Reading list in Philosophy of Thermal Physics

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 thermal physics (that is: thermodynamics and statistical mechanics), 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 the Boltzmann equation; I don't engage with more philosophical aspects of the arrow of time (in particular, in asymmetries of causation or counterfactual dependence), and (beyond a brief section on the radiation arrow of time) I don't discuss physics aspects of the arrow of time outside thermal physics; I don't engage with the vast literature on emergence and reduction except insofar as it directly touches on the relation of thermodynamics to statistical mechanics; I don't discuss chaos theory.

I've also drawn some fairly arbitrary distinctions as to what counts as philosophy of thermal physics. I have included some articles on indistinguishability in quantum physics because of its close connection to the Gibbs paradox, even though many of the issues that arise (issues of the metaphysics of symmetry and the identity of indiscernibles, in particular, would more naturally be considered part of the philosophy of spacetime and symmetry. I have omitted any real discussion of the renormalization group, considering that part of the philosophy of quantum field theory. Conversely, I have included a reasonably detailed list on the thermal physics of self-gravitating systems – and in particular, on black hole thermodynamics – even though that issue connects extensively with topics in quantum gravity that lie way outside philosophy of thermal physics.

My organization is a little idiosyncratic, by the normal standards of the subject: I distinguish (i) non-equilibrium statistical mechanics, which covers pretty much any study of quantitatively how systems change in time; (ii) equilibrium statistical mechanics, which includes both the definition of equilibrium and the study of more qualitative arguments about how systems eventually approach equilibrium; (iii) thermodynamics, which I construe narrowly to mean just the study of the laws of thermodynamics and the state function of systems. Readers should be warned that other sources construe "thermodynamics" much more broadly, to cover most aspects of time asymmetry, and treat qualitative and quantitative study of the approach to equilibrium both as "non-equilibrium statistical mechanics".

Over and above this, philosophy of thermal physics is a very interconnected subject in which it is hard to cleanly separate topics, so that my divisions into sections are in places arbitrary. Under "interconnections" in many sections, 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 judgment will give you the best idea of what the overall topic is about. Where I have starred one of my own articles (which, I will admit, is fairly frequently) I have (almost always) also starred another.

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 prioritize (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, two brief and fairly accessible introductions are:

R. Feynman, "The Distinction of Past and Future", chapter 5 of *The Character of Physical Law* (MIT Press, 1965).

D. Wallace, "The arrow of time in physics", in H. Dyke and A. Bardon (eds.), *A Companion to the Philosophy of Time* (Wiley, 2013).

At a slightly higher level, these are book-length discussions:

D. Albert, *Time and Chance* (Harvard University Press, 1999).

H. Price, *Time's Arrow and Archimedes' Point* (Oxford University Press, 1996).

Neither are textbooks, though: each argues for its own conclusions. But in a subject as contested as philosophy of statistical mechanics, it can be easier to see the stakes of a dispute by reading unashamed advocacy of this kind than by studying an overview.

The nearest I know to philosophy *textbooks* on the subject are:

R. Frigg, "A Field Guide to Recent Work on the Foundations of Thermodynamics and Statistical Mechanics", in Dean Rickles, ed., *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008). https://arxiv.org/abs/0804.0399

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993).

J. Uffink, "Compendium of the Foundations of Statistical Mechanics", in J. Butterfield and J. Earman (eds.), *Handbook of Philosophy of Physics, Part B* (Elsevier, 2007). http://philsci-archive.pitt.edu/2691/

Each makes some attempt at a neutral point of view, and each has good and extensive references.

I'll mention one more book that isn't out yet at time of writing:

W. Myrvold, *Beyond Chance and Credence.*

I've seen an advance proof of this, and I think it will be an excellent introduction for non-specialists once it's available (I expect 2019).

There are also several classic physics texts worth mentioning:

P. Ehrenfest and T. Ehrenfest, *The Conceptual Foundations of the Statistical Approach in Mechanics* (Teubner, 1912; English translation published by Cornell University Press, 1959).

Hugely influential in the foundations of statistical mechanics literature; somewhat uneven in its coverage.

R. Tolman, *The Principles of Statistical Mechanics* (Clarendon Press, 1938).

One of the first really systematic textbooks.

O. Penrose, "Foundations of Statistical Mechanics", *Reports on Progress in Physics* 42 (1979) pp. 1937-2006.

Technically oriented, detailed survey article. (NB: this is Oliver Penrose, brother of Roger Penrose.)

Physics background

If you have not studied the underlying physics (and I **strongly** recommend, if you want to work seriously in this subject, that you do study the underlying physics direct at some point, and don't simply attempt to learn it from foundational works) then there are literally hundreds of textbooks on thermodynamics and equilibrium statistical mechanics to choose from. For what it's worth, my recommendation is

Blundell and Blundell, *Concepts in Thermal Physics*

but don't mistake that for a recommendation based on an exhaustive study.

(It is *much* harder to find good introductory discussions of non-equilibrium statistical mechanics, which is generally presented at a much higher level and which lacks an agreed-upon overall formalism, even as compared to equilibrium statistical mechanics. I don't know something I'd unequivocally recommend, but the textbooks by Zwanzig, Balescu, Liboff, and Calzetta & Hu (first 2-3 chapters only) in the "non-equilibrium statistical mechanics" section are all good. (But these are all graduate texts in theoretical physics, and so are fairly demanding.)

The Poincare recurrence theorem, though itself an uncontentious mathematical result, turns up in many places in the subject and can be made to seem very obscure. I give a (hopefully) accessible but rigorous discussion in

D. Wallace, "Recurrence Theorems: a Unified Account", *Journal of Mathematical Physics* 56 (2015) 022105.

The mathematics required for (most of) philosophy of thermal physics is fairly undemanding by philosophy-of-physics standards: multivariate calculus and linear algebra, mostly.

2. Non-Equilibrium Statistical Mechanics

Many physical systems demonstrably obey equations of motion which (a) track only their larger-scale, more-collective degrees of freedom and (b) are irreversible in time. How are such equations derived and how are those derivations compatible with the apparent reversibility of the underlying microdynamics?

