20 Philosophy of Physics

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1 What Are Physics and the Philosophy of Physics?

The philosophy of physics concerns the philosophical foundations of specific theories in physics—classical mechanics, electrodynamics, statistical mechanics, quantum mechanics, relativity—and also more general philosophical issues concerning the nature and aims of physics, the metaphysical nature of fundamental laws, matter, fields, space and time, the direction of time, objective chance, reduction, and causation. Philosophy of physics is not only a major field in its own right but is also important for other parts of philosophy, especially epistemology and metaphysics. It is significant for epistemology because physics is the source of our most general and fundamental knowledge of the natural world and in particular knowledge of those parts of the world that are not accessible to observation. It is essential to metaphysics since it provides the best accounts we have of the universe's fundamental ontology and explanatory structure. Physics is arguably "the royal road to metaphysics."[1] This

[1] The idea that the primary source for metaphysics should be physics has been much discussed and forcefully advocated in recent years (Maudlin 2007, Ladyman and Ross 2007, . Of course the idea is not new (Descartes, Leibniz, and Newton among many others adhered to this view) but a good deal of metaphysical speculation and debate in the twentieth century has proceeded without much attention to developments in physics, especially developments involving relativity theories and quantum mechanics. The importance of the philosophy of physics to other parts of physics and the need for philosophers to have an acquaintance with physics and the philosophy of physics is emphasized by Michael Dummett; "The greatest lack, however, is of philosophers equipped to handle questions arising from modern physics [or older physics!]; very few know anything like enough physics to be able to do so. This is a serious defect, because modern physical theories impinge profoundly upon deep metaphysical questions it is the business of philosophy to answer. We may hope that some philosophers may become sufficiently aware of this lack to acquire a knowledge of physics adequate both to integrate

chapter discusses a few of the most interesting and accessible issues in the philosophy of physics and also some points at which developments in the philosophy of physics are relevant to epistemology and metaphysics. However, the reader is forewarned that the subject of philosophy of physics is vast and a great deal of it is technical. Perforce my selection of topics and emphasis are idiosyncratically shaped both by my particular interests and a desire to keep technicalities to a minimum.

Greek natural philosophers (Leucippus, Democritus, Epicurus, and Aristotle) laid down many of the ideas that that are central to the development physics. Specifically, they set the primary subject matter of physics as regularities in the *motions* of material objects. They also introduced the idea that some motions (e.g. circular, straight, etc.) are *natural*, which turned out to be very influential much later. Greek and Roman atomists held that material objects and processes are composed of a few kinds of fundamental unobservable parts (atoms) and that the behavior of complex phenomena is to be accounted for in terms of the arrangements and behavior of their parts. The scope of physics has been greatly extended over the centuries but the unobservable ontological posits that have been introduced (e.g. fields, space-times, wave functions, elementary particles, dark matter, etc.) ultimately earn their keep by the roles they play in accounting for the motions of quotidian material objects.

Although ancient Greek and Egyptian philosophers and astronomers described some motions with great accuracy (e.g. Ptolemy's description of the motions of the planets) it was not until the seventeenth century that the mathematics needed to describe motion and changes in motion (primarily the calculus) was sufficiently

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it with their treatment of metaphysical problems and to convey to philosophical colleagues who know less physics what they are talking about" (Dummett 2010).

developed and employed. Around the same time the modern conception of "law of nature" as expressed by differential equations emerged and it was recognized that the motions of celestial and terrestrial objects were governed by the same laws. These developments were essential elements to the creation of physics as an exact mathematical science whose aim is to explain all motion in terms of a few simple laws and a few ultimate constituents of matter. The crowning achievement was Isaac Newton's formulation in his *Principia Mathematica* of a few mathematical laws that he thought govern the motions of all material objects and his use of these principles to explain and thus unify terrestrial and celestial motions.

2 Newtonian Mechanics

If we understand Newtonian mechanics as an attempt to formulate a fundamental and complete theory of the world it claims that the universe consists of a fixed number of indestructible point particles that reside in a 3-D Euclidian space and move relative to the flow of time. Absolute space and time as they are called is the stage on which the particles perform. Particles have intrinsic properties (mass, electric charge, and so on) and extrinsic relations derived from their locations in space and time. Thus two particles are a mile apart at time t if they are located at points of space that are a mile apart and a particle is moving at an average speed of one mile/hour between times t and t' if the distance the particle traverses through absolute space divided by the duration from t to t' is one mile/hr.[2] The velocity at an instant is a vector quantity equal to the derivative of distance (in a direction) with respect to time and

[2] In standard discussions of mechanics a particle's velocity is defined as the time derivative of the particles's position. But there are two views concerning the metaphysical nature of velocity. One is that a particle's velocity at each time is metaphysically derivative on its trajectory. The other is that its trajectory is metaphysically derivative on its velocity at each time. Given Newton's notion of time as "flowing" the second seems more apt.

acceleration is the second derivative with respect to time.[3] The guiding idea of Newtonian mechanics is that a particle's *natural* motion (motion when no force is acting on it) is to continue in the same direction in a straight line at a constant speed. A change in a particle's speed or direction (acceleration) is due to the forces acting in that direction on the particle. The notions of straight line and constant velocity, etc. are specifiable in terms of the Euclidian structure of absolute space and time and forces acting on a particle are characterized in terms of laws.

Newtonian mechanics contains three types of laws; (a) laws of force that specify the forces acting on particles depending on their intrinsic properties and spatial arrangements, (b) laws concerning the nature and compositions of forces, and (c) a dynamical law that specifies how the total force on a particle affects its motion. Forces are also vector quantities. Examples of each kind of law are (a) Newton's law of gravitation $F(1,2)=Gm1m2/r(1,2)^2$, (b) the total force on a particle is the vector sum of individual forces on it, and (c) F(p)=ma(p) where F(p) is the total force on particle p and a(p) is the acceleration of p.

Newtonian mechanics is *complete*, *deterministic*, and *time reversible*. Newton did not know all the kinds of particles and forces there are but we can suppose that when they were discovered his account would be *complete* in the sense that an inventory of what particles exist, their intrinsic properties, their trajectories throughout all time, and the totality of forces and their associated laws represent absolutely everything that could be said about the physical history and operation of the universe in the fundamental language of physics. Insofar as macroscopic entities

[3] F(1,2) is the gravitational force that particle 1 exerts on particle 2 and r(1,2) is the distance between the two particles. The direction of the force particle 1 exerts on particle 2 is toward particle 1 and visa versa. F(2,1) = F(1,2).

and properties (planets, mountains, clouds, butterflies, etc.) supervene on fundamental physical history and fundamental laws macroscopic history would also be completely specified.

Newtonian mechanics is two-way *deterministic* in the sense that given the classical mechanical state at any time t (i.e. the positions and velocities of each particle and their intrinsic properties at t), the entire future and past history of the universe in every detail is determined by the laws.[4] Newtonian mechanics is time reversible in that for any sequence of states that is compatible with the laws there is a temporally reversed sequence that is also compatible with the laws. We will have more to say about time reversibility when we discuss the direction of time and statistical mechanics.

