When the Butterfly Effect Took Flight

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On a winter day 50 years ago, Edward Lorenz, SM ‘43, ScD ‘48, a mild-mannered meteorology professor at MIT, entered some numbers into a computer program simulating weather patterns and then left his office to get a cup of coffee while the machine ran. When he returned, he noticed a result that would change the course of science.

The computer model was based on 12 variables, representing things like temperature and wind speed, whose values could be depicted on graphs as lines rising and falling over time. On this day, Lorenz was repeating a simulation he'd run earlier—but he had rounded off one variable from .506127 to .506. To his surprise, that tiny alteration drastically transformed the whole pattern his program produced, over two months of simulated weather.

The unexpected result led Lorenz to a powerful insight about the way nature works: small changes can have large consequences. The idea came to be known as the "butterfly effect" after Lorenz suggested that the flap of a butterfly's wings might ultimately cause a tornado. And the butterfly effect, also known as "sensitive dependence on initial conditions," has a profound corollary: forecasting the future can be nearly impossible.

Like the results of a wing's flutter, the influence of Lorenz's work was nearly imperceptible at first but would resonate widely. In 1963, Lorenz condensed his findings into a paper, "Deterministic Nonperiodic Flow," which was cited exactly three times by researchers outside meteorology in the next decade. Yet his insight turned into the founding principle of chaos theory, which expanded rapidly during the 1970s and 1980s into fields as diverse as meteorology, geology, and biology. "It became a wonderful instance of a seemingly esoteric piece of mathematics that had experimentally verifiable applications in the real world," says Daniel Rothman, a professor of geophysics at MIT.

Read "Deterministic Nonperiodic Flow," Lorenz's ground-breaking 1963 paper in the Journal of Atmospheric Sciences, here (pdf). For links to Lorenz's papers, visit here.

As many researchers would recognize by the 1980s, Lorenz's work also challenged the classical understanding of nature. The laws that Isaac Newton published in 1687 had suggested a tidily predictable mechanical system—the "clockwork universe." Similarly, the French mathematician Pierre-Simon Laplace asserted in his 1814 volume *A Philosophical Essay on Probabilities* that if we knew everything about the universe in its current state, then "nothing would be uncertain and the future, as the past, would be present to [our] eyes."

Unpredictability plays no role in the universe of Newton and Laplace; in a deterministic sequence, as Lorenz once wrote, "only one thing can happen next." All future events are determined by initial conditions. Yet Lorenz's own deterministic equations demonstrated how easily the dream of perfect knowledge founders in reality. That the tiny change in his simulation mattered so much showed, by extension, that the imprecision inherent in any human measurement could become magnified into wildly incorrect forecasts.

"It was philosophically very shocking," says Steven Strogatz, a professor of applied mathematics at

Cornell and author of *Nonlinear Dynamics and Chaos*. “Determinism was equated with predictability before Lorenz. After Lorenz, we came to see that determinism might give you short-term predictability, but in the long run, things could be unpredictable. That’s what we associate with the word ‘chaos.’ ”

Weather, war, and computers

Edward Norton Lorenz was a lifelong New Englander, born in 1917 in West Hartford, Connecticut. As a boy, he once recounted, he was “fascinated by changes in the weather.” He received his undergraduate degree in mathematics from Dartmouth in 1938 and a master’s in the subject from Harvard in 1940. When the United States entered World War II, he joined the Army Air Corps and filled a growing military need by training as a weather forecaster at MIT, where the nation’s first meteorology curriculum had been established in 1928. After the war, he earned a doctorate in meteorology at MIT and largely stayed at the Institute until his death in 2008.

The military’s meteorology program that Lorenz completed had been developed by Carl-Gustaf Rossby, a former MIT professor who was an advocate of dynamic meteorology. That approach treated the atmosphere as one large system to be analyzed using the equations of fluid mechanics. “With my mathematical background, I naturally found dynamic meteorology to my liking,” Lorenz later wrote. Into the 1950s, however, dynamic meteorology did not produce reliable forecasts. A less scientifically sophisticated alternative called synoptic forecasting, which analyzed the weather by studying atmospheric structures such as high- and low-pressure systems, produced better results.

