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DETERMINISM

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Determinism is a contingent metaphysical claim about the fundamental natural laws that hold in the universe. It says:

> The natural laws and the way things are at time *t* determine the way things will be at later times.

The mathematician Pierre-Simon Laplace (1820) expressed his belief that determinism is true this way:

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes. The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such intelligence.

The physics of Laplace's day (the first decades of the nineteenth century) was Newtonian (classical) mechanics. Isaac Newton formulated principles that he thought express the laws describing how forces determine the motions of bodies ($F = ma$) and how the positions of bodies and other factors determine gravitational and other kinds of forces. Using these principles, Newton and physicists following him were able to predict and explain the motions of celestial and terrestrial bodies. For example, these laws account for the orbits of the planets, the trajectories of cannon balls, and the periods of pendulums. Like Newton, Laplace did not know all the forces there are but he envisioned that, once those forces (and the corresponding force laws) were known, Newtonian physics would be a *complete* physical theory. That is, its laws would account for the motions of *all* material particles. And since he thought that everything that exists in space is composed of various kinds of very small material particles (or atoms) he thought that Newtonian mechanics (once all the forces were known) would be what today we would call *the theory of everything*. It seemed clear to him that the completed Newtonian theory would be deterministic and that it would thus be in principle possible accurately to predict the future (and retrodict the past) from complete knowledge of the present. It should be noted, however, that there are subtleties concerning whether Newtonian mechanics is deterministic in the way Laplace imagined it to be. It has been shown that there are initial conditions compatible with the laws for which the laws do not determine all future positions. However, those conditions are unusual and it is plausible that they can be ruled out as obtaining in our world.

Many people find the idea of determinism abhorrent and incredible. It is felt to be abhorrent by those who think that determinism is incompatible with free will and human dignity. It may seem that if determinism obtains then people are like marionettes whose movements are under the control of impersonal laws of nature. It also strikes many as incredible because it seems that so much of what happens – not just deliberate human action, but also the weather, the stockmarket, falling in love, and so on – is irremediably unpredictable and so, they think, constitutes proof that determinism is false.

On the other hand, some people find determinism to be an attractive and even inspiring metaphysical view. It seems to imply that every event (except perhaps the first event, if there is one) has a *scientific explanation*. And while it is granted that we cannot predict much of the future it might be argued that the reason is not that determinism is false, but, as Laplace suggests, that our intellect is too feeble to acquire the relevant information and make the required calculations.

Whatever visceral reaction one has to determinism, it is widely believed that debates concerning it belong to a previous era since it is now known that Newtonian mechanics is false and the theories that replace it – in particular quantum mechanics – are not deterministic. But, as we will see, the situation is more complicated and interesting.

Clarifying determinism

In the formulation of determinism, "determine" means "logically necessitates." The Newtonian laws are (modulo the remark about unusual initial conditions above) two-way deterministic because they and the state at *t* logically necessitates both the future and the past of *t*. Some philosophers have something stronger in mind by "determines." Their idea is that the present (and the laws) do not just logically imply the future but that they *bring about* future states. On this understanding, a temporal direction is built into the characterization of determinism since we think of the past as bringing about the future but not the other way around. I will say more about "bringing about" when discussing *laws*.

The *state at t* is explained in terms of the space–time and the fundamental ontology and magnitudes. The existence of the state at *t* presupposes a view about space–time and fundamental ontology on which there is a complete temporal ordering of all events and the fundamental magnitudes are exemplified instantaneously. The values of all these quantities specify the state at *t*. In Newtonian mechanics the state at *t* is specified in terms of the positions, momentum and intrinsic quantities, like mass and charge, of each particle at time *t*. In field theories the state at *t* is specified in terms of the field values (which can be vectors) at all spatial points at time *t*. There are fundamental theories that posit space–times and ontologies that do not share those presuppositions. For example, in the space–times of Einstein's theory of special and general relativity there are events that are not temporally comparable. Nevertheless, versions of determinism can be formulated for many of those space–times by finding something that plays the role of the state at a time such that it and the laws determine the events throughout all of the space–time (Earman 1986).

