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EDWARD NORTON LORENZ
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A Biographical Memoir by

KERRY EMANUEL

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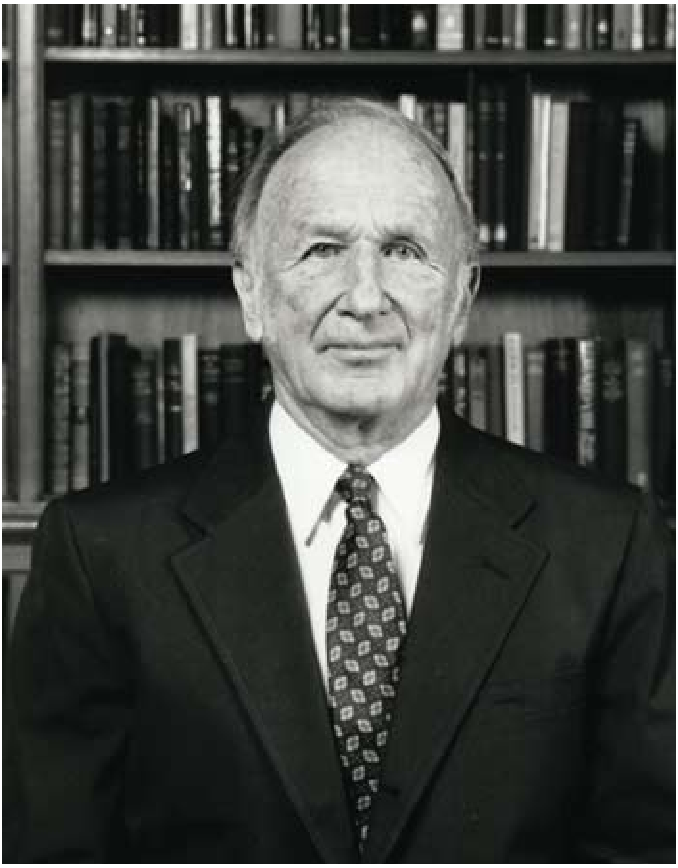

Edward N. Lorenz

EDWARD NORTON LORENZ

May 23, 1917–April 16, 2008

BY KERRY EMANUEL

ED LORENZ, WIDELY REGARDED as the founder of the modern theory of chaos, also developed revolutionary ideas about the energetics of stratified rotating fluids, and made important contributions to the understanding of atmospheric dynamics and weather prediction. He was a devoted husband and father whose love of the outdoors was legendary. Through his profound contributions to science as well as his quiet demeanor, gentle humility, and love of nature, he set a compelling example of what it means to be a gentleman and a scholar.

CHILDHOOD

Edward Norton Lorenz was born in West Hartford, Connecticut, on May 23, 1917. His father, Edward Henry Lorenz, was born in Hartford in 1882; he attended Hartford High School and Trinity College before majoring in mechanical engineering at the Massachusetts Institute of Technology, then located in downtown Boston. He was small in stature but an excellent distance runner and held the record for the 2-mile run at MIT. It was from him that his son acquired an early knowledge of science, particularly mathematics.

Ed's mother, Grace Norton, was born in Auburndale, Massachusetts, in 1887, but while a still young child, moved to Chicago with her mother and siblings after the untimely death of her father, Lewis M. Norton, who had developed the first course in chemical engineering in MIT's chemistry department in 1888. Grace's mother founded the department of home economics at the University of Chicago, the institution from which Grace ultimately graduated. Thereafter, Grace became a school teacher and contributed to many civic organizations. In his memoirs Ed states that his mother fostered in him a deep interest in games, particularly chess, and says she taught him more about life than anyone else.

Ed's parents met at Waterville Valley, a summer resort in New Hampshire, and after they were married in 1916 continued to summer there, imparting to their son a deep and abiding love of the outdoors. Ed spent many of his summers at Waterville Valley throughout his life.

Ed became fascinated with numbers at an early age. While his mother wheeled him down the street in a go-cart, young Ed would read out all the house numbers. Later, after he had learned multiplication, he took an interest in numbers that were perfect squares and could recite all such numbers between 1 and 10,000. He also enjoyed taking square roots using a longhand method, and even learned a method for extracting cube roots. He would spend many hours playing with mathematical puzzles with his father.