Lorenz and others began experimenting with statistical forecasting, which relied on computers to develop forecasting models by processing observational data on such things as temperature, pressure, and wind. By the late 1950s, he was using a computer to run complex simulations of weather models that he used to evaluate statistical forecasting techniques. Some of his simulations, however, were too regular to be realistic; they yielded periodic patterns, or precisely repeating sequences. As he knew, that wasn’t how the weather really worked. When his 1961 simulation deviated from its expected path, he saw that a change as small as the one he’d made in rounding a number can create a vast difference over time. Lorenz realized that sensitivity to initial conditions is what causes nonperiodic behavior; the more a system has the capacity to vary, the less likely it is to produce a repeating sequence. This sensitivity makes weather very difficult to forecast far in advance.

Confirming this intuition was a set of equations, using just three variables to represent the movement of a heated gas in a box, that Lorenz employed in his landmark 1963 paper. Even such a drastically simplified model produced “solutions which never repeat their past history exactly,” he noted. “Two states differing by imperceptible amounts may eventually evolve into two considerably different states … [meaning] an acceptable prediction of an instantaneous state in the distant future may well be impossible.”

Lorenz realized that if such a simple system was so sensitive to initial conditions, he had discovered something fundamental. “Ed’s work on chaos theory was a beautiful example of very clear reductionist thinking,” says Kerry Emanuel ‘76, PhD ‘78, an atmospheric scientist at MIT who for years had an office next door to Lorenz.

The principle of chaos drove home the importance of nonlinearity, a characteristic of many natural systems. If a group of 100 lions has a net gain of 10 members a year, that increase in population size can be plotted on a graph as a straight line. A group of mice that doubles annually, on the other hand, has a nonlinear growth pattern; on a graph, the population size will curve upward. After a decade, the difference between a group that started with 22 mice and one that started with 20 mice will have ballooned to more than 2,000. Given that type of growth pattern, the real-life pressures on species —normal death rates, epidemics, limited resources—will often cause their population sizes to rise and fall chaotically. While not all nonlinear systems are chaotic, all chaotic systems are nonlinear, as Lorenz observed.

Yet chaos is not randomness. One way that he demonstrated this was through the equations representing the motion of a gas. When he plotted their solutions on a graph, the result—a pair of linked oval-like figures—vaguely resembled a butterfly. Known as a “Lorenz attractor,” the shape illustrated the point that almost all chaotic phenomena can vary only within limits.

By 1965, Lorenz had pinpointed what he considered the primary source of nonlinearity in weather: advection, the horizontal and uneven wind-induced movement of heat, moisture, and other atmospheric properties. He had also concluded that the butterfly effect made it impossible to accurately forecast the weather two weeks ahead. Small errors regarding large-scale weather features, such as recording an imprecise location for a storm, would double in magnitude in about three days. Errors in observing small-scale weather features, such as imprecisely recording locations of individual clouds, could turn into errors on a larger scale within a day.

Meanwhile, a few scientists had begun grappling with Lorenz’s discoveries. Joseph Pedlosky ‘59, SM ‘60, PhD ‘63, now a scientist emeritus at the Woods Hole Oceanographic Institution, was a new assistant professor at MIT studying nonlinear eddying motion in the ocean and atmosphere when he saw Lorenz speak and realized that his meteorological and oceanographic models demonstrated chaos. Lorenz’s insight “allowed me to talk about chaotic and aperiodic behavior, and that was very exciting,” he says.

It took longer for chaos theory spread to other disciplines; in the mid-1970s, the biologist Robert May first suggested that populations of species fluctuate in chaotic fashion. Today we recognize that such disparate phenomena as a heartbeat and the erosion of a riverbed display chaotic behavior. Many scientists—including Emanuel—now rank chaos theory alongside relativity and quantum theory among the great scientific revolutions of the 20th century.

Dances with coyotes

A legend in the classroom, Lorenz earned students' votes as the meteorology department's best teacher year after year. "Eventually, the award was discontinued because no one else ever won it," Emanuel recalls. Yet Lorenz's research went largely unnoticed for a decade. "Ed was a very shy man who was as far from being a self-promoter as you could possibly imagine," says Emanuel. "He didn't go off giving scientific talks a lot."

Colleagues finally persuaded Lorenz to give his ideas a wider airing at the 1972 conference of the American Association for the Advancement of Science. His paper "Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?" introduced the butterfly image, courtesy of meteorologist Philip Merilees, who came up with the title. Previously, Lorenz had used the more prosaic example of a seagull causing a storm. In 1987, the term "butterfly effect" took flight in James Gleick's best seller *Chaos: Making a New Science*—and Lorenz's discovery reached a general audience.

