

for science. The main burdens of this Primer, then, are to say what determinism is and to describe in a way that is both introductory and realistic the problems and prospects of determinism in various branches of modern physics and at the same time to reveal how advances in understanding those problems and prospects are bound up with advances in mathematics, physics, philosophy of science, and metaphysics. I do not claim to have succeeded but only to have made a long overdue start on this neglected task. The challenge of completing the task will have to be left to abler hands.

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INTRODUCTION

With earth's first clay they did the last man knead,
And there of the last harvest sowed the seed.
And the first morning of creation wrote
What the last dawn of reckoning shall read.

Determinism is a perennial topic of philosophical discussion. Very little acquaintance with the philosophical literature is needed to reveal the Tower of Babel character of the discussion: some take the message of determinism to clear and straightforward while others find it hopelessly vague and obscure; some take determinism to be intimately tied to predictability while others profess to see no such bond; some take determinism to embody an *a priori* truth, others take it to express a falsehood, and still others take it to be lacking in truth value; some take determinism to undermine human freedom and dignity, others see no conflict, and yet others think that determinism is necessary for free will; and on and on. Here we have, the cynic will say, a philosophical topic *par excellence!*

Without any touch of cynicism one may ask what yet another tour of this Babel can hope to accomplish, save possibly to add another story to the Tower. My answer is not at all coy. Essential to an understanding of determinism is an appreciation of how determinism works or fails to work in physics, the most basic of all the empirical sciences; but it is just this appreciation I find lacking in the philosophical literature. My complaint does not center on technical niceties, though they become crucial at various junctures, but on the larger picture which emerges from the philosophical and the popular science literature. Classical physics is supposed by philosophers to be a largely deterministic affair and to provide the paradigm examples of how determinism works. Relativity theory, in either its special or general form, is thought merely to update classical determinism by providing for Newtonian mechanisms relativistic counterparts that are no less and no more deterministic. And it is only with the advent of the quantum theory that a serious challenge to determinism is supposed to emerge; the challenge is not simply that quantum mechanics is *prima facie* non-deterministic

but that "no hidden variable" theorems show that, under plausible constraints, no deterministic completion of the quantum theory is possible.

This picture is badly out of focus. Newtonian physics, I will argue, is not a paradise for determinism; in fact, Newtonian worlds provide environments that are quite hostile to determinism, and some of the alleged paradigm examples of Newtonian determinism are not examples of determinism at all, at least not without the help of props which sometimes have a suspiciously artificial and even question-begging character. The special theory of relativity rescues determinism from the main threat it faces in Newtonian worlds, and in special relativistic worlds pure and clean examples of determinism, free of artificial props, can be constructed. However, the general theory of relativity poses new and even graver challenges, challenges which are currently being addressed on the frontiers of scientific research. The quantum theory, of course, poses challenges of its own; but the first and foremost challenge is not to the truth of the doctrine of determinism but to its meaning in quantum worlds where the ontology may be nothing like that presupposed in the Newtonian and relativistic formulations of the doctrine.

Before we can have a Treatise on determinism, we need a Primer; we need first to learn how to spell and read the language of determinism before attempting lofty dissertations. The plan of this primer is as follows. In Ch. II I briefly review some of the many philosophical attempts to define determinism, and I propose a conception which, though vague, is nonetheless useful as a starting point for the discussion of classical and relativistic physics. Ch. III surveys the trials and tribulations that determinism faces in Newtonian worlds. Ch. IV is devoted to special relativistic physics and shows how this context makes possible the fulfillment of the classical dream of determinism, a dream which is disturbed by nightmares in Newtonian worlds. Ch. V interrupts the discussion of specific developments in physics to get a better fix on the crucial but troublesome notion of laws of nature. Ch. VI discusses the connections among determinism, mechanism, and effective computability. Computability is initially taken in Turing's sense and various results about the preservation of computability of initial data under deterministic evolution are reviewed; but it is also urged that deterministic systems give rise to a much broader notion of effective computability of which Turing's is but a special case. Ch. VII charts the relation of determinism to various time symmetries of laws, especially

time reversal invariance, periodicity, and time translation invariance. Ch. VIII offers some suggestions for understanding the concepts of randomness and chaos and the conditions under which random and chaotic behavior are and are not able to peacefully coexist with determinism. Ch. IX introduces the notion of instability, or sensitive dependence on initial conditions, and shows how it forms one of the bridges leading from determinism on the micro-level to apparent randomness on the macro-level. Chs. X and XI complete the survey of the implications of modern physics for determinism by discussing in turn the general theory of relativity and the quantum theory. Finally, Ch. XII offers a few comments on the determinism-free will controversy. My main aims here are to show what is at stake and to diagnose the reasons why the issues have seemed so intractable.

As befits a primer, not much is demanded of the reader in terms of scientific knowledge, for while a large number of illustrative examples are drawn from mathematical physics, their presentation is designed to make clear the import with only the minimum of technical detail. At the same time it has to be recognized that determinism has been fruitful in suggesting mathematical problems, and the success or failure of determinism can in turn depend on the delicate details of these problems. I try to indicate where this is so and refer the reader who wants to learn more to the relevant scientific literature. The real demand is on the reader's tolerance for gear shifting, for the presentation often swings from traditional philosophy of science to mathematics to speculative metaphysics and back to practical physics. These are not strands which can be woven neatly together, but as I will try to show, all of them must be grasped simultaneously if we are to get a real feel for determinism.