Interconnections

- There is no really sharp distinction between non-equilibrium statistical mechanics and the study of equilibrium statistical mechanics in the Boltzmann or Gibbs tradition
- In particular, coarse-graining approaches to equilibrium overlap with the Brussels-Austin school in the *Gibbsian approach to statistical mechanics*
- The Boltzmann equation – particularly in its "old kinetic theory" form – is closely related to the approach to equilibrium in the *Boltzmannian approach to statistical mechanics*
- Both the BBGKY hierarchy and the linear-systems approach to non-equilibrium systems have close cousins in *quantum statistical mechanics.*

Boltzmann's equation and the old kinetic theory

Boltzmann's equation governs the non-equilibrium behavior of dilute gases; as originally understood – and as still defended today in some foundational circles – it has nothing to do with probability but rather describes the statistics of large numbers of molecules.

(*) H. Brown, W. Myrvold and J. Uffink, "Boltzmann's H-theorem, its discontents, and the birth of statistical mechanics", *Studies in History and Philosophy of Modern Physics* 40 (2009), pp. 174-191.

J. Uffink, "Compendium of the Foundations of Statistical Mechanics", in J. Butterfield and J. Earman (eds.), *Handbook of Philosophy of Physics, Part B* (Elsevier, 2007), pp. 923-1074. Section 4.
http://philsci-archive.pitt.edu/2691/

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 2.II (pp.28-48).

P. Ehrenfest and T. Ehrenfest, *The Conceptual Foundations of the Statistical Approach in Mechanics* (Teubner, 1912; English translation: Cornell University Press, 1959), Chapter I (sections 1-8).

D. Wallace, "Probability and Irreversibility in Modern Statistical Mechanics: Classical and Quantum", to appear in D. Bedingham, O. Maroney and C. Timpson (eds.), *Quantum Foundations of Statistical Mechanics* (Oxford University Press, forthcoming). Sections 2-4, 8-10.

E. Jaynes, "Gibbs vs Boltzmann Entropies", *American Journal of Physics* 33 (1965) p.391.

Lanford's rigorous proof of Boltzmann's equation

Lanford proved Boltzmann's equation in full mathematical rigor, albeit under very restrictive assumptions; the conceptual importance of that proof is contested.

(*) J. Uffink, "Compendium of the Foundations of Statistical Mechanics", in J. Butterfield and J. Earman (eds.), *Handbook of Philosophy of Physics, Part B* (Elsevier, 2007), pp. 923-1074. Section 6.4.
http://philsci-archive.pitt.edu/2691/

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 7.II.1 (pp.224-227).

J. Uffink and G. Valente, "Lanford's Theorem and the Emergence of Irreversibility", *Foundations of Physics* 45 (2015) pp. 404-438.

Coarse-graining approaches: general considerations

Modern approaches to non-equilibrium statistical mechanics normally employ some kind of "coarse-graining" mechanism to construct an autonomous dynamics of collective degrees of freedom from the microdynamics.

(*) K. Robertson, "Asymmetry, abstraction and autonomy: justifying coarse-graining in statistical mechanics", *British Journal for the Philosophy of Science,* forthcoming (2018).

E. Calzetta and B. Hu, "Basic Issues in nonequilibrium statistical mechanics", chapter 1 of their *Non-Equilibrium Quantum Field Theory* (Cambridge University Press, 2008).

(*) D. Wallace, "The Logic of the Past Hypothesis", to appear in B. Loewer, E. Winsberg and B. Weslake, *Time's Arrows and the Probability Structure of the World* (Harvard University Press, forthcoming). http://philsci-archive.pitt.edu/8894/

K. Ridderbos, "The coarse-graining approach to statistical mechanics: how blissful is our ignorance?", *Studies in History and Philosophy of Modern Physics* 33 (2002) pp.65-77.

C. Callender, "Taking Thermodynamics Too Seriously", *Studies in History and Philosophy of Modern Physics* 32 (2002) pp. 439-453.

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), chapters 6-7, esp. pp.219-224, 246-250, 260-262.

T. Maudlin, "Review" [of Sklar, *ibid*], *British Journal for the Philosophy of Science* 46 (1995) pp. 145-149.

The BBGKY hierarchy and the probabilistic approach to Boltzmann's equation

In modern statistical physics, the Boltzmann equation is regarded as an equation for the one-particle marginal probability distribution of a gas, and is just one of a large family of equations which can be derived that way.

(*) D. Wallace, "Probability and Irreversibility in Modern Statistical Mechanics: Classical and Quantum", to appear in D. Bedingham, O. Maroney and C. Timpson (eds.), *Quantum Foundations of Statistical Mechanics* (Oxford University Press, forthcoming). Sections 2-4, 8-10.

J. Uffink, "Compendium of the Foundations of Statistical Mechanics", in J. Butterfield and J. Earman (eds.), *Handbook of Philosophy of Physics, Part B* (Elsevier, 2007), pp. 923-1074. Section 6.5. http://philsci-archive.pitt.edu/2691/

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 6.III.1 (pp.207-210).

(*) R. Balescu, *Statistical Dynamics: Matter Out of Equilibrium* (Imperial College Press, 1997), chapters 1-7 (pp. 1-104).

R. Liboff, *Kinetic Theory: Classical, Quantum, and Relativistic Descriptions*, 3rd edition (Springer, 2003), chapters 1-3.

> *Much of this is probably calculational material of limited foundational significance, but it is not a simple or uncontentious matter to make that division.*

Linear systems, Langevin's equation, and the Mori-Zwanzig formalism

Other than the Boltzmann equation and its relatives, the main paradigm of non-equilibrium statistical mechanics concerns one large system interacting with a great many smaller systems; this can (apparently) lead to stochastic (i.e., random) equations of motion, even when the underlying physics is deterministic.

H.D. Zeh, *The physical basis of the direction of time, 5th edition* (Springer, 2007). Chapter 3.

(*) R. Zwanzig, *Non-Equilibrium Statistical Mechanics* (Oxford University Press, 2000), chapters 1-2 (pp. 3-47).

D. Wallace, "The quantitative content of statistical mechanics", *Studies in History and Philosophy of Modern Physics* 52 (2015), pp.285-293.

