Review of *The Philosophy of Symmetry*, by Nicholas J. Teh (CUP 2024)

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Contents

1 Introduction

In his Cambridge Element, *The Philosophy of Symmetry*, Nicholas J. Teh introduces and systematises the conceptual aspects and significance of physical symmetries—and, in particular, those physical symmetries which only leave a subsystem invariant *qua* subsystem, but not relative to its environment (e.g., Galileo-ship-type symmetries).

Teh puts special emphasis on addressing the issue of how symmetries can be at once *formal* and *physical* by promoting an understanding of how representation works figuratively in physics: how mathematical formalism is used as a representational *medium* depends on how the modeller intends to use it; what the representational content really

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is, then, needs to be checked with due regard to what the representational medium *could* tell us given the modeller's intentions (as opposed to what it tells us if it is taken as an immediate stand-in for the world; in particular, what is expressed about the representational content in terms of propositions is not to be taken 'literally'[1]). Teh motivates his view on representation in analogy to how paintings represent, at least as understood and argued for by art historian and philosopher Michael Podro (1998) in his book, *Depiction*.[2]

And so, while at first sight one might say then that the overall goal of Teh's Element is just to demonstrate how Galileo-ship-type symmetries can be embedded into local gauge theory contexts, perhaps in the end an even more important mission for Teh is to articulate and develop a 'non-literalist' understanding of representation in physical theories. There is, however, also a third decisive theme to this Element over and above Galileo-ship-type symmetries in a gauge setting, and representation in physics—*viz.*, promoting Noether's formalism as a powerful tool for understanding Galileo-ship-type scenarios.[3]

In this review, we'll explore a few threads arising out of Teh's Element that we regard as being of particular significance—themes which, overall, demonstrate the incredible fecundity of his effort and thought. In particular, we'll (a) delve further into Teh's views about representation in the arts and sciences (§2), (b) consider Teh's conception of the 'dynamical approach' to spacetime theories (most famously associated with Brown (2005)) (§3), (c) assess Teh's novel conception of the relativity principle (§4), and (d) consider how Teh's views in the philosophy of symmetries connect up with the existing work in this field (§5).[4]

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[1] In personal correspondence, Teh has revealed that, while he accepts that one can write down propositions which are related to the content, he would consider such proposition to be mere abstractions. One can, indeed, identify such views in Teh's Element—for example, when he writes that "A representation is an embodied, performative kind of thought—we use the medium and its procedures to think the subject *in* the representation, and in so doing, we reenact the pattern of attention of the representation's maker(s), itself embodied in that medium and its procedures." (p. 7) We will use 'literally' in the following even for the non-propositional context—even though such an ascription makes, to wit, literally no sense.

[2] Teh's endorsement on Podro on the philosophy of painting implicates him in an essentially wholesale rejection of analyses by Elgin (2017a) and Goodman (1976), the former of whom we will discuss in significantly more detail below.

[3] For a recent edited volume on the physics and philosophy of Noether's theorems, see Read and Teh (2022).

[4] For a rightly-famous edited volume on the philosophy of symmetries, see Brading and Castellani (2002); for a more compact and recent survey of the literature on the philosophy of symmetries (of which Teh himself is co-author), see Brading et al. (2023).

2 Representation in art and science

In preparation for his account of physical symmetry (and not necessarily as a decisive statement of what representation is), Teh defends a 'non-literalist' account of representation in physics; one which aims at distinguishing clearly between representational *content* (e.g., an isolated physical system about whose internal structure we are uninterested) and representational *medium* (e.g., a mathematical test body) in a manner that Teh himself claims to be most closely connected to Cartwright on 'Fables and models' (Cartwright and Le Poidevin 1991). A general merit of taking the distinction between content and medium to be so central is that the substantial role of idealisations played in physics comes to the fore. More specifically, Teh's own take offers an interesting and valuable departure from previous work on this topic that has placed special emphasis on 'representation-as-if'—the idea that in particular idealisations "represent systems as if those systems possessed features they do not" (Potochnik 2019, p. 19) (e.g., a planet gets represented *as if* it were a point).[5] Teh identifies such notions as a distraction from the very distinction between representational content and medium to begin with. As Teh puts it with a simple example,

> it is not part of the representational content of a formal point particle model of a ball that the ball is in fact a point [as is the case on the representation-as-if line]; on the other hand, it is part of the (perhaps formally implicit) representational content that the empirical regime we want to model—the subject of the representation—is one such that it makes sense to invoke the formal device of a point. (p. 12, our addition)

As mentioned in §1 above, Teh's understanding of representation in physics is (at least) presented under recourse to the question of how art represents. As much as Teh's overall parallelism between representation in science and art is captivating—it truly is!—(and flattering: modellers in physics might well feel like Fra Angelicos, Botticellis, or Filippos in light of it!), some questions remain in the wake of his *tour de force*. Especially readers with more standard leanings towards similarity or structuralist positions on representation—see, for instance, Frigg, Nguyen, et al. (2020, §§3–4)—might well wonder whether they could not have achieved the same on *their* account of representation.

One important point to stress at the outset is that Teh aims at employing an *analogy* to representation in art. This becomes clear in a central passage characterising his notion of physical representation through empirical adequacy that, in this sense, is neither matched nor intended by representation in arts:

[5] Apart from Potochnik, see e.g. Frigg and Nguyen (2017) or Elgin (2017b).

> [A] physical representation is a kind of performative, embodied thought, in which we use the mathematical medium and its procedures (geometry, partial differential equations, the symmetries of these objects, etc.) to *embody a certain pattern of attention toward an empirical scenario*—the kind of attention that is concerned with understanding how to model and predict and measure, and to extend that understanding to novel scenarios. (p. 9, our emphasis)

It is arguably thereby that Teh can also argue to have given a sense of where the analogy breaks down.

