Reading list in Philosophy of Spacetime and Symmetry

David Wallace, June 2018

A note on electronic resources

When I include a book chapter or similar as a reference, and there is a preprint of that chapter on one of the permanent archives (arxiv.org or philsci-archive.pitt.edu), I have included a link to the preprint; be aware that there are sometimes small changes, and that citations and page references should be to the published version. I have not bothered to put preprint links for journal papers; however, for any paper published in the last 20 years or so it is likely that a preprint is online somewhere.

1. Introduction

This is a reasonably comprehensive reading list for contemporary topics in philosophy of spacetime and symmetry, aimed at researchers and graduate students specializing in philosophy of physics, at colleagues putting together readings for seminars and classes, at academics in related areas interested in the debate, and at ambitious upper-level undergraduates looking for thesis ideas.

Any such list betrays the prejudices, and displays the limitations, of the author. Where I have intentionally been selective, it represents my judgements as to what areas are interesting and what work in those areas is likely to stand the test of time, and which current debates are worth continuing attention, but I will also have been selective accidentally, through ignorance of work in one area or another of this very large field. (I am research-active in the field, but not in every area of it.) The only real way to work around these sorts of limitations is to look at multiple such lists by different people.

I'll call out some explicit limitations. I don't attempt to cover history of physics, beyond a very few readings on the history of general covariance, the equivalence principle, and the absolute-relationist dispute; I don't engage with spacetime issues in the history of philosophy at all (even as recently as Reichenbach *et al*); I don't discuss metaphysical issues about space and time that are mostly disconnected from physics (such as discussion of tense and becoming); at the other end of the technical spectrum, I don't discuss the connection between symmetry and category theory.

I've also drawn some fairly arbitrary distinctions as to what counts as philosophy of spacetime and symmetry. My readings on symmetry omit identical particles and the direction of time (which I treat as philosophy of statistical mechanics), the Aharonov-Bohm effect (which I treat as philosophy of quantum mechanics) and spontaneous symmetry breaking (which I treat as philosophy of quantum field theory); my readings on quantum gravity engage only with some topics close to more mainstream topics in philosophy of space and time, and do not attempt a more comprehensive discussion; I mostly disregard black hole thermodynamics; I do not engage with classical mechanics beyond questions of its spacetime presuppositions.

This is a fairly interconnected subject, and my divisions into sections are in places arbitrary. Under "interconnections" in each section, I try to give some indication of what connects to what. Also, in (pretty much) every subsection of the list I have marked one entry (very occasionally, two) with a star (*), which means: if you only read one thing in this subsection, read this. The starred entry is not necessarily the most important or interesting item, but it's the item that (in my judgement) will give you the best idea of what the topic is about.

I list items in a rough reading order, which is usually approximately-chronological. It doesn't indicate an order of importance: it means "if you read A and B, read A first", not "read A in preference to B". If you want to work out what to prioritise (beyond my starring of a few entries, above) then there isn't really a substitute for looking at the abstracts and seeing what's of interest. (And don't be afraid to skim papers, and/or to skip over the mathematical bits. Of course you'll need to read those if you ever engage closely with the debate, but if you just want an overview, it can be overkill.)

Introductory and general readings

If you are completely new to the subject, you could look at

N. Huggett, *Space from Zeno to Einstein* (MIT Press, 1999).
A collection of historical readings, with useful commentary.

L. Sklar, Time, Space and Spacetime (University of California Press, 1974).
A textbook, at a comparatively introductory level.

There is no up-to-date single-volume source on the whole subject at a more advanced level that I can recommend, but the following books provide fairly wide coverage (in roughly increasing order of difficulty).

T. Maudlin, *Philosophy of Physics: Space and Time* (Princeton University Press),

O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586.

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989).

H. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Viewpoint* (Oxford University Press, 2005).

Earman and Pooley are focused on one topic – the substantivalist/relationist debate – but arguably that is the central debate in the field, and touches on most other topics. Both attempt an overview of disparate views, though as always in philosophy, their own philosophical judgement plays a large role in how they organize and discuss the subject. Brown and Maudlin offer sustained expositions and defenses of their own views, and do not seriously attempt an extended presentation and defense of the alternatives; since their views are pretty much diametrically opposed, I recommend looking at both, though Brown's book is more technically demanding.

2. Math and Physics resources

To read most of the material on this list, you'll need familiarity with multivariate calculus, elementary classical mechanics, special relativity, and in some cases also electrodynamics, linear algebra, or elementary group theory. Here I discuss only material going beyond that level.

General Relativity

There are a vast number of textbooks on general relativity, at all levels and styles. Tastes vary; mine tend towards the less-rigorous, more-physically-intuitive style of mainstream theoretical physics.

