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SECTION 7.3

Randomness from the Environment

And as a result, it is reasonable to expect that this same mechanism should also occur in many systems in nature. Indeed, as I will discuss in this chapter and the chapters that follow, I believe that this mechanism is in fact ultimately responsible for a large fraction, if not essentially all, of the randomness that we see in the natural world.

But that is not to say that the other two mechanisms are never relevant in practice. For even though they may not be able to explain how randomness is produced at the lowest level, they can still be useful in describing observations about randomness in particular systems.

And in the next few sections, I will discuss various kinds of systems where the randomness that is seen can be best described by each of the three mechanisms for randomness identified here.

Randomness from the Environment

With the first mechanism for randomness discussed in the previous section, the randomness of any particular system is taken to be the result of continual interaction between that system and randomness in its environment.

As an everyday example, we can consider a boat bobbing up and down on a rough ocean. There is nothing intrinsically random about the boat itself. But the point is that there is randomness in the continually changing ocean surface that forms the environment for the boat. And since the motion of the boat follows this ocean surface, it also seems random.

But what is the real origin of this apparent randomness? In a sense it is that there are innumerable details about an ocean that it is very difficult to know, but which can nevertheless affect the motion of the boat. Thus, for example, a particular wave that hits the boat could be the result of a nearby squall, of an undersea ridge, or perhaps even of a storm that happened the day before several hundred miles away. But since one realistically cannot keep track of all these things, the ocean will inevitably seem in many respects unpredictable and random.

This same basic effect can be even more pronounced when one looks at smaller-scale systems. A classic example is so-called Brownian motion, in which one takes a small grain, say of pollen, puts it in a liquid, and then looks at its motion under a microscope.

What one finds is that the grain jumps around in an apparently random way. And as was suspected when this was first noticed in the 1820s, what is going on is that molecules in the liquid are continually hitting the grain and causing it to move. But even in a tiny volume of liquid there are already an immense number of molecules. And since one certainly does not even know at any given time exactly where all these molecules are, the details of their effect on the motion of the grain will inevitably seem quite random.

But to observe random Brownian motion, one needs a microscope. And one might imagine that randomness produced by any similar molecular process would also be too small to be of relevance in everyday life. But in fact such randomness is quite obvious in the operation of many kinds of electronic devices.

As an example, consider a radio receiver that is tuned to the wrong frequency or has no antenna connected. The radio receiver is built to amplify any signal that it receives. But what happens when there is no signal for it to amplify?

The answer is that the receiver produces noise. And it turns out that in most cases this noise is nothing other than a highly amplified version of microscopic processes going on inside the receiver.

In practice, such noise is usually considered a nuisance, and indeed modern digital electronics systems are typically designed to get rid of it at every stage. But since at least the 1940s, there have been various devices built for the specific purpose of generating randomness using electronic noise.

Typically these devices work by operating fairly standard electronic components in extreme conditions where there is usually no output signal, but where microscopic fluctuations can cause breakdown processes to occur which yield large output signals.

A large-scale example is a pair of metal plates with air in between. Usually no current flows across this air gap, but when the voltage between the plates is large enough, the air can break down, sparks can be generated, and spikes of current can occur. But exactly when and where the sparks occur depends on the detailed microscopic motion of the molecules in the gas, and is therefore potentially quite random.

In an effort to obtain as much randomness as possible, actual devices that work along these lines have typically used progressively smaller components: first vacuum tubes and later semiconductors. And indeed, in a modern semiconductor diode, for example, a breakdown event can be initiated by the motion of just one electron.

But despite such sensitivity to microscopic effects, what has consistently been found in practice is that the output from such devices has significant deviations from perfect randomness.

At first, this is quite surprising. For one might think that microscopic physical processes would always produce the best possible randomness. But there are two important effects which tend to limit this randomness, or indeed any randomness that is obtained through the mechanism of interaction with the environment.

The first of these concerns the internal details of whatever device is used to sample the randomness in the environment.

Every time the device receives a piece of input, its internal state changes. But in order for successive pieces of input to be treated in an independent and uncorrelated way, the device must be in exactly the same state when it receives each piece of input. And the problem is that while practical devices may eventually relax to what is essentially the same state, they can do this only at a certain rate.

In a device that produces a spark, for example, it inevitably takes some time for the hot gas in the path of the spark to be cleared out. And if another spark is generated before this has happened, the path of the second spark will not be independent of the first.

One might think that such effects could be avoided by allowing a certain "dead time" between successive events. But in fact, as we will also see in connection with quantum mechanics, it is a rather general feature of systems that perform amplification that relaxation to a normal state can effectively occur only gradually, so that one would have to wait an infinite time for such relaxation to be absolutely complete.

But even when the device used to sample the environment does no amplification and has no relevant internal structure, one may still not see perfect randomness. And the reason for this is that there are almost inevitably correlations even in the supposedly random environment.

In an ocean for example, the inertia of the water essentially forces there to be waves on the surface of certain sizes. And during the time that a boat is caught up in a particular one of these waves, its motion will always be quite regular; it is only when one watches the effect of a sequence of waves that one sees behavior that appears in any way random.

In a sense, though, this point just emphasizes the incomplete nature of the mechanism for randomness that we have been discussing in this section. For to know in any real way why the motion of the boat is random, we must inevitably ask more about the randomness of the ocean surface. And indeed, it is only at a fairly superficial level of description that it is useful to say that the randomness in the motion of the boat comes from interaction with an environment about which one will say nothing more than that it is random.

Chaos Theory and Randomness from Initial Conditions

At the beginning of this chapter I outlined three basic mechanisms that can lead to apparent randomness. And in the previous section I discussed the first of these mechanisms—based on the idea that the evolution of a system is continually affected by randomness from its environment.

But to get randomness in a particular system it turns out that there is no need for continual interaction between the system and an external random environment. And in the second mechanism for randomness discussed at the beginning of this chapter, no explicit randomness is inserted during the evolution of a system. But there is still randomness in the initial conditions, and the point is that as the system evolves, it samples more and more of this randomness, and as a result produces behavior that is correspondingly random.

As a rather simple example one can think of a car driving along a bumpy road. Unlike waves on an ocean, all the bumps on the road are already present when the car starts driving, and as a result, one can consider these bumps to be part of the initial conditions for the system. But the point is that as time goes on, the car samples more and more of