How satisfactory is this (vague) boundary drawn by Teh here? It's helpful at this point then to look to the wider literature on representation in art and science.[6] According to Elgin (2017a), for instance, the epistemic function of both art and science is to achieve *understanding*. The difference, says Elgin, is only that both are committed to a different trade-off between precision and mutual agreeability: the more precise a representation is, the more difficult it is for different subjects to agree on it (and *vice versa*); arts are then, contrary to the 'familiar stereotype' (p. 39), to be seen as in principle arbitrarily precise: 'every difference in certain respects—the thickness of line, extension of the leg, the timbre of the voice—can make a difference to what a work exemplifies or represents' (p. 39). By contrast, science sacrifices such arbitrary precision for the sake of intersubjective communicable representations:

> Science places a premium on intersubjective agreement. Because scientists build on one another's findings by taking them as unquestioned premises, they want it to be determinate and determinable what those findings are. [...] Because artists do not build on one another's work in the same way as scientists, they do not have the same incentive to sacrifice precision. (Elgin 2017a, p. 40)

Teh does not delineate *such* a boundary between (representation in) art and science.[7] Rather, to the contrary, he seems to move away from the inter-subjectivity of

[6] See Frigg and Hunter (2010) and Bueno et al. (2017) for recent collections, with many articles with themes overlapping with Teh on representation.

[7] Yet another related way of getting to a central disanalogy between art and science is from the angle of discovery. French (2017) argues that scientific theories are more discoverable (that is, by different people under different circumstances) than specific artworks. This links up to agreement and ultimately to precision again—the higher the precision, the less likely to be discovered. Now, although it's true that Teh in fact rejects the analyses of Elgin (2017a) and Goodman (1976) and as such he might not feel compelled to engage with these distinctions and ways of drawing the line between representation in art versus science, this is not particularly evident from the Element, and we would have liked—page limitations on an Element notwithstanding!—to have heard more about it.

Figure 1: Donatello's *Feast of Herod* (1423–1427)

science by steering the interpreter of physical theories to become more liberal and free-spirited in their reading of what a physical theory represents when he interludes rather standard and sober discussions of physics with rich, dynamic interpretations of e.g. an ancient wedding feast—Donatello's *Feast of Herod* (reproduced in figure 1).[8] Consider for instance the following passage:

> On this view, our appreciation of the (representational) possibilities inherent in a representation turns in part on our appreciation of the techniques and procedures of its medium. As an illustration, consider the linear perspective technique, of which there was a growing awareness amongst Florentines in the lead-up to the quattrocento, but which did not reach its maturity till it was geometrically articulated by Brunelleschi and in this form taken up by artists such as Donatello and Masaccio. Donatello's "Wedding Feast of Herod" [...]—a bronze relief on the baptistry of Siena's Duomo—is exemplary of this "taking up" of the medium's technique: here the linear perspective construction—a surface feature of the medium that properly belongs to the science of optics—is evident, but equally evident is how it is bent to a representational use; *witness the energy that is delivered to the representation when—in following the "geometric pavement"*

[8] In personal correspondence, Teh has doubled down on his position which sees the freedom to engage in practical reasoning in physics, while underestimated by many, as analogical to painting.

> *construction up to its vanishing point—we are made to pass through three different scenes, which are thus united in the representation*. (pp. 41–2, our emphasis)

After said analysis of this piece, Teh proceeds to the analogy with modern physics:

> *The situation with general covariance (or local symmetry) is somewhat similar*. Einstein no doubt had a growing awareness of the properties of general covariance—conceived of as a mathematical medium—but the proper technique for handling this idea was not articulated until the contribution of Emmy Noether, the pure mathematician who first deeply understood the rhythms and textures of general covariance, and who by all accounts knew and cared rather little about the physics. Noether's mathematical understanding of general covariance was encapsulated in two theorems—often simply referred to as "Noether's theorems" by physicists—that will be bent to the ends of physical representation in this section and the next. (p. 42, our emphasis)

There seems to be a dilemma then: Teh's excitement regarding artistic representation (see italicised text above) is either only to be seen as rhetorically enforced to hold for general covariance as well (see italicised text above), or the inter-subjectivity of representations in physics seems lost.[9]

That being said, we do think that it would be possible to expand upon and bolster the analogical reasoning which Teh seeks to deploy here. As stressed by Podro (1998), a medium in painting has momentum *qua* medium—the same, indeed, is true for mathematical media, and (like artistic representation) physical representation can benefit from good impulses and the momentum of the media in the hands of the expert practitioner. To use Teh's example from above: in the Feast of Herod, the method of linear perspective (which was originally a branch of optics—consider e.g. Alhazen's *Book of Optics*, prepared in the early 11th century—and was a tool whose representation fecundity was *prima facie* unclear) is leveraged in service of the representational subject. In the case of general covariance, there is likewise a momentum in the mathematical media of e.g. Noether's theorems (and, like linear perspective, the representation fecundity of those media was *prima facie* unclear—see Read and Teh (2022)) which can be fruitfully put to work in service of the representational subject.

[9] Teh has stressed to us that the guiding norm for *physical* representation is still empirical adequacy (see again his passage from p. 9 quoted above), but it is not clear to us that this is sufficient for guaranteeing inter-subjectivity.