Whether or not the reader agrees with the specific conclusions and morals I draw, I hope that he will come away with an appreciation of how exquisitely subtle a doctrine determinism is; how robust it is in some ways and how fragile it is in others; and, most of all, how exciting and how alive it is, despite the attempts of philosophers to relegate it to museum status.

SUGGESTED READINGS

Wesley Salmon's (1971) "Determinism and Indeterminism in Modern Science" provides a quick and very readable survey of the received philosophical opinion on this topic. Some useful historical background can be found in Richard Taylor's (1967) article "Determinism" in the *Encyclopedia of Philosophy*.

DEFINING DETERMINISM

Clearly our first problem must be to define the issue, since nothing is more prolific of fruitless controversy than an ambiguous question.

(Bertrand Russell, "Determinism and Physics")

Russell's advice seems the essence of good sense. But in trying to heed it we find ourselves in a Catch-22 situation: we cannot begin to discuss the implications of physics for the truth of the doctrine of determinism until we know what determinism is; on the other hand, no precise definition can be fashioned without making substantive assumptions about the nature of physical reality, but as we move from classical to relativistic to quantum physics these assumptions vary and the definition of determinism must, to some degree, covary with them.

If we cannot begin with a definition that is at once precise and general, then either precision or generality must be dropped. My suggestion is the seemingly perverse one that initially we drop both. The starting definition I will recommend is vague — as befits a vague doctrine — and is aimed towards classical physics — as befits the historical origins of the doctrine. The advantage of this approach is that it provides a common thread linking disparate material; all of the detailed, technical conceptions to be discussed in succeeding chapters can be seen as attempts to make precise the basic intuitive idea or else to modify it so as to fit some new development in physics.

1. CLASSICAL DETERMINISM: THE VISION AND THE CONTEXT

Before turning to various attempts to define determinism, it is important to have before us the vision which these definitions seek to capture. A most vivid rendering of the vision was given by William James in an 1884 lecture to the Harvard Divinity School:

What does determinism profess? It professes that those parts of the universe already laid down absolutely appoint and decree what the other parts shall be. The future has no ambiguous possibilities hidden in its womb: the part we call the present is compatible with only one totality. Any other future complement than the one fixed from eternity is

impossible. The whole is in each and every part, and welds it with the rest into an absolute unity, an iron block, in which there can be no equivocation or shadow of turning. (1956, p. 150)

The context of this vision is what I will call the classical world picture. Exactly what this means will be discussed in detail in the next chapter, but for now suffice it to say that the spatio-temporal structure of the world is assumed to embody an absolute or observer-independent simultaneity; 'the world-at-a-given-time' is, therefore, an invariantly meaningful concept. Further, at each instant, the state of the world is fully characterized by specifying the values of relevant physical magnitudes — instantaneous values of the positions and velocities of particles, instantaneous values of electric and magnetic field vectors, and the like. The context of this vision is thus broad enough to encompass both particles and fields, materialistic and non-materialistic ontologies. Determinism as it is understood here does not assume materialism or mechanism in any narrow sense; indeed, the magnitudes to be considered may be ones traditionally taken as 'mentalistic', and all that is required is that they be physicalistic in the minimal sense that they have a spatio-temporal representation.

2. WHAT DETERMINISM IS NOT: CAUSE AND EFFECT

Just as it is hard to make bricks without straw, so it is hard to do philosophy without straw men. Unfortunately, there are no out and out straw-man definitions of determinism. But there are some venerable definitions which are worthy of some philosophical bayonet practice and which also have the more positive virtue of pointing the way towards more adequate definitions.

Perhaps the most venerable of all the philosophical definitions holds that the world is deterministic just in case every event has a cause. The most immediate objection to this approach is that it seeks to explain a vague concept — determinism — in terms of a truly obscure one — causation. If we can achieve an analysis of determinism without explicit appeal to the notion of cause and effect, then that analysis is to be preferred to the one in question. A related objection concerns the lack of a perspicuous connection between the causation definition and James' sense of determinism. In one direction the connection can be made tight: if the world displays Jamesian determinism then the "Every event has a cause" can be vouchsafed by taking (as Laplace suggested —

see below) the state of the world at any moment as the cause of the state to follow. But in the other direction the connection is obscure: How does it follow as a result of every event's having a cause that the future has no ambiguous possibilities hidden in its womb? Perhaps the cause-effect relation can be explained in such a way that this implication becomes transparent; but it is that explanation we want and not the evocative but obscure formula "Every event has a cause." There is a reasonably precise explanation of cause-effect in terms of a causal chain or signal, i.e., the propagation of a disturbance, say, in the form of the continuous transmission of a quantity of mass or energy through space; but this explanation does not yield the desired result. Imagine a materialistic world consisting of massive particles whose trajectories are straight lines except where the trajectories happen to intersect. Every interesting event or happening in this world is a happening to a particle, viz., a change of position, a collision, etc. And every such event has a cause in terms of the earlier events on the causal chain or chains on which it lies. Yet this world may or may not be deterministic in James' sense; for it seems consistent with the description I have given that many future complements are compatible with the present state of this world.¹

The proponent of the "Every event has a cause" formula may complain that I have not used an appropriate sense of 'cause', an appropriate one being one on which the formula has the force of "Every event has a cause *and* same causes always produce the same effects." Or alternatively, it might be conceded that the second half of the expanded formula does not follow from the meaning of 'cause' and simply has to be postulated. In either case I would agree that the expanded formula comes much closer to supplying a sufficient condition for determinism. But I also believe that the valid kernel of the expanded formula can be retained while stripping off the chaff of 'cause', 'effect', and 'produce'.

