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Introduction

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1.1 Statistical mechanics and philosophy

Statistical mechanics attempts to explain the behaviour of macroscopic physical systems (in particular their thermal behaviour) in terms of the mechanical properties of their constituents. In order to achieve this aim it relies essentially on probabilistic assumptions. Even though in general we do not know much about the detailed behaviour of each degree of freedom (each particle), statistical physics allows us to make very precise predictions about the behaviour of systems such as gases, crystals, metals, plasmas, magnets as wholes.

The introduction of probabilistic concepts into physics by Maxwell, Boltzmann and others was a significant step in various respects. First, it led to a completely new branch of theoretical physics. Second, as Jan von Plato pointed out, the very meaning of probabilistic concepts changed under the new applications. To give an example: whereas before the development of statistical physics variation could be conceived as the deviation from an ideal value this was no longer a tenable interpretation in the context of statistical physics. Genuine variation had to be accepted (von Plato, 2003: 621).

Furthermore, the introduction of probabilistic concepts triggered philosophical speculations, in particular with respect to the question whether the atomic world does indeed follow strict deterministic laws (cf. von Plato, 1994; Stöltzner, 1999). For instance, in 1873 Maxwell gave a lecture entitled ‘Does the Progress of Physical Science tend to give any advantage to the opinion of Necessity (or Determinism) over that of the Contingency of Events and the Freedom of the Will?’ He wondered whether ‘the promotion of natural knowledge may tend to remove the prejudice in favour of determinism which seems to arise from assuming that the physical science of the future is a mere magnified image of that of the past’ (quoted in von Plato, 1994: 87). Other physicists in the field voiced similar views. Franz Exner, an Austrian physicist, argued in his lectures on the physical foundations of natural science that the concepts of causation and laws of nature have to be revised in the light of the need to introduce probabilistic concepts into physics. With respect to determinism he claims that deterministic laws obtain only in the macro-world and that there is no reason to assume that determinism is true at the level of atoms. It may very well be the case, he argues, that the most fundamental laws of physics are probabilistic. (The lectures were written in and before the first world war; Exner, 1922: lectures 86–95.) These views which arose in the context of philosophical reflections on the nature of the new statistical mechanics may well have contributed to the willingness with which some proponents of the newly emerging quantum mechanics gave up determinism.

Be that as it may, philosophical reflection on statistical mechanics came almost to an end with the advent of other new fundamental physical theories, such as quantum mechanics and the theory of general relativity. For sixty years philosophers of physics focused almost exclusively on the interpretation of quantum mechanics and the philosophical implications of the theory of general relativity. It was only with the publication of Lawrence Sklar's *Physics and Chance* (1993) that the discussion of philosophical and foundational problems of statistical mechanics became more popular again among philosophers of physics. Sklar (1993: 6) surmised that the neglect of statistical mechanics was partly due to the fact that the field itself is in a certain disarray. Compared to the situation in quantum mechanics and the theories of relativity there are not only different philosophical interpretations of physical theories but also widely diverging approaches and schools within statistical mechanics itself. It was Sklar's aim to provide a survey and make some of these approaches accessible and thus to stimulate further philosophical investigations. It seems that by and large he succeeded. The last decade has seen the field flourishing. There have been major philosophical monographs like David Albert's *Time and Chance* (2000) as well as a lot of other work – to a significant extent by the contributors of this volume.[1] There is even a recent volume entitled *Contemporary Debates in Philosophy of Science* (by Christopher Hitchcock, 2004), in which philosophical issues pertaining to statistical mechanics figure more prominently than those of quantum mechanics or the theories of relativity.

The main philosophical and foundational questions that are currently discussed concern the relation of statistical mechanics and thermodynamics. Thermodynamics started as a theory of heat engines. It gradually developed into a rather general theory that describes matter in all its phases and their thermal and magnetic behaviour in particular. Thermodynamics makes virtually no assumptions about the micro-structure of the systems it describes. But of course the systems described by thermodynamics do have a micro-structure. Statistical mechanics was developed in

[1] For a very helpful state of the art article see Uffink (2007).

the hope to explain the thermodynamic macro-laws in terms of the behaviour of the systems' constituents. Surprisingly, this reductive enterprise turned out to be rather difficult. Most foundational/philosophical issues are related in one way or another to the question of the reduction of thermodynamics to statistical mechanics. In particular, there are three focal issues:

(1) One law in thermodynamics exhibits a pertinent time-asymmetry (according to the second law of thermodynamics, the entropy in a closed system never decreases in time), whereas the fundamental laws of statistical mechanics fail to exhibit such an asymmetry. So, where does the time-asymmetry come in? And how is the thermodynamic time-asymmetry related to other 'arrows of time' in physics?
(2) Statistical mechanics is a probabilistic theory, while thermodynamics is not. So, how is the concept of probability to be interpreted in order to be coherent and to make thermodynamic behaviour intelligible?
(3) Thermodynamics allegedly is reducible to statistical mechanics. But how exactly, if at all, does the reduction work? And what concept of reduction is here employed anyway?