From his mother Ed developed a keen interest in games and learned to love card and board games of all kinds. This included chess, at which Ed excelled, becoming the captain of his high school and college chess teams. Later, while a faculty member at MIT, he would often spend his lunch hour at the faculty club playing chess with faculty colleagues, including Norbert Wiener, who routinely played simultaneous games with a set of his colleagues. In addition to games, Ed loved crossword and jigsaw puzzles and would spend hours solving them with his father. They would compete to see who could solve each puzzle most rapidly, and record the times on the inside covers of the boxes. Throughout his life Ed kept a collection of jigsaw puzzles from his childhood.

When he was seven, Ed's family went to visit friends who lived on a farm a few miles east of Hartford. By then he had already developed an interest in maps and would even draw maps of places that he had invented, drawing inset enlargements along the way. At this friend's house he found an atlas that contained a page showing circular objects of various sizes and was especially struck by something that looked like a ball with a ring around it that reminded him of a hat he had seen in a cartoon. His father explained that he was looking at illustrations of the planets, thus initiating a lifelong love of astronomy. A year later Ed witnessed a total eclipse of the sun on a bitterly cold day in Hartford, with shadow bands shimmering across fields of snow. He was also interested in the weather, though it did not then occur to him that he would one day make a profession of it.

Ed had a good ear for music and could, by the time he was three, tell that his mother was singing off key—but he loved to listen to her anyway. He began violin lessons at the age of nine but concluded that he did not have the manual dexterity to produce a really pleasing sound. Nevertheless, his passion for music continued to develop, and many of his friends and colleagues will remember attending concerts with him and his wife, Jane, at the Chautauqua resort in Boulder, Colorado, where they often spent part of their summers, or at MIT where they both were avid patrons of the student symphony orchestra. During the years they lived in Lexington, Massachusetts, Ed was a member of the town's choir.

Smaller than most boys his age, and also a year younger than most of his classmates, Ed did not excel at team sports and was not particularly welcome when he tried to enter a game. Even so, by the time he entered high school he was equal to his peers in swimming and could swim underwater further than anyone. During summers in New Hampshire, he grew fond of hiking and discovered that, owing to his light weight, he could reach the tops of mountains faster than most of his friends. He later related that mountains and music were his greatest spare-time interests.

UNIVERSITY

Ed entered Dartmouth in 1934, having already decided that he wanted to major in mathematics. It is telling that of roughly 700 students entering Dartmouth that year, only seven went on to major in mathematics. Ed preferred the logical clarity of math to any of the other courses he encountered, including history, physics, and geology. In 1938 he entered the graduate school of the mathematics department at Harvard, delighting in being able to focus exclusively on math. It was here that he was first exposed to such topics as group theory, set theory, and combinatorial topology, taught by such luminaries as Saunders Mac Lane, Marshall Stone, and James Van Vleck (who was later awarded the Nobel Prize in Physics). Ed relates that although he had originally been attracted to math by his love of numbers, during his graduate years he seldom saw any number other than 0, 1, and 2. Ed chose to work on a problem in mathematical physics under the guidance of George Birkhoff, an eminent mathematician proficient in many fields but perhaps best known for his proof of Poincaré's Last Geometric Theorem, a special case of the orbital three-body problem, which exhibits one of the key properties of chaos: sensitive dependence on initial conditions. Ed's master's thesis was not about dynamical systems, however, but concerned a topic in Riemannian geometry.

In 1942, just months before he expected to receive his doctoral degree, the war intervened and Ed had to choose between being drafted and training to become part of a team of weather forecasters for the army. Fortunately for science he chose the latter and in March 1942 enrolled as a cadet in the Army Air Corps (now the Air Force) in a special eight-month master's program down the Charles River at MIT, ostensibly to train as a weather forecaster. In Ed's own memorable words, "It soon became evident that we were studying to be meteorologists. The distinction is one that I was slow to appreciate."[1] Ed came to understand that meteorology concerned the scientific understanding of the atmosphere, while weather forecasting was simply a particular practical application of meteorology; it was possible to become a forecaster without having much real understanding of the atmosphere, and to aspire to the latter without being able to do the former. Nevertheless, the MIT program put equal emphasis on both. Mornings were devoted to theory, which seemed relevant to forecasting but had not really been shown to lead to improved forecasts. In the afternoons the trainees were taught to forecast, using sequences of past weather maps as case studies. He was exposed to MIT faculty members Hurd Willett, Henry Houghton, and Bernard Haurwitz, among others. According to Ed, "Our faculty in meteorology was as outstanding as any in the world, and it was natural that they should want to teach real science to their students. This was probably compatible with the Army's philosophy that an officer is a gentleman."[1] The dichotomy between the theory of weather and the practice of weather forecasting fascinated Ed through the rest of his career.