J. Luczak, "On How to Approach the Approach to Equilibrium", *Philosophy of Science* 83 (2016) pp. 393-411.

K. Robertson, "Asymmetry, abstraction and autonomy: justifying coarse-graining in statistical mechanics", *British Journal for the Philosophy of Science,* forthcoming (2018).

3. The Gibbsian Approach to Statistical Mechanics

In Gibbsian statistical mechanics – which, roughly, is the main approach used in mainstream physics – a system is represented by a probability distribution across phase space, and entropy is a property of that probability distribution, not of individual phase-space points.

Interconnections

- There is no very sharp divide between Gibbsian statistical mechanics and the study of coarse-graining in *non-equilibrium statistical mechanics*
- Since probability plays a central role in the formulation of Gibbsian statistical mechanics, there are obvious overlaps with *probabilities in statistical mechanics*
- The great bulk of *quantum statistical mechanics* is effectively carried out in the Gibbsian framework, with density operators replacing probability distributions.

General features

P. Ehrenfest and T. Ehrenfest, *The Conceptual Foundations of the Statistical Approach in Mechanics* (Teubner, 1912; English translation: Cornell University Press, 1959), Chapters II-III (sections 9-26).

(*) R. Frigg, "A Field Guide to Recent Work on the Foundations of Thermodynamics and Statistical Mechanics", in Dean Rickles, ed., *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), section 3. https://arxiv.org/abs/0804.0399

J. Uffink, "Compendium of the Foundations of Statistical Mechanics", in J. Butterfield and J. Earman (eds.), *Handbook of Philosophy of Physics, Part B* (Elsevier, 2007), pp. 923-1074. Section 5.
http://philsci-archive.pitt.edu/2691/

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 2.III (pp.48-59).

E. Jaynes, "Gibbs vs Boltzmann Entropies", *American Journal of Physics* 33 (1965) p.391.

K. Davey, "What is Gibbs' Canonical Distribution?", *Philosophy of Science* 76 (2009) pp. 970-983.

C. Werndl and R. Frigg, "Mind the Gap: Boltzmannian versus Gibbsian Equilibrium", *Philosophy of Science* 84 (2017) pp. 1289-1302.

Criticisms of the Gibbsian approach

The Gibbsian approach has been influentially criticized in recent philosophy of statistical mechanics by advocates of the rival "Boltzmannian" approach.

(*) C. Callender, "Reducing Thermodynamics to Statistical Mechanics: the Case of Entropy", *Journal of Philosophy* 96 (1999) pp. 348-373.

D. Albert, *Time and Chance* (Harvard University Press, 2000), chapter 4, esp. pp.85-91.

Ergodicity

"Ergodicity" – roughly, the conjectured tendency of a sufficiently-complicated physical system to pass, in time, through every possible state – has historically been thought to be central in understanding

equilibrium and probability in Gibbsian statistical mechanics, but it remains obscure just what role it is supposed to play.

L. Sklar, “Statistical Explanation and Ergodic Theory”, *Philosophy of Science* 40 (1973) pp. 194-212.

K. Friedman, “A Partial Vindication of Ergodic Theory”, *Philosophy of Science* 43 (1976) pp. 151-162.

D. Malament and S. Zabell, “Why Gibbs Phase Space Averages Work: the Role of Ergodic Theory”, *Philosophy of Science* 47 (1980) pp. 339-349.

S. Leeds, “Malament and Zabell on Gibbs Phase Averaging”, *Philosophy of Science* 56 (1989) pp. 325-340.

(*) J. Earman and M. Redei, “Why Ergodic Theory Does Not Explain the Success of Equilibrium Statistical Mechanics”, *British Journal for the Philosophy of Science* 47 (1996) pp. 63-78.

J. van Lith, “Ergodic Theory, Interpretations of Probability and the Foundations of Statistical Mechanics”, *Studies in History and Philosophy of Modern Physics* 32 (2001) pp. 581-594.

R. Frigg, J. Berkovitz and F. Kronz, “The Ergodic Hierarchy”, in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Summer 2016 edition).

P. Vranas, “Epsilon-Ergodicity and the Success of Equilibrium Statistical Mechanics”, *Philosophy of Science* 65 (1998) pp. 688-708.

R. Frigg and C. Werndl, “Explaining Thermodynamic-Like Behaviour in Terms of Epsilon-Ergodicity”, *Philosophy of Science* 78 (2013) pp. 628-652.

Interventionist accounts of equilibration

No realistic physical system is genuinely isolated from its environment; does this play a role in the approach to equilibrium?

J. Blatt, “An Alternative Approach to the Ergodic Problem”, *Progress of Theoretical Physics* 22 (1959) pp. 745-756.

(*) T. Ridderbos and M. Redhead, “The Spin-Echo Experiments and the Second Law of Thermodynamics”, *Foundations of Physics* 28 (1998) pp. 1237-1270.

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 7.III.2 (pp.250-255).

C. Callender, “Reducing Thermodynamics to Statistical Mechanics: the Case of Entropy”, *Journal of Philosophy* 96 (1999) pp. 348-373. Pages 361-363.

S. Leeds, “Interventionism in Statistical Mechanics”, *Entropy* 14 (2012) pp. 344-369.

The Brussels-Austin School

A minority – but influential – approach to classical statistical mechanics, associated in particular with Ilya Prigogine, aims to explicitly modify classical mechanics in order to understand equilibration.

R. Batterman, “Randomness and Probability in Dynamical Theories: On the Proposals of the Prigogine School”, *Philosophy of Science* 58 (1991), pp.241-263.

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 7.III.6 (pp.269-277).

V. Karakostas, "On the Brussels School's Arrow of Time in Quantum Theory", *Philosophy of Science* 63 (1996), pp.374-400.

(*) R. Bishop, "Nonequilibrium statistical mechanics Brussels–Austin style", *Studies in History and Philosophy of Modern Physics* 35 (2004), pp.1-30.

Jaynes' objective-Bayesian approach

Jaynes persuaded many people in physics (though fewer in philosophy) of the intimate links between information and entropy; to him, "equilibrium" is not a property of a system, but of our information about a system, and "the approach to equilibrium" is simply our losing information about the system.