S. Carroll, *Spacetime and Geometry: An Introduction to General Relativity* (Pearson, 2014).

> *Probably my recommendation if you're new to the subject.*

A. Zee, *Einstein Gravity in a Nutshell* (Princeton University Press, 2013).

> *An idiosyncratic approach to the subject; probably a little unmathematical to work as a sole introduction for philosophy of physics, but full of insight, and a good reminder of how styles vary across physics. (Be warned: that "nutshell" is 866 pages long.)*

C. Misner, K. Thorne, and J. Wheeler, *Gravitation* (Freeman, 1973).

> *A classic (and huge!) textbook and still my personal favorite, though it's mathematically a bit sloppy for some tastes. Chapters 1-7 review special relativity from a general-relativistic viewpoint; chapters 8-21 present the mathematics and physics of general relativity. From chapter 22 onwards some parts are out of date, so shouldn't be trusted uncritically.*

R. Wald, *General Relativity* (University of Chicago Press, 1984).

> *The standard reference, at least in philosophy of spacetime, and for good reasons. As pedagogy I find it a bit austere but as I say, tastes vary.*

D. Malament, *Topics in the Foundations of General Relativity and Newtonian Gravitation Theory* (Chicago, 2012).

> *The first two chapters of this elegant book provide a concise and technically demanding, but very clear and precise, presentation of general relativity and its mathematics from a conceptually-oriented viewpoint. It doesn't pretend to give a general overview of the subject (you won't do much in the way of calculations or applications).*

Classical (i.e., pre-relativistic) spacetimes

For presentations of the classical spacetimes mostly discussed in philosophy of spacetime, see (in increasing order of technical complexity):

Weatherall, "Classical Spacetime Structure", manuscript, to appear in E. Knox and A. Wilson (eds.), *The Routledge Companion to Philosophy of Physics* (Routledge, forthcoming).
http://arxiv.org/abs/1707.05887

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989), chapter 2.

M. Friedman, *Foundations of Space-Time Theories* (Princeton University Press, 1983), sections I-V, esp. pp.46-61, section II.

Mathematics

The mathematical framework for general relativity is differential geometry, and this framework is frequently used by philosophers to discuss other spacetimes. It can be unfamiliar, even if you've done physics courses in classical mechanics or special relativity.

Most of the General Relativity textbooks above have sections on differential geometry (Zee does not); of them, Carroll is probably the best place to start if you're completely unfamiliar with the subject (though I have a soft spot for Misner, Thorne and Wheeler); for a reference, or if you are coming from a pure math background, chapter 1 of Malament is good.

I also like

B. Schutz, *Geometrical Methods of Mathematical Physics* (Cambridge University Press, 1980)

which is aimed at physicists. At a higher level, but again aimed at physicists, is

M. Nakahara, *Geometry, Topology, and Physics* (2nd edition) (Taylor and Francis, 2016)

though only the first few chapters are relevant to most of philosophy of spacetime.

If you need a really serious reference on differential geometry, look at

Kobiyashi and Nomizu, *Foundations of Differential Geometry* (Interscience, 1963/1969).

M. Spivak, *A comprehensive Introdution to Differential Geometry* (3rd edition) (Publish or Perish, 1999)

Y. Choquet-Bruhat and C. DeWitt-Morette, *Analysis, Manifolds and Physics* (Elsevier, 1982).

3. The substantivalist/relationist debate

Is space (or, in modern versions, spacetime) a physical entity in its own right, or simply a way of encoding claims about the relations between material bodies?

Interconnections

- The *Hole Argument* is generally framed as the transfer of the substantivalist/relationist debate to General Relativity; conversely, some aspects of the Hole Argument impact prerelativistic physics.
- Arguments for/against absolute space (especially in Newtonian physics) are closely tied both to considerations of Leibniz equivalence in *philosophy of symmetry*
- The debate about *spacetime structure in prerelativistic physics* overlaps with the substantivalist/ relationist debate, in particular with questions about relational theories of dynamics.
- There are close – but in my view under-explored – connections between the substantivalist/relationist debate and the newer debate about *dynamical vs geometrical approaches to spacetime structure*.

Short introductions

P. Horwich, "On the Existence of Time, Space and Space-Time", *Nous* 12 (1978) pp. 397-419

(*)T. Maudlin, "Buckets of Water and Waves of Space: Why Spacetime is Probably a Substance", *Philosophy of Science* 60 (1993) pp. 183-203

S. Dasgupta, "Substantivalism vs Relationism About Space in Classical Physics", *Philosophy Compass* 10/9 (2015) pp.601-624.

Reviews

(*)O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586.
http://philsci-archive.pitt.edu/9055/

N. Huggett and C. Hoefer, "Absolute and Relational Theories of Space and Motion", in Edward N. Zalta (ed.), *Stanford Encyclopedia of Philosophy* (Spring 2018 edition).
https://plato.stanford.edu/archives/spr2018/entries/spacetime-theories/

J. Barbour, *The Discovery of Dynamics: A Study from a Machian Point of View of the Discovery and the Structure of Dynamical Theories* (Oxford University Press, 2001); originally published as *Absolute of Relative Motion? Volume 1, The Discovery of Dynamics* (Oxford University Press, 1989). (Focussed on this history; does not review the contemporary philosophical debate.)

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989).

Historical sources

Primary sources

R. Descartes, *Principles of Philosophy* part II, esp. sections 10-39, in *The Philosophical Writings of Rene Descartes*, vol. I, translated by J. Cottingham, R. Stoothoff, and D. Murdoch (Cambridge University Press,

1985). Useful selections are reprinted in N. Huggett (ed.) *Space from Zeno to Einstein* (MIT Press, 1999), ch. 6

I. Newton, *De Gravitatione*, in *Unpublished Scientific Papers of Isaac Newton*, translated and edited by A.R. Hill and M.B. Hall (Cambridge University Press, 1962) and *Newton: Philosophical Writings,* translated and edited by A. Janiak (Cambridge University Press, 2004). Useful selections are reprinted in N. Huggett (ed.) *Space from Zeno to Einstein* (MIT Press, 1999), ch. 7.