At the end of the master's program, in November 1942, Ed received orders that he, along with four classmates, would remain at MIT as instructors for the next year's program. This also gave Ed the opportunity to attend advanced classes, and he began to feel more like an experienced meteorologist. But he retained the nagging feeling that there was something important missing from the field.

Not only were we never shown how to use the dynamical equations to make weather forecasts, which I had naively assumed was the reason for our studying dynamic meteorology, but we were not even told whether they could be used in this manner. I also learned that some outstanding meteorologists at other universities believed that it was impossible.[1]

THE WAR

After completing the final training course at MIT, Ed received orders to go overseas. He first reported to Hawaii, where he absorbed another two months of training in tropical meteorology and then flew to Saipan in October 1944. With several Air Corps colleagues he helped set up a weather forecasting operation in support of airborne bombing raids against Japan. His principal job was forecasting upper-level winds, but the forecasters were hampered by a severe lack of observations because the Air Corps put little emphasis on weather data. (This problem culminated in December 1944, when Admiral William F. Halsey, commander of the U.S. Third Fleet, having refused to devote a few aircraft to weather reconnaissance, sailed his fleet directly into the center of a severe typhoon, losing 3 ships and 790 men as a result.) The only observations between Siberia and Saipan were taken by the crews of U.S. aircraft themselves; Ed complained that the pilots, to save time, would often simply repeat the forecast as the observation. This made for excellent forecast verification but hardly helped the forecasters make the next forecast.

In the spring of 1945 the weather operation was transferred to Guam,[2] where Ed was appointed head of the upperair section. The operation continued until a few months after the end of the war. Some insight into Ed's character during this period is provided by his fellow forecaster, Patrick Suppes:

> Although Ed was not a strongly outgoing individual, it turned out that he rather liked conversation on many topics, and of course as those who knew Ed will find unsurprising, he knew a lot and was prepared to talk about a great many different subjects."[3]

Professor Suppes notes that several members of the Weather Central, including Ed, were nominated for (but did not receive) a Bronze Star medal. Suppes's nomination letter, which he believes must be similar to the one written for Ed, states,

> Through high order technical skill and resourcefulness, he utilized scientific principles to adapt known techniques and to devise new techniques of analysis and forecasting in the institution of a successful combat weather forecasting service.[3]

Those who know Ed principally through his research contributions might easily overlook his interests in the practical art of weather forecasting and his love of weather in general. But generations of students and colleagues at MIT will remember many occasions when Ed would appear silently in their office, as if by magic, and enthuse over some feature of the current weather map.

POSTWAR YEARS AND FAMILY LIFE

At the end of the war Ed reached a critical turning point in his career with his decision to switch to meteorology rather than completing his doctorate in mathematics at Harvard. He reached this decision after considerable deliberation, which included several conversations with Henry Houghton, head of the meteorology department at MIT. In Ed's own words,

> Mathematicians seem to have no difficulty in creating new concepts faster than the old ones become well understood, and there will undoubtedly always be many challenging problems to solve. Nevertheless, I believed that some of the unsolved meteorological problems were more fundamental, and I felt confident that I could contribute to some of their solutions.[1]

Ed's thesis, which was performed under the supervision of James Austin, earned him a doctorate of science degree in 1948; it described an application of fluid dynamical equations to the practical problem of predicting the motion of storms. This was a time just before the application of digital computers to weather prediction, and Ed's method expanded the governing equations as power series in time. Even at the time he felt that his technique was "more cumbersome than some others that were currently being developed,"[1] and to my knowledge it was never actually used. But this work did show Ed to be an innovative and independent thinker.