In order to apply Newtonian mechanics to macroscopic objects, for example, the moon, projectiles, springs, and so on physicists need to make certain idealizing assumptions. For example, to apply the laws to planetary motions it is assumed that although a planet is an arrangement of a very large number of point particles persisting in more or less that arrangement it can be treated as a single "point particle" located at the planet's center of mass whose mass is the sum of the masses of all the particles that compose the planet, and that the only relevant forces are gravitational originating in the sun and other objects in the solar system. On the basis of such idealizations one can derive Kepler's laws, Galileo's laws of free fall, the law of the pendulum, Hooke's law, and so on. The explanatory unification brought about by Newtonian mechanics is nothing short of mind boggling!

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[4] This is an oversimplification. There are solutions to Newtonian equations (depending on what velocities and forces are allowed) that violate determinism but involve special initial conditions and forces. See Earman 1986.

On its face the fundamental ontology of Newtonian mechanics consists of space, time, material point particles (and their intrinsic properties/quantities), and perhaps also forces and laws.[5] If Newtonian theory is understood merely as an *instrument* for making predictions (e.g. of the apparent motions of the planets in the night sky) then one need not be too concerned about understanding this ontology or how it is that the macroscopic world is constituted by or supervenes on the lawful motions of material point particles. But if one understands Newtonian mechanics in *realist* fashion as an attempt to specify fundamental reality then questions concerning the nature of this ontology arise that are quite difficult. A good deal of the history of physics from the seventeenth century to the present can be seen as a battle between (sometimes more subtle forms of) instrumentalist and realist understandings of the aims and proposals of physics. The issue of whether physical theories can be understood in realist fashion as providing an account of the world will come up a number of times in the ensuing discussion.

In Newtonian mechanics point particles constitute the substance of the physical world. Mass (resistance to acceleration) is had by all particles and is what gives the world its heft. Presumably, there are particles that are identical in the values of their intrinsic properties and so differ only in their locations in their trajectories in space. Thus Newtonian mechanics violates some versions of the principle of the identity of indiscernible.[6] A Newtonian would say "so much the worse for the

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[5] Newtonian mechanics is often presented as though forces are some kind of entity or power and so are among the world's primitive ontology. It is possible to formulate mechanics without any reference to forces and simply in terms of equations of motion of particles, for example, Hamilton's equations. It is not clear whether Newton thought of laws as regularities grounded in forces and material particles or as something like divine edicts that govern particles and forces or in some other way.

[6] Of course points in absolute space already violate the PII.

principle." An ordinary physical object, for example, a stone, consists of many particles (perhaps with different masses and other intrinsic properties) arranged in a particular configuration and held together by forces of some kind. How the whole macroscopic world and especially so-called secondary qualities and mental phenomena are constituted by or supervene on or emerge from configurations of point particles is, to say the least, extremely difficult and puzzling. That discussion is beyond the scope of this article although, as we will see when we come to quantum mechanics, the relation between mental and physical has a way of intruding itself in to the philosophy of physics.

Newton thought of absolute space as an infinite 3-D Euclidian manifold completely uniform in its nature. Its points or locations persist over time so that it is an objective matter of fact whether a particle occupies the same or different locations at different times (i.e. whether the particle has changed location). Absolute space is a "substance" insofar as it exists independently whatever material particles inhabit it. On the Newtonian conception it would be possible for there to exist space without any particles although particles by their nature must have location in space. Newton held that time "of itself, and from its own nature, flows equably without relation to anything external."[7] Whatever "flow" may mean it is clear that he held that time exists independently of the material contents of space and that its "flow" determines the temporal ordering and the durations between all events (e.g. the time between two collisions). While Newton thought of both space and time as "absolute" he also thought of them as fundamentally different since time but not space "flows" and this flow provides time with an intrinsic direction.

[7] Scholium to Definition 8 of the *Principia* in Newton 1934

Newton’s views of space and time strike some as commonsensical. However, soon after he formulated his mechanics a controversy arose over whether the existence of absolute space and time are really required in order to account for motion and even whether they are comprehensible. Leibniz argued that absolute space offended theology and the principle of sufficient reason since God would have no reason to place the particles of the universe in one part of space rather than another. It also offends Leibniz’s principle of the identity of indiscernibles since distinct points in absolute space are qualitatively indistinguishable. These controversial metaphysical principles aside there are reasons to worry about absolute space that are more closely connected to Newtonian mechanics itself. In absolute space and time there are matters of fact concerning the spatial distance between events when they occur at different times and thus a matter of fact about a particle’s absolute velocity. But Newtonian theory implies that it is impossible to empirically determine absolute position and absolute velocity.

Newtonian space+time determines a frame of reference that can be characterized in terms of a coordinate system. By selecting an arbitrary point in absolute space and an arbitrary point in time as the origin, three mutually perpendicular directions in space and units of distance and duration each particle is provided with an address at each time. We can also define frames of reference (and coordinates) whose origin is moving uniformly with respect to the absolute frame. These are called “inertial frames.”[8] Both Newton and his critics realized that the Newtonian laws are invariant with respect to inertial frames in that they predict exactly the same forces, relative velocities, and accelerations in every inertial frame.

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[8] A “Galilean” transformation takes coordinates of one inertial frame to the coordinates of another inertial frame by the mapping $x'=x-vt$, $y'=y$, $z'=z$, $t'=t$.

It follows that there are no measurements or observations we can make that will tell us whether any particular inertial frame corresponds to the absolute frame and so there is no way to determine a particle's absolute velocity or the distance between two nonsimultaneous events. The best we can do is measure the distances between particles, their relative velocities at a time, and changes in their relative velocities. It seems that by positing absolute space and time Newton allows for "facts" that are irremediably inaccessible. One does not have to be much of an empiricist to find such "facts" suspect. Further reflection could lead one to think that absolute space is a spooky kind of entity whose only job may seem to be to provide relative distances and velocities for material objects.

Worries along these lines motivated relationist reworkings of Newtonian mechanics. Relationists about space reject the existence of absolute space and replace it with fundamental distance relations between particles. On a relationist account, instead of specifying the positions of particles relative to absolute space+time a complete inventory need only specify the *relative* distances between particles at each time. The relationist reworking of Newtonian mechanics is an attempt to specify the laws making use only of spatial relations that has the consequence of specifying exactly those spatial relations that are compatible with Newton's laws. To get a feel for the dispute will briefly describe (in updated form) one highlight in the early history of the debate between absolute and relationist conceptions of space.

