

## **Determinism and Indeterminism**

Jeremy Butterfield

### **Philosophical Concept**

Over the centuries, the doctrine of determinism has been understood, and assessed, in different ways. Since the seventeenth century, it has been commonly understood as the doctrine that every event has a cause; or as the predictability, in principle, of the entire future. To assess the truth of determinism, so understood, philosophers have often looked to physical science; they have assumed that their current best physical theory is their best guide to the truth of determinism. It seems that most have believed that classical physics, especially Newton's physics, is deterministic. And in this century, most have believed that quantum theory is indeterministic. Since quantum theory has superseded classical physics, philosophers have typically come to the tentative conclusion that determinism is false.

In fact, these impressions are badly misleading. The above formulations of determinism are unsatisfactory. Once we use a better formulation, we see that there is a large gap between the determinism of a given physical theory, and the bolder, vague idea that motivated the traditional formulations: the idea that the world in itself is deterministic. Admittedly, one can make sense of this idea by adopting a sufficiently bold metaphysics; but it cannot be made sense of just by considering determinism for physical theories.

As regards physical theories, the traditional impression is again misleading. Which theories are deterministic turns out to be a subtle and complicated matter, with many open questions. But broadly speaking, it turns out that much of classical physics, even much of Newton's physics, is indeterministic. Furthermore, the alleged indeterminism of quantum theory is very controversial: it enters, if at all, only in quantum theory's account of measurement processes, an account which remains the most controversial part of the theory.

### **1. Consensus**

Over the centuries, the doctrine of determinism has been understood, and its truth or falsity assessed, in different ways. (We follow the nearly universal practice of taking 'indeterminism' as simply the negation of determinism; so our discussion can focus on determinism.) Since the rise of modern science in the seventeenth century, it has been commonly understood as the 'law of universal causation', that every event has a cause; or as the predictability, in principle, of all of the future, given full knowledge of the present.

What evidence a philosopher takes to count for or against this doctrine varies immensely from one philosopher to another, according to their philosophical project. For example, many assess determinism in the light of their opinions about such metaphysical topics as free will or God (see Free will; Omniscience §3). Others see connections between determinism and broadly logical topics about time (see Many-valued logics, philosophical issues in §1). But this entry is restricted to formulating determinism, and assessing whether it is true, by considering the deliverances of physical theory. Of course, this restriction does not mean that our discussion only applies to wholly secular philosophers: many theistic philosophers, for example Kant, have discussed determinism in terms of the physics of their day. Some have even endorsed it, as part of their philosophy of nature; again Kant provides the outstanding example (see Kant, I. §7).

Making this restriction, we can say that since the seventeenth century, philosophers have typically taken their current best physical theory as their guide to the truth of determinism. And during the second half of this period, there has been a remarkable consensus about what that best theory is, and what it indicates about determinism.

During the nineteenth century, most of the educated public took Newtonian mechanics, and especially the Newtonian theory of gravitation, to be their best physical theory. Indeed, many took it to be an unrevisable foundation for physical theorizing. At its simplest, the idea was that Newton had laid down in his mechanics a schema for the mechanical explanation of the physical world. The schema was encapsulated in Newton's second law, that the force on a body is equal to its mass times its acceleration. Knowing the force and the mass, one could calculate the acceleration, and thus how the body moved. So to get a mechanical explanation of a given phenomenon, one had only to 'fill in the schema' by finding the forces involved. The paradigm case was of course gravitation; here Newton himself had discovered the nature of the force, and had calculated with stunning success how the planets and other celestial bodies move. Accordingly, many believed that Newtonian mechanics could in principle describe any phenomenon, perhaps by postulating strange forces (see Mechanics, classical §2).

They also believed that all the theories that could arise by thus filling in the schema would be deterministic; for the motion of a body would be determined by the forces on it (together with its initial position and velocity). The *locus classicus* for this view is a passage by Laplace, in which he not only states the doctrine that Newtonian mechanics is deterministic, but also provides formulations of determinism – first, in terms of causation, and then in terms of prediction; we shall later have reason to criticize both the doctrine and the formulations.

We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it – an intelligence sufficiently vast to submit these data to analysis – it would

embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes. The human mind offers, in the perfection which it has been able to give to astronomy, a feeble idea of such an intelligence.

