Reading list in Philosophy of Thermal Physics

David Wallace, June 2018

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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:


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


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:


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:


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


*One of the first really systematic textbooks.*


*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 uncontroversial 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


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.


http://philsci-archive.pitt.edu/2691/


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.


http://philsci-archive.pitt.edu/2691/
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.


http://philsci-archive.pitt.edu/8894/


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.


http://philsci-archive.pitt.edu/2691/


Much of this is probably calculational material of limited foundational significance, but it is not a simple or uncontroversial 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.


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


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.


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.


**Interventionist accounts of equilibration**

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


**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.


**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.


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


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?


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?


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?


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


Thermodynamics as an autonomous discipline

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


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.*


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.


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 Gibsian framework) and a reduction of thermodynamics to statistical mechanics; thus, this section is closely connected to most of the previous sections.

Overviews


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


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.


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.


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.)


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


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.


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.


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

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?


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


Equilibrium and entanglement

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


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?


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.


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?


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?*


Thermodynamic equilibrium for self-gravitating systems

*Can we make sense of “equilibrium” at all when systems self-gravitate?*


Thermodynamics of black holes

*Are black holes really thermodynamic systems?*


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


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.)


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

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?*


