Prising apart the Great "Puzzle" Ball of Thread: another look at the local validity of special relativity

Niels Linnemann* & James Read†

Abstract

A knotty issue in the philosophy of spacetime regards the relationship between the special and general theories of relativity. Is special relativity anything more than the theory of Minkowski spacetime (and material fields set thereon), and as such anything more than but one amongst many in the panoply of solutions of the general theory? Or is special relativity, rather, a theory which holds *locally* in the models of general relativity? In response to the latter of these questions, Fletcher and Weatherall (2023a,b) have raised pressing challenges to the claim that there is some readily identifiable *special* sense in which special relativity is locally valid in general relativity. In this article, we take a step back, highlighting a number of senses in which one might in fact be able to hold onto claims that special relativity is locally valid in general relativity (and is distinguished from other spacetimes in this respect), the results of Fletcher and Weatherall (2023a,b) notwithstanding. In addition, we point to a number of positions in the philosophy of science according to which claims regarding the local validity of special relativity in general relativity would seem to stand up to scrutiny. Our goal in this work is to be both irenic and synoptic; to isolate and tease apart the multifarious threads wrapped up in this issue in a way which (with any luck) will be useful to those philosophers of physics who choose to work on the topic going forward.

Contents

*University of Geneva, CH. niels.linnemann@unige.ch

†University of Oxford, UK. james.read@philosophy.ox.ac.uk

1 Introduction

A standard claim—perhaps even widely-accepted 'conventional wisdom'—is that the special theory of relativity is 'locally valid' in the general theory of relativity. This claim (sometimes motivated by the so-called 'equivalence principle', on which see Lehmkuhl (2021)), indeed, can be found in almost all textbooks on general relativity. It is a claim which stands out at first blush because while reduction of one theory of physics to some antecedent theory is relatively standard, the (apparent) explicit *containment* of the old theory within the new is not.

Before getting to the matter of whether the 'local validity' claim is in any sense true, it is important to recognise that it is *prima facie* ambiguous (as 'conventional wisdom' often is!): Fletcher and Weatherall (2023a,b) distinguish what they take to be two distinct questions regarding the local validity of special relativity in general relativity:

Geometry: In what sense is an arbitrary Lorentzian metric 'locally special relativistic'—i.e., locally Minkowskian?

Dynamics: In what sense are material dynamics in general relativity 'locally special relativistic'—i.e., locally akin to some saliently similar material dynamics in Minkowski spacetime?

The first of their two articles (Fletcher and Weatherall 2023a) regards **Geometry**; the second of their two articles (Fletcher and Weatherall 2023b) regards **Dynamics**. With Linnemann et al. (forthcoming), one might question whether there is indeed a wholly clean distinction to be drawn between these two threads (we return to this later), and thereby question the extent to which the above disambiguation is in the end helpful. These qualms notwithstanding, in this article we at least begin by following the lead of Fletcher and Weatherall (2023a,b) by distinguishing **Geometry** and **Dynamics**.

What do we seek to add to the literature on this topic which cannot already be found therein? The answer is simple: when it comes to both **Geometry** and **Dynamics**, there remains a great deal of work which has yet to be synthesised: to prise apart the Great Ball of Thread that is the local validity of special relativity in general relativity one must drawn upon more resources than those with which Fletcher and Weatherall (2023a,b) equip us. In this article, our goal is to show how all existing contemporary writing on the local validity of special relativity in general relativity fits together—in particular teasing apart and evaluating mathematical/formal, heuristic, and interpretational senses in which one might assert the claim. We do this, moreover, by considering not only senses from mathematics/physics (whether to do with **Geometry** or **Dynamics** or some admixture thereof) in which one might make the local validity claim, but also by identifying stances in the philosophy of science the endorsement of which would seem to legitimise claims regarding the local validity of special relativity in general relativity. Note that—in the spirit of good conceptual engineering (on which see Cappelen (2018))—we are content to allow for multiple and even far-stretched explications of the original idea of the local validity of special relativity, the only constraint being that one be after fruitful explications of the notion which can deliver genuine physical insight.

As such, here is our plan. In §2, we assess the suite of options for making sense of the local validity of special relativity in general relativity which has been countenanced in the context of **Geometry**; in §3, we do the same for **Dynamics**. In §4, we consider various philosophy of science positions which would seem to legitimise claims regarding the local validity of special relativity in general relativity. We close in §5.

2 Geometry

In this section, we consider **Geometry**—i.e., the question of whether there is any special geometrical sense in which an arbitrary Lorentzian metric is 'locally Minkowskian'. In §2.1, we evaluate a rejoinder to Fletcher and Weatherall (2023a) provided recently by Gomes (2025, 2026a,b), and explore connections between that work and the 'scale relative' perspective offered by Linnemann et al. (forthcoming). In §2.2, we assess the extent to which at least some of the insights of Fletcher and Weatherall (2023a) could be delivered via more elementary, coordinate-based methods. In §2.3, we consider and assess other approaches to **Geometry** which have up to this point not been mentioned (or at least emphasised) in the context of these discussions.

2.1 Geodesic deviation from a scale-relative perspective

We begin by considering geodesic deviation structure (as emphasised by Gomes (2025)) and a 'scale-relative', expansion-based perspective (as emphasised by Linnemann et al. (forthcoming) and arguably in line with the 'standard story' regarding the local validity of special relativity which one finds in physics textbooks). In §2.1.1, we present the latter and some anticipated concerns from Fletcher and Weatherall (2023a) regarding this narrative. In §2.1.2, we assess arguments from Gomes (2025, 2026a,b) to the effect that there is a sense in which Minkowski spacetime is 'locally special' in arbitrary Lorentzian spacetimes—a sense which has to do with geodesic deviation structure. In §2.1.3, we explore a related strategy for cashing out the local validity of special relativity in terms of geodesic deviation structure.

2.1.1 Expansions and anticipated concerns

When considering the question of whether there is any clear geometrical sense in which an arbitrary Lorentzian metric is 'locally special relativistic', Linnemann et al. (forthcoming, §2.1.3) consider a series expansion for that metric with a Minkowski metric as the base point, and higher-order terms featuring coupling to the Riemann tensor (associated with the Levi-Civita derivative operator for g_{ab}) and Riemann normal coordinates x^I (or written geometrically—i.e., without coordinates—in terms of the Synge world function), e.g.:

$$g_{IJ} = \eta_{IJ} - \delta^2 \frac{1}{3} R_{ILJK} x^L x^K + \mathcal{O}(x^3), \tag{1}$$

where "$\delta := \frac{l_{\text{probing}}}{l_{\text{curvature}}}$, i.e. the ratio of characteristic lengths as set by the experimental apparatus used for determining short and long scales respectively (think of two rods, one used for measuring the probing length and one for measuring the curvature length—then, they have length l_{probing} and $l_{\text{curvature}}$, respectively)" (Linnemann et al. forthcoming, p. 8).

One might question on behalf of Fletcher and Weatherall (2023a) whether the base point of this expansion is in any way 'special'. In particular, one could raise (at least) the following two questions:

1. Which *particular* Minkowski metric should one use as the base point of the expansion?

2. Why use a Minkowski metric as the base point of the expansion at all, rather than some other metric?

Fletcher and Weatherall (p.c.) aver that it is entirely a matter of pragmatics which metric one chooses as the base point of one's expansion (in the sense of Linnemann et al. (forthcoming)), thereby corroborating their argument (in Fletcher and Weatherall (2023a)) that there is no *special* sense in which, in terms of **Geometry**, special relativity is 'locally valid' in general relativity. We think that this is delicate for reasons from both physics and philosophy, as will become clear over the course of the remainder of this article.

2.1.2 Gomes on geodesic deviation

The first rejoinder argument (post Fletcher–Weatherall) in the context of **Geometry** to the effect that flat Minkowski spacetime might after all be 'locally special' in general relativity is due to Gomes (2025, 2026a,b).[1] Gomes' focus lies on geodesic deviation; he begins by spelling out a notion of 'δ-flatness', which he defines as follows:

Definition 1 (δ-flatness)**.** *A d-dimensional Lorentzian spacetime (M, g_{ab}) is δ-*flat *for $\delta > 0$, if for each and every $x \in M$, there is a neighbourhood $\nu(x)$ of x, such that for any timelike geodesic γ going through x:*

1. *There is a segment of the timelike geodesic $\gamma : [-1, 1] \to \nu$, such that the normal exponential map along γ, $\exp : T^{\perp}_{\gamma} M \to M$, i.e. the exponential map restricted to vectors orthogonal to γ, gives a diffeomorphism between*

[1]Throughout this article, by 'locally special', we mean 'locally valid' *and* distinguished from other metrics in this regard.

B_ρ and the open neighbourhood $\nu_\rho \subset \nu$, where $B_\rho := \{\boldsymbol{r} \in T^\perp_\gamma M \mid \|\boldsymbol{r}\| < \rho\}$ is the open 'cylinder' in $T^\perp_\gamma M \simeq [0,1] \times \mathbb{R}^{d-1}$ with radius $\rho > 0$ (ν_ρ is called a tubular neighbourhood *of the segment γ); and*

2. *given any other (connected segment of) timelike geodesic $\gamma' : [-\epsilon, \epsilon] \to \nu_\rho$, (where ϵ can be defined by the parameter times in which γ' enters and exits ν_ρ), there is a ρ such that the displacement vector $\boldsymbol{r}(t) \in T^\perp_\gamma M$, for which $\gamma'(t) = \exp r(t)$, has its acceleration at $t = 0$ bounded by δ:*

$$\left\| \frac{\mathrm{D}^2 \boldsymbol{r}(t)}{\mathrm{d}t^2} \right\| \leq \delta. \tag{2.3}$$

Gomes (2025, p. 10) then proves the following proposition:

Proposition 1 (δ-flatness)**.** *Every spacetime is δ-flat for all $\delta > 0$.*

The idea here is that every spacetime is such that, for any point, there will always be some region around that point where the geodesic deviation is less than δ. However, as Gomes (2025, p. 12) states, "Minkowski spacetime is the only spacetime that has this property for the limiting value of $\delta = 0$ (note that we keep $\rho > 0$)." That is to say: only Minkowski spacetime is such that one can always find a neighbourhood around any point where the geodesic deviation vanishes.[2]

Everything that Gomes (2025) writes on these matters is true—however, one might worry that his remarks are not yet sufficient to underwrite the claim that there is something *special* about Minkowski spacetime locally, as compared with other metrics. Gomes (2025, p. 13) anticipates this concern when he goes on to write the following:

> Now, one might say that δ-flatness is not a particularly special property, and that for any spacetime g_{ab}, one could define a similar Property A, which only g_{ab} has in the limit, but which any metric arbitrarily approximates. However, it seems to me that such a Property A would have to be substantially different than δ-flatness and so it would be beside the point of the question we are addressing here.

We think that this worry is *prima facie* more pressing than Gomes concedes. For it seems straightforward to contrive variants of δ-flatness which would obtain (as for δ-flatness) for regions of any spacetime, but which would be saturated uniquely by spacetimes other than Minkowski.

To be concrete, consider e.g. taking the norm of the difference of the 'physical' geodesic deviation associated with the metric g_{ab} and of some 'counterfactual' geodesic deviation associated with some other metric g'_{ab}, and assessing when this norm is less than some δ:

$$\left\| \frac{D^2 \boldsymbol{r}(t)}{dt^2}\bigg|_g - \frac{D^2 \boldsymbol{r}(t)}{dt^2}\bigg|_{g'} \right\| \leq \delta. \tag{2}$$

Then our variant of δ-flatness would have it that: for any spacetime g_{ab}, about any point, there is some region such that the difference between its geodesic

[2] For constructions *prima facie* similar to those of Gomes but upon which we will not comment further in this article, see Anandan (1996a,b); cf. the discussion in Brown (1997).

deviation structure and that of metric g'_{ab} is less than δ. But only metric g'_{ab} has this property for the limiting value of $\delta = 0$.