In philosophical parlance 'causality' is an ambiguous term, referring both to determinism and to the cause-effect relation. I suggest that this term either be shelved or else that it be reserved for determinism while 'causation' is used to name whatever goes on when one event causes another. The remainder of this book is devoted to a discussion of causality with only a few hesitant and apologetic references to causation.

3. PREDICTABILITY: LAPLACE'S DEMON

Pierre Simon Laplace offered a definition of determinism which

starts with a causal flavor but ends by equating determinism with predictability.

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 an intelligence. Discoveries in mechanics and geometry, coupled with those in universal gravitation, have brought the mind within reach of comprehending in the same analytical formula the past and the future state of the system of the world. All of the mind's efforts in the search for truth tend to approximate the intelligence we have just imagined, although it will forever remain infinitely remote from such an intelligence.²

While Laplace's approach comes closer to the mark than does the previous one, the appeals to an 'intelligence' (or 'demon' as it is often called) and to the concept of knowledge ought to sound warning bells. Depending upon what powers we endow the demon with, we get different senses of determinism. Endow it with the powers of the latest Cray computer or even with the powers of a universal Turing machine and we get a fairly interesting sense of determinism; but we also get a sense in which it is fairly certain that the universe is 'non-deterministic' in that future states are not always computable from present states, and this may be so even if the universe fulfills James' vision (see Ch. VI). Endow the demon with God-like powers and this difficulty is overcome, but only at the expense of the opposite difficulty; for now the demon will be able to foresee the future — to it no future event will be uncertain — but this foresight may be a reflection of its precognitive abilities rather than any deterministic feature of the world.

It could be replied that the intent of Laplace's definition is in the right direction and all that needs to be done is to cleanse it of any reference to a predictor. I applaud this sentiment, but I would go even further in recommending that the notion of prediction with all of its epistemological connotations be dropped altogether. The history of philosophy is littered with examples where ontology and epistemology have been stirred together into a confused and confusing brew. The Jamesian vision we are seeking to capture is an ontological vision; whether it is fulfilled or not depends only on the structure of the world, independently of what we do or could know of it. Of course, ontological

determinism does have epistemological implications and these will be discussed in the appropriate places. But let us not confuse the implications of the doctrine with the doctrine itself. And let us resist the temptation to manufacture 'senses' of determinism. Producing an 'epistemological sense' of determinism is an abuse of language since we already have a perfectly adequate and more accurate term — prediction — and it also invites potentially misleading argumentation — e.g., in such-and-such a case prediction is not possible and, therefore, determinism fails. The most notorious form of this argument is due to Sir Karl Popper.

4. PREDICTABILITY: POPPER'S DEMON

'Scientific determinism' in Popper's sense is

the doctrine that the state of any closed physical system at any given future instant of time can be predicted, even from within the system, with any specified degree of precision, by deducing the prediction from theories, in conjunction with initial conditions whose required degree of precision can always be calculated (in accordance with the principle of accountability) if the prediction task is given. (1982, p. 36)

Popper's basic demand is that Laplace's demon should be construed "not as an omniscient God, merely as a super-scientist". This means that

The demon, like a human scientist, must *not* be assumed to *ascertain initial conditions with absolute mathematical precision*; like a human scientist, he will have to be content with a finite degree of precision. (1982, p. 34)

Also, the demon must be able to predict from within the system; that is, the demon is not construed as a disembodied spirit but, like a human scientist, must be assumed to belong to and to interact with the system whose future it is trying to predict. The 'principle of accountability' is imposed to assure that the required degree of precision for the initial conditions can be known beforehand so that a prediction which fails to meet the specified error limits cannot be dismissed on the grounds that the initial data were not accurate enough.

Actually, the first part of Popper's demand is sufficient by itself to allow Popper to reach the conclusion that, contrary to widespread belief, classical physics exhibits systems which are not deterministic. I myself reach a similar conclusion, but for quite different sorts of cases and for quite different reasons. This matter will be taken up in some detail in the following chapter. The point I wish to emphasize here is

that the examples Popper uses to illustrate his conclusion serve only as a *reductio* of his definition of determinism. The combination of a strong form of instability, where small changes in initial conditions can give rise to large changes in future states, and the inability of the demon to ascertain initial conditions with mathematically exact precision can lead to a breakdown in prediction. But the proper conclusion to be drawn from this result is not that determinism fails but rather that determinism and prediction need not work in tandem; for the evolution of the system may be such that some future states are not predictable (at least not under Popper's strictures) although any future complement than the one fixed from eternity is impossible. Hadamard, the authority whom Popper cites on these matters, puts the point this way: if the future state does not depend continuously on the initial state, then "Everything takes place, physically speaking, as if the knowledge of . . . [the initial] data would *not* determine the unknown function" (1952, p. 38). Popper's definition cancels the crucial "as if".

