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ORIGINAL RESEARCH

Once upon a time in superspace: the diegetic ideal for the interpretation of physical theories

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Abstract
This paper offers a novel argument for superspace substantivalism. *Superspace* is a modified spacetime represented formally through combining ordinary spatial dimensions with anticommuting dimensions whose coordinates are labelled in Grassmann numbers rather than real numbers. At supersymmetric worlds, physical laws exhibit *supersymmetry*—viz., a symmetry that transforms bosons into fermions and vice versa. *Superspace substantivalism* is the thesis that, at supersymmetric worlds, among the most fundamental structures is superspace. Initially, the focus will be on a prevalent doctrine in the philosophy of physics literature which I call the *mimetic ideal*. On the mimetic ideal, interpreting physical theories aims primarily at specifying their *ontology*, namely at achieving accurate *reference* (in natural-language accounts of those theories) or *representation* (in model-theoretic portrayals of those theories) with respect to aspects of physical reality. However, I show that the mimetic ideal doesn't seem able to account for important aspects of physics practice (Sect. 2). In Sect. 3, therefore, I articulate and defend a new, *diegetic ideal*, according to which the interpretation of physical theories should aim at *perspectival coordination* between interpreters and practising physicists. Perspectival coordination, in the context of interpreting physical theories, means that interpreters and practising physicists share a perspective or a point of view on some aspect of physical reality described by that theory. In Sect. 4, I apply this analysis to the study of supersymmetric quantum field theories (QFTs): reframing the realist framework which underlies Baker's (2020) agnosticism, I examine the exciting upshot that superspace substantivalism is true. I conclude with some reflections on what perspectival coordination means for realism (Sect. 5).

Keywords Supersymmetry · Superspace · Substantivalism · The Hole Argument · Theoretical virtues · Narrative testimony

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1 Introduction

The principal aim of this paper is to offer a novel argument for superspace substantivalism. *Superspace* is a modified spacetime represented formally through combining ordinary spatial dimensions with anticommuting dimensions whose coordinates are labelled in Grassmann numbers rather than real numbers. At supersymmetric worlds, physical laws exhibit *supersymmetry*—viz., a symmetry that transforms bosons into fermions and vice versa. *Superspace substantivalism* is the thesis that, at supersymmetric worlds, among the most fundamental structures is superspace.[1]

But the approach taken will be oblique. Initially, the focus will be on a prevalent doctrine in the recent philosophy of physics literature which I call the *mimetic ideal*. The mimetic ideal is often taken to derive from the realist intuition that "physical theories—if we take them literally—tell us what [the] world is like, or at least what it might have been like" (Caulton, 2015, p. 153). On the mimetic ideal, interpreting physical theories aims primarily at specifying their *ontology*, namely at achieving accurate *reference* (in natural-language accounts of those theories) or *representation* (in model-theoretic portrayals of those theories) with respect to aspects of physical reality.[2] A paradigmatic example is Hempel's logical-empiricist view: interpretations should give an "objective" account—viz., one which is "independent of what particular individuals happen to…apply them" (1965, p. 426)—of reality as described by physical theories, through the reconstruction and logical analysis of those theories.[3] But van Fraassen's widely accepted "question[s] of interpretation" also conflate the mimetic ideal with the realist intuition: "Under what conditions is the theory true? What does it say the world is like?" (1991, p. 242; cf. Jacobs, 2021, p. 3; Ruetsche, 2011, p. 7).[4] In a similar vein, Caulton (2015, pp. 153–154) writes that the aim of interpretation is to "extract an account of the physical world from a theory" by constructing a "representation relation" which determines a "unique interpretation for the theory".

[1] Sometimes substantivalism is stated as a doctrine about the existence of spacetime points (see, e.g., Earman and Norton, 1987; Teitel, 2022). However, according to some metaphysicians, questions about what exists can be trivially answered in the affirmative (Fine, 2001; Schaffer, 2009). For this reason, Baker (2020), Dasgupta (2011), Field (1984) and North (2018) define substantivalism in terms of "relative grounding" or "fundamentality". I adopt this approach since it allows us to distinguish questions concerning superspace *fundamentality* from questions regarding superspace *spatiotemporality* (Baker, 2020, pp. 2382–2383; see fn.28).

[2] Wallace (2021a) cashes out the distinction between reference and representation in terms of the "language-first" and "maths-first" views of theories, respectively. I do not take a stand as to which view is better. Still, I am partial to Wallace's view that modern physical theories are better construed according to the maths-first view and will consider the popular semantic view of theories in Sect. 2. Wallace associates, but does not identify, the *semantic* with the *maths-first* view. Talk of *aspects of reality* simply refers to the domain-restrictedness of physical theories, that is, that theories need not be about all physical phenomena everywhere but rather, in general, describe some systems and not others. On this: Wallace (2021a1a, p. 9, 2021b).

[3] For analysis and criticism of the ideal of objectivity in scientific interpretation: Douglas (2009); Friedman (1974).