E. Jaynes, "Information Theory and Statistical Mechanics", *Physical Review* 106 (1957), p.620.

E. Jaynes, "Information Theory and Statistical Mechanics II", *Physical Review* 108 (1957), p.171.

(*) E. Jaynes, "Gibbs vs Boltzmann Entropies", *American Journal of Physics* 33 (1965) p.391.

K. Friedman and A. Shimony, "Jaynes' Maximum Entropy Prescription and Probability Theory", *Journal of Statistical Physics* 3 (1971), pp. 381-4.

D. Wallace, "Inferential vs. Dynamical Conceptions of Physics", in O. Lombardi (ed.), *What is Quantum Information?* (Cambridge University Press, 2017).

R. Frigg, "A Field Guide to Recent Work on the Foundations of Thermodynamics and Statistical Mechanics", in D. Rickles, ed., *The Ashgate Companion to the New Philosophy of Physics* (Ashgate, 2008). pp.168-174. https://arxiv.org/abs/0804.0399

J. Uffink, "Can the Maximum Entropy Principle be Explained as a Consistency Requirement?", *Studies in History and Philosophy of Modern Physics* 26 (1995), pp. 223-261.

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), section 7.III.3 (pp.255-260).

J. Uffink, "The Constraint Rule of the Maximum Entropy Principle", *Studies in the History and Philosophy of Modern Physics* 27 (1997), pp. 47-79.

R. Balian, "Information in statistical physics", *Studies in History and Philosophy of Modern Physics* 36 (2005), pp.323-353.

R. Baierlein, *Atoms and Information Theory: an Introduction to Statistical Mechanics* (W.H.Freeman, 1971). (An undergraduate textbook, written from a Jaynesian viewpoint)

4. The (Neo-)Boltzmannian approach to statistical mechanics

Boltzmann's name is associated with almost every well-known approach to statistical mechanics, but in contemporary philosophy of physics, "Boltzmannian" (or, sometimes, "neo-Boltzmannian") statistical mechanics refers to an approach where (i) thermodynamic properties are associated with "macrostates", regions of phase space with approximately-definite macroscopic features; (ii) the role of probability is strongly downplayed; (iii) a "past hypothesis" about the initial entropy of the Universe plays a central role.

Interconnections

- Although appeal to the Past Hypothesis is most commonly seen in the Boltzmannian approach, there is no logical requirement for this to be the case; *the Gibbsian approach to statistical mechanics*, and *non-equilibrium statistical mechanics*, can both make use of a Past Hypothesis.
- Boltzmann's kinetic-theory approach to *non-equilibrium statistical mechanics* has substantial overlaps with the neo-Boltzmannian approach; in particular, both ascribe properties to individual systems and downplay probability.
- The notion of typicality – discussed under *probabilities in statistical mechanics* – is often substituted for a more quantitative notion of probability in the Boltzmannian approach.
- Discussions of entropy and cosmology in the Past Hypothesis overlap with considerations of gravitational entropy in the *thermodynamics and statistical mechanics of self-gravitating systems.*

Overviews and introductions

J. Lebowitz, "Boltzmann's Entropy and Time's Arrow", *Physics Today* 46 (1993) p.32.

(*) S. Goldstein, "Boltzmann's Approach to Statistical Mechanics", in J. Bricmont *et al*, "Chance and Physics: Foundations and Perspectives" (Springer, 2001), p.39. http://arxiv.org/abs/cond-mat/0105242

D.Albert, *Time and Chance* (Harvard University Press, 1999), chs. 3-4.

Conceptual and technical issues

What technical assumptions does the Boltzmannian approach to macrostates and to equilibration require, and how should we understand its technical assumptions?

(*) R. Frigg, "A Field Guide to Recent Work on the Foundations of Thermodynamics and Statistical Mechanics", in Dean Rickles, ed., *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), section 2. https://arxiv.org/abs/0804.0399

C. Werndl and R. Frigg, "Reconceptualising equilibrium in Boltzmannian statistical mechanics and characterizing its existence", *Studies in History and Philosophy of Modern Physics* 49 (2015) pp. 19-31.

E. Winsberg, "Laws and chances in statistical mechanics", *Studies in History and Philosophy of Modern Physics* 39 (2008). pp. 872-888.

The Past Hypothesis: overall role

Exactly how does any hypothesis about the early Universe connect to the thermodynamic behavior of systems in the here and now?

(*) D. Albert, *After Physics* (Harvard University Press, 2015), chapter 3.

D. Parker, "Does the Big Bang explain what it purports to explain?", *Philosophy of Science* 72 (2005) pp. 751-763.

J. Earman, "The 'Past Hypothesis': Not Even False", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 399-430.

D. Wallace, "The Logic of the Past Hypothesis", to appear in B. Loewer, E. Winsberg and B. Weslake, *Time's Arrows and the Probability Structure of the World* (Harvard University Press, forthcoming). http://philsci-archive.pitt.edu/8894/

The Past Hypothesis: cosmological features

How do statistical-mechanical requirements about the early universe connect with how we understand it from cosmology?

(*) R. Penrose, "On the Second Law of Thermodynamics", *Journal of Statistical Physics* 77 (1994) pp. 217-221.

R. Wald, "The arrow of time and the initial conditions of the universe", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 394-398.

J. Earman, "The 'Past Hypothesis': Not Even False", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 399-430.

D. Wallace, "Gravity, Entropy, and Cosmology: In Search of Clarity", *British Journal for the Philosophy of Science* 61 (2010), pp. 513-540.

H. Price, "Why there is Still a Puzzle about the Low-Entropy Past", in C. Hitchcock (ed.), *Contemporary Debates in the Philosophy of Science* (Blackwell, 2004) pp. 219-239.

C. Callender, "There is No Puzzle about the Low-Entropy Past", in C. Hitchcock (ed.), *Contemporary Debates in the Philosophy of Science* (Blackwell, 2004) pp. 240--257.

5. Thermodynamics

Although "thermodynamics" is often used as a virtual synonym for thermal physics, and "the second Law" is used as a virtual synonym for "dynamics is irreversible", here I use it more narrowly, to mean the study of how work can be extracted from dynamical systems by external interventions.