Popper's view is particularly awkward in the case of classical statistical mechanics because it has the effect of brushing aside one of the central foundations problems; namely, how can the 'random' and 'chaotic' behavior exhibited on the macro-level by, say, a box of gas be reconciled with the micro-determinism of the gas molecules? After many decades of research, it has become apparent that a large part of the answer lies precisely in instability (see Ch. IX).

Why is such an acute philosopher as Sir Karl bent on using such a wrong-headed conception of determinism? (For those unfamiliar with the history of philosophy, I note that analogous questions arise for every Great Man.) Popper's avowed purpose in *The Open Universe* is to "make room within physical theory . . . for indeterminism" (1982, p. xxi). By construing determinism in terms of finite prediction tasks, Popper is able to achieve his goal, but the form of indeterminism he generates does not resolve the 'nightmare of physical determinism' of which he spoke so eloquently in "Of Clouds and Clocks." If physical determinism holds and the antecedent state of the universe suffices to fix the future physical state, including all of our movements and thus all of our actions, then "all our thoughts, feelings, and efforts can have no practical influence upon what happens in the physical world: they are, if not mere illusions, at best superfluous by-products ('epiphenomena') of physical events" (1972, p. 217); the whole world with everything in it would be a huge automaton and we would be "nothing but little cog-wheels, or at best sub-automata, within it" (p. 222). But if that is the

nightmare, it would seem to persist even after it has been shown that the deterministic unfolding of physical events cannot be exactly charted by a Popperian demon because, for example, the unfolding is unstable.

Nor can Popper's definition of 'scientific determinism' be justified by combining the desire to make determinism a scientific doctrine with Popper's thesis that falsifiability provides the demarcation between science and nonscience. Also needed is the notion that to be falsifiable determinism must be construed as an assertion about finite prediction tasks, a notion which is contrary to the spirit of Popper's original liberal interpretation of the falsifiability criterion.

Unlike Popper and his kindred spirits in logical empiricism, I am not afraid to attach the label 'metaphysical' to the doctrine of determinism; indeed, it seems to me that determinism as James, Laplace, and others understand it is *both* 'scientific' and 'metaphysical'. Like Popper, I am interested in how scientific evidence, reasoning, and inference can be brought to bear on the doctrine of determinism. But the ties that bind determinism to hard empirical evidence (however that is taken) are far too complex, subtle and tenuous to be encapsulated in a tidy formula couched in terms of falsifiability, verifiability, testability, or the like. Nevertheless, I hold that the evidential grounding of determinism is not mysterious, or at least it is no more mysterious than the grounding of many other high level scientific claims, viz., that total energy is conserved or that the temporal evolution of the world is time reversible. And the 'scientific' status of these claims surely does not turn on construing them as claims about prediction tasks that can be carried out by embodied super-scientists interacting with the systems whose futures they are trying to predict.

5. RUSSELL'S DEFINITION

Russell's essay "On the Notion of Cause" can usefully be viewed as an attempt to carry out the recommended cleansing of Laplace's definition of its epistemological components so as to produce a purely ontological formulation. Here is the upshot of Russell's housecleaning.

A system is said to be 'deterministic' when, giving certain data, e_1, e_2, \dots, e_n at times t_1, t_2, \dots, t_n respectively, concerning this system, if E_t is the state of the system at any time t , there is a functional relation of the form

$$E_t = f(e_1, t_1, e_2, t_2, \dots, e_n, t_n).$$

The system will be 'deterministic throughout the given period' if t , in the above formula, may be any time within that period If the universe, as a whole, is such a system, determinism is true of the universe; if not, not. (1953, p. 398)

This seems cogent enough at first reading, but the definition has, as Russell goes on to show, a very counterintuitive upshot. To illustrate, imagine a very simple universe containing a single dimensionless particle, and suppose that the state of the particle at any instant t is specified by its position coordinates x_t, y_t, z_t . The motion of the particle through space can be as complicated as you like as long as it can occupy only one place at a time. Then, as a matter of mathematical fact, there must exist functions f_1, f_2, f_3 such that $x_t = f_1(t), y_t = f_2(t), z_t = f_3(t)$. The example can be made more realistic by adding other particles and additional state variables, but the essential point remains the same. In Russell's own words:

It follows that, theoretically, the whole state of the material universe at time t must be capable of being exhibited as a function of t . Hence our universe will be deterministic in the sense defined above. But if this be true, no information is conveyed about the universe in stating that it is deterministic. (1953, p. 401)

Combining Russell and Popper, we have the first intimation of the Scylla and Charybdis between which determinism is forced to sail: tack one way in defining determinism and determinism wrecks on obvious falsity; tack the other way and it wrecks on triviality. Much of the later chapters will be devoted to the question of whether a clear course can be charted between these obstacles. The question is particularly thorny because it is not merely a matter of reading the answer off the relevant parts of physics, for the interpretation of the physics may turn in part on convictions about the form the answer should take.

