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INTRODUCTION

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Probabilities are ubiquitous in physics. Quantum probabilities, presumably, are most famous. As is well known, quantum mechanics does, in most cases, not predict with certainty what the outcome of a measurement will be. Instead, it only specifies probabilities for the possible outcomes. Probabilities also take a prominent role in statistical mechanics. Here, probabilities are ascribed to a system's microstates to explain its thermal behavior. Finally, physicists often construct probabilistic models, such as random-walk models, to account for certain phenomena. No doubt, then, that probabilities abound in physics: much contemporary physics is probabilistic.

The abundance of probabilities in physics raises a number of questions. For a start, what are probabilities and how can we explain the meaning of probabilistic statements? How can one justify physical claims that involve probabilities? Finally, can we draw metaphysical conclusions from the abundance of probabilities in physics? For example, can we infer that we live in an inherently chancy or indeterministic world?

Although these are distinct questions, they are connected and cannot be addressed in isolation. For instance, an account of the meaning of probabilistic statements would clearly be objectionable if it did not yield a plausible epistemology of probabilities. Further, the metaphysical lessons that we may wish to draw from the abundance of probabilistic claims hinge on the meaning of 'probability.' Hence, our three questions set one major task, viz. *to make sense of probabilities in physics*.

This task does not fall within the subject matter of physics itself, but is rather philosophical, because questions about meaning, evidence, and determinism have been addressed by philosophers for a long time. This is not to say that physicists are not, or should not, be interested in these questions—quite to the contrary: the point is rather that our questions are beyond the reach of those methods that are characteristic of physics.

The aim of this volume is to address the task that we have identified: to make sense of probabilities in physics. The main emphasis is on what we call an *interpretation of probabilities in physics*. The goal is to explain the meaning

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of probabilistic statements from physics in a way that guarantees a plausible epistemology and a defensible metaphysics of probabilities.

As it happens, the interpretation of physical probabilities is interwoven with a number of other, foundational and methodological, issues in physics. These include the interpretation of quantum mechanics and the Reversibility Paradox from statistical mechanics. Our strategy is to take up and discuss such issues, too.

To address our task, we have assembled thirteen original essays by leading experts in the field. As controversy and debate are characteristic of philosophy, the reader should not expect the emergence of one coherent account of probabilities in physics. What can be expected, however, is an up-to-date review and critical discussion of the lasting contributions to the debate. In this way, the volume will provide a guide through the thicket of the philosophical debates about probabilities in physics, and help the reader to make up her own mind. Yet, many contributions will also advance the debate by raising new and original points.

In the remainder of this introduction, we will first survey various interpretations of probabilities in physics, and thus set the stage for the following essays (Sec. 1). We will then outline the structure of this volume and provide a brief summary of the contributions (Sec. 2).

1 Puzzles and positions

What, again, are probabilities, and what do probabilistic statements mean?[1] There seems to be a straightforward answer to this question. In mathematics, probabilities are defined by a set of axioms. Amongst various proposals, the axioms suggested by Andrey Kolmogorov are most popular and widely used. Kolmogorov assigns probabilities to *random events* (or events, for short). These are subsets from a set Ω, the so-called sample space. The collection of events has the whole sample space as its member and is closed under set union, intersection, and complementation. The Kolmogorov axioms of the probability calculus then require that each event A be assigned a non-negative real number, denoted by $P(A)$. The measure P must be additive, that is, if two events A and B are disjoint (i.e. if $A \cap B = \emptyset$), then

$$P(A \cup B) \;=\; P(A) + P(B).$$

[1]Howson 1995, Gillies 2000a, Mellor 2005, and Hájek 2010 provide excellent introductions to the philosophy of probability, with an emphasis on interpretative questions and puzzles. See also Fine 1973, Skyrms 1999, Galavotti 2005, Hacking 2001, Howson & Urbach 2006, and Jeffrey 2004. For a historical perspective, see Hacking 1975 and 1990, and von Plato 1994. Eagle 2010 is a collection with readings in the philosophy of probability.

Finally, $P(\Omega)$ is required to be 1. If these axioms are satisfied, P is called a *probability function*.[2]

Kolmogorov's axioms concern *unconditional* probabilities. From them, *conditional probabilities* can be defined as follows: Assume that the event B has a non-zero probability. Then the conditional probability of an event A given B, denoted by $P(A|B)$, is the probability of the joint occurrence of A and B, divided by the probability of B:

$$P(A|B) = \frac{P(A \cap B)}{P(B)}.$$

There are other sets of axioms for probabilities, some of them strictly equivalent to Kolmogorov's axioms, some not.[3] Some of them take conditional probabilities as basic (see e.g. Popper 1955, Sec. 4, and Hájek 2003), others start with defining unconditional probabilities, as Kolmogorov's axioms do. It is also possible to assign probabilities not to events, but to propositions instead (see Howson & Urbach 2006, pp. 13–14). Indeed, we will take the liberty of switching between talk of events and of propositions when speaking about probabilities.

Whatever set of axioms we choose to set up the probability calculus, however, it does *not* suffice to explain the meaning of probabilistic statements from physics. As Kolmogorov (1956, p. 1) himself remarks, '[e]very axiomatic (abstract) theory admits ... of an unlimited number of concrete interpretations.' Suppose for example that a physicist claims that a certain atom will decay in the next two days with a probability of .5. This is a claim about the real world and not just one about abstract mathematical objects that are defined axiomatically. Also, there is no mathematical fact that fixes the probability of a real-world event at .5 rather than at .2, say. We thus need a story that adds *physical meaning* to probabilistic statements. This story is, of course, constrained by the axioms of the probability calculus, because the probabilities are supposed to satisfy the axioms. Ideally, the story would even explain *why* physical probabilities satisfy the axioms.[4]

Several such stories have been provided, and not just for probabilities in physics. Regarding the latter, one can choose between either of two broad strategies. The first strategy is to resort to physics itself to interpret the probabilities from physics. One may, for instance, define such probabilities as certain time-averages well known in statistical physics (see the contribution by Lavis on pp. 51–81). The other strategy is to draw on the general philosophical discussion about how probabilities (not just in physics) should be understood. In the latter

[2]See Kolmogorov 1956, Chs I–II, for the original statement of the axioms. Most mathematicians, including Kolmogorov himself, additionally assume countable additivity, which extends additivity to countably many events.