[4] Ruetsche (2011) argues against "pristinism" in the interpretation of quantum theories with infinitely many degrees of freedom (QM_∞) on the basis that this construes interpretation as a "lofty" affair which is concerned with only the general question of which worlds are possible according to a theory and not with the application of the theory to actual physical systems. The mimetic ideal depends rather on the priority of ontological specification in interpretation but it may turn out that rejecting the mimetic ideal supports the rejection of pristinism.

However, I show that the mimetic ideal doesn't seem able to account for important aspects of physics practice. In particular, physicists appeal to criteria for interpreting theories—*theoretical virtues*—some of which are more fine-grained than the criteria for accurate reference/representation warranted by the mimetic ideal (Sect. 2).

This suggests that physical theories—construed in terms of not just *what* they say (reference/representation) but *how* they say it (physics practice)—might tell us more about "what the world is like" than its mere ontology. In Sect. 3, therefore, I articulate and defend a new, *diegetic*[5] *ideal*, according to which the interpretation of physical theories should aim at *perspectival coordination* between interpreters and practising physicists. Perspectival coordination, in the context of interpreting physical theories, means that interpreters and practising physicists share a perspective or a point of view on some aspect of physical reality described by that theory. In brief, sharing a perspective goes above and beyond agreement on ontological content because, on the standard view, when agents coordinate on a perspective, they also share certain *attentional* dispositions (concerning what, in a given situation, is inclined to strike them as interesting/noteworthy, not mere background facts); *inquisitive* dispositions (concerning what kinds/methods of enquiry seem worthwhile and what kinds of explanations will close their enquiry) and *illative* dispositions (concerning which inferences and evaluations they are inclined towards) (Fraser, 2021, p. 4028; Camp, 2017).[6] In Sect. 4, I apply this analysis to the study of supersymmetric quantum field theories (QFTs): reframing the realist framework which underlies Baker's (2020) agnosticism, I examine the exciting upshot that superspace substantivalism is true. I conclude with some reflections on what perspectival coordination means for realism (Sect. 5).

This thesis is important notwithstanding that there is as yet no evidence to suggest that our world might count amongst the supersymmetric worlds.[7] This is because the interpretation of supersymmetry is crucial if we are to understand various promising research programmes including extensions of the Standard Model and quantum gravity theories, such as string theory. Supersymmetry remains an alluring feature of these research programmes in virtue of predicting the existence of particles which could constitute "dark matter", unifying three of the fundamental forces at high energies and, most importantly, its potential to solve the "hierarchy problem" concerning the vast discrepancy between aspects of the weak nuclear force and gravity (Baker, 2020, p. 2376; Martin, 2016, pp. 3–11; Menon, 2018, Sect. 1). Hence the significance of my arguments.

[5] Thanks to an anonymous reviewer for prompting me to use this standard antonym of mimetic.

[6] The terminology of "perspective" is from the recent epistemology literature on narrative testimony. It is not my intention thereby to take a stand as to the virtues of perspectival realism (Massimi, 2017), although my arguments may turn out to support it (Read, 2021).

[7] Worse, many believe that our ongoing failure to detect "superpartner" particles predicted by supersymmetric theories indicates the failure of supersymmetry as a hypothesis (Wolchover, 2012, 2016). Still, explicating the meaning of substantivalism at supersymmetric worlds has epistemic value regardless of whether the actual world is supersymmetric, in the same way that even somewhat outlandish philosophical thought experiments can shed light on the hidden assumptions and contingencies which lie undisturbed under parochial conceptual analysis. On the epistemic value of theorising non-actual possibilities to uncover the hidden assumptions embedded within physical theories: Friedman (2001); Menon (2018, Sect. 1) and Belot's (1998) discussion of the Aharanov-Bohm effect.

2 The mimetic ideal is not the hole story

In this section, I argue that the mimetic ideal is not the whole story when it comes to the interpretation of physical theories. Indeed, ontologically equivalent interpretations of one of our best physical theories, namely general relativity (GR), tell different stories about what the world is like. To see this, let's adopt the semantic conception of scientific theories, which associates a theory with a class of models.[8] The standard approach distinguishes two phases in interpreting physical theories. In the first phase, a theory is associated with a class of models. For example, in GR, the space of "kinematically possible models" (KPMs) comprises triples $\langle M, g_{ab}, \Phi \rangle$, where M is a differentiable manifold, g_{ab} a Lorentzian metric field on M, and $\varPhi$ a placeholder for the matter fields. The subspace of "dynamically possible models" (DPMs) comprises those KPMs whose geometrical objects satisfy Einstein's field equations and the dynamical equations of the Φ.[9] In the second phase, to pick out the ontological content of a theory, we construct a "representation map" from models to possible worlds.[10] The assumption that GR is empirically adequate—namely "that the theory makes true claims about the observed phenomena" (Caulton, 2015, p. 159)—imposes "a minimal [interpretation]…[which] hook[s] up the formalism with the empirical evidence" (Zinkernagel, 2011, p. 218). But which, if any, observationally indistinguishable models are *physically* equivalent—viz., correspond to the same possible world?[11] Of course, in practice, classes of observationally indistinguishable solutions are always shifting (Maxwell, 1962).[12] Fortunately, some solutions of GR seem *even in principle* observationally indistinguishable,[13] namely those which are related by isometries, viz., (four-dimensional) distance-preserving maps on M (Norton, 2022, Sect. 3.2). So let's take our ontological question to be: when, if ever, are isometric GR-models physically equivalent?