Interconnections

- Since thermodynamics is generally thought to rest on statistical mechanics, and since equilibrium and the approach to equilibrium play such central roles in thermodynamics, both the *Boltzmannian approach to equilibrium* and the *Gibbsian approach to equilibrium*, along with *non-equilibrium thermodynamics* more generally, connect with foundational topics in thermodynamics.
- *Maxwell's demon and Landauer's Principle* are essentially issues about the generality and scope of thermodynamics; they could have been parts of this section, but I have separated them out due to the amount that has been written on them.

Introduction

D. Albert, *Time and Chance* (Harvard University Press, 2000), chapter 2.

Thermodynamics as an autonomous discipline

Thermodynamics preceded statistical mechanics and important foundational questions about it can be asked without presupposing a statistical-mechanical underpinning.

H. Brown and J. Uffink, "The origins of time asymmetry in thermodynamics: the Minus First Law", *Studies in History and Philosophy of Modern Physics* 32 (2001) pp. 525-538.

(*) J. Uffink, "Bluff Your Way in the Second Law of Thermodynamics", *Studies in History and Philosophy of Modern Physics* 32 (2001), pp. 305-394.

J. Norton, "The Impossible Process: Thermodynamic Reversibility", *Studies in History and Philosophy of Modern Physics* 55 (2016), pp. 43-61.

E. Lieb, and J. Yngvason, "The physics and mathematics of the second law of thermodynamics", *Physics Reports* 310 (1999), pp.1-96.

D. Lavis, "The Problem of Equilibrium Processes in Thermodynamics", *Studies in History and Philosophy of Modern Physics* 62 (2018), pp. 136-144.

O. Maroney, "Thermodynamic constraints on fluctuation phenomena", *Physical Review E* 80 (2009) 061141.

The relation of thermodynamics to statistical mechanics

The most important foundational question in thermodynamics is its relationship to statistical mechanics and to the underlying dynamics of thermodynamic systems.

D. Wallace, "The quantitative content of statistical mechanics", *Studies in the History and Philosophy of Modern Physics* 52 (2015) pp. 285-293.

(*) D. Wallace, "Thermodynamics as Control Theory", *Entropy* 16 (2014), pp. 699-725.

L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), chapter 9.

(*) W. Myrvold, "Statistical Mechanics and Thermodynamics: a Maxwellian View", *Studies in History and Philosophy of Modern Physics* 42 (2011), pp. 237-243.

O. Maroney, "The physical basis of the Gibbs-von Neumann entropy", https://arxiv.org/abs/quant-ph/0701127.

Phase transitions and the thermodynamic limit

Phase transitions (e.g. ice/water, or ferromagnet/paramagnet) become sharply mathematically defined only in the limit of infinite volume, which never occurs in realistic systems; this raises subtleties for any account of reduction.

C. Callender, "Taking Thermodynamics Too Seriously", *Studies in History and Philosophy of Modern Physics* 32 (2002) pp. 439-453.

C. Liu, "Infinite Systems in SM Explanations: Thermodynamic Limit, Renormalization (semi-) Groups, and Irreversibility", *Philosophy of Science* 68 (2001) pp. 325-344.

(*) R. Batterman, "Reduction and renormalization", in G. Ernst and A. Huttemann (eds.), *Time, Chance and Reduction: Philosophical Aspects of Statistical Physics* (Cambridge University Press, 2010), pp. 159-189. http://philsci-archive.pitt.edu/2852/

R. Batterman, "Critical phenomena and breaking drops: Infinite idealizations in physics", *Studies in History and Philosophy of Modern Physics* 36 (2004) pp. 225-244.

T. Menon and C. Callender, "Turn and Face The Strange … Ch-Ch-Changes: Philosophical Questions Raised by Phase Transitions", in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford University Press, 2013), pp. 189-223. http://philsci-archive.pitt.edu/8757/

J. Fraser, "Spontaneous Symmetry Breaking in Finite Systems", *Philosophy of Science* 83 (2016) pp. 585-605.

J. Norton, "Approximation and Idealization: Why the Difference Matters", *Philosophy of Science* 79 (2012) pp. 207-232.

J. Butterfield, "Less is Different: Emergence and Reduction Reconciled", *Foundations of Physics* 41 (2011) pp. 1065-1135.

6. Maxwell's Demon and Landauer's Principle

Maxwell's demon is a hypothetical minute creature which, being able to manipulate the microstructure of a system, can induce a decrease in its entropy and a violation of the Second Law of Thermodynamics. Over the 20th century a consensus emerged in the physics literature that no demon could be built, and that the reason could be tracked to "Landauer's Principle", which mandates an energy cost whenever the demon resets itself. In the last 20 years, this consensus has been challenged by philosophers of physics.

Interconnections

- Discussions of Maxwell's demon presuppose both a framework for statistical mechanics (usually the Gibbsian framework) and a reduction of thermodynamics to statistical mechanics; thus, this section is closely connected to most of the previous sections.

Overviews

(*) O. Maroney, "Information Processing and Thermodynamic Entropy", in E. Zalta (ed.), *Stanford Encyclopedia of Philosophy* (Fall 2009 Edition).

H. Leff and A. Rex*, Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing* (Institute of Physics Publishing, 2003), Introduction. (The volume as a whole is also an invaluable collection of reprinted articles on Maxwell's Demon and related topics.)

Original development of the ideas in the physics literature

L. Brillouin, "Maxwell's Demon cannot operate: Information and Entropy I", *Journal of Applied Physics* 22 (1951) pp. 334-337. Reprinted in Leff and Rex, *ibid.*

L. Szilard, "On the decrease of entropy by the intervention of intelligent beings", *Behavioral Sciences* 9 (1964) pp. 301-310. Reprinted in Leff and Rex, *ibid.*

R. Landauer, "Irreversibility and Heat Generation in the Computing Process", *IBM Journal of Research and Development* 5 (1961) pp. 183-191. Reprinted in Leff and Rex, *ibid.*

(*) J. Earman and J. Norton "EXORCIST XIV: The Wrath of Maxwell's Demon. Part I. From Maxwell to Szilard", *Studies in History and Philosophy of Modern Physics* 29 (1998), pp.435-471.