(*)I. Newton, *Philosophae Naturalis Principia Mathematica* (1687), "Scholium to Definition VIII". Reprinted and translated in (inter alia) J. Earman, *World Enough and Spacetime* (ibid.), H. G. Alexander (ed.) *The Leibniz-Clarke Correspondence* (Manchester University Press, 1956), and N. Huggett (ed.), *Space from Zeno to Einstein* (MIT press, 1997). Available online at https://plato.stanford.edu/entries/newton-stm/scholium.html

Secondary sources

(*)R. Rynasiewicz, "By their Properties, Causes and Effects: Newton's Scholium on Time, Space, Place and Motion – I. The Text". *Studies in History and Philosophy of Science* 26 (1995), pp. 133-153.

R. Rynasiewicz, "By their Properties, Causes and Effects: Newton's Scholium on Time, Space, Place and Motion – II. The Context". *Studies in History and Philosophy of Science* 26 (1995), pp. 295-321.

H.G.Alexander (ed.), *Leibniz-Clarke Correspondence* (Manchester University Press, 1956). Introduction.

O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586. Section 2.
http://philsci-archive.pitt.edu/9055/

G. Rodriguez-Pereyra, "Leibniz's Argument for the Identity of Indiscernibles in his Correspondence with Clarke", *Australian Journal of Philosophy* 77 (1999), pp. 429-438.

Modern arguments

The case against and (mostly) for substantivalism, from a-contemporary physics viewpoint, albeit largely in the non-relativistic context.

O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586. Sections 4-5.
http://philsci-archive.pitt.edu/9055/

H. Stein, "Newtonian Space-Time", *Texas Quarterly* 10 (1967) pp. 174-200

(*) J. Earman, "Who's Afraid of Absolute Space?", *Australasian Journal of Philosophy* 48 (1970) pp. 287-319

T. Maudlin, "Buckets of Water and Waves of Space: Why Spacetime is Probably a Substance", *Philosophy of Science* 60 (1993) pp. 183-203

J. Barbour, "Relational Concepts of Space and Time", *British Journal for the Philosophy of Science* 33 (1982) pp. 251-274.

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989), ch.5,6,8

D. Baker, "Spacetime Substantivalism and Einstein's Cosmological Constant", *Philosophy of Science* 72 (2006) pp. 1299-1311.

Relational theories of dynamics

It is widely (not universally) thought that contemporary physics requires substantival space, so that a relationist is committed to reformulating dynamics.

(*) O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586. Section 6. http://philsci-archive.pitt.edu/9055/

N. Huggett, "The Regularity Account of Relational Spacetime", *Mind* 115 (2006) pp. 41-74.

O. Pooley and H. Brown, "Relationism Rehabilitated? I: Classical Mechanics", *British Journal for the Philosophy of Science* 53 (2002) pp.183-204.

O. Pooley, "Relationism Rehabilitated? II: Relativity", manuscript; available at http://philsci-archive.pitt.edu/221/

J. Barbour and B. Bertotti, "Mach's Principle and the Structure of Dynamical Theories", *Proceedings of the Royal Society of London A* 382 (1982) pp. 295-306.

G. Belot, "Rehabilitating Relationism", *International Studies in the Philosophy of Science* 13 (1999) pp. 35-52.

S. Gryb, "Implementing Mach's principle using gauge theory", *Physical Review D* 80 (2009) 024018.

Parity and parity violation

Since Kant, it has been argued that the need to distinguish left from right supports the substantivalist; these arguments have gained force from the discovery in the 1950s that physical interactions are not invariant under reflection.

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989), ch.7

N. Huggett, "Reflections on Parity Nonconservation", *Philosophy of Science* 67 (2000) pp. 219-241.

(*) O. Pooley, "Handedness, Parity Violation, and the Reality of Space", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp.250-281. http://philsci-archive.pitt.edu/713/

N. Huggett, "Mirror Symmetry: What is it for a relational space to be orientable?", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp.281-288. http://philsci-archive.pitt.edu/767/

S. Saunders, "Mirroring as an A Priori Symmetry", *Philosophy of Science* 74 (2007) pp. 452-480.

Continued relevance?

Is the substantivalist-relationist debate still meaningfully formulated in modern physics?

(*) C. Hoefer, "Absolute versus Relational Spacetime: For Better or Worse, the Debate Goes On", *British Journal for the Philosophy of Science* 49 (1998) pp. 451-467. Reply to Rynasiewicz, below.

R. Rynasiewicz, "Absolute Versus Relational Space-Time: An Outmoded Debate?", *Journal of Philosophy* 93 (1996) pp.279–306

E. Curiel, "On the Existence of Spacetime Structure", *British Journal for the Philosophy of Science* 69 (2018) pp. 447-483.

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989), ch. 8

4. The Hole Argument

General relativity has a diffeomorphism symmetry which, on a certain substantivalist reading of the theory, renders it viciously indeterministic.