The most controversial and philosophically significant concept in the characterization of determinism is that of *law of nature*. The idea that there are *laws of nature* and that it is the job of the sciences to discover them developed during the seventeenth and eighteenth centuries with the rise of classical mechanics. An overly simple suggestion that may have a grain of truth is that laws as the basis of explanation came to be seen as an intermediary between God's will and his creation or even as a replacement for theological explanation. It became a central tenet of physics (and many of the other sciences) that knowledge of the laws of nature is the key to scientific explanation and reliable prediction. Not every true generalization (equation or function that maps each state on to its future) is or is associated with a law. If it were, then determinism would be trivial. So the question is, What makes a generalization or equation lawful? Part of the answer is provided by the connections between laws and other central notions in the sciences, in particular explanation, counterfactuals, causation, and confirmation. Explanations often involve specifying how a law and initial conditions entail the event to be explained. Laws support counterfactual statements: for example, if the distance between the earth and the sun were r meters then the gravitational force between them would be $F = Gm_e m_s/r^2$. Further, propositions that are apt for expressing lawful generalizations are confirmed by their instances.

While the features just mentioned help to identify laws, there is still a question of what laws are. There are two main philosophical positions concerning the metaphysics of laws, which I will call "Humean" and "metaphysical" accounts. The most sophisticated version of the Humean view is due to David Lewis (1994) and the most sophisticated version of the metaphysical view is due to Tim Maudlin (see Maudlin 2007).

On Lewis's account the laws are contingent generalizations implied by the *best systematization* of the distribution of fundamental entities, magnitudes, etc. Here is the idea. Let *L* be a language whose atomic predicates express only fundamental magnitudes and relations and mathematical notions and let *W* be the set of all truths of *L*. The laws (call them "L-laws") are defined as follows:

> Take all deductive systems whose theorems are true. Some are simpler, better systematized than others. Some are stronger, more informative, than others. These virtues compete: an uninformative system can be very simple,

> an unsystematized compendium of miscellaneous information can be very informative. The best system is the one that strikes as good a balance as truth will allow between simplicity and strength. How good a balance that is will depend on how kind nature is. A regularity is a law iff it is a [contingent] theorem of the best system. (Lewis 1994: 478)

According to Maudlin's metaphysical account, laws (call them "M-laws") are not themselves generalizations or regularities but rather fundamental elements of the world's ontology that *produce* the lawful regularities. Maudlin says little more about what laws are and exactly how a law *produces* regularity. His idea seems to be that laws are described by dynamical equations (e.g., $F = ma$). Given the state of the universe at t the laws evolve that state into subsequent states, producing a regularity satisfying the equation.

The question is whether the fundamental laws of our world are L-laws or M-laws (or some other account). On Lewis's account the best system of a world is determined by the entire history of states of the universe. It follows that the L-laws *supervene* on the totality of states. In contrast, M-laws (if there are any) do not supervene on the totality of states since different laws can *produce* the same total histories. For some advocates of M-laws this contrast is enough to establish that L-laws are too weak to do the work that laws are supposed to do. They say that L-laws are incapable of explaining state-evolution since they are determined by the states. But the issue is more subtle since L-laws and the state do *entail* subsequent states. Advocates of L-laws go on to say that we have no idea of how M-laws *produce* states. We cannot settle the issue here but will note some other differences between the two accounts.

The two accounts of laws may render different verdicts concerning determinism since the generalizations entailed by the world's best theory (if there is one) may be different from the generalizations brought about by the world's M-laws (if there are any). The two accounts also differ with respect to the connections they make between laws and time. The metaphysical account presupposes a temporal direction since the laws evolve the world toward the future. The L-view does not presuppose any intrinsic temporal direction but attempts to account for temporal direction in terms of the distribution of the structure of the totality of states.

It has been suggested that views about laws have consequences for the threat that determinism poses to the existence of free will. It has been argued as follows: we have no control over the past and/or the laws, and if determinism is true it seems to follow that we have no control over the future either. Some philosophers have responded to this argument by observing that while the argument may be sound if laws are M-laws, it fails if laws are L-laws. The reason is that the L-laws are determined by the totality of facts including facts about what we chose; so, rather than constraining our choices, they are partly determined by them (Mele and Beebee 2002; Hoefer 2005). I do not assess the strength of this response here, except to note that if it proves a good response, it would cast doubt on the claim that L-laws can explain and support counterfactuals.

The belief that determinism entails predictability is a reason why some people find determinism abhorrent. They might fear that if determinism is true, then others (or a superior intelligence) would be able to calculate what they will do and thus thwart their plans. But determinism and predictability are quite different claims, and neither entails the other. Determinism is a *metaphysical* claim about the fundamental laws of the universe; predictability is an *epistemic* claim about what we can *know* about the future.