(Laplace [1820] 1951: 4)

During the twentieth century, quantum theory and relativity theory became our best physical theories; by 1930, they had superseded classical physics. Since these theories are comparatively new and technically demanding, they have not become part of ‘educated common sense’ in the way in which Newtonian theories did (at least eventually, say by the mid-nineteenth century). But most philosophers who have addressed the topic have concluded that while relativity theory is deterministic, quantum theory is indeterministic. Indeterminism is taken to be the lesson of the much-cited uncertainty principle. This conclusion also has authority on its side: the great majority of the discoverers of quantum theory endorse it. So philosophers have typically come to the tentative conclusion that determinism is false.

## **2. Controversy**

But this consensus has been badly misleading. First of all, formulations of determinism in terms of causation or predictability are unsatisfactory. And once we use a correct formulation, it turns out that much of classical physics, even much Newtonian physics, is indeterministic; and that parts of relativity theory are indeterministic (owing to singularities). Furthermore, the alleged indeterminism of quantum theory is very controversial – for it enters only, if at all, in quantum theory’s account of measurement processes, an account which remains the most controversial part of the theory.

Formulations of determinism in terms of causation or predictability are unsatisfactory, precisely because of philosophers’ interest in assessing determinism by considering physical theories. That interest means that determinism should be formulated in terms that are clearly related to such theories. But ‘event’, ‘causation’ and ‘prediction’ are vague and controversial notions, and are not used (at least not univocally) in most physical theories. Prediction has the further defect of being an epistemological notion – hence Laplace’s appeal to an ‘intelligence’; while the intuitive idea of determinism concerns the ontology or ‘world-picture’ of a given theory (see Causation; Events).

Fortunately, the intuitive idea of determinism can be formulated quite precisely, without these notions. The key idea is that determinism is a property of a theory. Imagine a theory that ascribes properties to objects of a certain kind, and claims that the sequence through time of any such object’s properties satisfies certain regularities. In physics, such objects are usually called ‘systems’; the properties are called ‘states’; and the regularities are called ‘the laws of the

theory'. Then we say that the theory is deterministic if and only if for any two such systems: if they are in exactly the same state as one another at a given time, then according to the theory (for example, its laws about the evolution of states over time), they will at all future times be in the same state as one another. (Montague 1974, pioneered this kind of formulation.)

We can make determinism even more precise in the context of specific physical theories, by using their notions of system, state and law (regularity). But the classification of theories as deterministic or indeterministic is not completely automatic. For the notions of system, and so on, are often not precise in a physical theory as usually formulated. So various different formulations of determinism are often in principle legitimate for a given theory; and there is room for judgment about which formulation is interpretatively best.

However, it is well-established that the main conclusions are as reported above. The philosopher who has done most to classify physical theories in this way is Earman (1986), who upholds these main conclusions. We shall just briefly support these conclusions with two points that his book does not cover. (The details of the above formulation of determinism will not be needed for these points.)

First, much Newtonian physics is indeterministic. Indeed, indeterminism is lurking in the paradigm case discussed by Laplace: point-masses influenced only by their mutual gravitational attraction, as described by Newton's law of gravitation.

But surely the motion of each point-mass is determined by thus forces on it, in this setting the gravitational force (together with its initial position and velocity)? (See Mechanics, classical §2.) Indeed it is, *locally*. That is: given the initial positions, velocities and forces, the motion of each point-mass is determined, for *some* interval of time extending into the future. But it might be a very short interval. (Technically, the equations of the theory have a unique solution for some interval of time, perhaps a very short one.) Furthermore, as time goes on, the interval of time for which there is such a solution might get shorter, shrinking to zero, in such a way that after some period of time, the solution does not exist any more. In effect, determinism might hold locally in time, and yet break down globally.

One way this might happen is by collisions: in general, Newtonian mechanics is silent about what would happen after two or more point-masses collide. But more interestingly, it seems that it might also happen *without* collisions. Thus it was conjectured in 1897 that one might somehow arrange for one of the point-masses to accelerate in a given spatial direction, ever more rapidly and at so great a rate, during a period of time, in such a way that it does not exist in space at the end of the period! By that time, it has disappeared to 'spatial infinity'. (The source for the energy needed by the acceleration is the infinite potential well-associated with Newton's inverse-square law of gravitation.) That this can indeed happen with just Newtonian gravity was finally proved

true by Xia in 1992 (using a system of five point-masses). So now we know that, even setting aside collisions, Laplace's vision of Newtonian determinism is only valid for local intervals of time.