In any case, let's now move on, and consider further what we in fact take to be some salient disanalogies between representation in art and science. A related phrasing of the difference between how representation works in the arts versus in the sciences is in terms of indeterminacy rather than in terms of the degree of intersubjective disagreement: pieces of art such as paintings, poems, or short stories have various layers of readings at once. As Darby et al. (2017) put it in the context of fiction:

> Is the governess in James's *The Turn of the Screw* haunted by supernatural apparitions or merely by symptoms of her own mental instability? Which of the two apparent realities in Smith's 'In the Imagicon' is the real world? Is the eponymous Babadook in the recent film a real monster or merely a representation of Amelia's grief? It seems to many (ourselves included) as if there are no determinate answers to these questions. (Darby et al. 2017, p. 102)

Notably, this indeterminacy—(i) that there is no single overall way of making sense of the piece under consideration—is very different from other (albeit not characteristic!) indeterminacies of art (and of fiction in particular), namely (ii) indeterminacy due to incompleteness (it is left indeterminate how many children Lady Macbeth has from the fictional work in which she stars), and (iii) indeterminacy inherent to the representational content (a book on, say, the GRW interpretation of quantum mechanics is arguably about a supposed objective indeterminacy in the world). (Notably, the indeterminacy in art due to incompleteness, i.e. (ii), is typically understood as being of an epistemic stripe only: while strictly speaking the absence of any fact about the exact number of children of Lady Macbeth in *Macbeth*, say, does in principle suggest true indeterminacy, in practice the background context is sufficiently clear to disqualify such a reading.)

With a distinction such as this regarding different notions of indeterminacy on the table, we are led to believe that Teh in many cases where he claims to invoke a parallelism to indeterminacy in art has in mind only what seems to be indeterminacy due to *incompleteness* (so (ii)). Consider for example his introductory discussion of how the massless Klein–Gordon equation

$$\eta_{ab}\nabla^a\nabla^b\phi = 0 \tag{1}$$

is to be understood as representing a subsystem *relative to* a (not explicitly modelled) environment. Evidently, this understanding of the content of (1) concerns facts that are left out as indeterminate and unspecified by this equation *per se*.

But is such an observation controversial or novel? Who would have thought that 'formulae' on their own say much about the world? Perhaps—and more charitably understood—Teh offers us with his work focal cases where this fact gets borne out especially clearly. This is not to say that one could never draw an analogy in the first sense of indeterminacy, (i): there are many layers to equations such as the Einstein equation, for instance, which allow for similarly multi-layered, partly-even-mutually-contradictory takes on structures from physics, just as do beautiful, interpretation-rich paintings. Consider e.g. the spin-2 view on general relativity (Barceló et al. 2014; Deser 1970; Linnemann et al. 2023) versus hydrodynamic views on the same theory (Hu 1996; Jacobson 1995; Padmanabhan 2025). On the spin-2 view, one would typically understand the gravitational degrees of freedom as being on a par with those of the other (material) fields; by contrast—and arguably in contradiction—on the hydrodynamical view, one traditionally regards the metric field as being a high-level field with underlying novel degrees of freedom such that this high-level field should *ipso facto* perhaps not even be quantised. More generally, in the spirit of Feynman, a physicist's understanding of an equation arguably coheres with their ways of deriving and reformulating that equation.[10]

If one considers what's known as 'the' wave equation ((1) is of course the prototypical wave equation), it is (no doubt) context-dependent which phenomena 'out there' in the world (water waves, electromagnetic waves, etc.) one takes the equation to describe. The physical structures to which one takes the constants and variables to refer are context-dependent. But these things can be specified further; there is nothing indeterminate about them by nature. Moreover, given the idealised nature of the wave equation (it just holds for a certain easy-to-treat regime—real wave phenomena need not at all be linear), many further aspects of what the equation actually describes are left unspecified. For instance, that electromagnetic waves have no carrier medium cannot be formally read off of Maxwell's wave equations.[11] But, to our minds, that is just something that wave equations on their own do not qualify; this is no indeterminacy in any interesting sense as we find it, however, as when we encounter artworks with various layers and angles of interpretation.

In the end, Teh draws all sorts of intriguing parallels between painting and physics—but ultimately it isn't clear (at least to us) where or why he really wants to depart from standard convictions on the need for agreement and determinacy. We take it that some of the intuitive pull and attraction in his work lies in his suggestive talks of paintings and physics in parallel, as if there were more representational freedom in physics than one might have thought. But in fact, as we have seen, the cases in physics which he studies

[10] In personal correspondence, Teh has pointed out to us that he is indeed primarily after describing an indeterminacy in (the representation of) physics of type (i)—in analogy to representation in the arts. For instance, the notion of reference frame in GR is highly polysemous.

[11] Cf. Bilson-Thompson et al. (2023) and Cheng and Read (2021).

seem only to be ones of representational incompleteness (in the sense of omission from the depiction).[12]

In addition to this, the literalism which Teh seeks to attack is not always straightforward to identify in the flesh. Consider as one example Teh's criticism of a point particle in Newtonian mechanics: who *genuinely* thinks that Newtonian mechanics describes how points—in the geometrical sense—'move'? Admittedly, there is talk of point particles as stand-ins for larger objects—these larger objects are taken to behave *as if* they were point particles; so, in a sense, then point particles are part of the representational content for some. But what one indeed means then is (in agreement with Teh, it seems—see his clarifications on the notion of the representation-as-if-talk at the end of p. 12) that larger objects can be replaced by regular, close-to-non-extended objects without any (relevant) internal structure. (However, the fault typically seems to go the other way around: who can genuinely imagine point particles as what they *formally* (i.e., left uninterpreted) are? Compare this to how school children do not think of a point 'in geometry' as points but rather as extended, albeit vanishingly small, entities after all.)

To be charitable, let's identify some actual literalists in contemporary philosophy of physics.[13] Actual literalism can typically indeed be found in contexts of the philosophy of physics—especially those which are removed from concrete modeling scenarios, and rather strive for overall metaphysical considerations (think of discussions of the arrow of time in the context of general relativity). In particular, literalism is standardly found among those who have signed up to doing naturalised metaphysics: while the methodology of naturalised metaphysics is by now quite diverse and systematically explored (naturalised metaphysics might be informed by science at both the methodological and the content-level, or at just one of them—see e.g. Emery (2023)), many contributors still seem to, at least at times, want to read out what the world is like from the physics in a non-qualified way (take primitivist account of laws of nature of Maudlin (2007), for instance; or those of wave function realism), or at the very least seem to think that naïve realist interpretations are worth discussion if only for their debunking.