Russell considers two suggestions for avoiding the trivialization of determinism. The first is to require that the Russell function be simple. This suggestion is quickly discarded; and rightly so since the connection between simplicity and determinism is indirect and tenuous. The world can be as simple as you like in its contents and temporal evolution and yet non-deterministic in James' sense; or it can be highly complex but leave no room for equivocation or shadow of turning in its future development.³ The second suggestion is that time not be allowed to enter explicitly into the Russell function. Russell is able to point to an independent motivation for this restriction; namely, the belief in the

“uniformity of nature,” meaning that “no scientific law involves time as an argument, unless, of course, it is given in integrated form, in which case *lapse* of time, though not absolute time, may appear in the formulae” (1953, p. 401). But one can doubt whether uniformity of nature in Russell’s sense is any more essential to determinism than is simplicity. Imagine a world in which the gravitational ‘constant’ is not constant but varies with time. Does such a time dependence automatically make the world nondeterministic, open to ambiguous future possibilities? This and other questions about the relation between determinism and time symmetries deserve careful scrutiny; some will be provided in Ch. VII, but for present purposes we can avoid the issue. For even if we grant Russell his “uniformity of nature” as regards laws of motion, it hardly follows that the Russell function will not involve time explicitly; indeed, if position changes with time, the Russell function can hardly avoid having time as an argument. Russell has confused a property of laws with a property of Russell functions.

6. WHAT DETERMINISM IS

At several points Russell refers, as we have just done, to laws of nature, and in the statement of the trivialization result he concludes from the existence of the Russell function that “the material universe *must* be subject to laws” (1953, p. 401). But on the usual understanding of natural laws, this is a non-sequitur. Laws may prohibit some instantaneous states, but the familiar dynamical laws of physics, or what have passed for them, typically allow a wide range of instantaneous states for any given system; viz., any set of non-coincident positions and (finite) velocities is an allowable state in Newtonian particle mechanics. The main bite of the dynamical laws comes in restrictions on the temporal transition from one allowable state to another. Laplacian determinism is a very special and very strong form of such a restriction: for any time t_1 and t_2 and any allowed state at t_1 , there is one and only one allowed state at t_2 .

This idea could be reexpressed in terms of the existence of a new type of Russell function F , now construed as a map from triples of allowed instantaneous states \times time \times time to allowed states. Read $s' = F(s, t_1, t_2)$ as: s' is the (unique) allowed state at t_2 when the state at t_1 is s , where s ranges over all allowed instantaneous states.⁴ But the only gain in such a formulation is in pedanticism.

Instead of using Russell functions I prefer a more pictorially appealing approach based on the now fashionable notion of possible worlds. A ‘world’ here means a four-dimensional space-time world, the actual world being the collection of all events that have ever happened, are now happening, or ever will happen, and a possible world being a collection of possible events representing possible alternative histories to that of the actual world. The starting assumption is that these events can be fitted into the classical world picture: their spatio-temporal relations conform to the structure required in classical physics and the events themselves can be analyzed, for example, as changes in spatio-temporal magnitudes. Taking space-time rather than instantaneous states as the basis of analysis becomes unavoidable in relativistic physics, but it is equally useful in the discussion of determinism in Newtonian physics, as I will try to show in the following chapter.

Letting \mathcal{W} stand for the collection of all physically possible worlds, that is, possible worlds which satisfy the natural laws obtaining in the actual world, we can define the Laplacian variety of determinism as follows. The world $W \in \mathcal{W}$ is *Laplacian deterministic* just in case for any $W' \in \mathcal{W}$, if W and W' agree at any time, then they agree for all times. By assumption, the world-at-a-given-time is an invariantly meaningful notion and agreement of worlds at a time means agreement at that time on all relevant physical properties. This concept of determinism can be broken down into two subconcepts. A world $W \in \mathcal{W}$ is *futuristically* (respectively, *historically*) *Laplacian deterministic* just in case for any $W' \in \mathcal{W}$, if W and W' agree at any time then they agree for all later (respectively, earlier) times.

Determinism needn’t be an all-or-nothing affair. A world may be *partially deterministic*, deterministic with respect to some magnitudes (agreement on the values of which at any time forces agreement at other times) but not with respect to others. But while such a bifurcation is imaginable, it can produce tensions. Try, for example, to imagine that the world is only partially deterministic because it is deterministic only with respect to the magnitudes which characterize the ordinary matter of which we and our scientific instruments are composed but not with respect to the magnitudes which characterize the behavior of a free-spirited species of particle, the freeon (say). But either the freeon magnitudes interact with ordinary magnitudes or not. In the latter case the freeons are scientifically suspect entities since as far as science can teach us they are unknowable ghosts in the deterministic machine. In the

former case it is hard to see how, without a cosmic conspiracy, the partial determinism for the ordinary magnitudes can be maintained since otherwise the non-deterministic evolution of the freeons would infect the evolution of ordinary matter. A concrete example of this tension will be examined in Ch. IV.

