



Introduction

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In recent years a growing number of philosophers of science have come to realise that the philosophical foundations of statistical mechanics are not as secure as was once thought.¹ Conceptual problems that had been swept under a carpet of technicalities, or simply ignored, have surfaced, solutions that were accepted are being questioned, and new routes are being explored. Thus, central issues such as the origins of time asymmetry, Maxwell's demon, and the compatibility of statistical and classical mechanics, are as urgent and intriguing today as they were when statistical mechanics took shape at the end of the nineteenth century. Research in the foundations of the theory of relativity and quantum mechanics has deepened our understanding of these fields. This special issue is motivated by recognition of the need for similar research in the foundations of thermodynamics and statistical mechanics.

The analogy between thermodynamics and other fundamental physical theories is itself a matter of controversy. On the one hand, thermodynamics has been recognised as a particularly profound theory, indispensable for our understanding of the physical world. Those who see it in this light are fond of quoting Einstein's celebrated remark regarding the impression made on him by classical thermodynamics. It was the only physical theory, he said, that he was convinced would never (within the limits of the applicability of its concepts) be overthrown. On the other hand, we frequently hear it said that with the emergence of statistical mechanics, the laws of thermodynamics, and the second law in particular, having been reduced to the law of large numbers, have been explained away. This latter view is often taken to indicate, further, that statistical mechanics is merely a second-order theory, a probabilistic

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¹In the area of the philosophy of science see, for example, Sklar (1993), von Plato (1994), Guttman (1999) and Albert (2001).

representation, from an anthropocentric point of view, of a world-order that is 'really' explained by more fundamental theories.

We are already in trouble. A number of problems have been glossed over in the preceding paragraph: 1. Does statistical mechanics really constitute the theoretical basis of thermodynamics? 2. Has thermodynamics in fact been reduced to either statistical or classical mechanics, or is such a reduction at least under way? 3. Does the probabilistic character of statistical mechanics really render it anthropocentric in the sense of representing human knowledge rather than physical reality? Let us look at these problems somewhat more closely.

The nature of thermodynamics: The prevailing view is that statistical mechanics provides the explanatory basis for thermodynamics in the same way that, say, physical optics explains geometrical optics. But this view has not gone unchallenged. In this issue, Jacob Bekenstein raises the question in the specific context of the thermodynamics of black holes, a context in which, to date, entropy has no acceptable statistical interpretation. This suggests the possibility that the thermodynamic concept of entropy does not originate in the statistical concept after all, though evidently it is empirically related to it in many areas of physics. More generally, Lieb and Yngvason have recently proposed a new axiomatisation of thermodynamics that is independent of the multi-particle constitution of matter, and does not seek a probabilistic treatment of the behaviour of these particles. The second law, they urge, 'must have a logical foundation that is independent of the fact that matter is composed of interacting particles'.²

While most of the papers included here presuppose the statistical construal of the second law, Harvey Brown and Jos Uffink address the possibility of an independent grounding more directly, ultimately rejecting it. Inspired by Einstein and Carathéodory, they draw an analogy between thermodynamics and special relativity, both of which lay down phenomenological principles as constraints on certain kinds of transformations. According to Brown and Uffink, the reformulation of both these theories in terms of more abstract mathematical structures (Minkowski spacetime in the case of special relativity, Carathéodory's or Lieb and Yngvason's topological structure in the case of thermodynamics) does not change their phenomenological nature. Hence, they must eventually be explained by, or reduced to, more fundamental theories. Despite the elegance of the new axiomatic approach, Brown and Uffink maintain that statistical mechanics is still called upon to anchor the phenomenological principles of thermodynamics in the underlying basic physical laws.

Reduction and time asymmetry: Assuming the relationship between thermodynamics and statistical mechanics is conceived as that between a phenom-

²Lieb and Yngvason (2000, p. 32). See also Lieb and Yngvason (1999). Lieb and Yngvason develop a line of reasoning that originated with Carathéodory's pioneering work, and was taken up by a number of physicists in the 1950s.

enological representation and its theoretical underpinning, questions arise as to the precise nature of this relationship. On the conventional understanding, thermodynamics has been reduced to statistical mechanics, or at least will be so reduced when residual technical obstacles are cleared. The papers in this issue see the conventional view as a gross over-simplification. Ideally, reduction of one theory to another requires the (theoretical) concepts of the reduced theory to be defined in terms of the concepts of the reducing theory, and a derivation of the laws of the reduced theory using these newly-defined concepts. But in actual cases from the history of science, the reducing theory tends to conflict with the reduced theory. From the perspective of Newtonian mechanics, both Galileo's law of free fall, and Kepler's laws, supposedly derivable from Newton's laws, are in fact false. If such typical cases are to exemplify reduction, the deductive account must be modified to the effect that the reduced laws are construed as (reasonably good) approximations of the laws actually derived from the reducing theory. This modification does not settle the case of thermodynamics, however, for here, the reduced laws and the reducing parallels are fundamentally different.