[3]See Gillies 2000a, pp. 65–9, for a discussion of two systems of axioms that are not equivalent.

[4]For general discussions about desiderata that any interpretation of probabilities should fulfill, see Hájek 1996, pp. 210–11, and Hájek 2010.

context, a dichotomy of two broad groups of views has emerged: the dichotomy between objectivist and subjectivist views. Let us explain.

According to *objectivist* views, probabilistic statements state matters of fact. That is, they have truth-conditions that are fully mind-independent and refer to frequencies of events or to propensities in the world. We can then use descriptions of the truth-conditions to form simple slogans such as 'probabilities are frequencies.' *Subjectivist* views, by contrast, take probabilistic statements to express degrees of belief. Thus, a fitting slogan is 'probabilities express credences.' Of course, we cannot assume that all probabilistic statements from physics and elsewhere are to be interpreted along the same lines. Hence, *pluralist* accounts of probabilities suggest different interpretations in different domains of discourse (see Gillies 2000a, pp. 180–6).[5]

There are strong reasons to give probabilities in physics an objectivist reading. After all, physics strives to find mind-independent truths about the world, and it seems very successful in this endeavor. Probabilistic theories and models are part of what physicists have come up with. So why not say that probabilistic statements describe the world as it is, like other statements from physics do? This is of course not to say that every probabilistic theory tracks the truth. Further developments of quantum mechanics, for example, may be necessary. Yet the subjectivist will have to explain why quantum mechanics with its probabilities is not a good shot at a theory that literally describes the world as it is.

Let us take a closer look at objectivist views. The simplest of these views is *actual frequentism*. The slogan, of course, is that probabilities are frequencies, by which relative frequencies are meant. To understand the details, consider the conditional probability that some type of event occurs given some reference class of events. Assume that a physicist claims this probability to have p as its numerical value. According to actual frequentism, this is simply to say the following: the relative frequency with which this type of event occurs in the reference class is p. Some everyday probabilistic statements may clearly be read in this way; for instance, when we say that people from Rome have a certain probability of owning a dog, we may simply be referring to the fraction of Romans that own a dog. Also, for finite reference classes, identifying probabilities with frequencies is sufficient to explain why the axioms of the probability calculus hold (cf. Ramsey 1926, p. 54).

[5]Unfortunately, in the philosophy of probability the term 'objectivist' is used in different senses. Some authors reserve it for accounts of probabilities that assume mind-independent truth-conditions for probabilistic statements (as we do). But others call an account objectivist if it claims, more generally, that, on top of the axioms, there are strong constraints that restrict the values of probabilities. 'Objective Bayesianism' (see e.g. Williamson 2010) is objectivist in the second sense, but not in the first.

But actual frequentism faces a number of objections (Hájek 1996). Many of them are particularly relevant with respect to probabilities in physics. For instance, when a die has a certain symmetric physical constitution, it seems more than natural to assign it 1/6 as its conditional probability to yield '1' if thrown. But the die may in fact never be thrown, or only be thrown once, giving a '2'. Actual frequentism would refuse to provide a probability in the first case and assign zero probability to the '1' in the second case. This is very counterintuitive, to say the least (see Hájek 1996, pp. 220–1). As Strevens puts a related point in his contribution to this volume (pp. 339–64), probabilistic statements support counterfactuals, whereas statements about frequencies do not.

Here is another problem: As stated, actual frequentism only makes sense if the reference class in question has a finite number of members, because only in this case can fractions be defined. But physicists often use probabilities while not knowing whether the corresponding reference class is finite or not. For instance, physicists specify probabilities that certain atoms decay two days after their generation, although it is not known whether the number of these atoms is finite. Note that it will not do to consider *limits* of fractions instead of fractions, when one deals with infinite reference classes. The reason is that the same infinity of cases can yield very different limits, or no well-defined limit at all, depending on how the cases are ordered (Hájek 2009, pp. 218–21). Finally, under actual frequentism, probabilities can only take rational numbers as their values. However, well-established physical theories assign some events conditional probabilities that do not have rational numbers as their values (Hájek 1996, pp. 224–5).

To overcome at least some of these difficulties, more sophisticated versions of frequentism can be devised. *Hypothetical frequentism* is a case in point (see Hájek 2009 for discussion). The idea is to identify probabilities not with actual frequencies, but with hypothetical frequencies that would arise if a certain experiment were repeated several times. Thus, the probability that a die yields '6' is thought to be the frequency of '6' that we would observe if the die were thrown repeatedly in the same type of circumstances. This proposal avoids some counterintuitive consequences of actual frequentism. But there are other serious problems. As Jeffrey (1977) famously argued, if a die has an objective probability of 1/6 to yield a '6', then there is no fact of the matter what would happen were the die thrown repeatedly. Also, it is compatible with this probability assignment that we would *never* get a '6' even if the die were thrown infinitely many times (Hájek 2009, pp. 217–18 and 222). Another problem arises from the following question: how often is an experiment to be repeated hypothetically to obtain the hypothetical frequencies with which we can identify probabilities? If we require a finite number of trials, we will run into some problems familiar from actual frequentism. But if we demand an infinite series of trials, the order of the trials will matter, and there will be other problems that originate from the infinity that is now involved (see Hájek 2009, pp. 218–21, 226–7, and 230–1, for details).

Richard von Mises proposed a more sophisticated version of frequentism.[6] He identifies the conditional probability of some type of event A given some other type of event B with the limiting value that an infinite collective of B-events produces for the fraction of A-events in the collective. Here 'collective' is a technical notion, which is defined as an infinite sequence that satisfies certain requirements. The precise requirements have been a matter of intensive mathematical research. A good proposal is summarized in Howson 1995, p. 14. In any case, collectives help avoiding some of the difficulties that hypothetical frequentism faces (Hájek 2009, pp. 224–5). Admittedly, collectives are purely mathematical constructions, but the idea is that collectives together with probabilities may be used to explain some features of real-world sequences of events. All of this looks very elegant at first glance. However, there are again problems. Gillies (2000a, pp. 101–5), for instance, criticizes that the relation between von Mises' collectives and empirical data is not clear. There must be such a relation, because the probabilistic statements that physicists put forward are meant to have empirical significance.[7]

Any brand of frequentism identifies probabilities with frequencies, or limits of frequencies. Since frequentism has many problems, it may seem promising to loosen the connection between frequencies and probabilities. This is what *propensity views* of probabilities do. According to such views, we ascribe a certain disposition (a 'propensity') to a system when we characterize it through probabilistic statements. This disposition persists even if it is never manifested.