Does this spell doom for Gomes' proposal? Answering this question is a little involved; in order to do so the first thing that one must do is attend to the norm which is used in Gomes' construction. Although not stated explicitly in Definition 1, Gomes (2025) avails himself of the physical (Lorentzian) metric g_{ab} in constructing this norm. As he points out, using this norm (rather than a Riemannian norm *à la* Fletcher and Weatherall (2023a)) means that, when considering a construction such as (2),

> the difference vector inside the norm lives in the full Lorentzian tangent space, not a spacelike subspace. Since, in Lorentzian signature, $\|X\| = 0$ does not imply $X = 0$, it is possible for the difference between the two terms to be a non-vanishing *null vector*.
>
> Therefore, the condition saturating at 0 does not imply that the Riemann tensors are equal. A counterexample is trivial to find: build a g' such that the difference is null along a curve; any other g'' differing from g' by a gravitational wave of a certain sort along this direction would also saturate the bound. (Gomes 2026b, p. 2, emphasis in original)

(Cf. Gomes (2026a, p. 7).) Perhaps the story doesn't end here, though. For example, this variant of δ-flatness works for any spacetime—and thus will not identify Minkowski as privileged—if one uses a Riemannian metric for the norm as do Fletcher and Weatherall (2023a). In this sense, one can envisage a response to Gomes (2025, 2026a,b) that the choice of the Lorentzian norm over some Riemannian norm is 'mere pragmatics'. But we think this would be too fast—after all, the Lorentzian metric g_{ab} is a *physical* field, not a counterfactual one.[3] Even if one seeks to give an 'operational' understanding of some Riemannian metric h_{ab}, understood as the contraction of two frame fields (themselves perhaps understood *à la* an operational approach to coordinates, on which see Giovanelli (2021) for excellent historical discussion), one's class of Riemannian metrics will be severely trimmed down by doing so—and *even then*, it would seem too fast to say that there is not an obvious sense in which the g-norm is privileged (after all, g_{ab} is the physical metric).[4]

But even if we do use the Lorentzian norm as suggested by Gomes (2025, 2026a,b), there is room—now taking the side of Fletcher and Weatherall (2023a)—to say that his proposal does in fact not pick out Minkowski spacetime as being 'locally special'. First: if one lets g_{ab} and g'_{ab} be conformally related, then they will agree on lightcone structure, and as such the object of which we take the norm on the LHS of (2) will remain spacelike, and as such will not generate the problems indicated above. So, it would seem that a variant of Gomes' δ-flatness is

[3] It is also worth noting that Fletcher and Weatherall (2023a) must use a Riemannian norm because they are ultimately interested in the distance between Lorentzian *metrics*, and there is no natural intrinsic notion of distance of which one can avail oneself for this purpose: it needs to be auxiliary. Gomes (2025, 2026a,b) is dealing with norms for *vectors*, in which case one can use the Lorentzian metic as a norm. We thank Henrique Gomes for this point.

[4] In general and absent further details, one might wonder about the physical significance of the fiducial Riemannian metrics h_{ab} deployed by Fletcher and Weatherall (2023a). (They are, as they admit themselves, tantamount to operating in a certain coordinate patch.) Presumably, they would respond (in the spirit of Fletcher (2016)) that they are offering a *schema* which can be completed in various ways depending upon the modelling context at hand.

in fact available, when one considers conformally related metrics. And developing on from this further: since Gomes' norms are evaluated *at a point* $p \in M$, if one were to systematically deform the 'reference' metric g'_{ab} away from p, the object of which we take the norm on the LHS of (2) will remain spacelike. So, as long as g_{ab} and g'_{ab} agree on their lightcone structure *at* p, it will be possible to construct a variant of δ-flatness which privileges not Minkowski spacetime but rather g'_{ab}.

But in response to this again, one could say: these variants of δ-flatness rely on a *specific* reference metric g'_{ab}, whereas Gomes' original definition of δ-flatness worked for *any* flat metric.[5] But how strong a point really is this? Granted, this is a *bona fide* difference between the two cases; however, we would maintain that it does not undercut the viability of the alternatives to δ-flatness which we have proposed. And even if one grants Gomes' own concerns about this 'conformal objection' (on which see Gomes (2026a, §3.2)), Gomes (2026a, §4) himself grants that in fact one can construct variants of δ-flatness, so that at best one can (according to him) say that spacetimes are locally *homogeneous* (i.e., of constant curvature) rather than locally flat, which would seem to undercut the scope of his original claim in any case.

Stepping back, it seems to us that Gomes (2025, 2026a,b) has pointed to a *prima facie* interesting geometrical sense in which the Minkowski metric *appears* to be 'locally privileged' for any Lorentzian metric, but that while one might be able to defend his use of a Lorentzian norm as 'non-pragmatic', the proposal nevertheless seems to falter in that it in fact significantly underdetermines the spacetimes which are 'locally special'. It also of course bears stressing that as yet Gomes' proposal is geometrical in nature; it does not have any explicit *dynamical* content. One can introduce this content by considering e.g. test bodies moving along the aforementioned geodesics—perhaps in turn understood through the field-theoretic formalism of general relativity via e.g. theorems regarding 'small body motion' due to *inter alios* Ehlers and Geroch (2004), Geroch and Jang (1975), and Geroch and Weatherall (2018). We see absolutely no problem with doing this—we would only stress that to invoke these results is already to elide a strict distinction between **Geometry** and **Dynamics**.[6]

2.1.3 Expansions and geodesic deviation

We now return to the scale-relative thinking with respect to the normal coordinate expansion of the metric. Recall the two concerns which we had identified before, namely: (1) Which particular Minkowski metric? (2) Why at all Minkowski at the base point?

The answer to (1) is straightforward: use *the* Minkowski metric at the base point p_0 for which the infinitesimal light cone is the same as that of the metric under consideration. For a spacetime *that does not even share the same infinitesimal lightcone with the spacetime under consideration at the base point* has no chance of being locally like that spacetime *in any interesting physical sense.* Addressing (2) is less straightforward—and it is to this question that we now direct our focus.

To attempt an answer as to why Minkowski should be used at the base point at all (instead of expanding around some other metric with the same infinitesimal

[5] Our thanks to Oliver Pooley for making this point.

[6] We should also note, with Dold and Teh (2025), that these theorems themselves invoke 'scale-relative reasoning'; that said, we do not perceive any problematic circularity here.

lightcone), we first make a short detour via what have been dubbed 'generalised normal coordinates'. Following Hari and Kothawala (2020), one can generalise the Riemann normal coordinates on a neighbourhood in Lorentzian spacetime (around a base point p_0) by employing an 'effectively curved' tangent space instead of the usual 'Minkowskian' tangent space—a new 'tangent space' which is to mimic the geodesic structure of a reference Lorentzian spacetime $\tilde{g}_{ab}$ and thus to allow for comparisons to a reference metric simpliciter. In formulae, such 'generalised normal coordinates' $\hat{x}^I$ for a point p in the neighbourhood read

$$\hat{x}^I(p) = -e^I_a \nabla^a \sigma(p_0, p) \cdot \tilde{\Delta}^{-1/3}(p_0, p) = s(p_0, p) u^I \tilde{\Delta}^{-1/3}(p_0, p), \tag{3}$$

where $\sigma(p_0, p) \propto s(p_0, p)^2$ is the Synge world function between p_0 and p; $s(p_0, p)$ their geodesic distance; and $\tilde{\Delta}(p_0, p)$ is the van Vleck determinant,

$$\tilde{\Delta}_\gamma(p_0, p) := \frac{\det\left\{\tilde{\nabla}_i^{p_0} \tilde{\nabla}_j^{p} \tilde{\sigma}_\gamma(p_0, p)\right\}}{\sqrt{\tilde{g}(p_0)\, \tilde{g}(p)}}. \tag{4}$$

The intriguing idea behind these generalised normal coordinates is, in short, to express geodesic (de)focusing in the 'generalised tangent space' at p_0 through the van Vleck determinant of the reference metric $\tilde{g}_{ab}$. In particular, in these generalised normal coordinates, one obtains an expansion of the metric around the base point that parallels the normal coordinate case, albeit with additional 'reference-curvature' contributions related to the reference metric $\tilde{g}_{ab}$ (expressions with tildes refer to $\tilde{g}_{ab}$; cf. Hari and Kothawala (2020, eq. 12)):

$$g_{IJ} = \eta_{IJ} + \frac{1}{3}\left(-R_{IJKL} + \frac{1}{3}\eta_{IJ}\tilde{R}_{KL} + \frac{2}{3}\eta_{K(I}\tilde{R}_{J)L}\right)\hat{x}^K \hat{x}^L + \mathcal{O}(x^3).$$

It seems then that a proposal such as that of Hari and Kothawala (2020) provides at the very least a *toy model* for expansion in terms of physical geodesic distance relative to other reference spacetimes than Minkowski. It is at this juncture that scale-relative reasoning can be injected once more. It turns out now that for sufficiently small geodesic distance s, the higher-order terms become negligible, and the metric is—just as for standard Riemann normal coordinates—*effectively* Minkowskian (the terms from $\tilde{g}$ are present for second order and above). This may then be taken to suggest that no matter the reference spacetime with which we begin, we eventually end up with a local geodesic behaviour as in Minkowski spacetime.

Admittedly, Fletcher and Weatherall (2023a) might well remain unconvinced by this proposal. After all, despite the modification of 'geodesic spray on the tangent space', there seems still to be a formal sense in which one proceeds by using Minkowski at the base point. Nevertheless, it strikes us that constructions such as this one here are at least *prima facie* interesting and worthy of discussion.

2.2 Coordinate-based reasoning

Fletcher and Weatherall (2023a,b) evince an ideological allergy to coordinates and as such abjure them in their constructions.[7] Although we do not object to those constructions *per se* (they are, after all, mathematically correct), we would

[7] Although see footnote 18 below.

like to raise here the gentle challenge that it seems (to us) that many of the points made by Fletcher and Weatherall (2023a) could be made using more elementary coordinate-based methods (of the kind that one would encounter in a first course on general relativity), when the latter are treated with suitable care.

Here is what we have in mind. At any point $p \in M$, first derivatives of the metric can be transformed away, but second derivatives cannot; moreover, the metric can be diagonalised at that point. All of this is standard lore about Riemann normal coordinates—but let us take the time to unpack it in more detail. Consistent with this lore, we write

$$g_{\mu\nu} = \eta_{\mu\nu} + \mathcal{O}\left(\partial^2 g (\delta x)^2\right), \tag{5}$$

where δx is the coordinate distance from p. (This is essentially another way of rewriting first two terms in expansions of $g_{\mu\nu}$ about $\eta_{\mu\nu}$ using Riemann normal coordinates from Linnemann et al. (forthcoming), e.g. (1).) One fruitful way in which to think about this is in terms of the number of degrees of freedom which can be transformed away at each order in metric derivatives. Recall that, generically, a coordinate transformation can be written

$$x^\mu \to x'^\mu(x). \tag{6}$$

Expanding this as a Taylor series, we have

$$x'^\mu = A^\mu{}_\nu x^\nu + \frac{1}{2} B^\mu{}_{\nu\rho} x^\nu x^\rho + \mathcal{O}(x^3). \tag{7}$$

Here, for an n-dimensional spacetime, the linear part $A^\mu{}_\nu$ has n^2 free parameters, while the quadratic part $B^\mu{}_{\nu\rho}$, which is symmetric in $\nu\rho$, has $n^2(n+1)/2$ free parameters. For $n = 4$, these are respectively 16 and 40 degrees of freedom.

Now, the metric at zeroth order in derivatives has $n(n+1)/2$ independent components, being a symmetric rank-2 tensor. At first order in derivatives, there are thus $n^2(n+1)/2$ independent components. For $n = 4$, these are respectively 10 and 40 components. What this means is that, at zeroth order the metric can be transformed to the Minkowski metric, and at first order there are exactly enough degrees of freedom to eliminate first derivatives of the metric. Following the same logic, one can show that second derivatives of the metric have 100 components, but there are only 80 degrees of freedom in the coordinate transformations—so, one cannot eliminate second derivatives of the metric using coordinate transformations. The outstanding 20 degrees of freedom precisely correspond to the Riemann tensor, which of course appears in the second-order term in the expansions of Linnemann et al. (forthcoming)—see again e.g. (1).

In more detail, consider Riemann normal coordinates at some point $p \in M$. Consider the vector e^a_{a} ($\mathsf{a} = 0, \ldots, 3$) pointing in each coordinate direction (note that this is now a coordinate-free object). We can then construct the Minkowski metric at p as:

$$\eta_{ab}(p) := \eta_{\mathsf{ab}} e^{\mathsf{a}}_a(p) e^{\mathsf{b}}_b(p), \tag{8}$$

where $\eta_{\mathsf{ab}} = \mathrm{diag}(-1, 1, 1, 1)$ is just an array of numbers,[8] and the e^{a}_a are the inverses of the e^a_{a}. So, given Riemann normal coordinates at p, we can construct a Minkowski metric at p.

[8]A 'confined object', in the sense of Pitts (2006, §2)—cf. Read (2023, ch. 3).

Now, in these Riemann normal coordinates at p, this constructed Minkowski metric diagonalises, as is straightforward to see:

$$\eta_{\mu\nu}(p) = -e^0_\mu(p)e^0_\nu(p) + e^i_\mu(p)e^i_\nu(p) = \mathrm{diag}(-1, 1, 1, 1). \tag{9}$$

So, $g_{\mu\nu}(p)$ and $\eta_{\mu\nu}(p)$ have the same components (*to first order in metric derivatives!*). But they are both tensors (we constructed both of them as coordinate-free objects), so we know they have the same transformation properties. So, they share the same components in all coordinate systems, and hence—to first order—are the same at p. In the end, these coordinate considerations suffice to show that—to first order!—every metric is locally every other metric at some $p \in M$; at least for the metrics which diagonalise in the same coordinates at p (i.e., the metrics which agree on lightcone structure at p). Once one considers second-order terms in the expansion of the metric, however, there is no longer sufficient coordinate freedom for this to be done, underwriting the claim that the equivalence of metrics at any $p \in M$ breaks down at second order.