(*)J. Earman and J. Norton "EXORCIST XIV: The Wrath of Maxwell's Demon. Part II. From Szilard to Landauer and Beyond", *Studies in History and Philosophy of Modern Physics* 30 (1999), pp.1-40.

Modern discussion of Maxwell's Demon

Although the distinction is not sharp, it is possible to consider the demon separately from the literature on Landauer's principle.

W. Myrvold, "Statistical Mechanics and Thermodynamics: a Maxwellian View", *Studies in History and Philosophy of Modern Physics* 42 (2011), pp. 237-243.

(*) D. Albert, *Time and Chance* (Harvard University Press, 2000), chapter 5.

O. Shenker and M. Hemmo, "Maxwell's Demon", *Journal of Philosophy* 107 (1981) pp. 389-411.

W. H. Zurek, "Algorithmic Randomness, Physical Entropy, Measurements, and the Demon of Choice". In *Feynman and Computation: Exploring the Limits of Computers,* ed. J.H. Hey (Perseus, 1999), pp.393-410.

Reprinted in Leff and Rex, *ibid.*

Philosophical criticism of Landauer's Principle

The recent philosophy literature on Landauer's principle starts with Earman and Norton's seminal paper and has seen many back-and-forths over the last 15 years.

J. Earman and J. Norton "EXORCIST XIV: The Wrath of Maxwell's Demon. Part II. From Szilard to Landauer and Beyond", *Studies in History and Philosophy of Modern Physics* 30 (1999), pp.1-40.

(*) C. Bennett, "Notes on Landauer's principle, reversible computation, and Maxwell's Demon", *Studies in History and Philosophy of Modern Physics* 34 (2003) pp. 501-510.

J. Bub, "Maxwell's Demon and the Thermodynamics of Computation", *Studies in History and Philosophy of Modern Physics* 32 (2002) pp. 569-579.

J. Norton, "Eaters of the Lotus: Landauer's principle and the return of Maxwell's demon", *Studies in History and Philosophy of Modern Physics* 36 (2005) pp. 375-411.

J. Norton, "Waiting for Landauer", *Studies in the History and Philosophy of Modern Physics* 42 (2011) pp. 184-198.

J. Ladyman and K. Robertson, "Landauer defended: reply to Norton", *Studies in History and Philosophy of Modern Physics* 44 (2013) pp. 263-271.

D. Wallace, "Thermodynamics as Control Theory", *Entropy* 16 (2014), pp. 699-725.

Thermodynamics of computation

Considerations of Landauer's principle birthed a field of thermodynamics of computation, in which – it is claimed – logical and thermodynamic irreversibility are intimately connected. (Again, the separation between this section and the Landauer's-principle section is not sharp.)

(*) C. Bennett, "The thermodynamics of computation – a review", *International Journal of Theoretical Physics* 21 (1982) pp. 905-940. Reprinted in Leff and Rex, *ibid.*

O. Maroney, "The (absence of a) relationship between thermodynamic and logical reversibility", *Studies in History and Philosophy of Modern Physics* 36 (2005) pp. 355-374.

O. Maroney, "Generalising Landauer's Principle", *Physical Review E* 79 (2009) 031105.

B. Groisman, J. Ladyman, S. Presnell, and T. Short, "The connection between logical and thermodynamic irreversibility", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 58-79.

J. Norton, "The end of the thermodynamics of computation: a no go result." *Philosophy of Science* 80 (2013) pp. 1182-1192.

J. Ladyman and K. Robertson, "Going Round in Circles: Landauer *vs* Norton on the Thermodynamics of Computation", *Entropy* 16 (2014) pp. 2278-2290.

7. Probabilities in statistical mechanics

Statistical mechanics makes extensive use of probabilistic ideas; how these are to be understood (particularly in classical mechanics, which is deterministic) is highly contested.

Overviews

(*) L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge University Press, 1993), chapter 3 (pp. 90-127).

T. Maudlin, "What could be objective about probabilities?", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 275-291.

W. Myrvold, "Probabilities in Statistical Mechanics", in A. Hajek and C. Hitchcock (eds.), *Probabilities in Statistical Mechanics* (Oxford University Press, 2016). http://philsci-archive.pitt.edu/11019/

D. Wallace, "Probabilities in Physics: Statistical, Stochastic, Quantum", in A. Wilson (ed.), *Chance and Temporal Asymmetry* (Oxford University Press, 2014). http://philsci-archive.pitt.edu/9815/

Objective probabilities in classical mechanics

Several authors have defended (and some have criticized) the idea that an objective notion of chance can be understood satisfactorily even in a deterministic theory.

B. Loewer, "Determinism and Chance", *Studies in History and Philosophy of Modern Physics* 32 (2002) pp. 609-620.

J. Schaffer, "Deterministic chance?", *British Journal for the Philosophy of Science* 58 (2007) pp. 113-140.

(*) W. Myrvold, "Deterministic laws and epistemic chances", in Y. Ben-Menahem and M. Hemmo (eds.), *Probability in Physics* (Springer, 2012), pp. 73-85. http://philsci-archive.pitt.edu/8585/

H. Brown, "Once and for all: the curious role of probability in the Past Hypothesis", to appear in D. Bedingham, O. Maroney and C. Timpson (eds.), *Quantum Foundations of Statistical Mechanics* (Oxford University Press, forthcoming). http://philsci-archive.pitt.edu/13008/

Typicality

Typicality can be thought of as a qualitative cousin of probability; it has been argued that all that statistical mechanics needs is this qualitative notion.

S. Volchan, "Probability as Typicality", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 801-814.

R. Frigg, "Typicality and the Approach to Equilibrium in Boltzmannian Statistical Mechanics", *Philosophy of Science* 76 (2009) pp. 997-1008.

(*) S. Goldstein, "Typicality and notions of probability in physics", in Y. Ben-Menahem and M. Hemmo (eds.), *Probability in Physics* (Springer, 2012).

M Hemmo and O. Shenker, "Probability and Typicality in Deterministic Physics", *Erkenntnis* 80 (2015) pp. 575-586.