The hole argument is usually taken to indicate that a natural representation map for GR, involving an injective mapping from models to possible worlds, will result

8 For details: French and Ladyman (1999); Suppes (1960); van Fraassen (1980, 1989, 2000). I will not examine the alternative, syntactic conception, critiqued in Suppe (1974) and defended in Lutz (2012).

9 See: Read and Møller-Nielsen (2020, p. 89); Read and Martens (2020); Pooley (2020).

10 Whilst it's usually assumed that the representation map relates DPMs to possible worlds, Curiel (2016) defends the interpretative significance of KPMs too. I wish to remain neutral so will refer simply to "models" in what follows.

11 Drawing on Read and Møller-Nielsen (2020: pp. pp. 94–95), I understand "observational distinguishability" using van Fraassen's (1980) "hermeneutic circle"-type reasoning, namely drawing on science itself (taken as a broad sweep of *acceptable* theories) to tentatively pick out those models which are in principle observationally distinguishable. This seems compatible with Caulton's proposal that we "tentatively follow the experimentalist: for she knows how to use the theory to generate empirical predictions", presumably based upon her acceptance of other theories (2015, p. 159).

12 Moreover, Sorites-type paradoxes might initially suggest that observationally distinguishable solutions may be related by a continuous series of solutions which are, in practice, observationally *in*distinguishable.

13 Popular views on vagueness support this appeal to *in principle* observational indistinguishability: according to epistemicists, Sorites-cases of purported non-transitive observational indistinguishability involve mere ignorance of where the actual threshold of distinguishability lies; supervaluationists view vagueness in Sorites-cases as mere semantic indeterminacy.

in unacceptable indeterminism (Earman & Norton, 1987; cf. Stachel, 1989).[14] This is why many authors have instead adopted what I call the "sophisticated" representation map, namely a surjective mapping from models to possible worlds, on which isometric models of GR are physically equivalent. One might motivate this mapping by noting, as Weatherall has, that isomorphism is the standard of identity in mathematics, and isometry is the standard of isomorphism for Lorentzian manifolds (2018, p. 335). Or one might appeal to anti-haecceitism, since the sophisticated mapping arguably corresponds to denying the existence of distinct, qualitatively identical worlds (Brighouse, 1994; Pooley, 2006; Rynasiewicz, 1994). Some combine the sophisticated mapping with a qualitative counterpart theory, where the counterpart relation is isometry, which also seems to avoid the hole argument (Butterfield, 1989, pp. 24–27). Crucially, let's grant for the sake of argument that the sophisticated mapping gets the ontology of GR right: any two isometric models are equally apt to represent any given possibility (Fletcher, 2020, pp. 239–240; Weatherall, 2018; Pooley, 2020, p. 15). That notwithstanding, as Belot (2018) highlights, the sophisticated mapping does not, in general, track *physics practice*. In particular, physicists sometimes treat isometric models as physically *distinct*. For example, when he discusses the Hamiltonian formulation of asymptotically flat sectors of GR, Wald adopts a more restrictive notion of physical equivalence: "one is led to choose as the new configuration space the metrics on [M]…*modulo diffeomorphisms which can be continuously deformed to the identity*" (1984, p. 467, emphasis mine; cf. Wald & Zoupas, 2000). Assuming that Belot's empirical account of physics practice is apt, on what basis would physicists distinguish between ontologically equivalent models?

One way to think about this is as follows. In theory-choice, physicists seem to appeal to "theoretical virtues" (Kuhn, 1977; Mizrahi forthcoming; Schindler, 2022). Standardly, these include:

- consistency (no intra-/inter-theoretic contradictions (Douglas, 2014; Schindler, 2022));
- empirical adequacy;
- unifying power (viz., identifying principles underlying seemingly disparate phenomena (Morrison, 2000; Schindler, 2014));
- simplicity (e.g. fewer free parameters (Forster & Sober, 1994; Sober, 2015), basic principles or basic entities (Baker, 2003; Jansson & Tallant, 2017; Nolan, 1997));
- fertility (e.g., a theory successfully predicts new phenomena (Schindler, 2022)).[15]

Now, consider the two reasons which Belot (2018) offers as to why physicists interpret some isometric models as physically distinct.

I submit that the first reason has to do with unifying power. In brief, through distinguishing isometric models which differ by time translations/spatial rotation at infinity, we can elegantly connect the conservation of mass/energy, which is only well-defined subject to asymptotically flat boundary conditions, with those dynamical symmetries (Belot, 2018, p. 970). By contrast, on the sophisticated approach glossed, whilst

[14] Although some believe that the indeterminism at issue *is* acceptable (Brighouse, 1997; Norton, 2019). For excellent overviews of the vast literature on the hole argument: Pooley (2020); Roberts and Weatherall (2020).