Second, quantum theory can be interpreted as being deterministic. De Broglie and Bohm showed that such an interpretation of elementary quantum theory is possible, despite the alleged proofs that it was impossible (given in the 1930s by some of the discoverers of quantum theory). The basic idea is that a quantum system consists of both a wave and a particle. The wave evolves deterministically over time according to the fundamental equation of quantum theory (the Schrödinger equation) and it determines the particle's motion, which therefore also moves deterministically, given the wave (hence this interpretation is also called the pilot wave interpretation). This contrasts with the orthodox interpretation. Roughly speaking, the orthodox interpretation accepts only the wave, and accommodates particle-like phenomena by having the wave evolve indeterministically (violating the Schrödinger equation) during processes of measurement (see Quantum mechanics, interpretation of §3; Quantum measurement problem). In recent years, the de Broglie–Bohm approach has been greatly developed so as to yield a deterministic interpretation of more and more of advanced quantum theory, including quantum field theory (see Cushing 1994). Suffice it to say, a deterministic interpretation of quantum theory is entirely coherent.

There remain two other controversial matters; which return us to general metaphysics and philosophy of science. First, should we apply the idea of determinism, as we have formulated it, to theories of the whole universe, that is, cosmologies? If so, then the 'systems' in question will be universes or 'possible worlds', that is, total possible courses of history. So one will in general not require that the systems whose states one compares must lie in the same possible world (see Possible worlds).

Second, should we accept the idea, for a given kind of system, of a complete theory, a theory that in some sense describes the whole truth about the systems? Some philosophers hold that this idea is incoherent: at least if it is filled out as allowing that such a theory is never formulated by humans; or at least if it allows that humans might be in principle incapable of formulating such a theory (see Scientific realism and antirealism §1). But if we accept some version of this idea, then we can reasonably talk of the systems, or perhaps the kind of system, being deterministic: namely, if and only if the systems' final theory is deterministic.

So the cautious answer to these questions is No. To answer Yes is to be bold: (some would say, incoherent). In particular, if we answer Yes to both questions, we are in effect accepting that it is meaningful to talk of the whole universe being deterministic. For we are accepting the idea of a complete theory of a given possible world (a total possible course of history). So we can reasonably call this theory the 'theory of the world', and its general propositions 'the laws of

nature' (see Laws, natural §1). (Again, humans are unlikely to have much idea of this theory or its laws.) And then we can say that the given world is deterministic if and only if its theory is. That is, the given world is deterministic if and only if any two worlds, obeying this theory, that have exactly the same state (in the sense of this theory) as one another at a given time also have exactly the same state at all later times.

The rest of this entry is restricted to discussing determinism for given physical theories. It thereby answers No to the second question; and, cosmological theories apart, it also answers No to the first question. But before embarking on this cautious strategy, we should briefly note that, historically, the bold (perhaps incoherent) idea of the entire world being deterministic, irrespective of any theory, has been very important; it has been the focus of countless philosophers' discussions of determinism (both for and against it).

### **3. Defining determinism**

In §2 we said that a theory is deterministic if and only if for any two systems of the kind described by the theory: if they are in exactly the same state as one another at a given time, then according to the theory, they will at all future times be in the same state as one another. But this formulation is still rough.

The main problem is that, whatever theory one considers, its systems are continually interacting with their environment: as physicists put it, no system is 'completely isolated'. For example, each system feels the gravitational pull of other objects. These interactions make determinism, as just formulated, an impossibly tall order. For, first, it will be very rare for two systems to be in exactly the same state at a given time. And even if they are, it will be virtually impossible that their subsequent interactions with their environments match so exactly that they are also in the same state as one another at all future times. But surely, determinism should not be so formulated that it will fail because of the vagaries of interactions with other systems: whether it fails or holds should be a matter internal to the theory considered.

The remedy is clear enough. To set aside such interactions, we need to formulate determinism in terms of completely isolated systems. But we cannot just think in terms of two systems in an otherwise empty universe. For in general the theory will take these two systems to interact with each other; so that again determinism can fail in a spurious way. That is to say, even if we suppose that at a given time the two systems are in the same state, at some future time they may well not be: their interaction, as described by the theory, might lead to their states differing. (The problem is of course aggravated if we think of the systems as also interacting in other ways, not described by the theory.)