Gleick's book made a scientific celebrity of Lorenz. Rothman and Strogatz, then a professor at MIT, began inviting him to present annual guest lectures to awed students. "Every year he would give a new lecture on what he had done in the last year," says Rothman. "It was astonishing. In the last five years of his life, the lectures started getting better. Deeper. He was very into it." But Lorenz would deflect students' questions about his old breakthroughs.

Modest and soft-spoken even around familiar colleagues, Lorenz could be more voluble about his family or the outdoors; he was a lifelong hiker and cross-country skier. "If you talked to him about the White Mountains of New Hampshire, he would completely open up," says Emanuel. One time, improbably, Emanuel ran into Lorenz and his wife, Jane, on vacation in the Southern California desert. They all went to a nature preserve, where Emanuel saw a group of coyotes napping under a tree. On a whim, he started clapping and hollering to wake up the coyotes, but they did not stir.

"All of a sudden I heard this really loud coyote yelp coming from right behind me," recounts Emanuel. "I shot up about three feet in the air. Then I turned around and it was Ed! He had snuck up behind me, and he knew how to talk to the coyotes. He woke them up right away, and they started carrying on some kind of conversation with him. This huge sound, coming from this guy who you ordinarily had a hard time hearing."

Pop goes the butterfly

The butterfly effect even filtered into pop culture. "A butterfly can flutter its wings over a flower in China and cause a hurricane in the Caribbean," says Robert Redford's character in the 1990 movie *Havana*, adding that scientists "can even calculate the odds." But they can't, as Lorenz made clear in his 1990 book, *The Essence of Chaos*. Nature's interdependent chains of cause and effect are usually too complex to disentangle. So we cannot say precisely which butterfly, if any, may have created a given storm. Moreover, as Lorenz stated in his 1972 paper, "If the flap of a butterfly's wings can be instrumental in generating a tornado, it can equally well be instrumental in preventing a tornado." And that would be impossible for us to know.

Lorenz would thus equivocate when asked whether a butterfly can really cause a tornado. "Even today I am unsure of the proper answer," he said in a 2008 lecture. The value of the question is the larger point it evokes: that nature is highly sensitive to tiny changes. "The idea has now entered the everyday vision of many scientists across all disciplines," says Rothman. "They understand that some things are chaotic, and that there's exponential divergence from initial conditions. They may not voice it, but they know it because it's in the air. That's the sign of a great achievement."

Lorenz's work has also led to improvements in weather forecasting, which he credited to three things: wider data collection, better modeling, and "the recognition of chaos" in the weather, leading to what's called ensemble forecasting. In this technique, forecasters recognize that measurements are imperfect and thus run many simulations starting from slightly different conditions; the features these scenarios share form the basis of a more reliable "consensus" forecast.

Imagining a Lorenz Institute

Beyond forecasting, Lorenz was "keenly interested in climate," Emanuel says, and made it clear that even if tracing the effects of small things is too hard to let anyone predict the weather a month ahead, the effects of large things, like the increase of carbon dioxide in the atmosphere, are not hard to discern. "He did not think that climate change is wholly unpredictable and would have been amused at those who say that because we cannot predict the weather beyond a few days, there is no possibility of predicting climate," he says.

Today, Emanuel and Rothman are working with MIT fund-raisers to find backing for a climate research center that they would like to call the Lorenz Institute. Emanuel thinks that would help compensate for the fact that Lorenz never held a titled professorship, despite his many professional awards. "He was a classic example of a prophet not honored in his own country here at MIT," he says bluntly.

The proposed Lorenz Institute, Emanuel says, would focus on pure research in service to a quest for "underlying principles in climate that make it easier to understand." As Lorenz wrote in 2005, "It has often been noted that a piece of pure research can lead, sometimes much later, to a practical application very likely not anticipated by the scientist performing the pure research."

Indeed, it is hardly fanciful to imagine Lorenz's insight as one such brief intellectual flutter, setting off currents that still affect the scientific atmosphere. Perhaps on some future winter day, another MIT climate scientist, ensconced in the Lorenz Institute, will return from a coffee break and instigate a breakthrough just as profound.