The world might be non-deterministic but still *conditionally deterministic* on a subset of magnitudes: if two worlds agree for all times on the values of the conditioning magnitudes and if they agree at any instant on the values of the other magnitudes, then they agree at any other instant. Faith in strict determinism and the discovery of conditional determinism will prompt the search for additional laws that determine the evolution of the conditioning magnitudes, thereby removing the condition and restoring determinism *simpliciter*.

It might be charged that the possible worlds analysis is a fraud: it is no more than a transcription of James' poetic vision into terms which are devoid of James' eloquence but which display not much compensating gain in clarity and precision. I couldn't agree more! But I also think that without prejudging detailed substantive issues in physics we cannot do much better for a direct ontological formulation of what is, after all, an ontological doctrine. The usefulness of the possible worlds formulation as a starting point for the discussion of these issues and their bearing on determinism will, I hope, become apparent in succeeding chapters. However, honesty also demands a confession of some of the potential pitfalls of the approach.

7. FEAR AND LOATHING

A principal reason for rejecting Russell's approach was the fear that, without the aid of artificial props, it would reduce determinism to a triviality. A similar fate awaits the possible worlds definition of determinism unless the properties which characterize the instantaneous state of the world are suitably restricted; in particular, they must be non-indexical and genuinely occurrent properties. Name the worlds in \mathcal{W} with the help of a suitable index set Δ . The property of a world W_δ ($\delta \in \Delta$) of having in world W_δ a particle with such-and-such a position at such-and-such a time is unique to world W_δ . Since no distinct worlds in \mathcal{W} ever agree on such world indexical properties the proposed working definition of determinism will be vacuously satisfied if such

properties are allowed to adjudicate the agreement or disagreement of worlds at a given time.

Our definition of determinism also risks triviality unless we banish overt and covert reference to past and future times. In some sense of property, it is now a property of the pen I am holding that five minutes ago it executed various motions and that five minutes from now it will be at rest on the desk. But such properties are not truly occurrent and like the world indexical properties should not be allowed to decide the agreement of worlds at a given time. The challenge is to distinguish the desired class of occurrent properties without begging the question of determinism. I will simply assume that the challenge can be met.

Even so there are still worries about the meaning of determinism and the adequacy of our definition of it. I will describe two of the worries with the help of a little cracked theology. Imagine that God is perversely energetic in His creation of the physically possible worlds. Specifically, He so loves diversity that He arranges it that the same (non-indexical, truly occurrent) instantaneous state never appears more than once in \mathcal{W} . This assures as a byproduct of our working definition that determinism cannot fail whatever else is true about the temporal evolution of the world.

The second example involves a more sacrilegious assumption. Imagine that at the dawn of creation God is fatigued. He is not up to instituting any physical laws in the sense familiar from physics. But because He desires things to go smoothly, He decrees that all physical magnitudes shall be analytic functions of time. If we admit into the instantaneous description of the world not only the instantaneous values of all the basic physical magnitudes but also the instantaneous values of their time derivatives of all orders (surely, all truly instantaneous properties), then the world is automatically Laplacian deterministic over at least some finite interval of time. For by definition, an analytic function can be expanded as a convergent power series; then just plug in the initial value of the function and the values of its time derivatives at the starting time to obtain the values of the function for earlier and later times within the radius of convergence. And even if the instantaneous state description excludes time derivatives of an arbitrary order, analyticity still backs a weakened version of Laplacian determinism since agreement over a finite stretch, no matter how short, on the basic magnitudes will force agreement over a longer stretch.

When the theology is stripped from these examples what we are left with are questions about how determinism is implemented by physical laws. In both examples the worry is that although the letter of the definition of determinism is satisfied, the spirit is not, since it is not at all evident that the future state is determined, in the intended sense, as a result of the way natural laws guide the unfolding of events. I do not believe that it is fruitful to try to assuage these worries by giving fancier definitions of determinism. Rather, the worries are best dealt with on a case by case basis in terms of the specifics of concrete laws. Towards this end the coming chapters will analyze in some detail a large number of examples drawn from mathematical physics. Even within this circumscribed context it is often difficult to decide whether we have something that deserves to be called genuine determinism. Even at its core the concept of determinism is slippery, and at its outer limits it is altogether too vague to make it worthwhile worrying in the abstract about whether determinism really and truly reigns whenever agreement of worlds at one time forces agreement at another time.

8. DEMOCRACY AND SYMMETRY

The laws of physics, or what have passed for them, have typically displayed a temporally symmetric form of determinism where futuristic and historical determinism stand or fall together. This feature derives from the fact that, until quite recently, all of the fundamental laws of physics were thought to be invariant under time reversal. Note, however, that while time reversal invariance is sufficient for symmetry with respect to futuristic and historical determinism, it is not necessary. The nature of various time symmetries such as time reversal invariance, time translation invariance, periodicity, etc., and their connections to determinism will be discussed in Ch. VII.