Quantum-mechanical interpretations of statistical probabilities

Ultimately, the world is quantum; can quantum-mechanical probabilities underpin applications of probability theory even in "classical" statistical mechanics?

(*) D. Wallace, "Probability and Irreversibility in Modern Statistical Mechanics: Classical and Quantum", to appear in D. Bedingham, O. Maroney and C. Timpson (eds.), *Quantum Foundations of Statistical Mechanics* (Oxford University Press, forthcoming).

A. Albrecht and D. Phillips, "Origin of probabilities and their application to the multiverse", *Physical Review D* 90 (2014) 123514.

D. Albert, *Time and Chance* (Harvard University Press, 1999), ch. 7.

M. Hemmo, & O. Shenker, "Can We Explain Thermodynamics By Quantum Decoherence?", *Studies in History and Philosophy of Modern Physics* 32 (202), pp.555--568.

8. Quantum statistical mechanics

The world is quantum; as such, all statistical mechanics is quantum statistical mechanics. But until recently, foundational discussions of statistical mechanics usually proceeded on the fiction of a classical world; this now appears to be changing.

Interconnections

- Most of quantum statistical mechanics assumes a quantum version of the *Gibbsian approach to statistical mechanics,* and the apparent relations between information and entropy realized in quantum mechanics are linked to considerations of Jaynes' approach to Gibbsian statistical mechanics.
- Most of the machinery in modern approaches to *non-equilibrium statistical mechanics* applies to quantum systems with only slight modification.
- Probability is intrinsic in quantum theory (in different ways, depending on how the measurement problem is to be solved), and that potentially transforms considerations of *statistical-mechanical probability.*

Equilibration in quantum systems

How do we understand the approach to equilibrium given quantum microdynamics?

(*) D. Wallace, "Probability and Irreversibility in Modern Statistical Mechanics: Classical and Quantum", to appear in D. Bedingham, O. Maroney and C. Timpson (eds.), *Quantum Foundations of Statistical Mechanics* (Oxford University Press, forthcoming).

M. Hemmo, and O. Shenker, "Quantum Decoherence and the Approach to Equilibrium", *Philosophy of Science* 70 (2003), pp.330-358.

A. Peres, *Quantum Theory: Concepts and Methods* (Kluwer, 1993), chapter 9, sections 1-4.

(*) N. Linden, S. Popescu, A. Short, and A. Winter, "Quantum Mechanical Evolution Towards Thermal Equilibrium", *Physical Review E* 79 (2009), 061103.

S. Goldstein, J. Lebowitz and R. Tumulka, "Long-time behavior of macroscopic quantum systems", *European Physical Journal H* 35 (2010) pp. 173-200.

Equilibrium and entanglement

There seem to be deep connections between quantum-mechanical entanglement and statistical-mechanical entropy despite the apparent conceptual gap between them.

(*) S. Lloyd, "Excuse our ignorance", *Nature Physics* 2 (2006) pp. 727-8.

L. D'Alessio,L. Kafri, A. Polkovnikov, and M. Rigol, "From quantum chaos and eigenstate thermalization to statistical mechanics and thermodynamics", *Advances in Physics* 65 (2016) pp. 239-262.

S. Goldstein, J. Lebowitz, R. Tumulka and N. Zanghi, "Canonical Typicality", *Physical Review Letters* 96 (2006) 050403.

S. Popescu, A. Short, and A. Winter, "Entanglement and the Foundations of Statistical Mechanics", *Nature Physics* 2 (2006) pp. 745-758.

The von Neumann entropy

The quantum version of the Gibbs entropy is the von Neumann entropy, which is also used as a measure of entanglement. Can we really establish that von Neumann entropy is in any way thermodynamic entropy?

O. Shenker, "'Is -tr(ρ ln ρ) the entropy in quantum mechanics?", *British Journal for the Philosophy of Science* 50 (1999) pp. 33-48.

(*) L. Henderson, "The von Neumann Entropy: a reply to Shenker", *British Journal for the Philosophy of Science* 54 (2003) pp. 291-296.

O. Maroney, "The physical basis of the Gibbs-von Neumann entropy", https://arxiv.org/abs/quant-ph/0701127.

9. Other topics in general philosophy of thermal physics

Identical particles and the Gibbs paradox

"Identical" particles play an important – but, in some contexts – paradoxical role in both classical and quantum statistical mechanics.

O. Stern, "On the term N! in the entropy", *Reviews of Modern Physics* 21 (1949) pp. 534-5.

N. van Kampen, "The Gibbs paradox", in W. Parry (ed.), *Essays in Theoretical Physics in honour of Dirk ter Haar* (Pergamon Press, 1984).

S. French and M. Redhead, "Quantum Mechanics and the Identity of Indiscernibles", *British Journal for the Philosophy of Science* 39 (1988) pp. 233-246.

D. Dieks, "Quantum statistics, identical particles and correlations", *Synthese* 82 (1990) pp. 127-155.

N. Huggett, "Atomic metaphysics", *Journal of Philosophy* 96 (1999) pp. 5-24.

S. Saunders, "On the explanation for quantum statistics", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 192-211.

(*) S. Saunders, "Indistinguishability", in R. Batterman (ed.), *Handbook of Philosophy of Physics* (Oxford University Press, 2013). https://arxiv.org/abs/1609.05504

The radiation arrow of time

Electromagnetism is time-reversal invariant, but the emission of radiation by charged accelerating bodies seems to pick out a clear arrow of time. What is the origin of this "arrow of radiation", and how is it related to arrows of time in thermal physics?

(*) J. North, "Understanding the Time-Aymmetry of Radiation", *Philosophy of Science* 70 (2003) pp. 1086-1097.

M. Frisch, "A tale of two arrows", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 542-558.

H.Price, "Recent work on the arrow of radiation", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 498-527.

D. Wallace, "The arrow of time in physics", in H. Dyke and A. Bardon (eds.), *A Companion to the Philosophy of Time* (Wiley, 2013). http://philsci-archive.pitt.edu/9192/

10. Thermodynamics and statistical mechanics of self-gravitating systems

Gravity significantly complicates thermodynamics, both technically and conceptually. These complications are already present in nonrelativistic gravitation but take their strongest form in the study of black holes, where over the last forty years (since Hawking's famous discovery that black holes radiate and cool down) a consensus has built up that black holes can be thought of as thermal systems in the fullest sense.