[15] For alternative accounts of fertility: McMullin (1976); Ivani (2018).

energy and angular momentum are well-defined for asymptotically flat solutions, we wouldn't be able to think of them as generating time-translations and rotations at infinity "because one would have thrown away the structure required to make sense of such notions" (Belot, 2018, p. 970). Sophisticated substantivalists, it seems, "should be at least wistful when they notice that they cannot relate [the ADM mass] to time translation invariance" (Belot: personal communication).[16]

The second concerns inter-theoretic consistency with research programmes in quantum gravity. The basic idea: on standard approaches to quantizing classical theories, treating all isometric GR-models as physically equivalent implies that all asymptotic rotations are gauge symmetries, which represents a prohibition on states with non-zero angular momentum (Belot, 2018, p. 968). As Belot explains, under standard approaches to quantizing classical theories, in which classical physical quantities correspond to Hermitian operators on the quantum Hilbert space, "the quantities that generate gauge symmetries are quantized by operators with zero as the *only* member of their spectrum", where its *spectrum* corresponds to the set of possible values of a quantity's measurement outcomes (Belot, 2018, p. 968). The quantity that generates asymptotic rotations in the asymptotically flat sector is angular momentum. Thus, if one counts all isometric models as physically equivalent, this implies that all asymptotic rotations are gauge symmetries, which represents a prohibition on states with non-zero angular momentum. Whilst rotating systems might turn out to be impossible in quantum gravity, "it would be outrageous to impose this by fiat" (*ibid*).

So: the reasons discussed in Belot (2018) for distinguishing between isometric GR-models boil down to concerns with certain theoretical virtues. Such considerations suggest that, to interpret physical theories in a way which fits physics practice, we need a more fine-grained notion of interpretation than the mimetic ideal of ontological extraction.[17] It is to the articulation and defence of one such notion that I turn in the next section.

3 The diegetic ideal

In this section, I articulate and defend the diegetic ideal through drawing a novel connection with the recent literature on narrative testimony—that is, testimony which takes the form of fictional or non-fictional stories (Fraser, 2021, p. 4027). The argument is simple:

[16] Furthermore, asymptotically flat solutions are crucial in deriving certain important results, broadly because key integrals diverge absent strong boundary conditions at spatial infinity (Belot, 2018, pp. 967–969; Ringström, 2009, Sect. 17.2). In particular, Ashtekar et al. (1991) show that, in GR, the application of asymptotic flatness is critical in order to derive the energy–momentum of an isolated gravitating system at null infinity.

[17] This call might be seen as answered by forms of selective/qualified realism on one hand, or by adherence to theoretical virtues on the other. My aim in this paper is rather to reframe this debate: once we view theories as embedded within physics practice, realism about a theory is about not just its ontological content, but also how that content is structured. Importantly, then, this is not about "naturalizing" ontology; I merely spell out how physics practice constrains philosophical interpretations of physical theories. Thanks to an anonymous reviewer for pressing me on this point.

P1. Certain structural features characteristic of narrative testimonial exchange (NTE) imply that NTE aims at perspectival coordination between speaker and hearer.[18]

P2. The interpretation of a physical theory, in a way which fits with physics practice, shares those structural features with NTE.

C. The interpretation of a physical theory, in a way which fits with physics practice, aims at perspectival coordination (between interpreter and practising physicists).

Fraser (2021) defends P1 at length so I will assume it in what follows.[19] I focus instead on arguing for P2. In particular, there appear to be three characteristic structural features of NTE, each of which implies that NTE aims at perspectival coordination rather than mere "opinional coordination", namely agreement on some set of propositions.[20]

Firstly, there are lots of different stories which I could tell you about the same propositional content. For instance, as Fraser (2021, Sect. 3) shows, to tell you the locations of different landmarks within a city, I could give you a list of claims specifying the co-ordinates of each landmark, a map-like representation of the landmarks or a set of instructions to get from one landmark to another (*ibid*: 4033). Each way of structuring the same propositional content cues a different suite of interlocking dispositions "to notice, explain, and respond" to the city—i.e., a different perspective (Camp, 2017, p. 6). Analogously, as we saw in Sect. 2, once we view theories as embedded within physics practice, there may be different theories about the same ontological content. These differ based on whether and how each theory instantiates various theoretical virtues. You might protest that theoretical virtues are too disputed or vague to pick out any determinate "physics practice" perspective. Whilst I do not purport to offer conclusive arguments, *pace* Kuhn's (1977, p. 358) pessimism on this front, recent empirical work in the philosophy of science suggests that physicists by and large *do* agree on the relative weightings and interpretation of theoretical virtues (Schindler, 2022; Mizrahi forthcoming).[21] Indeed, it appears that "there is an overall preference ranking for the standard theoretical virtues, rending theory-choice a much more determinate matter than previously assumed" (Schindler, 2022, p. 562). As such, I suggest that, given ontologically equivalent theories, the theory which we should interpret literally—the one which best fits physics practice—is generally the one which best satisfies the physicists' theoretical virtues.[22]

Secondly, stories present different aspects of the same propositional content as more fundamental than others. For example, Fraser (2021, Sect. 4) contrasts two stories which I might tell you about Daniel: one characterises him as a quarterback, the

[18] Talk of *aiming at* should be interpreted functionally (Fraser, 2021, fn.9): we have the practice of NTE, say, at least in part because it is useful for us to have a device which facilitates perspectival coordination.

