from Chance and Chaos by Ruelle

CHAPTER 5

Classical Determinism

The flow of *time* is an essential aspect of our perception of the world. And we have seen that *chance* is another essential aspect of our perception of the world. How do these two aspects fit together? Before tossing a coin, I estimate the probabilities of getting heads or tails to be both equal to 50 percent. Then, I toss the coin and get heads, say. At what moment does the coin decide to show heads? We have already asked ourselves this question, and the answer is not very easy: we are here confronted with one of those "pieces of reality" described by several different physical theories, and the connection between these different theories is a bit laborious. We discussed earlier the theory describing chance—the physical theory of probabilities. For the description of time, things get somewhat more complicated because we have at least two different theories at our disposal: *classical* mechanics and *quantum* mechanics.

Let us for a moment forget about tossing coins, and discuss mechanics. The ambition of mechanics—classical or quantum—is to tell us how the universe evolves over the course of time. Mechanics must therefore describe the motion of the planets around the sun, and the motion of the electrons around the nucleus of an atom. But while for large objects the classical theory gives excellent results, it becomes inadequate at the level of atoms and must be replaced by quantum theory. Quantum mechanics is thus more correct than classical mechanics, but its use is more delicate and difficult. And in fact neither

classical nor quantum theory applies to objects with a velocity close to that of light; in such cases we have to use Einstein's relativity (either special relativity, or general relativity if we also want to describe gravitation).

But, you may tell me, why stop at classical or quantum mechanics? Don't we rather want to use the *true* mechanics, taking into account all quantum and relativistic effects? After all, what interests us is the universe as it really exists, rather than this or that classical or quantum idealization. Let us have a good look at this important question. First of all we have to face the fact that the *true mechanics* is not at our disposal. At the time of writing we do not have a unified theory that agrees with all that we know about the physical world (relativity, quanta, properties of elementary particles, and gravitation). Every physicist hopes to see such a unified theory in action, and this may happen some day, but now it is only a hope. Even if one of the theories already proposed turns out later to be the right one, it is not at this time *in action* in the sense of giving us computational access to the masses of the elementary particles, their interactions, and so on. The best we can do at present is to use a somewhat approximate mechanics. In the present chapter we shall use classical mechanics. Later we shall see that quantum mechanics is based on somewhat less intuitive physical concepts. The relation between quantum mechanics and chance will therefore be more difficult to analyze. Everything seems to indicate that the physical concepts of the true mechanics will be difficult to grasp intuitively. It is thus reasonable to use classical mechanics—with its well-known physical concepts—to investigate the relation between chance and time.

As I have just said, the ambition of mechanics is to tell us how the universe evolves over the course of time. Among other things, mechanics must describe the revolution of the planets around the sun, or the trajectory of a space vehicle powered by rockets, or the flow of a viscous fluid. In short, mechanics must describe the *time evolution* of physical systems. Newton is the first person who understood well how to do this. Using a more modern language than that used by Newton, let us say that the *state* of a physical system at a certain time is given by the positions and velocities of the points at which the matter of the system is concentrated. We must therefore give the positions and velocities of the planets, or of the space vehicle in which we are interested, or of all the points constituting a viscous fluid in the process of flowing. (In this last case there is an infinite number of points, and therefore an infinite number of positions and velocities to consider.)

According to Newtonian mechanics, when we know the state of a physical system (positions and velocities) at a given time—let us call this the initial time—then we know its state at any other time. How is this knowledge obtained? A new concept is needed here, that of *forces* acting on a system. For a given system, the forces are at each instant of time determined by the state of the system at this instant. For instance, the force of gravity between two celestial bodies is inversely proportional to the square of the distance between these bodies. Newton now tells us how the variation of the state of a system in the course of time is related to the forces acting on this system. (This relation is expressed by Newton's equation.)[1] Knowing the initial state of a system, we may then determine how this state varies in the course of time and therefore find out, as announced, the state of the system at any other moment.

I have just presented in a few words that great monument of universal thought which is Newton's mechanics, now also called classical mechanics. A serious study of classical mechanics would require mathematical tools that cannot be presented here. But some interesting remarks can be made on Newton's theory without entering into a detailed mathematical discussion. First, let us note that Newton's ideas shocked many

of his contemporaries. René Descartes, in particular, could not accept the notion of "forces at a distance" between celestial bodies. He felt this idea to be absurd and irrational. Physics, according to Newton, consisted in gluing a mathematical theory on a piece of reality, and reproducing in this manner the observed facts. But this approach was too loose for Descartes. He would have wanted a *mechanistic* explanation, allowing contact forces, like that of a cogwheel on another cogwheel, but not forces at a distance. The evolution of physics has shown that Newton was right, rather than Descartes. And what would the latter have thought about quantum mechanics, in which the position and velocity of a particle cannot be simultaneously specified?

Coming back to Newtonian mechanics, we see that it gives a completely deterministic picture of the world: if we know the state of the universe at some (arbitrarily chosen) initial time, we should be able to determine its state at any other time. Laplace (or Pierre Simon, Marquis de Laplace, if you prefer) has given an elegant and famous formulation of determinism. Here it is.[2]

> An intelligence which, at a given instant, would know all the forces by which Nature is animated, and the respective situation of all the elements of which it is composed, if furthermore it were vast enough to submit all these data to analysis, would in the same formula encompass the motions of the largest bodies of the universe, and those of the most minute atom: nothing for it would be uncertain, and the future as well as the past would be present to its eyes. The human mind, in the perfection that it has been able to give to astronomy, provides a feeble semblance of this intelligence.

This quotation of Laplace has an almost theological flavor, and certainly suggests various questions. Is determinism compatible with man's free will? Is it compatible with chance? Let us first discuss chance, and then we shall have a brief look at the messy problem of free will.