Furthermore, the real difficulty is not confined to the relation between thermodynamics and statistical mechanics, but extends to the relation between both these theories and the underlying (classical or quantum) mechanics. Once again, the threat of incompatibility arises, but it is not an innocuous threat that can be easily taken care of, as above, by noting that a theory need only approximate another with which it is incompatible. Here the threat is downright contradiction—the notorious problem of time asymmetry. The century old reversibility arguments of Loschmidt and Zermello still stand in the way of reconciling directionality with time-symmetrical mechanics. The problem of reduction sometimes masks the much more disturbing problem of consistency.

A response going back to Boltzmann is to put much of the explanatory burden on the initial conditions. On this account, time asymmetry would not be explained by the laws of statistical mechanics alone, but by the laws together with very specific—and highly improbable—initial conditions. The ensuing regress leads to the conclusion that the initial conditions in question must be those of the universe as a whole. Not surprisingly, the relevance of these remote conditions to the mixing of milk and coffee in our cups every morning has been the subject of considerable scepticism. Other approaches are therefore being pursued. What is common to them all is that they seek to counter the reversibility arguments by employing some sort of interference that would destroy reversibility. In one way or another, many of the papers in this volume touch on this problem.

Addressing the problem of reduction, Craig Callender exposes some common mistakes regarding the relation between thermodynamics and statistical mechanics. Some of these mistakes derive from failure to fully appreciate either the probabilistic character of the second law in statistical mechanics, or the limits of the idealisations and approximations used in the

two theories. Others are even subtler. For example, Callender exposes the following blunder: one (mistakenly) construes the thermodynamic second law as requiring monotonous increase of entropy. Then, to comply with this alleged requirement, one seeks a statistical mechanical function that has this property, ignoring the fact that this function (if constructed) neither could nor need explain the thermal behaviour of the individual system.

Another question addressed in several papers is that of the relationship between indeterminism and time asymmetry. It has been argued that the injection of even minute random interference into an otherwise deterministic system can sometimes disrupt reversibility enormously.³ It should be noted, however, that the mere presence of indeterminism does not, in itself, do the job. To see why, consider a theory that is like classical mechanics, except that isotropic and stationary white noise have been added. In such a theory, the (probabilistic) equations of motion will be time symmetrical. In a similar vein, the measurement process in quantum mechanics cannot, on its own, be taken as the origin of time asymmetry.

Recently, David Albert (2001) has suggested that the special kind of indeterminism found in the spontaneous collapse theory of Ghirardi, Rimini and Weber (GRW) can explain the origin of time asymmetry. Here spontaneous collapse (i.e. objective and irreducible chance) is taken to guarantee that systems composed of a sufficiently large number of particles will not persist in entropy-decreasing trajectories. In their paper, Meir Hemmo and Orly Shenker compare Albert's approach with interventionist explanations based on decoherence. The interventionist approach, in general, conjectures that it is the inevitable impact of the environment on the thermodynamic system that interferes with the underlying time symmetry. Although in the GRW version of quantum mechanics the collapse process is internal to the closed system, the process has some similarity to that of decoherence resulting from the influence of the environment on an open system.

Brown and Uffink take a fresh look at the origins of time asymmetry in thermodynamics and statistical mechanics. Surprisingly, they identify the approach to equilibrium as the primary location of such asymmetry. That a system will in fact approach equilibrium, they argue, does not follow from the second law in either its thermodynamic or its statistical formulation. Rather, it is an independent law—the minus first law. It is interesting to review the previous solutions in light of this idea, for some of the worries over the relation between directionality and the second law may now seem misplaced, and others should, perhaps, be redirected to the minus first law.

The information-theoretic approach to statistical mechanics has received much attention of late. Proponents of this view identify (minus) entropy with information, and associate time asymmetry with decrease or loss of information. One important application of this approach has been Bennett and Landauer's attempt to exorcise Maxwell's demon. Recall that they

³See Elitzur (1999).

postulate that information erasure increases entropy, compensating for any decrease achieved by the demon's action. This solution has been strongly criticised in the philosophical literature⁴ on the grounds that Bennett (Bennett, 1982) and Landauer's argument against the demon is circular, and that, in addition, information erasure does not necessarily involve entropy increase. Jeffrey Bub presents a detailed argument for the thesis that overall entropy increase is demanded by the second law for the erasure of information, but not for its measurement, recording or memorisation. There is also a more general challenge here to the Earman–Norton charge of circularity: we are correct in presupposing the second law if what this presupposition means is that we use it to derive specific implications for the case at hand—erasure—and put these implications to the test. In fact, this is what sensible methodology recommends.