Newton argued that even though it is not possible to physically measure the absolute positions and velocities of particles absolute space is nonetheless required for the proper formulation of the mechanical laws and in particular to account for accelerations. Here is a thought experiment based on Newton's famous bucket argument and his related discussion of spinning globes that is intended to show this.[9] Consider a universe that consists entirely of two balls attached to opposite ends of a spring whose relaxed length is k. Imagine also that there is a time t(0) at which the length of the spring is greater than k and that no two particles (in the balls or the spring) are changing with respect to their mutual distances. On Newton's account the future motion of the balls and spring, whether it will oscillate or remain stretched, depends on whether the spring is rotating with respect to absolute space. If the spring is stationary, it will oscillate, but if it is rotating at just the right speed, it will remain stretched. The problem for relationism is that there is no fact at t(0) admitted by relationism concerning whether the spring is rotating or stretched since all the mutual distances among the particles and all the rates of change of distances are the same in either case. It follows that the state of the spring and balls at t(0) is not sufficient to determine its state at subsequent times. Thus relationism cannot distinguish two different possibilities at t(0) that lead to different subsequent behavior and consequently the relationist version of Newtonian mechanics is not deterministic.[10]

Relationists can respond by granting the failure of determinism in this simple universe but claim that this is of no consequence since the actual universe contains many more entities and relative to them there is a fact at each time as to whether a spring in the above condition is rotating. Ernest Mach proposed that acceleration should be defined relative to the "the fixed" stars or the bulk matter in the universe. In effect his suggestion to replace the frame that is determined by absolute space with the frame relative to which the fixed stars are not rotating. It follows that while on

[9] Newton describes a thought experiment similar to this one (Newton 1934, vol. 1, p. 12.). This version is due to David Albert.

[10] But relationist mechanics is almost deterministic since the state of the spring and balls at t(0) and a time close to t(0) will determine the extent of rotation.

Newton's conception there may be a fact as to whether the universe as a whole is rotating in absolute space Mach's account stipulates that the universe (the fixed stars) is not rotating.[11] So it not only rejects "unwanted" possibilities but also possibilities that seem genuine. A further, more peculiar, consequence of Mach's relationism involves a kind of nonlocality since whether or not the spring will oscillate depends on the distribution of the fixed stars.

There are other relationist responses to Newton's argument for absolute space.[12] All have costs since by eschewing absolute space they introduce complications in the formulation of the laws. Whether one is willing to pay the costs depends on how strongly moved one is by the empiricist considerations offended by absolute space and how strongly one prizes simplicity of laws. In any case, the whole issue of relationism versus absolutism looks very different from the perspective of contemporary physics, as we will see.

Absolute time in Newtonian mechanics is even more mysterious than absolute space. Newtonian absolute time would continue to flow even in a completely empty universe. Also there are possible worlds that match each other in the temporal sequences of all events but which systematically differ in the time intervals (as determined by the flow of absolute time) between events. The empiricist worry is that there is no way to determine which universe is actual and so one may wonder whether these are real possibilities. Further, it is not obvious how one can justify the claim that

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[11] For recent attempts to carry out Mach's program see Barbour 1999.

[12] For example, the relationist theory can be the claim that a history of changes in the distances between particles is physically possible if, and only if, these distances can be embedded in a fictional absolute space in such a way as to satisfy the Newtonian Laws. So absolute space is employed as part of a fiction to describe the actual world. This approach is not likely to please a realist about laws.

those physical mechanisms we consider to be good clocks actually measure duration of Newtonian absolute time or that we should care whether or not they do. Rather, good clocks measure relative durations (e.g. how many times the clock ticks while the earth revolves around on its axis). If clocks are coordinated with each other whether or not they are coordinated with the flow of absolute time seems irrelevant. Such thoughts have led to attempts to formulate mechanics without absolute time but only in terms of temporal duration between actual (or possible) events or even just temporal orderings of events.[13] Again there is a question whether this program can succeed and if it does whether the complexities are worth the cost.

3 Statistical Mechanics and Time's Arrows

Newton attempts to capture the idea that time has a direction by way of the metaphor that "time flows." It is not at all clear what he meant by this metaphor but it does suggest certain metaphysical views about time.[14] The metaphysics of time is controversial but it is not controversial that our world is full of temporally asymmetric processes, so-called arrows of time; for example, the melting of ice, the growth of plants, the life of the stars, causes precede effects, that we have records of the past but not the future, that we can influence the future but never the past, and so on. These asymmetries are pervasive and seem lawful but there is a problem accounting for them in Newtonian mechanics since its laws are oblivious to temporal asymmetries. For every sequence of states (positions and velocities of particles) that is compatible with the laws there is a temporally reversed sequence (obtained by reversing the

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[13] Barbour 1999.

[14] The metaphor of a flow of time suggests that there are irreducible tensed facts and so-called growing block or moving spotlight accounts of time (Callender 2012). Whatever these come to they do not seem required by Newtonian mechanics or the other fundamental theories we will discuss.

direction of velocities) that is also compatible with the laws. It follows that for every possible trajectory of positions of particles there is a temporally reversed sequence of positions. So if Newtonian mechanics were a correct account of our world then it would also be a correct account of a world in which temporal processes are reversed, for example, ice cubes grow bigger, people grow younger, and so on. It appears that the Newtonian laws cannot themselves explain the lawful temporally asymmetric processes. Although Newton's talk of time flowing introduces a directionality it is unclear what this has to do with the pervasiveness of temporally asymmetric pocesses. As far as Newtonian mechanics is concerned time could flow in the same direction whether the sequence of events is the melting of an ice cube or the spontaneous growth of an ice cube out of warm water.

The problem of reconciling temporally asymmetric processes with Newtonian mechanics became especially urgent to physics during the nineteenth century as physicists took seriously the idea that matter is composed of atoms and so that Newtonian Mechanics or something very much like it really could be the fundamental theory of the world. At the same time a science of macroscopic phenomena (involving systems composed of many atoms), thermodynamics, was developing that has smack right in the middle of it a temporally asymmetric law—the so-called second law. The second law, as it was first formulated, says that the entropy of an energetically isolated macroscopic system never decreases and typically increases over time until the system reaches thermodynamic equilibrium. Entropy and equilibrium are thermodynamic properties of macro systems that are characterized in terms of their relationships with other thermodynamic quantities; energy, pressure, work, temperature, etc. Roughly, the entropy of a system is inversely related to the quantity of useful work in the system and a system at equilibrium is one in which there is no useful work to be gotten out of the energy in the system. For example, the process in which a hot gas in a piston chamber is allowed to expand by pushing the piston is one in which work is extracted as the piston moves (the work can drive the wheels of a car) and entropy of the entire system increases as the gas expands and cools.

The problem of squaring thermodynamics with Newtonian mechanics is that since the latter deterministically accounts for the motions of all particles in terms of a temporally symmetric law there seems to be no room (without violating those laws) for an additional temporally asymmetric dynamical law governing particles and their motions. The first big steps toward reconciling the second law with Newtonian mechanics were taken by Ludwig Boltzmann. The upshot of his years of investigation is this: Boltzmann characterized the thermodynamic properties of a macro system, pressure, temperature, energy, entropy, equilibrium, etc. in terms of classical mechanical quantities (position, momentum, total energy, etc.) and a measure (the standard Lebesgue measure) over the set of possible states.[15] He then observed that even though there are infinitely many entropy-decreasing (toward the future) micro states that realize a nonequilibrium system (e.g. an ice cube in warm water) that evolve into lower entropy states (ice cube grows bigger) such states are, in a certain sense, *rare*. The sense is that on the standard measure the measure of the set of micro-states realizing the thermodynamic condition of an isolated nonequilibrium system that is entropy-decreasing is very small. Further, the measure of the set of entropy-decreasing states in small neighborhoods of typical micro states is also very

[15] The entropy of a macro condition M is given by $S_B(M(X)) = k \log |\Gamma_M|$ where $|\Gamma_M|$ is the volume (on the measure) in Γ associated with the macro state M, and k is Boltzmann's constant. S_B provides a relative measure of the amount of Γ corresponding to each M. Given a partition into macro states the entropy of a micro state relative to this partition is the entropy of the macro state that it realizes.

small. His next step was to construe the measure as specifying probabilities. It follows that the conditional probability of a system in a nonequilibrium macro condition M being in a micro state that lies on an entropy-increasing trajectory is approximately 1.[16] So it appeaed that Boltzmann explained how the temporally asymmetric second law can be reconciled with the temporally symmetric fundamental dynamical laws.