A few weeks after receiving his doctorate, Ed married Jane Loban, who had been working as a research assistant in the meteorology department at MIT. Jane was born in Dayton, Ohio, in 1919 but spent most of her childhood in Cedar Falls, Iowa. Her consuming interest was flying, and she flew small airplanes before she was old enough to drive a car. Her interest in flying led naturally to studies in meteorology, which in turn led to her appointment at MIT. Following their marriage they settled in Cambridge, Massachusetts, and lived in the Boston area for the remainder of their lives, raising three children: Nancy, Edward, and Cheryl. All three showed a keen interest in games and puzzles, as Ed had, and likewise acquired a great love of the outdoors, becoming first-class downhill skiers. According to Ed, "Many of my winter weekends were spent taking one or all of them, usually with my wife as well, to some ski area north of Boston; this, of course, was just what I had hoped would happen."[4]

Ed's devotion to his family was evident to all who came to know him well. Although a reticent man, there were a few topics that were sure to get him going: hiking in the mountains, and his family, which later included several grandchildren. Jane suffered a series of debilitating illnesses toward the end of her life, leading Ed put to aside his own research and other interests to care for her.

THE GENERAL CIRCULATION OF THE ATMOSPHERE

After completing his doctorate, Ed accepted a job as a research scientist on a project to study the general circulation of the atmosphere, a project headed by Victor Starr, who had come to MIT from the University of Chicago the year before. In some ways Starr was much like Ed: small in stature, reticent by nature, and intensely interested in the intellectual challenge of understanding the atmosphere. He became Ed's mentor and close friend and was, next to his parents, the most important influence on his intellectual development. According to Ed,

> In a day when there was still much confusion in meteorology, Starr's clear and deliberate analyses of some of the fundamental problems proved highly refreshing, and they removed any lingering doubts as to the desirability of my change from mathematics to meteorology. The things I remember best and cherish most, in looking back over my scientific career, are the almost daily conversations with Victor Starr during the more than twenty-five years that I worked with him, first as a protégé and then as a colleague. His clear explanations of some specific points, his enthusiastic far-reaching speculations regarding others, and his general comments about philosophical matters taught me more than anything else what meteorology and more generally what science really is.[4]

During the time that Ed worked on the general circulation project, he visited several research groups in the United States that were to influence his subsequent career. In the early 1950s he visited the laboratory of David Fultz at the

University of Chicago. Fultz was then conducting a series of "rotating dishpan" experiments, wherein rotating annular trays of water were heated at their peripheries and cooled in their centers, inducing a circulation of the water. While only a weak analog to the circulation of the atmosphere, many of the same features can be observed, including large-scale Rossby waves that may be stationary or whose amplitude may vacillate. At high enough rotation rates the waves become unstable and evolve irregularly in time, much like real weather systems. In 1951 Ed visited the Lowell Observatory in Flagstaff, Arizona, where meteorologists, including Seymour Hess and Ralph Shapiro, were working with astronomers such as V. M. Slipher, who discovered the red-shift in stellar spectra. Ed found the work fascinating but was not in residence long enough to make any contribution to it. He did, however, publish a paper on the depth of the Jovian atmosphere.

Perhaps the most important trip that Ed undertook during this period was a visit to Jule Charney, Norman Phillips, and others working under John von Neumann at the Institute for Advanced Study in Princeton, New Jersey, to apply the newly developed digital computer to the problem of numerical weather prediction. At this point Ed and Victor were not convinced that numerical solution of the equations governing atmospheric flow was even possible; indeed, the British mathematician L. F. Richardson had tried to do a calculation by hand in 1922 and failed rather spectacularly. Although Ed was not entirely persuaded during this visit, by the mid-1950s he saw that this was the way of the future. Ed must have made a positive impression on Charney because a few years later Charney made his own acceptance of the offer of a faculty position at MIT contingent upon the promotion of Ed to the faculty.

One of the problems Ed discussed with Victor Starr was that of the energetics of the atmosphere. Clearly the circulation of the atmosphere is an example of a forced dissipative system, but the flow of energy through the system had not been quantified. Whence, for example, do storms get their kinetic energy? Ed's answer to this question constitutes his first important contribution to the published literature in science (1955). He first defined a quantity called "available potential energy" (APE) as the difference between the nonkinetic energy (sum of the internal and potential energies) of a given state and that of a reference state, defined as the state that minimizes the nonkinetic energy under a strictly adiabatic rearrangement of mass in the system. This is the maximum amount of energy available for conversion to kinetic energy in the absence of external energy sources. He then showed that for suitably small departures of the actual state from the reference state, APE is proportional to the integral over the system of the square of the entropy perturbations from the reference state, provided the latter is stable to convective overturning. This allowed meteorologists to make accurate estimates of APE from atmospheric measurements. Ed next divided the kinetic and available potential energies into their averages over longitude and perturbations from those averages and showed that the mean state APE, generated by latitudinal gradients of heating, is first converted to eddy APE, then to eddy kinetic energy. Most of the eddy kinetic energy is then cascaded by unresolved eddies to smaller scales and finally to molecular dissipation, but some of it is transferred back to longitudinal mean kinetic energy. This upscale kinetic energy transfer, accomplished as large-scale eddies give up their kinetic energy to the background flow, was noted a few years earlier by Starr and others, and proves to be characteristic of a class of rotating stratified flows whose large-scale eddies share certain properties with strictly two-dimensional turbulence.

