in light of phenomena like the Aharonov-Bohm effect (e.g., see Jacobs (2023)).

[6] For recent papers on the interpretation of gauge transformations in particular, see, for example, Greaves and Wallace (2014), Teh (2015), Friederich (2015), Weatherall (2016), Nguyen et al. (2020), Gomes (2019), Bradley and Weatherall (2020), Murgueitio Ramírez (2022), and Wallace (2024).

tional role one talks of symmetry-related *models* or *solutions*, not of symmetry-related *states* of a system. This distinction is important when explaining how these two roles connect to measurements or observations; if two models (adequately) represent the same state of a system, then they should agree on the outcomes for measurements that can be performed on that system, which is very different from saying that *two* different states of the system yield the same outcomes under identical experiments. For instance, in the context of a Newtonian universe, one thing is to say that one could not measure the absolute velocity of a ship by studying the behavior of systems inside of it on the grounds that *different* absolute velocity states of the systems and ship are symmetry-related. A very different thing is to say that models of Newtonian mechanics related by boosts predict the same outcomes for measurements made on these systems on the grounds that they represent the very same state for each system (the underlying premise being that absolute velocity is not a genuine quantity, or not a quantity that characterizes a state). The former is an instance of the observational role; the latter, of the representational one.

2.3 Role 3: Symmetries Preserve Nomological Behavior

Finally, there is another important role symmetries seem to play in physics practice, one typically associated with observations of a *single* system made from two or more different inertial frames. To illustrate, consider the following situation:

> **Situation 3:** Two observers in different trains moving uniformly

> past an archery field are both watching the same flying arrow. Because boosts are symmetries of the laws for the arrow, they will agree on the laws governing the behavior of the arrow, but they will disagree about its motion.

Here, the fact that Galilean boosts are symmetries is said to explain why the two observers, even though they disagree on the arrow's speed, do agree about the laws for the arrow (i.e., agree about the regularities they see, here those associated with free fall or projectile motion). This kind of situation is rather common in physicists' discussions of the invariance of Newton's laws under Galilean transformations (as with the observational role, this one is often discussed in the context of the relativity principle). For instance, Emam (2021, p. 105) appeals to the invariance of Newton's laws under Galilean boosts to explain why "any two observers moving at constant speed and direction with respect to one another will obtain the same results for *all* physical experiments" (Emam, 2021, p. 106). Crucially, he goes on to clarify that the two observers will disagree about the motion of the relevant objects, which suggests that by "the results of all experiments," the author really means those results indicating what the laws of the various systems are (as opposed to results having to do with the specific motion of the object). Taylor and Wheeler make a similar point about two ships in relative uniform motion: a ball falling straight down on one appears to follow a parabolic course from the other, yet the laws of motion are the same in both ships due to the symmetries (Taylor and Wheeler, 1992, p. 57713). As a third example, Einstein (1905, p. 8) derives the result that different observers in uniform motion relative to one another agree on the law for a given electromagnetic wave by showing that the wave equation is invariant under Lorentz boosts.

We may call this third role that symmetries play in physics the "nomological role," for lack of a better term. Notice that in contrast to the observational role, symmetries in this case do *not* preserve all observations precisely because they do not preserve the motion of the various objects. Rather, as the name indicates, they preserve the "nomological behavior" or law-like behavior of the systems as observed or studied from different frames or perspectives. For example, if the observers in Situation 3 are related by a boost (a symmetry of the law of free fall), they will agree that the arrow behaves as an object in projectile motion behaves; if they were related by an acceleration transformation (not a symmetry of free fall in Newtonian mechanics), then they would not agree on this (in that case, only one observer will say it is a free fall object). In neither scenario, however, will they agree about the arrow's motion.