[12] And then again it is the question of why this point is novel, and needs the reference to art to be put into focus, to begin with: at least since the practice turn, it is widely agreed upon that theories and models are more than their syntatic statements but involve know-how, practices, use cases, etc. to be related to the world and made sense of.

[13] It is worth pointing out that common talk about the mathematical structures does not even acknowledge that there is a distinction between representational content and vehicle. As Caulton (2024) explicates, physicists should, however, not *literally* be taken to identify mathematical structure with the world; what they have in mind with statements such as 'a particle *is* an irreducible [group theoretic] representation of the Poincaré group' is that a particle is *represented* by such mathematical structure (whether literally or in a more sophisticated fashion).

Indeed, in presumably fundamental contexts, there is often no way around discussing what it would mean to take all of the basic laws literally, or all regions in a basic model (think of white-hole-to-black-hole tunnelling via an Euclidean region).[14] This in a way cuts the chase to a core issue with all sorts of sophisticated accounts of representation, or idealisation—and their demand to let practice speak: in the remote regimes of fundamental physics a literalist approach is all we have, at least as a departure point. But that does not mean we should not consider this to be a serious limitation.

3 Reading of the dynamical approach

Let's move on. In §2.2 of his Element, Teh puts forward an understanding of the 'dynamical approach' to spacetime theories due to Brown (2005) and Brown and Pooley (2001, 2004). As Teh has it, in the particular context of special relativity (which, after all, is the context in which much of the dynamical/geometrical debate has unfolded historically), according to the *received* understanding of the dynamical approach, the Minkowski metric is ontologically reduced to the symmetries of matter fields: the Minkowski spacetime is nothing over and above a codification of the symmetries of the dynamical laws.[15] According to Teh, however, there is also available a distinct, non-ontological, *representational* reading of the dynamical approach to special relativity:[16]

> [T]here is a second way of understanding Brown's claim that in SR, the Minkowski metric η_{ab} is merely a codification of the dynamics, and that is to understand "dynamics" here in a representational mode: as the evolution of the subsystem degrees of freedom of an empirical scenario (which presumes the background context of an environment, a particular regime of interest involving certain length scales, time scales, and measurement accuracy, etc.). From this point of view, the metric η_{ab}, the equations of motion, the relevant boundary conditions, and the Poincare [*sic*] symmetries—various aspects of the mathematical medium of the representation—are *all* codifications of the dynamics of an empirical scenario. Furthermore,

[14] But of course, following Cartwright (1999), Teh rejects 'fundamentalism' about physics, and so our point about literalism seemingly being called for in such cases might well be moot. On e.g. string theorists, Teh will more likely say that they are practitioners who feel the momentum of physically-inflected mathematics, and as such, no 'literalism' is necessary here.

[15] This is, indeed, a standard and accurate summary of the received understanding of the dynamical approach to special relativity: see Brown and Read (2022).

[16] Interestingly (albeit from a very different angle), Fletcher (2025) also proposes to understand the dynamical approach as a thesis about representation. We'll defer to a future work investigation into how Fletcher's reading compares with Teh's.

> while this representational reading of Brown's dynamical approach is compatible with various ontologies, one thing that is clear on this reading is that the mathematical medium of a physical representation should not be literalistically interpreted as suggesting some particular ontology. Understood in this way, the dynamical approach is not a statement about ontology at all. (p. 15)

The second, alternative reading of the dynamical approach to special relativity is first and foremost interesting insofar as it reveals an ambiguity in the notion of 'codification': it can mean ontological reduction—as the case ascribed to the received reading above—but it can *also* mean something like an object deployed in order to achieve some representational end.

That said, some worries about Teh's reading of the dynamical approach suggest themselves immediately: Teh's proposal lumps everything (metrics, boundary conditions, symmetries, etc.) into one indistinguishable whole; there are no ontological claims we can make based upon detailed theoretical structure; all that we can acknowledge (apparently) is that we ascribe dynamics to whatever in fact comprises the world. Perhaps a charitable reading of Teh here is to provide a *transcendentalist* conception of the world: we never see the world in itself, but only through its representation. But in fact, for Teh, the situation is even more drastic than this: Teh's background belief is that there is no such thing as 'the world in itself', echoing views of Thomists, Aristotelians, and Anscombian Wittgensteinians, and being in the spirit of Wittgenstein's "The human body is the best picture of the human soul." All talk about explicating ontology is, then, to be understood as talk about explicating representation.

On his own preferred reading of the dynamical approach, Teh writes:[17]

> I should acknowledge that my gloss on Brown runs contrary to the mainstream interpretation of the dynamical view by subsequent commentators such as Read (2020) (on the other hand, it is somewhat closely related to the interpretation of Brown given by Stevens (2020), albeit without the Humeanism). (p. 14)

Teh is correct to identify divergences from Read (2020), since the latter indeed adopts a 'received' reading of Brown (2005) (at least as an exegetical matter: after all, Brown and Pooley (2004) describe Minkowski spacetime as a 'glorious non-entity'!). But highlighting affinities with Stevens (2020), we think, could be misleading. After all, as Teh himself acknowledges, the core of Stevens' account is a liberalised *Humean* reading of

[17] References to journal articles have been updated in this quotation.