[19] The argument is therefore a "cantilever argument" (Miller, 2016, Sect. 2.1).

[20] Note: it is standard within the literature to assume that narratives have emergent properties, irreducible to the properties of single-sentence utterances. See, e.g., Fraser's (2021, pp. 4029–4031) critique of the "sheep-shearing" model of discourse interpretation.

[21] Cf. Duhem's Humean concept of "good sense" (1954, p. 218) which, the subjective nature of aesthetic judgments notwithstanding, enables scientists to agree on theory-choice (Stump, 2007; Ivanova, 2010, 2014, 2015).

[22] My arguments in Sect. 4 support this suggestion.

other as a computer science student. If Dan is both affable and shy, each characterisation will make these properties salient to different extents. For example, on the "quarterback story", Dan's affability will "stick out" more than his shyness and vice versa on the "computer science student story". In a similar way, I suggest, physical theories, once we view them as embedded within physics practice, present different aspects of the same ontology as more or less fundamental. For example, Earman's (1989) enthusiasm notwithstanding, it is usually agreed that the tensor and Einstein-algebra formalisms of GR are equally apt to represent any given possibility.[23] But the tensor formalism takes the point set as fundamental: GR-models are defined on differential manifolds, which are defined at the most basic level in terms of the point set. Meanwhile, Geroch's (1972, pp. 271–275) algebraic formalism defines GR-models based on an alternative definition of the differential manifold, which emphasizes the fundamentality of *differential structure*; the point set is then defined in terms of that structure.[24] When interpreting GR, since physics practice favours the tensor formalism over the algebraic one, this might suggest that we should think of the point set as among the most fundamental entities in GR.[25]

Thirdly, stories characteristically change how we respond to new propositional content. Indeed, Fraser (2021, Sect. 5) explains that NTE favours "long-term opinional coordination" because "agents who structure information in the same ways are far more likely to remember the same things, and to draw the same inferences, than those who structure the same information differently" (*ibid*). Analogously, it is well-known in the philosophy of science literature that physicists' dispositions "to notice, explain, and respond" to new data are shaped by not only which physical theory they work on but also general features of physics practice.[26] One of the clearest ways to think about this is in terms of Lakatos' (1970) methodology of scientific research programmes. Lakatos argued that we should conceptualise a theory within a research programme, that is, a collection of theories which share "hard core" assumptions, surrounded by a protective belt of "auxiliary hypotheses". In broad terms, the hard core consists in ontological and methodological commitments which are taken to be beyond refutation. The auxiliary hypotheses, meanwhile, comprise ontological and methodological hypotheses which are subject to review in light of new data (1970, pp. 48–50). The embeddedness of physical theories within this kind of research-programmatic structure supports the view, crucial to the diegetic ideal, that those theories are intrinsically tied to physics practice, within which they are understood, applied and revised. This practice picks out a richly structured way of looking at the world which goes above and beyond the desiderata of accurate reference/representation warranted by the mimetic ideal. As such, when interpreting physical theories, by analogy with NTE, we should aim at perspectival coordination with practising physicists. But why, you might wonder, does any of this matter?

[23] Rynasiewicz (1992) demonstrates that there is a one-to-one correspondence between algebraic and tensor models of GR. Rosenstock and others (2015) show that, according to one category-theoretic criterion, the algebraic and tensor formalisms of GR are theoretically equivalent.

[24] On defining GR-models within the algebraic formalism: Bain (2003, pp. 1073–1079).

[25] I return, in Sect. 5, to what this line of argument means for the substantivalism/relationism debate.

[26] For diverse traditional explorations of this issue: Conant (1957); Duhem (1998); Gillies (1993, 1998); Kuhn (1962/1970); Quine (1998). More recently: Azzouni (2004); Chang (2005).

4 Why it matters: superspace substantivalism

In this section, I argue that the diegetic ideal supports superspace substantivalism.[27] Following Baker (2020), I assume that some variety of substantivalism is correct. As such, my aim is to clarify and resolve the dialectic between two kinds of substantivalism—namely, Minkowski-spacetime substantivalism (MS), which holds that Minkowski spacetime is among the most fundamental structures of supersymmetric QFTs, and superspace substantivalism (SS). Since it remains moot how substantivalists about classical spacetime theories should understand supersymmetric QFTs, resolving this dilemma between MS and SS is crucial to clarifying what relationism—a view which is often taken to be the denial of substantivalism—means in supersymmetric QFTs. My arguments will therefore not only contribute to the existing debate concerning MS and SS in the literature on supersymmetric QFTs; they will additionally constitute an important preliminary stage in the wider substantivalism/relationism dispute.

The heart of the MS/SS debate consists in the interpretation of two formalisms for supersymmetric QFTs, namely the *component* and *superspace* formalisms. In the component formalism, component fields exhibiting supersymmetry are assigned to regions of Minkowski spacetime. In the superspace formalism, a *superfield* encapsulating the component fields is defined on *superspace*.[28] Since they share the same algebra of observables, it is usually assumed that the component and superspace formalisms describe the same physically significant quantities (Baker, 2020, p. 2385). I will not challenge this contention here.[29] As we saw in Sect. 3, formalisms which agree on ontological content may disagree as to which observable operators signify fundamental quantities, as opposed to merely physically significant (but derivative) quantities.[30] Indeed, the component formalism seems to support MS, the superspace formalism SS. I also suggested in the last section that one way to decide which of two such formalisms to adopt—which one best fits physics practice—is generally the one which best satisfies certain theoretical virtues, many of which are concerned not so much with the ontological content of a theory but rather with how that content is structured.