All of this is common knowledge in relativistic physics (albeit spelled out with somewhat more care than one might typically encounter in a textbook), but already substantiates claims from Fletcher and Weatherall (2023a) that to first order at any $p \in M$ any metric can be transformed to any other, but to second order one cannot do this.[9] It does so, moreover, in a way which (a) identifies a privileged class of metrics which are approximately one another locally (namely, those which agree on their lightcone structure at p—cf. our comments in §2.1.3 on this being the physically relevant class of metrics in any case), and (b) which is straightforwardly amenable to scale-relative reasoning *à la* Linnemann et al. (forthcoming) when it comes to the negligibility (or otherwise) of higher-order terms in the expansion. Given this, one wonders what further *physical* insight is delivered by the use of fiducial Riemannian metrics, distance functions, etc., as appear in Fletcher and Weatherall (2023a).

2.3 Other approaches

It is worth distinguishing these (broadly but perhaps not entirely) geometrical debates regarding whether special relativity is or is not 'locally valid' in general relativity in the sense that Minkowski spacetime is or is not 'locally privileged' in an arbitrary Lorentzian spacetime from three other recent topics in the philosophy of spacetime physics:

1. The use of so-called 'Kleinian methods' to fix spacetime structure.
2. The heuristics of theory construction and possible bootstraps from special relativity to general relativity.
3. The relationship between the special and general theories of relativity in terms of 'gauging the Lorentz transformations'.

We begin with Kleinian methods, i.e. (1). In a series of articles, Barrett and Manchak (2024a,b, 2025) ask whether it is possible to specify ('fix') the structure

[9] Moreover—and to repeat somewhat the previous subsections—note that the $\mathcal{O}\left(\partial^2 g(\delta x)^2\right)$ in (5) encodes a notion of curvature-imbued scale: the size of the region in which we can say that spacetime is Minkowskian is captured by the extent to which this term is negligible (in the spirit of Linnemann et al. (forthcoming), a scale-relative phenomenon).

of an arbitrary Lorentzian metric given a privileged class of (coordinate) transformations; they answer this question in the negative.[10] In opposition, Gomes et al. (2024) argue that pointwise specifications of Lorentz transformations—the automorphisms, of course, of Minkowski spacetime—suffice to fix an arbitrary Lorentzian metric g_{ab}. Of course, this is different to what Fletcher and Weatherall (2023a) have in mind in terms of comparing locally g_{ab} with a Minkowski metric; nevertheless, it illustrates a certain sense in which Minkowski spacetime, geometrically speaking, is 'locally special'.

Let us turn now to (2). Following the lead of Einstein (1916), one might enquire into whether (and if so how) one can generalise from a special relativistic theory to the structure of a general relativistic theory. One way in which to do this is in terms of what Hetzroni and Read (forthcoming) dub the 'methodological equivalence principle', whereby one (a) transforms special relativistic equations to an arbitrary frame of reference, (b) notes the form of the fictitious force terms in those arbitrary frames, (c) replaces said fictitious force terms with new physical fields with the same transformation properties, and (d) endows those new physical fields with their own dynamics. We needn't go any further into the details of these heuristics here; our point is simply that Minkowski spacetime can also be privileged from the point of view of the heuristics of theory *construction*. Of course, we fully acknowledge that this is again a different point to the target of Fletcher and Weatherall (2023a);[11] nevertheless, it's salutary to remind ourselves that special relativity can be privileged in this heuristic sense: as Hetzroni and Read (forthcoming, p. 24) write, "these entrenched representations do have intrinsic value; their being part of the syntax of special relativity does not mean that they are arbitrary, nor that they can discarded as merely 'syntactic'."[12]

Finally (3), i.e. the relationship between the special and general theories of relativity in terms of 'gauging the Lorentz transformations'. The idea here is that one 'localises', and as such 'gauges', the global Lorentz symmetries of Minkowski spacetime, such that one now has point-dependent Lorentz transformations; this leads naturally to the structure of a generic Lorentzian manifold, and as such to the kinematical structure of general relativity. This way of thinking has been discussed by philosophers in e.g. Bamonti et al. (2025) and Read and Teh (2018); in a way, it combines aspects both of (1) (in the sense that one considers pointwise privileged coordinates) and (2) (in the sense that one is considering again routes from the special to the general theory in the context of discovery); nevertheless, it also offers a clear sense in which special relativity—and its 'local validity'—has a special status in reasoning about (or to) the general theory.[13]

Now (as already indicated above), we anticipate that on (2) and (3), Fletcher and Weatherall (2023a) will have no bones to pick with viewing special relativity and its 'local validity' as 'special' when it comes to heuristic (or, more generally,

[10] The idea of fixing certain geometrical structures as the invariants of certain privileged classes of transformations is the core insight of Klein's 'Erlangen programme' for geometry, hence the nomenclature. The work of Barrett and Manchak (2024a,b, 2025) was inspired by the spirited advocacy of Kleinian approaches to geometry by Wallace (2019).

[11] Indeed, Fletcher seems happy to say that special relativity can be privileged from a heuristic point of view: see `https://youtu.be/nGT8iONXkRY?si=YoVk7ZiYaJ_TFJlx`.

[12] Hetzroni and Read (forthcoming) market this approach as proceeding without any initial geometrical assumptions; as such, we should flag that including it in this section on **Geometry** is somewhat delicate. (The sense in which the approach is indeed 'geometrical' is discussed in detail in that article.)

[13] For some earlier comments along similar lines which predate discussion of 'gauging the Lorentz transformations', see Schrödinger (1985, p. 82).

epistemological) routes into general relativity; these are routes to (the geometry of) the theory as opposed to structural claims regarding its geometry, which were the original concerns of Fletcher and Weatherall (2023a) and those of the conventional wisdom.

On (1): one might likewise reasonably expect that Fletcher and Weatherall (2023a) would have no gripes with the mathematics of 'Kleinian methods' which constitute the focus of (1); and, as a result, one might view this as compatible with their claims (see e.g. Fletcher and Weatherall (2023a, Theorem 5)) that every metric is 'locally like' every other metric. However, we also see here the possibility for a more assertive reading of the Kleinian approach, for given the results discussed at the beginning of this subsection, it seems that there is indeed a privileged role for local Lorentz symmetries and thus a privileged role for local Minkowskian spacetime over all other local spacetime structures after all—which is structural and not at all of a merely pragmatic nature. (This is, however, under the assumption that, using e.g. AdS/dS symmetries leads to Cartan geometries (see Sharpe (2000) and Wise (2007, 2010)) rather than Lorentzian geometries—something which itself needs to be investigated further.)

3 Dynamics

So far, we've seen that there are certain senses in which Minkowski spacetime geometry is 'locally privileged' in general relativistic spacetimes—i.e., in arbitrary Lorentzian manifolds—although the situation is overall rather delicate. This suffices to deal with **Geometry**; as such, we turn now to **Dynamics**. Here, the question is whether the dynamics of material fields in the generically curved spacetime settings of general relativity are 'sufficiently similar' to the dynamics of suitably kindred material fields in flat Minkowski spacetime—and whether there is any sense in which Minkowski spacetime is 'special' on this front.

There are various different ways in which one might take up this question. One approach which Fletcher and Weatherall (2023b, p. 9) attribute to Ehlers (1973, pp. 45–6) has it that "a [locally special relativistic] matter theory in general relativity is one with solutions that, in general, locally approximate the solutions of the corresponding equations, *mutatis mutandis*, in flat spacetime." Fletcher and Weatherall (2023b, p. 9) regard this as "promising", stating that "it has clear pragmatic value, for it suggests how to model local matter dynamics approximately in general relativity using knowledge from special relativity." And indeed, the suggestion has been taken up by March (2025), who substantially develops these ideas.[14]

A second—very different—dynamics-related approach to the question (at least broadly construed) of whether special relativity is 'locally valid' in general relativity is due to Wallace (2017). Essentially, the idea of this approach is that when one considers the behaviour of some subsystem in general relativity and 'zooms out' sufficiently far, one should recover a description of that system in terms of Poincaré symmetries familiar from special relativity.

[14]In this section, we pick up just a couple of threads from March (2025), but there is much else besides in that work which is relevant to these discussions. For example, March (2025) provides a geometrical statement of the 'strong equivalence principle' (thereby shoring up statements by Read et al. (2018) from criticisms by Fletcher (2020) and Weatherall (2020)), derivations of energy conditions from certain kinds of matter dynamics (substantially building on discussions by Earman (2014) and Weatherall (2014)), etc.

In this section, we consider both of these approaches to **Dynamics**, and more besides. In §3.1, we make some preliminary remarks on what we dub the 'Minkowski bottleneck'. In §3.2, we consider the above-mentioned approach to **Dynamics** due to March (2025). We then in §3.3 discuss how this plays with experimental physics work on 'tests of local Lorentz invariance', before turning to the approach to **Dynamics** due to Wallace (2017) in §3.4. We close the section in §3.5 with a discussion of the spin-2 reformulation of general relativity.

3.1 The Minkowski bottleneck

Let's return for a moment to **Geometry**. The proof of Theorem 5 from Fletcher and Weatherall (2023a)—that to first order in metric derivatives every Lorentzian metric is approximately every other Lorentzian metric—relies crucially on properties of Minkowski spacetime: roughly, every spacetime is locally like Minkowski spacetime, *ipso facto* every spacetime is locally like every other spacetime. This isn't to suggest that this theorem could not be proved without the Minkowski metric, but it is certainly true that leveraging the properties of Minkowski spacetime—with its flat associated derivative operator and maximal symmetries—often facilitates proofs about general relativity itself.

We dub this (perhaps dispensable, but nevertheless practically useful) appeal to the Minkowski metric in proofs about general relativity the *Minkowski bottleneck*. In a sense, it is another illustration of the heuristic utility of (the local validity of) special relativity complementary to that discussed in §2.3—but now not the heuristics of the *construction* of general relativity, but rather the heuristics of coming to *understand* it. Given their leaning on the Minkowski bottleneck in proofs such as the above, we take it that Fletcher and Weatherall (2023a) have no axe to grind *vis-à-vis* its deployment in proofs about general relativity.

Returning now to **Dynamics**, we in fact see the Minkowski bottleneck arise in this context also. One clear illustration of this can be found in the work of March (2025), who proves various results, e.g. covariant conservation of the stress-energy tensor in general relativity for material fields obeying dynamical equations of the right kind (minimally coupled, quasilinear, symmetric hyperbolic, etc.), by—just as in the case of **Geometry** discussed above—leaning on the special properties of Minkowski spacetime. As March (2025, p. 69) herself writes, this[15]

> substantially clarifies (and defuses) a recent debate between Fletcher and Weatherall (2023a), Gomes (2025), and Linnemann et al. (forthcoming) about the sense in which Minkowski spacetime is (or is not) 'special' for the purposes of understanding how matter comes to be adapted to a relativistic spacetime. [footnote suppressed] Lemma 4.1.1 and theorem 4.3.1 [regarding e.g. covariant conservation, as mentioned above] show precisely how (and why) one might take Minkowski spacetime in particular to be relevant to this issue—and that not just any Lorentzian manifold can be used in the same way—only flat, maximally symmetric, spacetime will do. In that sense, Minkowski spacetime is a salient one to consider.

So, Minkowski spacetime can be privileged from the point of view of the heuristics of understanding general relativity via the Minkowski bottleneck, both in the

[15] References have been updated in this quotation.

context of **Geometry** and **Dynamics**.[16] We take this to be uncontroversial—and, indeed, it seems that all parties can assent to the point.[17]

3.2 Local comparison of solutions

Fletcher and Weatherall (2023a) demonstrate in their Theorem 5 (already mentioned above) that (to first order in metric derivatives) every spacetime is approximately every other spacetime. They do this by way of introduction of a fiducial Riemannian metric h_{ab} (used to compare the Lorentzian metrics) and quantity ε (used to set a threshold of closeness for the metrics).[18] Of course, this is again **Geometry**, but March (2025, §5) (*inter alia*) pursues similar ideas in the context of **Dynamics**. Essentially, what she proves—using similar techniques of fiducial metrics and distance functions, etc.—is that, for material fields whose dynamics are described by suitable equations (again, minimally coupled, quasilinear, symmetric hyperbolic, etc.), the solutions of those equations are approximately those in curved spacetime; from this, an analogue of Theorem 5 from Fletcher and Weatherall (2023a) for **Dynamics** would follow.

March (2025, p. 74) offers the following reflections on her results:[19]

> I take the discussion of Linnemann et al. (forthcoming) about the importance of 'scale-relative' reasoning for making sense of criteria such as LSR to be consistent with—and in fact complementary to—the perspective offered here. Indeed, I take these kind of discussions to concern precisely such questions as, e.g. the relationship between the (maximum) size of the neighbourhood O' and the bound ε, for different systems of partial differential equations and different choices of section ψ in the LSR schema, given some distance function. That such a neighbourhood O' exists, for each ε, may well be a consequence of e.g. SEP and mathematical facts about continuity, as argued above, but figuring out exactly what it should be is a matter of deep physical significance which surely demands consideration of questions about relative lengthscales of e.g. curvature as compared with some neighbourhood of a point (Linnemann et al. forthcoming; Wallace 2017).

We concur with the core message of this: there is nothing technically incorrect with the strategy of Fletcher and Weatherall (2023a) in the context of **Geometry** or of March (2025) in the context of **Dynamics**, but ultimately these mathematical results need to be supplemented with *physical* reasoning to set an appropriate ε, etc. The relevance of 'scale-relative' physical reasoning of Linnemann et al. (forthcoming) is in this regard complementary.