Brown (2005)—one in the spirit of the 'regularity relationalism' of Huggett (2006). But since Stevens is exploring regularity relationalism as a way of *making sense* of the ontological reduction thesis of the dynamical approach to special relativity, he also appears to be closer to the 'received view'. Moreover, Stevens' entire approach is predicated, as we've mentioned, upon a version of Humeanism—but Humeanism is something which Teh emphatically abjures! Thus, it seems to us that it is best to understand Teh's reading of the dynamical approach as *sui generis*.

The final point which we'd like to make regarding Teh's discussion of the dynamical approach is this. Despite Teh's evidently regarding his project in his Element as in the spirit of the dynamical approach, perhaps—by lumping everything into a codification of the behaviour of physical bodies as leveraged in a particular modelling context—in the end there turns out to be no substantial difference between the dynamical and geometrical approaches anymore! (This would arguably be in the spirit of similar claims made by Pooley (2013) and Read (2020) in the context of the dynamical approach to general relativity.) From what we understand, Teh would insist that there is nothing wrong with an 'indistinguishable whole', insofar as they're all permeated by dynamics; the quintessence of the dynamical approach really being not a way of bringing into focus a formal dynamical-geometrical distinction but rather stressing the dynamical character of physics never mind exactly such formalities.

4 Understanding the relativity principle

Let's turn now to Teh's two major—and interlinked—themes within the philosophy of symmetry: on the one hand the relativity principle in GR, or more generally speaking Galileo-ship-type symmetries in gauge theories, and on the other hand the machinery of Noether's first and second theorems. It is in particular in §§4–6 of his Element that Teh develops an account of the relativity principle in GR (and of empirical significance of gauge symmetries more generally) by pulling together, among others things, notions of general covariance, and Hamiltonian charges, while turning again and again, as Teh puts it, the Noetherian crank.

Teh's account is as follows. The relativity principle has a literalist 'geometric', and a non-literalist 'representational' reading—the latter being closely tied to Teh's understanding of the dynamical approach (see §3), and Brown and Sypel's understanding of the relativity principle in particular (Brown and Sypel 1995). On the geometric reading, the relativity principle (say, in special relativity, or Newtonian physics) concerns how an isolated subsystem transforms relative to its environment under an element of the spacetime's stabiliser group. But on such a conception of the relativity principle, it is unclear how the relativity principle can ever be instantiated in general relativity (GR) in an interesting manner: there are simply no non-trivial automorphisms of a generic metric to begin with. Instead, then, Teh proposes adopting his representational perspective on the relativity principle, on which the question of extending the relativity principle to GR becomes, or so he claims, meaningful. The 'essence' of the representational relativity principle is exemplified by Teh as follows:

> [W]hen in SR one goes on to define a geometric object (the Minkowski spacetime metric) whose stabilizer group is precisely the symmetry group of the RP, one is merely codifying [...] *aspects of the comparative behaviour of different systems of physical rods and clocks in relative motion, where the behaviour of the target subsystem (whose inertial frames are related by these symmetries) is being measured with respect to an environment frame, from which the subsystem is dynamically measured*. (pp. 34–35, our emphasis)

In other words, the 'representational' relativity principle regards how an isolated subsystem behaves relative to its environment (as expressed in italics in the above quote) but without tying this to a specific mathematical formulation, i.e. to a specific 'representational vehicle'. And so, the stabiliser group is only a representational vehicle for expressing this idea, say, in the context of SR as the case in the quote—but not at all the essence of the relativity principle. In GR, rather, a different approach seems required—and, as Teh shows by 'construction' over the course of his Element, possible.

How, then, could the relativity principle be understood in GR from this representationalist perspective? And, more generally, how could a gauge symmetry be understood to be empirically significant?[18] Teh's proposed recipe is to translate the central relationships between subsystem and environment in terms of symmetry transformation into ones in terms of a charge—and ultimately back again (more on this later). Concretely, for a theory with a covariant phase space formalism, Teh proposes to proceed as follows: first, identify the gauge symmetry with what is called a 'non-trivial Noether charge'; second, adapt the non-trivial Noether charge by introducing boundary terms (modeling the system's isolation) to the Lagrangian so that it matches a Hamiltonian charge.[19] Only if both steps succeed (importantly, not every gauge theory is linked to a non-trivial Noether charge; and not always can the right boundary conditions be found) can we say that the gauge theory codifies a symmetry transformation associated with a Hamil-

[18] Of course, this is a question which has occupied many philosophers in recent years, the *locus classicus* of which is Greaves and Wallace (2014).

[19] The covariant phase space formalism was introduced by Iyer and Wald (1994, 1995), Lee and Wald (1990), and Wald (1993).

tonian charge—and with it a sense in which the isolated subsystem is invariant as such, albeit not relative to its environment.

Concerning the first step: that, for a given Lagrangian, symmetries and charges (or, first of all, rather currents) stand in a one-to-one correspondence is a well-known lesson from Noether's theorems.[20] In the context of a Lagrangian theory, distinguish then between Noether's two theorems as follows: the first links a rigid symmetry (relative to a Lagrangian) to a current, which is conserved only if the equations of motion hold. The second links a gauge symmetry (relative to a Lagrangian) to a current that is the sum of an exact term—a superpotential—and a term proportional to the equations of motion; consequently, the on-shell version of such a current (where the term proportional to the equations of motion vanishes) is mathematically identically zero. A charge can be associated with a current by integrating it over a Cauchy surface. Importantly, the on-shell exact current J_ζ from Noether's second theorem for symmetry ζ does not just give rise to a charge Q over Cauchy surface Σ; but Q can be understood as a 'corner' charge Q through Stokes' theorem, i.e.:

$$Q = \int_\Sigma J_\zeta = \int_\Sigma dU_\zeta = \int_{\partial\Sigma} U_\zeta, \tag{2}$$

where U_ζ is the superpotential relative to ζ. For a fixed slicing, this charge depends on the symmetry transformation ζ *and* the Lagrangian; by changing the boundary term of the Lagrangian (thus keeping the same space of solutions), the corner charge can be to some extent adapted (as needed for the proposed procedure).[21]

The core idea, then, is really to view gauge transformations as potentially yielding non-trivial corner charges. Gauge theories with non-trivial corner charges can then be used to describe isolated subsystems (to be expressed with the right boundary conditions) that are invariant under a certain symmetry transformation but not relative to their environment—provided that the non-trivial corner charge corresponds also to a Hamiltonian charge.