[27] For arguments that superspace should be conceptualised as *spacetime* structure: Menon (2018); Weingard (1988). For a riposte: Baker (2020). I set aside these debates here since a structure can be *fundamental* without being *spacetime* and, if the prevailing opinion among quantum gravity theorists is vindicated, spacetime need not be fundamental (Baker, 2020; De Haro and de Regt, 2018: pp. 632).

[28] Baker (2020) introduces the component and superspace formalisms using a one-dimensional supersymmetric field, formally identical to the composite system of a bosonic and a fermionic harmonic oscillator on one-dimensional spacetime. For a more detailed general account: Martins (2016).

[29] But I am sceptical. Firstly, whilst it's standard to assume that the algebra of observables contains all physically significant quantities in QFTs, interpretations like Bohmian mechanics involve ontology not represented in the canonical formalism (Baker et al., 2015, Sect. 3). Secondly, some physically significant quantities may be represented by operators outside the algebra of observables (Wallace, 2008, p. 21). Still, such operators generally fail to be invariant under important symmetries of the theory (Baker, 2020, p. 2385). Ruetsche (2011) also claims that the algebra of observables for QM_{∞} theories will not contain all of the physically significant observables. For a counter-argument: Feintzeig (2018).

[30] Baker (2020: fn.6) notes regretfully that he neglects such considerations. My aim in this section is to patch this lacuna.

I focus on the virtue of simplicity because, as this section evinces, there appear to be three strands of theoretical simplicity and it is illuminating to consider recent arguments for and against superspace substantivalism as a dispute regarding the appropriate weight to be allocated to each strand. Schindler (2022) found that natural and social scientists agree that a theory's simplicity is a function of three factors:

(i) *Limited parameter freedom*: other things being equal, a theory with fewer free parameters is simpler. The value of a *free parameter* is not determined theoretically, but has to be "fixed" on the basis of experiments (Forster & Sober, 1994; Sober, 2015). Think, for example, of particle masses in the standard model of particle physics (Friederich et al., 2014). Limited parameter freedom is a theoretical virtue since it's harder to accommodate phenomena in an ad hoc fashion (Forster & Sober, 1994; Hitchcock & Sober, 2004; Worrall, 2014; Sober, 2015, Schindler, 2022).

(ii) *Syntactic parsimony*: according to Schindler (2022, p. 545), "a theory is syntactically parsimonious [if] it employs relatively few theoretical principles in explaining the phenomena". Schindler does not offer any general account of how the counting of syntactic structure—that is, of those basic theoretical principles which explain the phenomena—is to be done. But this paper calls only for an account of syntactic parsimony in supersymmetric theories. I examine one below (Menon, 2018). But, for starters, consider Earman's dictum in *World Enough and Spacetime* that the dynamical and spacetime symmetries of a theory should be made to coincide (Earman, 1989, p. 46). In a restricted class of spacetime theories,[31] these symmetries may be distinguished as follows. Let P^is denote the geometric objects representing the dynamic elements of the theory—viz., matter fields and force fields which are subject to dynamical equations—andA^is represent the absolute geometric objects—viz., those geometric objects which are the same across all models. The *dynamical* symmetries of a theory are then those transformations to the P^is under which the dynamical equations retain their form; the *spacetime* symmetries are those transformations to the A^is which leave the A^is invariant. Earman's dictum may then be understood as a norm of syntactic parsimony that we should use the minimal structure that allows us to encode the universal dynamical facts.[32]

(iii) *Ontological parsimony:* Schindler (2022, p. 545) states that "a theory is ontologically parsimonious [to the extent that] it employs a relatively small number of basic entities in explaining the phenomena". There is often a misplaced focus, in the philosophical literature, on ontological parsimony at the expense of the other two strands of simplicity (Baker, 2003; Jansson & Tallant, 2017; Nolan, 1997). This focus is misplaced because natural scientists actually seem to rank (i) as most important in theory-choice, then (ii) and lastly (iii) (Schindler, 2022). Exemplifying this preoccupation with ontological parsimony, Baker (2020, pp. 2384–2385) suggests that MS is simpler than SS by appeal to ontological parsimony: the fields posited by the two formalisms differ only by ontologically

31 In particular, one where fields and particles have no degrees of freedom other than positions and momenta.

32 This interpretation of Earman's principle as encoding an Occamist norm on our theorising is elegantly defended in Menon (2018, Sect. 2) so I assume it here.

> insignificant operators extraneous to the algebra of observables; the superspace formalism, meanwhile, posits more spacetime structure. However, since the diegetic ideal prioritises perspectival coordination with *physicists*, who agree that limited parameter freedom and *syntactic* parsimony each matter more in theory-choice than ontological parsimony, SS remains preferable. Or so I argue.