Part one of this collection of essays is concerned mainly with the first topic (see Section 1.2), part two with the second (see Section 1.3), and part three with the third (see Section 1.4).

1.2 The arrows of time

Time seems to have a direction. However, it is not so clear what this claim exactly amounts to and whether a direction *of* time could be distinguished from processes *in* time having a direction. Even though the fundamental dynamical laws in physics do not have a temporal direction both in physics as well as in ordinary life we come across various temporally directed phenomena ('arrows of time'). There are several such arrows in physics (see the chapter by Kiefer): We only observe certain sorts of radiation, entropy never decreases and our universe expands. Similarly, causation seems to have a temporal direction. Furthermore, we seem to know more about the past than about the future. And counterfactual dependence seems to be temporally directed as well: 'If A had not occurred then C would not have occurred either' seems to be – in general – a good candidate for a true proposition only if what is described by A precedes what is described by C (see Horwich, 1987). The chapters by Mathias Frisch, Craig Callender and Claus Kiefer are all concerned with the arrows of time.

The contribution by Mathias Frisch deals with the question of how various of the temporal asymmetries are related to one another. There is a long tradition according to which the causal asymmetry is closely related to the temporal asymmetry embodied in the second law of thermodynamics. This view has recently been defended by David Albert and by Barry Loewer, who argue that the causal asymmetry can be grounded in those facts that explain the second law of thermodynamics.

Both accounts centrally involve the claim that it follows from Boltzmann's account of the thermodynamic asymmetry (the so-called past hypothesis, which postulates a low-entropy constraint on the early universe) that possible macro-evolutions are much more restricted toward the past than toward the future. The statistical mechanical account, as Loewer puts it, results in a time-asymmetric 'tree-structure' for possible macro-evolutions. Frisch argues that statistical mechanics allows not only for branchings but also for the reconvergence and merging of possible macro-histories. As a consequence he maintains that Albert's and Loewer's accounts do not work in their present form because they fail to explain how our *strict* concepts of causal influence and causal control emerge.

Craig Callender's chapter argues that it is essential for answering the problem of the direction of time to take gravity into account. More particularly, he deals with the question whether the low-entropy constraint is plausible given what we know about gravity. The past hypothesis, which is invoked to explain why entropy increases (or rather: never decreases) seems to be *prima facie* patently false. According to current cosmological theories the early universe is an almost homogeneous isotropic state of approximately uniform temperature, i.e. a very high entropy state, not a low-entropy state as postulated by the past hypothesis. The standard response to this objection is that we forgot to include gravity. Gravity, it is said, saves the past hypothesis. So now the essential question is whether the gravitational behaviour of the stars etc. can plausibly be interpreted as the movement to an equilibrium state. Callender argues that the inclusion of gravity into the Boltzmannian account of the direction of time is highly non-trivial. After sketching some serious problems with gravity, he develops a sketch of how one can obtain a never decreasing Boltzmann entropy in self-gravitating systems described by certain types of gravitational kinetic equations.

Claus Kiefer approaches the different arrows of time from the perspective of a physicist. His aim is to explain how the various physical arrows can in principle be understood on the basis of a fundamental theory of quantum gravity. After a brief discussion of the time-directed processes in question, the physical framework of a particular approach to quantum gravity, the canonical approach, is outlined. The fundamental equation (the Wheeler–DeWitt equation) is devoid of any classical time parameter, but involves a new type of dynamics with respect to an intrinsic time. In simple models this intrinsic time is given by the 'radius' of the universe. Standard time can be recovered in certain situations as an approximation. Kiefer claims that given a natural boundary condition on the Wheeler–DeWitt equation, an arrow of time follows automatically.

1.3 Probability and chance

Probabilistic reasoning is essential for statistical mechanics and discussions of the foundations of statistical mechanics often focus on how to justify particular probabilistic assumptions. There is, however, a problem that is systematically prior: What are these probabilities? Subjectivists argue that probabilities reflect our ignorance of the true state of the system. Objectivists deny this and submit that probabilities have to be objective, i.e. that they have to be chances.