Howeve, a problem was soon noticed (by Loschmidt, Zermelo, and others) with Boltzmann's proposal. As a consequence of the temporal symmetry of the fundamental laws the uniform probability distribution applied to a system at time t in macro condition M entails that the probability that the entropy of the system was greater at times *prior* to t also is approximately 1. Boltzmann's probability assumption entails that very likely the ice cube in an isolated Martini glass was smaller an hour ago and even earlier was entirely melted (assuming that the martini glass has been isolated during that t). More generally, Boltzmann's probability posit applied to the macro state of the universe at time t entails that it is likely that its entropy was greater at both later and earlier times. Of course this is absurd.[17] If we come upon an ice cube in a martini glass that we know has been sitting isolated in a warm room for an hour we can be certain that the ice cube did not spontaneously arise out of warm water but was previously larger. So, while on the one hand, Boltzmann's probability posit apparently accounts for entropy increasing toward the future, on the

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[16] So the second law should not have been stated in the first place as an absolute prohibition on the entropy of a system decreasing but rather as being enormously unlikely.

[17] If the Boltzmann probability posit is applied to the macro condition of the universe at t since it implies that it is likely that this macro condition arose out of higher entropy states and in particular this means that the "records" in books, etc. likely arose out of chaos and not as accurate recordings of previous events. This undermines the claim that there is evidence reported in those books that supports the truth of the dynamical laws and so results in an unstable epistemological situation.

other hand, it entails the absurdity that entropy was greater in the past. This is the "reversibility paradox."

The history of statistical mechanics is littered with responses to the reversibility paradox. One is to construe the Boltzmann probability only as advice for making predictions but refrain from using it for retrodictions. This avoids the paradox but in common with other instrumentalist proposals elsewhere in the sciences it leaves us completely in the dark as to why the prescription works.[18] This is not the place for a survey of various other attempts to ground the second law while avoiding the paradox so I will simply describe a proposal developed by David Albert (though it has many precedents) since, in my view, it is the most promising.[19] It turns out that this proposal has profound consequences not only for the second law but also for times' other arrows.

It is generally believed on the basis of cosmological observation and theory that the state of the universe at or right after the big bang has very low entropy.[20] Call the very low macro state at this time M(0). Albert proposes that it is a law that there is a uniform probability distribution over the possible micro states that can realize

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[18] Also, the prescription will prescribe incompatible probabilities at different times since the uniform distribution over the macro state at t will differ from the uniform distribution over the macro state at other times.

[19] See Sklar 1993 for a discussion of some proposals for responding to the reversibility paradox.

[20] Although there are issues concerning how to think of entropy in the very early universe it is generally held that cosmology supports the claim that right after the big bang the entropy of the universe was very tiny. This may strike one as counterintuitive since at the big bang the universe was enormously tiny and dense with matter/energy uniformly distributed in space. But because gravitation acts to clump matter this is a very low entropy condition. For a discussion see Callender 2010 , Carroll 2010, Penrose 2005, and Greene 2004.

M(0).[21] So according to Albert there are three ingredients to the fundamental theory of the world.[22]

(a) The fundamental dynamical and force laws (in our discussion so far these are the Newtonian laws);

(b) The claim that the initial macro state is M(0) and that the entropy of M(0) is very tiny (Albert calls this "Past Hypothesis" (PH));

(c) A law specifying a uniform probability over physically possible micro states.[23]

These three ingredients provide a probability map of the universe since they entail a probability distribution (or rather probability density) over the set of all possible micro-histories of the universe compatible with M(0). This solves the reversibility paradox and explains the second law. Here is how. It follows from (a), (b), and (c) that the probability distribution over the micro states (and histories) of a system in state M(t) is conditionalized on M(t) and *also* M(0). The measure of the set of micro states that realize M(t) on the uniform distribution that are entropy-increasing in both temporal directions from t is practically 1. But conditionalizing on

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[21] This idea is not original with Albert. For example, it is explicit in a lecture by Feynman 1974.

[22] While the account is developed on the assumption of Newtonian mechanics the same considerations carry over to deterministic versions of quantum mechanics (e.g. Bohmian mechanics, and Everettian QM). If the dynamical laws are probabilistic (as on GRW theory) then the initial probability distribution may no longer be needed although the past hypothesis still plays the role it plays in the account that I sketch. See Albert 2000 for a discussion.

[23] Maudlin suggested in discussion that if the uniform probability distribution accomplishes all Albert claims for it then infinitely many other distributions will do as well. If so and if probabilities are understood objectively in the way I discuss later then there may be empirically discernable differences among these distributions or it may be a case of massive underdetermination. It is reasonable to posit the uniform distribution since it is the simplest until evidence is adduced against it.

the very low entropy macro state M(0) excludes all but a set of tiny measure of those realizers of M(t) whose entropy increases to equilibrium toward the past. It thus blocks the argument that gave us the reversibility paradox. Further, it entails that conditional on the macro state at each moment prior to the universe reaching equilibrium it is overwhelmingly likely that entropy increases in the temporal direction away from the big bang.[24]

The probabilistic version of the second law not only says that the entropy of the whole universe likely increases (or rather is likely to never decrease) as long as the universe is not yet at equilibrium but also that this holds for typical subsystems, for example, an ice cube in a glass of warm water under a wide variety of conditions. Here is a rough "seat of the pants" argument that this obtains. Suppose that S is a small subsystem of the universe that at time t "branches off" from the rest of the universe to become more or less energetically isolated and that the macro state of S is m(t). We can think of the micro state of S as being selected "at random" conditional on m(t) from the macro state of the universe M(t). Since "almost all" (i.e. measure almost 1) micro states realizing M(t) are entropy-increasing "almost all" of those realizing m(t) will also be entropy-increasing; that is, P(entropy S increases/m(t)&M(0)) is approximately 1. Of course this does not mean that it is likely that the entropy of *every* subsystem of the universe is likely to increase. Some subsystems are interacting with other parts of the universe so as make entropy decrease likely (e.g. the glass of water in the freezer). Or a system may be specially prepared so that even when it becomes isolated its entropy will very likely decrease.[25]

[24] It is thought that the length of time it would take for entropy to increase to equilibrium is far greater that the approximately 14 billion years that have passed since the Big Bang.

[25] See Albert 2000 for a discussion of how a Maxwell demon may prepare a system so that its entropy likely decreases.

In these cases the second law will be violated. But that is as it should be. The job is to ground the second law *insofar as* the second law is correct and, arguably, Albert's account does that.