Connections

- The Hole Argument is intimately connected both to the *substantivalist/relationist debate* and to the question of Leibniz equivalence in *philosophy of symmetry.* (Arguably it is *part of* the substantivalist/relationist debate, but it has been such a dominant theme in the last 30 years of spacetime philosophy as to deserve a section of its own.)
- The diffeomorphism symmetry of general relativity is closely related to the gauge symmetries of classical field theory, discussed in *philosophy of symmetry*; indeed, on one disambiguation of "gauge", diffeomorphism symmetry just is gauge symmetry.
- The problem of time in the *philosophy of quantum gravity* has close (but contested) connections to the Hole Argument.
- There is no very sharp division between the Hole Argument and the topics of *general covariance, background independence, and the meaning of coordinates.*

Introductions and reviews

J. Earman and J. Norton, "What price spacetime substantivalism? The hole story", *British Journal for the Philosophy of Science* 38 (1987), pp. 515-525.

The original presentation of the hole argument in the philosophy literature.

J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989). Chapter 9.

(*)J. Norton, "The Hole Argument", in E. Zalta (ed.) *Stanford Encyclopedia of Philosophy* (Summer 2018 edition). https://plato.stanford.edu/archives/sum2018/entries/spacetime-holearg/

O. Pooley, "Substantivalist and Relationist Approaches to Spacetime", in R.Batterman (ed.), *The Oxford Handbook of the Philosophy of Physics* (Oxford University Press, 2013), pp. 522-586. Section 7. http://philsci-archive.pitt.edu/9055/

J. Stachel, "The Hole Argument and some Physical and Philosophical Implications", *Living Reviews in Relativity,* December 2014, 17:1. https://link.springer.com/article/10.12942/lrr-2014-1

Sophisticated substantivalist solutions

"Sophisticated substantivalism", the most widely-adopted solution to the hole argument, is the view that diffeomorphism-related solutions may be treated as representing the same physical possibilities without abandoning substantivalism. (This is a form of Leibniz equivalence; see under philosophy of symmetry.)

(*) J. Butterfield, "The Hole Truth", *British Journal for the Philosophy of Science* 40 (1989) pp. 1-28.

C. Brighouse, "Spacetime and Holes", *Proceedings of the Biennial Meeting of the Philosophy of Science Association* (1994) vol.1, pp. 117-125.

R. Rynasiewicz, "The Lessons of the Hole Argument", *British Journal for the Philosophy of Science* 45 (1994) pp. 407-436.

C. Hoefer, "The Metaphysics of Space-Time Substantivalism", *Journal of Philosophy* 93 (1996) pp. 5-27.

S. Saunders, "Indiscernibles, General Covariance, and Other Symmetries", in A.Ashtekar *et al (eds.)*, *Revisiting the Foundations of Relativistic Physics: Festschrift in Honour of John Stachel* (Kluwer, 2003). http://philsci-archive.pitt.edu/id/eprint/459

Spacetime structuralism

Spacetime structuralism is a variant of sophisticated substantivalism drawing on lessons from structural realism in philosophy of science, though stating it precisely is controversial.

M. Dorato, "Substantivalism, Relationism and Structural Spacetime Realism", *Foundations of Physics* 30 (2000) pp. 1605-1628.

M. Esfeld and V. Lam, "Moderate Structural Realism about Space-Time", *Synthese* 160 (2008) pp. 27-46.

(*) H. Greaves, "In Search of (Spacetime) Structuralism", *Philosophical Perspectives* 25 (2011) pp. 189-204.
Critical review of spacetime structuralism, ending on a skeptical note.

O. Pooley, "Points, Particles and Structural Realism", in D.Rickles, S.French and J.Saatsi (eds.), *The Structural Foundations of Quantum Gravity* (Oxford University Press, 2006) pp. 83-120.
http://philsci-archive.pitt.edu/2939/

Metric essentialism

According to metric essentialism, spacetime points stand in their metric relations essentially, and so diffeomorphisms do not create physical possibilities.

(*) T. Maudlin, "The Essence of Space-Time", *Proceedings of the Biennial Meeting of the Philosophy of Science Association* (1988) pp.82-91.

A. Bartels, "Modern Essentialism and the Problem of Individuation of Spacetime Points", *Erkenntnis* 45 (1996) pp. 25-43.

Considerations of determinism

Can the hole argument be dissolved by clearer understanding of what "determinism" means in physical theories? (See also Butterfield and Rynasiewicz, above)

S. Leeds, "Holes and Determinism: Another Look", *Philosophy of Science* 62 (1995) pp. 425-437.

C. Brighouse, "Determinism and Modality", *British Journal for the Philosophy of Science* 48 (1997) pp. 465-481.

(*) J. Melia, "Holes, haecceitism and two conceptions of determinism", *British Journal for the Philosophy of Science* 50 (1999) pp. 639-64.

Considerations from mathematical representation

Does the hole argument rest on a misreading of how mathematical modelling works in physics? (This is closely related to the discussions of determinism and structuralism.)

(*) J. Weatherall, "Regarding the 'Hole Argument' ", *British Journal for the Philosophy of Science* 69 (2018), pp. 329-350.

J. Roberts, “Disregarding the ‘Hole Argument’“, preprint, https://arxiv.org/abs/1412.5289.
Reply to Weatherall.

5. General Covariance, Background Independence, and the Meaning of Coordinates

General relativity famously is "generally covariant". Superficially this means that the theory can be formulated in arbitrary coordinate systems, but – as Kretchmann pointed out to Einstein in 1917 – any theory can be so formulated with a little mathematical help. A modern alternative view is that general covariance can be identified with "background independence", or the absence of absolute objects in the spacetime background, but it remains contentious how to characterize these notions.