Everything that we've just recapitulated can, in addition, be tied to a notion of general covariance which Teh regards as being *substantial*—namely, one which features non-trivial corner charges or even successfully extends the relativity principle; such a proposal is developed in significantly more detail in Freidel and Teh (2022), and has also been discussed (and critiqued) recently by Read (2023). For novices to the philosophy of symmetries, it may seem suboptimal from a pedagogical point of view that

[20] Albeit with some subtleties. There are arguably cases where charges do not always exist: see Brown and Holland (2003, §5) for examples.

[21] For a clear presentation of the mathematics here, see Ciambelli (2023).

Teh devotes considerable effort to discussing general covariance and more 'substantial' variants *first*, before fully clarifying how the corner charge represents the extended relativity principle in GR. On the other hand, if one is familiar with the field, then Teh's way of proceeding is natural, rightly acknowledging properly that the attempt to express the relativity principle in GR has traditionally been tied to the question of how to formulate a physicaly significant variant of 'general covariance'. In any case, it is unfortunate that the crucial connection between corner charge, Hamiltonian charge, and symmetry as an extension of the relativity principle is, at a general level, addressed in only about three pages (§5.2). Given its centrality to the entire Element, this is something which Teh could have unpacked in significantly greater detail, in particular on the question of how the Hamiltonian generator links back to a symmetry, and how to think of the symmetry as relating (explicitly modeled) system and its environment. (To be fair though, the point gets addressed in more detail *by example* in the context of electrodynamics—and maybe one cannot ask for more in a short Element such as this.)

In any case, there is a great deal that even experienced philosophers of physics working on symmetries will understand much better after having been exposed to this *coup de maître* from Teh. One key insight concerns Einstein's thinking about local gauge symmetries, including the Einstein–Klein dispute on the status of Noether currents from her second theorem. As Teh shows convincingly, Einstein was right to stress the dependence of currents from Noether's second theorem on the equations of motion *vis-à-vis* Klein (see, for a pedestrian's demonstration, Linnemann (2020) in reply to Wolff (2013)): he had already been aware of the important linkage of these on-shell exact Noether currents to corner charges. However, there are many subtleties in Teh's story that Einstein had not known:

> [T]he place where Einstein's understanding was most lacking was in his grasp of (i) the relationship between a choice of a Lagrangian L and a choice of boundary conditions, (ii) the potential mismatch between the Noether charge corresponding to some L and the Hamiltonian charge corresponding to some choice of boundary conditions, and (iii) the potential appearance of infinite-dimensional symmetries [...] in the asymptotic limit. (p. 62)

Unfortunately, there is little elaboration on point (iii) in Teh's Element, though it is praised as revealing that 'the search for Yuyi's boat in GR does not so much result in a replication of the subject, but a novel and radical reworking of it' (p. 62). Another revealing aspect of Teh's narrative concerns notions of general covariance and Kretschmann's objection. The link between general covariance, Hamiltonian charges, and the relativity principle (for an appropriately isolated system with the right Lagrangian) clarifies the intuition that general covariance entails more than a mere formal requirement. By showing that general covariance is necessary for a current but not sufficient for a non-trivial corner charge, Teh highlights how much structure is hidden in generic general covariance and how closely it aligns with a substantial, non-formal physical concept of the relativity principle.

5 Philosophy of symmetry

In recent philosophical discussions of symmetries in physics, authors typically proceed by (a) restricting attention to the symmetry transformations between models of a given theory which relate models which are empirically equivalent (for some, this will be part of the *definition* of a symmetry transformation, while for others it won't; moreover, what it means for two models to be empirically equivalent will require explication: for details here, see Dasgupta (2016) and Read and Møller-Nielsen (2020b)); (b) considering whether (or under what circumstances) one is justified in regarding those models *ab initio* as representing the same physical states of affairs (i.e., whether one is justified in regarding those models as being *physically* equivalent, where the notion of physical equivalence is stronger than empirical equivalence) or whether one can only do so after finding some 'metaphysically perspicuous explication' of their common ontology (this is the debate between 'interpretationalism' and 'motivationalism' in the philosophy of symmetries—see Luc (2023), Møller-Nielsen (2017), and Read and Møller-Nielsen (2020a)); (c) assessing the best way in which to articulate the common ontology of those symmetry-related models (this is the difference between 'reduction' and 'sophistication'—see Dewar (2019) and Martens and Read (2020)).