Statistical mechanics probabilities help with a problem we overlooked earlier. As we observed when Newtonian mechanics (or any successor mechanics) is applied to macroscopic phenomena, for example, the motions of the moon, physicists assume that the moon can be represented by a particle at its center of mass. But in fact there are possible arrangements of the particles that comprise the moon that are compatible with its macroscopic state and in which the moon ejects some particles at great velocity and flies out of its orbit. If the particles are so arranged the idealization is incorrect. But physicists neglect these aberrant arrangements. Statistical mechanics justifies this neglect since the probability of aberrant states is miniscule.

It is worth reflecting for a paragraph or two on some of the philosophical implications of statistical mechanics. First, it suggests the possibility that all "times arrows," are grounded in the temporal asymmetry introduced by points (a), (b), and (c). If this could be shown then we might consider dropping the metaphor of "time's flowing" since it would play no role to account for the temporal asymmetries.[26] An objection to the account is that it presupposes the past/future distinction rather than explain it since it says that the big bang state that occurred 13.7 billion years or so in the past has very low entropy. But this is a mistake. It specifies that there is a very low entropy macro condition M(0) at the time of the big bang and no similar very low entropy condition at any other time between this event and the time the universe reaches equilibrium. The macro condition at the time of the big bang will earn its

[26] See Albert 2000 and Loewer 2012 for suggestions of how the statistical mechanical account may explain all of time's arrows.

name as the "*Past* Hypothesis" if it can be shown that the other arrows of time are aligned with the entropic arrow entailed by the account. That is, if it can be shown that the account not only explains the second law but also explains the temporal asymmetries of knowledge and influence, why the past seems closed and the future open, etc. on the assumption that the temporal direction of the big bang is the past then it will provide a *scientific* account of the past/future distinction.

A second consequence, both for physics and philosophy is the introduction of probabilities into physics. Statistical mechanics posits a probability distribution over the trajectories of possible states of the universe. Exactly what does probability mean here? Since it is assumed that the dynamical laws are deterministic the answer must be compatible with determinism. We will see that this issue arises again in quantum mechanics that has both deterministic and indeterministic interpretations. It is no understatement to say that there is no consensus within philosophy of physics concerning the metaphysics of probability whether it occurs together with deterministic or indeterministic laws.[27]

Third, the status of the PH raises some interesting epistemological questions. How do we know that the condition of the universe 13.7 billion years ago was one of very low entropy? I mentioned that this is the conclusion of cosmologists. But if statistical mechanics is correct then on Albert's account that very condition is required to ground the justifiability of the inferences that lead to this conclusion since without it the statistical mechanical distribution entails higher entropy past. Further, some physicists and philosophers believe that the PH is in some sense very unlikely

[27] There are discussions of probability in statistical mechanics and in quantum mechanics in Loewer 2001 and 2004.

since it is such a low entropy state it cries out for explanation.[28] Some have argued that such an unlikely event requires an explanation from outside of physics in terms of theology. Others have proposed multiverse accounts on which our universe bubbles off from a “mother universe.” Alternatively, one might look more closely at the question of whether the low entropy condition PH really “requires” an explanation in any more urgent sense than any other fundamental law.[29]

4 Theories of Relativity

During the nineteenth century it became clear to physicists that a number of phenomena—light, magnetism, and electricity—were difficult to fit into classical mechanics. Newton thought that light consisted of particles that interacted by way of some kind of force with material particles but experiment showed that light behaves more like waves than particles. Like water waves light generates interferences and is associated with frequencies and amplitude. Waves require a medium in which to propagate so it was hypothesized that space was occupied by a kind of ethereal substance dubbed “the ether.” So it seemed that ether should be added to the fundamental furniture of the world.

Electric and magnetic forces were found to obey laws similar to the gravitational law although the behavior of moving electrically and magnetically charged particles turned out to be complicated. There is a connection between moving charges (electricity) and light as, for example, manifested by lightning. James Maxwell proposed that electric and magnetic forces are aspects of a single electromagnetic force that itself can best be characterized in terms of a field—the

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[28] Roger Penrose (1989) has been especially insistent on this point. He estimates that the probability of this particular type of past state occurring is 1 out of $10^{10^{123}}$

[29] For a discussion of these points see Loewer 2012 , Carroll 2010, and Callender 2003. The theological proposal is an example of finetuning argument for design and a designer.

electromagnetic field. Mathematically, a field is characterized by an assignment of numbers and vectors (or other mathematical objects) to points of space. At first fields were thought of merely as a convenient way of specifying the forces produced by or would be produced by a particle P on other particles that might be located at various positions relative to P. But in the theory of electromagnetism developed by Maxwell the electromagnetic field takes on a life of its own (there are solutions in which there are no charged particles). Further it was hypothesized that light, and other kinds of radiation can be understood as waves propagating in the electromagnetic field. The field itself seemed to be either a property of the ether or perhaps a fluid-like entity that plays the role of the ether. So if a metaphysician at the end of the nineteenth century were to look to physics for the account of the fundamental ontology of the world he might conclude that it consists of 3-D space and time (the arena), particles (some charged), fields (and the ether), the fundamental dynamical laws, and the laws of statistical mechanics.[30]

However, around the beginning of the twentieth century it became clear that there are deep problems unifying these ontologies and laws. Newtonian mechanics requires that the laws be the same in all inertial frames as characterized in terms of invariance under Galilean transformations. But Maxwell's laws explicitly entail that the speed of light is independent of the speed of the light's source and so are not Galilean invariant. Further, a famous experiment by Michelson and Morley showed that the speed of light is independent of the earth's motion thus suggesting that it is the Newtonian laws that would have to be adjusted.

[30] Of course this is immensely anachronistic. No philosopher I know of looked at physics at the time in quite this way and if she did she would have heard a lot of conflicting answers among which are those in my list.

To effect reconciliation between the Newtonian and Maxwellian laws Lorentz modified the class of transformations that characterize inertial frames.[31] This modification entails that while there is a true speed of light relative to absolute space and time the measurements of the speed of light will yield the same result in all inertial frames. Lorentz's theory entails that clocks and measuring rods in motion relative to absolute space systematically "malfunction" in just such a way as to imply this result.[32] As was the situation in Newtonian mechanics it is impossible to determine one's motion relative to absolute space but its existence is required to formulate the theory.

Einstein's special theory of relativity (SR) proposes a very different explanation of the constancy of the speed of light. SR rejects that there is an absolute distinction between space and time. In its stead it posits that the arena of the world is a 4-D manifold called "Minkowski space-time." The geometry of Minkowski space-time is characterized in terms of a "distance" between space-time points that specifies the paths that a beam of light can take when moving in a vacuum. Given a point p in Minkowski space-time there is a 4-D cone formed from the paths that light can take when emitted from that point and a cone corresponding to the paths that light can take to converge on that point. Paths entirely within light cone correspond to paths (world lines) that a material particle can have and straight lines within a cone correspond to inertial paths (paths taken by particles that are not accelerating).

Unnumbered Figure 1 Here

[31] The Lorentz transformations are: $x' = (x - ut) / \text{sqrt}(1 - u^2 / c^2)$, $y' = y$, $z' = z$, $t' = \{t - (u / c^2)\, x\} / \text{sqrt}(1 - u^2 / c^2)$.

[32] See Bell 2008 for an account of Lorentz's proposal.