To avoid this kind of spurious failure of determinism, we need to think of the theory as describing single completely isolated systems, each one alone in its universe. Let us say that a

sequence of states for such a single system, that conforms to the laws of the theory, is a *model* of the theory. So a model contains a system of the theory's kind, undergoing a history allowed by the theory: the model is a 'toy universe' or 'toy possible world', according to the theory. (This use of 'model' is common in general philosophy of science. In particular, it is often useful to consider a scientific theory as the class of its models in this sense, rather than in the traditional manner of logicians – as a set of sentences closed under deduction; see Models; Theories, scientific.) Using this notion of model, we can give a better definition of determinism, which avoids the problem of interactions. We say that a theory is deterministic if and only if: any two of its models that agree at a time  $t$  on the state of their objects, also agree at all times future to  $t$ . (This definition returns us to the first of the two questions at the end of §2: namely, should we apply the idea of determinism to theories of the whole universe, for example cosmologies? We now see that our strategy for avoiding spurious violations of determinism, due to interactions between systems, commits us to answering Yes to this question. For by taking a model of any theory to describe a single completely isolated system, alone in its universe, we are in a sense treating any theory as a cosmology. But since each of a theory's possible universes contains just one system of the kind treated by the theory, it is typically a humble, even a dull, cosmology!)

This definition is still a bit vague: precisely how should we understand a single time  $t$  in two models, and two models 'agreeing' on their states at  $t$ ? The answers to these questions lie in the idea of isomorphism of models, or parts of models; in the usual sense used by logicians. (There is no need for a 'meta-time' outside the two models, in terms of which their time series can be compared: thank goodness, since that would be very questionable!). Thus we can speak of an 'instantaneous slice' of one model (that is, the part describing the system at a single time) being isomorphic to an instantaneous slice of another model. And similarly, we can speak of isomorphism of 'final segments' of two models: that is, isomorphism of parts of two models, each part describing the system at all times future to some time within the model. Determinism is then a matter of isomorphic instantaneous slices implying that the corresponding final segments are isomorphic (where 'corresponding' means 'starting at the time of the instantaneous slice'). That is: we say that a theory is deterministic if, and only if: for any two of its models, if they have instantaneous slices that are isomorphic, then the corresponding final segments are also isomorphic.

#### **4. The notion of state**

To a philosopher, our definition of determinism looks very formal. And indeed, it is closely related to purely mathematical questions. For a physical theory is often presented as a set of equations, so-called 'differential equations', governing how physical magnitudes (for example, numerically measurable quantities like distance, energy and so on) change with time, given their values at an initial time. Our definition then corresponds to such a set of equations having a unique solution for future times, given the values at the initial time; and whether a set of

differential equations has a unique solution (for given initial values) is a purely mathematical property of the set.

But we should beware of identifying determinism with this purely mathematical property: there are conceptual, indeed metaphysical, matters behind the mathematics. The reason lies in the notion of state. We have taken states to be simply the properties ascribed by a theory to objects of a certain kind (the theory's 'systems'); and so as varying from one theory to another. But there are two general features which the notion of state needs to have if our definition of determinism is to be sure of capturing the intuitive idea. These features are vague, and cannot be formalized: but without them, there is a threat that our definition will be intuitively too weak.

First, states need to be intrinsic properties. It is notoriously hard to say exactly what is meant by 'intrinsic', but the idea is to rule out properties which might code information about how the future just happens to go, and thus support a spurious determinism. Thus, to take an everyday example, 'Fred was mortally wounded at noon' implies that Fred later dies. But the property ascribed at noon is clearly extrinsic: it 'looks ahead' to the future. And so this implication does not show that there is any genuine determinism about the processes that led to Fred's later death. Second, states need to be 'maximal', that is they need to be the logically strongest consistent properties the theory can express (compatibly with their being intrinsic). For in an intuitively indeterministic theory, there might well be some properties (typically, logically weak ones) such that models agreeing on these properties at one time implies their agreeing on them at all later times.

Do physical theories' notions of state have these two features? The question is vague because there is no agreed analysis of the ideas of an intrinsic, or a maximal, property. Perhaps 'maximal' can be readily enough analysed in terms of logical strength, as just hinted. But it is notoriously hard to analyse 'intrinsic'. But, by and large, the answer to this question is surely Yes. Physics texts typically define, or gloss, 'state' and similar words as a system's maximal (or 'complete') set of intrinsic (or 'possessed') properties; and in philosophy, the most commonly cited examples of intrinsic properties are the magnitudes figuring in the states of familiar physical theories, such as mass or electric charge. So it seems there is no widespread problem of spurious satisfactions of determinism.