Firstly, the argument for SS based on paucity of free parameters, which draws on Wells' fine-tuning argument in Baker (2020, p. 2386). On one hand, suppose that *Minkowski spacetime* is more fundamental than superspace. Clearly, Minkowski spacetime could support a variety of non-supersymmetric laws for the same fields. So the mass-equality for the bosonic and fermionic fields, which is required to generate supersymmetry, is left as a brute posit in the theory, a free parameter which needs fixing to achieve empirical adequacy at supersymmetric worlds. On the other hand, if *superspace* is more fundamental and the system is described as a superfield, then the mass-equality for bosonic and fermionic fields is fixed by the theory. This is because it is impossible for superfield theories on superspace to exhibit unequal masses for bosonic and fermionic fields. Of course, if you espouse Brown's (2005, p. 24) dynamical approach, on which "absolute space–time structure…codifi[es]…certain key aspects of the behaviour of particles", you might challenge the underlying assumption here that fundamental spacetime structure can explain dynamical symmetries. Unfortunately, I must set aside this criticism: Brown's approach relies upon the view that particle behaviour is more fundamental than spacetime structure, which is incompatible with substantivalism as defined in this essay (see North, 2018).

Secondly, the argument for SS based on syntactic parsimony. Menon (2018, Sect. 3) develops a way to articulate Earman's principle in the context of supersymmetric theories. In essence, the approach rests on restricting the class of dynamical symmetries to which Earman's principle is to apply to the "external" symmetries of the matter fields, where an external symmetry is a symmetry shared by all the different matter fields (Menon, 2018, p. 5). Now Earman's principle requires that the external symmetries of a theory should be encoded in its spacetime symmetries.

Suppose for the sake of argument that Minkowski spacetime is more fundamental than superspace in a supersymmetric system. So the absolute object is the Minkowski metric tensor. The symmetries of this object are just the Poincaré transformations. But the external symmetry group of a super-symmetric theory is the super-Poincaré group.[33] In other words, the matter fields exhibit an additional external symmetry, namely supersymmetry, which is not codified in that fundamental Poincaré structure, *contra* Earman's principle (Menon, 2018). If superspace is more fundamental, however, the symmetry group of the fundamental structure—namely, the super-Poincaré group— picks out all the external symmetries. I suggest, therefore, that SS is more *syntactically* parsimonious than MS. Indeed, this seems to be why physicists prefer the superspace formalism too. For instance, Martin (2016, p. 30) hails the "elegan[ce]" of the superspace formalism, which renders "invariance under supersymmetry transformations manifest by defining the Lagrangian in terms of integrals over a 'superspace'"

[33] The reasoning here is as follows. The dynamical symmetries of a supersymmetric theory are elements of the super-Poincaré group by construction (Menon, 2018, Sect. 3). Since this is the largest common symmetry group, this is the external symmetry group too (Menon, 2018, Sect. 2).

(*ibid*: 28). Likewise, Bertolini rejects "the usual space–time Lagrangian formulation" as "[in]convenient" since, "in ordinary space–time[,] supersymmetry is not manifest". Rather, "superspace…[is]…the best and most natural framework…to formulate supersymmetric theories" (Lecture 4). I have of course not compared the component and superspace formalisms as regards all theoretical virtues. But, *pace* Baker (2020), the superspace formalism is simpler provided that we understand simplicity as physicists seem to. So: if you accept the diegetic ideal, which prioritises the perspective of physicists,[34] I have offered a *prima facie* argument that you should support SS.

5 Closing remarks

In conclusion, I wish to consider some criticisms of my approach and gesture towards fruitful areas for future research. One criticism is as follows. Substantivalism is a realist position concerning what the world is like. As such, *contra* the diegetic ideal, the truth of substantivalism should not depend upon contextual features of physics practice. But I argue that the diegetic ideal *affirms* the realist intuition that physical theories, taken literally, tell us what the world is like. The central difference vis-à-vis the mimetic ideal is that the diegetic ideal views physical theories as intrinsically embedded within physics practice. As such, substantivalism—and what the world is like more generally—according to physical theories is not just a matter of ontology but of how that ontology is structured.[35] Does this mean that anything goes? Surely, you counter, given the history of science, the physicists' perspective is not always a guide to truth. Of course, this kind of "pessimistic meta-induction" (Laudan, 1981) is a general problem for *any* realist account of interpretation. Whilst it is therefore beyond my scope to explore the question in detail here, as a rule of thumb I would suggest that, when a research programme is progressive—that is, when its new theories explain everything which the old theories did and generate some corroborated novel predictions—a "no miracles"-type intuition (Putnam, 1975, p. 73) suggests that the physicists' perspective is some guide to what the world is like. At this point you might object that the appeal to physics practice for deciding on the truth of a certain thesis (such as substantivalism) is somewhat self-undermining in the context of supersymmetric physics where an absence of empirical corroboration has led some to question whether the research programme remains progressive.[36] But, as I discussed in Sect. 1, whether supersymmetric QFTs constitute a progressive research programme remains to be seen. As such, whether we should believe that superspace is among the fundamental structures of reality is an open empirical question.