Are symmetries in this third role relating different states, as in the observational role, or different solutions or models, as in the representational one? It turns out that there is some flexibility here. One can think of them as relating different states, but now the states are partially characterized in a manner that includes explicit information about the motion of the system relative to external observers or frames that might not be co-moving with the system. For example, a symmetry might be relating the state of an arrow at rest in frame F_1 to that of the arrow moving in frame F_2, or it can also relate the state of two identical arrows in a single frame F_1, one moving and the other one at rest. Alternatively, one can also think of the symmetries as relating *solutions* or *models* of the equations for the laws of the system, but now these models represent, not the very same state (as in the representational role), but rather different states of the system, and in fact, observably distinct ones (e.g., the arrow at rest in F_1 and the arrow moving in F_1).

Interestingly, the nomological role has received relatively little attention in philosophical discussions of symmetries, especially compared to the first two roles discussed above.[7] An exception is a series of papers by Murgueitio Ramírez (see 2024 and 2025), in which the author stresses that symmetries determine whether or not observers in *different* frames (not necessarily inertial) agree on the *type* of behavior of a given system.

3 Discussion of These Roles

We have discussed three main explanatory roles that symmetries seem to play in physics practice and that we have called “observational", “representational" and “nomological." This section briefly discusses problems with the first two.

3.1 Limitations of the Representational Role

Is it the case that for any physical system S, symmetry-related solutions of its laws represent the same physical state? The answer seems to be negative. As Belot (2013) convincingly showed, there are a significant number

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[7] Of course, philosophers agree that (dynamical) symmetries preserve the laws, but the nomological role discussed here is about the preservation of the laws in contexts in which the observations are not preserved (since the motion is not preserved).

of systems with laws such that (a) some solutions of the laws represent physically *distinct* states and (b) those solutions are related by symmetry transformations. One vivid example concerns certain symmetry transformations of the Kepler problem that relate solutions representing orbits of very different eccentricities. A solution representing a circular orbit for a planet around a star clearly does not represent the same physical state as a solution representing an elliptical one (not only are the states different, but they are associated with different observations). Another counterexample briefly mentioned by Belot and discussed in detail by Murgueitio Ramírez (2024, §5) concerns some symmetries of the classic harmonic oscillator that map solutions representing a spring as oscillating with some amplitude and speed around equilibrium to solutions representing the same spring as oscillating with a different amplitude and different speed. Notice, by the way, that these two cases also illustrate that, on some occasions, variant properties are measurable; both the eccentricity of an orbit and the amplitude of a spring are paradigmatic examples of measurable physical properties, yet they vary under the symmetries in question.

Now, even if there are some counterexamples like the ones just discussed, it remains true that, in a good number of cases, it is appropriate to take symmetry-related solutions as representing physically equivalent states (or even the very same state). As noted in §2.2, it is plausible to take two solutions for the potential related by a global shift, say ϕ and $\phi + C$, as just two different ways of representing the same physical state of a charged object. It is also very tempting to treat shift-related solutions in Newtonian gravitation or General Relativity as just notational variations that represent the very same physical state for the universe. Why, then, is it appropriate in some cases to treat symmetry-related solutions as representing physically equivalent states (or the very same state), while in others it is not?

An adequate answer to this question may require its own paper (or book!). Here, however, I offer a simple proposal that bears some resemblance to the view proposed by Read and Møller-Nielsen (2020). Briefly put, the idea is this: symmetry-related solutions represent either physically equivalent states or the very same state if they only differ in the values of physical properties that are not measurable. But how do we determine whether a physical property is measurable? We should not answer, "check whether the property is variant under the symmetries of the relevant laws" because, as we already saw, some variant properties such as the amplitude of a spring are measurable whereas others, such as the absolute value of the potential at a point, are not. Instead, it is the physicists themselves, through experimental and theoretical deliberations, who determine whether a given quantity is measurable. For instance, returning to the case from §2.2, physicists have strong reasons to believe that the absolute value of the electric potential is not measurable, and so models that differ only by a shift in it can be taken to represent the same state.[8] Similarly, since measurement outcomes plausibly supervene on relative distances and velocities, shift-related models in spacetime theories can be treated as representing either observationally equivalent states or the very same state. By contrast, the amplitude and velocity of a spring relative to equilibrium are clearly measurable, so models disagreeing

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[8] Again, the reasons cannot be that it is a variant quantity and the electromagnetic field is not because variance is not a universal signature of non-measurability.

on these represent distinct states.