The Newtonian and Maxwellian laws formulated in terms of this space-time entail that the speed of light is independent of the motion of its source since light emitted at a point travels on the surface of the forward light cone associated with that point irrespective of the motion of the source. This consequence is required to reconcile mechanics and electrodynamics. But there are other, astonishing consequences, of SR. For example, unlike Newtonian space in which all events are completely ordered in time, in SR only those events that lie within the past and future light cones of a point are temporally ordered. Two events that lie outside of each other's light cone are not temporally comparable (they are said to be "space-like" related). Newton's view that time flows equably throughout all of space is thus rejected. The properties mass, length, speed, and shape that have application at a time in Newtonian absolute space+time are strictly never instantiated in SR. That is, there is no such thing as *the* length of a rod, or *the* shape of an object, or *the* velocity of a body at a time t and for that matter there is no such thing as *the* time of an event.[33]

However, length, simultaneity, etc. have surrogates that are characterized relative to a Lorentzian inertial frame. In other words, while there is no true length of a rod in Minkowski space-time there is the length of a rod relative to a Lorentz frame. A Lorentz frame is a coordinate system defined in terms of a family of inertially co-moving clocks (i.e. clocks moving on parallel paths). It is possible to "synchronize" the co-moving clocks thus specifying a time coordinate and to lay down 3-D coordinates specifying spatial locations. These then define length, duration, velocity, and so on, but only relative to the coordinate system determined by this family. Another family of co-moving clocks determines another coordinate system. Relative

[33] Metaphysicians who think that shape at t is an example *par excellence* of an intrinsic property should take note.

to one coordinate system an object that is spherical and moving at velocity v at time t (in that frame) will have a different shape and velocity relative to another frame. Lorentz frames themselves of course have no fundamental existence. Rather they and the surrogate relative concepts are introduced as part of an explanation of how the manifest world—the macro world as it seems to us under normal conditions—appears to have a Newtonian structure when in fact the fundamental space-time is Minkowskian.

SR has many astonishing (and empirically confirmed) consequences. The most famous is the equivalence of mass and energy expressed by $E=mc^2$ but the most astonishing is the relativity of temporal duration to motion relative to a frame and to paths traveled through space-time. For example, particles moving at a very high velocity (relative to our frame of reference) have longer (relative to our frame) half-lives.[34] Another is that clocks that move from one point in space-time to another on different paths will record different times. If twins meet at point p and one speeds off to the stars at high velocity and then returns to meet his twin (so they travel on different paths in space-time) he will have aged less than the stay-at-home twin. This "paradox" is explained by the fact that the twins travelled on different paths through space-time (clocks are to "distance" traveled in Minkowski space-time as odometers are to distance traveled in space).

In Newtonian mechanics mass plays two different roles. On the one hand it measures the resistance of a body to being accelerated by force (inertial mass) and on the other it determines the extent to which any material body exerts an attractive gravitational force on other bodies (gravitational mass). These are equivalent in that

[34] This consequence of relativity explains why cosmic rays entering the earth's atmosphere at high speed live longer before decaying than would the same particles at rest.

the ratio of any body's inertial mass to its gravitational mass is a constant. Because of the equivalence bodies with different masses fall in a gravitational field at the same rate (as famously demonstrated by Galileo in Pisa). In Newtonian mechanics this equivalence seems completely coincidental. Einstein devised his generalized relativity theory (GR) to explain the equivalence by building gravitation into the geometry of space-time. The basic idea is that the distribution of matter and energy determines the curvature of space-time and the cuvuture determines the trajectories of matter and radiation in accordance with certain laws (Einstein's field equations). The resulting space-time geometry may be non-Euclidian (as, for example, the 2-D geometry on the surface of a sphere or the inside of a saddle). In a non-Euclidean space-time inertial paths (world lines of bodies on which there is no force) traveled by bodies are curved geodesics. Thus two nearby objects fall at the same rate in a gravitational field not because of a gravitational force (there is no such thing in GR) but because they are traveling on similarly curved (in space-time!) inertial paths. GR not only explains the equivalence of inertial and gravitational mass but it also does away with the issue of the mechanism of gravitation—how gravitational force can act over great distances—by eliminating gravitational force in favor of the geometrical structure of space-time.

There is an enormous variety of space-times compatible with GR. Among these are universes in which space-time is closed so that a light beam sent in a direction eventually returns to its origin, which contain black holes (masses so dense that no light can escape), space-times with causal loops in which it appears that time travel is possible, space-times in which there is an "initial" point in time (as the big bang is usually thought to be), space-times that expand (and contract), and so on. GR is the framework in which cosmological theories about the origin and nature of the universe are formulated.[35]

Space and time in SR and even more so in GR are radically different from Newton's view of space as the stage of the universe and time as pacing motion as it flows equably through it. SR and GR are even more hostile to Leibniz's idea of doing away with space and time in favor of relations among particles. SR eradicated the sharp separation between space and time (and with it the notions of absolute simultaneity, distance, duration, velocity, etc.). GR went further by allowing for non-Euclidian space-time and turning space-time from an arena into an active player alongside of matter and fields. It is interesting to note that throughout these changes the idea of an inertial path inherited from Newton (who inherited the idea of natural motion from the Greeks) remains central in the fomulations of laws of motion.

5 Quantum Mechanics

The development of the atomic theory of matter that at first seemed to support the Newtonian idea that the ontology of the world consists of minute particles then proved to be its undoing. The central problem again concerned the interaction between charged matter and radiation. It was discovered that atoms consist of positively charged particles surrounded by much lighter negatively charged particles. Electrodynamics and mechanics imply that this configuration is not stable. Negatively charged particles would be attracted by the positively charged particles and fall into the atom's nucleus emitting radiation. In other words, matter would collapse and the world would come to an end! But this was just the tip of the iceberg. During the first decades of the twentieth century an enormous amount of evidence accumulated involving the behavior of charged particles, atoms, and light that was flatly

[35] See Carroll 2010 for an accessible discussion of the physics of time travel.

incompatible with Newtonian mechanics and electrodynamics. It seemed that in some circumstances atomic particles behaved like waves but in other circumstances like particles depending, it seemed, on what observations an experimenter chose to make. This behavior is extremely puzzling calling into question the possibility of a realist understanding of the world.

In response to these problems physicists developed a theory, Quantum Mechanics (QM) that avoids the disastrous consequences of Newtonian mechanics and electromagnetism and correctly predicts the vast amount of data concerning atoms and radiation. Here are the basics of how elementary QM works. A system S is fully characterized by a mathematical object $\Psi_S(t)$—the wave function of S at t—which is a vector in an appropriate Hilbert space. $\Psi_S(t)$ replaces the Newtonian notion of the state of a system (the positions and momenta of all the particles that constitute the system). $\Psi_S(t)$ specifies that some (but only some) of the properties traditionally associated with particles have determinate values and what those values are and also specifies the probabilities of the outcomes of measurements of any property relevant to the S. When $\Psi_S(t)$ assigns a determinate value to a property O then $\Psi_S(t)$ is said to be "an eigenstate" of O. Curiously when $\Psi_S(t)$ is an eigenstate of some property O (e.g. position) it is not an eigenstate of certain other properties O* (e.g. momentum) although it does predict the probabilities of outcomes of measurements of O*. This is the gist of Heisenberg's uncertainty principle.