[16] March (p.c.) has confirmed that it is considerations of the Minkowski bottleneck which she had in mind in the above passage.

[17] Another distinct instance of the Minkowski bottleneck is arguably how we conceive of particle content—which happens via Lorentz symmetry or via its localisations. Think of spinors in curved spacetimes: they are defined in terms of the Minkowskian tangent space; see Wald (1984). These issues are discussed further in §3.5 below.

[18] Fletcher and Weatherall (2023a,b) claim to work only with coordinate-free methods. To the letter this is true, but since h_{ab} can be constructed via contraction of frame fields, to use a particular h_{ab} is not so far removed from using a particular coordinate system. Cf. §2.1.

[19] Again, references have been updated in this quotation.

3.3 Tests of local Lorentz invariance

What we have said in the previous two subsections regarding **Dynamics** allows us now to present—and resolve—a puzzle. When one consults the physics literature on experimental tests of general relativity, one finds substantial discussion of "tests of local Lorentz invariance"—see Will (2014) for the *locus classicus*. But given the experimental effort which has been put into these tests, and given their apparent lack of experimental violation, there does indeed (one might reasonably infer) appear to be something physically privileged about local Lorentz symmetries, and *ipso facto* Minkowski geometry and special relativity. How can this be made to square with the claims of Fletcher and Weatherall (2023a,b) that there is nothing 'special' about Minkowski geometry locally as compared with any other geometry?

In order to address this question, we must first get clear on what experimental tests of 'local Lorentz invariance' really amount to. Here is Will (2014, p. 13) summarising this work:

> A simple and useful way of interpreting some of these modern experiments, called the c^2-formalism, is to suppose that the electromagnetic interactions suffer a slight violation of Lorentz invariance, through a change in the speed of electromagnetic radiation c relative to the limiting speed of material test particles (c_0, made to take the value unity via a choice of units), in other words, $c \neq 1$ [...].

More precisely, what are being tested in these studies—see Will (2014, §2.2.3)—are theories "in which the limiting speed c_0 of massive test particles is unity, and the speed of light is c. If $c \neq 1$, [local Lorentz invariance] is violated". These theories have certain Lagrangians, which one could vary as usual in order to derive the equations of motion describing the behaviour of the material fields in such models, etc.[20]

Now, by logic alone, given that material solutions in such theories do not (e.g.) propagate along null geodesics, their equations of motion for material fields cannot be the kinds of partial differential equations considered by March (2025). So, what are being tested—and ruled out experimentally—are theories with certain 'non-adapted' dynamics. This, of course, is perfectly compatible both with the results of Fletcher and Weatherall (2023a) with respect to **Geometry** (including their Theorem 5), and with the analogous results for **Dynamics** of March (2025). As such, we take the puzzle here to have been cleared up.

3.4 Wallace's approach

We now consider a very different approach to **Dynamics**, due to Wallace (2017). Wallace's strategy is to consider isolated subsystems (which in themselves needn't be small or with negligible gravitational effects—for example, they might be black holes) and argue that, when one 'zooms out' from such subsystems sufficiently far, one recovers a special relativistic description of that subsystem:

> In effect, then, the equivalence principle applies in general relativity because the metric of isolated systems at sufficiently large distances

[20]Since these theories essentially have multiple different lightcone structures, they are committed to a preferred timelike direction—see e.g. Bilson-Thompson et al. (2023).

is the same as the metric of any system at sufficiently small distances. The relativity principle applies because, in addition to this, that metric has the Poincaré group as a symmetry group. (Wallace 2017, p. 265)

Naturally, we classify this approach as having to do with **Dynamics** since the notion of 'isolation' is a dynamical one (namely, tied to the boundary conditions of the field equations).[21] Evidently though, it is quite a different dynamical notion of the local validity of special relativity in general relativity to what we have seen so far—as such, we should now think through how these approaches relate to each other.[22]

Recall the explicit form of the expansions of Linnemann et al. (forthcoming) (already discussed *in extenso* above), e.g. (1). With (recall) $\delta := \frac{l_{\text{probing}}}{l_{\text{curvature}}}$, the thought is that when $l_{\text{probing}} \ll l_{\text{curvature}}$, we are effectively in the flat spacetime regime—this is along the lines of the geometric optics limit.[23] Wallace (2017), on the other hand, is considering the case $l_{\text{probing}} \gg l_{\text{curvature}}$, and when we have asymptotically flat spacetimes—which, of course, are the *correct* spacetimes to model isolated subsystems—the claim of self-similarity from the above quote kicks in: here, we have Minkowski spacetime asymptotically, which is exactly what we get in the geometric optics limit. One could, indeed, use the distance functions etc. of Fletcher and Weatherall (2023a) to say that when one zooms out *per* Wallace (2017), or when one takes $\delta \to 0$ *per* Linnemann et al. (forthcoming), one gets to Minkowski to within ε in both cases. Note, though, that when one is considering the long-distance limit *per* Wallace (2017), Theorem 5 from Fletcher and Weatherall (2023a) will not apply—at best, one will be able to say that every asymptotically flat spacetime is approximately every other asymptotically flat spacetime (which is, due to the restrictions to asymptotically *flat* spacetimes, not at all an 'asymptotic' analogue to Theorem 5). This, of course, should strike one as an entirely reasonable claim—but note also again the significance of (to recall §3.1) the 'Minkowski bottleneck' in asserting it.

As a supplement to Wallace's analysis, note also that there are contexts in which one is interested in spacetimes which are not asymptotically flat, but rather (say) asymptotically de Sitter (i.e. asymptotically of positive constant curvature)—see Belot (2023, ch. 6) for philosophical discussion and references to the relevant physics literature, and Cudek and Read (2025) for a review thereof. Given this, one might wonder whether something like the above analysis from Wallace (2017) can apply also to these cases. And indeed it can: in such cases, one has it that when $l_{\text{probing}} \gg l_{\text{curvature}}$ one finds oneself in the de Sitter regime; moreover, one can still make a self-similarity claim between large-scale (asymptotic) and small-scale (neighbourhood-wise) structure here, since when $l_{\text{probing}} \ll l_{\text{curvature}}$, using e.g. the results of Fletcher and Weatherall (2023a) that every spacetime is locally like every other spacetime (or alternatively an expansion around de Sitter in the style of Hari and Kothawala (2020)), we can just as well say that we are in the de Sitter regime also.[24]

[21] For a functional definition of 'isolation' presented in the context of a discussion of Wallace's work, see Steeger and Read (2026, §4).

[22] Moreover, given that Wallace (2017) makes heavy use of the asymptotic geometry of asymptotically flat spacetimes, his approach clearly also has something to do with **Geometry**.

[23] See Misner et al. (1973, p. 571) for classic discussion of the geometric optics limit and Linnemann and Read (2021) for more recent work on this topic.

[24] But one should of course keep in mind that, with respect to the small scale, the de Sitter

So, Wallace's version of the equivalence principle does not provide an immediate sense in which special relativity is invariably 'special' in general relativity, given other possible contexts in which one could make *prima facie* kindred claims with respect to e.g. asymptotic de Sitter structure. Which is to say: a spacetime probed at $l_{\text{probing}} \gg l_{\text{curvature}}$ begins to 'look' like its asymptotic structure which need, however, not be Minkowskian. There is the question then of *which* general relativistic spacetimes can be 'asymptotic boundary metrics' of another spacetime; it is unlikely that an answer to this (open) question will yield anything so strong as an analogue of the first-order-physics egalitarianism *vis-à-vis* local spacetime propounded by Fletcher and Weatherall (2023a).

3.5 The spin-2 reformulation of general relativity

In this subsection, we consider yet another—again very different—approach to **Dynamics**, this time related to the 'non-geometrical' particle physics view on general relativity (by Deser (1970, 1987, 2009), Fang and Fronsdal (1979), Feynman et al. (1995), Gupta (1954), Kraichnan (1955), and Wald (1986), among others—see Pitts (2016) for detailed references). The core of this particle physics view is the statement that the field equations represent (the dynamics of) a 'self-interacting spin-2 field'. A minimal explication of this statement runs as follows: the linearised order of Einstein's equation (around flat spacetime) corresponds to the (massless) Fierz–Pauli equations, which as such represent a (classical) spin-2 field in the precise sense of Wigner's classification (Heiderich 1991); generalisations of the linearised theory (either via self-sourcing or via gauge deformation considerations),[25] under very mild conditions and up to field redefinitions, yield general relativity uniquely; the number of degrees of freedom for general relativity is two, just as for linearised general relativity/massless Fierz–Pauli; thus, general relativity generalises 'spin-2' theory, and uniquely so, into a non-linear, self-interacting theory of the same number of degrees of freedom—rendering general relativity a theory of 'self-interacting' spin-2 fields.

One might want to give more flesh to the conception of general relativity as a theory of a 'self-interacting spin-2 field', as there is a certain ambiguity as to how one should understand the generalisation of the linearised spin-2 theory. Take, for instance, the following quote by Deser (1970), who remarks on his self-interaction bootstrap of general relativity from linear general relativity (which runs via sourcing the linear spin-2 equations by its very own energy-momentum tensor plus that of matter) that

> the geometrical interpretation of general relativity arises, since all matter now moves in an effective Riemann space of metric $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, and so the initial flat 'background' space $\eta_{\mu\nu}$ is no longer observable. (p. 4)

Is this the claim of a 'heuristic derivation' of a more general theory? Or a view of derivation in the sense of a reduction of curved to flat spacetime physics, arguably

nature is not singled out by these results but is rather only one of many ways to represent spacetime locally.

[25]There are also quantum variants of these arguments which are arguably of less relevance for a discussion focused on the classical regime of general relativity itself. See Weinberg (1964, 1965, 1972) and Boulware and Deser (1975), for instance.

with all its ontological weight?[26]

Salimkhani (2020, 2023) has argued explicitly for an ontic reduction of general relativity in the context of these spin-2 derivations.[27] Others, e.g. Delhom et al. (2023) and Padmanabhan (2008), have criticised the derivation heavily for a supposed sleight of hand in light of various ambiguities and reverse engineering problems (cf. Deser (2009)), rendering any claim of a reduction in a more narrow sense false. Relatedly, Linnemann et al. (2023) have made the case that the approach is indeed best understood as a generalisation under constraints, and not as a derivation in the narrow sense of reduction (*pace* Salimkhani (2020), but see Salimkhani (2023) for a metaphysically-motivated rejoinder).

In any case, what remains uncontroversial is that general relativity can be presented as a generalisation of a flat-spacetime massless spin-2 theory. But does this make flat spacetime special? Not immediately. Relative to some other background (whether also maximally symmetric—like de Sitter—or a generic background solution without any symmetries), one can of course still consider a perturbative expansion. Again, one will have a linearised order that looks similar to Fierz–Pauli, i.e. with the same linearised gauge group, but this time already at that order with linearised matter sourcing.

What potentially makes the analysis around flat spacetime (but arguably also Ricci-flat or -constant spacetimes more generally—see Deser (1987) and Deser and Henneaux (2007)) stand out is that the metric field (up to field redefinition) is revealed, only from that viewpoint, as pure spin-2—and not some mixture including spin-0 and spin-1 parts, as would generally be the case for expansions around an arbitrary spacetime. That means that there are suitable background expansions of general relativity that allow one to regard general relativity as a generalisation of pure spin-2 theory into an interacting theory.

What one makes of this depends, first and foremost, on the significance one attributes to the spin-classification. In the flat spacetime-based Standard Model of particle physics, all (relatively) fundamental equations are equations of fields, whose flat spacetime linearisations are pure spin representations (even Maxwell electrodynamics is a representation of pure spin-1), and where fields are successfully distinguished, even if interacting, via the spin classification. An ontology of just the regime of the Standard Model might thus naturally involve a differentiation based on spin. For general relativity, one can say that, in practice, concrete matter fields seriously considered (electrodynamics, etc.) are those whose (linearised) equation of motion amount to (curved spacetime generalisations of) pure spin representations. The generalisation of spinors to general relativity (Wald 1984, ch. 13) further testifies to the continued practical importance of the spin categorisations of fields in general. Even those who seek to quantise general relativity (say via loop quantum gravity—see Rovelli (2004)) wonder about how to integrate other fundamental forces: as such, they also seem to take for granted the flat spacetime-based spin classification (whether in their case just heuristically or more fundamentally is difficult to judge).

[26] Contrast this close-to-ontological take from Boulware and Deser (1975, p. 230, our emphasis)—"From this point of view, *Einstein's theory is an essentially phenomenological (albeit unique) theory for describing interactions at macroscopic distances and time*."—with Feynman's famous understanding of the derivation as a different method of discovery for the Einstein field equations (see Feynman et al. (1995)).

[27] See Linnemann (2026) for an analysis of Salimkhani's move as an unorthodox form of ontological reduction in the spirit of a design model (Pincock and Poznic 2025).