There are a number of considerations that show why determinism does not entail predictability. First it may be impossible (because of our natures and the laws themselves) for us to know what the laws are. Even if we knew the laws we might not be able to use them to gain knowledge of certain future events because accurate predictions require knowing an enormous amount – possibly an infinite amount – about the present. In the case of Newtonian mechanics, perfectly reliable predictions of the *exact* future motions of particles require knowledge of the exact present positions and motions of all the particles in the universe, and the exact position of a particle will typically be represented by an infinitely long decimal. It may turn out that the laws themselves entail that the knowledge required to make certain predictions is impossible to obtain. Further, small differences at one time can make for very big differences a short time later with respect to matters that concern us. Another obstacle to prediction is that the mathematical equations expressing the laws may not be solvable except approximately. This, in fact, is the case for the simple Newtonian world when three or more particles are involved. Laplace was idealizing enormously when he suggested that an "intelligence" could predict future states from the present state and the laws.

On the other hand, the failure of determinism does not preclude the possibility of reliable predictions about the future. Of course, the extent to which we can reliably predict the future depends on exactly what the laws are. If the laws are probabilistic, it may turn out that, given the state or even a partial description of the state at t, the laws specify probabilities very close to 1 for some future events. Thus, even if coin-tosses are fundamentally random, we can pretty accurately predict that 1,000 tosses of an ordinary coin will result in between 450 and 550 heads. The moral of all this is that we should keep in mind that determinism is a metaphysical claim about the laws while predictability is an epistemic claim about what we can reliably predict, and neither entails the other.

Determinism and quantum theory

Laplace considered determinism to be true because he accepted that Newtonian mechanics is the true theory of everything and that it entails determinism. But Newtonian mechanics has been superseded by quantum mechanics (QM), and so the question arises of its consequences for determinism.

In non-relativistic QM the state of an isolated system is specified, not by the positions and momenta of particles as in Newtonian mechanics, but by a vector-valued *wave function* $\psi(t)$ that specifies the probabilities of the values of measurements made at t of the *observable* quantities of the system. The observable quantities, corresponding to position, momentum, total energy, spin, and so on, are the properties of quantum systems. They need not literally be observable. No state ψ assigns a probability of 1 for every observable. In particular, no ψ assigns a probability of 1 to values of both the momentum and the position observables associated with, for example, an electron. This is an instance of Heisenberg's *uncertainty principle*. On the orthodox, or "Copenhagen," interpretation of QM, an observable O (e.g., a particle's momentum) is said to have a *determinate* value if and *only if* ψ assigns a probability 1 to a particular value of that observable. (The "Copenhagen" interpretation refers to a collection of ways of thinking about QM associated with Niels Bohr and Werner von Heisenberg that came to be accepted as the orthodox way of understanding QM. A good discussion can be found in Cushing 1994.) It follows that no electron (or any other QM system) has both a determinate position and a determinate velocity. In fact, for typical states of elementary particles, neither position nor momentum, nor any other familiar quantities, possess determinate values. QM also includes a dynamical law – Schrödinger's *equation* – describing ψ's evolution. Schrödinger's law is deterministic and linear. So the question naturally arises of how probabilities come into the picture. On the orthodox account, the answer is that ψ obeys Schrödinger's deterministic law *except* when a system is being measured (or observed). When a measurement of O is made, the system randomly jumps into a state in which O has the determinate value with the probabilities specified by ψ.

There are a number of novel and peculiar features of QM. The most striking is the claim that quantities like position may not be determinate. This lack of determinateness is different from a failure of determinism since it says that at a given time a certain quantity, for instance position, has no specific value. Underlying this is the QM principle of superposition. If ψ_1 is a state corresponding to a particle being located in region 1 and ψ_2 corresponds to the particle being located in a distinct region 2, then there are *superpositions* of these states, $a\psi_1 + b\psi_2$, that correspond to the particle being located somewhere in the union of the two regions *but at no specific* place within the union of the two regions. The coefficients a and b determine the probabilities of the outcomes of position measurements in the respective regions. On the orthodox interpretation, it is not just that we do not *know* the exact location of the particle but that its location is *indeterminate*. Another peculiar feature is the role of *measurement* (or *observation)* in the formulation of the laws. This seems to make QM peculiarly subjective and certainly makes it inexact, without a precise characterization of measurements. A third peculiarity is *non-locality*. It turns out that there are states of, for example, a spatially separated pair of electrons for which, when a measurement of one of the electrons is made, the state of it *and the other electron* jumps into a new state (Bell 1987; Albert 1992).

The peculiarity of these features encouraged many physicists to take an instrumentalist attitude towards the theory. Instrumentalists think of QM as *merely* providing rules for predicting the outcomes of measurements. So understood, QM is silent about the ontology and the laws, whatever they might be, that lie behind its predictions. Some physicists believed it to be impossible to supplement or modify QM while preserving its predictions and impossible to remove the notion of observation from the theory. If this were the last word about QM then QM would be silent on whether determinism is true.