Ed's work on atmospheric energetics and the general circulation of the atmosphere, begun when he was hired to work on Starr's general circulation project, culminated in the publication of a treatise on the general circulation of the atmosphere (1967), a beautifully crafted exposition of the main features of atmospheric circulation, still used as a starting point by students and professional researchers interested in the topic.

THE ROAD TO CHAOS

In 1953 Ed was invited to visit UCLA for one year, to fill in for a faculty member on leave. There he met the Norwegian meteorologists Jacob Bjerknes, Jorgen Holmboe, and also Arnt Eliassen, with whom he formed a lifelong friendship. While at UCLA, Ed received a letter from Henry Houghton inviting him to join the MIT faculty and to take over leadership of a statistical forecasting project started by Thomas Malone, who was leaving MIT to start a private forecasting venture.[5] Ed was attracted to the prospect of a faculty position, but he knew little about statistics even though statistical forecasting was at the time a major focus of research on forecasting techniques. Ed was more familiar with the concept of numerical weather prediction, then in its infancy, but began to see how the two techniques might be combined.

By this time a number of statistical forecasters had come to believe that linear regression models would perform at least as well as numerical methods ever could, apparently bolstered by a theorem developed by Norbert Weiner. Ed was deeply skeptical of this idea and determined to test it using a simple set of equations, which he would numerically integrate and then see how well the result could be reproduced using linear regression methods. To do the integrations he would need a computer. Robert White, then at MIT, came to his aid and together they settled on a Royal McBee LGP-30 (a very early example of a desktop computer), which sat in Ed's office for many years thereafter. This machine would now be regarded as unbelievably slow but was nearly state of the art in 1958 and faster than a desk calculator. "Suddenly I realized that my desire to do things with numbers would be fulfilled."[1]

Ed realized from the outset that if the equations he chose produced periodic solutions, these solutions could be trivially reproduced by statistical methods. So he set about finding a set of equations whose solution would vary irregularly in time. After learning how to write and optimize computer programs, Ed settled on a set of 12 ordinary differential equations that represented approximations to the equations of motion for a rotating stratified fluid. He found that the solutions to these equations were nonperiodic in character. When he applied the linear regression method to the simulation, it produced mediocre results, as he had foreseen.

At one point, in 1961, Ed had wanted to examine one of the solutions in greater detail, so he stopped the computer and typed in the 12 numbers from a row that the computer had printed earlier in the integration. He started the machine again and stepped out for a cup of coffee. When he returned about an hour later, he found that the new solution did not agree with the original one. At first he suspected trouble with the machine, a common occurrence, but on closer examination of the output, he noticed that the new solution was the same as the original for the first few time steps, but then gradually diverged until ultimately the two solutions differed by as much as any two randomly chosen states of the system. He saw that the divergence originated in the fact that he had printed the output to three decimal places, whereas the internal numbers were accurate to six decimal places. His typed-in new initial conditions were inaccurate to less than one part in a thousand.

"At this point, I became rather excited," Ed relates.[1] He realized at once that if the atmosphere behaved the same way, long-range weather prediction would be impossible owing to extreme sensitivity to initial conditions. During the following months, he persuaded himself that this sensitivity to initial conditions and the nonperiodic nature of the solutions were somehow related, and was eventually able to prove this under fairly general conditions. Thus was born the modern theory of chaos.