Probability: It is fair to say that what has been achieved so far is an explanation of thermodynamic phenomena in terms of (classical or quantum) mechanics + probability. Time asymmetry is, of course, just one facet of the nature of probability in statistical mechanics. A few papers in this issue directly address the origin and character of the probability distributions in statistical mechanics. Boltzmann suggested defining probability as limiting relative frequency, and tried to prove, on the basis of the underlying theory, viz., classical mechanics, that such frequencies are identical to the phase space averages. This is the source of the ergodic hypothesis that has since been adopted by other approaches to probability. So hopeful were the founders of this programme that in 1922 Hilbert remarked:

Nothing prevents us from taking as axioms propositions which are provable, or which we believe are provable. Indeed as history shows, this procedure is perfectly in order: examples are Legendre's prime-number postulate [...], Riemann's conjecture [...] and finally the so-called ergodic hypothesis, a mathematical proposition from whose proof we are today far removed, but which nevertheless has become the foundation of statistical mechanics (Hilbert, 1922; translated in Ewald, 1996, p. 1120).

Over the years enormous effort was invested in proving ergodicity, but for a number of reasons, confidence in the fruitfulness of this approach has waned. Not only has the ergodic hypothesis stubbornly resisted proof (for the typical system), but it also turns out that ergodicity is neither sufficient nor necessary for compliance with the second law. Evaluation of the success of this programme in solving conceptual problems occupies much of the philosophical literature.⁵ In her paper, Janneke van Lith provides a review of 'the plurality of ergodic approaches' and, in particular, an assessment of the argument by Malament and Zabell, and the generalisations it suggested. She adds a proposal to relax the restriction of stationarity somewhat, and indicates,

⁴ Earman and Norton (1998, 1999), Shenker (2000).

⁵ In the books cited in footnote 1. See also Malament and Zabell (1980), Earman and Redei (1996).

following Guttman, the role of the ergodic hypothesis in the subjective approach to probability.

In their influential (1980), Malament and Zabell suggested an explanation of why microcanonical averages successfully predict the values of thermodynamic functions. Their argument uses a combination of the law of large numbers (the Khinchin version) and the ergodic hypothesis. In his paper, Itamar Pitowsky utilises a similar combination of arguments. Following Khinchin, he notes that the requirement that we recover the averages of all functions defined on phase space from their relative frequencies is too strong. Only special functions are important in statistical mechanics and, in particular, the probability distribution itself. Pitowsky notes that apart from a factorisable multiplier (which represents an ideal gas), the distribution is completely determined by the correlations among local momenta fluctuations. Using this fact, we can define the conditions under which local observers, who are immersed in the gas and form part of it, can determine the entire distribution function from time averages. This gives rise to a new definition of 'equilibrium state' that is weaker than strict ergodicity.

Statistical mechanics has been construed epistemically (that is, as assuming the perspective of the more or less ignorant human observer), in a number of different ways. First, on some accounts, the notion of probability is itself a subjective notion, a measure of degrees of knowledge or belief. Second, in response to the problem of Maxwell's demon, entropy has been more directly associated with information (or lack thereof). The structural analogy between the mathematical expressions of entropy and information further encouraged this epistemic portrayal of entropy. Finally, statistical mechanics refers to macro-states comprising a vast number of microstates that are, from the perspective of the human observer, mostly indistinguishable. To the extent that such indistinguishability is essential to the theory, a human vantage point is indicated. The boldest conclusions have been drawn by Jaynes: entropy, on his view, is an anthropocentric concept. But how can an anthropocentric concept figure in the explanation of objective features of the world? How can our knowledge or ignorance explain cooling, mixing and aging?

It is commonly assumed that in the deterministic world governed by the laws of classical mechanics, there is no place for objective probabilities. The only way probabilities could enter our theory of such a deterministic world is, therefore, subjectively, as representing our ignorance and uncertainty. Barry Loewer contests the common assumption that determinism is incompatible with objective chance. Following David Lewis, he takes laws to be the (contingent) generalisations entailed by our best theory of the world—the theory that strikes the best balance between content and simplicity. Competing theories (deterministic ones included) are further allowed to specify probabilities, i.e. measures of fit between a particular world history and the theory in question. Loewer proceeds to argue that the probabilities thus specified by the best theory of the world are objective, and meet the desiderata of being explanatory and a guide to rational belief. Ironically, Lewis seems unaware of

the possibility explored by Loewer, and upholds the traditional view Loewer targets.

Yemima Ben-Menahem's paper focuses on the description-sensitivity of the notions of stability and probability, in general, and in the context of statistical mechanics in particular. Dependence on description, she argues, does not amount to subjectivity. The difficulty noted with regard to knowledge and ignorance—how they could possibly explain physical processes—does not arise here: as Davidson and Morgenbesser have argued, explanation is essentially description-relative without being subjective. Her analysis also has bearing on the question of whether the above solutions to the reversibility problem constitute a reduction of the second law to a more basic (causal or a-causal) level.

Unfortunately, we cannot announce that the foundations of statistical mechanics have been secured once and for all on the basis of the articles in this issue, but we hope that some progress has been made in our understanding of the difficulties still to be resolved. The papers were presented at a conference held in Jerusalem in May 2000. Due to earlier publication or commitments, not all the conference papers are reproduced here. We would like to thank all the participants for their formal and informal contributions.

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