At first sight, Laplace's determinism leaves no room for chance. If I toss a coin, sending it up in the air, the laws of classical mechanics determine with certainty how it will fall, showing heads or tails. Since chance and probabilities play in practice an important role in our understanding of nature, we may be tempted to reject determinism. Actually, however, as I would like to argue, the dilemma of chance versus determinism is largely a false problem. Let me try to indicate here briefly how to escape it, leaving a more detailed study for later chapters.

The first thing to note is that there is no logical incompatibility between chance and determinism. Indeed, the state of a system at the initial time, instead of being precisely fixed, may be random. To use more technical language, the initial state of our system may have a certain *probability distribution*. If such is the case, the system will also be random at any other time, and its randomness will be described by a new probability distribution, and the latter can be deduced deterministically by using the laws of mechanics. In practice, the state of a system at the initial time is never known with perfect precision: we have to allow a little bit of randomness in this initial state. We shall see that a little bit of initial randomness can give a lot of randomness (or a lot of indeterminacy) at a later time. So we see that in practice, determinism does not exclude chance. All we can say is that we can present classical mechanics—if we so desire—without ever mentioning chance or randomness. Later we shall see that this is not true for quantum mechanics. Two idealizations of physical reality may thus be conceptually quite different, even if their predictions are practically identical for a large class of phenomena.

The relations between chance and determinism have been

the object of many discussions and recently of a heated controversy between René Thom and Ilya Prigogine.[3] The philosophical ideas of these gentlemen are indeed in violent conflict. But it is interesting to note that when one comes to the specifics of observable phenomena, there is no disagreement between serious scientists. (The opposite would have been perhaps more interesting.) Let us note Thom's assertion that since the business of science is to formulate laws, a scientific study of the time evolution of the universe will necessarily produce a deterministic formulation. This need not be Laplace's determinism, however. We might very well obtain deterministic laws governing some probability distributions; chance and randomness are not so easily escaped! But Thom's remark is important with regard to the dilemma of chance versus determinism, and the related problem of free will. What Thom tells us in effect is that this problem cannot be solved by one or another choice of mechanics, because mechanics is by essence deterministic.

The problem of *free will* is a thorny one, but it cannot be left undiscussed. Let me present here briefly the point of view defended on the subject by Erwin Schrödinger, one of the founders of quantum mechanics.[4] The role left to chance in quantum mechanics has raised the hope, as Schrödinger notes, that this mechanics would agree with our ideas on free will better than Laplace's determinism does. But such a hope, he says, is an illusion. Schrödinger first remarks that there is no real problem arising from the free will of other people: we can accept an entirely deterministic explanation of all *their* decisions. What causes difficulties is the apparent contradiction between determinism and *our* free will, introspectively characterized by the fact that *several possibilities* are open, and we engage our *responsibility* by choosing one. Introducing chance into the laws of physics does not help us in any way to resolve this contradiction. Indeed, could we say that we engage our responsibility by making a choice at random? Our freedom of choice, actually, is often illusory. Suppose, says Schrödinger, that you attend a formal dinner, with important and boring people. (Obviously, he had more than his share of this kind of entertainment.) You can think, he says, of jumping on the table and starting to dance, breaking the glasses and dishes, but you won't do it, and you cannot say that you exercise your free will. In other cases, a choice is really made, responsible, painful perhaps; such a choice certainly does not have the features of being made at random. In conclusion, chance does not help us to understand free will, and Schrödinger does not see a contradiction between free will and either the determinism of classical mechanics or quantum mechanics.

Related to free will is the old theological problem of *predestination*: Did God decide in advance which souls will be saved, and which ones will be damned? This is a momentous problem for Christian religions: what is opposed to free will is here not determinism, but the omniscience and omnipotence of God. Rejecting predestination seems to limit the powers of the Almighty, but accepting it seems to make moral effort futile. The doctrine of predestination was defended by Saint Augustine (354–430), by Saint Thomas Aquinas (1225–1274), by the Protestant reformer Jean Calvin (1509–1564), and by the seventeenth-century Jansenists. The Catholic church, officially, was prudent and always reluctant to endorse hard-line predestination theories. And now the discussions on predestination, once so central to intellectual life, are receding into the past. Time is burying in the sands of oblivion the many thousand pages of theological disputes in medieval Latin. The old problems have not been solved, but little by little they make less sense, they are forgotten, they disappear . . .

My own views on free will tie in with the problem of computability, to be discussed in later chapters. To bring the question into focus, I like to think of the paradox of someone (the *predictor*) who uses the determinism of physical laws to fore-

see the future, and then uses free will to contradict the predictions. The paradox is especially pressing in science fiction stories in which there are predictors capable of making incredibly precise forecasts. (Think of Frank Herbert's *Dune* and Isaac Asimov's *Foundation*.) How do we handle this paradox? We could abandon either determinism or free will, but there is a third possibility: we may question the ability of any predictor to do the job so well that a paradox arises. Let us note that if a predictor wants to create a paradox by violating forecasts about a certain system, then the predictor must be part of the system in question. This implies that the system is probably rather complicated. But then the accurate prediction of the future of the system is likely to require enormous computing power, and the task may easily exceed the abilities of our predictor. This is a somewhat loose argument about a loosely stated problem, but I think that it identifies the reason (or one of the reasons) why we cannot control the future. The situation is similar to that of Gödel's incompleteness theorem. There also, the consideration of a paradox leads to a proof that the truth or falseness of some assertions cannot be decided, because the task of making a decision would be impossibly long. In brief, what allows our free will to be a meaningful notion is the complexity of the universe or, more precisely, our own complexity.