Ed had also been wondering why patterns on weather maps had certain preferred geometries and not others that were equally admissible under the governing equations; he suspected that the actual state space of the atmosphere lies on some sort of surface (not an energy surface since the atmosphere is dissipative) whose geometry might be described analytically. He now tried to find such surfaces in his 12-variable model but found that analyzing even such a limited model was rough going, and wondered whether it might be possible to find even simpler systems that exhibit nonperiodic behavior. About this time he visited Barry Saltzmann, who showed him the results of integrating a seven-variable model derived by truncating series expansion of equations governing thermal convection between parallel plates. While most of the solutions of this model are periodic in time, one set exhibited irregular variability, and Ed noticed that in this particular solution, four of the seven variables settled down to zero and stayed that way. Thus he realized that there are chaotic solutions to a three-variable system; this became the celebrated Lorenz (1963,1) model.

In analyzing the geometry of this model Ed showed that any finite volume in the three-dimensional state space would asymptotically vanish with time, so that two particles separated from each other in a suitable direction would approach each other and appear to merge. He recognized that such a merger had to be illusory.

It would seem, then, that the two surfaces merely appear to merge, and remain distinct surfaces. Following these surfaces along a path parallel to a trajectory, we see that each surface is really a pair of surfaces, so that, where they appear to merge, there are really four surfaces. Continuing this process for another circuit, we see that there are really eight surfaces, etc., and we finally conclude that there is an infinite complex of surfaces, each extremely close to one or the other of two merging surfaces.

Ed had discovered the fractal geometry of what would later be called a "strange attractor." It had previously been assumed that the vanishing with time of any initial volume in state space would preclude any strong divergence of trajectories; Ed showed that this was not the case, and forced dissipative systems, such as his three-variable model, could exhibit sensitive dependence on initial conditions.

SIGNIFICANCE OF LORENZ'S WORK ON CHAOS

Ed's 1963 paper was not the first to document nonperiodic behavior in mathematical systems. For example, Poincaré's work in the late 19th century showed that low-dimensional Hamiltonian systems can exhibit nonperiodic solutions. At the time Ed's paper appeared most physicists assumed that complex behavior is invariably the result of many degrees of freedom in the governing equations or boundary conditions. For example, Landau and Lifshitz (1959) qualitatively describe the complexity of turbulence in fluid flows as resulting from a large number of successive Hopf bifurcations involving ever-increasing degrees of freedom. Ed's work was more immediately foreshadowed by that of Allan (1962), who examined the nature of the solutions to the Rikitake equations, low-order truncations of the equations describing coupled dynamos. These are three coupled ordinary differential equations in time, quite similar to the Lorenz equations. While Allan focused on the fixed points and periodic solutions of these equations, he also performed some numerical integrations that for some sets of parameters, exhibit irregular behavior in time. While he did not explore such solutions in detail, he noted that "the topology of the set of all trajectories for these equations is certain to be very curious."

Curious indeed. What Ed demonstrated was that very simple, low-order forced-dissipative systems can produce highly complex solutions, described by fractal ("strange") attractors, and that exhibit sensitive dependence on initial conditions. His work inspired mathematicians, such as James Yorke, to pursue the fractal nature of strange attractors, and his later work on the predictability of weather entered the popular lexicon as the "butterfly effect"[6] through James Gleick's popular book on chaos (1987).

The true implications of the butterfly effect are not fully appreciated even today. In low-order chaos, such as exhibited by the Lorenz (1963,1) system, accurate solutions can be attained as far in the future as one likes by making the initial error sufficiently small. In higher-order systems, such as Lorenz himself later developed (1969), rapidly growing errors at the smallest scales can cascade upscale to influence the larger scales of interest. Such systems possess a finite predictability horizon even in the limit of vanishing initial error, and so are almost indistinguishable from nondeterministic systems. Do the solutions of the full three-dimensional Navier-Stokes equations exhibit such behavior? The answer is not yet known, and this question, together with the Riemann hypothesis, is one of the Clay Mathematics Millennium Prize problems, among the greatest unsolved problems of this century.

The advent of chaos theory constitutes one of the great scientific revolutions of the 20th century. It has influenced the course of all scientific and many engineering disciplines and has even begun to affect philosophy and other endeavors outside science. For example, it is now recognized that the orbits of asteroids and some planets (including Earth) may be chaotic, possibly resulting in sudden large excursions from regular, quasi-periodic orbits. In the field of ecology it was once thought that populations could achieve steady states in steady environments, but here too it has been shown that population may be inherently unstable and exhibit chaotic fluctuations. Chemical reactions were once thought to be predictable, but some catalytic reactions in both organic and inorganic chemistry have been shown to be chaotic and this has proven relevant for understanding the biochemistry of the nervous system. Chaos theory has had a large influence in economics, where an important question arises as to whether one can distinguish between the existence of a low-order attractor and high-order noise. The existence of the former would imply some degree of finite-time predictability.

