

Introduction

If the purpose of physics is to correctly describe nature, then two of the various aspects of this description are among the most important: what the constituents of the world are and how objects move. We want to know what the world consists of and what accounts for the changes we constantly observe, that is, what are the dynamical laws underlying these motions.

Any physical theory intended as an explanation of dynamics, of the changes occurring in the universe and the movements of the things in it, must of necessity be deterministic; otherwise it would not be regarded as explanatory. This does not mean that we have to assume the world necessarily to be causal in the sense that the occurrence of all events can be predicted on the basis of earlier events, but it means that the state of the universe today allows us to predict its state tomorrow and next year.¹ If nature were so constituted as to preclude such a deterministic description, the science of physics could not exist. This is part of what Einstein meant when he said

¹ Please note that I am using the word “causal” to mean that the occurrence of events is predictable on the basis of earlier events, and the word “deterministic” to mean that the state of a closed system, such as the universe, at one time determines its state at all later times. My use of these words differs from that of some other authors.

that “[t]he eternal mystery of the world is its comprehensibility... The fact that it is comprehensible is a miracle.”²

The miracle Einstein was referring to, however, requires some help from us. In order for a dynamical theory to allow the future state of the universe to be determined by its state at the present time, the theory must define what is meant by the “state” of the universe appropriately. If the state of a system of particles were defined simply as the collection of their position coordinates, Newtonian mechanics would not be deterministic (although Aristotelian mechanics would be, had the ancient philosopher aspired to such ends). Using Newton’s equations of motion, you cannot determine the future positions of the particles from their present positions alone. These equations are such that both the initial positions and the initial momenta (or velocities) of all the particles are required — and sufficient — for their future motions to be uniquely predictable. Therefore, the *state* of a system of n particles in classical mechanics is defined by a collection of $6n$ numbers: three numbers for each of their position coordinates and three numbers for each of their momentum (or velocity) coordinates. Once the state of a system is given, the values of all its other dynamical variables are fixed as well.

Thus, the classical state of a system of n particles can be thought of as a point in a $6n$ -dimensional space called the phase space. One of Einstein’s miracles of comprehensibility can then be pictured in classical mechanics as the fact that each closed system of particles follows a unique trajectory in its phase space.

As we shall see, there is an exact analog of this fact in quantum mechanics. However, in order for quantum mechanics to be a deterministic (not necessarily causal!) dynamical theory, the state of a system has to be defined probabilistically and with only an indirect connection to the reality of that system itself. This is precisely what lies at the bottom of the many weird aspects of quantum mechanics

² Einstein, *Ideas and Opinions*, p. 292.

and what drove Einstein to his opposition against it as a fundamental theory. The following chapters will recall this history as well as recount the earlier story of those parts of physics that deal with motion and structure. The long history of dynamics shows theories becoming increasingly abstract and losing intuitive contact with real experience, whereas the description of the world in terms of atoms became more and more real, although the atomic structure itself remained without explanation. As we shall see, it turned out that quantum mechanics was able to account extremely successfully for the structure of the world, which classical physics was quite unable to do. That the same theory could deal only probabilistically with dynamics has turned out to be of little consequence, all its strange and counterintuitive aspects notwithstanding. Even though Einstein was correct in his characterization of quantum mechanics as not directly dealing with reality in its basic architecture, the theory was a resounding success because it was able to explain remarkably accurately the observed particulate structure of the world. It is this ability that makes quantum mechanics still the most fundamental theory of physics.