Yet, from the vantage point of non-trivially generally covariant general relativity, any carrying over of the spin classification from flat spacetime seems to amount to a remnant of special relativistic thinking—to which one clenches because it is difficult and messy to do otherwise (in other words, for pragmatic reasons). After all, at least heuristically speaking, one would think that in regimes in which strong gravitational and quantum effects occur together, at least *prima facie* we cannot rely on the flat spacetime-based spin-distinction (or the Poincaré group) as relevant. Loosely, the claim of Fletcher and Weatherall (2023a) that general relativistic spacetimes cannot be declared *ab initio* to be 'special relativistic' in some special sense could then be taken to back this up.

4 Specific philosophy of science positions

So much for our synopsis and synthesis of approaches to the local validity of special relativity in general relativity in terms of both **Geometry** and **Dynamics** (and mixtures thereof). We turn now to philosophy of science matters. One's stance regarding the status and significance of the local validity of special relativity in general relativity will be a function of one's commitments in general philosophy of science. In this section, we elaborate on this point, by considering the local validity of special relativity from the point of view of (i) Cartwright's philosophy of science (§4.1), (ii) pragmatism (§4.2), (iii) empirical foundationalism (§4.3), and—perhaps more surprisingly—(iv) views analogous to those found in the common law tradition in jurisprudence (§4.4).

4.1 Cartwright's philosophy of science

Recall that according to Cartwright (1999), laws do not govern everywhere (in this sense, the world is "dappled"); rather, they hold only in specific domains. From this perspective, one should not view discussions of the local validity of special relativity in general relativity as seeking to *explain* why special relativity obtains locally, but rather as isolating the circumstances under which special relativity applies.

In more detail: a follower of Cartwright will say that special relativity holds *ceteris paribus* locally in regimes in which curvature effects are negligible relative to the phenomena of interest—where here 'locally' means relative to the scale of the experiment and the causal processes involved. Seen in this way (and now to use some further Cartwrightian terminology), local inertial frames in general relativity function much like Cartwright's *nomological machines* (see Cartwright (1999, ch. 3)): they are carefully specified arrangements that suppress certain causal factors—in this case, gravitational curvature—so that familiar regularities can manifest. Given all this, one sees that from a Cartwrightian perspective the local validity of special relativity is contextual and scale-relative—all of which chimes better with the physics-informed outlook of Linnemann et al. (forthcoming) than with the mathematical constructions of Fletcher and Weatherall (2023a) (though, of course, a Cartwrightian cannot deny the mathematical correctness of those constructions, and in this sense should be in no dispute with them).

At the same time, there is no reason why—relative to the phenomena of interest—one might not also take spacetime to be, say, constantly curved or, more generally, have any other curvature structure. But this shows that to adopt the Cartwrightian outlook is by no means to defend the special status of the local validity of special relativity (which, in turn, chimes better with Fletcher and Weatherall (2023a) than with Linnemann et al. (forthcoming)).

4.2 Pragmatism

Let us recall some reflections by Fletcher and Weatherall (2023a, p. 18) on the significance of their results (such as Theorem 5) to the effect that (e.g.) every metric is (to first order) locally approximately every other metric:

> Particular physical constructions or idealized observational contexts might suggest particular choices of approximating flat metric, but these are privileged only relative to those further choices.

The point here—and this goes back to our remarks regarding the base point of the expansions of Linnemann et al. (forthcoming) in §2.1—is that the choice of one approximating metric rather than another in a given context is, for Fletcher and Weatherall (2023a), a matter of pragmatic considerations to do with the context, the interests of the modeller, etc.

One initial comment to make here is that this apparent de-emphasis of pragmatics strikes us as being at least somewhat at odds with how philosophy of physics and science is currently practised: namely, with a substantial interest in and focus on pragmatics rather than only (or indeed primarily) logic and formal structures.[28] In any case, one might also wonder about the extent to which there is such a clean distinction between theory and practice and/or pragmatics. It is precisely here that there arise connections with 'pragmatism' in the more substantial sense of the pragmatist philosophical *tradition*. This strand of 'pragmatism' is associated historically with authors such as Dewey (1925, 1938), James (1907, 1909), and Peirce (1878, 1931–1935); in this subsection for the sake of constraining the narrative our focus will lie with Brandom (1994) and Price (2003, 2013).

There are different species of philosophical pragmatism, but for those who identify as 'inferentialists' (such as Brandom (1994)), the local validity of special relativity in general relativity will have less to do with mathematical claims and results (or with representation relations obtaining between theory and world—cf. e.g. Price (2013, ch. 1)[29]), and more to do with when it is apt to use the theory of special relativity in order to support (e.g.) a network of good inferences about the world—when the theory allows one to predict, explain, navigate, and control aspects of one's environment. Saying that special relativity holds locally in general relativity is a way of licensing certain inferential moves: when gravitational effects are negligible, one may use Lorentz transformations, inertial frames, and special relativistic kinematics without significant loss of accuracy. The claim earns its stripes from the practical success of these inferences—designing experiments, interpreting data, or simplifying calculations—not (necessarily) from any deeper story about how spacetime 'really is' in small regions.

Here one can even connect with the pragmatist views on truth by Price (2003). Price treats 'truth' not as a substantial correspondence relation that explains the

[28] An influential plea in the current spacetime context is Curiel's homage to Stein: see Curiel (2020). (Also discussed in the next subsection.)

[29] It is important to note that Price (2013) is not a full-blooded and self-declared inferentialist, although he is 'inferentialism curious'. Our thanks to Tushar Menon for stressing this.

success of our theories, but rather as a certain kind of *sui generis* norm of assertion. For Price (2003), then, to say that special relativity is 'locally valid' (or perhaps 'locally true') is to do nothing more than to signal that one is entitled to rely on special relativistic claims when gravitational effects are negligible. Evidently, this is a matter of practice, and as such again not incompatible with the mathematical results of Fletcher and Weatherall (2023a,b); nevertheless, since it vindicates talk of the local validity of special relativity, it remains a position worth mentioning in the context of these discussions. It is important to note here, however, that as in the Cartwrightian case considered previously, this pragmatist take does not necessarily render *special* the local validity of special relativity in general relativity: practical success of inferences in local de Sitter contexts, say, would just as well legitimise claims regarding the local validity of de Sitter.

4.3 Interpretational cascade

Fletcher (2025, ch. 2) objects to any claims to the effect that special relativity is (somehow or other) *mandatory* in the interpretation of general relativity,[30] but regards (say) historical or heuristic uses of the principle as acceptable.[31] Nothing we have said or discussed in the foregoing sections of this article implies that the local validity of special relativity in general relativity is indeed a mandatory aspect of (or precondition for) the interpretation of the latter. That being said, one could (for better or worse) embrace such a view; here, we explore what it amounts to, and its upshots.

We begin with a passage from Linnemann et al. (forthcoming, pp. 18–19), which we quote at length:

> Our position not only is consistent with what leading practitioners of GR have written on this topic (see e.g. Weinberg (1972), Hawking and Ellis (1973), Poisson and Will (2014)), but also takes seriously what philosophers of science have learned from numerous case studies of the empirical interpretation of a physical theory: said interpretation depends ultimately on bringing formalism into contact with relevant measurement scales, which are *de facto* classical; for this to happen, objects and/or functional roles played by objects in that theory must be associated with (or at least accounted for in) objects and/or functional roles played by objects in a classical measurement theory, or with objects and/or functional roles played by objects in some intermediate theory. [Footnote suppressed.] Mere association, however, is insufficient: one must also account for the regime of validity of the approximation. For example, the role played by a coherent state in a quantum theory should be linked effectively to the role played by a

[30] Fletcher (2025, ch. 2) imputes this claim to the 'dynamical approach' to spacetime theories associated with Brown (2005) and Brown and Pooley (2001, 2004), and more recently e.g. Read et al. (2018). It is not obvious to us that this approach should be read into those specific papers, although earlier writings by Brown (1997, p. 68) do suggest as much, e.g.: "It is a fundamental assumption in GR that the local structure of space-time, suitably defined, is special relativistic." In any case, we here set the matter aside; it is discussed further in Linnemann and Read (2026).

[31] Fletcher makes similar points in this talk: `https://youtu.be/nGT8iONXkRY?si=YoVk7ZiYaJ_TFJlx` (already mentioned in footnote 11). He goes on to state that much of the motivation of Fletcher and Weatherall (2023a,b) was to undermine claims regarding the interpretative necessity of the local validity of special relativity in general relativity. This is an important clarification, since the point is not given particular emphasis in those articles.

> configuration in a classical theory—but only for the regime in which the state actually is coherent.
>
> The same thinking underlies the account of the local validity of SR in GR which we have presented in this article: the local spacetime structure is to be linked effectively to a special relativistic—and ultimately a non-relativistic—structure; only if some expansion parameter is used can we thereby get an estimate of how good the measurement is according to GR. From this point of view—and given that GR is empirically relevant—it is not surprising that there exists an asymptotic series of the metric with the Minkowski metric as 'base point', or that a general relativistic spacetime has approximately and locally the symmetries of Minkowski spacetime.

The idea here is that in order for a theory to make contact with the empirical, it must 'schematise the observer', in the sense of Stein (1995) (see Curiel (2020) for extended discussion), which is to say that it must bring its theoretical architecture into contact with (idealised) measuring devices, observations, etc. As Stein (1995, p. 639) writes,

> [i]t would also, I should add, be impossible to understand a theory, as anything but a purely mathematical structure—impossible, that is, to understand a theory as a theory of physics—if we had no systematic way to put the theory into connection with observation (or experience).

If one says with Linnemann et al. (forthcoming, p. 18) that measurements are indeed "*de facto* classical", then one might as well hold that a new theory of physics makes contact with antecedent theories (where, one assumes, such schematisation of the observer has already been secured)—and as such, from this perspective, the interpretation of general relativity could be argued to go via the local validity of the special theory of relativity which preceded it.

This line of thought might trigger various responses. First, one might take umbrage at the claim that measurements are "*de facto* classical"—does this not smack of neo-Bohrianism? Concretely, one might argue e.g. that modern measurement devices in quantum theory rely heavily themselves on the theory of quantum mechanics, or that measurement data is always to be interpreted through a theoretical context (as a fitting example of such theory-ladenness in general relativity, consider e.g. how the observation of gravitational waves as predicted by general relativity builds—albeit not viciously—on contextualising detector data in terms of general relativistic models: see Elder (2025) for a discussion). However, this all trades on an ambiguity in what one means by 'measurement'. While description of the measurement device, and interpretation of the measurement data, are important concerns of measurement (theory), it nonetheless remains the case that the *readouts* of measurement devices (e.g. what a pointer shows on a scale) are 'classical', or rather something even more basic than that (think of various proposals in the style of sense data, protocol sentences, etc.).

But in any case what we need to clarify is (1) whether antecedent theories are necessary for accounting for measurement readouts relative to a given physical theory;[32] and, if so, (2) which of the antecedent theories are implicated. Now, a

[32] In the sense of obtaining *some* data, not in the sense of contextualising that data as subject to discussions of theory-ladenness.

striking counterexample to (1) arguably lies in the fact that, e.g., general relativity can be ‘constructively axiomatised’ (Reichenbach 1969) in terms of basic—which are taken to be empirically accessible—notions (first and foremost, local light rays and particles) that together allow for its empirical interpretation: presumably, the modern paradigm example of this is the axiomatisation by Ehlers et al. (2012), on which see Adlam et al. (2025) for extended discussion.[33] The empirical ‘interpretational’ basis in this case does not seem to derive from an antecedent theory. Another apparent counterexample is arguably that general relativity, through the construction of (say, light) clocks, includes—with some reservations—its own observation theory (thereby approaching the ideal of ‘Einstein–Feigl completeness’; see Adlam et al. (2025) and Carrier (1990)).[34]

This all seems to support strongly the general point that an ‘interpretational cascade’ is not at all inevitable. However, one might find such a proposal too remote from the ‘practical necessity’ for how we actually do science (reiterating that the measurer does see something classical after all, or maybe even something more basic than that), and so one might want to insist that the measurement observations in general relativity have to be cast in terms of more downstream theories. However, even then, it is not at all clear why one could not ‘jump’ over some downstream theories which are not directly related to what we see on the measurement apparatuses (the readings)—and why in the case of interest to us in this article one would in particular not want to skip special relativity for Newtonian mechanics (say). Going via all antecedent theories in making sense of the observations seems indeed only well-motivated by some additional methodological desire for modularity, and a *justification* thereof.