3.2 A Problem for the Observational Role

There appear to be no examples in physics of an experiment that could be performed *inside* a closed system, such as a spaceship far away from other objects, in order to determine the velocity, distance, or orientation of that system relative to other external systems, like the velocity of the ship relative to a distant star. This is presumably why the Relativity Principle, according to which (roughly speaking) the laws of physics are the same in any inertial frame, is deemed universal.[9] But do symmetries of the laws really explain or underwrite why there is no such experiment, or why the relativity principle is true?

Murgueitio Ramírez has recently argued that it is a mistake to appeal to the symmetries of a physical system to explain why such a system behaves in the same way (according to an observer co-moving with it) regardless of the velocity of the larger system that contains it (see, in particular, (2024, §7) and (2025, §5.2)). The reason, in a nutshell, is that there are systems whose laws are *not* invariant under Galilean boosts that behave the same way when boosted together with the observer. For example, the law for a classical wave is not invariant under transformation $x \mapsto x + vt$, yet one would not be able to figure out if the train is moving or not solely by looking at the vibrations of a string inside the train. Similarly, the law for the classic harmonic oscillator is not invariant under that same transformation, yet springs inside a train

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[9] See Murgueitio Ramírez (2025) for a critical discussion of the principle and for two different ways of making sense of it.

behave in the same manner (as described by the same differential equation) whether the train is parked or moving uniformly relative to the station.

The lack of invariance of these and other systems under boost transformations strongly suggests that the phenomenon captured by the observational role discussed in §2.1 is not, ultimately, about symmetries at all; physical transformations (i.e., a physical boost) that are symmetries and those that are *not* can both preserve the observations in question. And yet it does sound somewhat implausible to claim that physicists and philosophers are just completely wrong when suggesting that symmetries have something to do with the relativity principle or, more generally, with the preservation of observations inside closed systems. How can we resolve this situation? This is the task of the next and final section.

4 Two Notions of Invariance of a Law

We seem to face a dilemma associated with the observational role of symmetries. On the one hand, many physicists and philosophers have suggested that the fact that Galilean boosts are symmetries of Newtonian mechanics plays an important role in explaining why Newtonian systems are not affected by such boosts. On the other hand, the equations for the laws of some simple mechanical systems are not invariant under a transformation like $x \mapsto x + vt$. One way out of this dilemma is to suggest that many physicists and philosophers have simply missed the fact that the laws of some classical systems are not invariant under these transformations, and so to suggest the observational role is based on a mistake. However, this seems rather revisionary and implausible. Instead, in this section, I offer a novel way out that seems to be a bit less radical: each horn of this dilemma involves a different notion of symmetry, so the clash is only apparent. That is, I propose that there are *two* different notions of symmetries at play in this context,[10] associated with two different senses in which a law can be said to be invariant under a transformation. As we shall see, Galilean boosts (and other symmetries such as translations) can be symmetries of a given law according to one notion (in a way that makes the observational role come out true) and also fail to be symmetries of the same law according to the other notion.

One sense in which a law can be said to be invariant under a given transformation is very familiar from the physics and philosophy literature: the law is said to be invariant if the equation for the law is invariant under the transformation (or if the transformation maps solutions of the equation for the law to solutions). If the law is invariant in this purely *formal* sense, we say that the corresponding (mathematical) transformation is a symmetry of it. I will use "formal symmetries" to refer to the symmetries of a law in this sense. Note that mathematical transformations of the form $x \mapsto x+vt$ are *not* formal symmetries of the laws of systems such as springs or classical waves because the equations for these laws are not invariant under them. This, then, is a sense in which Galilean boosts, by which we mean mathematical transformations of the form $x \mapsto x + vt$, are not symmetries of these kinds of laws (in contrast, they are formal symmetries for the law of free fall). Notice

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[10] It is worth emphasizing that this context does not include the representational role, which suffers from the limitations noted in §3.1.

that this formal notion is tightly related to the nomological role discussed in §2.3: to say that the observers agree about the laws for the arrow is to say that the different solutions they use to represent such motion satisfy the same differential equations (e.g., those of objects in free fall). This would not be true if these equations were not invariant under Galilean boosts, as is the case of a spring or a classical wave.