The most famous proponent of a propensity view is certainly Karl R. Popper. Part of Popper's motivation for developing his propensity view was to save objective single-case probabilities.[8] Single-case probabilities are unconditional probabilities which refer to some particular event. Consider again the probability that this particular atom decays in the next two days. Quantum mechanics seems to dictate the value of this probability. Yet, no such probability can plausibly be construed as a frequency (unless it is 0 or 1). After all, we are talking about one particular event and not about a series of events. So frequentists can only recover this probability by identifying it with a conditional probability of a certain type of event given some sort of experimental setup. But what type of event and what sort of setup are we to choose? There are several types of events under which we can subsume the event under consideration; and there are many sorts of experimental setups under which the actual setup falls. Different choices

[6]See von Mises 1928 for his views. See Gillies 2000a, Ch. 5, for a good introduction.

[7]See also Jeffrey 1977 and Howson 1995, pp. 14–17.

[8]See Popper 1957 and 1959, particularly p. 27; see Gillies 2000a, Ch. 6, for the background of propensity views.

will yield different values for the probability. This problem is an instance of the *reference-class problem* (see e. g. Hájek 1996, pp. 214–15).

Single-case probabilities are indeed a delicate issue. Some authors take it that objective single-case probabilities are a bad idea from the outset. For example, Howson & Urbach (1989, p. 228) submit that 'the doctrine of objective single-case probabilities' is 'incoherent' (see Gillies 2000a, pp. 119–25, for a related discussion). Others think that frequentism does in fact have something to say about the single case (see Salmon 1979, pp. 199–208, for a discussion). Finally, it is also doubtful whether propensity views really avoid the reference-class problem (Eagle 2004, pp. 393–5; see also Hájek 2007). We will thus leave single-case probabilities on one side. Suffice it to say that they were important for Popper's motivation to develop a propensity view.

We can distinguish between several kinds of propensity views.[9] The crucial question is what kind of disposition a system has if it has a probability of p to produce a certain event. The disposition may either be an on–off disposition to produce a certain frequency p in a long, maybe infinite, series of trials (see Gillies 2000a, Ch. 7, for such a view). Alternatively, it may be a disposition of degree p to produce some event.[10] In the first case, there is still some explicit connection to frequencies, while the second option does not mention frequencies at all.

A problem with the first option is that it inherits some of the problems that beset hypothetical frequency accounts (Hájek 2010, Sec. 3.4). For instance, if probabilities are dispositions to produce certain limits of frequencies in infinite series of trials, different orderings of the trials can lead to different values of the probabilities. The other option has problems because there does seem to be a conceptual link between frequencies and probabilities, which becomes more obscure if probabilities are single-case propensities (Eagle 2004, pp. 401–2). Also, it is not clear why propensities, thus construed, should satisfy the axioms of the probability calculus (ibid., pp. 384–5).[11]

Altogether, the objectivist views that we have considered face difficult challenges. But maybe the problems of such views derive from a mistaken conception of what an objectivist account of probabilities has to deliver to begin with. So far, we have tried to formulate truth-conditions for probabilistic statements without using probabilistic notions themselves. In this sense, we have been aiming at a conceptual analysis or reduction. Such a reduction would demote probabilistic talk to a shorthand way of talking about something else. But this is in fact an odd prospect. Probabilistic statements would seem superfluous,

[9]See Gillies 2000a, Ch. 6, or 2000b, and Eagle 2004 for a taxonomy.

[10]This option is taken by Gillies (1973), Fetzer (see e. g. his 1974, 1981, 1983a, 1983b), the later Popper (1990), and Miller (1994). Mellor (1971) explains probabilities in terms of dispositions, too, but his account is quite different from the propensity views mentioned so far.

[11]See Hájek 2010, Sec. 3.4, and Eagle 2004 for more criticism of the propensity view.

since probabilistic talk could be safely replaced by more mundane talk about frequencies or so, without any loss. But why, then, do physicists still talk about probabilities?

So, maybe probabilistic notions cannot be reduced to nonprobabilistic ones (cf. Gillies 2000a, pp. 109–11). To suggest this is not to reject an objectivist account of probabilities. The idea is not that probabilistic statements do not have mind-independent truth-conditions, but rather that these truth-conditions cannot be spelt out in nonprobabilistic terms. For instance, the notion 'probability' may be part of a network of concepts that latches onto experience as a whole, and we may only be able to fix its meaning by specifying the role that probabilities play in the network, and by saying how the network relates to other things (e.g. to frequencies). A related suggestion is that the term 'probability' functions in a similar way to theoretical terms such as 'electron' and 'gravitational field' (cf. Gillies 2000a, pp. 138–45). These terms are not plausibly taken to be definable in purely observational terms. Instead, they have meaning because of the functional role that they play in a theory, which in turn accounts for certain observations. Or maybe the notion of probability is a primitive one. Carl Hoefer, in his essay in this volume (pp. 321–37), examines this suggestion and comes to reject it.

But nonreductive accounts of probabilities raise serious concerns too. For if probabilistic statements are true and refer to mind-independent states of affairs that do not coincide with more mundane facts about frequencies etc., our metaphysics has to encompass new kinds of facts. But parsimony is taken to be an important virtue in metaphysics, and the question arises whether probabilistic facts *sui generis* are metaphysically too costly, even if they successfully account for the objectivist feel that probabilistic statements from physics have. Also, from a God's-eye view, every possible event either does or does not occur. Thus, from this point of view, there seems to be no point in assigning events probabilities. But, as metaphysicians, should we not try to take a God's-eye view? This suggests that metaphysics does not have a place for objective probabilities, and that probabilities are rather characteristic of the perspective of beings with limited knowledge. A related worry is that probabilistic facts *sui generis* violate the much-discussed tenet of Humean supervenience (see the contributions by Maudlin and Hoefer, pp. 293–319 and 321–37).