In any case, there is a philosophical school which has not only pushed the full regress into the agent’s basic realm of experience, conceived of as denuded to the greatest extent possible of all theoretical commitments and prior to the possibility of quantitative measurements (‘lifeworld’), but which also effectively *argues* for an interpretational cascade between antecedent theories. This is the approach followed by the school of ‘methodological constructivism’ (in particular associated with Lorenzen) which seeks to reconstruct any knowledge endeavour (and in particular that of the special sciences) step-by-step such that, just as in a well-formulated mathematical theory, notions and also theories are introduced one after another, without any semantic circularities (‘methodological order’) (Lorenzen 1963).[35]

The basic concern of this school (and as such their reason for choosing ‘methodological order’ as their central rationality standard within their reconstructive project) is that of justification: we can only justify our achievements in logic, mathematics, physics, chemistry, etc., as ‘knowledge’—so the thought goes—if we are sure that the language behind these endeavours (with their empirical statements, theories, models, etc.) is both constructed non-circularly and well-grounded in the lifeworld from which any such knowledge endeavour sets out (Kamlah and Lorenzen 1967; Lorenzen and Schwemmer 1973; Rohs 1986). It is worth stressing that language—and with it sharp terminology—is deemed so central for justification because it is understood pragmatically: meaning is tied

[33]Our thanks to Chris Smeenk for raising this point.
[34]See also the discussion by Curiel (2009) on how general relativity needs no interpretation via ‘extratheoretical’ means.
[35]A good English language overview is provided by Janich (2012). For further original sources (many in German), see the references in Dewar et al. (2022, §5.2).

directly to action, and language directly to what we (can) do with theoretical statements and theories.[36,37] Put simply, notions are either determined directly from the actions which one undertakes (and the purposes and effects associated to them) or from abstractions and idealisations of such terms. This pragmatic understanding of language applies both to the reconstruction of formal sciences and of 'material' sciences such as physics or chemistry.[38]

It is only by such careful reconstruction—so the rationale goes—that we can separate justified notions from those implicated in illegitimate metaphysical presuppositions (there is a certain programmatic overlap with logical positivism in asserting which notions and which claims are meaningful; however, the way in which methodological constructivism achieves this—i.e., via pragmatic considerations—is different from the logical-foundationalist-coherentist analyses of meaning proposed by logical positivism). Certain abstracta such as 'object' ('Gegenstand') and 'world' ('Welt'), for instance, are dismissed on such grounds (Kamlah and Lorenzen 1967); others such as 'space' and 'time' are qualified to be of merely categorial character which, however, are not to be *reified*. In the context of scientific theories, even the meaning of terms from the most basic theories are seen as *prima facie* unclear and as having dubious referents.

A central application of methodological constructivism lies in first of all clarifying the basic notions of measurement that serve as the basis for the methodological build-up of that (empirical) special science. For physics, these basic notions of measurements are first and foremost length, time, and mass. Notably, one faces an issue of circularity in introducing such notions: theory requires measurement of such quantities for confirmation, while, at the same time the measurement of such quantities requires a definition from the theory (think about how Newtonian mechanics provides notions of length, time, and mass). So there is a clear violation of methodological order. Moreover, there is an immediate trilemma if one just sets out to define a basic notion of length, mass, or time operationally. For example, with respect to the question of why we can measure length with a rod, one might: (i) simply stipulate that a rod has a certain length (a form of conventionalism), (ii) attempt to justify this with reference to a deeper structure (thus threatened by regress), or (iii) be caught in a circle of justifying the length of a rod via that of another rod (circularity).

The ingenious move of methodological constructivism here is to retain an operationalist outlook but to locate it in the realm about which we are certain—that of lifeworld actions, i.e., actions in the pre-scientific, intuitive lifeworld—and experience or findings relative to those *actions*. Methodological constructivism then provides lifeworld-operation-based claims about when two lengths are of the same basic length, two clocks show the same basic time duration, or two balances the

[36]What is reconstructed is an 'ortho-language' (how to say things right). The reconstruction effort hereby in particular concerns terms from the theoretical, whereas typical everyday notions (and statements) are accepted from the get-go (in fact, they form the much-needed starting point for the construction). See Kamlah and Lorenzen (1967) and Lorenzen and Schwemmer (1973).

[37]Cf. our discussion of pragmatism in §4.2.

[38]It should not then be too much of a surprise that the emergent picture of science is one of technical reproducibility. As Janich (1994) puts it: "The concept of science actually recognized in our technological civilization (including by the natural sciences) is oriented entirely and exclusively toward the ideal of the technical reproducibility of artificial and natural phenomena." (Janich 1994, our translation, p. 75). In the German original: "Der in unserer technischen Zivilisation tatsächlich (auch von Naturwissenschaften) anerkannte Wissenschaftsbegriff für die Naturwissenschaften orientiert sich ganz und ausschließlich am Ideal der technischen Reproduzierbarkeit künstlicher und natürlicher Phänomene."

same basic mass. The twist then: these lifeworld-based claims which establish what it means to say that e.g. two lengths are congruent are not empirical claims. (Or rather not empirical in the sense of quantitative data. What one naïvely denotes as 'empirical' or 'experience' branches into a pre-scientific, intuitive lifeworld sense and what is from then on called empirical.[39]) Accounts of such basic measurement notions are called 'proto-theories'; for physics, this is 'proto-physics' (Janich 2012; Lorenzen and Schwemmer 1973).

As part of such proto-physics, *geometry* is first and foremost understood as the *non-empirical* theory that sets up the framework for basic length measurements. *Geometry* is simply what is determined by lifeworld operations (such as those undertaken by craftsmen) that follow norms for realising homogeneous objects—and it is argued to be Euclidean as a result (Lorenzen 1963; Lorenzen and Schwemmer 1973).[40] On methodological constructivism, it is therefore Euclidean *geometry*, and no other, that forms the basis for the further theoretical development of science.

Now, standardly, one might take the empirical success of relativity theory as 'evidence' that a presupposed notion of geometry must be revised. But this is not so within the 'logic' of methodological constructivism. Since *geometry* is a logical precondition for doing physics, it is not something that can be called into question by physics. Instead, special relativity, for instance, should—with a nod from Lorenzen to Lorentz—be understood as a revision of kinematics (Lorenzen 1977).[41] Kinematics (and dynamics) are determined empirically—so one may have been wrong about them, especially in previously unexplored regimes—but one cannot have been wrong about the preconditions required to make such errors intelligible in the first place, namely *geometry* and any further minimal account of measurement theory on which any physical proposal must rest (the basic measurement theory required for doing physics is usually taken to include an account of time and mass measurement in addition to that of length).

Of course, one might object to this view of geometry (and, to be clear, we do not *endorse* it here)—but the point cannot be, as a first reflex might have it, that such a view rests on some reactionary tenet about how to think of the geometry of the world: that would be to misunderstand a methodological view on scientific theories for the common *post hoc* view on physics. Rather, the view rests on a basic normative posit about what counts as a sensible rational reconstruction of physics and science—namely, that such a reconstruction should be methodologically ordered. Any objections should therefore be directed at this principle of methodological order, not *per se* at the result that singles out Euclidean geometry. Now, the discussion of methodological constructivism might seem to have taken us a bit on a tangent. Yet, we take it to be an important reminder of how much there is to be said about geometry beyond the mere exegesis of a specific theory's formalism.

[39]The account is called 'neo-transcendentalist' as claims about the lifeworld function as relativised *a priori*. As Rohs (1986) notes, nothing depends on using this terminology; it might even be misleading.

[40]The final status of the proto-geometry project is somewhat debatable (see e.g. Lorenzen and Schwemmer (1973, p. 168)). The proto-physicist could in principle also content themselves with something weaker than the claim that all of the basic geometry is non-empirically determined (Rohs 1986). For present purposes, however, the claim of Euclidean geometry is significant and will thus be assumed.

[41]See Schonefeld (2000) and references therein for subtleties in this project, as well as Rohs (1986).

Returning to the question of the status of intermediate antecedent theories for interpretation (our (2) above): while the focus of methodological constructivism in the context of the special sciences has been on the issue of basic notions (in physics, presumably length, mass, and time)—especially as a response to the long-standing trilemma for measurement—the reconstructive project (guided by the principle of methodological order) does not lose its force when it comes to the reconstruction of the actual empirical theories. It is here that the demand for methodological order translates into the demand to construct one theory after another—thus, in effect, requiring an interpretational cascade of all antecedent theories. At the end of the day, this is also what allows us to say, in light of the principle of methodological order, that general relativity builds atop special relativity. This, then, is the sense in which Minkowski is singled out *vis-à-vis* other spacetimes by methodological constructivism: the reconstruction from the lifeworld onwards goes via special relativity—and not via some theory of (say) global de Sitter or anti-de Sitter.

4.4 The common law tradition

To close this section, we note that there are interesting connections to be drawn between discussions of the local validity of special relativity in general relativity on the one hand, and the jurisprudence of the common law tradition on the other. To those with long memories for the philosophy of science, the initial surprise which such apparent links might engender is diminished once one recalls that connections between common law and science more generally were drawn by Kuhn (1970, p. 23) towards the beginning of *Structure*:

> In a science, on the other hand, a paradigm is rarely an object for replication. Instead, like an accepted judicial decision in the common law, it is an object for further articulation and specification under new or more stringent conditions.

In a recent enlightening and sympathetic essay, Trueblood and Hatfield (2022, pp. 95–6) have explored Kuhn's analogy here, writing that:

> Comparing *Anns*, *Wednesbury* [specific legal cases], and the relationship between special and general relativity is helpful too because malfunctions should not be disregarded altogether. [... E]ven though general relativity is generally understood theoretically to encompass and replace Newtonian gravity, [...] Newtonian gravity remains in wide use where appropriate (which is in fact most situations). Newtonian gravity also illustrates some aspects of gravity more intuitively perhaps than general relativity (which is typically extremely hard to visualize), and is important pedagogically for a number of reasons (e.g. illustration of inverse square law). The point is this: in both science and in law, students are not only taught the current paradigm but previous paradigms too. This is for good reason. The common law, as has been argued, is a textual mode of reasoning. In textual reasoning, the progress is part of the point. The progress helps to explain the current paradigm.

More recently, Bartha (2010, ch. 7) draws a similar parallel between common law and scientific reasoning, writing that "[t]he doctrine of precedent promotes consistency and predictability while still permitting the evolution of the legal system. We seek an analogous balance in scientific reasoning." Bartha develops this for the context of analogical reasoning in science specifically.[42]

Stepping back, all of this has to do with the foundational common lore principle of *stare decisis*, according to which determining points in litigation must proceed according to precedent. But as Postema (2002, p. 588) explains,

> *stare decisis* allows courts to 'distinguish' the cases they face from what might first appear to be relevant and binding precedents, and allows courts to 'extend' precedents beyond their explicit four corners by analogy. The doctrine, reluctantly and within narrow limits, even allows judges to overrule precedents when judges find them to be especially troubling. In this way, common law courts massage precedents and in the process make new law.

The analogy with the case of physics is clear: judges stand to a common law legal system as physicists and practitioners stand to some physical system (or theory); precedent of past rulings/theories must be adhered to, but can also be overruled and extended, when confronted with novel circumstances. This is exactly the situation which seems to obtain when one moves from—"massaging", but not wholly abandoning—the precedent set by special relativity to the new framework of general relativity. (The 'localisation' of the flat spacetime structure of special relativity on moving to general relativity is but one example. Consider also e.g. the modifications to our notion of energy conservation which were implicated in this move: the energy conservation concept was modified, but arguably not wholly abandoned.[43] Of course, there is a good case to be made that these topics are ultimately related, in the sense that the modification of the energy concept on moving to the general theory plausibly has something to do with the lack of global spacetime symmetries in generic models of that theory.)

But one cannot simply throw precedent entirely to the dogs:[44]

> Law was regarded not as a structured set of authoritatively posited, explicit norms, but as rules and ways implicit in a body of practices and patterns of practical thinking all 'handed down by tradition, use, [and] experience' (Blackstone 1765, p. 17). These rules were the product of a process of a common practice of deliberative reasoning, and constituted the basic raw materials used in it. Common law was 'reasonable usage' (Hedley 1968, p. 175), observed and confirmed in a public process of reasoning in which practical problems of daily social life were addressed. (Postema 2002, p. 588)

One might wager that were someone to be nonplussed by what we called above the 'first-order-physics egalitarianism' of Fletcher and Weatherall (2023a), this might have to do with the fact that it seems to fly in the face of such precedent.

In any case, another crucial aspect of common law is that it places paramount importance on the judgement of those involved in the concrete details of particular

[42]Without wishing to labour citations, another very nice discussion of the philosophy of the common law—albeit not specifically in the context of the philosophy of science—is provided by Brandom (2019, pp. 449–50).

[43]See e.g. Duerr (2019), Fletcher (2025), Hoefer (2000), Lam (2011), and Read (2020) for philosophical work on this topic.

[44]The reference to Hedley (1968) in this passage has been modified to reflect the year of the modern edition in which it is published; Hedley's original speech was delivered in 1610.

cases. Here is Postema (2002, pp. 593–94) writing about the 17$^{\text{th}}$ century common law theorist, Sir Matthew Hale:[45]

> Hale insisted that the reason of the common law was the embodied prudence and deliberative judgment of the judge who, through his emersion in the concrete details of common law is fluent in the common language of human affairs, and thus best able to articulate notions of the 'just and fit ... common to all men of reason'—better than philosophers or theologians who seek to do so 'transported from the ordinary measures of right and wrong' and cut off from 'the common staple of humane conversations' (Hale 1956, pp. 502, 503).
>
> [...] '[M]en are not born common lawyers', Hale remarked, 'neither can the bare exercise of the faculty of reason give a man a sufficient knowledge of it, but it must be gained by the habituating and accustoming and exercising that faculty by reading, study, and observation to give a man a complete knowledge thereof' (Hale 1956, p. 505).