In his Element, Teh makes a number of points which relate to these issues in the contemporary philosophy of symmetry. Let's begin with some comments which Teh makes in relation to (a) above—i.e., the question of whether (and when) symmetries relate empirically equivalent models, and of identifying the empirical content of models of theories. On this, Teh writes:

> Next, in order to avoid controversy surrounding what a symmetry is, Read and Martens introduce the minimal notion of a symmetry as transformations "...which (whether by definition or otherwise) are regarded as relating empirically equivalent models" (p. 7 of Martens and Read (2020)). At this point, representation is clearly on the scene, but if it is to be physical representation in the sense that I have established, then one needs to hear a lot more about the subject of the representation (in particular its subsystem-environment structure and the relevant scales in play) before

> one can arrive at a sensible judgment about whether two solutions are in fact "empirically equivalent." Since much of the literature in this vein seems content to ignore these details in its investigation of symmetry, its ends seem largely orthogonal to my own, a point that will further emerge as we now turn to the consideration of two pairs of approaches to symmetry that are discussed in this Element. (pp. 26–7)

As we see things, Teh isn't entirely fair to the literature here in imputing to it a failure to recognise the subtlety involved in articulating when models of physical theories are empirically equivalent. To take three examples: (i) Dasgupta (2016) dedicates the latter half of his article to cashing out exactly what empirical equivalence amounts to, in terms (for better or worse) of Quinean observation sentences, or of 'how things look'; (ii) Read and Møller-Nielsen (2020b) dedicate much of their article to explicating how the empirical equivalence of models can't be ascertained *ab initio*, but has to be established on the basis of delicate, 'hermeneutic circle'-style reasoning dependent upon the theory is used in practice (all of which should be congenial to Teh); (iii) Wallace (2022a,b,c) specifically spends much time articulating how empirical equivalence (or otherwise) depends upon how theories are used in practice. In our view, Teh's comments about empirical equivalence would seem to find their mark better against e.g. Weatherall (2016b), for whom the notion of empirical equivalence does indeed seem to be somewhat of an afterthought in his explication of the notion of theoretical equivalence, in that article understood in terms of categorical equivalence.

The second point to make is this. Later in the same section of his Element (§3.3), Teh considers the question of whether physical theories have 'surplus structure', and writes that

> there is the issue of how one should interpret the question of whether a certain structure is "surplus" or not. If the question is one of whether, for instance, the local U(1) symmetry of electromagnetism plays a role in *physical* representation (as opposed to a role ascribed to it by *a priori* metaphysical or semantic considerations), then not only is the question relevant to the present inquiry, but it has also been a central topic of discussion and interpretation *within* physics in the last century. On this conception, whether a structure is to be classified as "surplus" is something that needs to be adjudicated with respect to the structure's representational use in the context of various empirical subsystem-environment configurations. (pp. 27–8)

On this point, we're more inclined to agree with Teh: attempts by e.g. Weatherall (2016b) to identify 'surplus structure' at some entirely formal level are arguably at least not the whole story, for they are not *per se* sufficiently attuned to how such structure might be leveraged in representational practice. To take one example, Weatherall and Meskhidze (2024) argue that the theory of 'teleparallel gravity'—a curved-spacetime theory empirically equivalent to general relativity[22]—has 'surplus structure' as compared with general relativity. But given e.g. the greater suitability of teleparallel gravity to model physical phenomena such as those occurring on black hole boundaries, is it in fact reasonable to regard as 'surplus' the very structure which makes this possible?[23]

The final point which we'd like to raise here is more constructive. Again in the same section (§3.3), Teh tells us that

> since Grothendieck's "Pursuing Stacks" and the introduction of the Batalin–Vilkovisky formalism roughly 40 years ago, mathematicians and mathematical physicists have on the whole shied away from taking the naive quotient of a space with symmetries acting on it, preferring instead to work with what is known as a "quotient stack" (or at the infinitesimal level, with an L^∞-algebra), which retains information about the different ways in which isomorphic objects are related. (p. 28)

Let's think about this in a little more detail, from the point of view of the above-mentioned distinction between 'reduction' and 'sophistication' about symmetries. Recall that, according to Dewar (2019), when one has a physical theory with symmetries, one should (i) 'forget' about structure such that the models are now isomorphic, and (ii) then apply anti-quidditism/anti-haecetism one's interpretation of those models such that one can regard them as representing the same physical state of affairs; to follow this approach is to (internally) 'sophisticate' a theory.[24]

Now, the above passage from Teh suggests that there might be interesting connections to explore between the 'stacky' programme and sophistication. And indeed there are! To see this, first recall the following passage from a different article by Teh and two co-authors:

> [One can define] a richer structure called a moduli stack, in which one does not merely assign (categorical) sets of objects to regions of the base space, but rather a groupoid that includes information about the non-trivial automorphisms of the objects, and thus allows one to keep track of the various non-trivial ways in which they glue into families of objects.

[22] Notwithstanding the points raised by Wolf and Read (2023), which we'll set aside here.

[23] For further elaboration of this point, see Wolf and Read (2023) and Wolf et al. (2024).

[24] Dewar (2019) also has a notion of 'external' sophistication, which we won't discuss further here—for details, see Martens and Read (2020).

> [...] taking $\mathscr{C}_A$ as one's local theory is a key step in passing to the richer framework of moduli stacks—thus, from a broader mathematical perspective, one way of phrasing the moral of our philosophical discussion is that, in gauge theory, there are very strong grounds for thinking of a collection of models as a stack. (Nguyen et al. 2018, p. 27)

Here, $\mathscr{C}_A$ refers to a version of electromagnetism, understood categorically, with (i) objects given by models $\langle M, \eta, A\rangle$ with M a differentiable manifold, η a Minkowski metric on M, and gauge fields $A \in \Omega^1(M, \mathfrak{u}(1))$, and (ii) morphisms given by gauge transformations (this is $\overline{\mathbf{EM2}}$, in the terminology of Weatherall (2016a,c); cf. March et al. (2025)).

Teh is certainly correct that moduli stacks are worthy of the attention of philosophers of symmetries; that being said, it doesn't seem to us that what Nguyen et al. (2018, p. 27) say about the connection between $\mathscr{C}_A$ as presaging moduli stacks is quite correct. The reason for this is that there is a crucial distinction between category theory being used in order to encode interpretative standards of equivalence between models (on which see March (2024a), March et al. (2025), and Read (2025b)), versus the *objects themselves* being understood categorically: in the case of electromagnetism understood via moduli stacks we have an instance of the latter, but not in the case of the theory $\mathscr{C}_A$!