Control theory has also profited from research on chaos: we are learning how to control chaotic systems by introducing perturbations designed to keep systems close to their stable manifolds. In mathematics, chaos theory is being brought to bear on such problems as proving the normality of certain irrational numbers, such as π, which has been shown to be equivalent to proving that the attractors of certain chaotic dynamical systems have uniform statistical properties in state space. Perhaps the most interesting development in chaos theory is its possible relevance to the behavior of quantum systems near their classical limit. This endeavor, now known as quantum chaology, explores such issues as the implications of quantum uncertainty for macroscopic determinism.

LATER WORK AND LIFE

The general circulation of the atmosphere and the question of predictability of chaotic systems were Ed's two main research preoccupations for the remainder of his life, and he was keen on applying chaos theory to the practical problem of weather prediction. In 1964 Ed suggested that since the initial state of the atmosphere and ocean could never be known precisely, one should make a large number of numerical forecasts, each starting from slightly different but equally likely initial states. This practical alternative to the nearly impossible task of integrating the full Liouville equation provides information about the uncertainty of the forecast, and the mean of the different integrations is likely to be a better forecast than a single arbitrary integration. Today, ensemble numerical weather prediction has become a bedrock tool for weather prediction and is carried out by all the leading centers for computational weather prediction around the globe. Among these centers is the European Centre for Medium Range Weather Prediction, which Ed visited on a number of occasions. One visit led him to examine how small differences between analyzed or forecasted states one day apart grow with time in their operational numerical weather prediction model. He concluded that for the model then in use, errors in the pressure field roughly 5 km above the surface doubled in about 2.5 days; he, however, warned that as the spatial resolution of the model improved, enabling it to simulate finer-scale features with higher growth rates, this doubling time might decrease, leading eventually to a plateau in the skill of such forecasts.

Another problem that Ed recognized early on was the question of whether Earth's climate is intransitive (i.e., Does it possess more than one attractor?). He was particularly interested in "almost intransitive" systems in which the system state can reside in one attractor basin for a while and then switch unpredictably to another basin of attraction; the two or more basins are fractally intertwined. Clearly it would be difficult to characterize such systems as possessing a single "climate." The character of almost intransitive systems and the question of whether Earth's climate is an example of such a system remain outstanding and important issues.

The state space of chaotic systems usually contains voids: regions that the state does not naturally evolve through or evolves through only rarely. Nevertheless, it is always possible to initialize systems within such voids, and experience with many such systems shows that the state so initialized evolves away from the voids on timescales smaller than those characterizing the usual evolution. In equations governing the flow of rotating stratified fluids like the atmosphere, this rapid evolution corresponds physically to fast internal waves or convection, while the slower evolution corresponds to the slower Rossby waves that govern the more predictable day-to-day variations in wind and pressure. This behavior gave rise to the notion of a "slow manifold" and the issue arose as to whether such a slow manifold could be precisely defined as a distinct, invariant manifold within the whole state space of the system, so that a state initialized on the manifold would stay on it forever. The problem turned out to be subtle, and in his landmark 1986 paper on the subject, Ed showed that while manifolds that are locally invariant and locally slow do exist, global slow manifolds do not; this is related to the spontaneous generation of fast waves in an otherwise slowly evolving system.

Ed's interest in bringing the lessons of chaos theory to bear on the practice of weather prediction led him in the late 1990s to explore the idea of adaptive sampling of the atmosphere. In situ measurements are made from "platforms of opportunity," such as ships and aircraft, or by weather balloons launched from fixed points at specified times. Can one devise a sampling strategy that targets particular regions at particular times, depending on the state of the system? Using a 40-variable model, Ed showed that a simple strategy based on making observations where the prior estimate is most likely to be in error led to a significant improvement in the forecast compared to making random or fixed observations.

Ed's work ultimately brought him much recognition. Among many awards, he received the Carl Gustaf Rossby Research Medal from the American Meteorological Society in 1969, the Symons Memorial Gold Medal from the Royal Meteorological Society in 1973, The Holger and Anna-Greta Crafoord Prize from the Royal Swedish Academy of Science in 1983, the Kyoto Prize from the Inamori Foundation in 1991, The Roger Revelle Medal from the American Geophysical Union 1992, and the Buys Ballot Medal from the Royal Netherlands Academy of Arts and Sciences in 2004. He was elected to the National Academy of Sciences in 1975.