One might point out that the analogy with the common law applies (as also came out of the initial Kuhn quote presented above) to any form of successful antecedent theory–successful successor theory relationship (independently of whether one construes their relation as reduction or paradigm change). This is true to some extent, but it invites a distinction between weaker and stronger senses of the analogy to the common law: the stronger sense being when the new theory explicitly contains the old theory, and the weaker sense being when the old theory 'emerges' from the new theory in e.g. some suitable limit. The stronger sense is arguably rarer, but—as pointed out in the Introduction—it is arguably (and *prima facie*) the case for the relationship between special relativity and general relativity in the various geometric and dynamical senses which we have explored in this article. In the stronger sense, no appeals to Nagelian-style bridge laws at the syntactic level (see Riel and Van Gulick (2025)), nor to e.g. sophisticated 'frame theories' at the model-level (see Fletcher (2019)), are required.

5 Close

Our goal in this article has been to draw together all existing threads regarding the local validity of special relativity in general relativity, with a view to at least working towards some closure on this topic in the wake of the articles by Fletcher and Weatherall (2023a,b). We can summarise some of our main results as follows:

1. The results of Fletcher and Weatherall (2023a) regarding **Geometry** are correct, but Gomes (2025, 2026a,b) and Linnemann et al. (forthcoming) have sought to identify *bona fide* senses in which Minkowski spacetime is nevertheless 'locally singled out' geometrically. We have explored some subtleties involved in both of these proposals. As of now, it remains difficult to confidently render Minkowski as locally structurally singled out over some other spacetime through these notions.

[45] See also Postema (2017).

2. We have furthermore identified the Kleinian method to fix spacetime structure as a promising way—this time via coordinate transformations—in which to argue that Minkowski is indeed special in general relativity: it is by the specification of local Lorentz transformations (and arguably not of other coordinate transformations[46]) that any Lorentz metric can be determined, point-by-point.

3. There are also heuristic geometrical senses of the local validity of special relativity in general relativity that have more to do with theory construction and are *only* epistemological in nature. These needn't be taken to be in tension with the results of Fletcher and Weatherall (2023a).

4. Turning to **Dynamics**, we see in the discussions and proofs of March (2025) a clear example of the 'Minkowski bottleneck'—that is, the fact that proofs about general relativity often lean on properties of Minkowski spacetime. This thereby offers another sense in which special relativity is special at the level of heuristics—but now not the heuristics of *constructing* general relativity, but rather of coming to *understand* and *work* with it.

5. March (2025) offers an approach to **Dynamics** in the spirit of Fletcher and Weatherall (2023a,b). One can understand 'tests of local Lorentz invariance' (Will 2014) as ruling out theories in which the evolution of material fields is described by equations which violate assumptions on dynamics presented by March (2025); as such, there is no conflict between these experimental tests and the results of Fletcher and Weatherall (2023a,b) and March (2025).

6. Wallace (2017) offers important contributions to these discussions by capitalising on the self-similarity of large and small scales in asymptotically flat spacetimes (used to model isolated subsystems), but it is again not obvious that his approach always privileges Minkowski spacetime *in particular*.

7. Another understanding of the local validity of special relativity in general relativity in terms of **Dynamics** points to the spin-2 approach. Analogues to the bootstraps from a spin-2 field in flat spacetime to general relativity can, however, also be run by starting with linear metric perturbation theories around other backgrounds.

8. Despite suggestions that the local validity of special relativity is a mere pragmatic aspect (Fletcher and Weatherall, p.c.), one might wish to retain commitment to the *non-triviality* of the local validity of special relativity if one signs up to the philosophy of science of Cartwright (1999), to the general philosophical framework of pragmatism, or to the specific pragmatic framework of methodological constructivism. That being said, it is not the case that all these philosophical views can *always* single out the local validity of Minkowski as special *vis-à-vis* other spacetimes. Arguably, only methodological constructivism can do so, and also only in its very special sense of methodologically ordered theory reconstruction.

9. Physics practice has some affinities with the common law tradition in jurisprudence, in which central store is placed on practice and precedent. This

[46] Although, as mentioned in §2.3, there remains technical work to be done here.

sheds light on what one might find unsettling in the results of Fletcher and Weatherall (2023a).

At this stage, we come to the end of our tour (*de force*). Rather than say any more, let us close with a riddle:

I am the tangent truth at every point of grace,
Where freely falling frames erase all force and trace.
My flat connection reigns locally, though curvature may loom,
And lightcones still command what events can assume.
Globally I may fail, yet at the smallest scales I stand—
What spacetime is touched, but never curved, by Einstein's hand?

Acknowledgements

We are grateful to Harvey Brown, Sam Fletcher, Joakim Flinckman, Henrique Gomes, Ted Jacobson, Eleanor March, Tushar Menon, Oliver Pooley, Shelly Shi, Norman Sieroka, Chris Smeenk, Nic Teh, and Jim Weatherall for valuable conversations and feedback. We also thank the audience of the Black Hole Initiative Foundations seminar. N.L. acknowledges the support of the Swiss National Science Foundation as part of the project 'Philosophy Beyond Standard Physics' (105212_207951).

References

Adlam, Emily, Linnemann, Niels, and Read, James (2025). *Constructive axiomatics for spacetime physics*. Oxford University Press.

Anandan, J. (1996a). "Gravitational phase operator and cosmic strings". *Physical Review D* 53, pp. 779–786. DOI: 10.1103/PhysRevD.53.779. arXiv: gr-qc/9507049 [gr-qc].

— (1996b). "Reality and geometry in quantum theory". Contains material related to arXiv:gr-qc/9505011 ("Reality and Geometry of States and Observables in Quantum Theory"). DPhil thesis. University of Oxford. arXiv: gr-qc/9505011 [gr-qc].

Bamonti, Nicola, Cinti, Enrico, and Sanchioni, Marco (2026/01/03 2025). "Non-Relativistic Background Independence and the Gauging of Spacetime Symmetries". *The British Journal for the Philosophy of Science*. DOI: 10.1086/739787. URL: https://doi.org/10.1086/739787.

Barrett, Thomas William and Manchak, JB (2024a). "On Coordinates and Spacetime Structure". *Philosophy of Physics* 2, pp. 11, 1–24.

— (2024b). "On Privileged Coordinates and Kleinian Methods". *Erkenntnis*. DOI: 10.1007/s10670-024-00914-4.

— (2025). "What Do Privileged Coordinates Tell Us About Structure?" *Philosophy of Science* 92.3, pp. 528–547. DOI: 10.1017/psa.2024.53.

Bartha, Paul (2010). *By parallel reasoning*. Oxford University Press.

Belot, Gordon (2023). *Accelerating Expansion Philosophy and Physics with a Positive Cosmological Constant*. New York: Oxford University Press.

Bilson-Thompson, Sundance O. et al. (Dec. 2023). "Tachyonic media in analog models of special relativity". *Phys. Rev. D* 108 (12), p. 124020. DOI: 10.1103/PhysRevD.108.124020. URL: https://link.aps.org/doi/10.1103/PhysRevD.108.124020.

Blackstone, William (1765). *Commentaries on the Laws of England*. 4 vols. Published 1765–1769. Oxford: Clarendon Press.

Boulware, David G and Deser, Stanley (1975). "Classical general relativity derived from quantum gravity". *Annals of Physics* 89.1, pp. 193–240.

Brandom, Robert (1994). *Making It Explicit: Reasoning, Representing, and Discursive Commitment*. Cambridge: Harvard University Press.

— (2019). *A Spirit of Trust: A Reading of Hegel's* Phenomenology. Cambridge, MA and London, England: Harvard University Press.

Brown, Harvey R. (1997). "On the Role of Special Relativity in General Relativity". *International Studies in the Philosophy of Science* 11.1, pp. 67–81. DOI: 10.1080/02698599708573551.

— (2005). *Physical Relativity: Space-Time Structure From a Dynamical Perspective*. Oxford University Press UK.

Brown, Harvey R. and Pooley, Oliver (2001). "The origin of the spacetime metric: Bell's 'Lorentzian pedagogy' and its significance in general relativity". *Physics meets philosophy at the Planck scale*, pp. 256–272.

— (2004). "Minkowski Space-Time: A Glorious Non-Entity". In: *The Ontology of Spacetime*. Ed. by Dennis Dieks. Elsevier, pp. 67–89.

Cappelen, Herman (2018). *Fixing Language: An Essay on Conceptual Engineering*. Oxford: Oxford University Press.

Carrier, Martin (1990). "Constructing or Completing Physical Geometry? On the Relation between Theory and Evidence in Accounts of Space-Time Structure". *Philosophy of Science* 57.3, pp. 369–394. ISSN: 0031-8248. DOI: 10.1086/289564.

Cartwright, Nancy (1999). *The Dappled World: A Study of the Boundaries of Science*. Cambridge: Cambridge University Press.

Cudek, Franciszek and Read, James (2025). "Review of *Accelerating Expansion: Philosophy and Physics with a Positive Cosmological Constant*, by Gordon Belot". *Foundations of Physics* 55.18, pp. 1–20. DOI: 10.1007/s10701-025-00822-9.

Curiel, Erik (2009). "General relativity needs no interpretation". *Philosophy of Science* 76.1, pp. 44–72.

— (2020). *Schematizing the Observer and the Epistemic Content of Theories*.

Delhom, Adrià et al. (2023). "Bootstrapping gravity and its extension to metric-affine theories". *Journal of Cosmology and Astroparticle Physics* 2023.12, p. 006.

Deser, Stanley (1970). "Self-interaction and gauge invariance". *General Relativity and gravitation* 1.1, pp. 9–18.

— (1987). "Gravity from self-interaction in a curved background". *Classical and Quantum Gravity* 4.4, p. L99.

— (2009). "Gravity from self-interaction redux". *arXiv preprint arXiv:0910.2975*.

Deser, Stanley and Henneaux, M (2007). "A note on spin-2 fields in curved backgrounds". *Classical and Quantum Gravity* 24.6, p. 1683.

Dewar, Neil, Linnemann, Niels, and Read, James (2026/01/07 2022). "The epistemology of spacetime". *Philosophy Compass* 17.4, e12821. DOI: https://doi.org/10.1111/phc3.12821. URL: https://doi.org/10.1111/phc3.12821.

Dewey, John (1925). *Experience and Nature*. Chicago: Open Court.
— (1938). *Logic: The Theory of Inquiry*. New York: Henry Holt.
Dold, Dominic and Teh, Nicholas (2025). “Deriving the Geodesic Principle”. *Philosophy of Physics* 3.1, pp. 1–24.
Duerr, Patrick M. (2019). “Fantastic Beasts and Where to Find Them: Local Gravitational Energy and Energy Conservation in General Relativity”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 65, pp. 1–14. DOI: 10.1016/j.shpsb.2018.07.002.
Earman, John (2014). “No superluminal propagation for classical relativistic and relativistic quantum fields”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 48, pp. 102–108. DOI: https://doi.org/10.1016/j.shpsb.2014.07.005. URL: https://www.sciencedirect.com/science/article/pii/S1355219814000811.
Ehlers, J., Pirani, F.A.E., and Schild, A. (2012). “Republication of: The geometry of free fall and light propagation”. *General Relativy and Gravity* 44, pp. 1587–1609.
Ehlers, Jürgen (1973). “Survey of General Relativity Theory”. In: *Relativity, Astrophysics and Cosmology*. Ed. by Werner Israel. Dordrecht: Springer Netherlands, pp. 1–125. ISBN: 978-94-010-2639-0.
Ehlers, Jürgen and Geroch, Robert (2004). “Equation of motion of small bodies in relativity”. *Annals of Physics* 309.1, pp. 232–236. DOI: 10.1016/j.aop.2003.08.020. eprint: gr-qc/0309074. URL: https://doi.org/10.1016/j.aop.2003.08.020.
Einstein, Albert (1916). “Die Grundlage der allgemeinen Relativitätstheorie”. *Annalen Der Physik* 49.7. Translated as “The Foundations of General Relativity” in Lorentz et al., “The Principle of Relativity”, Methuen and Company, Ltd. Reprinted by Dover Publications (1923), pp. 769–822.
Elder, Jamee (2025). “On the “direct detection”of gravitational waves”. *Studies in History and Philosophy of Science* 110, pp. 1–12. DOI: https://doi.org/10.1016/j.shpsa.2025.01.002. URL: https://www.sciencedirect.com/science/article/pii/S0039368125000020.
Fang, J and Fronsdal, C (1979). “Deformations of gauge groups. Gravitation”. *Journal of Mathematical Physics* 20.11, pp. 2264–2271.
Feynman, Richard P, Morinigo, Fernando B, and Wagner, William G (1995). *Feynman lectures on gravitation*. Addison-Wesley Publishing Company.
Fletcher, Samuel C and Weatherall, James Owen (2023a). “The Local Validity of Special Relativity, Part 1: Geometry”. *Philosophy of Physics* 1.
— (2023b). “The Local Validity of Special Relativity, Part 2: Matter Dynamics”. *Philosophy of Physics* 1.
Fletcher, Samuel C. (2016). “Similarity, Topology, and Physical Significance in Relativity Theory”. *British Journal for the Philosophy of Science* 67.2, pp. 365–389. DOI: 10.1093/bjps/axu044.
— (2019). “On the Reduction of General Relativity to Newtonian Gravitation”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 68.C, pp. 1–15. DOI: 10.1016/j.shpsb.2019.04.005.
— (2020). “Apprxomate local Poincaré spacetime symmetry in general relativity”. In: *Thinking About Space and Time*. Ed. by Claus Beisbart, Tilman Sauer, and Christian Wüthrich. Birkhäuser.