Let's explore this in more detail. What would a version of electromagnetism formulated in terms of moduli stacks actually look like? It's not so hard to give a characterisation of its models.[25] These will be (in the source-free case) $\langle M, \mathscr{B}\mathrm{U}(1)_\omega\rangle$, where $\mathscr{B}\mathrm{U}(1)_\omega$ is the moduli stack of principal U(1) bundles with connections, itself understood as a groupoid (i) whose objects are given by pairs (P, ω), where P is a principal U(1) bundle over M and ω is a principal U(1) connection on P, and (ii) whose morphisms are given by gauge transformations, i.e. vertical principal bundle automorphisms which respect the connection. Evidently, this is just a different version of electromagnetism from that encountered in the philosophical literature up to this point—whether Nguyen et al. (2018) or Weatherall (2016a,c) or any other source!

Does this version of electromagnetism based upon moduli stack constructions count as a reduced or as a sophisticated theory? Well, since in this case all gauge symmetries are now built into the models themselves, there is a certain sense in which—when one is considering transformations which relate models!—our original version of electromag-

[25] Understood as its 'kinematical possibilities', which is all that we'll need for our purposes here; it would certainly be interesting to consider dynamics for such versions of electromagnetism, and whether they can avoid the kinds of pathologies identified by March et al. (2025) (in the different context of categorical approaches to certain geometric alternatives to general relativity), but we'll defer that task to another day.

netism (let this be electromagnetism based upon vector potentials) has been *purged* of symmetries: the only remaining symmetries are the identity! As such, the 'stacky' version of electromagnetism—perhaps surprisingly—looks to be a *reduced* rather than a sophisticated theory![26]

There are some additional questions here which are also worth exploring in further detail. For example, March (2024b) characterises theories which are not 'intrinsically' formulated as those which feature equivalence classes in their definitions.[27] Strictly speaking, our 'stacky' version of electromagnetism does not do this. However, it is possible to given an alternative characterisation of such moduli stacks in terms of 'stacky' quotients, which *do* make recourse to equivalence classes in their definitions. Now, of course, one could say that this is no problem: it merely tracks the fact that one can characterise a Newtonian 'standard of rotation' either in terms of an equivalence class of derivative operators $[\nabla]$ or 'intrinsically', as the object $\circlearrowright$ (see Weatherall (2018)), or conformal structure as an equivalence class of metrics $[g_{ab}]$ or 'intrisically', as a conformal metric density $\mathscr{g}_{ab}$ (see Adlam et al. (2025)). However, since one can always (it seems) simply insert additional morphisms into the objects of one's theory themselves (as in this 'stacky' version of electromagnetism), in what sense does this offer an improvement to 'intrinsicality', or 'perspicuity'? (Cf. again Jacobs (2022) and March (2024b).)

In summary, then: it seems to us that Teh has done the philosophy of physics a service by introducing moduli stack constructions into the literature. However, it does not strike us that everything that Teh (and, earlier, Nguyen et al. (2018)) say on this topic is exactly correct, and in any case there is a large number of further interesting issues to be pursued in this area.

6 Wrapping up

The abstract of Teh's Element declares it to be 'a concise, high-level introduction to the philosophy of *physical* symmetry' (our emphasis). We agree on 'concise' and 'high-level'. But with the term 'introduction', the situation is a bit more delicate: if one insists that an introduction to the philosophy of symmetry provide a *comprehensive* and *unbiased* survey of the literature, then arguably Teh's Element does not quite deliver: the philosophy of symmetry is by now a very diverse field, with a great many threads which are simply not touched upon in his piece. What Teh's Element *does* offer, rather,

[26] It's worth pointing out that while 'stacky' versions of electromagnetism might be reduced, they nevertheless afford one the resources to 'glue' subsystems, in the sense of Rovelli (2014).

[27] For related discussion of 'intrinsic' formulations of physical theories, see Jacobs (2022).

is a remarkably thought-provoking, original, and focused treatise on representation in physics and on the empirical significance of subsystem symmetries—it is an introduction to a field by way of the highly rewarding focal case of the relativity principle (pulling in Noether's machinery and considerations of representation), and arguably that's exactly what a short Element should strive to be. In having provided this, Teh is to be lauded for not simply rehashing or adding epicycles to well-trodden debates (one could easily have imagined a much duller piece on the hole argument, the AB effect, theoretical equivalence, etc.), and rather striking out into the frontiers of both art commentary and modern mathematical physics (including an extensive bibliography as a result of it), in order to shed substantial new light on the subject matter.[28]

With so much content in this Element, it could easily have been expanded to a book two or three times the length—and, indeed, this might have served to make Teh's discussions regarding both representation and symmetries more convincing (and comprehensible) to the reader. Plumbing the full depths of this remarkable work is very likely in the end to require a better understanding of the author's (not always orthodox) background philosophical commitments, which in turn are sourced—in part if not in whole—both from a pragmatism in the spirit of Aquinas and Newman, and from a take on metaphysics drawn from Aristotle, Aquinas, Anscombe, and Wittgenstein. However, as it stands, what we have in this Element is more akin to a light sketch or watercolour than to a rich oil—the reader is left to fill in many of the details for themselves. But in the end there is arguably something charming (and, true to Teh's leitmotif of understanding physics, also non-literalist) in the fact that he light-heartedly gestures as he guides us through this material. Ultimately, an introduction is never meant to be the end but the beginning, and Teh's Element surely leaves the reader curious and hungry (not just with its open-ended epilogue), longing for more—but only in a positive sense. The Element is rich with depth, inviting readers to return again and again for both the inspiration of its flowing ideas and the pleasure of its elegant presentation and layered allusions.

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[28] Teh's Element is, then, firmly in line with the injunctions in Read (2025a).

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