Given that all objectivist views have problems, objectivism itself may seem to be a bad idea. Interestingly enough, physics itself provides good reasons to doubt objectivism, as far as probabilities from statistical mechanics are concerned. At least one important task of statistical mechanics is to provide a microphysical account of macroscopic thermodynamic regularities. It is widely held that the microphysics could in principle be described without the use of probabilities, and that probabilities are only employed because many details at the microlevel are in fact not known and too complicated to deal with. But if this is so, why should we not be honest and admit that doing statistical mechanics is largely making the best of ignorance, and that the related probabilities are better interpreted as subjective?

Let us therefore take a closer look at subjectivist views. Under such views, probabilistic statements express the attitudes of their utterer. To say that the (unconditional) probability of some event is p is to express that one believes to the degree p that the event will occur. Probabilities thus measure degrees of belief, or at least degrees of belief that are rational in some sense. But what are degrees of belief?

The notion 'degree of belief' can be rendered precise by reference to betting behavior. Suppose we want to measure the degree to which John believes that an event A will occur. We offer John the following bet on A. If A occurs, John will receive \$ 1. If A does not occur, John will obtain nothing. In any case, John has to pay \$ p to enter the bet, where p is a real number. Clearly, other things being equal, the offer becomes less attractive for John as p increases. It does not make sense for John to pay \$ .99, unless he is almost certain that A will occur. Thus, the highest p for which John would accept the offer measures to what degree John believes A to occur. John's degree of belief concerning A is the highest p for which he is willing to bet on A as described.[12]

This approach was pioneered by Ramsey and de Finetti.[13] One of its great advantages is that it explains why degrees of belief obey the axioms of the probability calculus. Here is the crucial idea: If John's degrees of belief do not obey these axioms, we can offer him a Dutch book, i. e. a set of bets such that he will lose money no matter what combination of events will occur. If a rational agent will not accept Dutch books, we may then say that the axioms of the probability calculus follow from constraints of rationality. Probabilistic statements thus express rational degrees of belief.

An alternative way of measuring degrees of belief is due to Ramsey and Savage.[14] They assume that the preferences of a rational agent display a certain structure which, again, derives from constraints of rationality. The preferences can then be understood in an expected-utility framework, where an option is preferred to another one if and only if it yields a higher expected utility. The expected utilities arise from utilities and from degrees of belief, which can both be read off from hypothetical choices the agent would make. It can be shown

[12]We here follow Mellor 2005, pp. 67–9; for a different way of introducing probabilities in terms of bets, see Gillies 2000a, Ch. 5.

[13]See e. g. Ramsey 1926 and de Finetti 1931a, 1931b, and 1964. For historical accounts, see von Plato 1989a and Gillies 2000a, pp. 50–1.

[14]See Ramsey 1926, particularly Sec. 3, and Savage 1972, Chs 1–7; see Howson 1995, pp. 5–7, for a short overview.

that, given certain constraints, the degrees of belief thus defined obey the axioms of the probability calculus.[15]

However, the axioms of the probability calculus do not fix the values of probabilities uniquely. Different rational agents may come up with widely differing probability assignments. Physicists, however, often agree on probability assignments, and quite reasonably so. Many well-established physical theories and models provide numerical values of probabilities for certain types of events, and these are profound and informative results that it would be foolish to deny. If the subjectivist view is to succeed in physics, we need an explanation of why physicists often reasonably settle on certain probabilities.

One idea is to tighten the constraints of rationality, and to require agents to update their probabilities using *Bayesian conditionalization*. Let H be a general hypothesis and D a statement about new data. If D becomes known to the agent, Bayesian conditionalization requires her to replace her old degree of belief, or *prior probability*, $P(H)$, by a new degree of belief, the *posterior probability* $P'(H) = P(H|D)$.[16] When we apply Bayes' Theorem, which is a consequence of the probability calculus, to the right-hand side of this equation, we obtain

$$P'(H) \;=\; \frac{P(D|H) \times P(H)}{P(D)}\;. \tag{1}$$

There have been attempts to justify Bayesian conditionalization in terms of a Dutch book argument.[17] However, these attempts are much more controversial than the Dutch book arguments mentioned above (see Howson 1995, pp. 8–10, and Mellor 2005, p. 120).

Using Eqn (1), it has been shown that, given some rather mild conditions, agents who start with different prior probabilities, $P_1(H), P_2(H), \ldots$, and sequentially update on new data, will converge on the same posterior probability $P'(H)$ as more and more data come in. Subjectivists suggest that this suffices to account for the fact that physicists very often reasonably agree on probability assignments.[18]

However, convergence may be slow, and physicists who start with very different prior probabilities may still end up with significantly different probabilities for the same hypothesis. Given the extent to which physicists agree on probabilities, this is a severe problem. The position of *objective*, or 'logical,' *Bayesianism*

[15]For alternative justifications of the identification of degrees of belief with probabilities, see Joyce 2005 and 2009, and Leitgeb & Pettigrew 2010a and 2010b.

[16]Jeffrey 1967, Ch. 11, generalizes conditionalization to cases in which the data themselves are uncertain.

[17]Teller 1973, pp. 222–5, Lewis 1999; see also Mellor 2005, pp. 119–20, for a summary.

[18]See, for example, Savage 1972, pp. 46–50, and Blackwell & Dubins 1962 for mathematical results about convergence.

tries to avoid this problem by proposing an additional constraint of rationality (see Williamson 2009). They require that agents fix their prior probabilities following the *Principle of Insufficient Reason*. According to this principle, hypotheses that exhaust the space of possibilities but are mutually exclusive should each be assigned the same probability, provided no reasons are known that support one hypothesis rather than the others (see Keynes 1921, p. 42, for a statement of this principle).[19] If obedience to the principle can in fact be demanded from rational agents, probabilities are uniquely fixed by constraints of rationality and data. We may in this case speak of 'quasi-objective' probabilities.[20]

Unfortunately, the Principle of Insufficient Reason is fraught with difficulties. They arise from the fact that there are often several ways of partitioning the space of possibilities using hypotheses or events. Different partitions lead to mutually inconsistent assignments of the prior probabilities. Unless there are reasons to take one partition as natural, different rational agents can thus come up with different probability assignments again.[21]

But maybe we can replace the Principle of Insufficient Reason by some other constraint that helps fixing the probabilities of rational agents. Clearly, such a constraint cannot simply demand that degrees of belief track objective chances, as Lewis' famous Principal Principle[22] does, unless these objective chances can themselves be given some subjectivist reading. Another option starts from a result by Ryder (1981), according to which one can make a Dutch book against a group of people who have different degrees of belief in some event (see also Gillies 2000a, pp. 169–75). One may want to use this result to explain why certain groups of physicists agree on probabilities. However, such an explanation does not explain why the physicists' probabilities settle on just those values on which they in fact settle. Also, Ryder's result is only applicable to groups with a strong common interest (see Gillies 2000a, ibid.).