This division into subsections is somewhat arbitrary; there is much overlap.

Interconnections

- This topic is closely connected to the *Hole Argument*, and to the Problem of Time in *philosophy of quantum gravity.*

Historical review

(*) J. Norton, "General Covariance and the Foundations of General Relativity: Eight Decades of Dispute", *Reports on Progress in Physics* 56 (1993).

The meaning of general covariance

(*) S. Saunders, "Indiscernibles, General Covariance, and Other Symmetries", in A.Ashtekar *et al (eds.)*, *Revisiting the Foundations of Relativistic Physics: Festschrift in Honour of John Stachel* (Kluwer, 2003). http://philsci-archive.pitt.edu/id/eprint/459

J. Norton, "General Covariance, Gauge Theories and the Kretschmann Objection", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003) pp. 110-123. http://philsci-archive.pitt.edu/380/

J. Earman, "The Implications of General Covariance for the Ontology and Ideology of Spacetime", in D. Dieks (ed.), *The Ontology of Spacetime* (Elsevier, 2006) pp. 3-24.

J. Earman, "Two Challenges to the Requirement of Substantive General Covariance", *Synthese* 148 (2006) pp. 443-468.

O. Pooley, "Substantive General Covariance: Another Decade of Dispute", in M. Suarez *et al* (eds.), *EPSA Philosophical Issues in the Sciences* (Springer, 2010), pp. 197-209.

Commentary on Earman papers above

D. Dieks, "Another Look at General Covariance and the Equivalence of Reference Frames", *Studies in history and Philosophy of Modern Physics* 37 (2006) pp. 174-191.

The Anderson-Friedman absolute objects program

J. Anderson, "Covariance, Invariance and Equivalence: A Viewpoint", *General Relativity and Gravitation* 2 (1971) pp. 161-172.

M. Friedman, *Foundations of Space-Time Theories* (Princeton University Press, 1983), sections I-V, esp. pp.46-61.

J.B. Pitts, “The Anderson-Friedman Absolute Objects Program: Several Successes, One Difficulty”, manuscript. http://philsci-archive.pitt.edu/3005 .

The status of coordinate systems

(*) J. Stachel, “The Meaning of General Covariance”, in J. Earman *et al* (eds.), *Philosophical Problems of the Internal and Extermal Worlds: Essays on the Philosophy of Adolf Grunbaum* (University of Pittsburgh Press, 1993) pp. 129-160.

J. Anderson, “Relativity Principles and the Role of Coordinates in Physics”, in his *Gravitation and Relativity* (W.A.Benjamin, 1964) pp. 175-194.

J. Earman, “Covariance, Invariance, and the Equivalence of Frames”, *Foundations of Physics* 4 (1974) pp. 267-289.

(*) D. Wallace, “Who’s Afraid of Coordinate Systems: An Essay on the Representation of Spacetime Structure”, *Studies in history and Philosophy of Modern Physics*, forthcoming. http://philsci-archive.pitt.edu/11988

O. Pooley, “Background independence, Diffeomorphism Independence, and the Meaning of Coordinates”, in D. Lehmkuhl (ed.), *Towards a Theory of Spacetime Theories* (Birkhauser, 2017). https://arxiv.org/abs/1506.03512

6. Dynamical vs geometrical approaches to spacetime theories

Cutting across the substantivalist/relationist debate is a question about the relative primacy of laws and spacetime geometry. A default (if largely tacit) presupposition in most discussions of spacetime structure is that its structure is prior to, and constrains the form of, the laws. An alternative view, arguably tacit in much physical practice but explicitly developed in philosophy by Harvey Brown, is that spacetime structure is a codification of the form of the laws.

Interconnections

- There are close, and (I think) underexplored connections with the *substantivalist/relationist debate.*
- Some of the recent debate about *spacetime structure in pre-relativistic physics* has been carried out with reference to the dynamical approach, especially to Knox's spacetime functionalism.
- The conceptual and empirical status of symmetries in *philosophy of symmetry* is also closely connected.

The geometrical approach

As well as the readings here, much of the positive case for substantivalism can be reinterpreted as defending the geometrical approach.

(*) J. Earman, *World Enough and Space-Time: Absolute vs Relational Theories of Space and Time* (MIT Press, 1989). Ch.3

Maudlin, *Philosophy of Physics: Space and Time* (Princeton University Press), ch.1-3.

H. Stein, "Newtonian Space-Time", *Texas Quarterly* 10 (1967) pp. 174-200

Introduction to the dynamical approach

(*) H. Brown and J. Read, "The dynamical approach to spacetime theories", in E. Knox and A. Wilson (eds.), *Handbook of Philosophy of Physics*, forthcoming. http://philsci-archive.pitt.edu/14592

Reference for the dynamical approach

(*) H. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Viewpoint* (Oxford University Press, 2005).