During the late 1990s, Jane was afflicted by poor health and she passed away in late 2001. Ed set aside his research and other interests during this time and devoted himself to her care. After her death he returned to his research interests, publishing another nine or so articles. He had a bout of cancer in the 1980s, and, suffered another attack of the disease in 2007. He died at home in April 2008, surrounded by his family and having worked on proofs of his latest paper just a few days earlier.

SUMMARY AND PERSONAL REFLECTIONS

Those of us privileged to have known Ed Lorenz will remember him as a gentle, quiet soul, almost painfully shy and modest to a fault. But engage him on a favorite topic—a fine point in atmospheric or dynamical systems theory, the virtues of a particular mountain trail, or anything to do with his extended family—and with a twinkle of his bright blue eyes he would come to life; at such times one always felt as if he were inwardly smiling at life. Ed was a true gentleman and in his own quiet way showed a deep affection for his wife, Jane, and their children, and an old-fashioned sense of chivalry toward Jane. When invited to visit any of us with families, he would invariably bring some wonderful, usually mathematics-based toys for the children. He was much beloved as a teacher and for many years running won the prize awarded by MIT graduate students for the best teacher of the year.

Ed's scientific legacy will no doubt focus on his work on chaos in forced dissipative systems and his discovery of the fractal nature of the state spaces of such systems. It has already had a profound effect on a large spectrum of disciplines, from mathematics and geophysics to economics and even philosophy. If quantum chaology were to demonstrate a link between quantum uncertainty and chaos, then history may well record that Ed Lorenz had begun the process of hammering the last nail into the coffin of Laplace's daemon. Ed himself was not immune to some of the philosophical implications of his work, and in *The Essence of Chaos* (1993), mused in characteristic Lorenzian[7] fashion on the problem of free will:

> We must wholeheartedly believe in free will. If free will is a reality, we shall have made the correct choice. If it is not, we shall still not have made an incorrect choice, because we shall not have made any choice at all, not having a free will to do so.

MUCH OF THE material for this memoir was provided by Ed Lorenz's autobiographical note, "A Scientist by Choice,"[1] and through a published interview with him (WMO, 1996). Ed's son, Ned, and daughter, Nancy, contributed valuable suggestions. I am indebted to Tim Palmer of the European Centre for Medium Range Weather Forecasts, whose own biographical memoir for the Royal Society (Palmer, 2009) served as a valuable source, and to Joe Pedlosky at the Woods Hole Oceanographic Institution for helpful suggestions.

NOTES

1. A Scientist by Choice. Speech delivered on the occasion of Ed's acceptance of the Kyoto Prize in 1991.
2. In his memoir, Lorenz states that the weather forecasting operation was moved to Okinawa in the spring of 1945. However, his forecaster colleague Patrick Suppes states that the operation moved to Guam. Since the Battle of Okinawa did not end until mid June, 1945, it seems unlikely that the weather operation was moved to Okinawa, but it is possible that Lorenz moved to Okinawa in the summer of 1945.
3. Personal communication with author, August 2008.
4. Lorenz's reply to a questionnaire submitted in connection with his being awarded the Kyoto Prize in 1991.
5. It is not clear to me whether Ed knew that this offer was negotiated by Jule Charney as a condition of Charney's acceptance of an offer to join the MIT faculty.
6. Ed actually first used a seagull metaphor (Lorenz, 1963,2): "One meteorologist remarked that if the theory were correct, one flap of a sea gull's wings would be enough to alter the course of the weather forever. The controversy has not yet been settled, but the most recent evidence seems to favor the gulls." The butterfly term was probably introduced by Joseph Smagorinsky (1969), but the concept has a long lineage, dating back, perhaps, to Franklin's (1898) grasshopper: "Long range detailed weather prediction is therefore impossible, and the only detailed prediction which is possible is the inference of the ultimate trend and character of a storm from observations of its early stages; and the accuracy of this prediction is subject to the condition that the flight of a grasshopper in Montana may turn a storm aside from Philadelphia to New York!"
7. Ed's statement may be thought of as his version of Pascal's Wager.

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