However, there are realist ways and also deterministic ways of understanding QM that are now beginning to be taken seriously by some physicists and philosophers. The most important deterministic account is the so-called "hidden variables theory" devised by David Bohm in 1952 (see Bell 1987; Albert 1992; Cushing 1994). The ontology of Bohmian mechanics consists of particles (that always possess definite positions) and a quantum field that corresponds to the wave function. The state of a system at *t* is determined by the positions of the particles at *t* and the values of the quantum field at *t*. The dynamical laws are Schrödinger's law and a law (the "guidance equation") that specifies the velocities of the particles. These laws are thoroughly deterministic. Probabilities come into the picture through a probability distribution that is posited to hold over initial positions of particles of a system compatible with its wave function. Measurements are simply interactions between two systems that result in the value of a quantity of the measured system being correlated with a macro-state of the measurement instrument. The predictions of the results of measurements on Bohm's theory are exactly the same as those of orthodox QM. In particular, Bohmian mechanics entails the uncertainty principles and all the other probabilistic predictions of QM. The uncertainty is irremediable since it follows from the laws and the initial probability distribution that it is impossible to know the complete state of a system.

There are also realist versions of QM whose dynamical laws are indeterministic. The most fully worked out of these is the GRW theory, so called after its formulators: Ghirardi, Rimini, and Weber (see Albert 1992; Ghirardi 2005). The GRW theory replaces the deterministic Schrödinger law with an indeterministic law that specifies the probabilities of the state at *t* "jumping" into various possible states at subsequent times. The law has the consequence that for a system whose quantum state involves few degrees of freedom (with respect to particle position) the evolution will be as specified by Schrödinger's equation, except for very rare "jumps" that localize particle position. (The basic idea of the GRW theory is that the quantum state of a system evolves in accord with Schrödinger's law, except that there is a probability per unit time of the wave function of the state being multiplied by a very narrow Gaussian: see Ghirardi 2005.) But in macroscopic systems (e.g., a measuring device that consists of many particles) it is very likely that at least one of those particles will undergo a jump in a fraction of a second. Since the positions of the particles are correlated, when one jumps into a localized position state, the rest must follow. The consequence is that measurements and other macroscopic interactions result in quantum states in which macroscopic objects have determinate positions. There is no need to introduce the notions of "measurement" or "observer" into the formulation of the theory.

The most important point for our discussion is that orthodox quantum theory, GRW, and Bohmian mechanics are, for all practical purposes, empirically equivalent even though the first two are incompatible with determinism and the latter entails it. (There are, in principle, empirical differences between theories with collapses, like the orthodox theory and GRW, and no-collapse theories like Bohm's. However, it is plausible that they are empirically equivalent for all practical purposes, since it is unlikely that it will ever be possible to conduct an experiment whose outcomes discriminate among these theories.) This is a dramatic case of the *underdetermination* *of theory by all possible evidence*. Although neither of these theories is true (since they fail to take into account relativity), it is very plausible that if there is a theory of everything, there will be also be empirically equivalent theories that are deterministic and indeterministic. So it is very likely that the question of whether or not determinism is true is plausibly something that we will never be in a position to answer.

Determinism and statistical mechanics

Even if the dynamical laws are deterministic, as in Newtonian mechanics and Bohm's theory, probabilities are required for explanation and prediction. Suppose that, as Laplace thought, the world consists of point particles and the laws are given by classical mechanics. The macroscopic state of a system (even the universe) at a time is specified by the values of macroscopic quantities like temperature, average frequency of radiation, average mass, and charge density, in small, but not too small, volumes of space. The macroscopic state is typically insufficient to pin down, for example, whether or not there is an ice-cube floating in a pail of warm water in some particular room (or whether a room is full of people and other macroscopic features). For a given macroscopic state of a system at *t* there are infinitely many possible micro-states (states characterized by precise positions and momenta of all the particles that compose the system) only one of which *actually* composes the system at *t*. In Newtonian mechanics with a particle ontology (similar remarks apply to quantum theories) *the macroscopic* state of the universe (or an isolated system) at *t* and the deterministic dynamical laws determine very little about *the macroscopic* states at other times. For example, the macro-state of an ice-cube in warm water is compatible with "maverick" micro-states whose futures (as entailed by the deterministic laws) involve the ice-cube growing bigger or even forming the shape of Jimmy Durante's nose and jumping out of the water. So, if we just know the macro-state of the system (that it is an ice-cube floating in warm water), the deterministic laws are not sufficient to predict that the ice-cube will melt. The same point applies to the prediction of the motions of the planets and every other application of Newton's laws, if we think of planets, as Laplace did, as composed of atoms that obey Newton's laws.