Development and defense of the dynamical approach

H. Brown and O. Pooley, "Minkowski Space-Time: A Glorious Non-Entity", in D. Dieks (ed.), *The Ontology of Spacetime* (Elsevier, 2006) pp. 67-89. https://arxiv.org/abs/physics/0403088

(*) W. Myrvold, "How could Relativity be Anything Other Than Physical?", *Studies in history and Philosophy of Modern Physics,* forthcoming. http://philsci-archive.pitt.edu/13157

D. Wallace, "Who's Afraid of Coordinate Systems: An Essay on the Representation of Spacetime Structure", *Studies in history and Philosophy of Modern Physics*, forthcoming. http://philsci-archive.pitt.edu/11988

S. Stevens, "The Dynamical Approach as Practical Geometry", *Philosophy of Science* 82 (2015) pp. 1152-1162.

Critical assessment of the dynamical approach

(*) M. Janssen, "Drawing the Line between Kinematics and Dynamics in Special Relativity", *Studies in history and Philosophy of Modern Physics* 42 (2011) pp. 264-275.

N. Huggett, "Essay Review: *Physical Relativity* and *Understanding Space-Time"*, *Philosophy of Science* 76 (2009) pp. 404-422.

J. Norton, "Why Constructive Relativity Fails", *British Journal for the Philosophy of Science* 59 (2008) pp. 821-834.

M. Frisch, "Principle or Constructive Relativity", *Studies in history and Philosophy of Modern Physics* 42 (2011) pp. 176-183.

Physical status of the Lorentz transformations

According to the geometrical approach, the Lorentz transformations represent simply a recoordinatisation of Minkowski spacetime; on the dynamical approach, the structure of Minkowski spacetime is a consequence of the dynamics encoded in the Lorentz transformations.

(*) J. Bell, "How to Teach Special Relativity", in his *Speakable and Unspeakable in Quantum Mechanics,* 2nd ed (Cambridge University Press, 2004).

H. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Viewpoint* (Oxford University Press, 2005). Chapters 2,3,5.

H. Brown and O. Pooley, "The origin of the spacetime metric: Bell's 'Lorentzian pedagogy' and its significance in general relativity", in C. Callender and N. Huggett (eds.), *Physics Meets Philosophy at the Planck Length* (Cambridge University Press, 1999). https://arxiv.org/abs/gr-qc/9908048

Maudlin, *Philosophy of Physics: Space and Time* (Princeton University Press,), ch.4.

P. Acuna, "Minkowski Spacetime and Lorentz Invariance: The Cart and the Horse, or Two Sides of a Single Coin?", *Studies in history and Philosophy of Modern Physics* 55 (2016) pp. 1-12.

Spacetime Functionalism

Eleanor Knox's spacetime functionalism uses insights from the dynamical approach to spacetime to attempt a functional characterization of spacetime (or at least: inertial) structure.

(*) E. Knox, "Effective Spacetime Geometry", *Studies in history and Philosophy of Modern Physics* 44 (2013), pp. 346-356.

E. Knox, "Physical Relativity from a Functionalist Perspective", *Studies in history and Philosophy of Modern Physics,* forthcoming. http://philsci-archive.pitt.edu/13405/

D. Baker, "On Spacetime Functionalism", manuscript. http://philsci-archive.pitt.edu/14301/

7. Spacetime structure in pre-relativistic physics

What is the structure of spacetime according to Newtonian physics in general, and Newtonian gravity in particular?

Interconnections

- There are close links between these topics and the *substantivalist/relationist debate,* and also with the debate on *dynamical vs geometric approaches to spacetime structure.*

General

M. Friedman, *Foundations of Space-Time Theories* (Princeton, 1983), ch. III.

J. Bain, "Theories of Newtonian Gravity and Empirical Indistinguishability", *Studies in history and Philosophy of Modern Physics* 35 (2004) pp. 345-376.

J. Weatherall, "Are Newtonian Gravitation and Geometrized Newtonian Gravitation Theoretically Equivalent?", *Erkenntnis* 81 (2016) pp. 1073-1091.

E. Knox, "Newtonian Spacetime Structure in Light of the Equivalence Principle", *British Journal for the Philosophy of Science* 65 (2014) pp. 863-880.

S. Saunders, "Rethinking Newton's *Principia*", *Philosophy of Science* 80 (2013) pp. 22-48.

(*) D. Wallace, "Fundamental and Emergent Geometry in Newtonian physics", *British Journal for The Philosophy of Science,* forthcoming; http://philsci-archive.pitt.edu/12497/

Comment on, and synthesis of, Knox and Saunders, above.

J. Weatherall, "Maxwell-Huygens, Newton-Cartan, and Saunders-Knox Space-Times", *Philosophy of Science* 83 (2016) pp. 82-92.

Another comment on Knox and Saunders, focusing on technical issues from a differential-geometric viewpoint.

N. Dewar, "Maxwell Gravitation", *Philosophy of Science* 85 (2018) pp. 249-270.

Newtonian cosmology

D. Malament, "Is Newtonian Cosmology Really Inconsistent?", *Philosophy of Science* 62 (1995) pp. 489-510.

(*) J. Norton, "The Force of Newtonian Cosmology: Acceleration is Relative", *Philosophy of Science* 62 (1995) pp. 511-522.

D. Wallace, "More Problems for Newtonian Cosmology", *Studies in History and Philosophy of Modern Physics* 57 (2017) pp. 35-40.