All in all, subjectivist views of probabilities are attractive in that they have no problem to explain why the axioms of the probability calculus hold. They also do not come with any metaphysical burden. Their main drawback is that they have a hard time explaining why some probability assignments, for instance in quantum mechanics, seem to be much more reasonable than other assignments.[23]

[19] Sometimes this principle is also called the *Principle of Indifference*. It is in a way generalized by the Maximum-Entropy Principle proposed by E. T. Jaynes (1957, 1968, 1979). For a recent defense of a version of objective Bayesianism, see Williamson 2010.

[20] See n. 5 though.

[21] See Gillies 2000a, pp. 37–49, and Mellor 2005, pp. 24–9, for more discussion. The problems with the Principle of Insufficient Reason also affect the so-called logical interpretation of probabilities (see Keynes 1921 for a statement and Gillies 2000a, Ch. 3, for an introduction).

[22] See Lewis 1980 and 1994, particularly pp. 483–90, for the Principal Principle.

[23] See Earman 1992 and Howson & Urbach 2006 for more discussion about subjective probabilities and scientific inference.

There are also some interpretations of probabilities on the market that straddle the borderline between objectivism and subjectivism. Some authors explore the idea that probabilities originate as credences that are then objectivized in some way.[24] Mellor (1971) suggests that probabilities are real-world characteristics that warrant certain credences.[25] Lewis (1980) notes that the Principal Principle has nontrivial implications about objective probabilities (or chances, in his terms), and explores the possibilities of obtaining an analysis of probabilities. Lewis 1994 makes a new suggestion for analyzing the notion of lawhood and chance at the same time. It turns out that the Principal Principle has to be modified if this is to make sense. Lewis' ideas are explored in the contributions by Maudlin (pp. 293–319) and, in particular, Hoefer (pp. 321–37).[26]

To sum up this section: The question of how to interpret probabilities in physics is wide open. Here we could only flag some issues that provide the background for what is to come. There are many more philosophical discussions, which the essays in this volume address. Let us shortly review the latter.

2 Outline of this volume

When we are interested in probabilities in physics, it seems appropriate to focus on mature and well-established probabilistic claims. Two theories, or maybe groups of theories, are most relevant in this respect: statistical physics and quantum theory. This volume starts out, in Part I, with the older of these, viz. statistical physics. The focus is on *classical* (i.e. non-quantum) statistical physics, simply because classical statistical physics is sufficiently puzzling, and much philosophical discussion has been devoted to this topic. Note, however, that Ruetsche and Earman, in their essay in Part II (pp. 263–90), also cover quantum statistical physics.[27]

Our first two contributions deal with subjectivist and objectivist readings of probabilities in statistical mechanics. *Jos Uffink* (pp. 25–49) begins with a historical account of both subjectivism and statistical mechanics. His essay shows that a marriage between statistical mechanics and subjective probabilities was for a long time not obvious to many. Early work in statistical mechanics by Daniel Bernoulli was not couched in terms of probabilities at all, and when Maxwell first derived the velocity distribution named after him, he was thinking

[24]See Howson 1995, pp. 23–7, for a brief review.

[25]See Salmon 1979 and Eagle 2004 for a discussion of Mellor's proposal.

[26]Other interpretations of probabilities well known from the history are the 'classical' and the 'logical' interpretations. They are not considered to be viable anymore, though (see Gillies 2000a, Chs 2 and 3).

[27]See Sklar 1993, Albert 2000, and Uffink 2007 for philosophical issues in statistical physics. Guttman 1999 is a monograph about the notion of probability in statistical physics. See Ernst & Hüttemann 2010 for a recent volume on reduction and statistical physics.

of frequencies and averages. It was later recognized that the Principle of Insufficient Reason would justify a crucial assumption of Maxwell's. This invites us to think of the Maxwell distribution as a probability function, and to understand probabilities in terms of credences. In the twentieth century, it was E. T. Jaynes who vigorously argued for a subjectivist construal of statistical mechanics. From a systematic point of view, Uffink takes subjectivism to provide a viable interpretation of probabilities in statistical mechanics. In particular, he rejects David Albert's accusation that subjectivism about probabilities in statistical mechanics amounts to letting beliefs explain real-world events. But Uffink also denies claims that subjectivism in statistical mechanics can overcome problems that objectivists have. In particular, he finds Jaynes' 'proof' of the Second Law of Thermodynamics wanting.

In the second contribution (pp. 51–81), *D. A. Lavis* refines and defends a particular objectivist construal of probabilities in statistical mechanics. The basic idea is to identify probabilities with time-averages: the probability that the system is in a particular macrostate is simply equated with the average time fraction that the system spends in that state. If a system has the property of being ergodic, then time-fraction averages are well defined and turn out to coincide with a phase-space measure that is, in a certain sense, unique, and thus very natural. When a system is not ergodic, things become more difficult. Lavis uses ergodic decomposition and Cartwright's notion of a nomological machine to define probabilities in this case. The values of the probabilities are in any case taken to be matters of mind-independent fact. Obviously, this account has some affinity to frequentist theories of probabilities. Lavis also relates his account to the Boltzmann and Gibbs approaches to statistical mechanics. Since Lavis' aim is to spell out an objectivist view drawing on recent results from statistical mechanics, it is more technical than many other papers in this volume. An appendix to this contribution outlines basic results from ergodic theory.