Continuous space-time symmetries foster democracy for determinism. If, for example, the laws of nature are invariant under space translation, then for any $W \in \mathcal{W}$, W is deterministic iff every W' generated from W by space translation is likewise deterministic. General democracy reigns when determinism holds for all members of \mathcal{W} when it holds for any and fails for all when it fails for any. Linear field laws typically display this democratic character. But lest it be thought that determinism requires democracy, I will mention that

interesting forms of determinism are compatible with subtle forms of anti-democratic behavior. Let \mathcal{W}_n^G stand for worlds which forever and always contain no more than n point mass particles obeying Newton's laws of gravitation. Then assuming that no collisions occur, \mathcal{W}_2^G and \mathcal{W}_3^G form deterministic collections whereas \mathcal{W}_5^G does not. Or again, let \mathcal{W}_n^B stand for worlds with n equal mass billiard balls obeying the laws of elastic impact. Then for any finite n , \mathcal{W}_n^B is a deterministic collection while $\mathcal{W}_{+\infty}^B$ is not. These matters will be illustrated in Ch. III.

9. NON-LAPLACIAN VARIETIES OF DETERMINISM

According to the Laplacian brand of determinism, the instantaneous state of the world suffices to uniquely fix the state at any other time. Other varieties of determinism can be produced by modifying the types of space-time regions which are determined and which do the determining. Thus, we can say that $W \in \mathcal{W}$ is (R_1, R_2) deterministic just in case for any $W' \in \mathcal{W}$, if W and W' agree on space-time regions of type R_1 , then they agree on regions of type R_2 . Laplacian determinism simpliciter is (R_1, R_2) determinism with R_1 a time slice and R_2 the rest of space-time; futuristic Laplacian determinism is (R_1, R_2) determinism with R_1 a time slice and R_2 the future of that slice; etc. Close cousins of Laplacian determinism can be obtained by taking the determining region R_1 to be a finite sandwich instead of an infinitely thin slice, the entire past lying below a time slice, etc. These relatives will prove to be useful in discussing determinism for relativistic particle mechanics where strict Laplacian determinism may fail (see Ch. IV).

Laplacian determinism and its close relatives are, to my knowledge, the only varieties which have received attention in the philosophical literature. The explanation cannot be that no other variety is relevant to the analysis of modern science, for giving data on a null surface in relativistic physics is in some respects more natural than giving it on a time slice (see Ch. X). I suspect that the reasons derive from the widespread association of determinism and prediction and the preoccupation with examples drawn from classical physics. But once the illicit nature of the association is revealed and once our horizons are extended beyond the classical, the way is opened for considering non-standard forms of determinism.

10. CHE SARÀ SARÀ

What has been has been; what is is; and just as surely and just as trivially, what will be will be. But the refrain "the future's not ours" is supposed to indicate an inevitability that goes beyond these trivialities. Laplacian determinism entails one kind of non-trivial inevitability: given the way things are now, the future can't be other than it will be, where the 'can't' is the can't of physical impossibility. This is an interesting kind of inevitability but it doesn't quite capture the full sense of uncontrollability and unavoidability of fatalist teachings.

Let us say that an event or state is *X-fated* just in case it occurs in every *X*-possible world. (Alternatively, we might want to say that the event is *X-fated* for an individual *i* just in case that event happens to the individual in every world where *i* (or an *i* counterpart) exists.) Thus, an event is *naturalistically fated* just in case it occurs in every physically possible world. If there are such fated events, then in one clear sense some things are going to happen no matter what — vary the initial conditions as much as you like (within the bounds of physical possibility) and the fated event will nonetheless eventuate. Naturalistic fatalism in this sense neither entails nor is entailed by determinism. Nor is naturalistic fatalism a very controversial or exciting doctrine, being illustrated by the most commonplace of examples. I take it, for instance, that the laws of biology dictate that I am naturalistically fated to die; but I also take it that the particular time and manner of my death are not fated by any of the laws of nature. This is, perhaps, Aristotle's point when he wrote:

... it is necessary that he who lives shall one day die ... But whether he dies by disease or by violence, is not yet determined, but depends on the happening of something else. (*Meta.* 1027b, 10–14)

Weaker types of natural fate can also be defined. A feature can be said to *asymptotically fated* if it emerges in the limit as $t \rightarrow +\infty$ for every $W \in \mathcal{W}$. Such is the hypothesized 'heat death' of the world which may not obtain at any finite time in the future but may emerge in the limit. Or a feature can be said to be *weakly fated* in the actual world W_\circ if it emerges in every $W \in \mathcal{W}$ which has a state that does not depart from the present state of W_\circ by more than some specified degree. What we are obviously moving towards is an association between fatalism and stability: the fated features are the ones which are stable under

variations of starting conditions. This is a notion which admits of degrees and the reader is invited to quantify for himself.

Contrary to what is sometimes asserted, perhaps in an attempt to stigmatize, fatalism as applied to human actions need not entail that actions are inefficacious in the objectionable sense that they are 'causally discontinuous' with the future (see Wilson (1955)). Fatalism can allow that our actions do have effects; it is rather that the hand of Fate — as it acts here through the laws of nature — shapes the course of events so that the effects of our actions bring about the fated event. Oedipus was fated to kill his father Laertes and marry his mother Jocasta. All his strivings to avoid his fate were not without effects; indeed, it was these very actions which brought about his fate.