Technical reference

D. Malament, *Topics in the Foundations of General Relativity and Newtonian Gravitation Theory* (Chicago, 2012), ch.4.

8. Spacetime topics in quantum gravity

Many of the conceptual problems in quantum gravity turn on issues in quantum field theory, or on the details of string theory, loop quantum gravity, or other specific approaches to the subject. But two topics can be, and have been, discussed in the general context of philosophy of spacetime.

Interconnections

- It has been argued that the Problem of Time is really a version of the Hole Argument in a quantum-gravity (or canonical-general-relativity) context.

General discussions

(*) J. Butterfield and C. Isham, "Spacetime and the philosophical challenge of quantum gravity", in C. Callender and N. Huggett (eds.), *Physics Meets Philosophy at the Planck Scale* (Cambridge University Press, 2001), pp.33-89. https://arxiv.org/abs/gr-qc/9903072

D. Rickles, "Quantum Gravity: a Primer for Philosophers", in D. Rickles (ed.), *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), pp. 262-382.

The problem of time

(*) G. Belot and J. Earman, "Pre-Socratic Quantum Gravity", in C. Callender and N. Huggett (eds.), *Physics Meets Philosophy at the Planck Scale* (Cambridge University Press, 2001), pp.213-255.

D. Rickles, "Time and Structure in Quantum Gravity", in D. Rickles, S. French and J. Saatsi (ed.), *The Structural Foundations of Quantum Gravity* (Oxford University Press, 2006) pp. 152-195.

J. Earman, "Thoroughly modern McTaggart: Or, What McTaggart would have said if he had read the general theory of relativity", *Philosophers' Imprint* 2(3) (2002) pp.1-28.

T. Maudlin, "Thoroughly muddled McTaggart: Or, How to Abuse Gauge Freedom to Generate Metaphysical Monstrosities", *Philosophers' Imprint* 2(4) (2002) pp.1-23.

Response to Earman; includes short reply by Earman.

The hole argument in quantum gravity

D. Rickles, "A new spin on the hole argument", *Studies in History and Philosophy of Modern Physics* 36 (2005) pp. 415-434.

O. Pooley, "A hole revolution, or are we back where we started?", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 372-380.

Response to Rickles.

D. Rickles, "Bringing the hole argument back in the loop: a response to Pooley", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 381-387.

The emergence of spacetime

(*) N. Huggett and C. Wuthrich, "Emergent Spacetime and Empirical (In)coherence", *Studies in history and Philosophy of Modern Physics* 44 (2013) pp. 276-285.

E. Knox, "Effective Spacetime Geometry", *Studies in history and Philosophy of Modern Physics* 44 (2013), pp. 346-356.

9. Philosophy of Symmetry

Philosophical discussion of symmetry has largely turned on the question of when symmetry-related situations are the same situation redescribed, or are distinct but empirically-indistinguishable situations. A related but distinct question is: what empirical status to symmetries have? Underlying this is the difficulty of giving a sufficiently clear and general definition of "symmetry" in the first place.

Interconnections

- Leibniz equivalence is a central theme in the *substantivalist/relationist debate* and in the *hole argument*
- Interpretative issues of gauge symmetry are closely connected to the *hole argument,* to debates over the *meaning of general covariance,* and to the Problem of Time in the *philosophy of quantum gravity.*

Overview of the physics

(*) S. Bangu, "Symmetry", in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford University Press, 2013), pp. 287-317.

G. Belot, "Notes on Symmetries", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 393-412.

General status of symmetries

(*) J. Ismael and B. van Fraassen, "Symmetry as a Guide to Surplus Structure", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 371-392.

J. Roberts, "A Puzzle about Laws, Symmetries and Measurability", *British Journal for the Philosophy of Science* 59 (2008), pp. 143-168.

S. Dasgupta, "Symmetry as an Epistemic Notion (Twice Over)", *British Journal for the Philosophy of Science* 67 (2016) pp. 837-878.

Leibniz equivalence

"Leibniz equivalence" is the thesis that symmetry-related situations are the same situation redescribed.

(*) S. Saunders, "Physics and Leibniz's Principles", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 289-307.
http://philsci-archive.pitt.edu/2012/

N. Dewar, "Sophistication About Symmetries", *British Journal for the Philosophy of Science,* forthcoming.
http://philsci-archive.pitt.edu/12469

(*) G. Belot, "Symmetry and Equivalence", in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford University Press, 2013), pp. 318-339.

G. Belot, "Fifty Million Elvis Fans Can't Be Wrong", *Nous,* forthcoming;
https://onlinelibrary.wiley.com/doi/abs/10.1111/nous.12200

T. Møller-Nielsen, “Invariance, Interpretation, and Motivation”, *Philosophy of Science* 84 (2017) pp. 1253-1264.

Empirical consequences of symmetries

When a symmetry is applied to a subsystem of the universe, sometimes this gives rise to an empirically distinct state of affairs. When does this happen?

P. Kosso, “The Empirical Status of Symmetries in Physics”, *British Journal for the Philosophy of Science* 51 (2000) pp. 81-98.

K. Brading and H. Brown, “Are Gauge Symmetry Transformations Observable?”, *British Journal for the Philosophy of Science* 55 (2004) pp. 645-655.

(*) H. Greaves and D. Wallace, “Empirical Consequences of Symmetries”, *British Journal for the Philosophy of Science* 65 (2014), pp. 59-89.