Since its origins, statistical mechanics is beset with a number of foundational problems, such as the Reversibility Paradox. Some of these problems are taken up and connected to probabilities by *Craig Callender* (pp. 83–113). On Callender's analysis, the Boltzmannian and the Gibbsian approach both rely on positing what he calls 'static probabilities.' Static probabilities concern the question whether the system's microstate lies in a particular region of the phase space. But as the Reversibility Paradox shows, the static probabilities that are posited seem incompatible with the microphysics that is supposed to govern the system. Callender examines several suggestions for solving this problem. One is the Past Hypothesis as advocated by Albert. In Callender's terms, the crucial idea is to posit static probabilities together with a low entropy for the initial state of the whole universe. But constraining the probabilities for the global state of the universe in the far past does not underwrite statistical mechanics as applied to small subsystems of the universe, such as coffee cups, or so Callender argues. Also, he does not think that the problem can be solved by taking a more instrumentalist stance on probabilities. Callender's own solution has it that statistical mechanics is a special science: by its very definition it deals with systems that start from a low-entropy state.

A key notion from statistical physics is entropy. Entropy is known from thermodynamics, where it is used to characterize equilibrium states. It figures most famously in the Second Law of Thermodynamics. But entropy is also often given a microphysical interpretation using probabilities. And so we ask: is entropy a covertly probabilistic notion? In the fourth contribution (pp. 115–42), *Roman Frigg* and *Charlotte Werndl* provide a guide through the thicket of discussions concerning entropy. Their central point is that several different notions of entropy need to be distinguished. Concerning thermodynamics and statistical mechanics, the most important notions that need to be kept apart are thermodynamic entropy, the fine-grained Boltzmann entropy, and the coarse-grained Boltzmann entropy, as well as the fine-grained and the coarse-grained Gibbs entropy. Frigg and Werndl provide the definitions of these notions and identify relations between them. In some cases there are formal analogies. In other cases it can be shown that, under certain assumptions, two notions of entropy coincide. For instance, for an ideal gas in which the particles do not interact, the fine-grained Boltzmann entropy coincides with thermodynamic entropy. Remarkably, most notions of entropy can in some way be traced back to information-theoretical entropy as introduced by Shannon. As Frigg and Werndl further remark, some notions of entropy in statistical mechanics use probabilities, whereas others do not. When entropy is defined in terms of probabilities, there may be a preferred interpretation of the probabilities, but this does not preclude other interpretations.

Statistical physics, in a broader sense, is not restricted to providing a microscopic underpinning for thermodynamics. Statistical physicists also construct and analyse random or probabilistic models. Random-walk models, which are used to understand Brownian motion, or point-process models of the galaxy distribution are cases in point. Yet, random models raise the following puzzle: Models are used to represent a target, and probabilistic models do so by suggesting probabilities for the target. But how can probabilities be useful in representing a target? After all, that an event has a probability of .2, say, is compatible with the event's occurring and with its not occurring. This puzzle is at the center of the contribution by *Claus Beisbart* about probabilistic models (pp. 143–67). To solve the puzzle, he assumes that we can learn about a target if the latter is represented by a model. He then observes that probabilistic models are often used to learn about the statistics of certain events. This is so if the target of the model is not just a single system, but rather a series of equally prepared systems. We can also use probabilistic models to learn about the statistics of a type of event within one single system. Beisbart argues that this kind of learning is best understood by claiming that we should use probabilities to set our degrees of belief. This is compatible with both subjectivist and objectivist views of the probabilities from models. However, if the probabilities are objective, then there should be an objectivist methodology to confirm or disconfirm probabilistic models using data. Beisbart argues that the natural candidate, viz. error statistics, which is widely used in physics, does not provide the right kind of methodology. Accordingly, he is more sympathetic to a subjectivist account, although this construal faces various difficulties as well. To conclude his essay, Beisbart explores the metaphysical consequences that one might wish to draw from the fact that probabilistic models are widely used in physics.

The second part of this volume deals with quantum theory.[28] Probabilities in quantum mechanics, or quantum probabilities, are quite different from the probabilities that occur in classical statistical mechanics. First, in a sense, the former are more fundamental than the latter. Whereas a nonprobabilistic description of the microphysics is thought to be in principle possible in classical statistical mechanics, quantum mechanics characterizes the microphysics through the use of the wave-function, which, in turn, has only probabilistic significance. Second, quantum probabilities display correlations that do not occur in classical systems. Finally, the basic ontology of quantum mechanics remains a matter of controversy. Although there is a very successful formalism, rival interpretations compete in unfolding what the theory really says about the world. Modal interpretations, the Everett interpretation, and the Bohm theory (often also called the 'de Broglie–Bohm theory') are most discussed these days.[29] The implications for the interpretation of quantum probabilities are severe: interpreting probabilities from quantum mechanics becomes part of the larger enterprise of interpreting the theory in general.

Part II begins with an essay (pp. 171–99) that explores the role quantum probabilities play in the formalism of quantum mechanics. The author, *Michael Dickson*, does not commit himself to a particular interpretation of quantum mechanics. However, he urges that quantum probabilities should not be assimilated to classical probabilities, and suggests a more general framework for thinking about probabilities. This framework, which is based on effect algebras, is explained and defended in detail. In quantum mechanics, the effect algebra is formed by the projection operators on a Hilbert space. Once the effect alge-

[28]For the philosophy of quantum mechanics, see Redhead 1987, Hughes 1989, D. Z. Albert 1992, and Dickson 2007. A couple of essays on probabilities in quantum mechanics are collected in a special issue of *Studies in History and Philosophy of Modern Physics* (Frigg & Hartmann 2007).

[29]Strictly speaking, one should distinguish between *interpretations* of quantum mechanics and *theories* that slightly *modify* quantum mechanics.

bra of quantum mechanics is set up, we need to connect it to experiments and measurements. The Born Rule, which connects quantum-mechanical states to probabilities of measurement results, is pivotal in this respect. Dickson provides various formulations of the Born Rule. A crucial question is how one can justify the validity of the Born Rule. Dickson presents and critically examines a couple of derivations of the Born Rule. Some of them presume a particular interpretation, whereas others only draw on the formalism. Dickson is particularly critical of an argument by Deutsch and Wallace, which will resurface in Timpson's contribution. As indicated above, quantum probabilities turn out to display very strange correlations. Dickson explains the peculiarity of quantum correlations and summarizes the challenges that quantum probabilities pose. He concludes with a few remarks about the interpretation of quantum probabilities, setting the stage for the next two contributions.