But there is another sense in which a law can be said to be invariant under a transformation, one that, until now, has gone largely unnoticed.[11] Consider once again the train, and imagine that we have a string attached to two fixed points in the cabin. If we make the string vibrate when the train is at rest, we can describe the vibrations with the classical wave equation. If we make the string vibrate once again but now when the train is moving uniformly relative to the station, we can once again use the wave equation to describe these vibrations. That is, as seen by a person inside the cabin, the string obeys the exact same law (the same differential equation) in both cases. The fact that the very same equation can be used in the two instances even though the velocity of the system has changed relative to other systems suggests a sense in which boosts are symmetries of the law for classical waves, even though they are not *formal symmetries*. Since these symmetries cannot be inferred by looking at the mathematical form of the law, I will use "implicit symmetries" to refer to them.

For example, just by looking at $\ddot{x} = -\omega^2 x$ we would not be able to tell

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[11] Murgueitio Ramírez (2025) points out that there is this other sense of invariance of a law under a boost, one that he associates with the "Internal Galilean Relativity Principle." However, he does not say it is a *symmetry* of the law presumably because he was thinking of *formal symmetries* only, as is customary in contemporary discussions of symmetries.

that the spring-like objects modeled by this equation would behave in the same manner (as judged by someone co-moving with them) when the train is moving or parked at the station. In other words, the equation by itself does not tell us that Galilean boosts (understood actively or physically) are *implicit symmetries* of the corresponding law. As a second example, note that nothing in equation $\ddot{x} = 0$ implies that a ball moving with no acceleration in a train at one station behaves in the same way as in a train at a different station. Of course, we can check that translations of the form $x \mapsto x + d$ are *formal symmetries* of this law, but just from that it does not follow that the equation would have adequately modeled an object in free fall if we had been in a different region of the universe. In fact, if we had been in a universe with a privileged region R such that objects in R slow down on their own (similarly to an Aristotelian universe with a privileged center), $\ddot{x} = 0$ might have (successfully) modeled the ball only in regions outside R. And yet, even in that universe, $x \mapsto x + d$ would have still counted as a formal symmetry of the corresponding law. In other words, these two examples show that one cannot infer the implicit symmetries from the formal[12] ones!

Thus, there is a sense in which the orthodox position is right and a sense in which it is wrong. It is right in that there is, in fact, an interesting link between some symmetries and the preservation of certain observations. But it is wrong in that it has treated the symmetries in a purely formal

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[12] This should not be surprising; the implicit symmetries have to do with transformations of properties not explicitly represented by the variables of the equations for the laws, such as the speed of the system inside the train relative to the station or to a distant star, or the region in the universe the system occupies.

manner, whereas the symmetries that actually preserve observations (in the sense of §2.1) are the *implicit* ones. In other words, orthodoxy has made the (very common!) mistake of trying to explain why observations inside a closed system do not depend on the location, orientation, or velocity of that system (relative to some external system) by appealing to the invariance of the equations for the relevant laws under the corresponding transformations (or by looking at whether the corresponding transformations map solutions of the law to solutions). Once again, that this kind of explanation is defective is illustrated by the fact that many systems for which Galilean boosts are not formal symmetries still exhibit the same law-like regularities as judged by observers actively boosted along with them.

To end, note that many scholars have suggested that Corollaries V and VI to the laws in the *Principia* have to do with the symmetries of the laws. However, for the same reasons as noted above, it would be a mistake to think of the relevant symmetries formally (also note that the corollaries in question talk explicitly about the *motion* of the bodies, not of their laws). After all, many physical systems for which both corollaries apply have laws that are invariant under neither Galilean boosts nor accelerations (the spring and the string are, once again, good examples). Thus, if *implicit symmetries* hold the key to making sense of the observational role of symmetries and *formal* ones to making sense of the nomological one (since it is the invariance of the equations that captures whether two observers agree on the laws), it seems that it is the former that we need to invoke to make sense of these corollaries.

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