More generally, if $\Psi_{Sk}(t)$ is an eigenstate of the position of an electron located at point k and Ψ_{Sk}'(t) is an eigenstate of the electron being located at k' then there is a state $\mathbf{a}\Psi_{Sk}(t) + \mathbf{b}\Psi_S{}'(t)$ called the *superposition* of these states. An electron in this state lacks (if this is the complete physical state) a determinate position. However the coefficients **a** and **b** specify the probabilities of finding the electron at k and at k' when position is measured. One of the most notable features of QM is the existence of so-called entangled states that involve particles in distinct regions of space. There are entangled states of a pair of particles states that are eigenstates of the outcomes of measurements of certain properties of the pair being correlated but are not eigenstates of any of these properties on either electron. In other words, QM (on the usual understanding) is saying that the values of the properties are correlated but there is no matter of fact (until measurement) as to what those values are.

QM replaces Newtonian dynamics with a linear deterministic equation specifying the time evolution of $\Psi_S(t)$ (Schrödinger's equation). This law holds in all situations *except* when measurements are made. If a measurement of a property quantity O (say position) of a system is measured then $\Psi_S(t)$ "collapses" into a new wave function $\Psi^*_S(t^*)$ in which O has a determinate value. The probability associated with the collapse is the same as the probability that a measurement of O on S at t yields that determinate value. In other words, if an electron is in state $\mathbf{a}\Psi_{Sk}(t)$ + $\mathbf{b}\Psi_S'(t)$ and its position is measured the collapse will result in a state in which the electron is located at k, k' with probabilities associated with **a** and **b**.

The wave function of an atom of hydrogen (consisting of an electron "orbiting" a proton) ensures the stability of the atom, appropriate wave functions predict the frequencies of light emitted by excited helium atoms, predict the periodic table, and so on. As a predictive tool QM is enormously successful. But even my brief description of the theory should be enough to see that it is very puzzling. What reality can possibly lie behind the wave function? What can be going on when a measurement is made? One reply associated with the orthodox or "Copenhagen" interpretation is that one should not press these questions very hard and instead should be content with an instrumentalist understanding of the QM.

The appeal of the Copenhagen view is that if one tries to understand QM in a realist way one is confronted with problems at every turn. First off the idea of a particle possessing a determinate position but not determinate velocity is, well, mind boggling (as is there being a determinate correlation but no determinate values that are correlated). Note, QM is not saying that when $\Psi_S(t)$ assigns a determinate position to S then S's velocity is 0. Rather, if $\Psi_S(t)$ is the complete state of S (as the standard account of QM maintains) then it says that S has no determinate velocity at all! How can it be that an electron is in a state in which it has no determinate position but assigns a probability to finding it at a particular location? Further, if the only dynamics of the wave function were Schrödinger's linear equation and if QM applies to macro systems like cats then, as Schrödinger showed, there are easily describable situations in which the wave function applicable to the cat fails to assign to the cat a state in which it is determinately alive or determinately dead.

The *measurement problem* in QM is the problem that in measurement (and many other) interactions if the governing law is expressed by Schrödinger's equation then the post measurement state of the measuring apparatus + system measured does not specify an outcome. The "collapse dynamics" was introduced exactly to avoid this absurd (and self-defeating) consequence. One cost of "solving" the measurement problem this way is that there are two radically different laws of evolution for quantum states; one deterministic and linear and the other probabilistic and nonlinear. The cost is steep since this way amounts to characterizing the fundamental laws in terms of a vague macroscopic notion of "measurement." Exactly which interactions count as measurements? One idea that was seriously proposed is that measurements occur only when a conscious being interacts with the physical system. It was suggested that mind is required for the existence of a determinate physical world. It is not surprising then that many physicists are content to construe QM as a mere predictive instrument and that some have even claimed that the success of QM demonstrates that a realist theory of a mind-independent world—the kind of theory that Newton, Maxwell, Boltzmann and Einstein were hoping to find—is out of the question.

Or is it? Einstein noticed that the anti-realism of the orthodox interpretation was closely connected to its reliance on the collapse and the assumption that the quantum mechanical description of state $\Psi_{Sk}(t)$ is complete; that is, there are no further facts about the situation of, for example, an electron whose QM state is $\mathbf{a}\Psi_{Sk}(t) + \mathbf{b}\Psi_{S}'(t)$ that would determine that it is located at k or that it is located at k'. Proponents of the Copenhagen interpretation gave proofs—no hidden variable proofs—that they thought showed that the QM state cannot be supplemented by further facts.[36] To the contrary, Einstein famously gave an argument that he thought showed that the QM state cannot be the complete state of the electron. Briefly, his argument (in a recent version due to Bohm) is this:

> There is a family of infinitely many properties of electrons ("spin properties") each of which can take one of two values—"up," "down"—such that when the state of a single electron is an eigenstate of one of these properties it is not an eigenstate of any other property in the family. Also there is an entangled state (the EPR [Einstein-Podolsky-Rosen] state) of a pair of electrons which is not an eigenstate of any of the spin properties for either electron. However, this state is an eigenstate of the values of the properties (for any of the properties) being correlated. In other words if a measurement of one of these properties is

[36] There is a famous argument due to von Neumann that allegedly establishes this. For a discussion of this argument and how it goes wrong see Bell 2008.

made on one of the electrons and the result is “up” than a measurement of the same property on the other one will yield “down.” Einstein imagined a situation in which the electrons are spatially separated (it makes no difference how far apart) and one of the properties P of one of the electrons is measured. According to orthodox QM upon measurement of P the state of the pair of electrons instantaneously collapses into a state in which both electrons have determinate values of P. Einstein noticed that this collapse seemed to involve some kind of non-local influence since the state of both electrons was altered by a local interaction with just one. He reasoned that the non-locality could be avoided only if the two electrons had determinate values of P all along that were revealed by and not brought about by measurement.[37] But this would mean that the QM state is not the complete state. In other words, he seemed to suggest that if and only if there is more to the state of a system than its wave function described then the collapse law with its “spooky” non-locality and the concomitant instrumentalism could be avoided.

Bohr and Pauli (and other defenders of the orthodox account) were not impressed by Einstein’s argument or at least did not budge from their claim that the QM state is complete. But 15 years later David Bohm devised an alternative to QM in which particles always have positions and the quantum state is not merely a mathematical object but represents something like a force field that guides the motion of the particles associated with it. The time evolution of this field is governed only by the linear Schrödinger law (no collapse) and there is an additional law (the guidance equation) that determines how the field guides its respective particles. In order to

[37] This account is rough but gives the gist of the argument. For a careful exposition see Bell 2008.

recover the probabilistic predictions of QM Bohm also added a probability distribution over possible locations of particles that is also determined by their quantum state in accordance with the usual QM prescription. Bohmian probabilities play a role not unlike the statistical mechanical probabilities.[38]

Bohmian mechanics makes the same probabilistic predictions as orthodox QM for the outcomes of measurements that are recorded in the positions (as all measurements ultimately are).[39] But unlike orthodox QM there is no "collapse" of the quantum state and the notion of measurement plays no role in the formulation of the theory. The apparent "collapse" of the wave function in measurement is explained by the theory itself. Schrödinger's cat paradox (and more generally the measurement problem) is solved since although the quantum state does not specify whether the cat is alive or dead the positions of its particles do.