The essay by *Christopher Timpson* (pp. 201–29) analyses realist views of quantum mechanics. These views take crucial elements of the formalism as literally true descriptions of the world. The Ghirardi–Rimini–Weber (GRW) theory, for instance, takes the Projection Postulate to reflect a real collapse of the quantum-mechanical wave-function. Timpson concentrates on three realist views of quantum mechanics—the GRW theory, the Bohm theory, and the Everett interpretation—and asks each of them two questions: First, which interpretation of quantum-mechanical probabilities goes best with it? Second, which status does it assign to the Born Rule? Timpson's result concerning the GRW theory is that it takes the world to be chancy at a fundamental level, at which 'hits' occur following an objective probability distribution. Under the Bohm theory, the world consists of deterministically moving particles. Timpson proposes to say that there is an objective probability distribution over the initial positions of the Bohmian particles, but he points out problems that Bohmians have with the Born Rule. In their setting, the Born Rule corresponds to an equilibrium, and there are difficulties in understanding how this equilibrium has arisen. These difficulties sound familiar from classical statistical physics. Timpson himself is most enthusiastic about the Everett interpretation. Against first appearances, the Everett interpretation can not only make sense of probabilities, but can also explain how the Born Rule originates, or so Timpson argues, drawing on results by Deutsch and Wallace. The idea is that a rational agent must set Born Rule probabilities, if she is to choose between certain quantum games. Ironically, then, a realist interpretation of quantum mechanics is married to a more subjectivist view of quantum-mechanical probabilities.

In a way, *Jeffrey Bub's* contribution (pp. 231–62) is the counterpart to Timpson's. Bub expounds and defends an information-theoretic interpretation of quantum-mechanics. His view is ultimately realist, but Bub does not assume real hits or Bohmian particles. Neither does he think that quantum-mechanical wave-functions are part of the furniture of the world. Rather he takes them to be book-keeping devices. Bub develops his interpretation by looking at quantum games in which a so-called 'no signaling' constraint is to be obeyed. These games provide an excellent introduction to quantum correlations more generally. Bub then points out that the famous Lüders Rule may be seen as a rule that tells us how to update probabilities following certain events. But quantum conditionalization comes with inevitable losses of information. Bub therefore suggests that quantum theory implies new constraints on information, just as the theories of relativity implied new constraints on events in space-time. The emerging view about quantum mechanics does not provide a deeper-level story that explains the new constraints. Nevertheless, Bub thinks that quantum probabilities are at least intersubjective. The point is simply that the Hilbert-space structure of quantum mechanics fixes probabilities via Gleason's Theorem. Bub contrasts his account with the more subjectivist views of Christopher Fuchs.

The essays by Dickson, Timpson, and Bub are concerned with nonrelativistic quantum mechanics. But how can we think of probabilities in relativistic quantum theory or in quantum field theory? *Laura Ruetsche* and *John Earman* address this question in their contribution on pp. 263–90. As they point out, interpretations of nonrelativistic quantum mechanics typically rely on the fact that the algebra of operators that represent the observables has atoms, i.e. minimal projection operators. An example is the projector on the specific momentum **p**. This atom is thought to be linked to the state after **p** has been measured. The probability that **p** is measured is given via the Born Rule. But as Ruetsche and Earman point out, in quantum field theory (and also in quantum statistical mechanics), we are faced with algebras that do not have atoms. Type-III factor von Neumann algebras are a case in point. The question, then, is how quantum probabilities can be understood in such a setting. To answer this question, Ruetsche and Earman review important characteristics of Type-III factor algebras. They point out that Gleason's Theorem can be generalized to the case of Type-III factor algebras, but that severe problems concerning the interpretation of probabilities arise. There are several strategies to solve these problems, each of them having its own problems. This contribution goes beyond the mathematics familiar to most philosophers of physics. Yet, one aim of the essay is precisely to disseminate results that are important for the interpretation of quantum mechanics. To this aim, Ruetsche and Earman explain the key concepts in appendices. The authors also contrast quantum field theory with nonrelativistic quantum mechanics and lay out a general framework for interpreting quantum probabilities.

Ruetsche and Earman's contribution finishes our survey of probabilities in physics. We have deliberately omitted the use that physicists make of probabilities in hypothesis testing and in the analysis of data. It is of course true that physicists use probabilities and statistical methods to deal with data. As a result, they come up with confidence regions for the values of physical parameters, or with probabilities concerning hypotheses. There are interesting philosophical issues in this field. Roughly, in the foundations of statistics, two approaches, viz. Bayesianism and error statistics, compete with each other.[30] Bayesians take probabilities on hypotheses to reflect degrees of rational belief, and use constraints of rationality to adjust the degrees of belief in response to new evidence. The error-statistics approach is often tied to objectivist views of probabilities. The main idea is that we can reject a probabilistic claim if some test-statistic calculated from the data takes a value that is very improbable, given this claim. Put differently, the probabilities that we falsely accept, and that we falsely reject, a probabilistic hypothesis are to be minimized. Although the clash between Bayesian statistics and error statistics is very interesting, it is not peculiar to physics. Hypothesis testing, parameter estimation, and other statistical techniques are used in many sciences and are thus a subject matter that belongs to the general philosophy of science, and not to the philosophy of physics, which is the focus of this volume. We hence concentrate on issues which are peculiar to physics. Note, though, that Beisbart, in his contribution, briefly discusses Bayesian statistics and error statistics.

Part III of this volume puts probabilities in physics into a larger philosophical perspective. Which claims about probabilities in physics can be made independently of specific theories? And which general philosophical questions are raised by the use of probabilities in physics? In his essay on pp. 293–319, *Tim Maudlin* explores various philosophical proposals how to make sense of objective probabilities in physics. The motivation should be clear enough: Probabilities figure in well-confirmed (or severely tested) theories that are applied in practice again and again and that appear to form part of the most profound knowledge we have of the world. So why not take the probabilistic claims at face value, as describing the world as it is? Maudlin distinguishes between three routes to objective probabilities. The first route is called the 'stochastic-dynamics approach.' The idea is simply that probabilistic statements are made true by the chancy dynamics of, for example, decaying radium atoms. The account does not provide a reductive analysis of probabilistic statements, but Maudlin does not think that this is a major drawback. However, the stochastic-dynamics account is at odds with a tenet that is much discussed in metaphysics, viz. Humean supervenience. The problem is, roughly, that almost any assignment of numerical values to objective chances is compatible with the facts about particulars and their relations. This motivates Maudlin's second route, the Humean approach to objective chances. Humeans take it that probabilistic statements describe objective facts