But although there is not a problem, the need for these features brings out the main point: determinism is not a formal feature of a set of equations. Indeed, there are many examples of a set of differential equations which can be interpreted as a deterministic theory, or as an indeterministic theory, depending on the notion of state used to interpret the equations.

The idea of states as intrinsic also brings out two other points, one philosophical and one technical. The philosophical point concerns the ideas at the end of §2 about laws of nature, and



the whole universe (as against a given theory) being deterministic. One of course expects that making sense of the idea of laws of nature will involve the theory of properties. But we now see a more specific point: that making sense of the universe being deterministic will involve the general analysis of 'intrinsic'.

The technical point concerns theories that treat all the states up to the given time, taken together, as contributing to determining the future states. (There are a few such theories. It does not matter here whether all these earlier states taken together do determine all the future states: as, one might say, whether there is determinism of the future by the whole past.) At first sight, it looks as if such theories add to the usual intrinsic notion of state, a highly extrinsic notion – for which the state at a given time encodes some of the information in all earlier intrinsic states. What is going on?

In fact, in all such theories (so far as this author knows) the extrinsic notion is a technical convenience, rather than a new notion of state. The theory refers to the arbitrarily distant past (typically in some time-integral from minus infinity to the given time) just as a mathematically tractable way of stating information about the state at the given time, information that contributes to the future development of the system. (Wanting to state this information of course reflects the idea of states as maximal.) For example: in statistical physics, some such time-integrals define correlations in the present state; and in theories that study systems interacting with their environment, the past states of the system yield useful information about the present influence of the environment (which is otherwise not represented in the formalism).

Note that this explanation accords with a familiar tenet about causation: that past states influence the future, but only via their influence on the current state – there is thus no 'action at a temporal distance'. This tenet is widely held by philosophers; and to the extent that one can talk about causation in physical theories, it is upheld in physics. This is especially true of relativity theory; for relativity both unifies space and time, and upholds the principle of contact-action (see Relativity theory, philosophical significance of §3; Spacetime). The tenet is also closely related to a very common property (being Markovian) of probabilistic theories, both in physics and beyond. Indeed, according to some probabilistic theories of causation, the tenet is equivalent to the theory being Markovian.

Theories that refer to past states are relevant to our final topic: the fact (mentioned in §2) that there are some uncontroversial variations on our definition of determinism. So far we have for simplicity assumed that there is a single intuitive idea of determinism: the idea of the present state determining future states. But as we have just seen, there is an analogous idea: that all the states up to the present, taken together, determine future states. It just so happens that (using an intrinsic, maximal notion of state!) this idea is not obeyed in known physical theories: they have no 'action at a temporal distance'. But that is no reason to deny to the idea the name

‘determinism’; or, more clearly, ‘determinism of the future by the past’ (rather than by the present).

This point is reinforced by other analogous ideas, ideas which *are* obeyed in known physical theories. Thus in general relativity, and in quantum field theory, diverse technical reasons make it much easier to define a state on an interval of time (called a ‘sandwich’ of spacetime!) than at an instant of time (a ‘slice’ of spacetime). There is no hint here of action at a temporal distance: the interval can be arbitrarily short – it is just that for technical reasons it must have some duration. But such states prompt rather different definitions of determinism, requiring (roughly speaking) that for any interval, no matter how short, states to the future of that interval are determined by the state on it. And these definitions are often satisfied.

One can instead strengthen the definition of determinism, requiring the state at the given time to determine not only future states, but also past states. Many important physical theories have a property called ‘time-symmetry’ or ‘time-reversal invariance’, which implies that they satisfy this stronger definition, if they satisfy our first one. A famous example is Newtonian mechanics. Indeed, it may well be that Laplace had in mind this point (rather than just the intelligence having a memory), when he said in the quotation above ‘as the past’ (see *Mechanics, classical; Thermodynamics* §§4–5).

### References and further reading

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(Technical paper pioneering the kind of definition given in §2–3. This collection was posthumous published.)

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(Mathematical paper proving indeterminism in Newtonian gravitation.)

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