APPENDIX C—THE BUTTERFLY EFFECT[306]

In 1960, Edward Lorenz, a research meteorologist at M.I.T., created a computer model of the Earth's atmosphere. Fed by such data as temperature, air pressure, and wind velocity, the computer generated recognizable, ever-changing patterns—proof that Nature itself was deterministic. Given enough data, the right formulas, and a computer, scientists could accurately model even the most complex phenomenon. Quantifiable causes had quantifiable effects, and if we could identify and measure the former, we could predict the latter.

Then, in the winter of 1961, it all fell apart. Lorenz, wishing to more closely examine a particular sequence of modeled events, started a run at the midpoint. Instead of using the same initial conditions normally input to the system, he took his numbers from a printout that his program had previously generated. To his surprise the new numbers quickly diverged from the original calculations. They should have been identical—exactly matching the data from the earlier run—and yet they were different.

Lorenz eventually realized that the problem was that printout displayed numbers to three decimal places—one part in a thousand. The computer, on the other hand, used six decimal places in its calculations. These tiny, almost immeasurable, differences had caused the two runs to diverge dramatically within relatively few iterations (i.e., calculation cycles).

Because of the iterative nature of mathematical models like Lorenz's, the cumulative effects of inaccuracies in the data and in the calculations grow rapidly. For example, the temperature that is calculated for tomorrow, given today's conditions, becomes the input for calculating the next day's temperature, which, in turn, is used to determine the following day's conditions, and so on. Errors creep in due to inaccurate and incomplete starting data and because the model's mathematical formulas can only approximate the complex processes at work. These errors, piled one on top of the other, eventually cause the projections to diverge from actual conditions.

Can projections be improved by collecting more data with greater precision, revising the formulas, and carrying out the calculations to more decimal

[306]The information in this Appendix is adapted from James Gleick, *Chaos* (New York: Viking, 1987).

places? As James Gleick explained in his book, *Chaos*, "Suppose the earth could be covered with sensors spaced one foot apart, rising at one-foot intervals all the way to the top of the atmosphere. Suppose every sensor gives perfectly accurate readings of temperature, pressure, humidity, and any other quantity a meteorologist would want."[307] At a given instant all of the sensors are read, and the information fed into a computer.

Even with such incredibly accurate starting information, computers would still be unable to calculate the weather at a given point a month from now. "The spaces between the sensors will hide fluctuations that the computer will not know about, tiny deviations from the average."[308] The instant after the data is collected, these fluctuations will shift the weather toward a path different from that calculated by the machine.

Enormous effects, then, can result from immeasurably small and undetectable causes—causes that perhaps cannot be identified even in hindsight. This concept of "tiny differences in input . . . quickly becoming overwhelming differences in output" became "half-jokingly known as the Butterfly Effect—the notion that a butterfly stirring the air today in Peking can transform storm systems next month in New York."[309] But the consequences of Lorenz's discovery are quite serious. It meant, Lorenz realized, that despite the quantity or accuracy of the data amassed, "*any* physical system that behaved nonperiodically would be unpredictable."[310]

The fundamental unpredictability of complex systems gives rise to *the law of unintended consequences*. This law states that a change to any complex system will have effects that were never intended and which could not have been foreseen.

It is easy to make the mistake of assuming that if a change to a given system yields unpredictable results, that system must be fragile. In fact, the opposite is true. The more complex and varied a system, the stronger and more resilient it is. If a particular *ecosystem* contains only one predatory animal and only one species that serves as food for that predator, then the extinction of either species—the hunter or the hunted—would be catastrophic. At the same time, such a simple system the effects of either loss would be entirely predictable. If the hunters die out, then the population of the hunted species will explode. If, on the other hand, the food species were to become extinct, the predators would soon follow.

[307] Ibid., p. 21.

[308] Ibid.

[309] Ibid., p. 8.

[310] Ibid., p. 18.

By contrast, an ecosystem that supports a wide variety of species can withstand the loss of one or more of those species without a severe disruption to the entire system. Because of the large number of different organisms present, there would necessarily be many interactions between them. Some relationships would be adversarial (hunter and hunted), some symbiotic, some parasitic, and some benign. These myriad connections help stabilize the system while at the same time ensure that any alteration would yield unforeseeable results.[311]

[311]These principles may be applied, by way of analogy, to economic systems as well. The more complex and varied an economy, the better able it will be to survive the loss of a company or even an entire industry. By the same token, as an economy becomes more complex, the less predictable will be the effects of changes imposed upon it.