Fletcher, Samuel C. (2025). *Foundations of General Relativity*. Elements in the Philosophy of Physics. Cambridge: Cambridge University Press. ISBN: 9781108949286. DOI: DOI:10.1017/9781108954082. URL: https://www.cambridge.org/core/product/00EFDFCE622638B5AEEF786C8D70DD33.

Geroch, Robert and Jang, Pong Soo (1975). "Motion of a body in general relativity". *Journal of Mathematical Physics* 16.1, pp. 65–67. DOI: 10.1063/1.522416. URL: https://doi.org/10.1063/1.522416.

Geroch, Robert and Weatherall, James Owen (2018). "The Motion of Small Bodies in Space–time". *Communications in Mathematical Physics* 364.2, pp. 607–634. DOI: 10.1007/s00220-018-3268-8. eprint: arXiv:1707.04222. URL: https://doi.org/10.1007/s00220-018-3268-8.

Giovanelli, Marco (2021). "Nothing but Coincidences: The Point-Coincidence and Einstein's Struggle with the Meaning of Coordinates in Physics". *European Journal for Philosophy of Science* 11.2, pp. 1–64. DOI: 10.1007/s13194-020-00332-7.

Gomes, Henrique (2025). "Is spacetime locally flat?" *Philosophy of Physics*.

— (2026a). "Are spacetimes locally homogeneous?"

— (2026b). "Local Flatness Extension". Unpublished note.

Gomes, Henrique et al. (2024). *How to Recover Spacetime Structure from Privileged Coordinates*. arXiv: 2408.10674 [physics.hist-ph]. URL: https://arxiv.org/abs/2408.10674.

Gupta, Suraj N (1954). "Gravitation and electromagnetism". *Physical Review* 96.6, p. 1683.

Hale, Matthew (1956). "Reflections by the Lord Chief Justice Hale on Mr. Hobbes His Dialogue of the Lawe". In: *A History of English Law*. Ed. by William Holdsworth. 7th ed. 17 vols. Text written in the 1670s; reprinted in the 7th edition. London: Methuen.

Hari, K and Kothawala, Dawood (2020). "Normal coordinates based on curved tangent space". *Physical Review D* 101.12, p. 124066.

Hawking, Stephen W and Ellis, George FR (1973). *The large scale structure of space-time*. Cambridge University Press.

Hedley, Thomas (1968). "Speech in Parliament on Royal Impositions". In: *Proceedings in Parliament 1610*. Ed. by Elizabeth Read Foster. Speech originally delivered in 1610. New Haven: Yale University Press.

Heiderich, Karen Rachel (1991). "Spin-two fields and general covariance". PhD thesis. University of British Columbia.

Hetzroni, Guy and Read, James (forthcoming). "How to Teach General Relativity". *British Journal for the Philosophy of Science*. DOI: 10.1086/729059.

Hoefer, Carl (2000). "Energy Conservation in GTR". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 31.2, pp. 187–199. DOI: 10.1016/s1355-2198(00)00004-6.

James, William (1907). *Pragmatism: A New Name for Some Old Ways of Thinking*. New York: Longmans, Green, and Co.

— (1909). *The Meaning of Truth*. New York: Longmans, Green, and Co.

Janich, Peter (1994). "Protochemie: Programm einer konstruktiven Chemiebegründung". *Journal for General Philosophy of Science* 25.1, pp. 71–87.

— (2012). *Protophysics of time: Constructive foundation and history of time measurement*. Vol. 30. Springer Science & Business Media.

Kamlah, Wilhelm and Lorenzen, Paul (1967). *Logische Propadeutik*.

Kraichnan, Robert H (1955). "Special-relativistic derivation of generally covariant gravitation theory". *Physical Review* 98.4, p. 1118.

Kuhn, Thomas S. (1970). *The structure of scientific revolutions*. University of Chicago press Chicago.

Lam, Vincent (2011). "Gravitational and Nongravitational Energy: The Need for Background Structures". *Philosophy of Science* 78.5, pp. 1012–1024. DOI: 10.1086/662260.

Lehmkuhl, Dennis (2021). "The equivalence principle(s)". In: *The Routledge companion to philosophy of physics*. Routledge, pp. 125–144.

Linnemann, Niels (2026). "A philosophical look at the spin-2 particle physics approach to GR".

Linnemann, Niels and Read, James (2021). "Comment on 'Do electromagnetic waves always propagate along null geodesics?'" *Classical and Quantum Gravity* 38.23, p. 238001.

— (2026). "Review of 'Foundations of General Relativity', by Samuel C. Fletcher".

Linnemann, Niels, Read, James Alexander Mabyn, and Teh, Nicholas J. (forthcoming). "The Local Validity of Special Relativity From a Scale-Relative Perspective". *British Journal for the Philosophy of Science*. DOI: 10.1086/732151.

Linnemann, Niels, Smeenk, Chris, and Baker, Mark Robert (2023). "GR as a classical spin-2 theory?" *Philosophy of Science* 90.5, pp. 1363–1373.

Lorenzen, Paul (1963). "Methodisches denken". *Logique et Analyse* 6.21/24, pp. 219–231.

— (1977). "Relativistische Mechanik mit klassischer Geometrie und Kinematik". *Mathematische Zeitschrift* 155.1, pp. 1–9.

Lorenzen, Paul and Schwemmer (1973). "Konstruktive Logik, Ethik und Wissenschaftstheorie".

March, Eleanor (2025). "Minimal coupling, the strong equivalence principle, and the adaptation of matter to spacetime geometry". MA thesis. University of Oxford.

Misner, Charles W., Thorne, K. S., and Wheeler, J. A. (1973). *Gravitation*. San Francisco: W. H. Freeman. ISBN: 978-0-7167-0344-0, 978-0-691-17779-3.

Padmanabhan, Thanu (2008). "From gravitons to gravity: Myths and reality". *International Journal of Modern Physics D* 17.03n04, pp. 367–398.

Peirce, Charles Sanders (1878). "How to Make Our Ideas Clear". *Popular Science Monthly* 12, pp. 286–302.

— (1931–1935). *Collected Papers of Charles Sanders Peirce*. Ed. by Charles Hartshorne and Paul Weiss. 6 vols. Cambridge, MA: Harvard University Press.

Pincock, Christopher and Poznic, Michael (2025). "Non-representational models and objectual understanding". *Erkenntnis* 90.8, pp. 3335–3356.

Pitts, J Brian (2016). "Einstein's Equations for Spin 2 Mass 0 from Noether's Converse Hilbertian Assertion". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 56, pp. 60–69.

— (2006). "Absolute objects and counterexamples: Jones–Geroch dust, Torretti constant curvature, tetrad-spinor, and scalar density". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 37.2, pp. 347–371. DOI: https://doi.org/10.1016/j.shpsb.2005.11.004. URL: https://www.sciencedirect.com/science/article/pii/S1355219806000104.

Poisson, Eric and Will, Clifford M (2014). *Gravity: Newtonian, post-Newtonian, relativistic*. Cambridge University Press.

Postema, Gerald J. (2002). "Philosophy of the Common Law". In: *The Oxford Handbook of Jurisprudence & Philosophy of Law*. Ed. by Jules Coleman and Scott Shapiro. Oxford University Press.

— ed. (2017). *Matthew Hale: On the Law of Nature, Reason, and Common Law: Selected Jurisprudential Writings*. Oxford University Press.

Price, Huw (2003). "Truth as Convenient Friction". *Journal of Philosophy* 100.4, pp. 167–190. DOI: 10.5840/jphil200310048.

— (2013). *Expressivism, Pragmatism and Representationalism*. Ed. by Simon Blackburn et al. Burlington, VT: Cambridge University Press.

Read, James (2020). "Functional Gravitational Energy". *British Journal for the Philosophy of Science* 71.1, pp. 205–232. DOI: 10.1093/bjps/axx048.

— (2023). *Background Independence in Classical and Quantum Gravity*. Oxford University Press.

Read, James, Brown, Harvey R., and Lehmkuhl, Dennis (2018). "Two miracles of general relativity". *Studies in history and philosophy of science Part B: Studies in history and philosophy of modern physics* 64, pp. 14–25.

Read, James and Teh, Nicholas J (Aug. 2018). "The teleparallel equivalent of Newton–Cartan gravity". *Classical and Quantum Gravity* 35.18, 18LT01. ISSN: 1361-6382. DOI: 10.1088/1361-6382/aad70d. URL: http://dx.doi.org/10.1088/1361-6382/aad70d.

Reichenbach, Hans (1969). *Axiomatisation of the theory of relativity*. University of California Press.

Riel, Raphael van and Van Gulick, Robert (2025). "Scientific Reduction". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta and Uri Nodelman. Winter 2025. Metaphysics Research Lab, Stanford University.

Rohs, Peter (1986). *Ist eine ausweisbare Zeitmessung möglich? Zur 'Protophysik der Zeit'*.

Rovelli, Carlo (2004). *Quantum gravity*. Cambridge Monographs on Mathematical Physics. Cambridge, UK: Univ. Pr. DOI: 10.1017/CBO9780511755804.

Salimkhani, Kian (2020). "The dynamical approach to spin-2 gravity". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 72, pp. 29–45.

— (2023). *The Non-Fundamentality of Spacetime: General Relativity, Quantum Gravity, and Metaphysics*. Routledge.

Schonefeld, Wolfgang (2000). "Protophysik und spezielle Relativitätstheorie". *Journal for general philosophy of science* 31.1, pp. 157–178.

Schrödinger, Erwin (1985). *Space-Time Structure*. Cambridge Science Classics. Cambridge: Cambridge University Press. ISBN: 9780521315203. DOI: DOI : 10.1017/CBO9780511586446. URL: https://www.cambridge.org/core/product/554B50728DF38139E42E60BBED654D85.

Sharpe, R. W. (2000). *Differential Geometry: Cartan's Generalization of Klein's Erlangen Program*. Graduate Texts in Mathematics. Springer New York. ISBN: 9780387947327. URL: https://books.google.co.uk/books?id=d7w6AKaD_DkC.

Steeger, Jer and Read, James (Feb. 2026). *Everettian chance in no uncertain terms*. URL: https://philsci-archive.pitt.edu/28291/.

Stein, Howard (1995). "Some reflections on the structure of our knowledge in physics". In: *Logic, Methodology and Philosophy of Science iIX*. Ed. by D

Prawitz, B Skyrms, and D Westerståhl. Vol. 134. Studies in Logic and the Foundations of Mathematics. New York: Elsevier, pp. 633–655.
Trueblood, Leah and Hatfield, Peter (2022). "Precedent and Paradigm: Thomas Kuhn on Science and the Common Law". *The Philosophical Foundations of Precedent (Forthcoming, OUP)*.
Wald, Robert M (1986). "Spin-two fields and general covariance". *Physical Review D* 33.12, p. 3613.
— (1984). *General Relativity.* Chicago, USA: Chicago Univ. Pr. DOI: 10.7208/chicago/9780226870373.001.0001.
Wallace, David (2017). "The Relativity and Equivalence Principles for Self-gravitating Systems". In: *Towards a Theory of Spacetime Theories.* Ed. by Dennis Lehmkuhl, Gregor Schiemann, and Erhard Scholz. New York, NY: Springer New York, pp. 257–266. ISBN: 978-1-4939-3210-8. DOI: 10.1007/978-1-4939-3210-8{_}8. URL: https://doi.org/10.1007/978-1-4939-3210-8_8.
— (2019). "Who's Afraid of Coordinate Systems? An Essay on Representation of Spacetime Structure". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 67.C, pp. 125–136. DOI: 10.1016/j.shpsb.2017.07.002.
Weatherall, James Owen (2014). "Against dogma: On superluminal propagation in classical electromagnetism". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 48, pp. 109–123. DOI: https://doi.org/10.1016/j.shpsb.2014.08.005. URL: https://www.sciencedirect.com/science/article/pii/S1355219814000896.
— (2020). "Two dogmas of dynamicism". *Synthese* 199, pp. 253–275.
Weinberg, Steven (1964). "Photons and gravitons in S-matrix theory: derivation of charge conservation and equality of gravitational and inertial mass". *Physical Review* 135.4B, B1049.
— (1965). "Photons and gravitons in perturbation theory: Derivation of Maxwell's and Einstein's equations". *Physical Review* 138.4B, B988.
— (1972). "Gravitation and cosmology: principles and applications of the general theory of relativity".
Will, Clifford M. (2014). "The Confrontation between General Relativity and Experiment". *Living Reviews in Relativity* 17.1, p. 4. DOI: 10.12942/lrr-2014-4. URL: https://doi.org/10.12942/lrr-2014-4.
Wise, Derek (2007). "Topological Gauge Theory, Cartan Geometry, and Gravity". PhD thesis. University of California, Riverside.
— (Aug. 2010). "MacDowell–Mansouri Gravity and Cartan Geometry". *Classical and Quantum Gravity* 27.15, p. 155010. ISSN: 0264-9381, 1361-6382. DOI: 10.1088/0264-9381/27/15/155010. (Visited on 05/16/2022).