It is now often assumed that the probabilities introduced into statistical mechanics should not be given an epistemic or subjectivist reading. David Albert, for instance, comments on the subjectivist approach: 'Can anybody seriously think that [our epistemic situation, A. H.] would somehow *explain* the fact that the *actual microscopic conditions of actual thermodynamic systems are statistically distributed in the way that they are*? Can anybody seriously think that it is somehow *necessary*, that it is somehow *a priori*, that the particles that make up the material world must arrange themselves in accord with *what we know*, with what *we happen to have looked into*? Can anybody seriously think that our merely being *ignorant* of the exact microconditions of thermodynamic systems plays some part in *bringing it about*, in *making it the case, that (say) milk dissolves in coffee*? How could that be?' (Albert, 2000: 64). The chapters in the second part of this volume focus on the interpretation of probabilities and related metaphysical issues.

Jacob Rosenthal and Roman Frigg discuss objectivist approaches to probability. Usually two versions of this approach are considered, the frequency interpretation of probability and the propensity interpretation. Both of these face serious challenges – as interpretations of probabilities in general (see Rosenthal's chapter for a brief review) as well as for physical reasons when applied to probabilistic reasoning in statistical mechanics (see Section 6.2 of Frigg's chapter). Jacob Rosenthal defends a third objectivist interpretation of probability, the natural-range conception of probability. It considers probabilities as deriving from ranges in suitably structured initial state spaces. Roughly, the probability of an event is the proportion of initial states that lead to this event in the space of all possible initial states, provided that this proportion is approximately the same in any not too small interval of the initial-state space. The range approach to probabilities is usually treated as an *explanation* for the occurrence of probabilistic patterns, whereas Rosenthal examines its prospects for an objective *interpretation* of probability, in the sense of providing truth conditions for probability statements that do not depend on our state of mind or information. The main objection to such a proposal is that it is circular, i.e. presupposes the concept of probability, because a measure on the initial state has to be introduced. Rosenthal argues that this objection can be successfully met and that the range approach has better prospects to provide a satisfactory objective interpretation of probability statements than frequency or propensity accounts.

Roman Frigg focuses on the question of how different approaches to statistical mechanics introduce probabilities and what kind of interpretation of probabilities has to be assumed. He confines himself to approaches that follow Boltzmann in defining an entropy function $S_{B(t)}$ in terms of the micro-state of the system. Different approaches in this tradition diverge in how they introduce probabilities into the theory and in how they explain the tendency of $S_{B(t)}$ to increase. The most fundamental distinction is between approaches that assign probabilities directly to the system's macro-states ('macro-probabilities'), and approaches that assign probabilities to the system's micro-state being in particular subsets of the macro-region corresponding to the system's current macro-state ('micro-probabilities'). More particularly, Frigg discusses Boltzmann's own proposal to assign probabilities to the system's macro-states and the view by Paul and Tatiana Ehrenfest that these should be interpreted as time averages, presupposing the ergodicity of the system. It is now well known that this approach faces serious difficulties. Frigg's point is that even if these were surmounted there would be a grave problem not so much with the probabilistic assumptions as such but rather with the dynamical laws that are supposed to bring about the increase in entropy. The micro-probabilistic alternative discussed, has been proposed by David Albert (2000). Frigg discusses this approach and Barry Loewer's suggestion for understanding these probabilities as Humean chances in David Lewis's sense. Frigg reaches the same conclusion as in the discussion of macro-probabilities. All that is needed to *explain* why things happen is the initial condition and the dynamics. Frigg opts for an epistemic interpretation of probabilities in statistical mechanics. Probabilities have no role to play in *explaining* why a system behaves as it does. They are introduced for reasons of epistemic limitations.

The chapter by Michael Esfeld deals with metaphysical issues. In particular, he is concerned with the opposition between Humean metaphysics and the metaphysics of powers. Esfeld argues that within the bounds of Humean metaphysics everything is a matter of contingency. Consequently, there is no deep metaphysical difference between a deterministic world and a world in which only probabilistic laws hold. This position is contrasted with the foundations of probabilities according to the metaphysics of powers, in particular with the view that traces probabilities back to propensities. Esfeld discusses arguments for and against both positions. In the end he opts for the metaphysics of powers, mainly for two reasons: (1) the metaphysics of powers avoids certain troublesome commitments; (2) contrary to a widespread belief, the metaphysics of powers is compatible with physics, and it is able to provide a complete and coherent ontology that does justice to both physics and the special sciences.

1.4 Reduction

There are many meanings of the term ‘reduction’. The shared background for most discussions in philosophy of science is Nagel’s account of the formal criteria of reduction (Nagel, 1961: ch. 11). Nagel’s primary concern was whether an older theory (the reduced theory) is reducible to its successor (the reducing theory). Reduction was conceived of as a special case of deductive-nomological explanation. Successful ‘Nagel reduction’ integrates the old theory into the successor theory and provides a clear sense in which the successor theory is better than its predecessor. Ironically, Nagel presented the relation of thermodynamics to statistical mechanics as a paradigm case for a successful reduction in the sense he developed. In fact, this reduction is a highly non-trivial affair (cf. Ernst, 2003).