R. Healey, “Perfect Symmetries”, *British Journal for the Philosophy of Science* 60 (2009) pp. 697-720.

S. Friederich, “Symmetry, Empirical Equivalence, and Identity”, *British Journal for the Philosophy of Science* 66 (2015) pp. 537-559.

N. Teh, “Galileo’s Gauge: Understanding the Empirical Significance of Gauge Symmetry”, *Philosophy of Science* 83 (2016) pp. 93-118.

Gauge symmetry

Gauge symmetries are essential in modern physics (and the diffeomorphism symmetry of general relativity is, on one disambiguation, a gauge symmetry). What is their status; how do they differ from non-gauge symmetries?

(*) M. Redhead, “The interpretation of gauge symmetry”, in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 124-139.

J. Earman, “Tracking Down Gauge: an Ode to the Constrained Hamiltonian Formalism”, in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 140-162.

> *Presentation of a powerful – but technically demanding – mathematical formalism to approach gauge theory.*

D. Wallace, “Time-dependent Symmetries: the Link Between Gauge Symmetries and Indeterminism”, in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 163-173.

> *Commissioned as an elementary exegesis of the philosophical issues addressed in Earman’s paper, above.*

J. Weatherall, “Understanding Gauge”, *Philosophy of Science* 83 (2016) pp. 1039-1049.

Symmetry and conservation

A central theme of modern physics is the close connection between symmetries and conservation laws.

(*) K. Brading and H. Brown, "Symmetries and Noether's Theorems", in K. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections* (Cambridge University Press, 2003), pp. 89-110.

H. Brown and P. Holland, "Dynamical versus Variational Symmetries: Understanding Noether's First Theorem", *Molecular Physics* 102 (2004) pp. 1133-1139.

M. Lange, "Laws and Meta-Laws of Nature: Conservation Laws and Symmetries", *Studies in history and Philosophy of Modern Physics* 38 (2007) pp. 457-481.

S. Smith, "Symmetries and the Explanation of Conservation Laws in the Light of the Inverse Problem in Lagrangian Mechanics", *Studies in history and Philosophy of Modern Physics* 39 (2008) pp. 325-345.

10. Other topics in special and general relativity

Interconnections

- Questions of the relativity and conventionality of simultaneity, and of the status of the geodesic principle, overlap with *dynamical vs geometric approaches to spacetime structure*
- The equivalence principle has been extensively discussed in recent work on s*pacetime structure in pre-relativistic physics.*

Relativity and conventionality of simultaneity

D. Malament, "Causal Theories of Time and the Conventionality of Simultaneity", *Nous* 11 (1977) pp. 293-300.

(*) A. Janis, "Conventionality of Simultaneity", in E.Zalta (ed.) *The Stanford Encyclopedia of Philosophy: Fall 2002 edition.*

S. Sarkar and J. Stachel, "Did Malament Prove the Non-Conventionality of Simultaneity in the Special Theory of Relativity?", *Philosophy of Science* 66 (1999) pp. 208-220.

(*) H. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Viewpoint* (Oxford University Press, 2005), pp. 95-105.

T. Maudlin, *Philosophy of Physics: Space and Time* (Princeton University Press, 2012) pp. 83-105.

The equivalence principle

J. Norton, "What was Einstein's Principle of Equivalence", *Studies in history and Philosophy of Science* 16 (1985) pp. 203-246.

(*) J. Read, H. Brown, and D. Lehmkuhl, "Two Miracles of General Relativity", *Studies in history and Philosophy of Modern Physics*, forthcoming.
https://www.sciencedirect.com/science/article/pii/S1355219817300667

D. Wallace, "The relativity and equivalence principles for self-gravitating systems", in D. Lehmkuhl *et al* (eds.), *Towards a Theory of Spacetime Theories: Einstein Studies 13* (Springer, 2017), pp.257-266.

The geodesic principle

H. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Viewpoint* (Oxford University Press, 2005), chapters 8-9.

D. Malament, "A Remark about the 'Geodesic Principle' in General Relativity", manuscript.
http://philsci-archive.pitt.edu/5072/

(*) J. Weatherall, "On the status of the geodesic principle in Newtonian and relativistic physics", *Studies in history and Philosophy of Modern Physics* 42 (2011) pp. 276-281.

Gravitational energy

(*) C. Hoefer, "Energy Conservation in GTR", *Studies in history and Philosophy of Modern Physics* 31 (2000) pp. 187-199.

V. Lam, "Gravitational and Non-Gravitational Energy: The Need for Background Structures", *Philosophy of Science* 78 (2011) pp. 1012-1024.

N. Dewar and J. Weatherall, “On Gravitational Energy in Newtonian Theories”, *Foundations of Physics* 48 (2018) pp. 558-578.

E. Curiel, “On Geometric Objects, the Non-Existence of a Gravitational Stress-Energy Tensor, and the Uniqueness of the Einstein Field Equation”, manuscript. http://philsci-archive.pitt.edu/10985/1/nonexist-grav-seten-uniq-efe.pdf

Global structure

(*) J. Manchak, “Global Spacetime Structure”, in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford University Press, 2013) pp. 586-606.

J. Earman, *Bangs, Crunches, Whispers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes* (Oxford University Press, 1995).

E. Curiel, “The Analysis of Singular Spacetimes”, *Philosophy of Science* 66 (1999) pp. S119-S145.