A warning is in order: black hole thermodynamics and statistical mechanics is one of the central topics of contemporary quantum gravity, and sits at the intersection of general relativity, quantum field theory, and statistical physics. The technical level of the readings in this section – especially those pertaining to black holes – is dramatically higher than in the rest of this reading list. For the most part I've tried to keep the most technical readings off the list; still, unless you are reasonably comfortable with general relativity and quantum field theory, you may find many of these readings unapproachable.

Statistical mechanics of Newtonian gravitation and cosmology

How does the introduction of long-range gravitational forces, and the non-equilibrium background of Big Bang cosmology, affect statistical mechanics?

(*) R. Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics* (Oxford University Press, 1989), chapter 7.

(*) D. Wallace, "Gravity, Entropy, and Cosmology: In Search of Clarity", *British Journal for the Philosophy of Science* 61 (2010), pp. 513-540.

C. Callender, "The Past Hypothesis meets Gravity", in G. Ernst and A. Huttemann (eds.), *Time, Chance and Reduction: Philosophical Aspects of Statistical Physics* (Cambridge University Press, 2010), pp. 34-58.

J. Binney and S. Tremaine, *Galactic Dynamics*, 2nd edition (Princeton University Press, 2008), chapter 7 (pp. 554-638).

Thermodynamic equilibrium for self-gravitating systems

Can we make sense of "equilibrium" at all when systems self-gravitate?

C. Callender, "Hot and Heavy Matters in the Foundations of Statistical Mechanics", *Foundations of Physics* 41 (2011) pp. 960-981.

(*) J. Binney and S. Tremaine, *Galactic Dynamics*, 2nd edition (Princeton University Press, 2008), section 7.3 (pp. 567-573).

R. Sorkin, R. Wald and Z. Jiu, "Entropy of Self-Gravitating Radiation", *General Relativity and Gravitation* 13 (1981) pp. 1127-1146.

Thermodynamics of black holes

Are black holes really thermodynamic systems?

(*) D. Wallace, "The Case for Black Hole Thermodynamics, Part I: Phenomenological Thermodynamics", *Studies in History and Philosophy of Modern Physics*, forthcoming. https://arxiv.org/abs/1710.02724

D. Christodolou and R. Ruffini, “Reversible transformations of a charged black hole”, *Physical Review D* 4 (1971) pp. 195-265.

J. Bardeen, B. Carter, and S. Hawking, “The four laws of black hole mechanics”, *Communications in Mathematical Physics* 31 (1973) pp. 161-170.

K. Thorne, R. Price and D. Macdonald (eds.), *Black Holes: the Membrane Paradigm* (Yale University Press, 1986).

(*) R. Wald, *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics* (University of Chicago Press, 1994), ch. 5.

R. Wald, “Black hole entropy is Noether charge”, *Physical Review D* 48 (1993) pp. 3427-3431.

T. Dougherty and C. Callender, “Black hole thermodynamics: more than an analogy?”, to appear in A. Ijjas and B. Loewer (eds.), *Philosophy of Cosmology* (forthcoming). http://philsci-archive.pitt.edu/13195/

Statistical mechanics of black holes

If black holes really are thermodynamic systems, does their thermodynamic behavior have a statistical-mechanical underpinning – and if so, what is it?

(Note: this section and the next, much more so than most topics in this list, are extremely active areas of current research with huge and growing literatures. The readings here only scratch the surface.)

(*) D. Wallace, “The Case for Black Hole Thermodynamics, Part II: Phenomenological Thermodynamics”, https://arxiv.org/abs/1710.02725

(*) D. Harlow, “Jerusalem lectures on black holes and quantum information”, *Reviews of Modern Physics* 88 (2016) 124008.

J. Bekenstein, “Black holes and entropy”, *Physical Review D* 7 (1973) pp. 2333-2346.

C. Wuthrich, “Are black holes about information”, to appear in R. Dawid, R. Dardashti, and K. Thebault (eds.), *Epistemology of Fundamental Physics: Why Trust a Theory* (Cambridge University Press, forthcoming). https://arxiv.org/abs/1708.05631

J-G. Demers, R. Lafrance, and R. Myers, “Black hole entropy without brick walls”, *Physical Review D* 52 (1995) pp. 2245-2253.

L. Susskind and J. Lindesay, “An Introduction to Black Holes, Information and the String Theory Revolution: the Holographic Universe” (World Scientific, 2005).

R. Wald, *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics* (University of Chicago Press, 1994), chs. 6-7.

A. Sen, “Logarithmic corrections to rotating extremal black hole entropy in four and five dimensions”. http://arxiv.org/abs/1109.3706

A. Perez, “Black Holes in Loop Quantum Gravity”, *Reports in Progress of Physics* 80 (2017) 126901.

The black hole information-loss paradox

Does the evaporation of a black hole, treated quantum-mechanically, imply that quantum gravity violates unitarity? And why does it matter?

S. Hawking, "Breakdown of predictability in gravitational collapse", *Physical Review D* 14 (1976) pp. 2460-2473.

D. Page, "Information in black hole radiation", *Physical Review Letters* 71 (1993) pp. 3743-3746.

G. Belot, J. Earman and L. Ruetsche, "The Hawking information loss paradox: the anatomy of a controversy". *British Journal for the Philosophy of Science* 50 (1999) pp. 189-229.

(*) D. Wallace, "Why black hole information loss is paradoxical", manuscript (2017) https://arxiv.org/abs/1710.03783

(*) S. Mathur, "The information paradox: a pedagogical introduction", *Classical and Quantum Gravity* 26 (2009) 224001.

W. Unruh and R. Wald, "Information loss", manuscript (2017), https://arxiv.org/abs/1703.02140

A. Almheiri, D. Marolf, J. Polchinski, and J. Sully, "Black holes: complementarity or firewalls?", *Journal of High-Energy Physics* 1302 (2013) 062.