Ludwig Boltzmann faced this problem when he tried to explain how the laws of thermodynamics are related to the fundamental dynamical laws. Thermodynamics includes laws that are temporally asymmetric and that reliably and deterministically predict how a system evolves. For example, the *second law of thermodynamics* says that *the entropy* of an isolated system never decreases. The entropy of a system is, roughly, the size of the collection of micro-states that are compatible with the system's macro-state. The increase in entropy of the ice-cube in warm water corresponds to the ice-cube's melting. So, the problem Boltzmann faced was how to square the temporally directed second law with the temporally symmetric fundamental laws. Boltzmann's solution is based on the observation that micro-states which the laws evolve to states realizing macro-states with greater entropy – maverick micro-states – are, in a certain sense, "rare." The sense in which maverick states are rare is not that there are fewer of them – there are infinitely many – but that a very natural measure on the set of micro-states assigns the set of maverick states a measure close to 0. (See Sklar 1993 and Albert 2000 for philosophical discussions of statistical mechanics.)

Boltzmann construed this measure as a probability distribution over the micro-states that are compatible with a given macro-state, and this has the consequence that maverick micro-states (e.g., those that spontaneously form into the shape of a nose) are exceedingly unlikely. It turns out (again not surprisingly since the dynamical laws are temporally symmetric) that the uniform distribution over the micro-states compatible with the ice-cube in warm water entails that it is highly likely that in the past (just as in the future) the pail contained water at a uniform temperature. A way of avoiding this consequence while preserving the good consequences is to posit the uniform distribution over micro-states compatible with the macro-state of the universe immediately after the Big Bang and to posit that the entropy of this is very, very low. This has the consequence that it is very likely that the entropy of the entire universe (and its relatively isolated subsystems) increases over time.

Given the dynamical laws and the initial micro-state, the statistical–mechanical probability distribution implies that the evolution at a macroscopic level appears to be indeterministic. Very small differences in the micro-states that realize a macro-state entail very different future evolutions. Even if a demon knows a very detailed macro-description of the roulette wheel and the motions of the croupier's hand, and so on, and knows the dynamical laws and could perform the relevant calculations, he could not predict the outcome of a turn of the wheel. Our world is apparently full of macroscopic phenomena (so-called "chaotic systems") whose future evolution is very sensitive to the initial micro-states that realize their macro-states.

There is controversy concerning exactly what "probability" means in statistical mechanics since the dynamical laws are deterministic. The same issue arises in Bohmian mechanics, as its dynamical laws are also deterministic. Since the outcome of a turn of the roulette wheel is strictly determined by the laws and the complete *micro*-state of the world prior to the turn of the wheel, it is often said that the probabilities involved in deterministic theories must reflect *merely* subjective ignorance. But this doesn't seem quite right, since these probabilities are based on objective facts about our world and are supposed to explain the second law. For that reason it is plausible to consider them objective and lawful. (There are proposals for how to understand probabilities objectively if determinism obtains, including a generalization of Lewis's best-system account of laws discussed earlier: see Loewer 2001 and 2004.)

Conclusion

At the turn of the twenty-first century, physicists have not realized Laplace's dream of a theory of everything and if there is such theory, it is not known whether it is deterministic. Nonetheless, the success of QM and statistical mechanics (which must be accounted for by any complete theory) provides very strong reason to believe that scientific account of the universe will involve probabilities either in indeterministic dynamical laws (as in orthodox QM and GRW) or as initial-condition probabilities (as in statistical mechanics and Bohmian mechanics). Further, it is very likely that if there is an empirically adequate proposal for a complete theory whose dynamical laws are probabilistic, there will also be an empirically equivalent account in which the fundamental laws are deterministic. The upshot is that it is likely that we will never know whether or not determinism is true; but it is certain that if it is true then there can be no predicting the future with certainty. This conclusion will doubtlessly be frustrating to those who think that whether or not determinism obtains has vast consequences for free will and other philosophical issues.

See also Laws of nature; Physics; Probability; Underdetermination.

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Further reading

The best book-length discussion of determinism is Earman (1986). For various views about the nature of laws, see Carroll (2004) and Lange's contribution to this collection. For Maudlin's view of laws, see Maudlin (2007). For elementary but philosophically sophisticated discussions of quantum mechanics and statistical mechanics, see Albert (1992) and (2000). For advanced discussions of the philosophy of quantum mechanics see Bell (1987). For advanced discussions of the philosophy of statistical mechanics, see Sklar (1995).