It is helpful to distinguish various senses of reduction. First, there is *diachronic* reduction. Diachronic reduction concerns the evolution of disciplines and their theories. This is the aspect Nagel had in mind when he introduced his account. This perspective can be contrasted with *synchronic* reduction. Synchronic reduction concerns the relation of two theories that pertain to the same realm. At least two cases of synchronic reduction in this sense can be distinguished. First, the two theories in question may be related as limiting cases. Robert Batterman has developed this view in his *The Devil in the Details* (2002) and works with it in his contribution (see below). Second, it may be the case that one theory describes the behaviour of compound systems (in a certain terminology) and the other theory describes the behaviour of the constituents of the systems (in a different terminology). In these cases we want to know how the different theoretical accounts fit together. It seems plausible that in this case reduction is required for reasons of coherence. Interestingly, if it turns out to be difficult to bring about coherence it is not necessarily the higher-level assumptions that are put into question. In the case of thermodynamics and statistical mechanics it is assumptions about micro-states that turned out to be most controversial.

The contribution by Ulises Moulines concerns diachronic reduction. Moulines distinguishes four different types of diachronic structures in the evolution of scientific disciplines: (a) the *evolution* of a theory; (b) the *replacement* of one theory by another; (c) the *embedding* of one theory into another; (d) the (slow) *crystallization* of a theory out of different previous elements. He argues that a typical example of crystallization is provided by the gradual emergence of phenomenological thermodynamics in the middle of the nineteenth century. A major role in this process was played by several writings of Rudolf Clausius. Two of them are analysed in the present chapter: *Über die bewegende Kraft der Wärme* (1850) and *Über eine veränderte Form des zweiten Hauptsatzes der mechanischen Wärmetheorie* (1854). By employing some formal tools of the structuralist reconstruction methodology (in particular, the notions of *model* and *theory-net*), three different theories are identified in Clausius' papers, thereby showing how much they still owe to the caloric theory, how much they contain germs of future developments of thermodynamics (such as the notion of *internal energy* or the difference between *reversible* and *irreversible cycles*), and finally how there are conceptual tensions in the interrelationships between Clausius' own theories.

Robert Batterman considers the so-called reduction of thermodynamics to statistical mechanics from both historical and relatively contemporary points of view. Today, most philosophers of physics doubt that the relation of the two theories can be described as a reduction in the sense of Nagel. Batterman turns to J. Willard Gibbs who can be seen as sharing the scepticism about the possibility of such a philosophical reduction of thermodynamics to statistical mechanics. Gibbs' account is not only discussed for his caution in connecting thermodynamical concepts with those from statistical mechanics. Batterman takes him to suggest that one should look for how thermodynamic quantities emerge from statistical quantities when certain limiting conditions are satisfied. The paper then develops the idea that the limit of statistical mechanics, as the number of degrees of freedom goes to infinity, should yield the continuum thermodynamic theory. Batterman sketches a program for reductive relations that involves deep connections between results in probability theory on limit theorems and the so-called real space renormalization techniques that play such an essential role in understanding the universality of critical phenomena. It turns out that this kind of (feasible) reduction yields only an association of thermodynamic properties, such as temperature and entropy, and a so-called universality class of statistical mechanical structures. This contrasts with Nagel-reduction, which requires (according to the standard reading) a one-to-one association of thermodynamic and statistical mechanical quantities.

Jos Uffink discusses the problem of explaining the emergence of irreversible processes in classical statistical mechanics from the point of view of stochastic dynamics – and thus the question of synchronic reduction in the second sense, i.e. concerning the relation of the behaviour of compound systems to that of their constituents. An influential approach to the foundations of classical non-equilibrium statistical mechanics claims to obtain a satisfactory explanation of irreversible behaviour by characterizing the evolution of macroscopic physical systems as a Markov process, or more abstractly, in terms of a semigroup of non-invertible evolution operators. The general formalism developed in this approach, sometimes called 'stochastic dynamics', can in fact be obtained from a variety of physical motivations, e.g. by assuming that the physical system interacts with an environment (the 'open systems' or 'interventionist' approach) or that only a few macroscopic variables from the detailed microscopic state of the state are relevant for its physical description ('coarse graining'). Uffink argues that, despite appearances, the usual assumptions of this approach remain fully time-reversal invariant, and hence do not embody irreversible behaviour. It is argued that a proper account of irreversibility should not focus on the Markov property but on a different definition of reversibility for stochastic processes.

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More Information

Part I

The arrows of time