Bohmian mechanics can be understood as an account of the fundamental ontology and laws of a mind-independent world. One might think, at first, that this is just the sort of theory Einstein was hankering after since it rejects the completeness of the quantum state and adds to the state positions of particles. Also its dynamical laws are deterministic (no dice playing) to boot. However, Einstein did not embrace it. Perhaps the reason was the way it handles the EPR experiment. On the Bohmian

[38] But the wave function in Bohm plays a very different role from the macro state in statistical mechanics since the former is an element of fundamental ontology.

[39] This claim requires some qualification. Since orthodox QM specifies that the quantum state collapses in measurement interactions there will be some in principle differences in the predictions it makes and the predictions Bohmian mechanics make regarding the measurements of certain very complex properties of the measurement apparatus. But we will never be in a position to know exactly what properties these are or even if we did make such measurements. So for all practical purposes orthodox QM and Bohmian mechanics are empirically equivalent.

account the outcomes of the measurements of spin properties are determined by the EPR quantum state, and the exact positions of the electrons prior to the measurements. However, it turns out that the way the quantum state yields correlated results is for the *first* measurement made on one of the electrons to alter the quantum state in just such a way as to "guide" the second electron into a trajectory that guarantees the correlation. In other words Bohmian mechanics has nonlocality built right into it. Einstein would have seen trouble for relativity on this account.

The way the Bohmian laws work there needs to be a matter of fact about which measurement of the electrons occurs *first* (if the other electron had been measured first the outcomes of both measurements might have been different.) This means that there is a conflict between Bohmian mechanics and SR understood as claiming that Minkowski space-time is the whole structure of space-time since there may be no matter of fact about which measurement occurs first. Bohmian mechanics requires there to be a preferred reference frame that is a real part of the space-time just as Lorentz assumed. So Bohmian mechanics was definitely not what Einstein had in mind when he imagined a replacement for QM.[41]

The nonlocality of Bohmian mechanics and its reliance on a preferred reference frame are often brought up as objections to it by adherents to the orthodox approach. But it should be recalled Orthodox QM (the collapse law) is also nonlocal and also has trouble with relativity.[42] An instrumentalist perspective encourages

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[41] Einstein said of Bohm's theory that "it is too cheap." Exactly what he had in mind is not completely clear but he was likely bothered by its apparent conflict with SR (Cushing 1994)

[42] The collapse can be formulated in Minkowski space-time (Aharonov and Albert 1984) but it is difficult to take their proposal as a serious realist account of the evolution of the quantum state.

proponents of the orthodox account to not be much troubled by the mismatch between QM and relativity. A more serious problem is that the Bohmian account has not yet been successfully developed for quantum field theory. In any case, Bohm's account did not receive a positive reception from the physics community and only fairly recently has it begun to be seen by some physicists and philosophers of physics as a promising realist alternative to orthodox QM.[43]

The question naturally arises as to whether the nonlocality found in Bohmian mechanics and in orthodox QM is inevitable. Could there be a satisfactory theory of the world that yields the same predictions as QM but is local?[44] In 1964 John Bell (Bell 2008 produced a simple proof that demonstrates that *no* local theory can recover exactly the predictions of QM. Further, the relevant predictions of QM that implicate nonlocality have been tested and found to be correct. The astonishing conclusion is that nonlocality is a feature of our world.[45] In other words, an event occurring in region R of space-time can affect what happens in some other region R* even when these regions are so separated that a light signal (or any other physical process) can get from R to R*. This may be the most important consequence of recent physics for

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[43] Bell (2008) argued that Bohm's account should be taken seriously and subsequently it has been greatly developed and clarified by Shelly Goldstein and his group (Goldstein 2012). In philosophy of physics one hardly sees a mention of Bohm's theory prior to the books by Albert (1992) and Maudlin (1994).

[44] Defining what it is for a theory or law to be local is subtle. The basic idea is that if A affects B it does so via a chain of events that are in an appropriate sense next to each other in 3-D space and time. Bohmian mechanics clearly violates this for the causes of an event in a small spatial region R. For a discussion on this see Maudlin 1994.

[45] There have been a number of attempts to get around Bell's argument and the empirical evidence that implicates nonlocality. Suffice it to say that in my view non are successful.

metaphysics. One the face of it nonlocality is a problem for various traditional metaphysical doctrines.[46]

There are other “interpretations” of QM in addition to Bohmian mechanics that can be understood as attempts to provide realist accounts. The most significant is Everett’s “Many Worlds” interpretation. The basic idea of the Many Worlds theory is that the measurement by a macroscopic measuring device of a particle that is in a quantum state like $\mathbf{a}\Psi_{Sk}(t) + \mathbf{b}\Psi_{S}'(t)$ (a superposition of the electron being located at k and being located at k’) results in the “branching” of the universe into two distinct, noninteracting universes, in one of which the particle is measured to be at k and in the other it is measured to be at k’. There are a number of ways of developing the Everett account. One is to take the basic ontology of the universe to be an evolving (in accordance with the Schrödinger law) quantum state understood as a kind of field that inhabits a very high (perhaps infinite) dimensional space. As it evolves the wave function “decoheres” with respect to certain degrees of freedom of the field and these “bunch up” and evolve as though they were separate “worlds.”[47] The Everett account faces two big issues. One, which has received a great deal of attention recently, is making sense of probabilities in the account. The Schrödinger evolution is deterministic and unlike Bohm’s theory there are no extra matters of fact (fundamental particle positions) over which probabilities can be defined. The other problem is explaining how our material world (perhaps along with many other

[46] Entangled states and the resulting nonlocality of QM are incompatible with the view that a complete account of the universe is specifiable by the contents of each small region of space-time (David Lewis’ doctrine of Humean Supervenience). See Lewis 1987, Loewer 1996, and Maudlin 2007.

[47] Decoherence of the wave function depends on the particular wave function of the system and its environment and the law of evolution.

worlds) with its quotidian material objects supervenes on a branch of the quantum state.[48]

6 Conclusion

At the beginning of the twentieth century physicists were faced with the problem of reconciling Newtonian mechanics and electromagnetic theory. The results were relativistic space-times and quantum mechanics. At the start of the twenty-first century physicists are faced with the problem of reconciling these. We already saw that realist versions of quantum mechanics seem to require a preferred reference frame and so to that extent are already at odds with SR. But the conflict between QM and relativity goes much deeper. Reconciliation of the two will require a quantum mechanical account of gravitation. While there are ideas about how that might be accomplished (string theory, loop quantum gravity) it is an open problem. Instrumentalists may be content to apply GR to the very large and QM to the very small and not worry so much about reconciling the two. But the realist dream (the dream of Einstein) will be realized only by a complete theory that specifies space-time, the particles and fields, etc. that inhabit it and the laws that govern the two. However that will go, it is certain that there is a lot in physics and philosophy of physics to be digested by metaphysics and epistemology.

Notes

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[48] For discussions of Many Worlds theories see Albert and Loewer 1988and Saunders et al. 2010. And Wallace 2012.

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