[30] See Spiegelhalter & Rice 2009 for an introduction to Bayesian statistics, and Howson & Urbach 2006 for a philosophical defense; for philosophical work about error statistics, see Mayo 1996 and Lenhard 2006. See also Kendall & Stuart 1979, Chs 22 and 23.

if they provide good summaries of the frequencies with which certain types of events arise. The facts that are stated in probabilistic statements are then clearly compatible with the tenet of Humean supervenience. Maudlin's third route to objective probabilities is the typicality approach, which in some way goes back to Boltzmann. Following the lead of Detlef Dürr, Maudlin uses a Galton board to illustrate the approach. A Galton board is a deterministic system for which it is typical that certain types of events occur with specific frequencies. That is, under a broad range of initial conditions we obtain the same statistics for the related events. One can then identify typical frequencies with probabilities. As Maudlin points out, this approach does not yield probabilities for certain single events occurring. This is not a drawback, however, he argues. To conclude, Maudlin explores the significance of the typicality approach for statistical physics.

In his contribution on pp. 321–37, *Carl Hoefer* pursues the second of Maudlin's three routes in more detail, and discusses several varieties of Humeanism about probabilities. Hoefer starts with the observation that there are apparently two kinds of laws of nature, viz. nonprobabilistic and probabilistic ones. Probabilities that occur in probabilistic laws may be taken as primitive, but Hoefer argues that such an approach would not be able to provide probabilistic laws with content. He rather prefers to follow the lead of David Lewis, who defined laws of nature as axioms from a system of axioms that provides the best account of the facts in the world, or as theorems that follow from this system. Lewis allowed for probabilistic statements in such a system. The idea then is that real-world chances are the probabilities that the best system takes there to be. The best system strikes an optimal balance between simplicity and informational content, and there are good reasons to adjust one's credences to the values of the objective probabilities, just as the Principal Principle has it. Hoefer points out that Lewis' account of objective chance would very well fit to the GRW theory. But there is one problem with Lewis' account. There seem to be objective chances for all kinds of macroscopic events, such as a die yielding a '3' and so on. Underwriting these probabilities using a best system of the world seems to be a bit far-fetched. Hoefer therefore pleads for a more pragmatic Humean account. Objective chances are divorced from the best system and connected to systems of *probability rules*. These rules need not be as simple as Lewis requires laws to be. The best system of probability rules may then well contain rules concerning dice, if adding such rules gives the system more content.

Michael Strevens, on pp. 339–64, takes up and elaborates Maudlin's third route. His aim is to assign objective truth-conditions to probabilistic claims that can hold even in a deterministic world. By discussing an example that is similar to Maudlin's Galton board, Strevens points to dynamical laws that produce a stable distribution over some outcomes quite independently of the distribution over the initial conditions. But, for Strevens, this fact in itself does not underwrite objective probabilities. The reason is that the distribution over the outcomes is not entirely stable. There are some distributions over initial conditions that are not well-behaved, as it were, which produce completely different distributions over the outcomes. In Strevens' view, it will not do to exclude such peculiar distributions as untypical in a definition of probabilities. His crucial idea is instead to use actual frequencies to constrain the initial conditions. This, then, is Strevens' proposal in very rough terms: a coin lands heads with a probability of p if and only if the dynamics produces a fraction of p for the coin's landing heads from any 'well-behaved' distribution over initial conditions, and if long series of trials with this coin and similar coins can be fitted using such a well-behaved distribution over the initial conditions. Of course Strevens gives a precise definition of 'well-behaved,' and he elaborates on the account such that it explains why probabilistic statements support counterfactuals. He also points out how probabilistic claims can be used for prediction and explanation.

Despite Strevens' proposal, the best case that one could make for objective chances, it seems, is to argue that the world follows an indeterministic dynamics. But is the universe indeterministic, i.e. unlike a deterministic clockwork? And can we ever *know* whether it is so? These questions are pivotal for understanding probabilities in physics, and they are explored in the last essay of this volume (pp. 365–89). The author, *Christian Wüthrich*, adopts Earman's well-known definition of determinism and looks at classical as well as quantum theories to explore the prospects of determinism. Analyzing dynamical systems in classical terms, Patrick Suppes has argued that the determinism issue transcends any possible evidence. Wüthrich does not find this argument convincing, partly because it is couched in classical terms. In quantum mechanics, things become much more complicated. Conventional wisdom has it that the time evolution of the wave-function according to the Schrödinger Equation is deterministic, whereas the results of measurements are indeterministic. But for Wüthrich this is too simplistic. He points to reasons for doubting that the Schrödinger evolution of the wave-function is deterministic. Regarding measurements, everything hinges on a solution of the measurement problem. Competing solutions to this problem differ on whether the quantum world is deterministic or not. Whereas it is indeterministic under the GRW theory, it is not so under the Bohm theory. Some of the rivaling interpretations may be distinguished in terms of their implications for experiments, but, as Wüthrich points out, the Bohm theory has an indeterministic but empirically equivalent rival, viz. Nelson's mechanics. A more promising route to decide the determinism issue may be to draw on the formal apparatus of quantum mechanics only. One may argue that Gleason's Theorem implies indeterminism, and recently Conway & Kochen (2006) have proven a theorem that they call the Free Will Theorem and that they take to imply indeterminism. However, as Wüthrich shows, the arguments put forward have loopholes, and so there is no easy route from the quantum formalism to indeterminism. Wüthrich concludes that neither are there decisive arguments in favor of determinism or indeterminism, nor has it been shown that the determinism issue is undecidable.

So much for the essays in this volume. As will have become clear, there are themes that resurface more than once, and this could hardly be avoided given the ways the issues are interrelated in this field. We take it to be an advantage that, for example, Gleason's Theorem is mentioned by several authors, so that the reader can compare different perspectives on the theorem.

We have chosen not to unify the mathematical notations in the contributions, simply because different fields of physics tend to come with their own notational conventions. Each essay is self-contained, and the essays can be read in any order whatsoever. We hope that this volume will help the reader to find her own way through the field and to develop her own stance. Last but not least, it will also stimulate further discussions about probabilities in physics—or so we hope.

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