[34] Note: this appeal to the "perspective" of physicists is to be understood according to the technical concept of perspective developed in Sect. 3; what physicists have on their minds is not an issue with which we need concern ourselves per se. On this: fn.38.

[35] Recall the analogy with NTE: to tell you the locations of different landmarks within a city, I could give you a list of claims specifying the co-ordinates of each landmark, a map-like representation of the landmarks or a set of instructions to get from one landmark to another. Similarly, different theories offer different ways of structuring ontological content, corresponding to different perspectives.

[36] Thanks to an anonymous reviewer for pressing me on this point.

Fruitful areas for future research abound. Given the difficulties which accrue to the mimetic ideal, there has been a reorientation in the recent philosophy of physics literature towards the notion of *understanding*—as opposed to, say, *reference to* or *representation of* aspects of reality—as one of the primary aims of interpreting physical theories (De Haro & de Regt, 2018, 2020; de Regt, 2017). But the notion of understanding is expressly neutral as to the truth of realism (De Haro & de Regt, 2018, p. 3, Sect. 1). The danger, then, is of throwing out the realist intuition that scientific theories tell us *what the world is like* when dispensing with the mimetic ideal. One way to think of the diegetic ideal, by contrast, is as a way of cashing out how interpreting physical theories tells us what the world is like in a way which is not exhausted by accurate reference or representation. Further examination of the relationship between the diegetic ideal and the aim of understanding is beyond the scope of this paper; still it calls for analysis.[37]

Finally, I suggested in Sect. 3 that physical theories behave epistemically a little like stories. I'm not the first to suggest this (Feyerabend, 1975, 2011).[38] I'm also not the first to emphasise the importance of physics practice in the interpretation of physical theories (Belot, 2018).[39] Indeed, drawing on some remarks by Stein (1994), Curiel (2020, p. 2) has argued that "an adequate semantics for theories cannot be founded on ontology, but rather on epistemology and methodology", that is, "the real application of the theory in actual scientific practice".[40] In a similar vein, Lemkuhl (2016) has criticised the "literal" approach to interpretation, which broadly instantiates the mimetic ideal, and defended the "careful" approach, according to which.

37 This is related to another worry which I am grateful to an anonymous reviewer for raising. In the case of quantum mechanics, one might worry that the diegetic ideal would militate in favour of interpretations that are compatible with a "shut up and calculate" attitude that is very common among physicists. This might appear to be a *reductio* of the diegetic ideal. But the worry seems to depend upon a misconception: the diegetic ideal is not about physicists' attitudes but about how physics tells us literally true stories about what the world is like in ways which go beyond ontological extraction. A story can be true even if some of its characters would tell a different tale; similarly, a scientific theory can be true even if some of its characters reject realism.

38 But I am the first to connect this idea to the literature on NTE in arguing that the interpretation of a physical theory aims at perspectival coordination (Sect. 3).

39 Teh has suggested that a literal interpretation of a theory's formalism (e.g., the dynamical equations) does not exhaust the content of that physical theory (of some field φ, say), which "does not just specify how φ is constrained by the theory's equations of motion, but also provides modal information about what other fields it is possible for φ to interact with" (Teh, 2011, pp. 13–14).

40 Curiel's argument focuses upon how the "schematic representation" of the observer (more generally: measuring instruments and experimental arrangements) grounds the semantics of a theory. He draws on two case studies to which I refer the reader since they indicate one way in which attending to physics practice may guide interpretation. First, Curiel considers the comparison of the observed to the calculated values for the planetary orbital periods and the semi-major axes of the orbits in Book III of the *Principia*: Newton defends his identification of his theory's models with the Keplerised orbits by explaining that, e.g., one expects variation in the observed size of Jupiter's apparent diameter, and thus in the distance its satellites appear to be from its centre, when using telescopes of different sizes and resolving powers (Book III, Phenomenon I). Second, Curiel considers the detection of gravitational waves by LIGO (Abbott et al. 2016). The schematic representation of the observer, he argues, appears in the calculation of the response of the instrument to applied stress–strain from passing gravitational waves. For details: Curiel (2020, Sect. 7).

> an interpretation of the theory or model or formalism [should engage] both with the details of its mathematical structure and with how it is applied to the natural world", that is, with "what the theory does in practice, how it is used (Lemkuhl, 2016, pp. 3, 17).[41]

But no one so far has considered what the rejection of the mimetic ideal might entail for superspace substantivalism. Nor has anyone else connected the rejection of the mimetic ideal with the notion of scientific theories as stories. According to the diegetic ideal which I have articulated and defended, the interpretation of physical theories is about entering into the story which physics gives us about the world. And there is much more to the world of a story than its mere ontology.

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

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[41] One difference between the "careful" interpretative approach sketched in Lemkuhl (2016) and the diegetic ideal as discussed in this paper is that Lemkuhl expressly argues that careful interpretation is neutral between realists and antirealists. I have assumed realism throughout because (i) I took the mimetic ideal to derive from a realist intuition (Sect. 1) and (ii) the paper's principal aim is to offer a novel argument for superspace substantivalism (Sect. 4). I have not considered how antirealists would react to the diegetic ideal but would be curious to know.

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