Of course, Oedipus' fate was not induced naturalistically. Still, the above analysis will serve with the appropriate replacement for the collection \mathcal{W} of physically possible worlds. The suggestion is that we construe the workings of super-natural fate in terms of higher laws which are imposed over and above the natural laws. Perhaps these super-natural laws come in the form of decrees of Gods, decrees of Fate, or what-have-you. The resulting set \mathcal{W}' of super-naturally possible worlds is then a subset of \mathcal{W} . The most extreme version has $\mathcal{W}' = \{W_\circ\}$, as would follow if, for example, God necessarily chooses to actualize the best of all possible worlds, with the result that every actual event is super-naturally fated. Leibniz sought to avoid this absolute metaphysical fatalism, though his principle of sufficient reason pushes him towards it.

There is a long tradition in philosophy which seeks to prove that the laws of logic suffice to establish fatalism for human actions (see Taylor (1983)). From the perspective of our analysis of fatalism, this tradition is opaque, for it would seem that the laws of logic narrow the collection \mathcal{W} of physically possible worlds not one wit, each of the members of \mathcal{W} having been antecedently assumed to be logically possible. So either we have failed to appreciate the relevant sense in which human actions are fated, or we have misunderstood what the 'laws of logic' involve, or the classical proofs of fatalism are so much hocus-pocus. The actual situation is, I think, a mixture of all three (the main ingredient being the third), but this is not the place to try to disentangle the mess. The Idealists contend that physical necessity is but dimly perceived logical necessity (see Ch. V), with the results that the set \mathcal{W} of physically possible worlds is coextensive with the set of logically possible worlds and, hence, that naturalistic and logical fate are the same. But these results seem to make fatalism harder, not easier, to secure.

11. DETERMINISTIC THEORIES

Positivism and logical empiricism promoted a fear of the ontological and a flight towards the linguistic. Thus, it is not surprising to find that many philosophical discussions of determinism are couched in terms of theories, construed as linguistic entities. But since determinism is a doctrine about the nature of the world, no problem is avoided by this linguistic detour; for to be adequate, a definition of determinism in terms of theories must guarantee that the axioms of the theory express laws of nature and that these laws have just the deterministic property required in the possible worlds definition. It may be, however, that while no problems are avoided, gains in understanding are made by taking the linguistic route. For instance, it may be that the concept of laws of nature is inextricably bound up with scientific theorizing.⁵ Or it may be that we can get a firmer grip on how ontological determinism operates by clarifying the concept of a deterministic theory and then studying examples of such theories.

In what is almost standard usage, philosophers identify theories with deductively closed sets of sentences of some formal language. E. Nagel (1953, 1961), Smart (1968), and others have recommended a syntactical characterization of determinism for such theories. Roughly, a theory T is deterministic just in case, given the state description $s(t_1)$ at any time t_1 , the state description $s(t_2)$ at any other time t_2 is deducible from T . Montague (1974) noted that for the kinds of formal languages commonly used, there is a difficulty in giving this definition a literal reading. A 'state description' is, presumably, a sentence of the language of T , but while there may well be a non-denumerable infinity of physically possible states of a system, the standard formal languages contain only a denumerable number of sentences.

Two reactions are possible. We can resort to infinitary languages which have the requisite expressive power. However, this increased power may be purchased at the expense of some ugly logical features, e.g., completeness may fail so that the relation of deducibility may not after all be appropriate for characterizing determinism for theories. The other approach, explored by Montague, is to stick with standard languages but to switch from a syntactical to a semantic analysis which mirrors the possible worlds definition using models of T as the counterparts of possible worlds; roughly, T is deterministic just in case for any pair of models of T , if they agree at one time then they agree at

all times. Though the idea is the same, there is a gain in working through the formal details of how the concepts are implemented for concrete T 's. The interested reader is referred to Montague's brilliant pioneering work.⁶

The formal-systems approach will not play much of a role in my discussion of substantive issues of determinism in modern physics. Most of the putative laws of physics take the form of differential equations for which questions of determinism principally involve existence and uniqueness properties of solutions, and these properties can be discussed with as much rigor as is ever needed without having to resort to formal systems. If philosophers had spent less time trying to achieve for determinism the superficial 'precision' afforded by formal symbolic notation and had spent more time studying the content of physical theories they might have confronted the truly fascinating substantive challenges that determinism must face in classical and relativistic physics. Most philosophers pay lip service to Carl Hempel's remark that there is no real gain in clarity and precision to be had by translating 'A man crossed the street' into 'There exists a man m , a street s , and a time t such that . . .' But many seem to cling to the notion that an advance is to be achieved by applying really powerful formal machinery. Good luck to them.

12. CONCLUSION

We have barely begun and already we are in very deep waters. Space, time and space-time; laws, theories, and formal systems; symmetries and invariances; cause and effect; prediction, instability, and randomness; materialism and physicalism — these are some of the concepts we have encountered in trying to get no more than a preliminary fix on determinism. This is already enough to make strong the suspicion that a real understanding of determinism cannot be achieved without simultaneously constructing a comprehensive philosophy of science. Since I have no such comprehensive view to offer, I approach the task I have set myself with humility. And also with the cowardly resolve to issue disclaimers whenever the going gets too rough. But even in a cowardly approach, determinism wins our unceasing admiration in forcing to the surface many of the more important and intriguing issues in the length and breadth of the philosophy of science.